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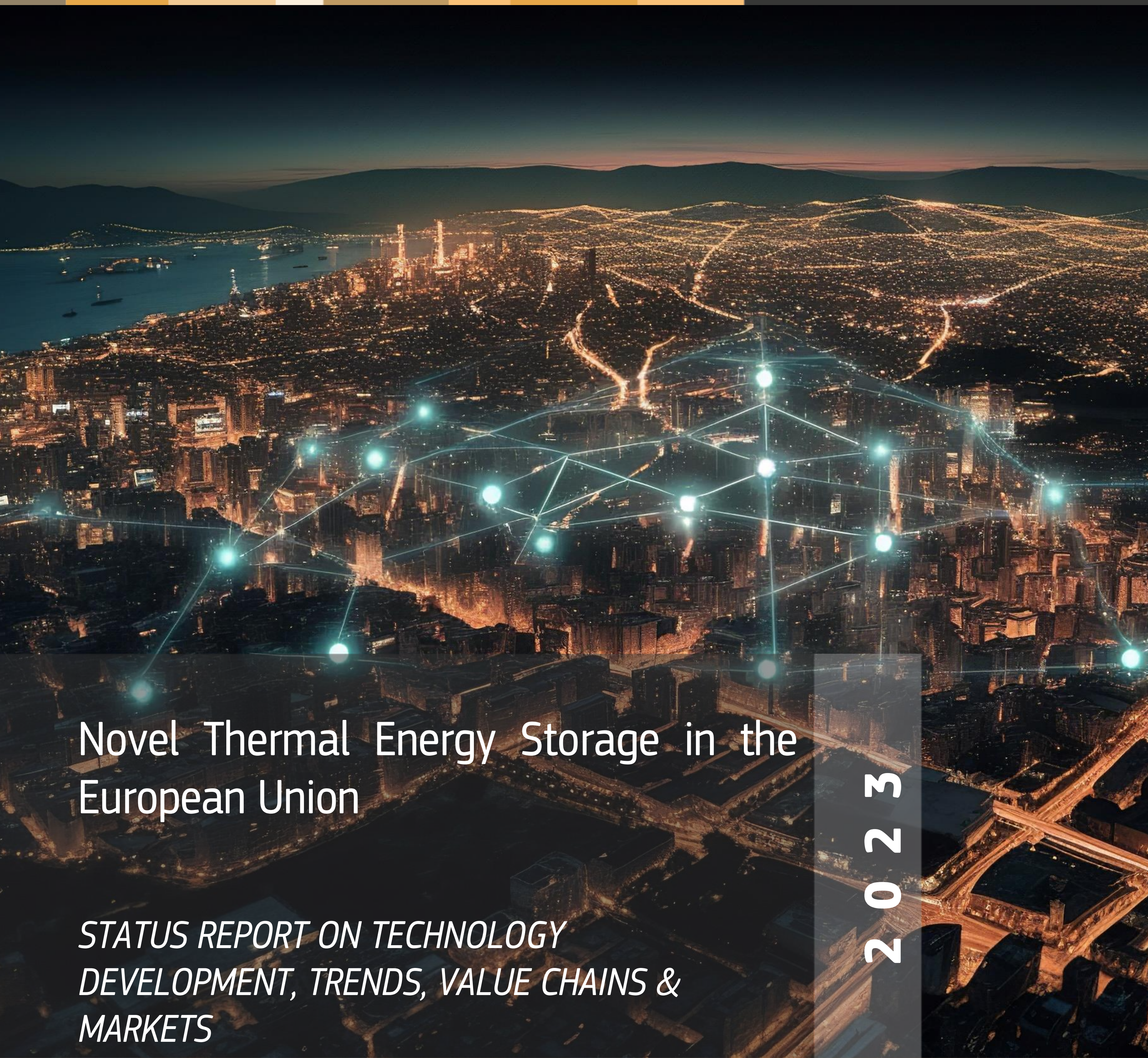

Novel Thermal Energy Storage in the European Union

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

2023

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Contents

Abstract

This report analyses the technology status, value chain, and markets of novel thermal energy storage (TES) technologies. While most technologies currently have low technology readiness levels, they hold substantial potential for storing energy at low costs in the future. TES technologies are used to match the consumption and production of heat and cold, yet they can also effectively integrate the thermal networks with the wider energy system. This would make the entire energy system more flexible and efficient. The TES technologies, currently on the market, have a low thermal energy density, while the novel technologies have higher energy density, which means they can store heat for longer periods of time and require less space. These novel TES technologies have the potential to contribute to the decarbonisation of the energy system.

Foreword on the Clean Energy Technology Observatory

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 ScenariosOverall Strategic Analysis of Clean Energy Technology Sector
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

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Executive Summary

Thermal energy storage (TES) technologies balance the thermal energy demand and supply. TES enables the storage of excess energy during periods of abundant supply and subsequently use it during periods of supply scarcity. Likewise, it achieves cost savings as inexpensive energy can be stored and then used during more expensive periods. This feature also makes it suitable to integrate a higher share of renewable energy sources. For example, wind power produces electricity which is used by a heat pump to generate heat which is stored in a TES. Furthermore, TES technologies are recognised by the European Commission, in its recommendation of 14 March 2023,[1] as candidates to contribute to a decarbonised and flexible energy system.

Researchers and companies are exploring novel TES technologies that could increase their energy density. Increasing the density is key as it requires less space, reduces infrastructure costs and thus increases its applicability. The conventional TES technology is the water tank, which is widely used. The frontiers of the novel TES comprise storing heat and/or cold in air, liquid compression and reversible-based reactions.

Estimating the capacity currently installed in the EU is challenging. Most of the data obtained is based on data collection from existing individual facilities or on assumptions to estimate the order of magnitude. Additionally, some technologies may be capable of storing heat but are actually used to produce electricity, further blurring the boundaries.

The EU plays a leading role in TES research, with significant contributions to both scientific and high-impact publications. Several EU projects are exploring the potential of novel TES and to improve their technological readiness.

The supply chain for TES technologies varies depending on the technology used, but it is generally similar to that of other heating technologies.

The markets for TES technologies are promising as facilities that store heat could be used to produce electricity at a later stage or to deliver the heat directly. For example, solid-state thermal energy storage can be used for both purposes.

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

Strengths – Promising research in novel thermal energy storage technologies, with several ongoing pilot projects. – High potential of the novel thermal energy storage technologies. – Offer flexibility to the wider energy system, enabling a higher share of variable renewables, such as wind and solar – Bridges the gap between energy production and supply	**Weaknesses** - Low technological readiness for most novel technologies. - - The thermal energy storage technologies on the market have much lower energy density than the novel technologies. - High cost of the novel technologies.
Opportunities - Increase the thermal energy storage density with the novel technologies. – Enable synergies with the wider energy system. – Cost savings for the energy operators as it flattens out the peaks in the system – Less installed capacity needed of flexible power and heat technologies.	**Threats** - Reliability of the final user in other more mature technologies. - Lack of data and potential to monitor progress.

Source: (JRC, 2023).

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023H0320%2801%29&qid=1679302898964

1 Introduction

Thermal energy storage (TES) can support the transition of our energy system to sustainable and renewable sources in multiple ways:

- TES (mostly water tanks) is a widely used technology. When combined with conventional gas or oil burners, it can help to reduce emissions by meeting peak demands and replacing frequent burner start-ups. Nowadays, with the growing use of solar thermal or heat pumps, TES can also help to balance out the mismatch between solar thermal or solar electricity generation and hot water or heating demands.
- Integrating thermal storage systems in district heating with cogeneration (e.g. future ready H2 or ammonia plants) or waste heat plants allows for decoupling of power and heat generation. The need for curtailment decreases as surplus electricity can be converted to heat and stored in TES. This allows for integrating larger shares of intermittent renewable energy sources in the energy system. The focus of R&D efforts is to achieve longer-term or seasonal storage, such as pit storage or thermo-chemical storage solutions.
- Thermal storage furthermore plays a key role in the electrification of the heating sector, not only the residential, but in particular also the industrial heating sector:
  - In combination with a power-to-heat system, either a direct electrical heater, electric boiler or heat pump, a TES stores energy from intermittent renewable electricity (e.g. from behind-the-meter PV generation). When connected to the electricity grid, the storage can also optimise or minimise electricity costs for heat generation, protecting the owner from price. Recent studies showed that, under certain conditions, TES can provide such heat as cost-effective as conventional gas boilers (LDES Council, 2022).
  - The integration of power-to-heat with thermal storage creates flexibility in the electricity grid, as the electric heater can be operated independently of the heating demand. This means that the heater can provide ancillary services, if an appropriate market model is in place. In Germany, many district heating network operators have installed electric boilers for this purpose.

Finally, TESs are key elements of a wide range of mid to long-duration electricity storage systems, converting electricity into heat (PHES) and/or compressed (CAES) or liquefied air (LAES), as detailed below.

In 2021, the use of renewable energy resources and biofuels for gross heating production in the EU increased by 33% compared to 2015.[2] One example of these renewable energy resources is solar thermal energy, which increased by 132%[2]. Solar thermal energy is not always available when there is demand, so storing this energy can help to decarbonise the heating and cooling sector.

TES technologies find numerous applications within energy systems, with discharge durations ranging from hours to months. These include methods like sensible thermal heat storage (STES) involving fluids and solids, phase change storage or latent heat storage (LTES), and thermochemical storage (TCTES), each with distinct advantages and disadvantages, as well as preferred application domains.

The thermal energy stored can be used for heating purposes, but also for generating electricity in systems called Electro Thermal Energy Storage (ETES), examples of ETES are Pumped Heat electricity storage or Carnot Batteries. The stored energy can either then be used for heating when there is a deficit in heat production or for electricity generation. The technologies are created using, for example, sensible thermal storage (STES) such as molten salt, sand, or rocks.

TES technologies can improve efficiency of Compressed-air Energy Storage (CAES) and Liquid Air Energy Storage (LAES) systems. In CAES, TES can be used to store heat generated during the compression. This heat can then be used to preheat the air before entering the expansion turbine, again improving efficiency. This preheating eliminates the requirement for external heating, which significantly improves CAES efficiency. Similarly, in LAES, the heat emitted by the air during compression can be stored using TES, thereby optimising efficiency before entering the turbine expansion phase. This report compiles an overview of different TESs. It provides a comprehensive evaluation of the available technologies and their applications. Furthermore, the report discusses technology costs, patents and competitiveness. Also, the energy storage density of different technologies will be analysed and compared.

[2] https://ec.europa.eu/eurostat/databrowser/product/view/NRG_BAL_PEH?lang=en&category=nrg.nrg_quant.nrg_quanta.nrg_bal

1.1 Scope and context

The report aims to provide an evidence-based analysis of novel thermal energy storage technologies to the policy making process. It highlights the potential of these technologies which could make them valuable for future policies, R&D activities or private investments in the most novel technologies. Moreover, the information contained in the report could be linked to the CETO report focusing on the integration of different technologies, such us district heating management. This is due to the ability of TES technologies to increase the synergies between the power and thermal grid, which could be a key factor in order to meet the energy targets for 2030 or 2050. Study of energy storage[3] from European Commission has provided valuable data for the study, which in part is aligned with the scope of that study.

