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Novel Energy Storage in the European Union

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Contents

Abstract

This report analyses the technology status, value chain and markets of energy storage technologies which are considered ‘novel’. While most of the technologies covered are still in the research phase and therefore fall into the novel category, some classic energy storage technologies are also included to provide the bigger picture. Energy storage technologies can contribute significantly to the decarbonisation of the energy system, cost reduction, and the enhancement of energy system flexibility by saving large amounts of energy for a later moment of need. By deploying innovative energy storage technologies, the European Union can unlock new opportunities for the global energy transition.

Foreword

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

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Executive summary

Energy Storage Systems (ESS) are envisaged to play an increasingly important role in the future energy system. By incorporating storage solutions, utilities can optimise resource utilisation, address intermittency challenges related to renewable energy sources, and boost overall system reliability. Additionally, energy storage technologies enable cost savings by storing inexpensive energy for use during periods of higher costs while also reducing overall grid extension costs. Performance characteristics, including cycle longevity, efficiency, energy density, and storage duration, differ across storage technologies and must be considered when determining their suitability for specific applications. The novel technologies selected for the study cover mechanical, electromagnetic and thermal energy storage technologies. Some mature technologies like latent and sensible thermal energy storage technologies are covered in the study as well. While some mature technologies like adiabatic compressed air energy storage are ready for widespread implementation, emerging technologies like isothermal compressed air energy storage and thermochemical energy storage are still in development and require optimisation.

Estimating the installed capacity of novel energy storage at the global and European scale is complex. Limited data from existing research, individual systems, and assumptions to approximate the order of magnitude pose significant challenges. This underscores the need for more comprehensive data and research in this area.

The global turnover for thermal energy storage, compressed air, and supercapacitors has been stable or slightly growing, while technologies like gravity energy storage, superconducting magnetic energy storage, and flywheels have reduced turnovers. Europe dominates the thermal energy storage market and holds a significant market share in other energy storage technologies, with key companies based in Germany, France, Italy, Spain, and Finland.

EU companies, including start-ups and established energy-related firms, contribute to technology development and deployment across various energy storage systems. Research and implementation efforts vary among EU countries, with Spain, France, Germany, Italy, Greece, Ireland, and Austria being key players. The EU leads in public investments in energy storage technologies, with Germany being the fourth country with the highest number of patents registered.

The supply chain of energy storage technologies varies depending on the specific system used. Notably, the novel energy storage systems considered here have very low reliance on critical raw materials.

Table 1. CETO SWOT analysis of the competitiveness of novel energy storage technologies

Strengths	**Weaknesses**
– High TRL systems are available for most technologies. – Offer options for long-duration and scalable energy storage. – High power density and high efficiency of some technologies. – Address intermittency challenges and provide continuous energy supply at the time needed.	– Low energy density can limit the deployment of some systems. – Energy losses. – Limited R&I projects in the EU for some of the technologies. – Low commercialisation level of some technologies.
Opportunities	**Threats**
– Support the electrification and decarbonisation of energy systems. – Improved flexibility and cost reductions for energy suppliers. – Energy security in rural or isolated areas not connected to the grid.	– Lack of data and potential to monitor progress. – Further deployment is necessary to best evaluate costs and performances. – Restrictive access to public funds and the possibility to grow in the EU after the R&I stage.

Source: (JRC, 2024)

1 Introduction

Energy Storage Systems (ESS) have evolved due to changing operational requirements and market opportunities for energy providers, leading to the development of various storage technologies with unique characteristics like response times, power densities, round-trip efficiencies, sizes, and costs. These variations enable different storage technologies to cater to diverse use cases, such as addressing intermittency and dispatchability challenges for Renewable Energy Sources (RES). Applications range from uninterruptible power supply, transmission and distribution, customer energy management, and ancillary services, tailored by factors like discharge time and power capacity. This report offers an extensive overview and evaluation of energy storage technologies, examining their applications, costs, competitiveness, environmental and socio-economic impacts, resource efficiency, and market positioning.

1.1 Scope and context

This report provides a comprehensive analysis of novel energy storage technologies. Several energy storage technologies depend on rare earth metals sourced and processed outside the EU, which make them susceptible to economic and political conditions.

This study focuses on specific technologies to shed light on the competitiveness and reliance on critical raw materials for non-electrochemical energy storage technologies (Table 2). These technologies cater to diverse energy storage applications, with some focusing on long-term storage needs while others address short-term requirements such as flywheels and supercapacitors.

The term "novel" is employed broadly to encompass the selected technologies despite their diverse nature and varying degrees of deployment in the global market. This work delivers a comprehensive comparison of the selected energy storage technologies, encompassing different technology readiness levels. Additionally, the report includes an analysis of the technologies' value chain and assesses the positioning of the EU industry in the global market.

Table 2. Technologies selected for the study

Energy conversion type	Selected technologies
Electromagnetic	• Supercapacitors (SC) • Superconducting magnetic energy storage (SMES)
Mechanical	• Flywheel energy storage (FES) • Liquid air energy storage (LAES) • Compressed air energy storage (CAES) • Gravity energy storage (GES)
Thermal	• Sensible thermal energy storage (STES) • Latent thermal energy storage (LTES) • Thermochemical energy storage (TCES)

1.2 Methodology and Data Sources

The methodology followed in the report includes analysing data and information available in the public domain for all the selected technologies. The data collected focuses on three different topics, structuring the publication:

Maturity and developments of the technologies studied

The current state of the energy storage systems (ESS) is analysed based on factors like installed capacity, costs, and investments, with varying depths of discussion for sub-technologies depending on available data. The maturity levels for various ESS are assessed using existing research and market data, with varying methods and levels of detail depending on the specific sub-technologies.

Installed capacities sometimes differ by source, with estimations from secondary sources or non-exhaustive lists of recent deployments. Cost assessments include capital and maintenance expenditures, and levelised storage costs and material costs where data is available.

Value chain analysis

In this second part of the report, the value chain of each technology and, where possible, its segments are assessed by collecting data and research on turnover, sustainability performance, the role of EU companies, and employment.

Following an in-depth analysis of various market reports and data obtained from EASE members and other industry stakeholders, multi-year estimations of technology market value and its distribution per geographical area, sub-technology, and application type are presented. Furthermore, key global and EU mature market players and start-ups are identified, and their products or services are investigated to determine their positioning in the value chain. Additionally, data on gained funds and insights into EU start-ups' overall funding opportunities and barriers are reported.

Through comprehensive research and assessment of scientific papers, with inputs from EASE members and other industry stakeholders, findings on the main life cycle environmental impacts and socio-economic impacts are reported and synthesised.

Energy and employment databases were consulted to identify technology-related employment trends and key players. However, both global and EU data specific to each technology are limited. To mitigate this gap, non-exhaustive information on EU countries and companies that are employing professionals is provided based on data collected from, for example, company websites, as well as on internal data from EASE members and other industry stakeholders.

Market development and EU competitiveness

Investments, publicly funded projects and resource efficiency are considered to contextualise the EU's global position. The primary materials utilised in technologies are outlined, and assessment methods vary based on data availability to gauge the resource efficiency of storage systems and the EU's potential material dependence. Specific European innovation and commercialisation projects are outlined to discuss the development of novel ESS technologies in the EU. EASE contributed with internal insights, and their interviews broadened the scope of available information, adding depth to the overall assessment of these technologies.

2 Technology status and development trends

2.1 Technology readiness level

This study covers a broad range of novel energy storage technologies. They were classified into three main types: mechanical, electromagnetic and thermal energy storage. Table 3 exemplifies the performance characteristics of some of the technologies covered in the report.

Table 3. Performance characteristics of different energy storage technologies

	Reference	Energy density (Wh/kg)	Power (MW)	Storage duration	Lifetime (years)	Discharge time	Number of cycles	Cycle eff (%)
Flywheel energy storage	(Chmielewski, et al., 2020)	20 - 80	0.1 - 0.2	Seconds-minutes	15 - 20	Millisecs-15 min	20 000 - 10 000 000	89-95
Gravity energy storage	(Mitali, Dhinakaran, & Mohamad, 2022)	-	40 - 1 600	-	-	1 - 4 hours	-	75-80
Compressed air energy storage	(Chmielewski, et al., 2020)	2-6	> 300	Hours-months	20 - 40	1 - 24 hours+	8 000 - 17 000	42-54 (70 for A-CAES)
Liquid air energy storage	(Chmielewski, et al., 2020)	80 - 120	15 - 400	Minutes-hours	30+	1 - 24 hours+	7 000 - 17 000	55-62
Superconducting magnetic energy storage	(Chmielewski, et al., 2020)	0.2 - 6	0.1 - 10	Millisecs-hours	20 - 30	>30 min	Up to 10 000	95-97
Supercapacitors	(Mitali, Dhinakaran, & Mohamad, 2022)	1.5 - 2.5	0-0.3	-	> 20	Millisecs-1 hour	-	75-95
Latent thermal energy storage	(Chmielewski, et al., 2020)	148 - 200	Up to 50	Hours	Up to 25	1 hour	> 1 000 000	60-97
Sensible thermal energy storage	(Mitali, Dhinakaran, & Mohamad, 2022)	15 - 80	0.1 - 300	Minutes-days	5 - 30	1 - 24 hour	-	50-90

2.1.1 Mechanical energy storage

Mechanical energy storage (MES) systems convert electrical to mechanical forms such as potential or kinetic energy and vice versa. Excess electricity generation is stored as mechanical energy and can be transformed into electricity when demand increases. MES systems exist in various forms, including flywheel energy storage, gravity-based storage, compressed air energy storage, liquid air energy storage, and pumped-storage hydropower. Most MES systems can quickly convert and release stored mechanical energy (Mitali, Dhinakaran, & Mohamad, 2022).

Flywheel energy storage (FES) uses kinetic energy by coupling a flywheel with an electric machine and surrounding the rotating flywheel with a vacuum, often created by a vacuum pump. The electric machine acts as a motor, spinning the flywheel rotor at high speeds. When energy is needed, the motor switches to generator mode, slowing down the flywheel and producing electricity. The round-trip efficiency is in the range of 90–95% for the most advanced systems. The lifetime is more than 20 years. However, their storage capacity is limited, see Table 3. The acquisition costs are high but compensated by long lifetimes and low maintenance requirements.

FES power densities can be up to 5–10 times that of batteries. Since they have relatively lower volume requirements and longer working life, they can be a supplement or an alternative to batteries in specific applications (transportation and space vehicles, etc.) (Pullen & Amiryar, 2022). Furthermore, FES has a specific application niche in the energy system, thus not competing with many other options.

Recent innovations on the material side are leading to improvements in the energy storage cycle performance, pushing this energy storage technology to the multi-hour energy storage capacity[1].

Gravity energy storage (GES) employs a mechanical lifting process to elevate a block or piston, gathering potential energy that is later released during peak periods to generate electricity. During charging, off-peak electricity drives the motor, converting it to mechanical energy to raise the block and store energy. In the discharge phase, the descending block applies pressure to drive the turbine and generate electricity.

GES systems can be divided into different categories based on multiple aspects. Some are constructed underground (Gravity Power, Gravitricity), while others are above ground (Energy Vault, Energy Cache, ARES, GravitySoilBatteries) or offshore (SinkFloatSolutions). Several GES technologies are still at the concept level, but some systems have already completed demonstration projects (Tong, et al., 2022). The specific characteristics and maturity status of example technologies can be found in Table 4.

Table 4. GES Technologies' performance characteristics.

	Tower-GES	Shaft-GES	Piston-GES	Mountain Mine-Car-GES	Mountain Cable-Car-GES	Linear Electric Machine-based -GES
Energy storage capacity (MWh)	20 – 5 000	1 – 20	1 – 8 000	5 – 1 000	1 – 20	1 – 5
Cycle efficiency	90	80 – 90	75 – 80	78	85	81
Location adaptability	Good	Poor	Good	Poor	Poor	Good
Response time	Seconds	Seconds	Seconds	Seconds	Seconds	Seconds
Lifetime (years)	30 – 40	50	40 – 60	40	15	50
Modularity	Good	Poor	Poor	Good	Good	Good
TRL	6-7	5	3-4	6-7	3-4	3-4

Source: (Tong, et al., 2022).

Compressed air energy storage (CAES) operates, similarly to gas turbines, by compressing air or another gas, storing it under pressure until needed for peak periods to drive a turbine and produce electricity. Stored energy levels rely on factors such as container volume, pressure, and temperature. CAES plants can be large, medium, and small-scale according to the magnitude of energy that can be stored (Mohanty, et al., 2023) (Soltani, et al., 2022) (Zohuri, 2022). CAES systems can store compressed air either above ground in pressurised vessels or underground caverns such as abandoned underground gas wells, salt-rock caverns or mine caverns (MIT - Massachusetts Institute of Technology, 2022) (Soltani, et al., 2022).

[1] https://www.qnetic.energy/

CAES technologies are classified according to their approach to managing the heat produced during air compression, resulting in three distinct types: diabatic (D-CAES), adiabatic (A-CAES), isothermal (I-CAES) and Supercritical CAES (SC-CAES) (Borri, Tafone, Comodi, Romagnoli, & Cabeza, 2022). Adiabatic-CAES systems, the most widely used, store and use heat from compression with an efficiency of about 75%. The main advantage of Adiabatic-CAES is that external energy sources like fossil fuels are not needed. Diabatic-CAES is the simplest and cheapest design approach of CAES (Soltani, et al., 2022) (Chmielewski, et al., 2020). A drawback is the energy loss due to heat during compression, reducing efficiency (Vecchi, Li, Ding, Mancarella, & Sciacovelli, 2021) (Soltani, et al., 2022). Adiabatic-CAES offer a limited number of cycles of 1,000 compared to existing Diabatic-CAES, which can reach 20 000 (ENTEC – Energy Transition Expertise Centre, 2023).

The main advantages of Isothermal-CAES are that less power is required for the compression stage compared to A-CAES and that efficiency can be very high (about 80%) (Soltani, et al., 2022). However, no such operational system exists as of today. New systems are being developed, but several diabatic systems are already operational and adiabatic ones are also being developed, see Table 5.

CAES can be coupled with thermal energy storage (TES) to save and reuse the heat generated in the compression phase of the process. Due to this hybridisation, the total efficiency of the plant can be increased, and the fuel consumption reduced (Soltani, et al., 2022).

CAES is the only ESS option, apart from pumped-storage hydropower, that is widely available and can store large amounts of energy and release it over long periods. Despite being very suitable for large capacity storage for grid integration, the overall roundtrip efficiency of CAES is lower when compared to pumped-storage hydropower systems. Therefore, its use for RES based power plants is challenging. Other drawbacks and risks associated with CAES are limited geologic formations, safety (rupture of the tank), and cost (mostly financing difficulties due to underground construction) (Zohuri, 2022).

Liquid air energy storage (LAES) stores electricity by compressing air or nitrogen and then cooling it to liquid form. Air and nitrogen are used both as storage medium and working fluid (Liang, et al., 2022). During charging, electricity compresses air, which is cooled in intercoolers to ease compressor workload. After compression, the air is further cooled in stages, transforming it into liquid.

LAES is already a well-developed technology but is not extensively deployed with a TRL ranging from 7 to 9, depending on the systems. A few new prototypes are being set up and several systems are operational around the globe.

LAES systems are generally considered an electrical storage technology to be used to provide grid services, such as price arbitrage, peak-shaving, renewable capacity firming, operating reserve, back-up power, and flexibility. These systems can also provide high-level multi-vector energy services from small to medium scales (Liang, et al., 2022).

Pumped Heat Electricity Storage (PHES). This type of technology is linked to power-to-heat-to-power systems. A novel concept that uses this technology is named "Carnot Battery"[2]. Electricity is used to store heat. The TES technology selected depends on when and at what temperature the heat should be stored. During the discharge, the heat stored will be part of a thermodynamic cycle producing electricity.

[2] https://en.wikipedia.org/wiki/Carnot_battery

There are some demonstration plants like the one of Siemens Gamesa with a storage capacity of 130 MWh_{th} and turbine of 1.2 MW operating in a Rankine cycle, and this technology is considered to have reached a TRL of 5-7 (Vandersickel, et al, 2023) . Furthermore, another plant developed by Azelio uses a Stirling engine with a capacity of 13 kW_{el} and electric heating (Vecchi, et al., 2022). The technology is still at an early stage and not widespread in the market, so the TRL should be between 5 and 7. CHESTER prototype was a project funded under the framework of H2020 and reached a TRL of 3-5 (Vandersickel, et al, 2023).

2.1.2 Electromagnetic Energy Storage

Electromagnetic Energy Storage (EMES) stores energy in a magnetic field. The technologies included under this type of energy storage are: superconducting magnetic energy storage and supercapacitors. Both receive electrical energy and transform it into magnetic energy and vice versa. These technologies utilise superconducting materials and offer energy storage applications, from grid stabilisation to electric vehicles.

Overall, the main advantages of electromagnetic energy storage are the almost immediate response, the possibility for indefinite power storage with low power loss and the absence of moving parts (superconducting magnetic energy storage). The latter means high durability and no moving parts (supercapacitors). The main disadvantages are the high cost and cooling requirements (superconducting magnetic energy storage), the ability to provide power only over a short duration, high self-discharge (supercapacitors) (Panchabikesan, Mastani Joybari, Haghighat, Eicker, & Ramalingam, 2022).

Superconducting magnetic energy storage (SMES) employs a magnetic field in a superconducting material for energy storage. The material is generally cooled below its critical superconducting temperature. With SMES, almost immediate power extraction is guaranteed, with high outputs over a short duration. The drawback is that a dedicated cryogenically cooled refrigeration system is needed, and this is costly. Magnetic storage is feasible both at large and small scales. However, large scale SMES usually have high costs and small scale applications are preferred (Panchabikesan, Mastani Joybari, Haghighat, Eicker, & Ramalingam, 2022). The TRL of SMES systems ranges between 5 and 9, meaning new systems are being developed, but the technology is generally well deployed as an efficient storage solution (Table 5).

Feedback from industry stakeholders (2024) indicated that SMES based on liquid helium-cooled superconductors had reached grid integration while new generation high-temperature superconductors only reached TRL 4-5. They specified that second-generation materials going through development, sometimes called ReBCO coated conductors, and magnesium diboride can operate at high temperatures.

Supercapacitors (SC), sometimes referred to as ultracapacitors or electric double-layer capacitors, are a specific type of capacitor. Ultracapacitors can supply devices with high currents, up to several kiloamps, making them ideal for peak power demand situations (Chmielewski, et al., 2020).

Carbon nanowires, graphene, nanocrystalline diamonds, c-dots, and 2D MXene are the most commonly used materials. Graphene-based SC are among the most favourable electrodes. These types of electrodes are lightweight, durable, low cost, thin, flexible, and safe. Moreover, they have a large surface area (about 2 500 m^2/g) that offers a significantly high number of charges to store electrical energy.

SC has gained relevant attention in recent years due to its high power density, fast charge-discharge rate, and outstanding cycle life. Among the drawbacks of supercapacitor energy storage systems are significant voltage fluctuations during operation.

SC offers rapid energy storage for short-term needs. They are also well established in the storage markets, with TRLs from 6 to 9, see Table 5. SC applications include network stabilisation, transportation (e.g., alongside truck batteries), electric vehicles (augmenting Li-ion batteries), personal electronics and the military industry.

2.1.3 Thermal Energy Storage

Thermal energy storage (TES) systems store energy by heating or cooling a medium to be used later. The storage can occur for hours, days, months, or seasons. Sources for charging include renewable or non-renewable energy, including nuclear energy, combustion, solar thermal and waste heat (MIT - Massachusetts Institute of Technology, 2022).

Several options are available for energy storage materials. The choice of storage system varies based on the application, period for which the energy should be stored, area availability, financial condition, and safety requirements. TES stands out as a promising solution for long-duration storage needs, primarily owing to its ability to effectively retain heat within materials that are affordable and readily available (MIT - Massachusetts Institute of Technology, 2022).

According to a more exhaustive list of applications classified according to sectors, TES is used in the building sector for air conditioning, domestic water heating, peak load management, energy sustainability, support to the operation of renewables, and district heating and cooling networks. If heat or cold is needed, and the energy supplies use electricity, TES allows energy storage on the demand side, and thereby shaving load off the electricity grid at peak times. In the industrial sector, TES is used for waste heat recovery, thermal management of large-scale PV arrays, telecommunication and software equipment. (Panchabikesan, Mastani Joybari, Haghighat, Eicker, & Ramalingam, 2022).

The maturity of each TES technology varies, from low TRLs of 2-5 with thermochemical technologies, to technologies that are in the market since several years like water tanks technologies, boreholes or ice (IRENA, 2020).

Latent thermal energy storage (LTES) operates by utilising the latent heat absorbed or released during a phase change in the storage material. Latent heat is usually much higher than the sensible heat of the material. When used in buildings, LTES systems are classified, based on their integration, into active or passive. A system is passive if heat is charged or discharged through natural convection or solar radiation, and there is no mechanical input or additional energy. On the opposite, active LTES systems need mechanical input, forced convection or additional energy (Sevault, Vullum-Bruer, & Lehn Tranås, 2022). LTES, depending on the materials used for its phase change process, reaches TRLs from 5 to 9 (Table 5). While some systems are well deployed, LTES technology is currently not as established as sensible heat storage (Systemiq, 2024).

The most common application LTES using PCM are as follows: TES for solar energy; passive storage in buildings or bioclimatic architecture; cooling; heating and domestic hot water; thermal protection of food; thermal protection of electronic devices; medical applications; cooling of engines; thermal comfort in vehicles; solar power plants; cold storage in industry; heat storage in industry; cold chain; human body, etc. (Prieto, Vérez, & Cabeza, 2022) (Mehling, Brütting, & Haussmann, 2022).

The classification of LTES systems categorises them based on phase change type and storage material. Various forms of LTES systems exist, including solid-solid, solid-liquid, solid-gas, and liquid-gas transitions. Among these, solid-liquid transitions are particularly favoured in TES systems due to their lower latent heat and minimal volume changes compared to other transitions (Mitali, Dhinakaran, & Mohamad, 2022). While there are several solutions and diverse materials that can be used for LTES, Roca Reina et al. (2023) use the following classification to discuss them:

- Ice Storage (IS)
- Sub-zero temperature PCMs (SZTPCM)
- Low-Temperature phase change material (LTPCM)
- High-Temperature phase change material (HTPCM)

The multiple applications of PCM already mentioned are distributed also according to the temperature associated to each of these materials: Ice Storage and Sub-Zero Temperature PCM are mainly used for air conditioning and in the food processing industry; Low-Temperature PCM are used for for solar, electronic, building and energy saving; High-Temperature PCM are mostly dedicated to concentrated solar power, industrial and aerospace applications (Chandrasekar, Reuben Raj, & Suresh, 2022).

LTES are classified also based on storage type. Packed bed storage (TRL 5-6) are one of the most studied. It is applicable for both high and low temperature systems. Some disadvantages are poor heat transfer in case of large dimensions of encapsulation, high void fraction, less compact and significant pressure drop. However, these systems are considered the simplest and most reliable ones. Shell-and-tube type storage (TRL 6-7) , made of a bundle of tubes enclosed in a shell. One of the main disadvantages is the low thermal conductivity. In plate based LTES (TRL 5-6), PCM is encapsulated in a rectangular plate shape, and installed longitudinally along the flow direction of HTF. Slurry (TRL 4-5) is made of a carrier fluid and a dispersed phase represented by the PCM (Yang, et al., 2022).

Sensible Thermal Energy Storage (STES) stands as the most widely used TES system, storing heat energy by raising the temperature of a solid or liquid without phase change. The presence of STES in the storage market is clear with TRLs of 8 or 9 depending on the systems (Table 5). A core advantage of STES is its reversible charging and discharging (Mitali, Dhinakaran, & Mohamad, 2022).

Materials employed need to guarantee stability in a broad and high temperature range. The most commonly used liquid material with high heat capacity is water. Commonly used solids are bricks, concrete, sand, soil, and metals. (Datas, 2022) (Panchabikesan, Mastani Joybari, Haghighat, Eicker, & Ramalingam, 2022). Among sensible storage media that are not solid, steam and water at high temperatures and pressures can be stored in a steam accumulator, which is a good option for mid-term heat storage, due to its high discharging rate and short reaction time. However, the pressurised container required causes high initial investment.

For industrial applications above 400ºC, Molten Salt TES (MSTES) are used. These have nearly null vapor pressures, optimal thermal stabilities, high boiling points and large heat capacities. However, MSTES have a very high viscosity, causing a higher pumping cost. Liquid metals are another option for high-temperature sensible heat storage media. Nevertheless, their application is limited by high costs, considerably strong chemical corrosivity and possible toxicity.

Aquifer TES (ATES) and Borehole TES (BTES) are two groups of underground TES. ATES make use of open geothermal systems extracting and returning water from the aquifer via a system of cold and warm wells. They are usually used to store natural cold in winter and this is later used for cooling in summer. In a similar way, also the excess summer heat can be stored for heating. Geophysical characteristics and the climate conditions highly influence the suitability of these technologies.

Therefore, they are promoted in countries with appropriate conditions, such as Sweden and Netherlands in the EU (Cabeza, Mehling, & Romaní, 2022) (Casasso, Giordano, Bianco, & Sethi, 2022).

Thermochemical energy storage (TCES). This technology usually stores thermal energy by using reversible chemical reactions. This type of equilibrium reactions are endothermal, meaning they need energy to start. For this reason, heat sources that could be considered "free", such as solar energy or waste heat, could create these reactions and store thermal energy without thermal losses. Metal oxides could be considered one of the chemical compounds that are more promising for these type of reactions that allow us to store thermochemical energy. Regarding the status of the technology, there are several pilot-plants working with TCES. This means that the TRL that could be assigned could reach 7. Of course, depending on the chemical reaction studied, the TRL could be even lower.