1.2 Methodology and Data Sources

The methodology followed during the study has been based on the analysis of actual data about four different topics:

Maturity and developments of the technologies studied: In this part of the report, the current state of the different technologies is analysed, taking into account several factors like installed capacity, costs and investments.

Value chain analysis: This chapter covers some parts of the value chain analysis like environmental sustainability or the evaluation of companies working on the field. There is lack of data to do an analysis of other parts of the value chain, like turnover, gross value added or EU production data.

Market development and EU competitiveness: Finally, market information is considered, although the lowest TRL technologies could not be included. Some data in the report represent facilities that produce electricity and heating, so makes the market for novel TES technologies less clear.

[3] https://op.europa.eu/en/publication-detail/-/publication/dfcaa78b-c217-11ed-8912-01aa75ed71a1/language en?WT_mc_id=Searchresult&WT_ria_c=37085&WT_ria_f=3608&WT_ria_ev=search&WT_URL=https%3A//energy.ec.europa.eu/

2 Technology status and development trends

2.1 Technology readiness level

TES technologies can be classified in three main technologies: Sensible, latent and thermochemical. The main purpose of these technologies is to store heat.

STES refers to a thermal energy storage mechanism that involves the accumulation and release of heat within a material without changing its physical state. This process relies on the material's capacity to absorb and discharge heat due to temperature fluctuations. STES typically employs solid or liquid substances, such as rocks, concrete, or salts as the storage medium. During the charging phase, the temperature of the material is raised. During the discharge phase, the stored heat can be released by transferring it to a heat transfer fluid or a heating system. STES is known for its simplicity, adaptability, and effective energy preservation, and it is used in a variety of applications, including the integration of renewable energy sources, stabilisation of energy distribution networks, and enhancement of industrial operations.

LTES technologies are based on the heat emitted by a substance during a phase change process. The substances used are known as phase change materials (PCM). The most common phase change process is liquid-solid, which occurs at constant temperature. The temperature remains steady while the heat is being used by an external source. LTES technologies have bigger energy storage density than STES technologies. In particular, for small temperature differences around the melting/solidification temperature of the PCM, it can store significantly more heat than an STES (Tian & C.Y. Zhao, 2013).

TCES are based on reversible chemical reactions that absorb heat during an endothermic reactions and emit heat during exothermic reactions. The main challenge of TCES is to maintain the thermodynamic conditions needed for reversible chemical reactions to occur. TCESs can be classified into two types: chemical reactions and sorption systems. The former involves a reversible chemical reaction, while sorption systems involve a solid material called adsorbent that emits heat when it comes in contact with other fluids. Sorption systems can also be used to control humidity. TCES have higher energy density and are less mature than other TES technologies.

These technologies offer diverse energy storage solutions, each with unique strengths and requiring targeted research efforts to enhance efficiency, cost-efficiency, reliability, and applicability in sustainable energy systems.

2.1.1 Sensible Heat Storage (STES)

STES, as mentioned before, are the most widely deployed TES technologies on the market. There are several ways to store sensible heat. The ones included in the report are:

- Water Tank thermal energy storage (TTES)
- Solid media thermal energy storage (STES)
- Borehole thermal energy storage (BTES)
- Tank-Pit thermal energy storage (TPTES)
- Aquifer thermal energy storage (ATES)
- Molten salts thermal energy storage (MSTES)

Water Tank Thermal Energy Storage (WTTES): widely used STES technology. It is based on the storing a specific fluid in an insulated tank. The most commonly used thermal fluid is water, due to its thermodynamic properties, low cost, availability and harmless properties. WTTES has been used in the building sector for several years, for example for domestic hot water (DHW) systems.

Thermal stratification is a key factor in the efficiency of DHW storage tanks. The water used in this technology has an average temperature of 45 – 50 °C but is substituted by cold water from the grid, usually at 9 – 10 °C. Stratification is especially important for the efficiency of heat pumps used only for DHW. Those heat pumps are similar to the water tank presented before but they use a refrigerant loop instead of an electric resistance element. They are typically air/water heat pumps tested according to the UNE 16147 standard. The efficiency of these heat pumps can increase by 28% with stratification due to the higher heat transfer efficiency with water temperature at 10 °C rather than at 35 – 40°C. (Aguilar & Vicente, 2020).

Other sectors that require large of heating, such us District Heating (DH) grids and networks, also use TTES. In these cases, water is still the main heat transfer fluid, but temperatures are typically higher, with a maximum temperature of 95°C for atmospheric single tank thermoclines and about 135°C for combined two-tank systems. However, in this sector TTES can bring flexibility and improve the efficiency of several heat production systems. The volume and the quantity of energy that this technology can store for these purposes depends on to the type of grid it is connected to, the temperature level, and other factors. The size of the TTES storages varies depending on the annual heating demand. Depending on the size of the storage system, it can provide heat for hours, days or weeks (Gadd & Werner, 2021). Some research of this TES technology is focused on improving the insulating materials of the water tank, to maintain the thermal properties longer (Sarbu & Sebarchievici, C, 2018).

This technology has a TRL of 9, as it is fully integrated in sectors like buildings, industries or district heating.

Solid media thermal energy storage (SMTES). In this storage type, a gaseous heat transfer medium, such as flue gas or air, directly interacts with a solid storage material to facilitate heat exchange as it traverses this designated path within the storage material. To enhance heat transfer efficiency, the gas flow direction is reversed during charge and discharge cycles. The solid medium is arranged as a stack of uniformly shaped bricks, often called "packing" or "checkerwork". Noteworthy industrial applications encompass implementations in the steel industry (e.g., hot blast stoves or "Cowper" stoves), the glass industry, and industrial air purification systems. The current industrial utilisation of solid-media storage is limited to processes with short discharge durations and high load cycling rates. Its use for RE applications requires a substantially modified design. SMTES offers design flexibility that can be used for application-specific optimisation.

Regenerator storage, which uses a packed bed configuration, is less common in current practice, but it presents an opportunity to reduce investment costs. In addition to its cost-effective material utilisation, this approach provides a large heat transfer surface, optimising thermal efficiency and discharge dynamics. However, the design of large packed bed systems introduces uncertainties tied to thermomechanical factors, particularly when considering utility-scale implementation. The point-to-point contact between particles can result in elevated mechanical stresses, potentially compromising the structural integrity of the inventory or containment insulation. This concern s even more pronounced in the context of the thermal energy storage's cyclic operation, where repetitive expansions and contractions of the bed amplify mechanical forces on both particles and containment walls. These and other aspects are the subject of research efforts (Laing & Zunft, 2015). This SMTES variant has been considered for various applications such as ACAES or CSP (Laing & Zunft, 2015).

Concrete is a material used in this technology. It is used in the form of concrete blocks, which can have a sieve of 20 m3 per block (Laing. et al, 2011). To bring an order of magnitude, for a 50 MW_{el} parabolic trough solar thermal power plant using oil as heat transfer fluid, the authors estimated that the concrete SMTES capacity was 1100 MWh_{th}. In one year, the plant can generate 175 GWh_{el}, of which 30% was covered by the storage (Laing, Bahl, C, Bauer, T, & Fiss, M, 2011). Concrete has need to be addressed to reach the full potential of concrete as TES technology. These issues include in-situ construction, poor thermal conductivity of concrete, heat transfer fluids with limited operating temperatures, and the migration of oil/salt in contact with concrete. A novel design based on modular concrete blocks with direct-fit male-female connections that addresses these issues has been studied, making the construction of these facilities easier. (Cabeza, Vérez, Zsembinszki, Borri, & Prieto, 2022). Several companies are entering the market using different variations of the above storage principle. The company ENERGY Nest, e.g. has multiple pilots and first commercial projects, the company Brennmiller uses compacted sand around the heat transfer tubes. Other companies in the space of solid media storages are the Australian company 1414, or the German company KAM, which offers ceramic stone.

SMTES has a variable maturity depending on the material, material arrangement, and use case. Specific designs in the steel and glass industries are commercially viable today (TRL 9), but customized designs, including packed storage for novel power plant processes on a utility-scale, have only been realized on a pilot scale (TRL 5).

Siemens Gamesa built a pilot of a packed bed plant in Hamburg (Germany). The analysis shows it can store 130 MWh_{th} at 750 °C (von der Heyde & Schmitz, 2022). Kraftblock is currently constructing the first commercial granulate-based packed bed storage in the Netherlands.

For example, concrete-based solid sensible storage is in the prototype stage (Laing, Bahl, C, Bauer, T, & Fiss, M, 2011) (Bergan & Greiner, 2014) (Hoivik, et al., 2019). Therefore, its TRL should be 5-7. In contrast, electric radiators that use ceramic bricks are already commercially available. These radiators store heat in ceramic bricks at night when electric prices are lower. As this technology is already in the market, the TRL is 9.

Although the first storage systems are appearing, further development is needed to cost-effectively scale up these types of storage systems to multi-MWh or GWh sizes.

Borehole thermal energy storage (BTES) uses the ground as a heat storage medium. It is commonly used to store energy from one season to another. For example, during the summer season, there is much solar radiation, but the heating demand is lower. BTES can store underground for the next heating season.

The main components of a BTES system are the pipes that form branches in the underground. These pipes can be drilled to depths between 30 and 200 m (Cruickshank & Baldwin, 2016). The pipes are not isolated at the greater depths to preserve heat transfer capacity, but they are insulated in the upper part to reduce thermal losses (Reuss, 2015) pipes. Therefore, a good volume-area ratio should be found (Reuss, 2015). Also the depth of the boreholes is very important in estimate their storage capacity.

One challenge for BTES technology increasing the groundwater temperatures (Schulte, Rühaak, Welsch, & Sass, 2016). Deeper holes are required to allow insulation medium-deep borehole thermal energy storage (MD-BTES). It can maintain storage efficiency with a maximum deviation of about 3% despite having fault zones (Seib, Welsch, Bossenner, Frey, & Sass, 2022). Drilling deep with MD-BTES technologies, about 600 to 3000 m, in low-enthalpy crystalline rocks can lead to a tenfold increase in the efficiency of geothermal boreholes. This technology allows higher temperatures from the geothermal source, and if used in a heat pump, it can improve the coefficient of performance since the temperature lift is lesser.

Research improving the design conditions of the MD-BTES is ongoing. The larger the surface area of the pipes in the boreholes, the higher the heat transfer rate and energy production. Higher surface temperatures lead to better energy yields. , vacuum-insulated tubing outperforms standard high-density polyethylene in terms of energy and temperature production. Considering the flow rate, the greater the flow rate, the more thermal energy is produced and the lower the outlet fluid temperature. Also, this technology requires fewer wells as the wells go deeper (Piipponen, et al., 2022).