Table 5. TRL results of the different TES technologies

	TRL (Technology Readiness Level)								
Sub-Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Mechanical energy storage									
Flywheel energy storage (FES) (Chmielewski, et al., 2020)*: 7-9* (Mitali, Dhinakaran, & Mohamad, 2022)*: 5-7*									
Gravity energy storage (GES). (Tong, et al., 2022)*: 3-7*									
Compressed air energy storage (CAES). (Chmielewski, et al., 2020)*: 9* (Vecchi, Li, Ding, Mancarella, & Sciacovelli, 2021)*: 5-9* (European Commission, 2023)*: 7-8*									
Liquid air energy storage (LAES) (Chmielewski, et al., 2020)*: 7-9* (Vecchi, Li, Ding, Mancarella, & Sciacovelli, 2021)*: 7-8* (European Commission, 2023)*: 9*									
Pumped Heat Electricity Storage (PHES): 5-7									
Electromagnetic Energy Storage									
Superconducting magnetic energy storage (SMES) (Chmielewski, et al., 2020)*: 5-9* (Mitali, Dhinakaran, & Mohamad, 2022)*: 5-6* (European Commission, 2023)*: 5-8*									
Supercapacitors (SC) (Chmielewski, et al., 2020)*: 8-9* (Mitali, Dhinakaran, & Mohamad, 2022)*: 6* (European Commission, 2023)*: 9*									
Thermal Energy storage									
Sensible Thermal Energy Storage (STES) (LDES Council, 2022)	*See the sub-technologies below.*								
Graphite									
Ceramics, silica, and sand									
Molten salts									

Concrete									
Rocks									
Steel									
Underground water									
Water									
Latent Thermal Energy Storage (LTES) (LDES Council, 2022)	*See the sub-technologies below.*								
Microencapsulated metals									
Inorganic salts and eutectic mixtures									
Sodium									
Other liquid metals									
Molten aluminium alloy									
Paraffin waxes, fatty acids									
Salt hydrates									
Salt-water mixtures									
Ice									
Thermochemical Energy Storage (TCES) (European Commission, 2023)									

Source: JRC own analysis using several sources mentioned throughout the chapter.

2.2 Installed Capacity and Production

The installed capacity documentation of emerging storage technologies poses challenges because of different reasons. These technologies are relatively new and lack standardised reporting mechanisms for their capacities. Additionally, the dynamic nature of research and development in this field means that capacity figures may fluctuate rapidly, complicating efforts to maintain accurate records. As a result, estimates are often necessary to assess the scale of deployment and understand the potential impact of these technologies on energy systems.

2.2.1 Mechanical energy storage

Flywheel energy storage (FES). With an estimated global power capacity of close to 400 MW according to Mitali et al. (2022) estimations. The DOE database of energy storage projects suggests that new projects' capacity are slightly above 1 GW and 400 MWh in 2020 (DOE – US Department of Energy, 2021). However, this data does not necessarily verify whether those projects are still operational. It was estimated in 2020 that FES installed power capacity would reach 1 GW in 2020 (Chmielewski, et al., 2020).

Several FES installations globally stabilise wind farms, such as Coral Bay in Australia and Marsabit in Kenya (Chmielewski, et al., 2020). In the EU, ABB delivered an FES system in the municipality of Lanzarote, Spain, that can deliver a maximum power of 1.65 MW to the grid (DOE – US Department of Energy, 2021).

Gravity energy storage (GES). GES systems have emerged as promising contenders in the realm of energy storage, delivering a power installed capacity ranging from 64 MW to 80 MW and an energy capacity of 110 MWh to 137 MWh (Table 6). Although still in the early stages of deployment, GES systems offer a compelling solution for long-term and large-capacity energy storage needs. Examples of operational projects globally are:

- **T-GES:** Energy Vault has developed a T-GES system in Rudong, China, with a capacity of 25 MW and a large energy storage capacity of 100 MWh (KSERC - Kerala State Electricity Regulatory Commission, 2023).
- **S-GES:** Gravitricity installed a 250 kW-class prototype in Edinburgh, Scotland in 2020. They intend to embark on a 4 MW-scale project and debut its first commercial 8 MW-scale project in the Czech Republic. In Romania, the state-owned coal mine operator Complexul Energetic Valea Jiului signed an agreement with Green Gravity to potentially convert 17 coal mines into S-GES systems to help cut coal usage.
- **P-GES:** From the multiple studies presented by Tong et al. (2022), P-GES storage capacity can reach tens of MWh and over 5 MW rated power. Gravity Storage, in Germany, is working on a P-GES concept, although no installations have been implemented to date.
- **MM-GES:** A 50 MW project in Pahrump, United States involves 10 multi-rail tracks, each holding 210 cars loaded with material weighing 75 000 tons (Viswanathan, Mongird, Franks, Li, & Sprenkle, 2022). Advanced Rail Energy Storage, the US company in charge of the project has not communicated existing developments.

A research project called GrEnMine studies the potential gravitational energy storage capacity in the Post-Mine Areas (2024-2027). It is led by Wroclaw University of Science and Technology (PL).

Compressed air energy storage (CAES). Eleven operational projects were identified globally by Mitali, Dhinakaran, & Mohamad (2022), CAES represented approx. 0.2% of the 190 GW global energy storage installed capacity in 2022. It then held an estimated capacity between 406 and 1 614 MW depending on the sources' data and methods (Table 6). The estimation from a database that contains both operational and announced projects could be considered an overestimation (DOE – US Department of Energy, 2021), also explaining why they estimate energy capacity above 40 GWh.

The global landscape presents only two notable high-power CAES facilities: McIntosh (110 MW) in Alabama, USA, and Huntorf (321 MW) in Germany. The efficiency of the latter is about 42%, and that of McIntosh is around 54%. The Huntorf plant is the world's first CAES power station and has been operational since 1978. It is used to provide peak shaving, spinning reserves and VAR support. A volume of 11 million cubic feet is stored in two underground salt caverns. The McIntosh project is the world's second CAES facility since 1991. It is used to store off-peak power, generate peak power and provide a spinning reserve. A volume of 19 million cubic feet is stored in a salt cavern and can provide full power output for 26 h. The system recovers waste heat, reducing fuel consumption by about 25% if compared to the Huntorf Plant (Zohuri, 2022). Corre Energy aims to use four underground salt caverns in Ahaus, Germany, to implement CAES installations delivering over 500 MW of power[3], to develop the CAES Zuidwending in the Netherlands with 320 MW and 1 920 MWh (European Commission, 2023) and the Green Hydrogen Hub in Denmark with 320 MW[4]. The latter will use technology from Siemens Energy to employ a D-CAES with hydrogen instead of natural gas. The construction of a 1 000 MW CAES installation named the Western Energy HUB in Utah, USA (Chmielewski, et al., 2020) was also announced in 2019 but there have not been public updates on the project since.

[3] Ahaus cavern construction in Germany now 75% complete (corre.energy)

[4] Green Hydrogen Hub Denmark - Gas Infrastructure EuropeGas Infrastructure Europe (gie.eu)

Regarding specific type of CAES, A-CAES is the one with more information available. The capacity is expected to increase rapidly with projects such as Eni's 100 MW / 400 MWh A-CAES system in China commissioned in 2022 and Alliant Energy's 200 MWh system which should be finalised in 2024 (KSERC - Kerala State Electricity Regulatory Commission, 2023). Hydrostor also announced 2 500 MW / 5 GWh A-CAES projects in California, intending to complete them in 2025 (Aurora Energy Research Ltd., 2022).

Liquid air energy storage (LAES). LAES technology has already reached significant development milestones, with commissioned demonstration projects ranging from 350 kW to 50 MWh capacities, but it still requires more time for extensive commercialisation (Viswanathan, Mongird, Franks, Li, & Sprenkle, 2022).

LAES systems host a power capacity of 50-100 MW and an energy capacity of 280-650 MWh globally according to the research from the KSERC (2023). Highview Power's LAES cryo-battery, located in Greater Manchester, England, is one of the largest of its kind, delivering a capacity of 50 MW and 250 MWh (KSERC - Kerala State Electricity Regulatory Commission, 2023).

One EU-funded project called CryoHub is developing Cryogenic Energy Storage at Refrigerated Warehouses as an Interactive Hub (2016 – 2021) led by London South Bank University (UK).

2.2.2 Electromagnetic energy storage

Superconducting magnetic energy storage (SMES). This technology currently represents a costly solution, and multiple systems are still in the research phase, explaining the lack of available information on operational systems. Low-temperature superconductor based SMES has been deployed with installations reaching up to 10 MW according to industry stakeholders' feedback (2024). Commercial installations are notably operated in Japan, with indications of 325 MW installed globally in 2019, but no information on energy capacity (EERA – European Energy Research Alliance, 2019).

B&W will build and install a 500 kWh SMES to provide spinning reserve to the Anchorage Municipal Light and Power (AML&P) utility (Zohuri, 2022). Moreover, multiple USA companies produce small SMES systems (micro-SMES of about 1 MW) for power quality improvements to selected customers rather than as grid or network solutions.

The EU has witnessed significant progress in SMES technology through various successful R&D initiatives. Despite these advancements, there is currently no presence of commercial SMES suppliers in Europe, with most expertise concentrated within R&D institutions (European Commission, 2023). Notably, projects like France's "Super SMES" by the Centre National de la Recherche Scientifique have led to the development of high-temperature superconducting SMES units (European Commission, 2023). Similarly, Germany's Karlsruhe Institute of Technology (KIT) has explored hybrid SMES concepts in conjunction with hydrogen storage. Siemens has been working on design and evaluation studies, such as the one on a 2 MWh/50 MW SMES for providing frequency stabilization to the electric system.

Supercapacitors (SC). Supercapacitors exhibit a power capacity ranging from 150 MW to 500 MW and an energy capacity from 600 MWh to 1 200 MWh (Table 6).

2.2.3 Thermal energy storage

Latent thermal energy storage (LTES). The diversity of latent heat storage systems, which can utilise various phase change materials and configurations tailored to specific applications, complexifies the capacity installed analysis. LTES currently represents a small share of TES installations, but its deployment is increasing (DOE – US Department of Energy, 2021). In 2020, the DOE database indicates that LTES capacity reached 104.6 MW and 660.3 MWh (DOE – US Department of Energy, 2021). Based on data collected by Cabeza, Mehling, & Romaní (2022), the installed capacity of ice storage from three large manufacturers reached 23.5 GWh and an installed power of 2 300 MW.

Sensible thermal energy storage (STES). Regarding STES, data from the DOE database (2021) indicates an increased expansion of STES with the development of new projects. In 2018, 3 GW power capacity and 20 GWh of power output worldwide were referenced (DOE – US Department of Energy, 2021) but not all installations are covered by the database, meaning these figures likely underestimate the actual number.

IRENA (2020) indicates that TES in 2019, predominantly for space heating, amounted to 234 GWh, while molten-salt-based electricity storage reached 21 GW. IRENA's projections for 2030 suggest a total storage capacity of 850 GWh, with molten-salt-based storage expected to contribute 630 GWh. Additional planned capacity stands at 73 GWh, with potential deployments ranging from 55 to 540 GWh (IRENA, 2020). A large part of molten salts installations since 2015 have been concentrated in district heating and solar power but no specific figures were identified (EASE members, 2024).

Concerning molten salts, there are 31 operative commercial plants for CSP worldwide: 21 in Spain, three in South Africa, three in the USA, one in Morocco, one in Chile, one in China, and one in Italy. The total thermal storage capacity of Molten Salt TES is estimated to be equivalent to 38 GWh_{th}. Concerning underground TES (Aquifer TES and Borehole TES), estimating the storage capacity is complex, since the boundaries of the storage system are not clear and the temperature gradient depends on working conditions and weather. Hence, the capacity is usually measured through the installed power capacity and total heat supply. Based on pilots from Sweden and Netherlands, the installed capacity of Aquifer TES was 2 659 MW, while the one of Borehole TES was considerably lower (315 MW) in 2016.

Thermochemical energy storage (TCES). There are some plants working with CaL and CO_2 capture, with a capacity around 5 MWth. Other facilities are located in Hualien (1.9 MWth), La Pereda (1.7 MWth) and Darmstadt (1 MWth) (Ortiz, Valverde, Chacartegui, Pérez-Maqueda, & Gimenez-Gavarrell, 2021).

Table 6. Summary of capacity installed taken from several data sources

Technology and references	Global power capacity (MW)	Global energy capacity (MWh)
FES		
(Mitali, Dhinakaran, & Mohamad, 2022)	408	-
(DOE – US Department of Energy, 2021)	1.02	413
GES		
(KSERC - Kerala State Electricity Regulatory Commission, 2023)	64	110
(DOE – US Department of Energy, 2021)	80	137

CAES		
(Mitali, Dhinakaran, & Mohamad, 2022)	407	-
(Vecchi, Li, Ding, Mancarella, & Sciacovelli, 2021)	431	-
(DOE – US Department of Energy, 2021)	1 614	40 087
LAES		
(KSERC - Kerala State Electricity Regulatory Commission, 2023)	50	250
SMES		
(EERA – European Energy Research Alliance, 2019)	325	-
SC		
(DOE – US Department of Energy, 2021)	150-500	600 -1 200
LTES		
(DOE – US Department of Energy, 2021)	105	660
STES		
(DOE – US Department of Energy, 2021)	2 864	20 905

2.3 Technology Costs

Existing research served as the core data source for examining the costs of various storage technologies. It is important to acknowledge that different studies employ diverse data sources and assessment methodologies, which may introduce limitations and discrepancies in the results.

Moreover, the costs associated with energy storage technologies are heavily influenced by the specific systems under consideration and their intended applications. Key factors contributing to cost discrepancies include storage capacity and duration. These variables account for the wide range of costs observed for the same technology across different implementations.

Energy capital expenditure (CAPEX) describes the initial investment required to install the energy storage system per unit of energy capacity, typically measured in euros per kilowatt-hour (€/kWh). The power CAPEX, on the other hand, represents the initial investment needed for the power capacity of the storage system, measured in euros per kilowatt (€/kW). Analysing energy and power CAPEX in the evaluation of energy storage technology costs is crucial for gaining comprehensive insights into their economic viability and operational efficiency. Next to CAPEX, operating expenses (OPEX) describe costs associated with the use of the systems, encompassing fixed and variable components.

The introduction of the levelised cost of storage (LCOS) enables an objective comparison of different storage technologies from an economic standpoint. LCOS quantifies the potential costs associated with storing 1 kWh, considering various system characteristics. It reflects the life costs related to the annual installed storage capacity of an energy storage system throughout its entire life cycle.

To evaluate a system's LCOS, the scope of system characteristics to be considered largely depends on available data. For instance, Chmielewski et al. (2020) encompass the system's CAPEX and OPEX, as well as replacement outlays, utilisation costs, and electricity charges for charging and discharging activities. The LCOS facilitates the evaluation of the economic feasibility of various energy storage technologies thanks to the multitude of factors considered.

2.3.1 Mechanical energy storage

Flywheel energy storage (FES). The energy CAPEX varies from 223 to 581 €/kWh while their power CAPEX ranges from 894 to 8,940 €/kW according to (Chmielewski, et al., 2020), but estimations among sources vary significantly (Table 12). According to Pullen & Amiryar (2022) estimations from 2020, energy CAPEX varies from 839 to 11 700 €/kWh and power CAPEX ranges from 210 to 294 €/kW. According to estimations from previous years, the capital cost per unit power of different technology configurations can vary between 503 and 2 181 €/kW, while the cost of operation and maintenance may vary between 5 and 5.3 €/kW-year. The International Renewable Energy Agency estimates that by 2030 the per unit energy installation costs of FES could fall by 35%, to 895–3 491 €/kWh (Kale & Secanell, 2022). The large differences, particularly in power expenses, can be explained by the difference in requirements between low-speed and high-speed FES. Fixed OPEX spans from 5.8 to 17.9 €/kW-year, while variable OPEX ranges from 0.0013 to 0.004 €/kWh.

The LCOS for FES is low, at 0.161 €/kWh, compared to other storage solutions other than batteries, in addition to advantages such as its rapid response times and long cycle life. FES used to have a cost advantage in specific power cost, but recent high-cost reductions for Li-Ion have nullified this aspect.

Regarding projections for 2030, Qnetic states that they could reach an LCOS of about 0.094[5] €/kWh.

Gravity energy storage (GES). Viswanathan, et al. (2022) obtain an average of 556-803 €/kW power CAPEX and 145-444 €/kWh energy CAPEX when comparing different GES systems. Data from technology providers presented by Tong et al. (2022) indicate a positive impact of GES technologies on LCOE, with T-GES allowing for LCOE 0.2 times PGES and 0.5 times lithium-ion batteries for S-GES. Table 7 demonstrates the importance of a GES' power capacity and storage duration on its costs. (Viswanathan, Mongird, Franks, Li, & Sprenkle, 2022).

Table 7. 2021 GES CAPEX and fixed OPEX

	100 MW			1,000 MW		
	4 H	**10 H**	**24 H**	**4 H**	**10 H**	**24 H**
CAPEX (€/kWh)	595.27	370.75	257.85	347.28	216.93	154.85
CAPEX (€/kW)	2 381.91	3 707.35	6 188.42	1 389.14	2 169.20	3 716.31
Fixed OPEX (€/kW-yr)	18.57	21.35	27.99	11.63	14.47	21.11

Source: (Viswanathan, Mongird, Franks, Li, & Sprenkle, 2022)[6]

Table 8 shows that the choice of materials can have a significant impact on the CAPEX of GES systems.

[5] Note that the estimation was expressed in USD and it was converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

[6] Note that all estimations were expressed in USD and these were converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

Table 8. Properties of different materials and their heavy material unit capacity costs

Material	Density per unit weight	Price per unit weight
	10^3 kg/m^3	(€)
Lead	11	222
Brass	9	1 039
Iron	8	14
Tin	7.3	4 764
Zinc	7	388
Aluminium	2.7	288
Concrete	2.5	6.5
Sand	1.5	1.3

Source: (Tong, et al., 2022)[7]

Compressed air energy storage (CAES). Chmielewski et al. (2020) estimate the energy CAPEX ranging from 1.8 to 107 €/kWh and power CAPEX between 358 and 787 €/kW (Table 12). Viswanathan et al. (2022) provide similar estimations with more depth detailing the fluctuations of costs depending on systems' parameters. Notably, there is a drastic reduction in CAPEX for CAES systems with large storage durations (Table 9).

Table 9. 2021 CAES CAPEX and fixed OPEX

	100 MW			1,000 MW		
	4 H	**10 H**	**24 H**	**4 H**	**10 H**	**24 H**
CAPEX (€/kWh)	240	99	44.52	15	221	92
CAPEX (€/kW)	962	994	1 312	1 068	885	915
Fixed OPEX (€/kW-yr)	13	13	13	15	8	8

Source: (Viswanathan, Mongird, Franks, Li, & Sprenkle, 2022)[8]

While capital costs are considerable, O&M expenses are low once the system is set up. Fixed OPEX ranges from 2.7 to 13.4 €/kW-year, and variable OPEX from 0.003 to 0.004 €/kWh, with LCOS of 0.307 €/kWh (Chmielewski, et al., 2020).

Utilising natural reservoirs offers significantly higher cost efficiency, while constructing a cavern exclusively for CAES in hard rock can escalate costs by as much as 80% (IRENA - International Renewable Energy Agency, 2020).

[7] Note that all estimations were expressed in USD and these were converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

[8] Note that all estimations were expressed in USD and these were converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

Table 10. CAES subcomponent costs

Subcomponent	Share of total costs (%)
Cavern	40
Turbine	30
Compressor	14
Owner's costs	7
Balance of plant	6
Engineering and procurement	3

Source: (IRENA, 2020)

Adiabatic-CAES generally has a slightly higher CAPEX with a 785 €/kW power expense average, when Diabatic-CAES is estimated at 759 €/kW by Viswanathan et al. (2022).

LAES has a CAPEX of 179 to 402 €/kWh, reflecting the investment required for the storage infrastructure and related components (Table 12). Salem & Kaira (2023) showcase the differences in energy CAPEX depending on the LAES systems. Particularly, they note that the most cost-efficient systems are solar-integrated LAES with 134.66 €/kWh due to low input energy consumption. Using recovered waste heat and gas can also enable low energy costs (Salem & Khaira, 2023). Power CAPEX falls within the range of 715 to 1,608.7 €/kW (Table 12), covering the costs associated with installing power generation equipment such as turbines and compressors. Additionally, fixed OPEX for LAES varies from 17 to 22.3 €/kW-year, representing ongoing expenses for maintenance and operational management. Variable OPEX for LAES spans 0.003 to 0.004 €/kWh, including costs related to energy consumption during the storage and retrieval process.

The LCOS for LAES, at 0.469 €/kWh (Table 12), showcases the overall cost efficiency of the technology over its operational lifespan but the technology remains more expensive compared to alternatives like CAES at this stage, notably due to high initial investment. Vecchi et al. (2021) indicate that the LCOS for standalone LAES systems tend to span between 0.13 and 0.3 €/kWh.

2.3.2 Electromagnetic energy storage

Superconducting magnetic energy storage (SMES). SMES systems require a significant initial investment, with energy CAPEX ranging from 4 468.7 to 64 348.9 €/kWh (Table 12), highlighting the substantial upfront costs associated with constructing the storage infrastructure and implementing superconducting coils.

Fixed OPEX for SMES ranges from 14.3 to 16.5 €/kW-year, covering maintenance and operational management costs, including cryogenic cooling. Variable OPEX is relatively low, averaging around 0.001 €/kWh.

Supercapacitors (SC). The energy CAPEX for SC ranges from 2 681.2 to 12 512.3 €/kWh, while power CAPEX spans from 22.3 to 402.2 €/kW, covering the costs associated with installing power generation components such as superconducting magnets and cooling systems (Table 12). Fixed OPEX and Variable OPEX are both minimal, as reported by Chmielewski et al. (2020) are less than 0.001 €/kW-year and less than 0.001 €/kWh, respectively. The LCOS for SC stands at 0.241 €/kWh (Table 12).

In terms of materials, using waste-based biomass for SC electrodes proves to be a highly economical option. The emergence of biomass-derived precursors overcomes the drawbacks of existing carbon materials, boosting commercial-scale production (Pynadathu Rumjit, et al., 2022).

2.3.3 Thermal energy storage

Latent thermal energy storage. According to Datas (2022), among High-Temperature PCM, silicon has a low cost of about 2 €/kg or about 4 €/kWh, while boron has a high cost. The investment costs of High-Temperature PCM are provided by IEA-ES, which are around 50-100 €/kWh[9]. Furthermore, IRENA estimated investment costs between 21.9 €/kWh and 201.8 €/kWh depending on the application, estimating an evolution to a range of 21.9-162.3 €/kWh by 2030 (Roca Reina, et al., 2023). Low-temperature PCM has investment costs, according to IEA-ES, between 20 and 100 €/kWh[10]. On the other hand, IRENA estimated installation costs between 50.9 and 202 €/kWh (Roca Reina, et al., 2023). High costs are also driven by the PCM and heat exchanger costs. High-performance or specific PCMs may cost almost 5 €/kg[11]. Heat exchanger costs are high when high heat transfer rates are expected. With an LCOS averaging 0.563 €/kWh for the different PCM materials, LTES overall emerges as a competitive storage option.

Sensible thermal energy storage. The energy CAPEX for STES ranges from 2.5 to 107 €/kWh by the account of Chmielewski et al. (2020), which considers Water Tank TES, Pit TES, Borehole TES and Aquifer TES but without specifying the specific CAPEX from each. (Yang, Liu, Kramer, & Sun, 2021) concluded that some UTES facilities had a levelised cost of heating between 20 and 180 €/MWh. Molten salts systems could have levelised costs from 20 to 70 €/kWh[12], and other estimations came up with installation costs between 22 and 35 €/kWh (Roca Reina, et al., 2023). Solid media energy storage, according to IEA-ES, can have investment costs from 15 to 40 €/kWh[13]. The materials used in TES are key to determining the effectiveness and costs of thermal storage, notably by considering the density of materials (Wang, Qin, Tong, & Ji, 2020).

[9] https://iea-es.org/wp-content/uploads/public/FactSheet_Thermal_Latent_HT_2022-10-19.pdf

[10] https://iea-es.org/wp-content/uploads/public/FactSheet_Thermal_Latent_LT_2022-10-19.pdf

[11] Note that this estimation was expressed in USD and this was converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

[12] https://iea-es.org/wp-content/uploads/public/Application_Thermal_Sensible_Liquid_Salt_2022-10-21.pdf

[13] https://iea-es.org/wp-content/uploads/public/FactSheet_Thermal_Sensible_Solids_HT_2022-10-21.pdf

Table 11. STES materials density and cost

Material	Type	Density (kg/m³)	Cost (€/m³)[14]
Rock	Solid	1 500 – 2 800	64 – 742
Concrete	Solid	2 000	76
Sand and gravel	Solid	1 700 – 2 200	6 – 8
Ceramic tile	Solid	2 000	1 600 – 3 500
Gypsum (coating)	Solid	1 000	78
Ceramic brick	Solid	1 800	36 – 64
Wood	Solid	450	404
Water	Liquid	990	1.6
Oil	Liquid	888	6,560
Nitrate salts	Liquid	1 825	2 200
Carbonate salts	Liquid	2 100	6 050
Liquid sodium	Liquid	850	2 000

Source: (Wang, Qin, Tong, & Ji, 2020)

Table 12. Costs of several Energy Storage technologies

Technology	Energy CAPEX	Power CAPEX	Fixed OPEX	Variable OPEX	LCOS
	€/kWh	€/kW	€/kW-year	€/kWh	€/kWh
FES	223 - 581	894 - 8 940	6 - 18	0.0013 - 0.004	0.161
CAES	2 - 107	357.5 - 786.5	3 - 13	0.003 - 0.004	0.307
LAES	179 - 402	715 – 1 609	17 - 22	0.003 - 0.004	0.469
SMES	4 469 - 64 349	179 - 437	14 – 16.5	0.001	0.715
SC	2 681-12 512	22 - 402	< 0.001	< 0.001	0.241
LTES	18 - 143	894 – 3 396	48	-	0.563
STES	2.5 - 107	82 – 328.5	107	-	-

Source: Chmielewski et al. (2020).[15]

Thermochemical energy storage. For reversible reactions, IRENA estimated costs between 70.2 and 140.4 €/kWh (Roca Reina, et al., 2023). Depending on the application the cost for sorption-based energy storage vary from 10.5 to 132 €/kWh (Roca Reina, et al., 2023).

2.4 Public RD&I Funding and Investments

The analysis carried out in this chapter is based on the International Energy Agency (IEA) data of 2024. The codes selected for the analysis are the ones linked to the technologies covered in the report. The investments are converted from national currency to euros using OECD average exchange rates for each specific year. Furthermore, two views are presented in the chapter: The EU and the rest of the world and the situation of investments inside the EU.

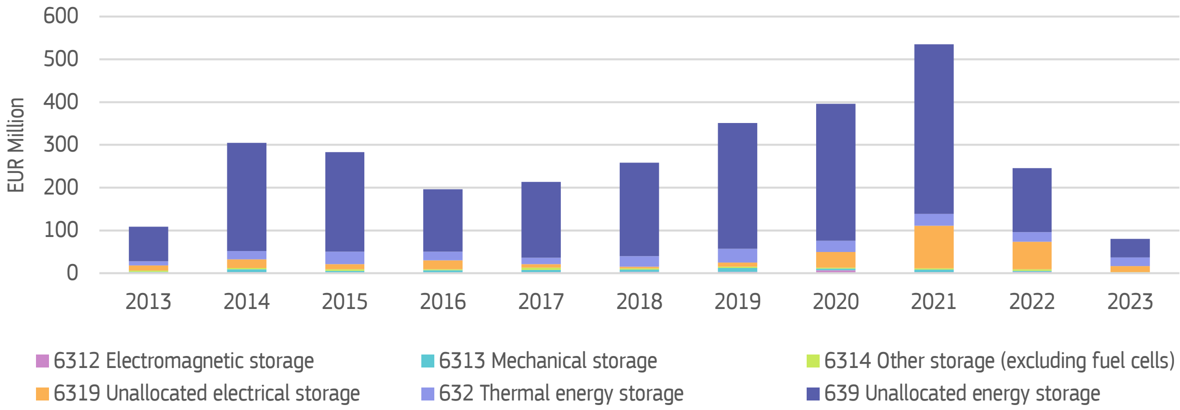
[14] Cost refers to the material specifically and thus impacts STES systems' OPEX.

[15] Note that this estimation was expressed in USD and this was converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

Figure 1 shows the results of the world public investments in energy storage technologies. The year 2021 showed a peak of more than €500 million. Afterwards, the investments have decreased every year. It is worth mentioning that, according to the available codes, it is hard to distinguish how many investments a technology had, as the classification "Unallocated energy storage" could cover some of them and the combination of some technologies.

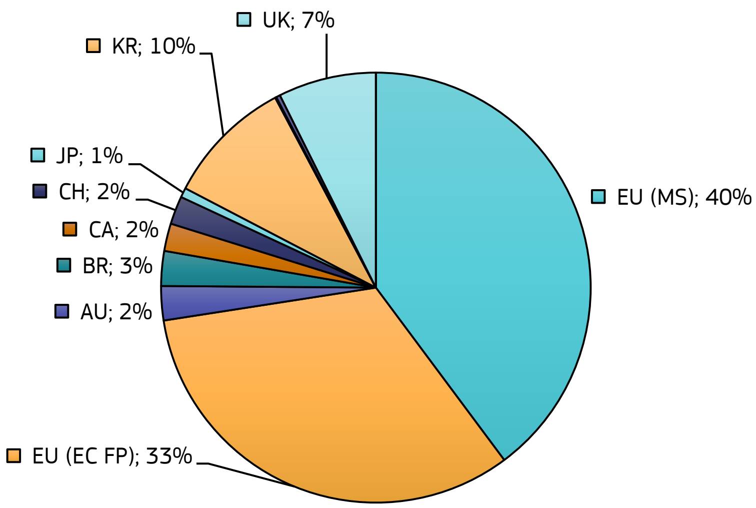
Figure 2 shows the share of global public investments, the EU reaching 33% with investments from Framework Programmes and 40% from the MSs' public sources.

Figure 1. World public investments in energy storage technologies



Source: JRC based on (IEA, 2024).

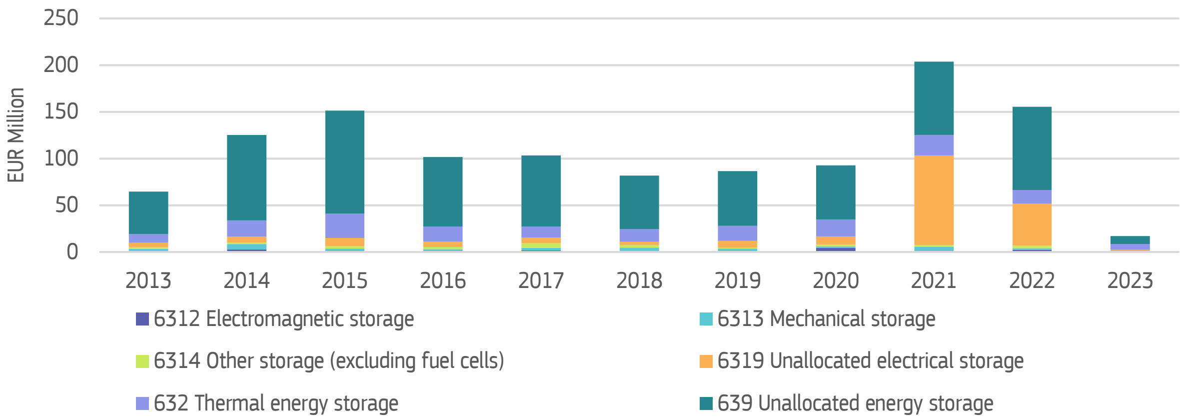
Figure 2. Share of global public investments



Source: JRC based on (IEA, 2024).

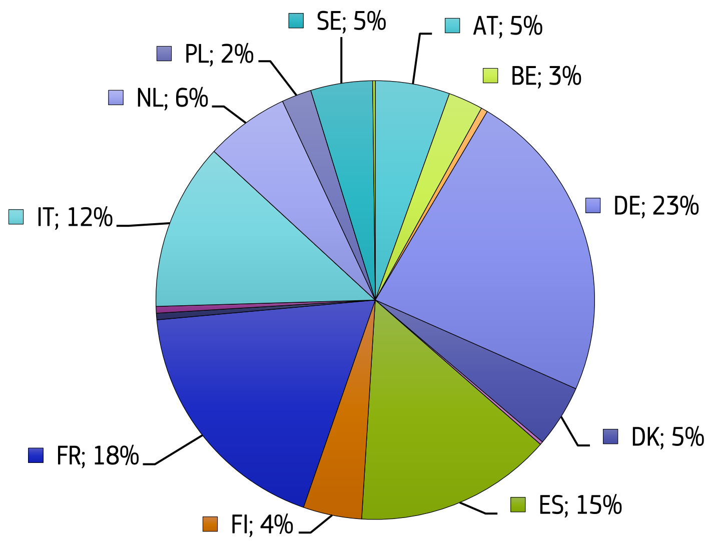
Figure 3 represents the results within the EU. The tendency through the years is almost the same as in Figure 1 due to the fact that most of the global investments come from the EU. The highest investment was in 2021, with around €200 million invested in these technologies. Germany, France, Spain and Italy are the leading MS in public energy storage investments (Figure 4). Similarly as for the global data, EU data has many investments in “Unallocated energy storage”, so there could be some inaccuracies in the data exposed in the subchapter.

Figure 3. EU public investments in energy storage technologies



Source: JRC based on (IEA, 2024).

Figure 4. Share of EU public investments



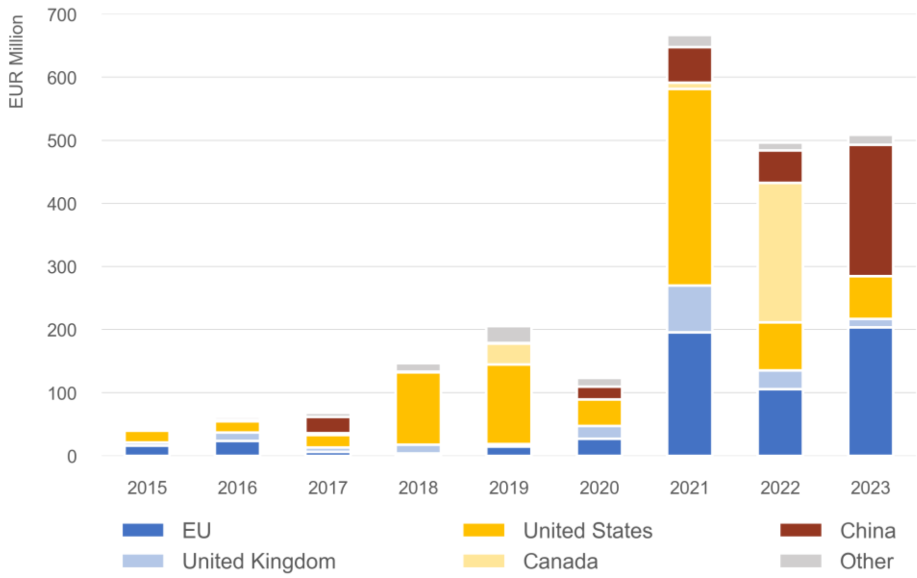
Source: JRC based on (IEA, 2024).

2.5 Private RD&I funding

This chapter presents private investments in terms of Venture Capital (VC), which is the investment in early-stage, high-potential, and high-risk companies. The companies analysed are in the energy storage sector, working with technologies listed in the report.

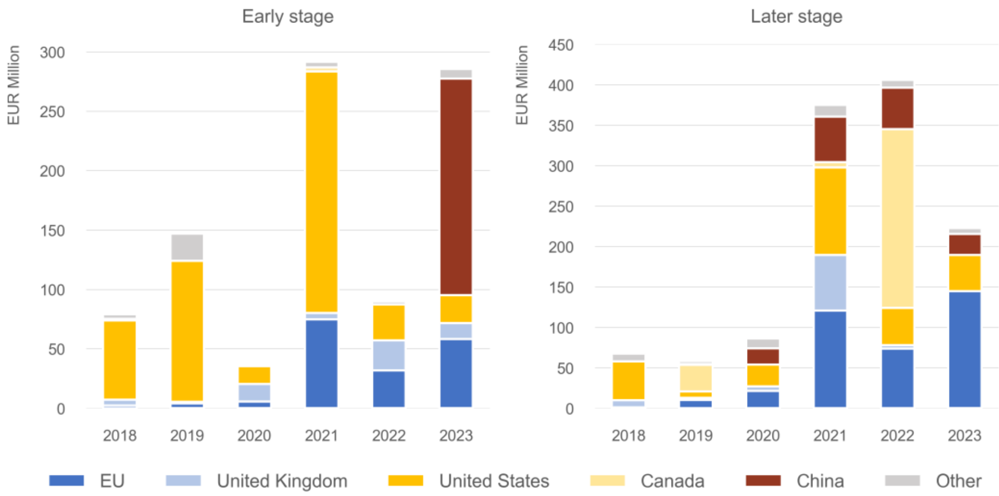
Figures 5 and 6 compare the venture capital investments per region and type of company. Since 2021, there is a high increase in venture capital investments for all the stages. In 2023, there was a total venture capital investment of €500 million in China (more with early-stage companies) and EU (higher share with later-stage companies), the largest investors with around €200 million. One of the reasons for this increase in venture capital investments in the EU could be the new targets of renewable energy for 2030 and 2050. These new targets require the presence of energy storage to integrate the renewable energy production in the power/thermal energy systems.

Figure 5. Global venture capital investments



Source: JRC based on PitchBook, 2024.

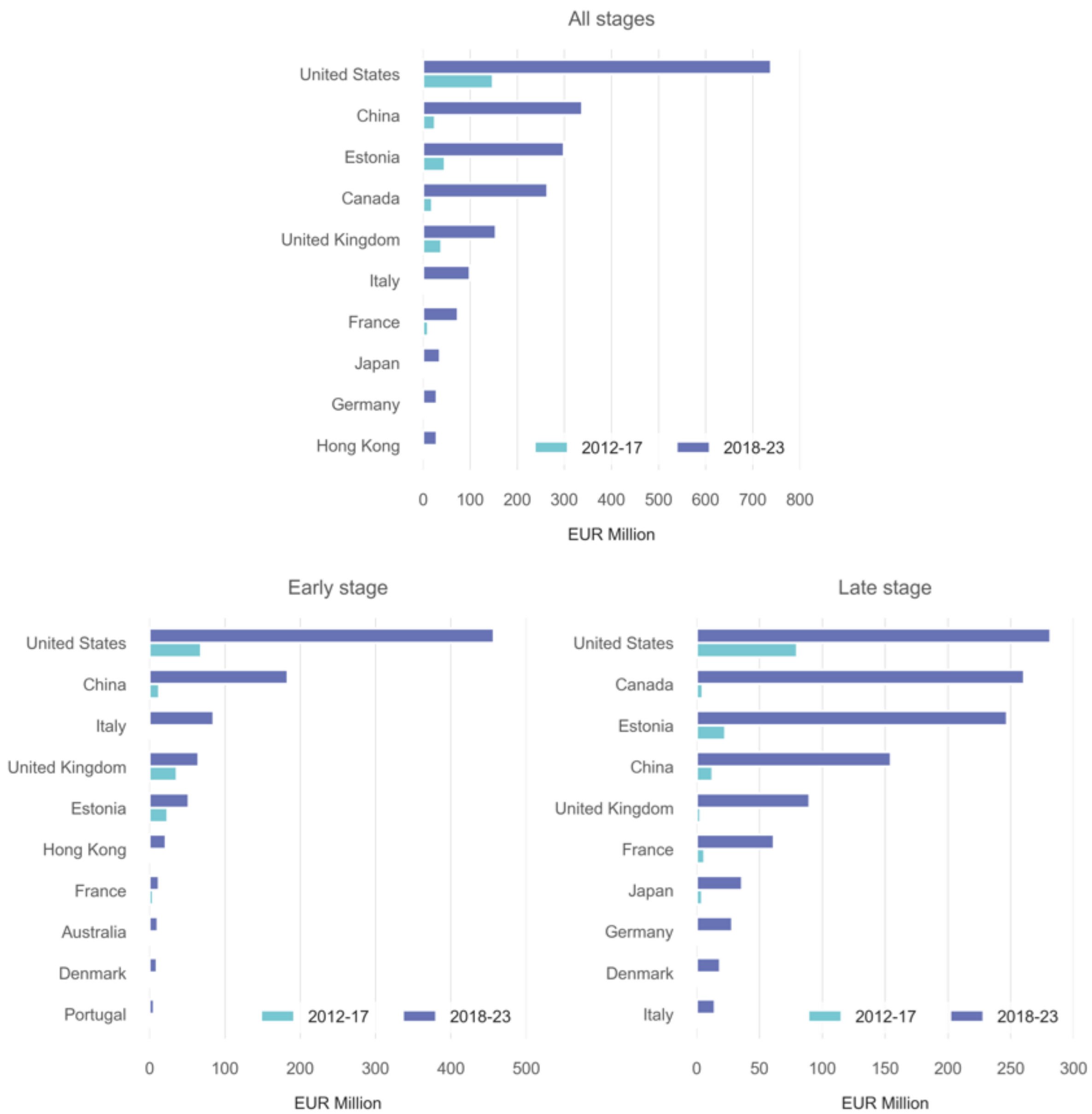
Figure 6. Global venture capital investments by type of company



Source: JRC based on PitchBook, 2024.

Another approach to compare the investments in venture capital is the analysis by periods, for example, from 2012-2017 and 2018-2023. There is a high increase in the period of 2018-2023 compared with the previous period, which is linked to the results shown in Figure 7. According to Figure 7, the US had a total investment in venture capital of more than €700 million, followed by China with more than €300 million. The US has invested less than China in 2023 but it has been investing on energy storage for a longer period.

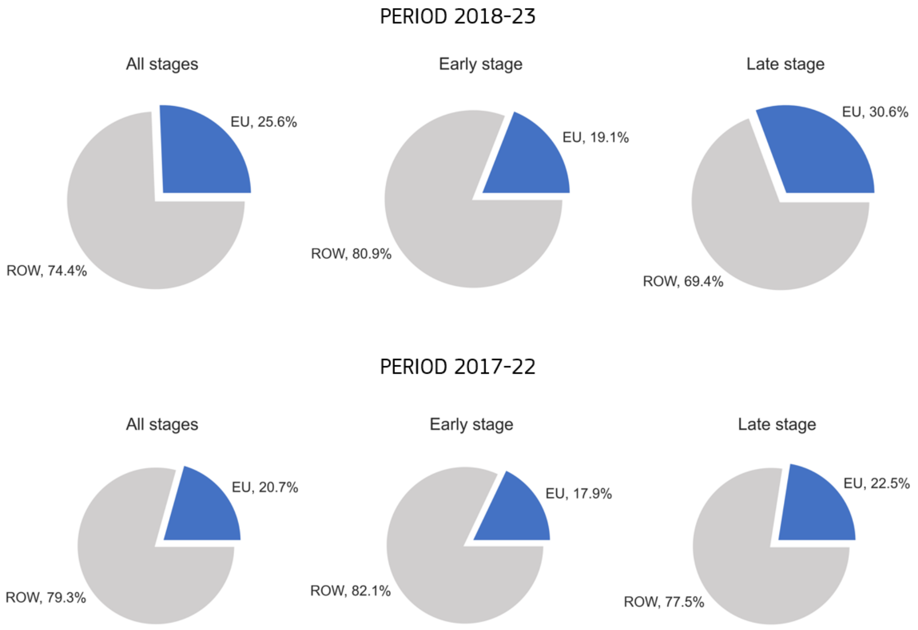
Figure 7. Global venture capital investments by periods



Source: JRC based on PitchBook, 2024.

In addition to the period analysis, from 2017 to 2023, regardless of whether the global investments were higher or lower, the EU has always received between 21% and 26% of the total shares of venture capital investments. Figure 8 shows this approach.

Figure 8. Global venture capital investments - Share of EU venture capital investments by period

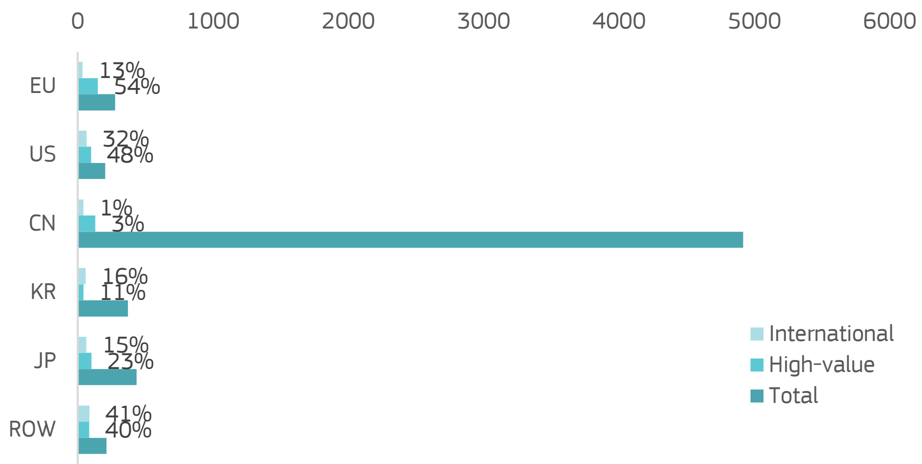


Source: JRC based on PitchBook, 2024.

2.6 Patenting trends

In this chapter, we analyse the results regarding the patents of the energy storage technologies covered in the report. Patents can be a valuable source of information in terms of research activities, as they can show how many inventions from each technology were made over the years. Patents are classified as "high-value" when filed in different patent offices. Figure 9 shows the results of inventions from 2019 to 2021, with China taking the lead with almost 5 000 inventions that involve energy storage technologies. On the other hand, only 3% are considered "high-value", and 1% are international, which means that the patent is protected in a country that is not the country of residence of the applicant.

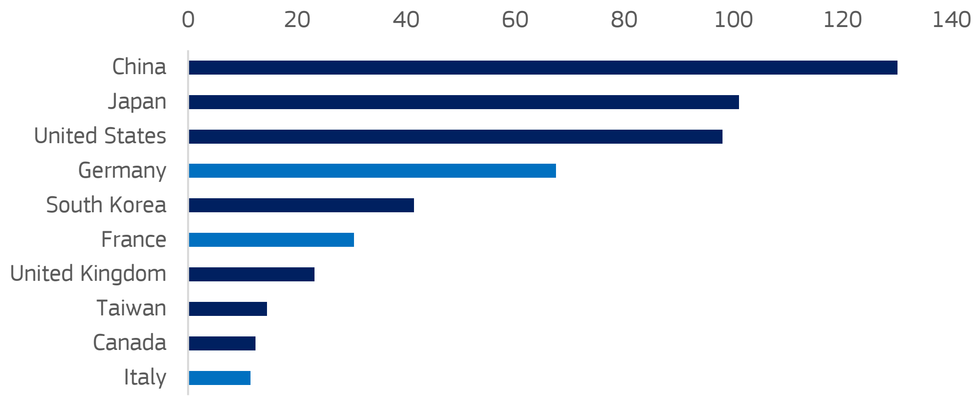
Figure 9. Number of inventions and share of high-value and international activity (2019-2021)



Source: JRC based on EPO Patstat, 2023a.

Regarding the contribution in terms of high-value patents, Figure 10 shows the result of the analysis, with China taking the lead with 130.

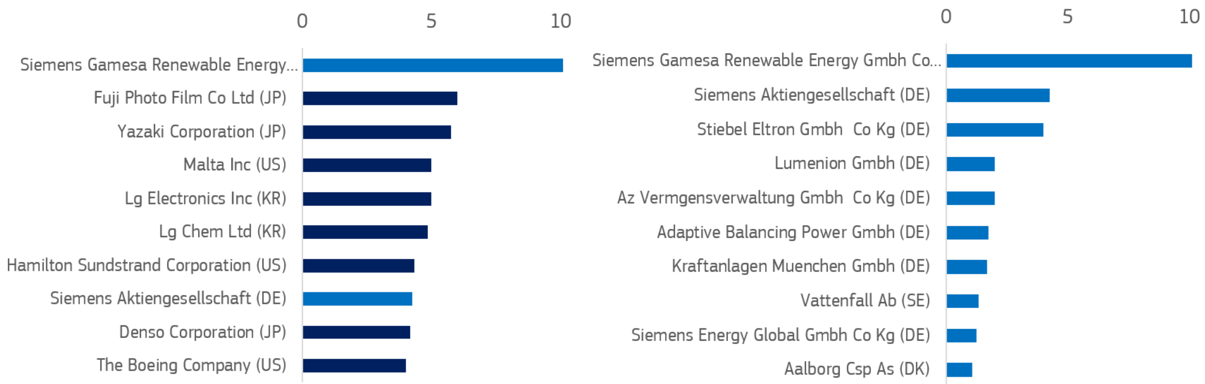
Figure 10. High-value inventions - Top 10 countries



Source: JRC based on EPO Patstat, 2023a.

Finally, Figure 11 shows the companies with the highest number of high-value inventions globally and in the EU during 2019-2021, with Siemens Gamesa Renewable Energy being the top applicant.

Figure 11. Patenting companies in the world (left) and in the EU (right)

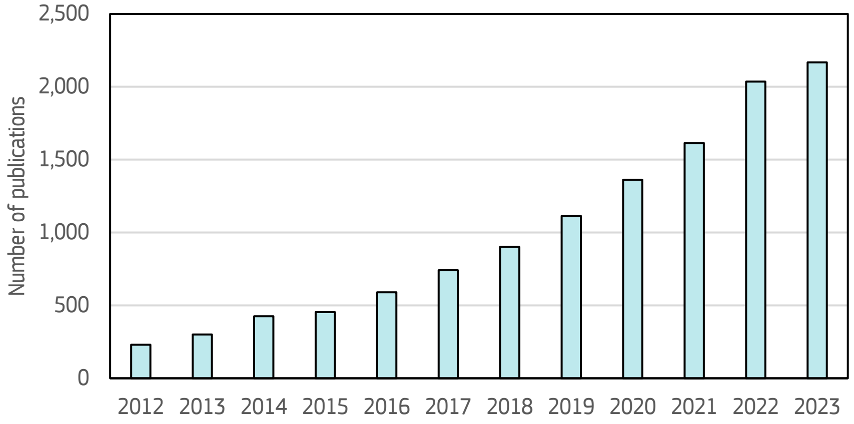


Source: JRC based on EPO Patstat, 2023a.

2.7 Scientific publication trends

The number of scientific publications on energy storage has increased in the last few years. The low TRL of most of the technologies analysed is related to the high number of scientific publications in the last years. Figure 12 shows the results of using the tool TIM. The total number of 2 000 publications refers only to the technologies listed in the report, which are the most novel ones.

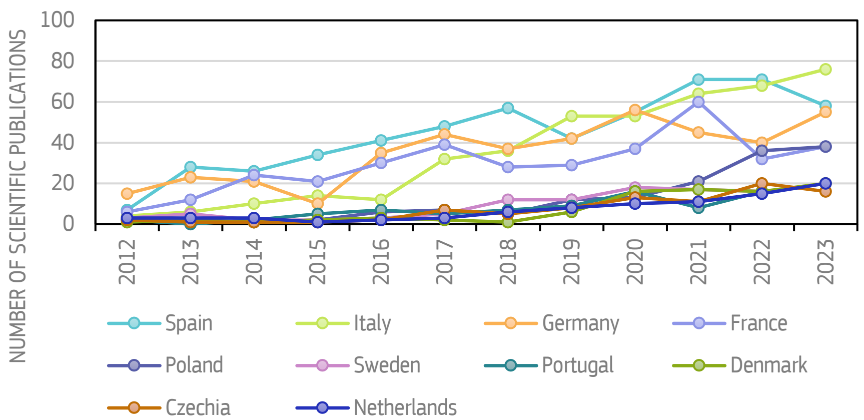
Figure 12. Number of publications in the Energy Storage field

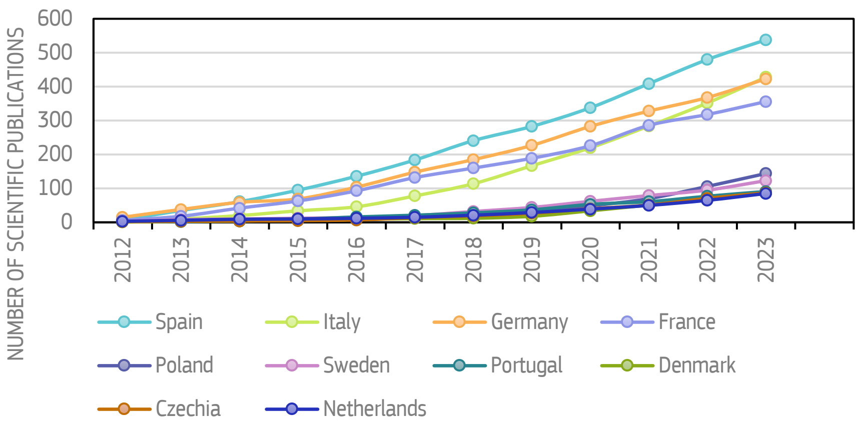


Source: (JRC, 2024).