This technology is already in the market and is commonly used for district heating purposes. For that reason the TRL is 9 (IRENA, 2020). According to the International Energy Agency's ETP Clean Energy Technology information, the TRL is also considered 9.[4]

Tank-Pit thermal energy storage (TPTES) is another way to store heat for long periods. It consists of a storage tank, which can be buried completely or partially buried in the ground. Are used for large water storages that are not pressurised. The most challenging aspect is to find a site with adequate geological properties to allow large excavations. Once the excavation is, a plastic liner is installed to make the storage waterproof. Water tanks are a similar concept, but they also include a concrete structure, which makes more independent from the geological conditions. It is important to insulate the tanks and pits, at least the roof and side walls. If the storage temperature is for the consumer, a heat pump can be elevate the temperature.

The tank's geometry can play a key role in obtaining the best efficiency. This geometry can lead to reduction and stratification benefits. One parameter to take into account is the height–to-diameter ratio. Thermal losses are reduced by having a height–to-diameter ratio of more than two because the tank has less surface exposure to the ambient. It also benefits stratification the tank is slimmer (Kocijel, Mrzljak, & Glažar, 2020).

Tank-Pit is a technology widely used for District Heating. Considering this, TRL is 9 (IRENA, 2020).

Aquifer thermal energy storage (ATES) stores water underground. It is usually formed after rain. The water seeps into impermeable rock, which causes these aquifers to form. There are a limited number of aquifers at suitable locations, but they could be an interesting energy storage solution due to their large storage capacity or aquifers. The first is the Multi-well system, which consists of one or more groups of well doublets that store energy separating hot and cold in lateral zones. The second is Mono-well systems, which separate hot and cold vertically through an individual well (Mahon, O'Connor, Friedrich, & Hughes, 2022).

One of the most significant uncertainties associated with ATES is the conditions of the aquifer, as the storage medium is not built like tanks or pits. Several models are used to study the thermal conditions of aquifers. These models can consider various factors such us groundwater composition and climatic or socio-economic factors (Lu, Tian, & He, 2019). Different kind of models were developed by diverse authors, for example 3D geological models (Boon, et al., 2019) or models based in electrical resistive tomography (Lesparre, Robert, Nguyen, & Boyle, 2019). All those examples highlight the importance of further improving the models.

[4] https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedCCTag=Storage

Other important research topics of minerals and the growth of microorganisms the reinjection of warm water into aquifers (Bonte, Stuyfzand, van de Berg, Hijnen, & M, 2011). These phenomena can negatively impact the aquifer's hydraulic characteristics (Mahon, O'Connor, Friedrich, & Hughes, 2022). In high-temperature aquifers, CO2 can prevent mineral precipitation (Spycher, et al., 2021).

Borehole, aquifer, and tank/pit technologies, commonly known as underground heat storages, are classified as commercially mature (TRL 9) by (IRENA, 2020). Several facilities have been developed using these technologies, like the CSP in Alberta (Canada) that works with BTES. The pit in Vorje (Denmark), with a volume of 203.000 m3 can store energy from a solar thermal installation with 71.000 m2 of solar panels. This technology is typically used for district heating purposes. In terms of aquifers, there is an ATES system used in Stockholm (Sweden), which provides the heating and cooling demand of a building together with a ground source heat pump. ATES is a common storage technology used in district heating. IRENA (IRENA, 2020) and ETP Clean Energy Technology consider the TRL to be 9.[5]

Molten salt thermal energy storage (MSTES) is used as heat transfer fluids and storage medium in high-temperature applications. The most common installation where molten salts can be found is in concentrated solar power plants (CSP). Molten salts have the following advantages: high thermal stability (high operating temperature suitable for efficient steam turbines), no vapour pressure (unpressurised flat-bottom tanks) and suitable material properties (low cost, high heat capacity, non-toxic, non-flammable). Using a solar thermal power plant with molten salts allows it to produce electricity at night, using the heat obtained during the day.

The operating temperature range of this technology is limited by: 1. the upper limit of 500 – 560 °C withstand, 2. the lower limit of 260 - 290 °C which is based on the melting conditions of the molten salts (Bauer, Odenthal, & Bonk, 2021).

The most commonly used fluid for solar applications is a mixture of NaNO3 + KNO3, also known as Solar Salt. Due to its chemical properties, this salt has the development of several CSP systems that can store 15 hours of energy. Research activities are focusing on the development of salts with good physiochemical properties. Examples are the adaption of the melting temperature and heat capacity (Ushak, Fernández, Prieto, & Grageda, 2021).

The stability of the salt at high temperatures is also an essential property, as it allows it to operate for more hours with high enthalpy fluids in the system. Several additives can be added to the solar salt to make it steadier at high-temperature conditions. With temperature variations and be exposed 1200 hours to a constant high temperature (Wu, Li, Ren, Zhi, & Ma, 2018). Stabilization of Solar Salt with alternative gas atmospheres was also examined (Bonk, Braun, Sötz, & Bauer, 2020). Alternatively, other salt mixtures with higher thermal stabilities (e.g. chlorides and carbonates) can be used.

On a component level, molten salt research focuses on improved two-tank designs, development of alternative single-tank designs, improvement of power-related molten salt components (e.g. solar receiver, electric heater, steam generator), and additional molten salt components (e.g. pumps, valves, flanges, seals, flexible hoses, insulation, instrumentation) (Bauer, Odenthal, & Bonk, 2021).

Besides the commercial CSP application of molten salt TES, other potential application fields are industrial process heat (electrification and waste heat utilization), improvement of power plant flexibility, power-to-heat-to-power storage systems (also called Carnot Batteries) with electric heater or heat pump cycle (pumped TES), Adiabatic Compressed Air Storage (A-CAES) and Liquid Air Energy Storage (LAES) (Bauer, Odenthal, & Bonk, 2021).

The TRL of this technology is 9, according to its CPS utilization (IRENA, 2020). There are several commercial examples of this technology. One of them is the Andasol power plants. Using a direct configuration, those plants have a storage capacity of 1000 MWh_{th}. The plants operate between 292 and 386 °C with a storage duration of 7.5 hours. The oil sets the maximum temperature of work. The solar field comprises 624 units and a total surface of more than 500.000 m2. Other examples are tower power CSP plants (e.g. Cerro Dominador in Chile, NOOR3 in Morocco). Molten salt temperatures reach 565 °C, and storage durations up to 17h.

[5]https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedCCTag=Storage

2.1.2 Latent Heat Storage (LHS)

Latent heat technologies are very popular for their ability to charge and discharge the heat within a range of temperatures. The storage medium is selected on an application-specific basis so the phase change temperature

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

PCM materials are y classified by their melting temperature. Ice and PCM with a melting temperature. PCMs with melting temperatures between 29°C and 60°C could be used for heating and domestic hot water. PCMs with melting temperatures s absorption or electric production systems or for waste heat recovery (Cabeza, Castell, Barreneche, de Gracia, & Fernández, 2011).

Ice Storage (IS). No chemical or complex processes are needed to produce ice. However, ice is not usually available in the market, so it must be produced by chillers or ice generators. A chiller usually has to work with a brine solution to operate at temperatures below 0°C. During the charging mode, the brine passes through a coil inside a water tank, converting the water into ice. In the discharging mode, the ice provides cooling energy to the brine loop, which meets the cooling demand.

This technology has been used in district cooling installations, such as in Paris. This grid operates compression chillers with a total capacity of 280 MW and uses ice as thermal storage.

There are several studies on the improvement of the efficiency of these processes. For example, a three-year demonstration experiment showed that 59% of the latent energy stored was used for cooling at the end of the experiment, and the initial cost of this system with snow/ice storage was 96% of the cost of a conventional cooling system (Hamada, Nagata, Kubota, Ono, & Hashimoto, 2011).

There are also reserves of snow that are used for storage, such as Sapporo airport in Japan. These storages need much space to meet high demand. According to data from the Sapporo airport facility, 120,000 m3 (20,000 m2) of snow is needed to provide 8,000 GJ, with a maximum cooling power of 2,500 kW. As the price of land could be a barrier in populated areas where a district cooling network could play a key role, underground caverns could be the solution for this kind of storage (Nordell, 2015).

This technology is already in the market, for that reason the TRL assigned is 9 (IRENA, 2020).

Sub-zero temperature PCMs (SZPCM) are based on the same principle as ice storage, but melting occurs at temperatures of -50°C or -80°Ceven lower. Several materials are under research. Some pure substances can be considered sub-zero PCM, which can be classified as organic and inorganic. The organic ones are composed of hydrogen and carbon. T0 °C depending on the composition. Inorganic substances like helium, oxygen or hydrogen have a transition temperature below -173 °C. Dry ice and nitrogen are usual storage solutions for cold chain applications (Yang, et al., 2021).

When the melting temperature needs to meet the conditions of the cooling demand, pure substances are not flexible. In this way, mixtures of PCM are needed to reach the proper conditions to satisfy the cooling demand. The mixtures that are used the most are eutectic materials, due to its thermal properties. Eutectic materials can be organic or inorganic. Inorganic materials have a lower cost, high latent heat and thermal conductivities. Despite this, due to its composition, they can be corrosive and unstable. Organic eutectic mixtures are also studied, but compared to the inorganic, there are fewer commercially available (Yang, et al, 2021).

Nanoparticles help PCM to increase their thermal conductivity and reduce the subcooling effect. Some of the most studied include graphene nanoplatelets (GnP), graphene oxide (GO), TiO2, and multi-walled carbon nanotubes (MWCNT). One issue with adding nanoparticles is that the latent heat is decreased. Nevertheless, their potential of being used for sub-zero PCMs is worth exploring.

Matrix composite materials can also improve the heat conductivity of the PCM a low cost. Matrices such as aluminium foam, graphene, and carbon are studied. For temperatures below -150 °C, the energy density of sub-zero PCM is not much higher than that of sensible materials, which makes less attractive to study in th range. Future research could focus on improve the thermal properties of these PCMs of that temperature level to make them more efficient and commercially available (Yang, et al., 2021).

One of the barriers to making the use of these materials challenging is the variation of the volume during the phase change and the low thermal conductivity. Procedures should therefore be developed to avoid this issue, for instance, the macro-encapsulation of the materials. Macro-capsules compensate for the volume change because the air inside can compensate the volume variations. Also, the walls of the capsules increase the surface of heat exchange, which increases efficiency (Höhlein, König-Haagen, & Brüggemann, 2018). One of the materials that can be part of the capsules is the stainless steel 316, which is recommended for long term use (Oró, et al., 2013).

Microencapsulation is another procedure consisting of encapsulating 1000 μm. This procedure increase the heat transfer because of the surface/volume ratio of the capsules (Mehling & Cabeza, 2008). Those capsules can be made of polymers and could present problems in long term use. Future work could be focus on limiting the leakage from the capsules, which is an important factor for its commercial acceptance (Yang, et al., 2021).