In the EU, the tendency is also positive during the last period of years. In 2023, Italy, Spain and Germany were the member states with the most scientific publications on novel energy storage. Spain had the most publications from 2012 to 2023. Most of the MS, in general, follow a linear growth in terms of scientific publications. This indicates increasing interest in energy storage technologies within the EU, see Figure 13.

Figure 13. Publications linked to the technologies selected - Annual (Up), Cumulative (down)

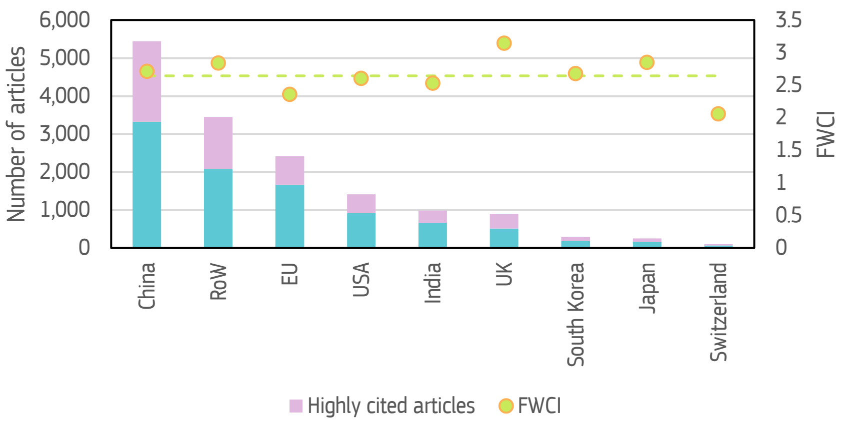




Source: (JRC, 2024).

Another indicator to evaluate the situation of scientific publications is the number of highly cited articles and the Field Weighted Citation Impact (FWCI). According to Figure 14, China has the largest share of highly cited articles with more than 2 000 publications, meaning that they produce scientific work that receive a lot of attention and is cited by other scientists. The EU occupies the third position, after RoW in this regard. The UK has the highest FWCI at almost 3.2. This indicator represents the frequency of citations for the different articles. In this regard, the EU has a FWCI of 2.5, which is lower than the average of the rest of the countries analysed.

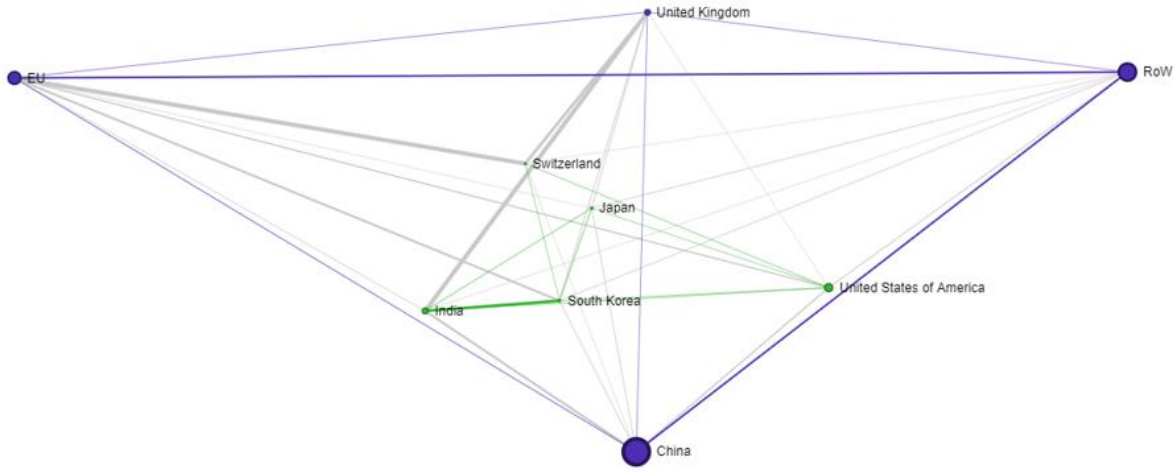
Figure 14. Number of publications and FWCI indicator

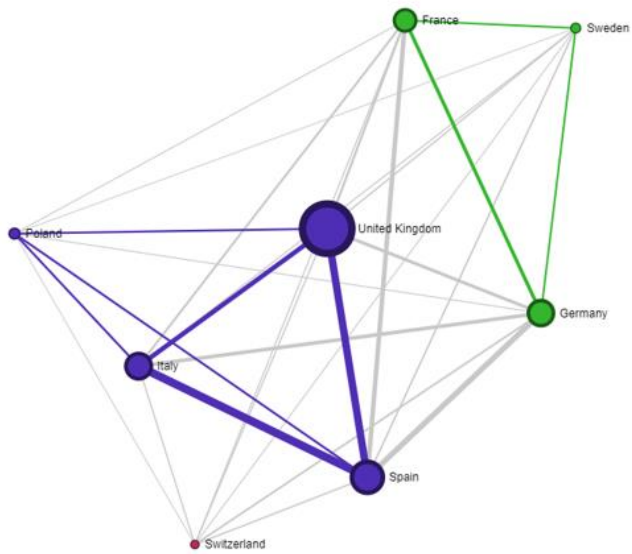


Source: (JRC, 2024).

The last indicator to analyse the scientific publications refers to the collaboration within different countries. Globally, authors from the EU and China collaborate to produce more scientific work. China has established more collaborations than the rest of the countries. The EU MSs having the most scientific collaborations are Italy and Spain.

Figure 15. Links in terms of publications between MS and regions





Source: (JRC, 2024).

3 Value Chain Analysis

This section provides an analysis of the technologies' value chains. The review concentrates on key indicators such as financial turnover, environmental impact, and socio-economic effects. It also outlines the involvement and influence of EU companies, including industry leaders, and scrutinises employment trends within the sector.

3.1. Turnover

Turnover reflects a company's revenue over a certain period, and the total turnover across companies indicates the market value of a technology. However, detailed financial data for specific segments or regions, like the EU, is often limited and inconsistent due to varying research methods and market dynamics. In this document, we present a summary of the available turnover figures for each technology, but these should not be viewed as definitive market trends.

Not surprisingly, the technologies with the largest turnovers are the most mature technologies, including thermal energy storages, as well as supercapacitors.

Table 13. Novel energy storage technologies. Estimated global turnover, lowest and highest figures available. A full list with more data and sources is in the Annex.

Turnover value (Million €)		FES	GES	CAES	LAES	SMES	SC	TES	LTES	STES
Lowest estimations	2023	290					443		433	17 400
	2022	280	62	813	215	66	397			10 200
	2021	242	54	670	285	54	320	3 800	423	14 900
	2020	268					721	3 800		
	2019	271				31	457	3 700		14 900
	2018						306			
Highest estimations	2023	1,200					4 200		1,500	3 800
	2022	994	127	3900	971	48	3 900	32 100		3 400
	2021			3300			2 900	21 300	1 500	
	2020						1 400	18 600	1 200	1 200
	2019						2 900		971	572
	2018							16 800		

Flywheel energy storage. According to Fortune Business Insights (2023), the estimated global sales value stands at € 290.7 million for the year 2023. Conversely, Global Market Insights (2023) places the figure significantly higher at €1.2 billion for the previous year, 2022.

In 2022, North America dominated the market, holding a 79.2% share, making it the most significant regional player. Europe followed as the region with the second-highest installed capacity in 2021. Examining application segments, uninterruptible power supply (UPS) led with a 55.6% market share in 2021, with distributed energy generation coming in as the second most prominent segment. (Fortune Business Insights, 2023; Market Data Forecast, 2023).

Gravity Energy Storage. In 2022, estimates of the global value of sales reported by different market research firms varied. Blue Weave Consulting and Cognitive Market Research estimated the market value at approximately 62.1 million euros, while Industry Research provided a higher estimate of 126.5 million euros for the same period.

Cognitive Market Research's 2023 report indicates that in 2022, North America held the predominant position in the market, securing the largest share, with Europe trailing closely as the second-largest market. In terms of application segments, grid stabilisation and electricity generation collectively dominated, representing the largest proportion of the global market share within that year.

Compressed Air Energy Storage. In 2023, Global Market Insights estimated that the global sales value for the market in question reached 812.8 million euros in 2022. Meanwhile, an estimate by other research firms, including Stats Market Research, Imarc Group, Maximize Market Research, and Research and Markets, suggested that the average market size for compressed air energy storage was significantly higher, amounting to approximately €3.6 billion in the same year. This divergence can be explained by that the latter estimate include a wider range of types of compressed air energy storage (including traditional, liquid gas and others) and a wider geographical scope.

In 2023, Global Market Insights reported that North America maintained a dominant position in the market, commanding a 58% share during both 2021 and 2022. Adiabatic compressed air energy storage was the largest sub-segment, representing around 74% of the market in 2022.

Liquid Air Energy Storage. In 2023, Market Research Update and Cognitive Market Research reported that the global sales value averaged €248 million in 2022. In contrast, Maximize Market Research provided a significantly higher estimate of the market size for the same period, valuing it at €971 million. In their 2023 reports, Cognitive Market Research and Maximize Market Research identified North America as the leading regional market from 2019 to 2022, followed by Europe and Asia Pacific. The most significant revenue within this market was attributed to liquid air energy storage systems utilised in grid electricity and power stations. Maximize Market Research also highlighted that in 2022, the electro-chemical segment held the majority market share. Additionally, when broken down by capacity, the 5-15 MW range was the most prevalent in the market, with the 50-100 MW category following behind.

Considering more novel LAES technologies, such as CO_2 batteries, their value chain mirrors that of the conventional power generation sector. The total turnover for component manufacturing and application can be derived from the market sizes of gas turbines, radial compressors, pressure vessels, and gasholder domes. An approximate estimation suggests that this total turnover could exceed 100 billion euros annually in 2023, according to data collected by EASE and its members (2024).[16.]

Its notable that the reports assessing the liquid air energy storage market include a wide variety of technologies associated with LAES, including batteries (solid state and flow batteries). Consequently, this leads to an inflated market turnover figure when applied to a more narrowly defined segment of Liquid Air Energy Storage

Superconducting magnetic energy storage. In 2023, Market Reports World estimated the global sales value for 2022 at €67 million, while Research and Markets, in their 2024 report, provided a higher valuation of €48 billion. According to Market and Growth Reports' 2022 analysis, North America held the largest market share, approximately 35%, in 2021. Europe was the second-largest market, contributing 25% of the global sales value that year.

[16] Data collected from EASE members (2024).

Supercapacitors. In 2022, Markets and Markets projected the global sales value for 2023 to be 443.2 million euros, whereas Precedence Research forecasted a substantially larger market size of 4.2 billion euros. This considerable discrepancy is thought to be consistent with the scope of their analyses; although both reports evaluated the same supercapacitor types and materials, Precedence Research's estimate uniquely factored in the application of the technology within the defence sector.

Asia-Pacific dominated the market, owning the highest market share in 2022. North America and Europe were the second and third-largest markets in 2021. According to a report from Precedence Research in 2022, pseudocapacitors[17] were the predominant sub-segment within the supercapacitor market in 2021, with hybrid capacitors ranking as the next largest sub-segment. In the context of module voltages, modules ranging from 10 volts to 25 volts accounted for the majority market share. With respect to applications, the automotive sector was the leading market segment in both 2021 and 2022, with the consumer electronics sector following closely behind.

Thermal Energy Storage. In 2023, Research and Markets, Global Market Insights, The Insight Partners, and Market Research Future collectively estimated the 2022 average market size for thermal energy storage technologies at €22 billion. KBV Research and Market Research Future reported comparable revenues for 2021, but 360 Research Reports and Skyquest noted lower values for the same year, likely due to their more limited geographical analysis.

In their reports, The Insight Partners (2023) and Market Research Future (2024) indicated that Europe led the thermal energy storage market with the largest share, valued at €6.4 billion in 2022, with North America and the Asia-Pacific region following behind. This was confirmed by EASE members (2024), who noted that the turnover in Europe amounted to €6.7 billion in 2023[18].

According to KBV Research (2022), Sensible Thermal Energy Storage held the largest market share among sub-technologies, whereas Latent Thermal Energy Storage had the smallest. Water-based and molten salt technologies generated the bulk of the revenues, with molten salt also leading the market in 2021, as per Market Research Future (2024). These technologies are expected to grow at a CAGR of 7.5% until 2032 (Global Market Insights, 2023). However, detailed data on their specific contributions to STES market share is not provided in these sources. For applications, Market Research Future (2024) notes that the commercial and industrial sectors dominated the market in 2021, with residential and utility sectors also contributing significantly.

Latent Thermal Energy Storage (LTES). Imarc Group (n.d) reported that the global market value of Phase Change Materials (PCM) reached €1.5 billion in 2023, whereas Verified Market Research (2024) provided a significantly lower estimate of €433.3 million for the same year. Most of the market value was concentrated in Europe, driven by the region's heightened emphasis on integrating energy efficiency in building and construction initiatives. In 2020, Europe claimed a 30% share of the global PCM market, as noted by Strategic Market Research (2022). Furthermore, Fortune Business Insights (2024) recorded that Europe's PCM revenues were €443 million in 2019 and €372 million in 2018.

[17] A pseudocapacitor is a hybrid in between a battery & an EDLC (electric double layer capacitor). It includes two electrodes which are separated through an electrolyte. The storage of charge occurs through chemical & electrostatic processes (Pseudocapacitor : Working, Types, Differences and Its Applications (elprocus.com)).

[18] This value was retrieved by EASE members from Affordable Market Research and Subscriptions (businessmarketinsights.com).

Imarc Group (n.d) and Allied Market Research (2022) predicted that organic PCMs would lead the market from 2020 to 2023, although Markets and Markets (2022) found that inorganic PCMs had the largest share in 2020. In terms of form, encapsulated PCMs were the dominant type in 2023 according to Imarc Group (n.d.). Building and construction emerged as the top application sector during 2020-2023, as per multiple sources including Imarc Group, Strategic Market Research, and Polaris Market Research. Markets and Markets (2022) reported that the cold chain and packaging had the largest market share in 2020, with thermal energy storage being the fourth-largest application. Fortune Business Insights (2024) placed thermal energy storage as the third-largest PCM application in 2019, following building and construction, and HVAC.

It is worth noticing that all these reports include PCM from a wide range of applications (building and construction, packaging, HVAC[19], energy storage, textiles, electronics, and others).

Sensible Thermal Energy Storage (STES). Future Market Insights (2024) forecasts the global Water Tank Thermal Energy Storage (WTTES) market to reach 18.5 billion euros in 2024, with Asia Pacific having the largest market share in 2021. WTTES systems with 100 to 250 liters capacity are expected to maintain a consistent 30% share of sales turnover from 2022 to 2024. In 2021, however, the 30 to 100-liter range was more prevalent. The electric energy source segment dominated the market in 2021 and 2022 across various reports.

Precedence Research (2024) estimates that the Molten Salt Thermal Energy Storage market will be valued at €3.9 billion in 2024. When looking at the geographical distribution, Europe owned the biggest market share in 2022 (78.5%) and 2020 (78.2%). North America followed with 10.6%, while 5.9% and 3.7% were attributed to Asia Pacific and Latin America, respectively. Middle East and Africa owned the lowest market share (1.3%) in 2022. Technology deployment in Europe has been fostered by early strict rules on emission standards and the utilisation of renewables (Precedence Research, 2024; Transparency Market Research, 2022). However, according to TechSci Research (2023) and Knowledge Sourcing Intelligence (2021), Asia Pacific is the global market leader and is expected to register the fastest growth in the upcoming years. Based on the type of systems (parabolic trough, power tower, fresnel reflector), the parabolic trough ones are the most widely used. They are estimated to generate the highest market value in 2024 (Precedence Research, 2024).

3.2. Gross value added

Data on the gross value added by novel energy storage technologies is not available.

3.3. Environmental and socio-economic sustainability

The availability of key sustainability performance data and references varies significantly depending on the novel energy storage technology. These are rarely specific per segments of the value chain. Data for less commercialised technologies is mainly descriptive and qualitative. On the contrary, mature technologies have been thoroughly assessed by applying consolidated methodologies that cover multiple life cycle stages. Scientific references for each sustainability pillar (environmental, social, and economic) are reported in separate sections for all assessed technologies is, presented in Annex III.

[19] Heating, Ventilation, and Air Conditioning.

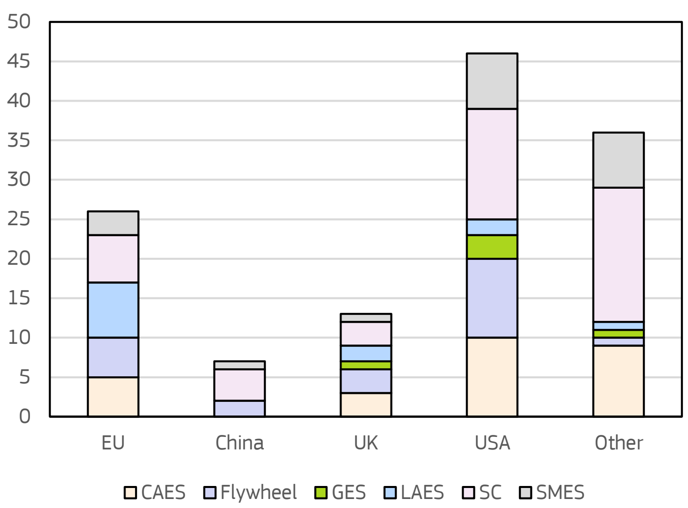
Flywheel energy storage systems, while emission-free during operation if powered by renewables, have environmental impacts in the extraction and processing of manufacturing materials. Gravity, compressed air, and liquid air energy storage methods offer more environmentally friendly alternatives with lower emissions, especially when integrated with renewable energy sources. Superconductors, supercapacitors, and thermal energy storage technologies, including latent and sensible systems, also show promise for reducing emissions, although their environmental impacts vary based on materials used and operational practices.

3.4. Role of EU Companies

The EU companies working with novel energy storage technologies operate in different segments of the value chain. In Annex IV, lists of global key players and shares of companies located in the EU are provided, based on insights from market reports mentioned in the Turnover section (3.1), as well as data collected from EASE members (2024) and other industry stakeholders. Concerning start-ups, data is frequently scarce and not exhaustive enough to provide shares of companies and capital relative to the EU. However, the names of start-ups and funding data associated with these were identified where possible.

Figure 16 shows the number of companies working on different novel energy storage technologies per country/region. While including the most prominent companies, the list is not all-encompassing.

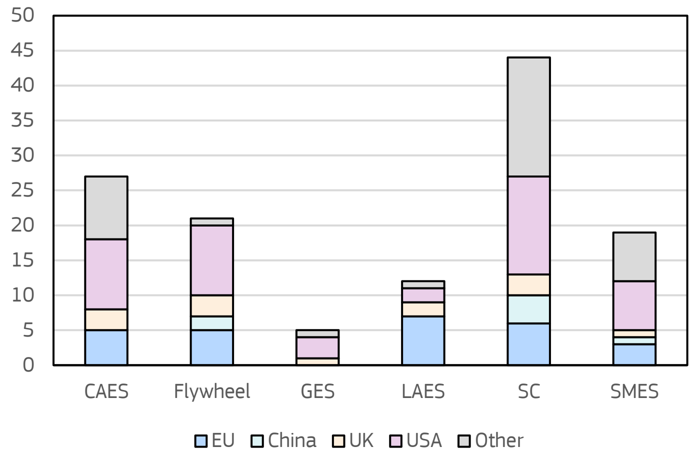
Figure 16. Number of companies working with Energy Storage technologies by region



Source: Companies' websites cited in Annex IV.

Figure 17 shows that most companies are focused on supercapacitors, followed by compressed air energy storage and flywheel energy storage. The more mature thermal energy storage technologies (e.g. sensible and latent) are not included.

Figure 17. Number of companies working with on Energy Storage technologies by technology



Source: Companies websites cited in Annex IV.

3.4.1. Start-ups

Flywheel energy storage (FES). Up to this point, two FES start-ups, located in the EU, have been identified. Teraloop (Finland) provides FES that offers scalability, efficiency, and sustainability. It complements renewable generation assets by balancing supply and demand variations. Moreover, it supports battery storage, making it suitable for critical industrial applications. It was founded in 2014 and its funding amounted to €2.4 million, according to Energy Startups (2023)[20]. Energiestro (France) develops low-cost FES systems made of worldwide patented prestressed concrete and simple ball bearings instead of expensive magnetic thrust bearing. It was founded in 2001, and in 2015-2021, it received €2 million financing from business angels. Between 2021 and 2024, it received about €20 million in financing, mostly for constructing the first manufacturing plant. Other funding for other projects is planned for the period 2025-2027. The company has been mostly supported by the European Commission, BPI France, Région Centre and the French town of Châteaudun. Among all investments, access to EU financing has been the toughest[21].

Gravity energy storage (FES). Considering that the GES industry is in an early stage, some companies are still in the start-up stage from a technological point of view. According to a list provided on the website of Tycorun Energy (2022)[22] Swiss Energy Vault, UK Gravitricity, USA Gravity Power, and ARES are the top innovative players. One EU company identified by the above -mentioned market reports as key market player is also still at the start-up level. Gravity Storage GmbH (Germany) purchased the assets of Heindl Energy GmbH in 2021 and has been working on developing a new GES concept to sell to investors. Projects promoted by these companies are still being conceived or at proposal stage. According to data collected from industry stakeholders by EASE, from a financial

[20] Teraloop (Finland) Funding: $2.7M (energystartups.org); Note that currency data reported in this paragraph was expressed in USD and this was converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

[21] Data collected by EASE from industry stakeholders.

[22] Top 5 gravity energy storage companies in the world The Best lithium-ion battery suppliers | lithium ion battery Manufacturers - TYCORUN ENERGY (takomabattery.com)

perspective, GES technology and start-ups are more advanced and acknowledged in the USA. Therefore, many EU start-ups tend to move there to seek funding and implement their projects[23].

Compressed air energy storage (CAES). When cross-referencing available data on CAES start-ups[24] up to this point, no entity proves to be located in the EU, except for Corre Energy B.V., which has already been mentioned in the section above as a more mature company.

Liquid air energy storage (LAES). Up to this point, two LAES start-ups in the EU have been identified. Phelas (Germany) provides a novel thermodynamic storage system inspired by LAES principles. Their process design features internal heat management, custom cooling, and simplified liquefaction. It was funded in 2020, and its funding amounted to €600 000, according to Energy Startups (2023)[25]. Energy Dome is a scale-up that develops and offers a market-ready CO_2 battery that employs a thermodynamic cycle. This gets charged by drawing carbon dioxide from a 'Dome' gasholder, storing it under pressure, and finally dispatching it via the evaporation and the expansion of the gas through a turbine back into the gasholder. It was founded in 2020, and during its operation it raised €135 million from mostly private investors, the European Commission (€65 million) and the European Investment Bank[26].

Supercapacitors (SC). According to Start US Insights (2021)[27], SC start-ups are mostly located in the USA and Europe, based on data from 2021. When cross-referencing data from Start US Insights (2021) and Tracxn (2024)[28], Table 32 (in Annex IV) proves to be a non-exhaustive list of worldwide supercapacitors start-ups and 15% of these are located in the EU: EnergoPlus Tech (Latvia); Nawa Technologies (France). EnergoPlus Tech is a Latvian start-up that, by utilising materials like carbon nanotubes (CNTs) and polyaniline, has developed supercapacitors with a stable performance over extended cycling periods, boasting an impressive capacity of 600 F/g. These products find applicability in batteries for smart devices, electric cars, and various energy storage applications. No data on its capital is available up to this point. Tracxn (2024) states that its funding amounts to €312 million. Nawa Technologies is an advanced material manufacturing company specialising in organised nanostructures for diverse applications. The company produces next-generation ultra-rapid carbon batteries, employing the supercapacitor principle. What sets these batteries apart is the use of electrode materials featuring aligned, functionalised carbon nanostructures. With superior energy density, the product outperforms lithium or lead batteries in long-term energy storage. Tracxn (2024) states that its funding amounts to €45 million[29].

[23] Gravity Storage (gravity-storage.com); data collected by EASE from industry stakeholders.

[24] Top 4 Compressed Air Energy Storage startups (energystartups.org); 4 Compressed Air Energy Storage (CAES) Startups - Nanalyze.

[25] Phelas (Germany) Funding: €600K (energystartups.org)

[26] Energy Dome | The Only Alternative For Long-Duration Energy Storage; data collected from EASE members.

[27] 5 Top Energy Startups Developing Supercapacitors (startus-insights.com)

[28] Top 60+ startups in Ultracapacitors - Tracxn

[29] Note that currency data reported in USD was converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

Latent thermal energy storage (LTES). Based on a list of worldwide energy storage start-ups provided by Energy Startups (2023)[30], LTES innovators located in the EU are HeatVentors (Hungary) and Eco-Tech Ceram (France). HeatVentors offers the HeatTANK, a TES tank utilizing PCM technology. It was funded in 2018 with €193 000[31]. Eco-Tech Ceram provides a high-temperature LTES (HTPCM). It efficiently manages energy intermittence by capturing, storing, and delivering carbon-free megawatts. It was funded in 2014, and its funding amounted to 450 thousand euros[32]. According to info provided by EASE members (2024) and a non-exhaustive list extracted from the recent report Catalysing the Global Opportunity for Electrothermal Energy Storage by Systemiq (2024), another EU LTES start-up is Termophoton from Spain. They provide a technology that stores electricity by melting silicon alloys at high temperatures (>1000 ºC) (HTPCM) and recovering the heat back to electricity on demand with TPV (thermophotovoltaics). The system benefits from the low cost and high energy density of silicon alloys, as well as the simplicity and compactness of TPV generation. It was founded in 2012, starting the most relevant activities in 2017. No info could be retrieved on the company's financing, however, most of the activities have been implemented after its multidisciplinary group of professionals have taken part in AMADEUS and NATHALIE, two EU projects whose financing amounted to €3.3 million and almost €100 000[33].

Sensible thermal energy storage (STES). Based on the list of worldwide energy storage start-ups provided by Energy Startups (2023)[34], STES innovators located in the EU are Polar Night Energy (Finland), Hyme (Denmark), Silbat (Spain) and Newton Energy Solutions B.V (Netherlands). Polar Night Energy provides STES employing sand as a storage medium, ensuring safety and natural equilibrium in the storage process. The heat transfer system efficiently facilitates energy transport to and from the storage. Their storage units maintain heat for extended periods, ranging from hours to months, while minimising heat loss. Storage solutions, ranging from small to large capacities, can be installed underground, conserving valuable surface area. It was funded in 2021, and its funding amounted to 500 thousand euros[35]. Hyme is in the process of developing a grid-scale MSTES solution. This solution aims to significantly enhance the integration of sustainable energy within the energy system. It was funded in 2021 and amounted to €17 million[36]. Silbat converts electricity into heat and stores it in molten silicon (MSTES), leveraging its abundant availability and high latent heat of fusion. Upon demand, heat is converted into electricity using thermophotovoltaic (TPV) cells, efficiently harnessing infrared emissions from the radiant source. It was funded in 2020, and its funding amounted to 2.4 million euros[37]. Newton Energy Solutions works with a special type of water tank called "NEStore", used for hot water applications. In May 2024, it was announced that they were funded €2.5 million to continue their research[38].

[30] Top 10 Energy Storage startups (energystartups.org)

[31] Note that currency data reported in USD was converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu). Heatventors | Intelligent Thermal Battery

[32] Note that currency data reported in USD was converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu). Valorizing industrial waste heat- Eco-Tech Ceram. (ecotechceram.com)

[33] Thermophoton; Next GenerAtion MateriAls and Solid State DevicEs for Ultra High Temperature Energy Storage and Conversion | AMADEUS | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); New markets technological positioning for ultra-high temperature latent heat energy storage | NATHALIE | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu).

[34] Top 10 Energy Storage startups (energystartups.org).

[35] Technology — Polar Night Energy

[36] Hyme

[37] Energy Storage in Molten Silicon - Silbat

[38] https://siliconcanals.com/delft-newton-energy-solutions-bags-2-5m/#:~:text=Delft%2Dbased%20Newton%20Energy%20Solutions%2C%20a%20company%20specialised%20in%20thermal,Metall%20Group%2C%20Newton%20Energy%20Solutions.

According to info provided by EASE members (2024) and the non-exhaustive list extracted from Systemiq (2024), other EU STES start-up/scale-ups are Kraftblock and Carbon-Clean Technologies (Germany), Magaldi Green Energy (Italy) and BUILD TO ZERO (Spain). Kraftblock offers STES using an innovative storage material that can store temperatures up to 1 300°C. The technology can store energy for up to two weeks. Carbon-Clean Technologies has developed the Carnot Battery (STES), which is based on a ceramic packed-bed storing energy in the form of high-temperature heat (900-1200 °C. Magaldi Green Energy provides a short and long-duration high-temperature STES technology that uses a fluidized bed of solid particles. This system can use both electricity and heat for the charging phase, and then it releases energy in the form of heat when needed. BUILD TO ZERO offers a system that combines power-to-heat technology with MSTES. With direct electrical heating of a circuit of molten salts, their thermal box generates decarbonized process heat as steam or fluid.

While confirming most of the start-ups mentioned above, the overview provided by the Solar Thermal World platform[39], adds four other EU start-ups/scale-ups to the list. Lumenion (Germany) offers an STES system that can be individually scaled through its modular concept. It is a high-temperature energy storage system that stores fluctuating power as thermal energy through virtually loss-free conversion. This can be released and later employed as process heat or for district heating. The company was founded in 2016, but no data on its funding has been identified[40]. Storasol (Germany) provides three types of thermal batteries (STES). Their high-temperature heat accumulator guarantees a cost-effective way to store heat at a high-temperature level and for multiple applications. It was founded in 2013, but no data on its funding has been identified[41]. Heliac (Denmark) provides an STES technology that stores heat up to 300 °C using granite rocks in large steel tanks. Heat sources can be a customer's waste heat or heat generated from a Heliac solar field. It was founded in 2014 and has raised a total funding, with its last round of €126 000 in 2021. Its last funding round amounted to €49 000[42]. Finally, Rpow Consulting (Spain), besides providing multiple energy consultancy services, develops advanced TES systems through active storage based on molten salts (MSTES) and passive storage based on concretes. These are a cost-effective solution adequate for 200 to 600ºC temperatures. The company was founded in 2018, and while no data has been identified on its funding, it is more mature than the others mentioned since it also has offices in the UAE[43].

3.5. Employment

Similarly to other energy technologies, employment in the energy storage industry concerns multiple value chain steps, including the design of the project, manufacturing of materials and components, system construction and installation, O&M, dismantling and EoL. The professional figures generally required are engineers, geologists, ecologists, economists, technicians, and other skilled workers. Also, scientists who work in corporate and academic R&D activities are included (Quaranta, et al., 2023).

IRENA estimates energy storage, among others, to be pivotal in promoting the energy transition, and this will contribute to the emergence of job opportunities and influence the dynamics of the employment market and its requirements in the sector (IRENA, 2023).

[39] Worldwide overview of high-temperature energy storage system providers | Solarthermalworld

[40] Thermal energy storage for zero-carbon heat | LUMENION

[41] STORASOL - Company Profile - Tracxn ; Storasol: Anbieter von Hochtemperatur-Wärmespeicher

[42] Heliac - Raised $142K Funding from 4 investors - Tracxn ; Home | Heliac ; Note that currency data reported in USD was converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

[43] Home RPOW - RPOW CONSULTING

According to the latest World Energy Employment IEA report (2023), clean energy (including energy storage) drives worldwide energy employment growth. Based on the agency estimates, 39% of workers in the power sector (7.8 million) were employed in transmission, distribution and storage combined in 2022. New jobs have been created mostly in the manufacturing of equipment and construction of new facilities. Total employment increased by over 3% in the 2021-2022 period. With around 1 million people employed, Europe, together with North America, was the third region with more professionals in this subsector; China (2.2 million) and India (1.6 million) were the most relevant players in the same year. However, since the transmission, distribution and storage category is significantly wide and more specific data for energy storage as a whole or per specific technology is not provided in the above-mentioned report, it is unclear to which extent these estimations can apply to the non-battery technologies listed in Table 2[44].

While some worldwide and USA data is available, there is a significant lack of sources when searching for energy storage employment data in the EU. Furthermore, where available (IEA - International Energy Agency, 2023), the granularity of the data is not high enough to retrieve info specific per technology. Other relevant energy or employment related worldwide sources, such as IRENA, ILOSTAT or the JRC, do not have data that is specific enough. Data is available only for bigger sector related categories, like renewables or electricity. Hence, the non-exhaustive information provided in the following paragraphs is based on data collected from companies' websites and other sources mentioned in previous sections of this report, as well as on internal data from EASE and non-EASE technology stakeholders (2024).

Flywheel energy storage (FES). Based on data collected from market reports mentioned in the FES Turnover section (Table 13) and presented in the Role of EU Companies section[45], Germany and France are the two EU countries where the headquarters of some worldwide key market players are located. These companies are Piller Group GmbH, Stornetic GmbH, Adaptive Balancing Power GmbH, Siemens Energy AG and Alstom Transport SA. Available employment data for these companies is presented in Table 14.

Table 14. Employment in companies working with FES

Company	Country	FES Value Chain Position	Overall Employees	FES Employees	Year	Source
Piller Group GmbH	Germany	Technology provider (components and systems manufacturer)	1 000	-	2021	Piller
Stornetic GmbH	Germany	Technology provider (components and systems manufacturer)	11-50	11-50	2024	Stornetic
Adaptive Balancing Power GmbH	Germany	Technology provider (components and systems manufacturer)	18	18	2024	Adaptive Balancing Power
Siemens Energy AG	Germany	Technology provider (components and systems manufacturer)	97 000 (worldwide)	-	2023	Siemens Energy

[44] See 1.1 Scope and context.

[45] See chapter 3.4.1 about mature companies.

Alstom Transport SA	France	Technology provider (deployment and application)	>80 000 (worldwide)	-	n.d	Alstom

Concerning EU start-ups identified in the Role of EU Companies[46], Teraloop and Energiestro are from Finland and France, respectively. The former employs 22 people[47], while around 11 professionals are employed by Energiestro[48].

Based on EU projects reported in Annex II, countries where professionals have been or are actively involved in the development and deployment of FES technologies are: Ireland (4 projects); Germany (3 projects); Netherlands (2 projects); Denmark, Sweden, Belgium, Poland, Spain, France and Italy (1 project)[49].

Gravity energy storage (GES). Based on market reports information mentioned in the Turnover section (Table 13) and presented in the Role of EU Companies section[50], since there are no mature companies located in the EU, neither are people employed.

However, concerning EU start-ups, Gravity Storage GmbH has been identified[51]. It is located in Germany, and it involves seven experienced professionals[52].

Based on EU projects reported in Annex II, one non-EU start-up (Gravitricity) is engaging in feasibility studies and actively planning to install GES systems in countries located in the EU, such as Germany, Czech Republic, Poland and Slovenia[53]. Hence, if successful, EU professionals may be involved in future. Furthermore, in Romania, the state-owned coal mine operator has recently signed an agreement with Australian Green Gravity to potentially convert 17 coal mines into S-GES systems to help cut coal usage. Partners will assess the technical, economic and environmental aspects, as well as the potential benefits and challenges of integrating GES. Therefore, Romanian experts may be involved in contributing to boosting GES-related employment in the EU[54]. Furthermore, Poland and Romania are expected to employ professionals, from research and industry in the upcoming years for the GrEnMine – Gravitational Energy Storage in the Post-Mine Areas – 2024-2027 project. Other EU countries whose experts will have the opportunity to work on GES in the same project are Greece and the Czech Republic[55].

[46] See 3.3.1.2 Start-ups

[47] Teraloop Oy | LinkedIn

[48] Data collected by EASE from industry stakeholder.

[49] 2nd Life for Power Plants | 2LIPP | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu); Demonstration of dynamic grid stabilisation with an Adaptive-flywheel/battery Hybrid energy Storage system in Ireland and UK | AdD HyStor | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); Dynamic Energy System Services to Achieve Renewable Targets | DESSART | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); Flywheel energy storage for Increased Grid Stability | FlyInGS | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); MeRIT - Maximising Renewable Energy Integration | MeRIT | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); POwer StoragE In D OceaN | POSEIDON | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu); A highly scalable grid-scale energy storage system utilising 3rd generation flywheel technology for effective integration of renewable energy. | Teraloop ESS | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu).

[50] See 3.3.2.1 Mature Companies.

[51] See 3.3.2.2 Start-ups

[52] Gravity Storage (gravity-storage.com).

[53] Gravitricity – Renewable Energy Storage.

[54] Green Gravity signs deal for energy storage tech in Romania – pv magazine International (pv-magazine.com).

[55] Gravity energy storage in post-industrial areas | Industry Insider – The World of Manufacturing

Compressed air energy storage (CAES). According to data collected from EASE members (2024), Germany, Netherlands and Denmark are the EU countries with the highest number of people employed in the CAES sector. This is coherent with data collected from market reports mentioned in the CAES Turnover section (Table 13) and presented in Annex IV. Indeed, the above-mentioned countries, together with the Czech Republic and France, are the EU countries where the headquarters of some worldwide key market players are located. These companies are Siemens Energy AG, Corre Energy B.V., Doosan Škoda Power, IFP Energies Nouvelles, and MAN Energy Solutions SE. Available employment data for these companies is presented in Table 15.

Table 15. Employment in companies working with CAES

Company	Country	CAES Value Chain Position	Overall Employees	CAES Employees	Year	Source
Siemens Energy AG	Germany	Technology provider (deployment and application)	97 000 (worldwide)	-	2023	Siemens Energy
Corre Energy B.V	Denmark, Netherlands	Technology provider (deployment and application)	11-50	11-50	2024	Corre Energy
Doosan Škoda Power	Czech Republic	Technology provider (components manufacturer)	1 000-1 500	-	2024	Doosan Škoda Power
IFP Energies Nouvelles	France	Technology provider (R&I)	1 549	-	2021	IFPEN
MAN Energy Solutions SE	Germany	Technology provider (components manufacturer)	15 000 (worldwide)	-	n.d	MAN

Concerning start-ups, none of the currently operating ones are in the EU[56]. Therefore, we assume that no EU professionals are engaged at this level.

Based on EU projects reported in Annex II, countries where professionals have been or are actively involved in the development and deployment of CAES technologies are: Spain (4 projects); Germany and Italy (3 projects); Denmark, Portugal, Belgium and Greece (2 projects); Sweden, France, Czech Republic and Austria (1 project)[57].

Table 16 lists required employment estimations provided by EASE members (2024) involved in the GHH Denmark project (DK1) aiming to combine large-scale hydrogen production with underground hydrogen storage and CAES to promote Denmark's green energy transition. The project targets a 180 MW electrolyser, 77 GWh hydrogen storage capacity and a CAES facility with 320 MW production

[56] See chapter 3.4.1 about Start-ups.

[57] Advanced adiabatic compressed air energy storage (AA-CAES) | AA-CAES | Project | Fact sheet | FP5 | CORDIS | European Commission (europa.eu) ; Air isothermal compression technology for long term energy storage | Air4NRG | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu) ; Home - ASTERIx-CAESar ; PUSHING THE LIMITS OF LARGE-SCALE ENERGY STORAGE: OPTIMIZED COMBINED CYCLE CAES | PUSH-CCC | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu) ; Design Study for the European Underground Research Infra-structure related to Advanced Adiabatic Compressed Air Energy Storage | RICAS2020 | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu)

output capacity[58]. Additionally, this kind of project is expected to contribute to creating a hydrogen value chain, which will also create employment.

Table 16. Estimations of employment in the GH Denmark project (DK1)

Project Phase	Required workforce
Technology Development	approx. 25 FTEs[59]
Building	Project management and central topics: approx. 10 FTEs over 4 years
	Engineering: 50 FTEs over 2 years
	Construction: approx. 50 external employees + an additional 400-500 (during peak activities) over 2 years
Operational	6-8 FTEs

Source: EASE members (2024)

Liquid air energy storage (LAES). Based on data collected from market reports mentioned in CAES Turnover section (Table 13) and presented in Annex IV, Germany, Sweden, Italy, and France are the four EU countries where the headquarters of some worldwide key market players are located. These companies are Messer Group, Siemens Energy AG, MAN Energy Solutions SE, Atlas Copco, Cryostar, Bonfiglioli, and Rossi. Available employment data for these companies is presented in Table 17.

Table 17. Employment in companies working with LAES

Company	Country	LAES Value Chain Position	Overall Employees	LAES Employees	Year	Source
Messer Group	Germany	Technology provider (deployment and application)	11 259 (worldwide)	-	2022	Messer Group
Siemens Energy AG	Germany	Technology provider (deployment and application)	97 000 (worldwide)	-	2023	Siemens Energy
MAN Energy Solutions SE	Germany	Technology provider (components manufacturer)	15 000 (worldwide)	-	n.d	MAN
Atlas Copco	Sweden	Technology provider (components manufacturer)	53 000 (worldwide)	-	2023	Atlas Copco
Cryostar	France	Technology provider (components and	776	-	2023	CRYOSTAR

[58] Green Hydrogen Hub Denmark | Energy is life. Let's save it.

[59] "FTEs" stands for "Full-Time Equivalents." In the employment context, it refers to the total number of hours worked by all employees on a full-time basis, converted into the equivalent number of full-time positions. This metric is often used to represent the total workforce capacity, accounting for both full-time and part-time employees (What Is Full-Time Equivalent (FTE)? (With Example Calculation) (indeed.com).

		systems manufacturer)				
Bonfiglioli	Italy	Technology provider (components manufacturer)	4 000 (worldwide)	-	2022	Bonfiglioli
Rossi	Italy	Technology provider (components manufacturer)	1 000 (worldwide)	-	2024	Rossi

Concerning EU start-ups, the only two identified in the Role of EU Companies[60], Phelas and Energy Dome are from Germany and Italy, respectively. The former employs 18 people[61], while around 40 professionals are employed by Energy Dome. The latter doubled its employees from 2022 to 2023 and registered an employment AAGR (Average Annual Growth Rate) of 61%.[62]

Based on EU projects listed in Annex II, countries where professionals have been involved in developing and deploying LAES technologies are Belgium, France, Spain, Bulgaria, and Poland (1 project)[63].

Superconducting magnetic air energy storage (SMES). Based on data collected from market reports mentioned in the SMES Turnover section (Table 13) and presented in Annex IV, Germany, France, and Italy are the three EU countries where the headquarters of some worldwide key market players are located. These companies are Nexans SA, ASG Superconductors SpA, and Bilfinger Nuclear & Energy Transition GmbH. Available employment data for these companies is presented in Table 18.

Table 18. Employment in companies working with SMES.

Company	Country	SMES Value Chain Position	Overall Employees	SMES Employees	Year	Source
Nexans SA	France	Technology provider (components manufacturer)	28 500 (worldwide)	-	2024	Nexans
ASG Superconductors SpA	Italy	Technology provider (components manufacturer)	>200 (Europe)	-	2024	ASG
Bilfinger Nuclear & Energy Transition GmbH	Germany	Technology and knowledge provider (components manufacturer)	>28 650 (worldwide)	-	2023	Bilfinger

[60] See chapter 3.4.1 about Start-ups.

[61] phelas – Energy Storage Solutions.

[62] Data provided by EASE member.

[63] Home - ASTERIx-CAESar ; PUSHING THE LIMITS OF LARGE-SCALE ENERGY STORAGE: OPTIMIZED COMBINED CYCLE CAES | PUSH-CCC | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu) ; Design Study for the European Underground Research Infra-structure related to Advanced Adiabatic Compressed Air Energy Storage | RICAS2020 | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu)

Supercapacitors (SC). Based on data collected from market reports mentioned in the SC Turnover section (Table 13) and presented in Annex IV, Ireland, Germany, Estonia, and France are the four EU countries where the headquarters of some worldwide key market players are located. These companies are Eaton Corporation PLC, Skeleton Technologies, Supreme Power Solutions, and Blue Solutions. Available employment data for these companies is presented in Table 19.

Table 19. Employment in companies working with SC

Company	Country	SC Value Chain Position	Overall Employees	SC Employees	Year	Source
Eaton Corporation PLC	Ireland	Technology provider (components and systems manufacturer)	94 000 (worldwide)	-	2023	Eaton
Skeleton Technologies	Estonia	Technology provider (components and systems manufacturer)	235	235	n.d	Skeleton
Supreme Power Solutions	Germany	Technology provider (components and systems manufacturer)	201-500	201-500	2024	Supreme Power Solutions
Blue Solutions	France	Technology provider (components manufacturer)	400	-	2024	Blue Solutions

Concerning EU start-ups identified in the Role of EU Companies[64], EnergoPlus Tech and Nawa Technologies are from Latvia and France, respectively. The latter employs around 48 people[65], while no information could be found on professionals who are employed by EnergoPlus Tech.

Based on EU projects considered in Annex II, countries where professionals have been or are actively involved in the development and deployment of SC technologies are France (8 projects); Italy (5 projects); Germany (4 projects); Sweden and Spain (3 projects); Finland, Denmark, Belgium and Netherlands (2 projects); Latvia, Greece, Austria, Croatia, Poland, Estonia, Ireland, Portugal and Czech Republic (1 project)[66].

[64] See chapter 3.4.1 about Start-ups

[65] NAWA, making the impossible by sculpting carbon at nanoscale (nawatechnologies.com)

[66] 3D micro-supercapacitors for embedded electronics | 3D-CAP | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); ARMS Project - Partners (arms-project.eu) Efficient materials and processes for high-energy supercapacitors for smart textiles and electromobility applications | EMPHASIS | Project | Fact sheet | HORIZON |; European Network to Empower Research on CAPacitors | ENERCAP | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu); ESTEEM Project - The University of Nottingham; Graphene, MXene and ionic liquid-based sustainable supercapacitor | GREENCAP | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu); High Energy Density Asymmetric hybrid supercapacitors for applications in consumer goods and electrification | HEDAsupercap | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu); Printable Hybrid Micro-Supercapacitor Based on 2-D Inks using Graphene, TMDs and M-Xenes | PHyS-2D-GraM | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu); POwer StoragE In D OceaN | POSEIDON | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu); Second-Generation Hybrid Electrolyte Supercapacitor | SGHES | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); Smart MEMs Piezo based energy Harvesting with Integrated Supercapacitor and packaging | smart-MEMPHIS | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); Structure-performance relationships in porous carbons for energy storage | SuPERPORES |

Thermal energy storage (TES). Based on data collected from market reports mentioned in the TES Turnover section (Table 13) and information collected in Annex IV, Germany, France, and Denmark, are the EU countries where the headquarters of some worldwide key market players are located. These companies are Man Energy Solutions, Siemens Gamesa Renewable Energy S.A., Aalborg CSP A/S., Cryogel Thermal Energy Storage. Available employment data for these companies is presented in Table 20.

Table 20. Employment in companies working with TES

Company	Country	TES Value Chain Position	Sub-Technology	Overall Employees	TES Employees	Year	Source
MAN Energy Solutions SE	Germany	Technology provider (components manufacturer)	LTES (IS & SZTPCM & LTPCM)	15 000 (worldwide)	-	n.d	MAN
Siemens Gamesa Renewable Energy S.A.	Germany	Technology provider (deployment and application)	STES	28 150 (worldwide)	-	2024	Siemens Gamesa
Aalborg CSP A/S	Denmark	Technology provider (components and systems manufacturer)	STES (Solid, TPTES, MSTES)	51-200	-	2024	Aalborg CSP A/S
Cryogel Thermal Energy Storage	France	Technology provider (components and system manufacturer)	LTES (IS)	11-50	11-50	2024	CRYOGEL

When looking at specific segments of the value chain, according to data collected by EASE from its members (2024), Sweden, Germany, Spain and Italy are the top EU countries that are employing the highest number of workers for materials production and components manufacturing. Turbomachinery and heat exchangers are among the components bought from suppliers in these countries by companies with their supply chains in the EU. Spain and Italy are also the top employers for deployment and application.

Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); Upscaling of fluorographene chemistry for supercapacitor electrode material | UP2DCHEM | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu).

Latent thermal energy storage (LTES). Concerning the LTES EU start-ups identified in Annex IV, HeatVentors (PCM) and Eco-Tech Ceram (HTPCM) are from Denmark and France, respectively. The former employs 13 people[67], while around 40 professionals work at Eco-Tech Ceram[68].

According to info provided by EASE members (2024) and a non-exhaustive list extracted from Systemiq (2024), Spain is another EU country with a relevant LTES (HTPCM) technology provider (Termophoton), and this company is currently employing seven professionals[69]. Taking into account EU projects reported in Annex II, countries where professionals have been or are actively involved in the development and deployment of LTES (HTPCM) technologies: Spain (3 projects); Germany, Italy and Greece (2 projects); Poland, Austria, France, Czech Republic, Netherlands (1 project)[70].

Sensible thermal energy storage (STES). Concerning the EU start-ups identified in the Role of EU Companies[71], Polar Night Energy (STES), Hyme (MSTES) andSilbat (MSTES) are from Finland, Spain and Hungary, respectively. Hyme employs around 41 professionals[72], while 15 and 9 experts are involved in Silbat[73] and Polar Night Energy[74].

According to info provided by EASE members (2024) and a non-exhaustive list extracted from Systemiq (2024), Germany and Italy, together with Spain, are other EU countries with relevant STES technology providers. Kraftblock (STES), Carbon-Clean Technologies (STES), Magaldi Green Energy (STES) and BUILD TO ZERO (MSTES) are currently employing around 3 375, 376, 777 and 678 professionals, respectively.

While confirming most of the companies mentioned above, according to the latest worldwide overview of high-temperature energy storage system provided by the Solar Thermal World platform[79], Germany is also home to three other STES technology providers. Kraftanlagen (TTES) employs 2 000 professionals (also working on multiple solutions other than STES)[80], while around 20[81] and 1-10[82] people work at Lumenion (STES) and Storasol (STES), respectively. Moreover, Heliac (STES), with about 40 employees[83], is another company located in Denmark. Finally, with Rpow Consulting (MSTES) employing around 18 professionals[84], Spain adds another company to its list.

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[67] HeatVentors: Overview | LinkedIn

[68]Valorizing industrial waste heat- Eco-Tech Ceram. (ecotechceram.com).

[69]Thermophoton

[70] Next GenerAtion MateriAls and Solid State DevicEs for Ultra High Temperature Energy Storage and Conversion | AMADEUS | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); Innovative compact HYbrid electrical/thermal storage systems for low energy BUILDings | HYBUILD | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu); A Ferrosilicon Latent Heat Thermophotovoltaic Battery | THERMOBAT | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu).

[71] See chapter 3.4.1 about Start-Ups

[72] Hyme | LinkedIn.

[73] Energy Storage in Molten Silicon - Silbat.

[74] Polar Night Energy
[75] KRAFTBLOCK | LinkedIn.
[76] Enabling the clean energy transition - carbonclean technologies GmbH.
[77] Energy Storage Technologies | Magaldi Green Energy.
[78] Build to Zero - Build to Zero.
[79] Worldwide overview of high-temperature energy storage system providers | Solarthermalworld.
[80] Kraftanlagen - Your experts in Decarbonization.
[81] LUMENION | LinkedIn.
[82] STORASOL (Storasol GmbH) (startbase.com).
[83] Home | Heliac.
[84] RPow | LinkedIn.

Considering EU projects in Annex II, countries where professionals have been or are actively involved in the development and deployment of STES (Solid, MSTES) technologies: Spain (3 projects); Germany, Greece, Sweden, France (2 projects); Netherlands, Denmark, Italy, Portugal, Czech Republic, Finland (1 project)[85].

3.6. Energy intensity and labour productivity

Not enough data to properly assess.

3.7. EU Production Data

Codes to identify novel energy storage technologies were hard to find because the materials used are also common in other technologies.

[85] HIGH-TEMPERATURE THERMOCHEMICAL HEAT STORAGE POWERED BY RENEWABLE ELECTRICITY FOR INDUSTRIAL HEATING APPLICATIONS | HERCULES | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu) ; sCO2 Operating Pumped Thermal Energy Storage for grid/industry cooperation | SCO2OP-TES | Project | Fact sheet | HORIZON | CORDIS | European Commission (europa.eu) ; Storage-Enabled Sustainable Energy for Buildings and Communities | SENSIBLE | Project | Fact sheet | H2020 | CORDIS | European Commission (europa.eu)

4. EU Market Position and Global Competitiveness

The final chapter of this paper considers the role of European regional and national investments as well the resource efficiency of the selected technologies to evaluate the global position of the EU and the rest of the world.

4.1. Global & EU market leaders

There was not enough data found to make a proper analysis of the EU market position for novel energy storage, due to that the market is not developed.

4.2. Trade (Import/export) and trade balance

There was not enough data found to make a proper analysis of energy storage technologies trade. In terms of materials used, like aluminium, barium or copper, there is no specific data for energy storage technologies.