According to the information provided by IRENA in 2020, sub-zero PCMs have a TRL between demonstration and commercial for cold storage and for refrigerated transportation, which means that TRL

Not only the sub-zero PCM possibilities are worth mentioning, but also the way those PCMs are stored. PCM materials can be stored in different ways, and with various levels of efficiency. The storage possibilities are as follows:

- **Packed-bed:** This is one of the most studied storage systems. The PCM is macro-encapsulated inside a structure. The heat transfer fluid passes through those capsules, and the heat transfer occurs. The technology is easy to design but has a lower heat transfer rate and energy density. The TRL of this technology is 5-6 (Yang, et al., Active TES With PCM for Refrigeration Applications, 2022).
- **Shell-and-tube:** This technology is based on shell-and-tube heat exchanger technology. The PCM is located between the shell, which in this case will be the tank, and the tubes bundle. One interesting characteristic of this technology is the ability to handle stress, but fins on the tube are necessary to improve the heat transfer. The TRL considered of this technology is 6-7 (Yang, et al., Active TES With PCM for Refrigeration Applications, 2022).
- **Plate:** In this case, plates are used to store the PCM. The plates are installed inside a structure to improve the heat transfer between the plates and the heat transfer fluid. This technology allows it to work with both gaseous and liquid heat transfer fluids. However, thermal stress is present in the plates and long-term storage periods have yet to be validated. Thus, the TRL of plate technology is 5-6 (Yang, et al., Active TES With PCM for Refrigeration Applications, 2022).
- **Slurry**: Slurries consist of a fluid with a PCM dispersed in it. This type of storage has to maintain the liquid state, as this allows the fluid to be pumped and stored in different conditions. So far, only PCMs have been used as thermal storage in slurry form, which makes them known as Phase Change Slurries (PCS). This technology needs microencapsulation or additives, which makes it more expensive. The TRL of PCSs is 4-5 (Yang, et al., Active TES With PCM for Refrigeration Applications, 2022).

Low-temperature PCMs (LWPCM). Low-temperature PCM could have a melting temperature between 0°C and 120°C. Common use applications are heating and cooling of buildings (IRENA, 2020), because hydronic heating and cooling systems use temperatures in the range 55-35°C for heating and 7-12°C for cooling. Since the temperature levels match, the latent heat of this materials can be used.

The usage of these materials can be classified as passive and active (Heier, Bales, & Martin, 2015). An example of a passive solution could be the integration of the PCM in the envelope of the buildings, which helps to maintain the building's inertia and interior conditions. The integration can be achieved by adding PCM during the concrete preparation process. The development of novel concretes from using PCM (Paraffin-wax based) can result in improved thermal capacitance, good mechanical properties, low weight and enhanced reliability (D'Alessandro, et al., 2018). Other solutions include using PCM in other parts of the building, such as integrating it in the ceiling or floor (Navarro, de Gracia, Castell, Álvarez, & Cabeza, 2015).

There are active solutions which have a charging and discharging process (Sevault, Vullum-Bruer, & Tranås, 2022). Low-temperature PCMs can be integrated with HVAC systems, such as air/air heat pumps. Depending on the exterior conditions, PCMs can reduce the heat pump's electricity consumption and capacity. For example, electricity consumption savings of about 9% could be expected from using RT-20 as PCM in the climate of Thailand (Chaiyat, 2015). These PCMs can also be employed in ventilation facilities to improve the process efficiency. In such cases, it is important to take into account the exterior temperature and temperature difference between the PCM and the heat transfer fluid (Panchabikesan, Vincent, Ding, & Ramalingam, 2018).

The prospects of low-temperature PCMs in buildings depend on the design complexity. Some situations require specific PCMs with a particular latent heat storage heat exchanger to meet specific needs. It requires a comprehensive study of the whole process and a multi-criteria analysis to identify the optimal solution that fulfils all the requirements. On the other hand, costs are one of the main challenges of this technology as they cannot compete against water tanks in terms of affordability (Sevault, Vullum-Bruer, & Tranås, 2022).

The technology readiness level of this technology for buildings applications is still in prototype stage (IRENA, 2020), which means levels of 6-7.

Low-temperature PCM can also be used for cold-chain purposes, aiding in maintaining the required temperature during transport of food or products needing special conditions, like pharmaceutical products. The TRL of LTPCM for these applications could be at the demonstration stage or already commercial, thus in the TRL range of 5-9 (IRENA, 2020).

The technology is also being studied for the cooling of electronic devices. The aim of using LTPCM in electronic devices is to reduce the peak temperature of the device and achieve a more uniform distribution temperature throughout the body. However, further investigation is needed to assess its performance over long time periods and develop the design procedure (Bianco, De Rosa, & Vafai, 2022). According to this, this technology can be classified with a TRL of 4-7 for these specific purposes.

High-temperature PCMs (HTPCM) have melting temperatures above 120 °C (IRENA, 2020), or 150 °C (Gasia, Miró, & Cabeza, 2017). Considering these temperature levels, the use of these PCM is more limited and requires specific properties, such as: chemical stability, high thermal conductivity, no fire hazard, high density, or low vapour pressure (Gasia, Miró, & Cabeza, 2017). Organic, inorganic and eutectics forms can be found as -temperature PCMs. Several aspects should be considered before selecting the final material for use. This is essential as the operating conditions for these materials can reach temperature of 350 °C (Pointner & Steinmann, 2016) (Johnson, Vogel, Hempel, Hachmann, & Dengel, 2017), making both the material and the heat exchange process critical. Organic PCMs could have different melting temperatures, but the thermal conductivity could reach low levels. On the other hand, inorganic PCMs have higher thermal conductivity but are corrosive (Jouhara, Żabnieńska-Góra, Khordehgah, Ahmad, & Lipinski, 2020).

In the building sector, as the application temperatures of these PCMs are very high, they cannot be used directly for heating purposes. However, they can be used for cooling purposes in absorption systems. Furthermore, high-temperature PCMs with similar results in terms of power production and with lower investment costs due to the reduction in system size (Prieto & Cabeza, Thermal energy storage (TES) with phase change materials (PCM) in solar power plants (CSP). Concept and plant performance, 2019).

Another use for these PCMs is the storage of waste heat from industries. Several studies about this technology application are under development, but are limited to waste heat temperatures lower than 200°C (Prieto, Vérez, & Cabeza, Active Thermal Energy Storage (TES) With Phase Change Materials (PCM) for High Temperature, 2022).

Finally, the TRLs of high-temperature PCM-Storages in district heating and cooling grids are categorised under “prototype, demonstration and commercial” phases, ranging from TRL 4 to 8. This technology for application in buildings has a TRL of “demonstration and commercial”, which is a TRL about 5-8 (IRENA, 2020). As for the integration of PCM-Storage in operating industrial processes, this technology has reached a TRL of 5 (Johnson & Fiss, 2023).

2.1.3 Thermochemical energy storage (TCES)

The main sub-technologies studied under TCES are as follows:

- Reversible-based reaction energy storage (RBRTES).
- Sorption-based energy storage (SBTES).

Reversible-based reaction thermal energy storage (RBRTES). Thermochemical energy storage (TCES) is characterised by storing thermal energy in chemical compounds. The eversible-based storage type consists of supplying thermal energy to a chemical compound, which in turn dissociates in an endothermic reaction, creating a gas component (sorbate) separate from the solid or liquid (sorbent).[6] The energy provided is stored by the heat in the chemical bonds within each molecule, which in turn are stored separately (IRENA, 2020). When energy is needed, a reverse reaction occurs by synthesizing the two chemical compounds (sorbate and sorbent) through an exothermic synthesis reaction, releasing the energy that was originally absorbed. TCES utilises pairs of materials, and several pairs are currently being tested. Some of the materials utilised include metal oxide redox pairs (MOX/MOX-1), non-stoichiometric perovskites (ABO3/ABO3-δ), alkaline earth metal carbonates and hydroxides (MCO3/MO, M(OH)2/MO with M = Ca, Sr, Ba) (André & Abanades, 2020). While metal oxides and perovskites can operate with air for heat transfer, carbonates and hydroxides require fluid, which are usually in the form of water (Risthaus, Linder, & Schmidt, 2022) (Schmidt & Linder, 2017) or CO2 (André & Abanades, 2020). The difference between sorption and reversible-based processes lies in the chemical reaction, as a new chemical compound is formed in the reversible-based reaction (IEA, 2022). Promising systems involve the utilisation of low-cost ore minerals and recycling waste, such as limestone and dolomite (CaCO3/CaO) (André & Abanades, 2020). One major difference between sorption and reaction-based systems is related to the distinct reaction temperature which, independent from the state of charge/conversion. This allows for synergies between storing and pumping thermal energy. Examples are Thermal Upgrade for waste heat utilization (Stengler & Linder, 2020) or synergies between hydrogen as energy carrier and reaction partner (Kölbig, Weckerle, Linder, & Bürger, 2022).

Reversible-based reactions, with a special focus on calcium looping, have previously been explored in the context of carbon capture technologies. CaL was implemented in a cement factory in Taiwan as a carbon capture method, achieving a capture rate of up to 90%.[7] The application of this technology in thermal energy storage is in its early stages. Given its properties, however, the technology shows great deployment potential in different sectors. In the power sector, chemical looping systems are currently being explored in storing energy harnessed through CSP. The properties of calcium carbonate make it a strong candidate for CSP energy storage, having a high energy density of up to 3.2 °C (IRENA, 2020). With its high energy density and capacity to store energy for extended periods with minimal losses, the technology shows strong potential for applications in seasonal storage and peak-shifting (EERA, 2018). Chemical looping also holds promise in industrial process heat with heat transformation, industrial waste heat and district heating, although these are still in the early stages of research[8] (IRENA, 2020).

Reversible-based TCES, especially chemical looping, have highly attractive characteristics, making it a sought-after technology for research. This system can operate at very high temperatures and has a high energy density. The system can store thermal energy over long periods of time, with virtually no energy loss, although some losses still occur during charging and discharging (IRENA, 2020). Today, round trip efficiency ranges between 32 – 46% (Atkinson, Hughes, & Macchi, 2023). One of the main characteristics of this technology is that it allows for control discharging features, adjusting temperature, power level, and release rate8 since temperature is a function of pressure. Furthermore, the chemical looping process often requires low-cost and widely available materials (IRENA, 2020). Despite being promising, and attracting significant research interest, this technology is still in its early developmental stages, especially regarding renewable energy integration. Technology readiness level is evaluated to be at level of 3 – 46. Other sources categorise its TRL to this technology under the research and prototype level in the industrial sector, indicating a TRL range of about 2-5 (IRENA, 2020).