4.3. Resource efficiency and dependence in relation to EU competitiveness

This concluding section focuses on the materials utilised in constructing and operating the selected energy storage technologies. The analysis assesses their susceptibility to supply risks or possible strategic advantages if contributing to European resource independence. To achieve this, we refer to the 2023 EU classification of critical raw materials, which helps identify essential resources and evaluate the resource efficiency of the analysed storage systems. Ashby and Polyblank (2012) analysed the composition of energy storage systems, see Table 21.

Table 21. Main materials used in the technologies selected

Technology	Main materials	Critical materials
FES	barium, carbon fibre, carbon steel, copper, plastics, yttrium	barium, copper, yttrium
GES	aluminium, brass, concrete, iron, lead, sand, tin, zinc	aluminium
CAES	carbon steel, chromium, concrete, copper, high alloy steel, iron, manganese, molybdenum, plastics, silicon, vanadium	copper, manganese, vanadium
LAES	aluminium, copper, glass, gravel, stainless steel	aluminium, copper
SMES	barium, carbon steel, copper, sulfuric acid, yttrium	barium, copper, yttrium
SC	activated carbon, aluminium, plastics, ammonium salts in acetonitrile, yttrium	aluminium, yttrium
LTES	calcium silicate, carbon steel, chromium, concrete, foam glass, mineral wool, molten salt, nickel, nitrogen, refractory brick, silica	

STES	calcium silicate, carbon steel, chromium, concrete, foam glass, mineral wool, molten salt, nickel, nitrogen, refractory brick, silica	

Source: (Ashby & Polyblank, 2012)

Table 22 highlights the few CRMs that can be identified in some of the selected technologies using Grohol & Veeh's (2023) study, which sheds light on the EU's dependency on these resources and their sources. The supply risk is evaluated based on global and EU supply concentration, weighted by a governance performance index, and adjusted for recycling and substitution parameters. A supply risk score exceeding 1 signifies significant importance, while scores below 1 denote lower risks. For instance, yttrium is assigned a supply risk score of 3.5, indicating high risks for the EU, while copper scores 0.1, signifying a low risk level.

Table 22. Supply of relevant critical raw materials

Raw material	EU import reliance	Main EU sourcing countries	Main global producers	Supply Risk (stage)	Recycling rate
Aluminium / bauxite	89%	Guinea-62% Brazil-12% Greece-10%	Australia-28% China-21% Guinea-18%	1.2 (extraction)	32%
Baryte / barium	74%	China-44% Morocco-28% Bulgaria-11%	China-32% India-25% Morocco-9%	1.3 (extraction)	0%
Copper	48%	Poland-19% Chile-14% Peru-10%	Chile-28% Peru-12% China-8%	0.1 (extraction)	55%
Manganese	96%	South Africa-41% Gabon-39% Brazil-8%	South Africa-29% Australia-16% Gabon-14%	1.2 (extraction)	9%
Yttrium	100%	-	China-85% Malaysia-11%	3.5 (processing)	3%

Source: (Grohol & Veeh, 2023)

Flywheel energy storage (FES). FES harnesses the power of lightweight yet durable materials like carbon fibre and barium to store rotational energy effectively (Table 22). Copper and yttrium are the only raw materials that might be used to enhance conductivity and magnetic properties (Ashby & Polyblank, 2012). Hence, FES systems utilising yttrium barium copper oxide superconductors and CFRP disks may strain the availability of yttrium. While the EU can sustain half of its copper supply on its own, it fully relies on external states to access yttrium, justifying yttrium's 3.5 supply risk assessment (Table 22).

The ENTEC study (2023) relying on diversified stakeholders' feedback indicates that manganese could be used in some FES systems, but its low use and 1.2 supply risk (Grohol & Veeh, 2023) does not make it a barrier to the development of FES.

Gravity energy storage (GES). GES systems leverage a diverse range of materials, from concrete stability to aluminium and zinc's versatility. These materials form the foundation for constructing gravitational storage facilities, enabling the efficient conversion of potential energy into electrical energy. (Ashby & Polyblank, 2012).

GES systems often demand substantial resources for their construction due to the need for large-scale infrastructure such as reservoirs and associated components. Despite this, aluminium is the only critical raw material possibly used for their operation (Table 21). This metal might be utilised in various aspects, including structural elements, piping, and containment vessels. With a supply risk score of 1.2, aluminium provision can face potential risks, but the increasing recycling rate of the material and the diversity of producing countries maintain this risk at a minimum level (Table 22).

Compressed air energy storage (CAES). The backbone of CAES systems relies heavily on robust materials such as carbon steel, copper, and vanadium, facilitating the compression and storage of air (MIT, 2022). Manganese and vanadium can be used to enhance the performance and longevity of CAES systems (Ashby and Polyblank, 2012). CRMS are not necessaryor D-CAES, A-CAES or I-CAES systems (ENTEC – Energy Transition Expertise Centre, 2023).

Although CAES may employ several critical raw materials, the quantities needed are minimal, and significant supply risks are unlikely to be encountered. The primary obstacle to CAES advancement lies in securing suitable locations and geological conditions for its deployment.

Liquid air energy storage (LAES). LAES systems utilise materials like aluminium and stainless steel to contain and manage the liquefied air (Table 21). These materials provide the corrosion resistance required to safely store and retrieve liquid air (MIT - Massachusetts Institute of Technology, 2022).

Both aluminium and copper are useful to the construction of LAES systems due to their specific properties and roles within the infrastructure. While their usage is crucial, it is worth noting that they are not utilised on a large scale compared to other materials, according to the information provided by EASE members (2024). EASE members added that recent LAES systems do not necessarily require aluminium and copper, as confirmed by the ENTEC study on energy storage (2023). Aluminium and copper might both be used in some LAES systems, but they should remain accessible with supply risk scores of 1.2 and 0.1 respectively (Table 22).

Superconducting magnetic energy storage (SMES). Ashby and Polyblank (2012) indicate that SMES systems utilise a combination of robust materials such as carbon steel and copper to construct superconducting coils and associated components. These materials provide the strength and conductivity for efficient energy storage and retrieval operations. Additionally, barium and yttrium might be used to enhance superconducting properties of materials (Table 21). Yttrium is the main material representing risk for the resource sustainability of SMES systems, with an estimated 3.5 supply risk score, much beyond the 1.00 threshold (Table 22).

Supercapacitors (SC). SC systems incorporate advanced materials such as activated carbon and aluminium to facilitate the efficient storage and release of energy. These materials enable the construction of high-performance superconducting magnets and capacitors, ensuring rapid energy transfer and minimal energy losses. Similarly, as for SMES, yttrium can be used to improve the superconducting properties of SC materials (Table 21).

Furthermore, the availability of other materials crucial for supercapacitor production, such as carbon and various metals, is abundant, reducing concerns about material scarcity (Chmielewski, et al., 2020).

Thermal Energy Storage (TES). Several materials can be used in TES. However, aluminium is the preferred choice for its suitability in sensible, latent, and thermochemical TES facilities. Derived from bauxite, aluminium is classified as a Critical Raw Material. As it has a supply risk of 1.2 on a scale of a maximum 5, it has a low level of supply risk for the EU (European Commission, 2023).

High-temperature TES applications require stainless steel, which is an alloy that includes chromium and iron. Taking into account their supply risks (0.7 and 0.5, respectively), they have low levels of risks for the EU (Carrara, et al., 2023).

5. Conclusions

Several of the technologies studied in this report offer innovative energy storage solutions with beneficial performances and opportunities for various applications. The integration of energy storage systems could play a key role in improving grid stability, resilience, and efficiency by providing voltage support and grid balancing. By incorporating storage solutions in generation facilities, utilities can streamline resource utilisation, alleviate intermittency challenges linked to renewable energy sources, and enhance overall system reliability. Other opportunities include gravity and thermal energy storage systems. Shaft gravity energy storage can be used, for example, to reuse closed mines as storage facilities. Molten salt heat-to-power has the potential to enhance the performance of existing power plants by storing excess heat generated during off-peak periods and delivering during peak demand.

Performance characteristics are key in highlighting the benefits of specific energy storage technologies. For instance, the cycle longevity of some flywheel systems distinguishes them, while superconducting magnetic technologies stand out for their cycle efficiency. Factors like energy density and storage duration are also crucial in determining the suitability of these technologies for different applications.

Various technologies with high readiness levels have proven their performance and advantages and are now set for market deployment. For instance, adiabatic compressed air energy storage stands ready for widespread implementation, offering substantial potential to address energy storage demands. By storing compressed air in underground caverns during low-demand periods, adiabatic compressed air energy storage systems can effectively generate electricity during peak demand, reducing dependence on conventional fossil fuels and reducing carbon emissions.

Other technologies, like isothermal compressed air energy storage systems, are still in the development phase and require optimisation before they can be adopted widelydevelopment and require optimisation before they can be widely adopted. While thermochemical energy storage can offer efficiency without thermal losses, it remains, so far, unfeasible in terms of costs.

One of the challenges in analysing emerging energy storage systems markets is the lack of comprehensive information on the installed capacity of different storage systems. Despite rising interest in numerous technologies, reliable data on their deployment and utilisation remain limited. Bridging this knowledge gap will require collaborative efforts to refine assessment methodologies and develop robust monitoring tools to track research and industry projects effectively. Comparing costs across different storage technologies is another challenge, influenced by the system's charging capacity and discharging duration.

When looking at energy storage systems value chains, the global turnover generated in recent years has been either stable or slightly growing, with thermal energy storage, compressed air and supercapacitors registering the highest market values. Meanwhile, gravity energy storage, superconducting magnetic energy storage, and Flywheels achieved considerably lower turnovers. Europe dominates the thermal energy storage market and has the second or third highest market share in other technologies, such as Flywheels and liquid air energy storage, based on the data available.

From an economic perspective, technologies perform differently according to their maturity and level of commercialisation. The costs and payback periods of investments vary widely, not only from one technology to another but also according to specific projects. Some technologies, even if they are fully mature, do not have a role in the energy transition that is clear enough yet, and this slows down their adoption.

Concerning the role of EU companies in the value chains, it is worth noticing that between 13% and 46% of key market players for each technology have their headquarters in one of the EU-27 countries. These technology providers are either components and systems manufacturers or contributors to the final large-scale deployment and application. Most of them are big and widely known energy-related companies that have also been working on other non-energy storage technologies for many years. However, there are also start-ups located in the EU which have recently started working exclusively on these novel energy storage systems, and they are progressively gathering funds from both private and public entities.

Among the EU-27 countries, Germany, France and Italy are those in which more people are assumed to be working on novel energy storage technologies since they host the headquarters of key companies. Together with Spain and Finland, they host at least two start-ups employing highly skilled technology experts. Finally, these countries also participate in most EU-funded projects, along with Greece, Sweden, Portugal, Czech Republic, Netherlands and Denmark.

Research and project development in Europe exhibit significant variations depending on the technologies, showcasing diverse levels of investment and commitment. The United Kingdom generally emerges as a prominent player in this domain. Spain, France, Germany, Italy, Greece, Ireland and Austria stand out as key EU players in energy storage research and implementation.

The EU has the lead in public investments in energy storage technologies, with 33% of funds coming from framework programmes and 40% from public institutions of the Member States. The data available does not enable a breakdown of these funds per technology.

In terms of high-value inventions, EU submitted 277 claims during 2019-2021 – a stark contrast with China, with almost 5 000 claims. Nevertheless, Germany has the fourth highest number of inventions registered in more than one patent office, at 67. Ten of these were from the company Siemens Gamesa Renewable Energy, which filed the highest number of inventions of all companies globally during this period.

Most technologies examined in this report do not rely on critical raw materials or utilise them in minimal quantities. However, further assessment should be made of the components and materials used in these systems.

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List of abbreviations and definitions

Abbreviation	Extended Version
A-CAES	Adiabatic Compressed Air Energy Storage
AAGR	Average Annual Growth Rate
ADP	Abiotic Depletion
ALOP	Agricultural Land Occupation Potential
ARES	Advanced Rail Energy Storage
ATES	Aquifer TES
BTES	Borehole Thermal Energy Storage
CAES	Compressed Air Energy Storage
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditures
C-CAES	Carbon Capture and Compressed Air Energy Storage
CDR	Carbon Dioxide Removal
CED	Cumulative Energy Demand
CSP	Concentrated Solar Power
D-CAES	Diabatic Compressed Air Energy Storage
DMT	Dual Media Termocline
EASE	European Association for Storage of Energy
EERA	European Energy Research Alliance
EES	Electrochemical Energy Storage

EIB	European Investment Bank
ERS	Energy Recovery System
ETES	Electrothermal Energy Storage
EU	European Union
FES	Flywheel Energy Storage
GBES	Ground-Breaking Energy Storage
GES	Gravity Energy Storage
GHGs	Greenhouse Gas Emissions
GHS	Globally Harmonized System
GPM	Gravity Power Module
GWP	Global Warming Potential
HHS	Hydraulic Hydro Storage
HTF	Heat Transfer Fluid
HTPCM	High-Temperature PCM
HTS	High Temperature Superconductor
HVAC	Heating, Ventilation, and Air Conditioning
HTPc	Human Carcinogenic Toxicity Potential
I-CAES	Isothermal Compressed Air Energy Storage
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRP	Ionising Radiation Potential
IS	Ice Storage

KERS	Kinetic Energy Recovery System
LAES	Liquid Air Energy Storage
LCOE	Levelised Cost of Energy
LCOS	Levelised Cost of Storage
LEM-GES	Linear Electric Machine Gravity Energy Storage
LTES	Latent Thermal Energy Storage
LHTES	Latent Heat Thermal Energy Storage
LTDH	Low-Temperature District Heating
LTPCM	Low-Temperature PCM
MC-GES	Mountain Cable Car-Gravity Energy Storage
MDP	Mineral Depletion Potential
MEP	Marine Eutrophication Potential
MES	Mechanical Energy Storage
MM-GES	Mountain Mine Car-Gravity Energy Storage
MSTES	Molten Salts Thermal Energy Storage
NGPP	Natural Gas Power Plant
NPV	Net Present Value
ODP	Ozone Depletion Potential
OPEX	Operational Expenditures
PC	Photochemical Oxidation
PCM	Phase Change Materials
PMP	Particulate Matter Formation Potential

PE	Primary Energy consumption
P-GES	Piston-Gravity Energy Storage
PSH	Pumped-storage hydropower
PV	Photovoltaic
PV-ACAES	Photovoltaic Adiabatic Compressed Air Energy Storage
RES	Renewable Energy Source
ROI	Return on Investment
SC	Supercapacitors
SDGs	Sustainable Development Goals
S-GES	Shaft-Gravity Energy Storage
SHS	Sensible Heat Storage
S-LHTES-PCM	Solar – Latent Heat Thermal Energy Storage – Phase Change Materials
SMES	Superconducting Magnetic Energy Storage
SMT	Single-Medium Thermocline
SPHES	Seawater Pumped Hydro Energy Storage
ST	Shell-and-Tube
STES	Solid media Thermal Energy Storage
STESMs	Sensible Thermal Energy Storage Materials
SWOT	Strengths, Weaknesses, Opportunities, and Threats
SZTPCM	Sub-Zero Temperature PCM
T&D	Transmission and Distribution
TEP	Terrestrial Ecotoxicity Potential

TES	Thermal Energy Storage
T-GES	Tower-gravity Energy Storage
TPTES	Tank-Pit Thermal Energy Storage
TPV	Thermophotovoltaic
TRL	Technology Readiness Level
UK	United Kingdom
UOSS	Underwater Ocean Storage Systems
UPHES	Underground Pumped Hydro Energy Storage
UPS	Uninterruptible Power Supply
USA	United States of America
USD	United States Dollars
WTTS	Water Tank Thermal Energy Storage

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Annex I - Summary Table of Data Sources for the CETO Indicators

Theme	*Indicator*	*Main data source*
Technology maturity status, development and trends	Technology readiness level	(IRENA, 2020), (Chmielewski, et al., 2020), (Mitali, Dhinakaran, & Mohamad, 2022) & (MIT, 2022)
	Installed capacity & energy production	(DOE, 2021), (Kerala State Electricity Regulatory Commission, 2023) & (ETIP SNET, 2023)
	Technology costs	(Viswanathan et al., 2022), (EASE members, 2024) & (Chmielewski et al., 2020)
	Public and private RD&I funding	(IEA, 2024)
	Patenting trends	JRC own analysis
	Scientific publication trends	JRC own analysis
Value chain analysis	Turnover	Market Reports (multiple sources outlined in chapter 3.1)
	Gross Value Added	No data available
	Environmental and socio-economic sustainability	Scientific articles and reports (multiple sources outlined in chapter 3.2)
	EU companies and roles	Market Reports, Companies Websites (multiple sources outlined in chapter 3.3)
	Employment	IEA, IRENA, DOE, Companies Websites (multiple sources outlined in chapter 3.4)
	Energy intensity and labour productivity	No data available
	EU industrial production	No data available
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	(ENTEC, 2023) & (EASE members, 2024)
	EU market share vs third countries share, including EU market leaders and global market leaders	Different sources outlined in chapter 4.1
	EU trade (imports, exports) and trade balance	No data available
	Resource efficiency and dependencies (in relation EU competiveness)	(Ashby, & Polyblank, 2012), (Grohol & Veeh, 2023), (EASE members, 2024) & (MIT, 2022)

Annex II – Notable EU research projects on Novel Energy Storage Technologies

Mechanical energy storage

Regarding Mechanical Energy Storage, projects like RICAS2020, funded under Horizon 2020 and finalised in 2018, enabled research on Adiabatic-CAES to accelerate its deployment. In this case, concepts were provided to set up a research infrastructure in Austria dedicated to underground storage of green energy in large quantities.[86]

Flywheel energy storage (FES). FES has been receiving increasing attention in the EU since 2017, particularly due to its potential in the transport sector for various vehicles. Both the FlyIngs and FLYwheel projects were launched in 2017 to offer business cases in the transport sector. The former used market data and expert interviews based on the public transport sector in Germany while the latter focused on trucks and buses in the UK. They were both used to introduce FES to manufacturers and develop commercial relationships.

The AdD HyStor project led by Schwundgrad Energie funded under the Fast Track to Innovation programme between 2017 and 2020 enabled the demonstration of an FES system in Rhode, Ireland. The technology was tested on the Irish and UK power systems, leading to TRL 8 but it was noted that both markets did not reward the high cycle capacity of FES technology.

Energy Cluster Denmark has been leading the 2LIPP demonstration project in Bornholm, Denmark since 2023 and is set to conclude in 2026. The concept aims to use existing power plants and to add scalable FES in combination with a battery to improve the lifetime and efficiency of energy storage.

Beyond EU-funded R&I, the Austrian government's Technological Lighthouses on E-Mobility programme enabled the FlyGrid project led by the Graz University of Technology between 2018 and 2023[87]. FlyGrid developed FES integrated into EV charging stations that would contribute to peak power load mitigation. Germany funded the DEMIKS demonstration of an FES test facility linked to renewable energy producers and DEMIKS 2 which emphasised its deployment.

Gravity energy storage (GES). According to the research conducted for this report, the development of GES did not benefit fom public European funds until recently. The sole project that was identified is GrenMine, led by the Wroclaw University of Science and Technology, which was initiated in 2024 and should be concluded in 2027. The project is among the first funding activities of the EU Research Fund from Coal and Steel (RFCS), it will establish a pilot facility at the Turow Brown Coal Mine to test rail-based and conveyor-based GES.

Compressed air energy storage (CAES). CAES benefits from different projects related to its different technologies. An early trace of EU research is the AA-CAES project working on A-CAES concepts. THE RICAS2020 study on a potential European Underground Research infrastructure focused on A-CAES is another example of EU innovation ambitions for A-CAES.

Regarding D-CAES, the ASTERIx-CAESar project aims to include CAES in solar-thermal power plants while PUSH-CCC explores the scalability and financial viability of CAES in Europe. Both projects were initiated in 2023 and are led in Spain. They focus on development stages rather than deployment.

[86] RICAS2020 Design Study

[87] FlyGrid - Home (tugraz.at)

The AIR4NRG project led by Zabala Brussels started in 2024 and aims to create an I-CAES prototype, reaching TRL 5.

Liquid air energy storage (LAES). The EU and the UK are global leaders, with several core companies working on the technology located in Germany, Italy and the UK (Table 30). However, the CryoHub project coordinated by the London South Bank University is the only identified EU funding linked to LAES. With a focus on air cryogen for refrigerated warehouses, a demonstration system was studied between 2016 and 2021. The financial interest of the technology is explored, demonstrating savings enabled by off-peak tariffs.

Electromagnetic energy storage

Electromagnetic energy storage has garnered significant attention in the European Union due to its versatility and the diverse range of hybrid storage opportunities it present. Several projects have been initiated, focusing specifically on the development of new and innovative systems incorporating advanced materials to enhance overall performance.

Superconducting magnetic energy storage (SMES). SMES is employed in a few EU-funded projects aimed at enhancing energy storage systems. The V-ACCESS project aims to increase the TRL of hybrid systems, including SMES with batteries. Universita Degli Studi di Trieste, leading the study, will attempt to integrate these hybrid storage systems into a novel microgrid for power control to facilitate the commercialisation and scaling of these hybrids.

There is limited data on the development of SMES in the EU. Except for Germany, most companies working on the technology are concentrated in the US and Japan. However, important findings could be made through the ongoing Horizon Europe POSEIDON which aims to evaluate the applicability of FES, SC, as well as SMES in the waterborne sector, possibly extending their range of uses and sustainable shipping. POSEIDON will notably conduct a life cycle analysis of SMES, together with SC and FES. The research will evaluate their potential integration with other technologies and determine safety issues and potential long-term risks.

The DRYSMES4GRID project, funded by the Italian Ministry of Economic Development between 2017 and 2021, delivered a demonstration of SMES based on magnesium diboride superconductor with a cryogen-free cooling system[88]. DRYSMES4GRID was coordinated by ASG Superconductors and four other Italian partners.

Supercapacitors (SC). SC systems benefit from many EU-funded projects, especially in hybrid system, and with specific studies on materials and components used for these technologies. For instance, the potential of SC technology has been explored in the ESTEEM project from 2017 through 2021 via the concept of enhanced electrical energy management. ESTEEM was led by the University of Nottingham. The 3D-CAP project coordinated by Centre National de la Recherche Scientifique between 2018 and 2023 worked on the development of micro 3D SC electrodes.

The UP2DCHEM project managed by Univerzita Palackeho v Olomouci from 2020 through 2021 contributed to scaling up the production of an innovative graphene derivative used for SC electrodes. Additionally, Politecnico di Milano has explored new electrode materials that could improve the efficiency of SC between 2022 and 2024. EMPHASIS, coordinated by Pleione Energy since 2023 and

[88] Home (cnr.it)

set to conclude in 2025, works on optimising the performance and environmental footprint of SC electrodes, current collectors and electrolytes.

In 2023, the EU also initiated the development of the European Network to Empower Research on CAPacitors (ENERCAP), a training network to be operational in 2027, under the coordination of Politechnika Poznanska. The network will aim to nurture a new generation of researchers to lead SC innovation and effectively integrate them into the market. The Centre National de la Recherche Scientifique had already studied new concepts of SC for improved efficiency through simulations in the SuPERPORES project between 2017 and 2022.

The GREENCAP project led by BeDimensional utilises 2D materials like graphene and MXenes for electrode materials with ionic liquids as high-voltage electrolytes to develop a novel SC technology. After starting in 2023, they aim to reach TRL 6 with an industrial environment demonstration in 2025. New materials are also explored through the ARMS project coordinated by Tampereen Korkeakoulusaatio from 2023 through 2027 to develop more environmentally sustainable SC systems using atomic layer deposition.

Thermal energy storage

Latent Thermal energy storage (LTES). The EU importantly contributes to the development of LTES, which requires much more R&I than STES. NPMSSES, coordinated by the University of Leeds between 2017 and 2021, used metal foam and high conductive nanoparticles to improve the stability of PCMs usually used for solar energy storage. Aluminium oxide nanopowder and graphene were applied to enhance pure salt, along with solar salt and HITEC salt.

The THERMOBAT project is a good example of ongoing innovation under Horizon Europe to develop a latent heat thermo-voltaic battery to store large amounts of renewable energy and that could be commercialised[89]. THERMOBAT was initiated by the Universidad Politecnica de Madrid in 2022, following their work on AMADEUS between 2017 and 2019 to develop energy storage and conversion at temperatures beyond 1000ºC. That project studied PCMs based on silicon-boron binary (Si-B) and ternary (Si-B-X) alloys. The technology studied in THERMOBAT can use LTES over 1 200°C to melt ferrosilicon alloys. From 2019 through 2021, the University of Birmingham researched novel phase change microemulsion bas heat transfer fluid as well as LTES material through the project THERMES.

Furthermore, the project THERMOBAT led by Universidad Politecnica de Madrid between 2022 and 2026 builds on the AMADEUS project by aiming to develop a thermophotovoltaic latent heat battery for combined heat and power generation and LDES. COMSA coordinated the HYBUILD project between 2017 and 2022 which used three demonstration sites to improve energy storage in buildings. To do so, they studied the potential of an aluminium micro-channel heat exchanger with multiple PCM layers.

Sensible Thermal energy storage (STES). STES has not required as much research effort as LTES due to its important development and deployment levels. Thus, TES R&I efforts have rather been focused on PCMs. STES is generally studied in projects attempting to improve its use. The SENSIBLE project tested STES integration in building energy management systems from 2015 through 2018 while HERCULES, initiated in 2023, is working on its combination with electrochemical ESS to support renewable energy integration.

[89] Thermobat – Storing sunshine and wind to make cheap energy available at all times.

One innovation area still being explored is the power-to-heat-to-power energy storage which generally requires efficiency development but offers considerable opportunities for renewable energy integration. These systems, sometimes called Carnot batteries, are being studied from 2023 through 2027 in the SCO2OP-TES project coordinated by Universita Degli Studi di Genova. SCO2OP-TES will deliver a pilot plant of a Carnot battery, reaching TRL 5, using STES with innovative molten-salt and turbomachinery.

Thermochemical energy storage (TCES). The companies working with thermochemical energy are working on research to make this technology cost-effective. EU companies working with this technology are Texel and SaltX, based in Sweden and working with metal hydrides and salt hydration respectively. Other company originally from Australia called Calix contributed to the SOCRATCES project with an innovative Catalytic Flash Calcination[90].