[6] https://iea-es.org/wp-content/uploads/public/FactSheet_Thermal_Thermochemical_CR_2022-10-19.pdf
[7] https://www.cemnet.com/News/story/155559/taiwan-itri-to-receive-award-for-its-heclot-carbon-capture-technology.html
[8] https://www.eera-energystorage.eu/component/attachments/?task=download&id=559:JPES-SP3-Technology-Factsheets-Brochurelogy-Factsheets-Brochure.pdf

Sorption-based thermal energy storage (SBTES). Sorption-based storage has a similar dynamic to reversible-based reactions, wherein the system relies on the reaction between a sorbent and a sorbate. Similar to the previous technology, energy can be stored virtually °C. The sorbate used in the process is usually water in different phases. Once energy is required, water is added to the sorbent, in which the absorption process releases the demanded heat. There are three different forms of sorption-based storage: salt hydration, liquid-based sorption and porous solid sorption.

This technology has many potential applications at both small and large scales. The European Association for Storage of Energy identifies potential applications in heating, cooling and air-conditioning, varying from mobile cold storage for beer kegs and food to containers up to district heating.[9] The European Energy Research Alliance also identifies potential for the technology, such as domestic heating/cooling, industrial waste heat recovery, industrial process heat, solar cooling, and solar power plants. The agency believes the technology to be promising in the area of seasonal storage.[10] IRENA indicates that salt hydration, more specifically, is especially promising in regard to seasonal and diurnal storage for domestic buildings (IRENA, 2020), but this system still presents several issues due to aggressive materials, corrosion of containment structure, material stability and degradation or agglomeration. Salt hydration is also considered for potential applications in the industrial sector in waste heat processes, but also integrating solar energy in low-temperature industrial processes (IRENA, 2020). Absorption cycles, on the other hand, are better suited for low heat utilisation and has potential applications in the building sector and industrial processes (IRENA, 2020). Absorption system is also projected to be used for space cooling in the cold chain. In district heating, salt hydration can be potentially used for seasonal storage, capturing heat during the summer to be later used during the winter. Absorption systems, on the other hand, have a great application potential in district cooling.

Although the sorption system has already been applied for other purposes, such as refrigeration, its utilization as a thermochemical storage still faces challenges. The readiness of the technology varies depending on the sorption type. The technology has reached the demonstration stage, with pilot projects under development. Therefore, the TRL assigned should be 5-7 (IRENA, 2020).

2.1.4 Mechanical-thermal Energy Storages

The technologies covered in this chapter are as follows:

- Adiabatic Compressed Air Energy Storage (A-CAES)
- Liquid Air Energy Storage (LAES)
- Pumped heat electricity storage (PHES)

Adiabatic Compressed Air Energy Storage (A-CAES). A compressed air energy storage (CAES) system compresses and stores high-pressure air in subterranean caverns. When energy is needed, the pressurised air expands into a turbine, generating power. In traditional compressed air storage systems, the heat produced during compression dissipates as waste (IRENA, 2020). In the adiabatic compressed air energy storage (A-CAES), this heat is captured and stored in a high-temperature TES system.[11] Later, this stored heat is used in the expansion process, making the system more efficient overall but with higher investment costs (IRENA, 2020). The temperature of compressor discharge can exceed 600 °C.[11] By placing the TES unit inside the compressed air storage eliminates the need for a high-pressure vessel (IRENA, 2020).

The A-CAES technology has a more limited range of applicability than the previously mentioned thermal energy storage technologies. The interest in A-CAES derives from the necessity for energy storage integration to renewable energy generation in the power sector. Its utility would be mainly towards peak shaving, daily and weekly balancing arbitrage, ancillary services, and demand services[11] (IRENA, 2020).

The technology is not yet at a fully commercial scale; however, a few demonstration projects have been developed and some full-scale projects are currently being designed, although they still require funding. The technology is under prototype/demonstration status, so the TRL is about 3-7 (IRENA, 2020). A-CAES highly benefits from economics of scale, therefore, even demonstration plants have a high storage capacity, with the smaller ones in the range of 100 MW being able to store heat for a week.[11] Given this characteristic, the technology has high scale-up potential. However, given that it uses underground voids for air storage, such as subterranean caverns and repurposed mines, there are some geographic limitations to the technology's deployment. EASE points out that new developments in tunnel-boring machine technologies may significantly

[9] https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Thermal_Adsorption.pdf

[10] https://www.eera-energystorage.eu/component/attachments/?task=download&id=559:JPES-SP3-Technology-Factsheets-Brochurelogy-Factsheets-Brochure.pdf

[11] https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_ACAES.pdf

impact on A-CAES feasibility by bringing costs down and lowering the geographical constraints. In addition, it does not require critical raw materials to be developed, making it less exposed to abrupt disruptions in the supply chain.

Liquid Air Energy Storage (LAES). Liquid Air Energy Storage (LAES) is another system that compresses air to store energy. LAES uses renewable or off-peak energy to compress air to high pressure, storing heat generated in the process. The air is then cooled to extremely cryogenic temperatures (-150°C),[12] transforming it to a liquid state being stored in a low-pressure tank. To generate energy, the air is reheated, partially by the stored heat from the previous step in the process, while now storing some of the waste cold, turning back to its gas form.[13][14] This can then be used to turn turbines to produce electricity. An important characteristic of this process is that energy is stored by liquefying air, meaning that it can be transported elsewhere, for example it can be used as fuel in engines, while the stored cold can be used for refrigeration (IRENA, 2020). The technology's efficiency can be increased by locating LAES near LNG terminals.[15]

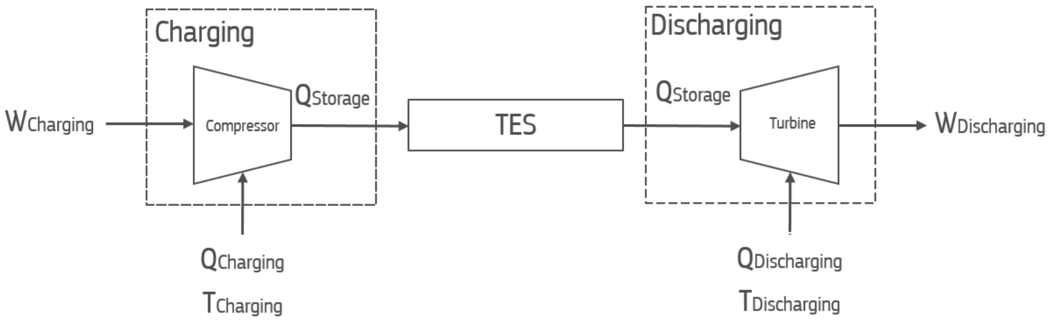
LAES has the potential to further decarbonize the power sector by storing off-peak renewable energy to be later used to produce electricity. Besides smoothing the supply of renewable energy, facilitating its integration, and providing grid balance, LAES can be used to perform energy arbitrage and to some extent given its slower response time, ancillary services[13] (IRENA, 2020). Furthermore, this system also has the potential to couple the cold chain with the power sector. This potential may be achieved as LAES produces and stores cold, which, if not used during the liquefaction process, could be used for refrigeration applications. Another sector coupling potential for LAES is its potential efficiency boost by co-locating the technology with industrial parks, as waste heat could be used in the expansion process[15].

Although the LAES system is still in development, the technology per se utilises off-the-shelf components[14]. Demonstration projects have been deployed and tested and a few commercial-scale projects are being developed. The technology is considered having a readiness level of 8, and nearly achieving commercial readiness.[16] According to other sources, this technology, in sectors like power or cold chain, has a TRL of about 4-7, as it is under prototype/demonstration status (IRENA, 2020). Highview Power completed a demonstration site in the UK in 2018, having built a 5 MW power unit with a total storage size of 15 MWh, becoming the world's first grid-scale LAES.[17] New research and companies are emerging around this technology, with the potential to improve the efficiency of the system, its Levelized cost of storage, and more. The company phelas uses a system that reaches temperatures down to -200°C.[18]

Pumped Heat Electricity Storage (PHES). This solution refers to a power-to-heat-to-power solution. Moreover, a novel technology that uses this approach is named "Carnot Battery", a term invented by Andre Thess in 2018.[19] This technology could make the power and heating grid synergies even bigger. Furthermore, it could bring more stability to the power grid, as the excess electricity could be used in an electric heater or a heat pump. Then, this excess of electrical energy could be converted into thermal energy. This thermal energy feeds the TES technology and then this heat stored could be used when necessary. The choice of technology for storing the heat would depend on, for example, how much time the thermal energy is stored and the level of temperatures that have to be maintained. Then, the thermal energy is converted into electricity by using a thermodynamic cycle, such as Rankine or Brayton.

[12] https://www.britannica.com/science/cryogenics
[13] https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_LAES.pdf
[14] https://energystorage.org/why-energy-storage/technologies/liquid-air-energy-storage-laes/
[15] A closer look at liquid air energy storage – pv magazine International (pv-magazine.com)
[16] https://www.pv-magazine.com/2021/08/02/a-closer-look-at-liquid-air-energy-storage/
[17] https://www.energy-storage.news/world-first-grid-scale-liquid-air-energy-storage-project-completed-in-northern-england/
[18] Liquid Air Energy Storage Explained by a Developer - Green Dealflow
[19] https://en.wikipedia.org/wiki/Carnot_battery

Figure 1. Carnot Battery principle



Source: (IEA Energy Storage Task 36 – Carnot Batteries, 2023).

An example of a Carnot battery is the demonstration plant built by Siemens Gamesa Renewable Energy. It has a storage capacity of 130 MWh_{th} and a Rankine turbine with a capacity of 1.2 MW. The heat is stored at 750°C in a packed bed. (Vecchi, et al., 2022). The TRL of this technology is low,[20] as it is not widespread in the market. As a prototype is developed, the TRL should be 5-7. Another plant, developed by Azelio (Vecchi, et al., 2022), uses a Stirling engine of 13 kW_{el} with electric heating (Vecchi, et al., 2022). The CHESTER[21] project works on demonstration of heat pumps working with a Rankine turbine, the TRL is lower than 5.

Table 2 summarises all technologies covered in this chapter.

Table 2: TRL results of the different TES technologies

	TRL (Technology Readiness Level)								
Sub-Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Thermal tank energy storage									■
Solid media thermal energy storage					■	■	■	■	■
Borehole thermal energy storage									■
Tank-Pit thermal energy storage									■
Aquifer thermal energy storage									■
Molten salts thermal energy storage									■
Ice Storage									■
Sub-zero temperature PCMs						■	■	■	■
Low-Temperature phase change material				■	■	■	■	■	■
High-Temperature phase change material				■	■	■	■	■	
Reversible-based reaction thermal energy storage		■	■	■	■				
Sorption-based thermal energy storage					■	■	■		
Adiabatic Compressed Air Energy Storage			■	■	■	■	■		
Liquid Air Energy Storage				■	■	■	■		
Pumped Heat Electricity Storage				■	■	■	■		

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

[20] https://www.nedo.go.jp/content/100899761.pdf
[21] https://www.chester-project.eu/news/first-experimental-results-from-the-prototypes-of-chest-technology/#:~:text=The%20experimental%20results%20are%20very,of%2080%2D85oC.

2.2 Installed Capacity and Production

The capacity and production of TES depends on the heat source and at which level of temperature the heat is required. There is no data on the capacity installed across Europe for TES. On the other hand, some assumptions can be made to assess the order of magnitude TES technologies are employed.

Sensible thermal energy stored can be estimated for DHW purposes. Based on unitary demand and temperature use levels, the energy needed per person for DHW can be estimated. (Cabeza, Mehling, & Romaní, Installed Capacity of Thermal Energy Storage, 2022), see table 3. This assumption only considers storages with electric resistance. Furthermore, in the last few years, heat pumps for DHW uses have become popular. Inertia tanks is present in heating and cooling facilities too. Therefore, more capacity is likely installed than estimated with this methodology.

Sensible energy storage using molten salts in concentrated solar power plants is another technology examine. The result shown in table 3 is based on data collection from various sources (Cabeza, Mehling, & Romaní, Installed Capacity of Thermal Energy Storage, 2022).

The final technology presented in the report is the UTES technology. The information available differentiates between ATES and BTES, and is collected from Sweden and The Netherlands (Cabeza, Mehling, & Romaní, Installed Capacity of Thermal Energy Storage, 2022). The installed capacity in terms of power and energy production data are in Table 3.

Table 3: Data about capacity installed of some TES technologies

	Installed Capacity	Rated Storage Capacity	Production	Production
	MW	GWh_{th}	GWh_{th}/year	GWh_{el}/year
Domestic Hot Water Tanks	-	124.85	-	-
Molten salts for Concentrate Solar Plants	2,087.22	37.95	-	5,574
Aquifer Thermal Energy Storage	2,569	-	3,184	-
Borehole Thermal Energy Storage	315	-	1,097	-

Source: (Cabeza, Mehling, & Romaní, Installed Capacity of Thermal Energy Storage, 2022).

The data obtained about the different technologies come from various sources that use different assessment methods, which makes challenging to compare them. On the other hand, energy storage is not like other technologies with a fixed capacity. Storage can have different capacities depending on its final use. If the conditions of the final user change (E.g., supply temperature of heating), the storage capacity also changes. Assessing the thermal energy supplied, and how much energy was consumed by the storage to reach its conditions. This indicator provides a good estimate of their usage and implementation in the systems.

Table 4 shows another approach to estimate the capacity installed of TES technologies. The information is taken from operational facilities and the identified technologies from the study include CAES, molten salts and sensible thermal energy storage technologies in general. These results stem from a broader study encompassing various energy storage types. However, the presented results are restricted to thermal energy storage and operational facilities. (European Commission, Directorate-General for Energy, Andrey, C., Barberi, P., Nuffel, L., 2020).

Table 4: Data about capacity installed of some TES technologies 2

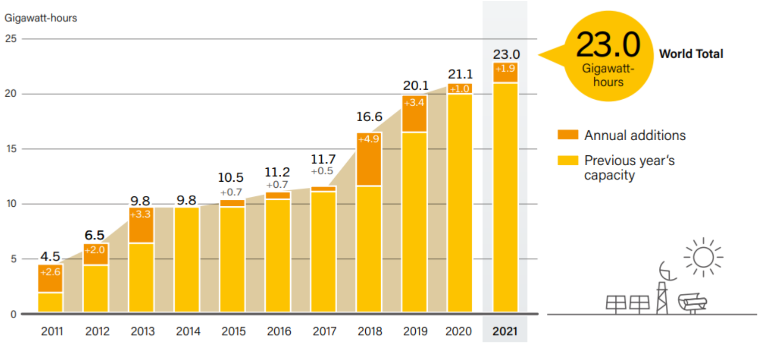
	Power Installed Capacity	Energy Capacity
	MW	MWh
Molten salts	1,083	8,442
STES	73	61
CAES	321	580

Source: (European Commission, Directorate-General for Energy, Andrey, C., Barberi, P., Nuffel, L., 2020).

Another source of information about the installed capacity of TES, mostly molten salts, comes from the global status report of 2022 of Ren21.[22] Figure 2 shows the results of the analysis, which estimates the installed capacity of TES to 23 GWh in 2021. Note that this study is almost only concerns molten salts, obtained from research on CSP plants across five continents.[22]

[22] https://www.ren21.net/gsr-2022/

Figure 2. Thermal Energy Storage Global Capacity Installed in CSP (Almost 100% of them are based on molten salts)



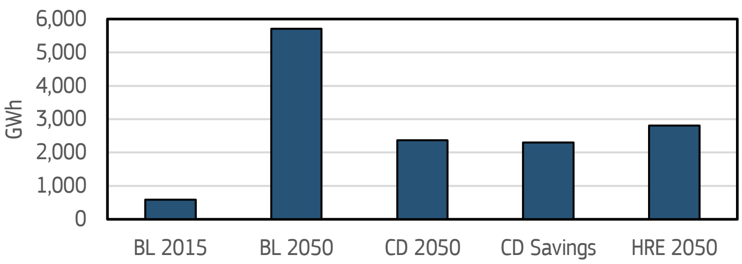
Source: (REN21, 2022).

An estimated 190 GWh of total thermal energy is stored in solar systems in 2021.[23] Other sources estimated the global capacity installed of thermal energy storage in Europe, categorised it into different sectors and provided information about specific technologies. In 2019, the total thermal energy stored for heating purposes was estimated to be 234 GWh of which 46%, 53%, and 1% corresponded to buildings, district heating and the industrial sector, respectively. From this, 21 GWh of thermal energy storage was in concentrated solar power plants that work with molten salts. (IRENA, 2020).The sources analysed used different approaches to categorise installed capacity of thermal energy storage. Hence, comparisons between sources were challenging.

The projections of the share of renewable energy and the energy targets for 2050 highlight the importance of increased energy storage capacities, as more flexibility and stability of the energy systems will be required. Furthermore, thermal energy storage technologies could increase the synergies between the heating and power grids, allowing them to use the surplus of electricity, store it as thermal energy and use it when there is a deficit in heating production. Increased shares of variable renewable energy in the grids will increase the need to store energy for longer times. This means that grid storage technologies should have long-term storage media. A share of solar PV and wind in the electricity grid greater than 60%-70% will increase the demand of longer storage durations, for example, days or weeks (Albertus, Manse, & Litzelman, 2020).

Several sources have researched possible scenarios of projections following different criteria. For example, in the Heat Roadmap Europe project,[24] one approach estimated the evolution of the heat storage capacity in 13 Member States. That study also analysed different scenarios based on different policies. There are two baseline scenarios (2015 and 2050), one is based on the application of actual policies, and the other called "Conventional Decarbonisation scenario (CD)", in which the share of renewables plays a key role. The final scenarios are "Heat Roadmap scenarios". The characteristic of these scenarios are the decarbonisation of the energy system, but also a reorganised heating and cooling sector (Paardekooper, 2018). Considering these scenarios and based on data provided from the Heat Roadmap Europe Project,[25] a representation of the estimations has been carried out in Figure 3.

Figure 3. Heat storage needs in the Heat Roadmap 4 scenarios

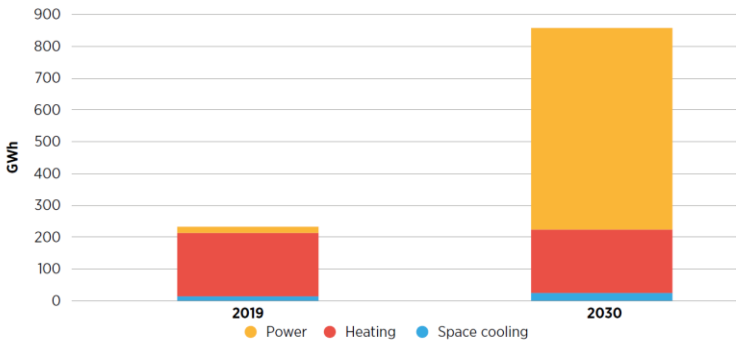


Source (Heat Roadmap Europe, 2019).

[23] https://solarthermalworld.org/wp-content/uploads/2022/06/Solar-Thermal-Roadmap-2030.pdf
[24] https://heatroadmap.eu/
[25] https://heatroadmap.eu/roadmaps/

In a study by IRENA, the analysis highlights a "Transforming Energy Scenario" aligned with the Paris Agreement. The results shows that the total TES capacity[26] will reach 800 GWh by 2030, as can be seen in Figure 4 (IRENA, 2020).

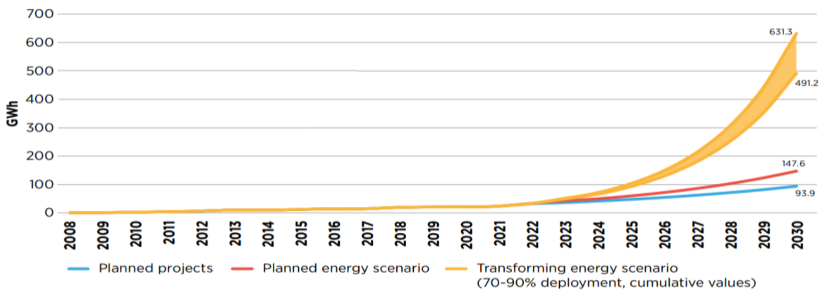
Figure 4: Current and projections of TES capacity



Source: (IRENA, 2020).

The projections shown in figure 3 and figure 4 do differentiate between technologies. Instead, IRENA analysed projections for specific technologies, which molten salts being one of the highlighted. Figure 5 reflects the Transforming Energy Scenario done by IRENA, following the Paris Agreement targets (IRENA, 2020).

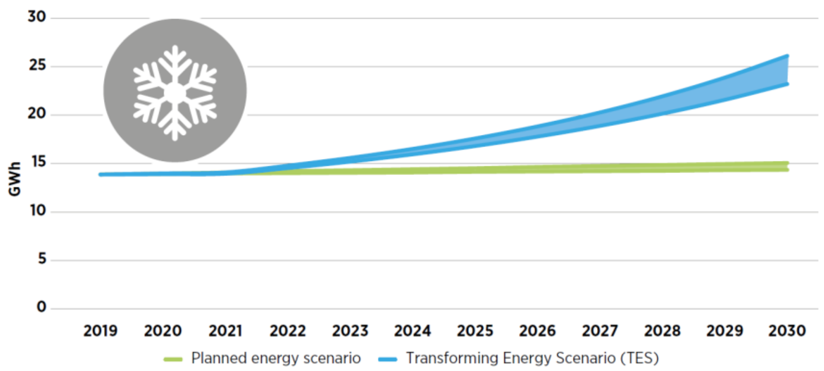
Figure 5. Molten salts TES installed capacity



Source: (IRENA, 2020).

Finally, IRENA also made a study in which they mentioned the projections of TES used for space cooling purposes. Figure 6 shows the results of the study, predicting more than 25 GWh of installed capacity of TES only for space cooling purposes (IRENA, 2020).