[90] https://calix.global/technology/

Annex III – Sustainability

Environmental Sustainability

Flywheel energy storage. Flywheel energy storage systems do not emit GHGs or other polluting gases or compounds during operation, as long as the power is provided by renewables (Chmielewski et al. 2020). However, the extraction and processing of materials and components for manufacturing novel energy storage technologies do have environmental impacts, yet its possible to recycle the materials (Pullen & Amiryar, 2022). Table 24 desribes the carbon footprint of the main materials used in producing flywheel energy storages.

Table 23. Carbon footprint Flywheel Energy Storage (Chmielewski, et al., 2020)

Material	Carbon footprint of materials extraction ($kgCO_2eq/kg$)
Low alloy steel	2.2
High strength steel	2.8
Aluminium	9.7-18.3
Magnesium	25.8
Glass reinforced polymers (CFRP)	2.4
Carbon fibre reinforced polymers; based on Poliakrylonitryl – PAN	14.6

A study evaluated a 20 MW flywheel energy storage system's sustainability considered indicators like Global Warming Potential, Cumulative Energy Demand, LCOS, and Raw Materials Supply Risk. It concluded that the steel-based vacuum chamber and power conversion system were the most impactful on Global Warming Potential (83%) and Cumulative Energy Demand (48%). Compared to other storage technologies, the flywheel's cradle-to-gate Global Warming Potential is higher (478.25 kgCO2eq/kWh) because of its low energy-to-power ratio.

Another study analysed the lifetime GHG emissions of 20 MW flywheel energy storage systems with steel and composite rotors. Emissions ranged from 75.2 to 121.4 kgCO2eq/MWh for steel rotors and 48.9 to 95.0 kgCO2eq/MWh for composite rotors, significantly influenced by the electricity mix used. The study emphasised charging and standby as key phases affecting emissions and highlighted the potential variability due to different energy sources (Rahman, Gemechu, Oni, & Kumar, 2021)..

Gravity energy storage. The environmental impact of the gravity energy storage method, which employs decommissioned mines and sand as storage media, can be lower in terms of underground water contamination risks compared to alternatives like pumped hydroelectric storage systems (Hunt, et al., 2023).

Compressed Air Energy Storage (CAES). These systems prove to be very favourable when geological conditions are well suited for implementation and no energy is required for the creation of a cavern. Generally, among the different sub-technologies, A-CAES (Adiabatic CAES) systems have a lower impact, since no fossil fuel is combusted. Nevertheless, the impacts of all types of systems are lower than those generated by natural gas power plants.

According to Chmielewski et al. (2020), A-CAES systems do not emit GHGs, but the electric energy used for compressors can be supplied by fossil fuel power plants. Based on a comparative life cycle assessment for three types of energy storage (PSH, A-CAES and C-CAES) in Canada, GHGs emissions relative to different A-CAES life cycle stages are listed in Table 25. Energy generation and operation are the most impactful stages, while decommissioning stage is relatively the least impactful. A-CAES systems perform better than PSH systems in terms of materials used and in the construction stage, while they perform worse in terms of energy required, operation and decommissioning stage. Compared to C-CAES (Carbon capture and storage CAES) they perform better in terms of energy required and in the operation phase, while they perform worse or equal in terms of materials used and in the decommissioning phase.

Table 24. GHGs emissions CAES (based on the Canadian energy mix)

Life Cycle Stage	GHGs emission (gCO_2eq/kWh)
Material	2
Energy	230
Construction	4
Operation	227
Decommissioning	0.19

Source: (Chmielewski, et al., 2020)

Cocco et al. (2022), also evaluate the life cycle environmental impact of an A-CAES system. The case study considers the electrical energy demand of a small town, with a maximum power load of about 10 MW and a PV plant of multiple sizes (20-40 MWp). Two types of CAES, underground caverns and gas pipelines, are investigated. The goal is to confront the impacts on human health, ecosystem quality, climate change, and resource consumption of the PV power generation plant and the integrated PV-ACAES system with those of a reference scenario where the end user demand is met entirely by the grid. The highest reduction in environmental impacts (85–95%) results from a small PV plant (20 MW) without the A-CAES section. When the A-CAES system is integrated, energy self-consumption improves, but the environmental impact increases, mainly for air storage in gas pipelines. The best option is a 30 MW PV plant integrated with an A-CAES section using an underground cavern. This alternative ensures between 38% and 61% higher energy self-consumption and 80–91% (depending on the impact category) lower environmental impact, compared to the reference scenario (Cocco, Lecis, & Micheletto, 2023).

Liquid Air Energy Storage (LAES). Based on literature reviews by Azhdari (2023) and Chmielewski et al. (2020), LAES does not require a lot of storage space, due to its relatively high energy density. Additionally, these systems do not demand the use of environmentally harmful materials and do not generate toxic wastes. Extensive use of rare metals or harmful chemicals is avoided during construction, and operational processes do not generate GHGs emissions.

Superconducting magnetic Energy Storage (SMES). Lu (2022) investigates the sustainability of SMES systems based on the SDGs (United Nations Sustainable Development Goals). Considering that the use of fossil fuels or other types of fuel is not required for operation, the technology can contribute to the reduction of fuel consumption and GHGs or other harmful gases emissions in a certain area.

Furthermore, the systems do not generate a relevant level of acoustic pollution during operation. SMES systems could also contribute to the improvement of the aquatic environment, where dams or hydroelectric plants are built. Due to their large energy storage capacity and discharge power, a moderate amount of water would be taken away by dams for power generation and smaller dams could be removed. The flow of rivers and watersheds cut off by dams would be restored, making the environment suitable for the growth of native aquatic plants and animals. Moreover, the energy stored in the SMES systems would not be lost in heat dissipation or evaporation, preventing the habitat ecology from being negatively affected by the additional heat dissipated into the air (Lu R. , 2022). In accordance with Lu (2022), Chmielewski et al. (2020), confirm that SMES do not emit GHGs or other polluting gases or compounds during operation. There may be a negative environmental impact deriving from a strong magnetic field, but this is still to be further studied. Production phase implies impacts related to materials used, the carbon footprint of selected primary raw materials is listed in Table 26.

Table 25. Carbon footprint SMES

Material	Carbon footprint of materials extraction ($kgCO_2eq$/100000 t)
Aluminum	383
Copper	125
Iron	167
Lead	163
Nickel	212
Tin	218

Source: (Chmielewski, et al., 2020)

Supercapacitors (SC). Nowrot & Manowska (2023) discuss that to enhance energy decarbonisation and the replacement of coal-fired power plants with solar and wind farms in Poland, large energy storage facilities are needed. The research indicates that SC may be a great option. Since rechargeable batteries have a short lifespan, and GHGs emissions that result from their production are significant, the use of SC discloses new possibilities and boosts decarbonisation efforts (Nowrot & Manowska, 2023).

Based on findings from Chmielewski et al. (2020), airgels, one of the materials used, have a carbon footprint of 4.2 kgCO2eq/kg. SC do not emit GHGs or other polluting gases or compounds during operation.

El Halimi et al. (2023), provide a review on carbon-based materials for SC that originate from affordable coal deposits or crop waste, and on the replacement of organic liquids electrolytes with less hazardous solutions, like aqueous electrolytes in which salt is highly concentrated. The latter proves to be a remarkable strategy for the design of sustainable devices. Indeed, these low-cost systems contribute to reducing costs, preserving the environment and are promising for deployment on a commercial level.

Latent Thermal Energy Storage (LTES). GHGs emissions related to the production stage of an LTES system using PCM can reach 75% of the assessed life cycle (Wickramasinghe & Zhang, 2022). When comparing STES in solid media (high-temperature concrete), STES in liquid media (molten salt based) (MSTES), and LTES using a PCM (eutectic salt), the latter and the solid media do not generate negative operational impacts. On the opposite, molten salts generate negative environmental impacts also during the operational phase. The use of an LTES system with encapsulated PCM can improve the storage capacity of a hot water tank.

Nartowska et al. (2023), investigate the potential impact on the environment and human health of inorganic salt hydrates that are employed as PCM material in solar installations and evaluate the social perception of this technology. Assessed inorganic salt hydrates are: magnesium chloride hexahydrate, magnesium nitrate hexahydrate, sodium sulfate decahydrate, sodium acetate trihydrate, sodium carbonate decahydrate, calcium chloride hexahydrate, disodium hydrogen phosphate dodecahydrate, barium hydroxide octahydrate. According to findings, disodium hydrogen phosphate dodecahydrate proves to be the most promising salt in terms of environmental properties for use in solar installations. The waste that it generates is not classified as hazardous, and the elimination of most common defects (supercooling, phase separation, and corrosiveness) is easily achievable. Overall, if not properly used, salt hydrates can generate diverse threats. In case of fire, hazardous vapours may be released (hydrogen chloride gas, magnesium oxide etc.). Furthermore, they can be hygroscopic, corrosive, they can generate hazardous waste and enhance eutrophication (Nartowska, Stys-Maniara, & Kozlowski, 2023).

Sensible Thermal Energy Storage (STES). According to Systemiq (2024), ETES (Electrothermal Energy Storage) technologies, including STES, that use electricity to produce heat and later store it in a heat storage medium to be used in the food and beverage, chemicals, textiles and paper and pulp sectors could contribute to abate up to about 2% of global energy-related GHGs emissions by 2030, if the equivalent of about 8% of current global gas use is electrified. This reduction is expected to reach 10-14% by 2050. Non-industrial markets such as district heating and direct air carbon capture could increase the reachable market by almost 2.5 times. Consequently, by 2050, ETES could replace the equivalent of about 30–40% of current global gas use and reduce current energy-related GHGs emissions by up to 14%.

Based on multiple life cycle assessment studies reviewed by Wickramasinghe & Zhang (2022), MSTES systems generate the lowest GWP when compared to CAES systems and vanadium redox flow batteries. ATES, a geothermal system for long-term storage in groundwater, generates up to 97% less GHGs than oil heating systems. A solar BTES system integrated into a Canadian housing community (DLSC) result in considerably less GHGs emissions when compared to a conventional Canadian house that is powered by fossil fuels. Basalt-air packed bed storage system can generate a 12% reduction of GWP indicator, compared to the generic 20% contribution of a TES integrated in a CSP (Concentrated Solar Power) plant. When compared to a conventional two tanks MSTES system, this reduction can reach 60% (Wickramasinghe & Zhang, 2022).

Social Sustainability

Flywheel energy storage (FES). In terms of social performance and, more specifically, public acceptance, Jones et al. (2018), Gaede et al. (2020) and Jones et al. (2021) report on the findings of online surveys shared with UK and Canadian residents. These were asked to give their opinion on CAES, FES, lithium-ion batteries and PSH, and the factors that determine intentions to accept them. FES proved to be the third most preferred technology (14%), following PSH (37-40%), and lithium-ion batteries (23-25%) in both countries. Preference for CAES was either equal to or worse than FES (13-17%).

Gravity energy storage (GES). Although there is no comprehensive scientific research on the social performance of GES, its public acceptance is assumed to be positive, according to actors working on the technology. Gravitricity expects GES systems to enhance the repurposing of valuable assets by extending the life of existing infrastructure, maintaining communities, saving decommissioning costs, and re-using grid connections[91].

GES can contribute to reducing dependence on fossil fuels and centralized power generation facilities. Through the storage of locally generated renewable energy, underserved or off-grid communities can improve their energy independence and be more resilient to external disruptions. The renewable energy sector may benefit through stimulated economic growth, driving also energy costs down, and job creation.

When decommissioned mines are used for UGES, communities that rely on these for their economic output are less prone to record a negative impact on local employment. UGES projects can create vacancies as the mine could provide energy storage services after its usual operations are stopped, according to a researcher from the IIASA (International Institute for Applied Systems Analysis) Energy, Climate, and Environment Program[92.]

However, according to Pullen & Amiryar, (2022), when above ground GES vertical systems are built, public acceptability can be an obstacle, if these are built near population centers, similarly to what happens with wind turbines. According to a study concerning 12,640 residential property sales in Denmark, there is a negative price premium of around 3% for those that are close to at least one wind turbine, and an additional 3–7% negative premium due to noise.

Compressed Air Energy Storage (CAES). In terms of social performance and, more specifically, public acceptance, Jones et al. (2018), Gaede et al. (2020) and Jones et al. (2021) report on the findings of online surveys shared with UK and Canadian residents (Gaede, Jones, Ganowski, & Rowlands, 2020); (Jones, Gaede, Ganowski, & Rowlands, 2018); (Jones, Hilpert, Gaede, & Rowlands, 2021). Respondents were asked to give their opinion on CAES, FES, lithium-ion batteries, and PSH, and the factors that determine intentions to accept them. PSH (37-40%), and lithium-ion batteries (23-25%) proved to be the most preferred technologies in both countries. Preference for CAES (13-17%) was either equal or worse than FES (14%).

Thomas et al. (2019), by conducting workshops with members of the British public, assess perceptions about energy storage technologies deployed in the UK. When considering social acceptance of CAES, some misconceptions arise. For example, people fear that the technology may require the injection of toxic chemicals underground, damaging ecosystems. Other risks attributed to CAES are mechanical failure, toxicity and the fact that it may not prove to be realistic. Participants' acceptance of CAES depends on cost, lower/higher environmental impact and safety compared to alternatives. Despite the perceived risks, people are more willing to accept the technology if it is located underground. In terms of benefits, CAES is perceived as being natural and under demanding maintenance in the long term. Other attributed benefits are use of existing and abundant resources, re-use of existing infrastructure, reduced CO2 emissions, renewables deployment, being safe in comparison to alternatives, and high tech and low carbon features (Thomas, Demski, & Pidgeon, 2019).

[91] Technology – Gravitricity

[92] Gravity batteries: Abandoned mines could store enough energy to power ‘the entire earth’ | Euronews

Concerning impacts on human health and safety, (O' Brien, Brandsen, & Fletcher, 2021) provide a review of hazards and initiating events related to storing compressed air in salt caverns. These have usually proven to be safe for natural gas storage, although some accidents have been reported. However, useable sites are limited. Depleted Natural Gas Reservoirs and abandoned coal mines are potential alternatives. No specific standards framework was identified, besides general regulations such as PSSR 2000, its related code of practice “Safety of pressure systems” and guidance notes on “Compressed air safety”. Nonetheless, it is worth noticing that operational experience and associated standards related to the storage of gas underground are abundant. According to the authors, the relative immaturity of CAES, and the diversity of possible locations, do not require an immediate need for standards development.

Liquid Air Energy Storage (LAES). In terms of social performance, according to the literature review by Azhdari (2023), LAES is considered a safe alternative. Nevertheless, safety concerns may arise when handling liquid air, since oxygen can be a fire and explosion hazard. These risks can be controlled through well-insulated systems, consistent monitoring of oxygen levels in the liquid air, and ensuring the absence of organic materials close to areas with oxygen enrichment. Also, extremely low operating temperatures can generate hazards to both individuals and materials.

According to O’ Brien et al. (2021), since LAES systems are generally associated with grid scale storage deployment, detailed hazard analysis should be conducted as part of the design and construction of a plant. There are no specific LAES system H&S standards, but industry experience for similar applications offers a basis for assessment. For instance, the European Industrial Gases Association “Safe Practices Guide for Cryogenic Air Separation Plants” guidance document covers hazards related to air liquefaction and cryogenic fluid storage. Moreover, COP CP 36 by the British Compressed Gases Association provides specific industry guidance around storage of cryogenic fluid and more general requirements are provided with the Pressure Systems Safety Regulations (PSSR) 2000. In addition to handling liquid air, most of hazards are due to the potential risks associated with the storage of cryogenic fluids. However, the use and storage of cryogenic fluid, such as liquid nitrogen, is commonplace in industry, hospitals, laboratories etc., and so hazards are well understood and mitigated. Since liquid air for energy storage may be used at smaller scales in the future, more robust standards than the ones that are currently defined may be required.

Superconducting Magnetic Energy Storage (SMES). According to Lu (2022), the high energy storage and high efficiency of SMES systems decrease the cost per unit of energy. In socially and economically underdeveloped areas, through SMES technology application on hydropower or wind power, more residents could afford clean energy at a lower cost. Ideally, production and living patterns could be innovated and new jobs could be created.

Huang (2021), a study specific to the Chinese rural context, states that SMES can be used to store electricity that is not used by rural families, whose power source is solar, and be transmitted to the national power grid. This could generate national energy supply costs saving and the government could allocate more funds to enhance the development of poor areas.

When looking at impacts on human health, the strong magnetic field of SMES may be related to abnormal heart rates, irregular changes in brain activity, damage to the immune system, the appearance of skin diseases, etc. Since SMES is a novel technology, comprehensive information on associated hazards is relatively limited (Huang, Ru, Shen, & Zeng, 2021).

Based on a review from O' Brien et al. (2021), biological effects of long term and acute exposure magnetic fields are unlikely, considering that close interaction with personnel is rare. If good safety practice is guaranteed, risks posed by these hazards are not highly concerning. No specific standards for SMES have been identified through the review.

Supercapacitors (SC). According to O' Brien et al. (2021), hazards associated with SC systems are similar to those generated by battery systems, although the risk profile may differ. These mainly derive from the electrical response and may result in electric shock, arc flash or cable movement. SC systems may also cause fire, explosion, exposure to harmful chemicals, substances or toxic gases. Concerning standards related to supercapacitors, general capacitor device level design and test standards exist, and these provide details on device requirements (the BS EN 62391), to minimise the failure of designed components. Standards specific application also exist ((hybrid electric vehicles (BS EN IEC 62576:2018) and railway applications (BS EN 61881-3)), but grid applications are not covered. It is worth noticing that identification of specific hazards associated with supercapacitor systems within standards is scarce, nevertheless some manufacturer guidance covers these gaps. Specific SC standards for stationary applications are also limited, considering that supercapacitors are currently rarely used for large scale energy storage and demand for further standardisation is low.

Latent Thermal Energy Storage (LTES). According to surveys from Nartowska et al. (2023), there is a significant public concern towards the impact on the environment and human health of inorganic salt hydrates that are employed as PCM material in solar installations in Poland. When asked about photovoltaic panels with converters that contain salt hydrates, 35% of people living in villages and small towns were not aware of this type of materials, however 43% of them expressed concern or were convinced of their severe impact on human health. While only 16% of people living in medium and large cities had no knowledge about salt hydrates, 60% considered them to be harmful to human health. Based on the risk level identified in the GHS (Globally Harmonized System), magnesium chloride hexahydrate, magnesium nitrate hexahydrate, sodium sulphate decahydrate, sodium acetate trihydrate, and disodium hydrogen phosphate dodecahydrate do not cause harm to human health. On the opposite, sodium carbonate decahydrate and calcium chloride hexahydrate are identified as medium harmful salts and can generate considerable irritation and discomfort. The hazard posed by barium hydroxide octahydrate is medium if ingested or it is in short-term contact with the skin and it may result in permanent damage to organs if long-term inhalation takes place (Nartowska, Stys-Maniara, & Kozlowski, 2023).

Sensible Thermal Energy Storage (STES). Based on the research carried out by (Barns, Taylor, Bale, & Owen, 2021), STES, especially tank-based, proves to be the most common technology deployed in assessed projects. These involve energy storage through water in tanks (WTTES) and in slow-moving aquifers (ATES), ceramics heating (STES) in electric storage heating, as well as in the earth through boreholes (BTES). Among the identified indirect benefits of TES overall, mitigating the need for grid reinforcement, which frequently affects consumers through energy bills, especially applies to dwellings that are served by electric night ceramic bricks storage heaters. When asked about their knowledge and application of three TES technologies (WTTES, PCM and Trombe walls), only 42% of professionals replied that they had used them in projects, and these consisted of the application of WTTES. These were integrated into sanitary hot water facilities (50%) and solar energy systems (36%). A common technical barrier that, according to respondents, hinders the application of WTTES is the large space required for installation.

Economic Sustainability

Flywheel energy storage (FES). According to Cellura et al. (2022), mentioned in previous sections, investment and charging costs contribute the most to the LCOS of FES, while replacement costs contribute the least. In terms of Supply Risk, both for raw materials and aggregated FES, natural graphite and aluminium are the major contributors. Rahman et al. (2021) estimate steel rotor and composite rotor FES systems to have NERs that range from 2.5 to 3.5 and 2.7 to 3.8, respectively.

When looking at the economic sustainability of specific materials and components, according to data collected by EASE from industry stakeholders (2024), using prestressed concrete instead of carbon fibre secures more cost-effective manufacturing of FES systems. Furthermore, being locally available, the supply chain of concrete is usually less prone to international disruptions.

Gravity energy storage (GES). Tong et al. (2022) conducted a bibliometric study between 2010 and 2021 to verify whether solid GES technology can be suitable for large-scale applications. Through a SWOT analysis, strengths, opportunities, weaknesses and threats are identified. Compared to other large-scale energy storage technologies, it guarantees the following strengths: easy scalability; long service life (30-50 years); high cycle efficiency (80%-90%); low cost of electricity; environmental friendliness; good geographical adaptability. In terms of opportunities, it can benefit from the rapid rise in installed renewable energy capacity and the development of the energy service market. Lack of public awareness and technical maturity, as well as being uneconomical in small-scale scenarios are the most concerning weaknesses. Moreover, the predominance of major large-scale energy storage technologies and not sufficiently improved related policies and systems represent a threat to solid gravity energy storage deployment.

According to Hunt et al. (2022), weekly to pluriannual energy storage cycles with energy storage investment costs of about 1 to 9 €/kWh can be guaranteed by underground GES. Globally, the technology has a 7 to 70 TWh storage potential.

Hunt et al. (n.d) analyse mountain GES. Similarly to underground GES, this technology moves sand or gravel from a lower storage site to an upper elevation. The cost varies from 45 to 90 €/MWh of stored energy and 900 thousand to 1.8 million €/MW of installed capacity. Therefore, the application of this technology could be favourable in the following contexts: micro-grids; small islands and isolated areas; power systems where electricity costs are high and monthly or seasonal demand for energy storage does not exceed[93].

Compressed Air Energy Storage (CAES). Li et al. (2021), report the results of a comprehensive life cycle techno-economic and environmental optimisation analysis of an A-CAES located in China. Higher life cycle environmental impacts are correlated to lower investment costs. When assessing the round-trip efficiency of the system, this increases as the investment capital cost increases as well. In terms of raw materials use, the consumption of raw coal decreases gradually as the investment cost increases. Nevertheless, the consumption of natural gas, crude oil, and other energy sources increases.

[93] Note that all estimations reported in this paragraph were expressed in USD and these were converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

Hunt et al. (2023) investigate a specific isothermal CAES system that consists of two floating storage vessels in the deep ocean. This operates by balancing the pressure of the upper and lower tanks with the oceanic pressure. Findings prove that, since the maximum compression ratio between the two storage vessels is four, the efficiency of the system considerably increases, and compression costs decrease. The technology is a cheap alternative for storing compressed air since large, pressurised tanks or sand cavers are not required. The cost is expected to be between 9 and 49 €/kWh for electric energy storage and between 734 and 1400 €/kW for the installed power capacity (Hunt, et al., 2023). In islands and coastal regions located close to the deep sea, this isothermal CAES system can be a favourable[94].

Liquid Air Energy Storage (LAES). The maximum scale that LAES systems can reach is several hundred megawatts. This falls between the capacities of CAES and PSH and it is higher than the capacities of batteries and hydrogen storage. Additionally, the components of LAES systems have a lifespan of 20 to 60 years, this duration is comparable to the one of batteries, which typically last 5 to 15 years. Overall, LAES is a practical energy storage alternative, but its feasibility significantly depends on multiple factors: system efficiency, electricity prices, costs, and waste cold/heat availability (Azhdari, 2023).

Mazzoni et al. (2019) investigate the economic dispatch of an eco-building in Singapore by comparing the use of either EES (Electrochemical Energy Storage) or LAES. Despite drawbacks mentioned above, at the higher end of the capacity range, the latter proves to have higher NPV (Net Present Value) after 20 years and the time required to obtain a return on investment is shorter (Mazzoni, et al., 2019).

Superconducting Magnetic Energy Storage (SMES). According to Lu (2022), since SMES systems have a relatively high-power density and high efficiency, the technology is flexible and reliable enough. The energy conversion efficiency can reach or exceed 96% when ideal conditions occur. These systems can guarantee a fast response capability, supporting a longer lifetime and operation cycle of the whole system (around 20 years), allowing the energy storage and supply to be continuous and stable over a long-time span while meeting the high energy supply demand. Nevertheless, the cost of manufacturing the superconducting components is relatively high and this may limit the overall economic sustainability of SMES systems.

Supercapacitors (SC). Yassine & Fabris (2017), investigate the performance of commercially available SC and their use in the transportation sector. These prove to be a favourable alternative to batteries when demands of energy storage systems are to be met. The development of SC guarantees growth potential considering that they respond to key market and social needs. The technology is perceived as being eco-friendly, supportive of energy storage, and an enhancer of systems performance (Yassine & Fabris, 2017).

Latent Thermal Energy Storage (LTES). (Castro Flores, Rossi Espagnet, Chiu, Martin, & & Lacarrière, 2017) Conducted a techno-economic assessment of active TES systems that operate with LTDH (Low-Temperature District Heating). Results of a quantitative and qualitative comparison between LTES and water based STES are reported. LTES proves to have a (1.5-4 times) higher energy storage cost, and this is mainly because of the cost of the storage media. Nevertheless, small-scale active LTES are expected to become more cost-competitive, since the cost of storage media is also expected to decline in the future.

[94] Note that all estimations reported in this paragraph were expressed in USD and these were converted to Euros using as a reference InforEuro, the exchange rate of the Euro currency (europa.eu).

The LTES systems PCM categories investigated by Castro Flores et al. (2017) include paraffins, fatty acids, salt hydrates and metallics. Since all of them are not usually sold in large quantities and have a relatively high price, they contribute the most to the overall system cost. The most expensive PCM, based on 2017 wholesale estimations carried out by authors, is Methyil-12. Lauric acid is estimated to be the most convenient one.

Sensible Thermal Energy Storage (STES). Despite having lower energy densities than LTES and TCES, STES is more cost-effective, especially for medium–high temperature industrial applications (Koçak, Fernandez, & Paksoy, 2021). When looking more closely at the performance of storage materials and media employed in STES systems:

Concerning specific STES systems, according to the research done by Koçak et al. (2020), packed-beds (STES) are economically convenient when storing heat for industrial applications, if compared with LTES and TCES. Commonly used STESMs, such as rock, bricks, sand, soil etc., are both low cost and abundant. Waste and industrial byproducts are also alternative low cost STESMs. Alumina is one of the most expensive STESMs, but it is still preferable in industrial applications due to its high stability, high heat capacity and high thermal conductivity properties. When comparing the cost of a 2-tank molten salt (MSTES), SMT (single-medium termocline), DMT (dual media termocline) and ST (shell-and-tube) using low-cost concrete. The 2-tank system may have higher costs in a range of 17-60% than the other mentioned technologies (Koçak, Fernandez, & Paksoy, 2020).