Figure 6. Installed and estimated TES for space cooling



Source: (IRENA, 2020).

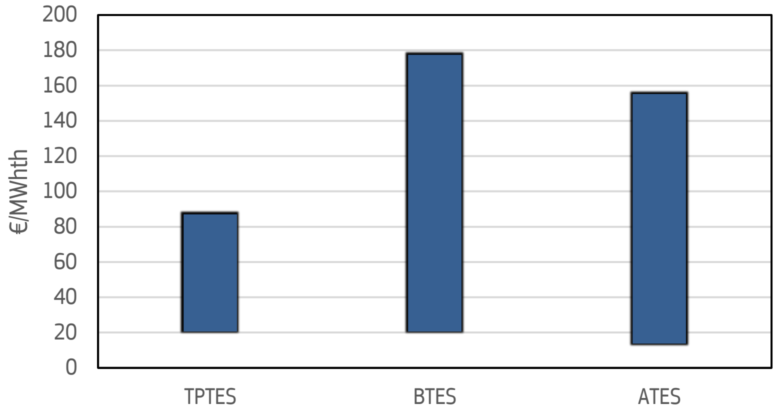
[26] According to the information from (IRENA, 2020), this capacity refers to stationary storage (utility-scale and decentralised PV facilities), storage for electro mobility and heat.

2.3 Technology Costs

The costs of novel TES can vary significantly due to diverse technology basis of each approach. The data presented has been gathered from several sources and includes projections for the next years. However, it is worth mentioning that the costs are not only determined by the technology itself, but also on the application of the heat storage system. Consequently, it is challenging to compare technologies due to their different end uses. For example, PCMs can be used for cold chain purposes or to enhance thermal inertia in buildings, whereas, technologies like solid state could be used for thermal energy storage with the aim to produce electricity. This chapter covers specific cases based on available data, therefore, the information presented should not be generalised for all TES facilities.

Underground thermal energy storage (UTES). UTES are referred to the technologies listed in chapter 2 that are underground, like tanks, pits, boreholes or aquifers. The costs considered for these technologies are the Levelized Cost of Heat (LCOH), which is related to the cost of every unit of thermal energy delivered (Yang, Liu, Kramer, & Sun, 2021). Figure 7 shows approximate values of LCOH of thermal energy storage of several projects within the EU.

Figure 7. LCOH for several UTES facilities in the EU



Source: (Yang, Liu, Kramer, & Sun, 2021).

Molten salts thermal energy storage (MSTES). The MSTES investment cost per kW is highly dependent on its applications. According to IEA-ES, the investment cost ranges from 20 to 70 €/kWh.[27] However, IRENA estimates installation costs between 21.9 and 35.1 €/kWh,[28] with a projection to reduce investment costs to below 13.2 €/kWh by 2030 and below 10.5 €/kWh[28] by 2050 (IRENA, 2020).

High-temperature solid media storage. The investment costs vary depending on the size of the installation, temperature spread and other requirements of the application process. According to IEA-ES, the investment cost ranges from 15-40 €/kWh for low-pressure installations.[29]

Low-temperature PCMs. The investment cost per kW of low-temperature PCMs varies depending on the material and the chosen application, such as cold chain or buildings. According to IEA-ES, the investment cost ranges from 20 to 100 €/kWh.[30] However, IRENA estimates installation costs between 50.9 and 202 €/kWh,[28] with a projection to reduce investment costs to a range between 39.5-162.3 €/kWh[28] by 2030 and between 30.7-122.8 €/kWh[28] by 2050. The source includes low-temperature and below-zero PCMs in the projection (IRENA, 2020).

High-temperature PCMs. IEA-ES estimates that the investment cost of HT-PCMs ranges from 50 to 100 €/kWh, while O&M is expected to be around 1% of the investment cost.[31] IRENA estimates that costs can be as low as 21.9 €/kWh[28] in the power sector, and as high as 201.8 €/kWh[28] for district heating applications. In addition, IRENA projects a reduction of investment costs down to a range between 21.9-162.3 €/kWh[28] by 2030 and between 10.5-122.8 €/kWh[28] by 2050, including all potential applicable sectors in those ranges (IRENA, 2020).

[27] https://iea-es.org/wp-content/uploads/public/Application_Thermal_Sensible_Liquid_Salt_2022-10-21.pdf
[28] Original values in USD. 1 USD= 1.14 EUR (Average exchange rate in 2020 - Available at: https://www.bde.es)
[29] https://iea-es.org/wp-content/uploads/public/FactSheet_Thermal_Sensible_Solids_HT_2022-10-21.pdf
[30] https://iea-es.org/wp-content/uploads/public/FactSheet_Thermal_Latent_LT_2022-10-19.pdf
[31] https://iea-es.org/wp-content/uploads/public/FactSheet_Thermal_Latent_HT_2022-10-19.pdf

Reversible-based reaction energy storage. Given the technology is currently at low TRLs, its costs are not yet considered. However, IRENA projects that the technology will reach pilot scale by 2030, having a cost range of 70.2 to 140.4 €/kWh[28], and will reach demonstration scale by 2050 with a cost below 70.2 €/kWh[28] (IRENA, 2020).

Sorption-based energy storage (SBES). For both the power sector (CSP) and industry sector, IRENA reports a potential cost in the range between 70.2-140.4 €/kWh[28] by 2030 with a further cost decrease to below 70.2 €/kWh[28] by 2050. Cold chain application has reportedly a cost range between 10.5 and 131.6 €/kWh[28] nowadays, with a future perspective to keep it below 83.3 €/kWh[28] by 2050. In the case of district heating and cooling, sorption-based storage the current cost range is between 13.2 and 131.6 €/kWh[28], with a projected decrease to 13.2-105.3 €/kWh[28] by 2030, and finally reaching demonstration stage by 2050 with a cost range between 8.8 and 70.2 €/kWh[28] (IRENA, 2020).

Adiabatic Compressed Air Energy Storage (A-CAES). The European Association for Storage Energy estimates the CAPEX of A-CAES projects to range between 1200 and 2000 €/kW. Hydrostor gives a range between 877.2 and 2196 €/kW, and 78.9 to 350.9 €/kWh.[32,28] This variation depends on the type of storage area (eg. hard-rock geology or salt geology), power rating (MW) and discharge duration (hours).

Liquid Air Energy Storage (LAES). There is not much information available about the cost of the technology. However, a cost estimation of building a LAES system is at about 300-600€/kW.[33]

2.4 Public RD&I Funding and Investments

The analysis in this chapter is based on information from projects under the Horizon 2020 and Horizon Europe. There is insufficient data available to estimate the position of EU in terms of public research and investments and compare it with Asia, USA or other part of the world.

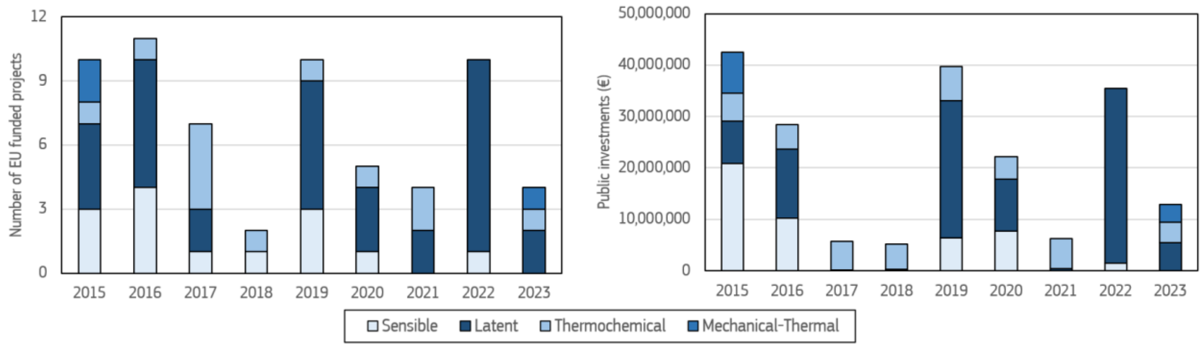
The chapter aims to show how many public investments are destined to TES, without considering its final use. This means the final use of the thermal energy could be for thermal purposes or electricity production.

More than 60 different projects were on TES or related topics with a total amount of more than 140 M€ under the frame of the H2020 program. The EC funded those projects between 2015 and 2021, and Figure 8 shows the number of projects and investments per year. The technology with more related projects and investments was latent TES, particularly PCM. The sensible TES technologies are second place, in which molten salts played a key role. Finally, thermochemical TES (Reversible reactions and sorption systems) have less public investments. The results show that despite the high levels of storage capacity and low TRL of thermochemical TES, there are fewer investments than in molten salts or PCMs. The reason could be the ease of applying the technology rather than the storage capacity.

Data on Horizon Europe funded projects are available for 2022 and 2023. Fourteen projects have been identified as approved with a total EU contribution of over 45 M€. Figure 8 illustrates the distribution of EU funded research projects from 2015 to 202. Most of the research projects under Horizon Europe focus on PCMs. A noteworthy aspect of PCMs is that it can contribute to create better materials for the building envelope, which improves their thermal inertia. Furthermore, PCMs can play a role in cold chain activities and in storing thermal energy from industries. The versatility of PCMs across various sectors has led to a surge in research projects exploring this technology. Note that the years 2022 and 2023 in Figure 8 concern Horizon Europe, while previous years Horizon 2020.

[32] 20200214-JFS_Hydrostor-comments-on-draft-assumptions.pdf (nspower.ca)
[33] A closer look at liquid air energy storage – pv magazine International (pv-magazine.com)

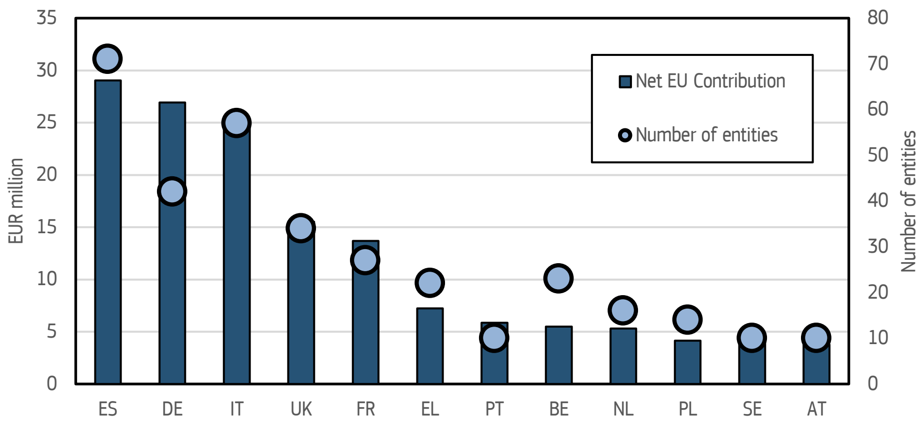
Figure 8. Numbers of Horizon 2020 and Horizon Europe projects and investments



Source: (JRC, 2023).