Annex IV – List of companies

Flywheel energy storage (FES). When cross-referencing all market reports mentioned in FES Turnover section (Table 15), companies listed in Table 26 prove to be the currently active global key players. It is worth noticing that many of these operate in more than one country and multiple regions. EU market leaders in the global context are: Piller Group GmbH; Stornetic GmbH; Adaptive Balancing Power GmbH; Siemens Energy AG; Alstom Transport SA.

Table 26. Mature companies working with FES technologies

Company Name	Country	FES Value Chain Position	Source
Calnetix Technologies, LLC	USA	Technology provider (components manufacturer)	Calnetix Technologies, LLC
ABB Ltd	Switzerland		ABB Ltd
Active Power	USA	Technology provider (components and systems manufacturer)	Active Power
Amber Kinetics, Inc	USA		Amber Kinetics, Inc
Beacon Power, LLC	USA		Beacon Power, LLC
Piller Group GmBH	Germany		Piller Group GmBH
Powerthru	USA		Powerthru
VYCON, Inc	USA		VYCON, Inc
Stornetic GmbH	Germany		Stornetic GmbH
Revterra	USA		Revterra
Adaptive Balancing Power GmbH	Germany		Adaptive Balancing Power GmbH
Bc New Energy (Tianjin) Co., Ltd. (BNE)	China		Bc New Energy (Tianjin) Co., Ltd. (BNE)
PUNCH Flybrid	UK		PUNCH Flybrid
Kinetic Traction Systems, Inc.	UK		Kinetic Traction Systems, Inc.
Siemens Energy AG	Germany		Siemens Energy AG

GKN Hybrid Power	UK		GKN Hybrid Power
Rotonix USA Inc	USA		Rotonix USA Inc
Pentadyne Power Corporation	USA		Pentadyne Power Corporation
Beijing Qifeng	China		Beijing Qifeng
Alstom Transport SA	France	Technology provider (deployment and application)	Alstom Transport SA
EnSync Energy	USA		EnSync Energy

Gravity energy storage (GES). Companies identified for this technology are listed in Table 27, all of them identified as technology providers.

Table 27. Companies working with GES technologies

Company Name	Country	GES Value Chain Position	Source
Energy Vault	Switzerland	Technology provider (components and systems manufacturer)	Energy Vault
ARES North America	USA		ARES North America
Gravitricity	UK		Gravitricity
Gravity Power LLC	USA		Gravity Power
StratoSolar Inc	USA		StratoSolar

Compressed air energy storage (CAES). Table 28 shows the companies identified for this technology. These companies, the same way it happened with FES, seem to be key players of the technology and are based in more than one country.

Table 28. Companies working with CAES technologies

Company Name	Country	CAES Value Chain Position	Source
Dresser-Rand Group	USA	Technology provider (components and systems manufacturer)	The Technology | rangeenergystorage
Hydrostor	Canada		Hydrostor
Bright Energy Storage Technologies	USA		Bright Energy Storage Technologies
Alacaes SA	Switzerland		ALACAES

Storelectric Limited	UK		Green Energy
Augwind Energy	Israel		Augwind Energy
Cheesecake Energy Ltd	UK		Cheesecake Energy
Enairys Powertech	Switzerland		Enairys Powertech
Green-Y Energy AG	Switzerland		Green-Y Energy AG
Lige Pty Ltd	South Africa		Lige Pty Ltd
TerraStor Energy Corporation	USA		TerraStor
Sherwood Power	UK		Sherwood Power
General Compression	New Zealand		General Compression
Carnot Compression Inc	USA		Carnot Compression
Doosan Škoda Power	Czech Republic	Technology provider (components manufacturer)	Doosan Škoda Power
Kobe Steel, Ltd	Japan		KOBE STEEL, LTD
MAN Energy Solutions SE	Germany		MAN Energy Solutions
Apex CAES	USA	Technology provider (components and systems manufacturer)	APEX CAES
Pacific Gas and Electric Company	USA		Pacific Gas and Electric Company
Siemens Energy AG	Germany		CAES-Siemens
Magnum Development LLC	USA		Magnum Energy
Brayton Energy, LLC	USA	Technology provider (deployment and application)	Brayton Energy
Corre Energy B.V	Netherlands, Denmark		Corre Energy
General Electric Company	USA		GE
Mitsubishi Power	Japan		Mitsubishi Power Americas, Inc.
Czero Inc	USA	Technology provider (R&I)	Czero
IFP Energies Nouvelles	France		IFPEN

Liquid air energy storage (LAES). Taking into account the information in the LAES Turnover section (Table 13), a non-exhaustive list of companies currently working with LAES is in table 29. Most of them are based in Europe.

Table 29. Companies working with LAES technologies

Company Name	Country	LAES Value Chain Position	Source
Highview Power	UK	Technology provider (components and systems manufacturer)	Highview Power
Cryostar	France		CRYOSTAR
Linde Kryotechnik AG	UK	Technology provider (components manufacturer)	Linde
MAN Energy Solutions	Germany		MAN Energy Solutions
Atlas Copco	Sweden		Atlas Copco Group
Custom Metalcraft	USA		Custom Metalcraft
Bonfiglioli	Italy		Bonfiglioli
Rossi	Italy		Rossi
Apexdynamics Inc	USA		APEX DYNAMICS, INC
Messer Group	Germany	Technology provider (deployment and application)	Messer Group
Siemens Energy AG	Germany		Siemens Energy AG
Mitsubishi Hitachi Power Systems	Japan		Mitsubishi Power

Superconducting magnetic energy storage (SMES). Following the same approach as with other technologies, table 30 shows the companies identified that currently work with SMES.

Table 30. Companies working with SMES technologies

Company Name	Country	SMES Value Chain Position	Source
Nexans SA	France	Technology provider (components manufacturer)	Nexans SA
Luvata U.K.	UK		Luvata
SuNam Co., Ltd.	South Korea		SuNAM Co
Sumitomo Electric Industries, Ltd	Japan		Sumitomo Electric Industries, Ltd.
General Cable Superconductors Ltd.	New Zealand		General Cable
Fujikura	Japan		Fujikura

Bruker Energy & Supercon Technologies	USA		Bruker
ASG Superconductors SpA	Italy		ASG
Super Power Inc	USA		SuperPower
Southwire Company	USA		Southwire
Hyper Tech Research	USA		Hyper Tech Research
American Superconductor Corporation	USA		AMSC
ABB Inc	Switzerland		ABB
Beijing Innopower Superconductor Cable Co. Ltd	China		Innost
Toshiba Energy Systems and Solutions Corp	Japan		Toshiba
Meidensha Corp	Japan		MEIDENSHA
HYPRES Inc	USA		Hypres, Inc.
Bilfinger Nuclear & Energy Transition GmbH	Germany	Technology and knowledge provider (components and systems manufacturer)	Bilfinger
PNNL	USA	Technology Provider (R&I)	PNNL

Supercapacitors (SC). The companies that work with this technology are listed in Table 31. Companies located in EU countries (Ireland, Germany, Estonia and France) cover 13% of the whole list. EU market leaders in the global context are: Eaton Corporation PLC; Skeleton Technologies; Supreme Power Solutions; Blue Solutions.

Table 31. Companies working with SMES technologies

Company Name	Country	SC Value Chain Position	Source
CAP-XX Ltd	Australia	Technology provider (components and systems manufacturer)	CAP-XX Ltd
Nippon Chemi-Con Corp	Japan		Nippon
UCAP Power	South Korea		UCAP-Maxwell
Eaton Corporation PLC	Ireland		Eaton
Cornell Dubilier Electronics, Inc	USA		Cornell Dubilier
SPEL Technologies Private Limited	India		SPEL
Skeleton Technologies	Germany, Estonia		Skeleton

Evans Capacitor Company	USA		EVANSCAPS
KORCHIP Corporation	South Korea		KORCHIP
Advanced Capacitor Technologies, Inc	India		Advance Capacitors
FastCAP Systems, Inc	USA		Fastcap
LS Mtron Ltd	South Korea		LS Mtron
ELNA CO., LTD	Japan		ELNA CO., LTD.
KEMET Corporation	USA		KEMET
KYOCERA AVX Components Corporation	USA		KYOCERA AVX
Murata Manufacturing Co., Ltd	Japan		Murata
Seiko Instruments Inc	Japan		Seiko
Shanghai Aowei Technology Development Co. Ltd	China		Aowei
Tecate Group	USA		Tecate
VINATech Co.,Ltd	South Korea		VINA Tech
Yunasko	Ukraine		Yunasko
Nichicon	Japan		NICHICON CORPORATION
Jinzhou Kaimei Power	China		Jinzhou
Samwha	South Korea		Samwha
Ningbo CRRC New Energy Technology	China		CRRC
Jianghai Capacitor	China		Jianghai
Supreme Power Solutions	Germany		SPSCAP
Cornell-Dubilier Electronics Inc	USA		Cornell Dubilier
Blue Solutions	France		Blue Solutions
Kilowatt labs, Inc	USA		Kilowatt Labs
Mouser Electronics, Inc	USA	Technology provider (distributor)	Mouser

For SC we also present a non-exhauistive list of start-ups working on the field:

Table 32. Start-ups working in the field of SC

Start-up	Country
Allotrope Energy	UK
Capacitech	USA
EnergoPlus Tech	Latvia

FlexCap Energy	Canada
SECH	Switzerland
Nanoramic	USA
Integrated Graphene	UK
Ioxus	USA
Nawa Technologies	France
Power Roll	UK
Nesscap	South Korea
Inmantech	USA
EESTOR	Canada

Thermal energy storage (TES). A non-exhaustive list of companies working with TES are listed in Table 33. EU market leaders in the global context are: Man Energy Solutions; Siemens Gamesa Renewable Energy, S.A; Aalborg CSP A/S; Cryogel Thermal Energy Storage. The latter seems more at start-up or scale-up level[95], compared to the other mentioned companies, which are well known global market players working also on multiple other technologies. Man Energy Solutions provides LTES (IS, SZTPCM and LTPCM) solutions and Siemens Gamesa Renewable Energy, S.A promotes deployment and application of STES systems. Aalborg CSP A/S is a STES components and systems manufacturer, while Cryogel Thermal Energy Storage provides LTES (IS) solutions.

Table 33. Companies working with TES technologies

Company Name	Country	Sub-Technology	Source
Kelvin Thermal Energy	Canada	STES	Kelvin
Evapco, Inc.	USA	LTES	EVAPCO
Sunamp Ltd	UK	STES	Sunamp Global
CALMAC	UK	LTES	CALMAC
Steffes, LLC	USA	STES	Steffes
Axiotherm	Germany	LTES - PCM	axiotherm
Pluss Advanced Technologies Ltd.	India/Netherlands	LTES - PCM	PLUSS
Rubitherm Technologies GmbH	Germany	LTES - PCM	Rubitherm
Sunamp Ltd	Scotland	LTES - PCM	sunamp

[95] Ice Thermal Storage - CRYOGEL.

Va-q-tec	Germany	LTES - PCM	Va-q-tec
B Medical Systems S.a r.l.	Luxembourg	LTES - PCM	Bmedical
Newton Energy Solutions	Netherlands	STES – Water tanks	newton-energy
Croda International Plc	UK	LTES - PCM	Croda
Climator	Sweden	LTES - PCM	Climator
Phase Energy Ltd	UK	LTES - PCM	Phasenergy
PCM products Ltd	UK	LTES - PCM	PCM
BEKA	Germany	LTES - PCM	BEKA
Cowa Thermal Solutions AG	Switzerland	LTES - PCM	Cowa
SENER Group	Spain	STES – Molten salts	SENER
Torresol Energy	Spain	STES – Molten salts	Torresol
MAN Energy Solutions	Germany	STES – Molten salts	MAN
Siemens	Germany	STES – Molten salts	Siemens
Yara International	Norway	STES – Molten salts	Yara
ACWA Power	Saudi Arabia	STES – Molten salts	ACWA
BrightSource Energy	Israel	STES – Molten salts	Brightsource
Kraftblock	Germany	STES – Solid Media	Kraftblock
Energy NEST	Norway	STES – Solid Media	NEST
1414	Australia	STES – Solid Media	1414
Brenmiller	Israel	STES – Solid Media	Brenmiller
Rondo	US	STES – Solid Media	Rondo
Lumenion	Germany	STES – Solid Media	Lumenion
MAN Energy Solutions	Germany	A-CAES	MAN
Siemens Energy	Germany	A-CAES	Siemens
Alfa Laval	Sweden	A-CAES	Alfalaval
Geostock	France	A-CAES	Geostock
Hydrostor	Canada	A-CAES	Hydrostor
ALACAES	Switzerland	A-CAES	ALACAES
Lane Power & Energy Solutions	US	A-CAES	LANE
Agapito Associates	US	A-CAES	Agapito
China Huaneng Group	China	A-CAES	Huaneng
MAN Energy Solutions	Germany	LAES	MAN

Phelas	Germany	LAES	Phelas
Highview Power	UK	LAES	Highview Power
Sumitomo	Japan	LAES	Sumitomo

Based on data collected from EASE members (2024), some of the below listed companies are mostly EPC (Engineering, Procurement and Construction) related to TES. According to their expertise, Malta Inc (USA) and Kyoto Group (Norway), Carbon Clean Technologies (Germany) are well-known technology providers, focusing only on TES, which are worth mentioning. Malta Inc. and Kyoto Group provide STES (MSTES) systems[96], while Carbon Clean Technologies offers STES using solid media (STES)[97]. The latter is briefly discussed in the start-ups section[98].

According to the latest worldwide overview of high-temperature energy storage system provided by the Solar Thermal World platform[99] Kraftanlagen is another big company located in the EU (Germany) that, among its multiple technologies and services, engages in the manufacturing, deployment and application of STES (WTTES) systems[100.]

When looking at suppliers of specific materials used for TES, Rubitherm (Germany) manufacture paraffins used as organic PCM for LTES (Sevault, Vullum-Bruer, & Lehn Tranås, 2022).

[96] Our Solution | Malta (maltainc.com) ; Kyoto Group AS - The Norwegian Thermal Battery Company

[97] Enabling the clean energy transition - carbonclean technologies GmbH

[98] See start-ups information in chapter 3.4.1

[99] Worldwide overview of high-temperature energy storage system providers | Solarthermalworld.

[100] Thermal storage - Kraftanlagen Energies & Services SE.

Annex V – List of Turnover sources

This annex provides the sources used to write section 3.1 and table 13. There is a table with the sources per technology.

Table 34. Estimations of FES turnover

LOWEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2023	290.7 million	Flywheel Energy Storage Market | Size, Growth | 2023 to 2028 (marketdataforecast.com)
2022	279.5 million	Flywheel Energy Storage Market Size, Share & Growth [2029] (fortunebusinessinsights.com)
2021	242.3 million	Flywheel Energy Storage Market Size, Share & Growth [2029] (fortunebusinessinsights.com)
	265.9 million	Flywheel Energy Storage System Market Size, Growth, Trends | Report 2022-2030 (visionresearchreports.com)
	318.6 million	Flywheel Energy Storage Market Size [2031], Share, Growth Report (businessresearchinsights.com)
	265.8 million	Flywheel Energy Storage System Market Size, Share & Trends Analysis Report By Application (UPS, Distributed Energy Generation, Transport, Data Centers), By Region, And Segment Forecasts, 2022 - 2030 (researchandmarkets.com)
	253.4 million	Flywheel Energy Storage System Market Size Report, 2030 (grandviewresearch.com)
2020	268.1 million	Flywheel Energy Storage Market Forecast Report, 2030 (psmarketresearch.com)
2019	270.6 million	Flywheel Energy Storage Systems Market Size, Trends & Forecast (verifiedmarketresearch.com)
HIGHEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	1.2 billion	Flywheel Energy Storage Market Size & Share, Forecasts 2032 (gminsights.com)
2021	993.7 million	Flywheel Energy Storage Market Size & Share, Forecasts 2032 (gminsights.com)

Table 35. Estimation of GES turnover

LOWEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	62.3 million	Gravity Energy Storage Systems Market Size, Share & Demand 2029 | BlueWeave (blueweaveconsulting.com)
	61.9 million	Gravity Energy Storage Systemsmarket size was USD 70.2 million in 2022! (cognitivemarketresearch.com)
2021	55.6 million	Global Gravity Energy Storage System Industry Research Report 2023 Competitive Landscape Market – Industry Reports
	54 million	Global Gravity Energy Storage System Market Research Report 2022 (Status and Outlook)
HIGHEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	126.5 million	Gravity Energy Storage Systems Market Size, Share & Demand 2029 | BlueWeave (blueweaveconsulting.com)

Table 36. Estimations of CAES turnover

LOWEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	812.8 million	Compressed Air Energy Storage Market Size, Global Report 2023-2032 (gminsights.com)
2021	669.9 million	Compressed Air Energy Storage Market Size, Global Report 2023-2032 (gminsights.com)
HIGHEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	3.3 billion	Compressed Air Energy Storage Market | Size, Share, volume 2023 to 2030 (statsmarketresearch.com)
	3.9 billion	Compressed Air Energy Storage (CAES) Market Size and Share 2023 (imarcgroup.com)
	3.8 billion	Compressed Air Energy Storage Market-Analysis and Forecast 2029 (maximizemarketresearch.com)
	3.4 billion	Compressed Air Energy Storage - Global Strategic Business Report (researchandmarkets.com)
2021	3.3 billion	Compressed Air Energy Storage Market Size & Industry Analysis: 2031 (researchdive.com)
	3.3 billion	Compressed Air Energy Storage Market Size, Share - 2031 | Industry Trends (alliedmarketresearch.com)

Table 37. Estimations of LAES turnover

LOWEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	215.3 million	Germany Liquid Air Energy Storage Systems Market Statistical analysis 2023 growth, trends, size, share, opportunities, revenue 2028 (marketresearchupdate.com)
	281.4 million	Liquid Air Energy Storage Systems' market size was USD 318.9 million in 2022! (cognitivemarketresearch.com)
2021	305.5 million	Global Liquid Air Energy Storage Systems Market – Industry Reports (researchreportsworld.com)
	305.5 million	Liquid Air Energy Storage System Market Size & Trends - 2031 (businessresearchinsights.com)
	285 million	Global Liquid Air Energy Storage System Industry Research Report Competitive Landscape Market – Industry Reports (researchreportsworld.com)
HIGHEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	970.5 million	Liquid Air Energy Storage Systems Market – Industry Analysis (maximizemarketresearch.com)

Table 38. Estimations of SMES turnover

LOWEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	66.4 million	Global Superconducting Magnetic Energy Storage Smes Systems Industry Research Report 2023 Competitive Landscape Market – Market Reports World
2021	57 million	Global Superconducting Magnetic Energy Storage Smes Systems Market – Industry Reports (marketgrowthreports.com)
	53.8 million	Global Superconducting Magnetic Energy Storage Smes Systems Industry Research Report Competitive Landscape Market – Industry Reports (360researchreports.com)
2019	30.6 million	Superconducting Magnetic Energy Storage Market Size (globenewswire.com)
HIGHEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	47.8 billion	Superconducting Magnetic Energy Storage (SMES) Systems: Global Strategic Business Report (researchandmarkets.com)

Table 39. Estimations of SC turnover

LOWEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2023	443.2 million	Supercapacitor Market Size & Forecast [Latest] (marketsandmarkets.com)
2022	396.6 million	Supercapacitor Market worth $1.27 Billion by 2030 - (globenewswire.com)
	726 million	Supercapacitors - Global Strategic Business Report (researchandmarkets.com)
2021	319.9 million	Supercapacitor Market Size, Share & Forecast by 2022-2028 (kbvresearch.com)
2020	721.3 million	Supercapacitor Market Size & Share: Industry Report, 2022-2027 (knowledge-sourcing.com)
2019	425.6 million	The global Supercapacitors market was valued at USD 487.45 million in 2019, and it is expected to reach USD 1570.75 million by 2025, registering a CAGR of 21.8% from 2019 to 2025 (prnewswire.com)
2018	871.5 million	Supercapacitors Market Outlook, Size, Share & Forecast 2033 (futuremarketinsights.com)
	306.3 million	Supercapacitor Market Size, Share & Forecast by 2022-2028 (kbvresearch.com)
HIGHEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2023	4.2 billion	Supercapacitors Market Size USD 12.37 Billion by 2032 (precedenceresearch.com)
2022	3.9 billion	Supercapacitor Market Size, Share, Growth And Analysis 2023-28 (imarcgroup.com)
	2.9 billion	Supercapacitor Market Size, Trends & Growth - 2031 (transparencymarketresearch.com)
2021	2.9 billion	Global Supercapacitors Market – Industry Reports (360researchreports.com)
	1.3 billion	Supercapacitors/Ultracapacitors Market Size, Share, Trends & Forecast (verifiedmarketresearch.com)
2020	1,4 billion	Supercapacitor Market Size, Growth, Share & Trends 2030 (zionmarketresearch.com)
2019	2,9 billion	Supercapacitor Market Size, Share | Future Analysis and Trends by 2027 (alliedmarketresearch.com)

2017	2.2 billion	Supercapacitor Market Research Report: Market size, Industry outlook, Market Forecast, Demand Analysis, Market Share, Market Report 2021-2026 (industryarc.com)

Table 40. Estimations of TES turnover

LOWEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2021	3.8 billion	Global Thermal Energy Storage Industry Research Report Competitive Landscape Market – Industry Reports (360researchreports.com)
	4 billion	Thermal Energy Storage Market Size, Share, Growth Analysis, By Product, Technology, Storage Material, Application, End-Use - Industry Forecast 2023-2030 (skyquestt.com)
2020	3.8 billion	Global Thermal Energy Storage Market - Forecasts from 2022 to 2027 (researchandmarkets.com)
	3.8 billion	Thermal Energy Storage Market | Global Industry Report, 2031 (transparencymarketresearch.com)
2019	3.7 billion	Study on Thermal Energy Storage Market Size & Share Predicted to Reach USD 8558.34 Million by 2026 (fnfresearch.com)
HIGHEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2022	12 billion	Thermal Energy Storage Market Size and Forecasts 2020-2030, Global and Regional Share, Trends, and Growth Opportunity Analysis Report Coverage: By Type, Storage Material, Application, and End User (researchandmarkets.com)
	32.1 billion	Thermal Energy Storage Market 2032 | Size Analysis Report (gminsights.com)
	17.3 billion	Thermal Energy Storage Market Size Report | Growth & Analysis 2030 (theinsightpartners.com)
	26 billion	Thermal Energy Storage Market Size, Share, Trends Report 2030 - Industry Growth Analysis (marketresearchfuture.com)
2021	17 billion	Thermal Energy Storage Market Size, Forecast & Share by 2028 (kbvresearch.com)
	21.3 billion	Thermal Energy Storage Market Size, Share, Trends Report 2030 - Industry Growth Analysis (marketresearchfuture.com)
2020	18.6 billion	Thermal Energy Storage Market Market Growth Drivers & Opportunities | MarketsandMarkets
	18.6 billion	Thermal Energy Storage Market Size and Growth Analysis-2030 (alliedmarketresearch.com)
2018	16.8 billion	Thermal Energy Storage Market Size, Forecast & Share by 2028 (kbvresearch.com)

Table 41. Estimations of LTES turnover

LOWEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2023	433.3 million	Phase Change Materials (PCM) Market Size, Share & Forecast (verifiedmarketresearch.com)
2021	423 million	Global Phase Change Material Market Size, Industry Share Growth Forecast Report, [Latest] (marketsandmarkets.com)
HIGHEST ESTIMATIONS		
Year	**Value (€)**	**Source**
2023	1.5 billion	Advanced Phase Change Materials Market Analysis 2024-32 (imarcgroup.com)
2021	1.5 billion	Phase Change Materials Market Size, Share, Growth Analysis, 2030 (strategicmarketresearch.com)
	1.3 billion	Advanced Phase Change Materials (PCM) Market Growth & Trends - 2030 (polarismarketresearch.com)
2020	1.2 billion	Advanced Phase Change Materials Market Size | Forecast, 2030 (alliedmarketresearch.com)
2019	970.5 million	Phase Change Materials Market Size, Share, Latest Trends, 2032 (fortunebusinessinsights.com)

Table 42. Estimations of STES turnover

Water tanks thermal energy storage		
Year	**Value (€)**	**Source**
2024	18.5 billion	Storage Water Heater Market Size, Share & Forecast to 2034 (futuremarketinsights.com)
2023	17.4 billion	Storage Water Heater Market Share | Growth Analysis 2024-2032 (gminsights.com)
2021	10.2 billion	Water Heater Storage Tank Market Size, Share Analysis And Forecast 2032 (quincemarketinsights.com)
2019	14.9 billion	Storage Water Heater Market Size, Share & Forecast to 2034 (futuremarketinsights.com)
Molten salts thermal energy storage		
Year	**Value (€)**	**Source**
2024	3.9 billion	Molten Salt Thermal Energy Storage Market Size, Report 2032 (precedenceresearch.com)
2023	3.5 billion	Molten Salt Thermal Energy Storage Market Size, Report 2032 (precedenceresearch.com)
	3.2 billion	Molten Salt Thermal Energy Storage Market Size, Share, Growth Analysis - Industry Forecast 2023-2030 (skyquestt.com)
	3.8 billion	Molten Salt Thermal Energy Storage Market | Size | 2024 to 2029 (marketdataforecast.com)
2022	3.4 billion	Molten Salt Thermal Energy Storage Market Size, Report 2032 (precedenceresearch.com)

	2.5 billion	Molten Salt Thermal Energy Storage Market By Share, Size & Forecast 2028 | TechSci Research
	2.5 billion	Molten Salt Thermal Energy Storage Market - Global Industry Size, Share, Trends, Opportunity, and Forecast Segmented by Technology (Parabolic Trough, Fresnel Reflector, and Power Tower), By Region, Competition, 2018-2028 (giiresearch.com)
2020	1.2 billion	Molten Salt Thermal Energy Storage (TES) Market Overview 2031 (transparencymarketresearch.com)
2019	572.4 million	Molten Salt Thermal Energy Storage Market Size & Report: 2021-2026 (knowledge-sourcing.com)

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