Many entities from different countries were involved in the Horizon projects. An estimation of the EU contribution to the projects in which entities from several countries were involved can be seen in Figure 9. For example, the EU contribution for one specific country, Germany, refers to the net EU contribution (H2020 & Horizon Europe) to publicly funded research projects involving German entities. Moreover, number of participants from different countries involved in the projects was analysed.

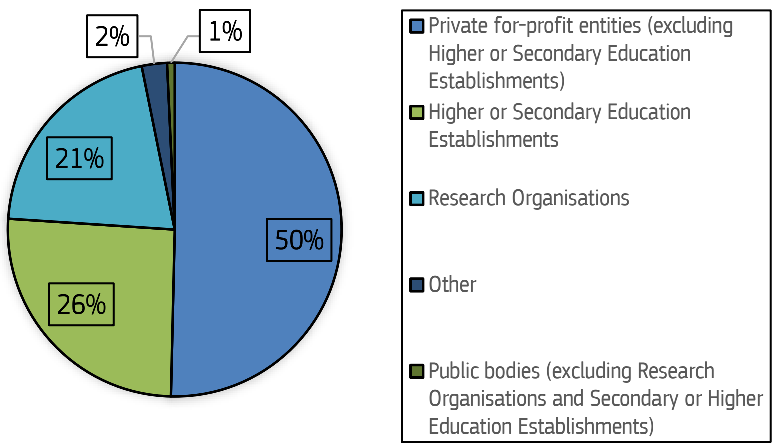
Figure 9. Analysis of the EU contribution and participation of entities from several countries



Source: (JRC, 2023).

Finally, Figure 10 shows the entities involved in these projects. Most entities were from the private sector, followed by education establishments and research organisations.

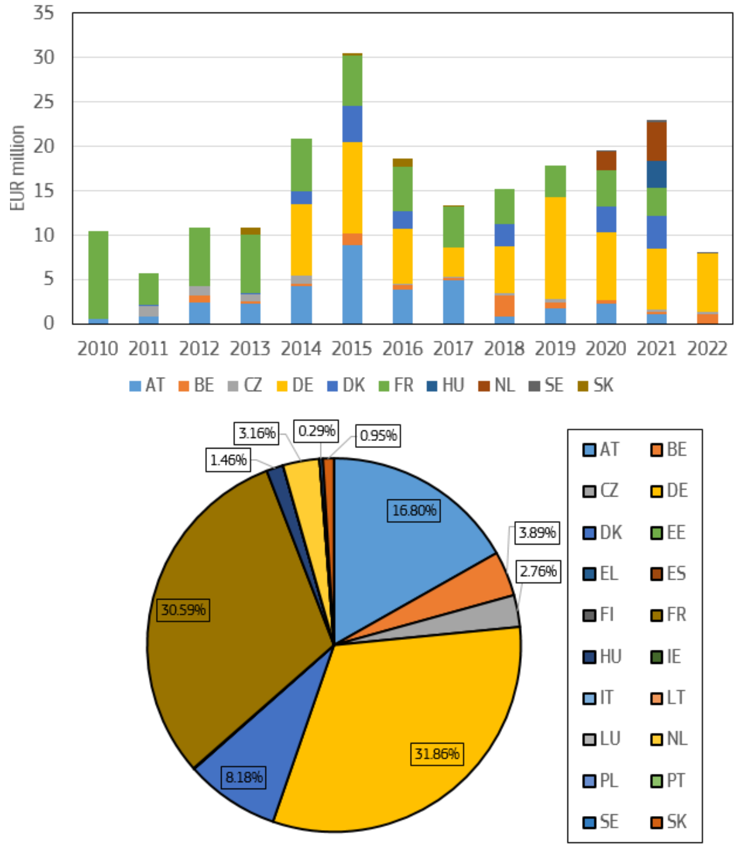
Figure 10. Type of entities involved in EU funded projects



Source: (JRC, 2023).

A second approach analysed public investments by ministries of every MS. Germany and France have the largest public investments, see Figure 11, contributing of 31.86% and 30.59% of the total from 2010 to 2022.

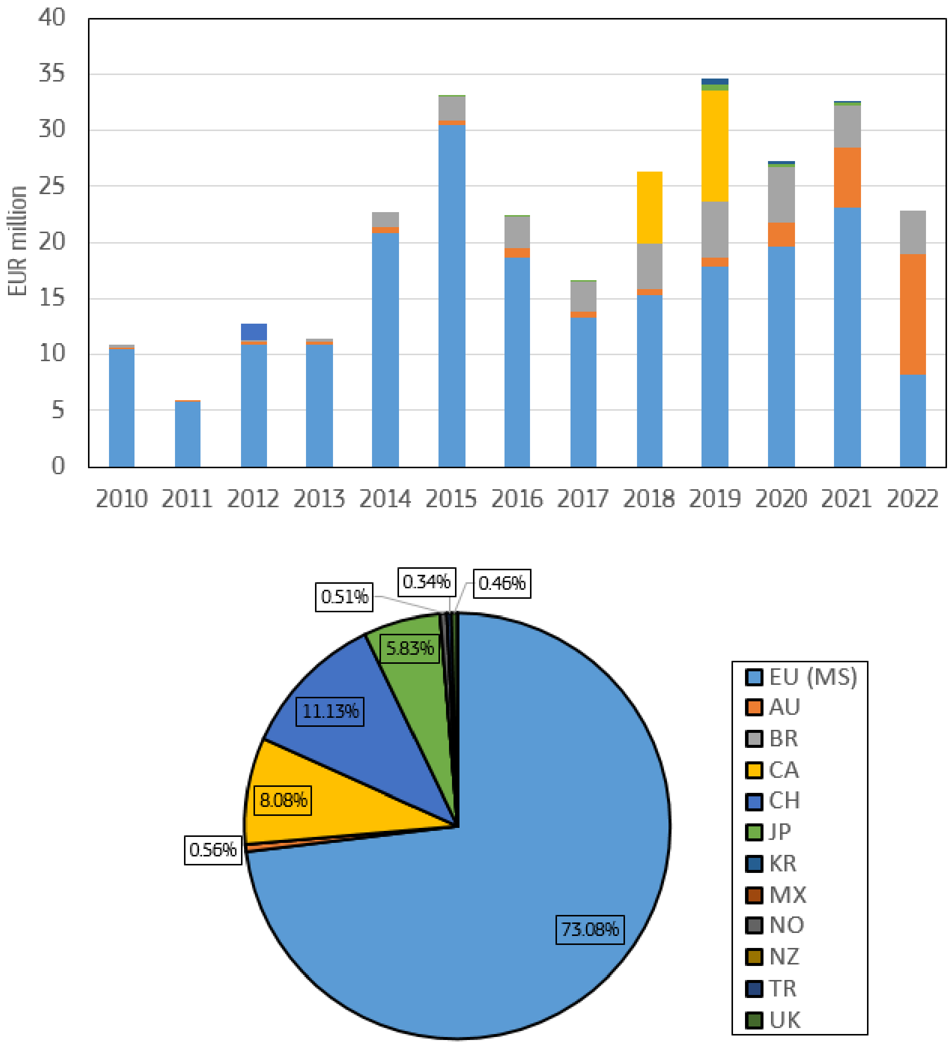
Figure 11. Public investments in the EU in TES, 2010-2022



Source: JRC based on (IEA, 2023).

Figure 12 displays a comparison of the public investments in TES in large regions globally. There are big differences between the EU and countries like China or Japan. The EU (73.1%) has the biggest share, followed by China (11.1%) and Japan (8.1%).

Figure 12. Global public investments in TES, 2010-2022



Source: JRC based on (IEA, 2023).

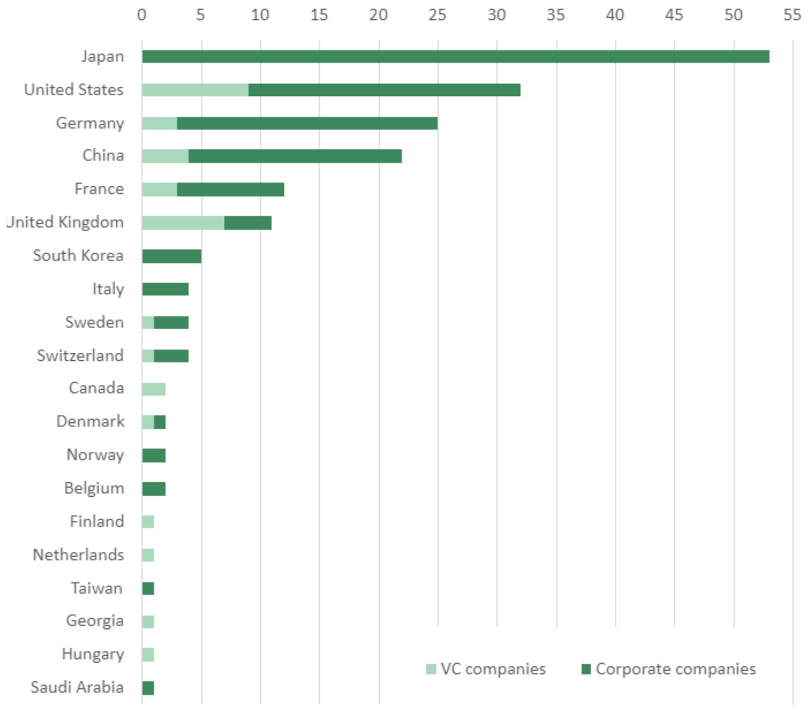
2.5 Private RD&I funding

This chapter analysed investments in start-ups or small companies linked to the TES sector. The indicator used is Venture Capital (VC), a private equity investment in early-stage, high-potential, and high-risk companies.

Additionally to these companies, corporate companies have also been part of the analysis. These include top R&D investors from the EU industrial R&D Investment Scoreboard with a significant patenting contribution.

Figure 13 shows the number of VC and corporate companies per country with research activities on TES. Japan has the greatest contribution with more than 50 companies, followed by the USA. Among European countries, Germany has the biggest share with 25 companies, most of them corporate companies.

Figure 13. Non-exhaustive list of VC and corporate companies linked to TES technologies



Source: (JRC, 2023).

It is important to note that these investments are directed to companies dedicated to TES, regardless how the stored energy is used, i.e. thermal or electricity production. While the analysis aims to quantify VC investments in TES companies, the specific markets they serve can vary significantly.

Figure 14 displays the VC investments in TES from 2010 to 2022. Global VC investments in TES firms started to take off in 2017, display a sharp increase over 2021-22 (x 5.5 as compared to 2020) and reach EUR 293 million in 2022. Over 2017-22, global VC investments amounted to EUR 688 million, which represents an eight–fold increase as compared to the previous 2011-16 period of very low investment levels.

The large-scale deployment of variable renewable energy and the consequent need for more flexibility could be the reason of such evolution. Canada and United States are the largest investors, followed by UK and China.

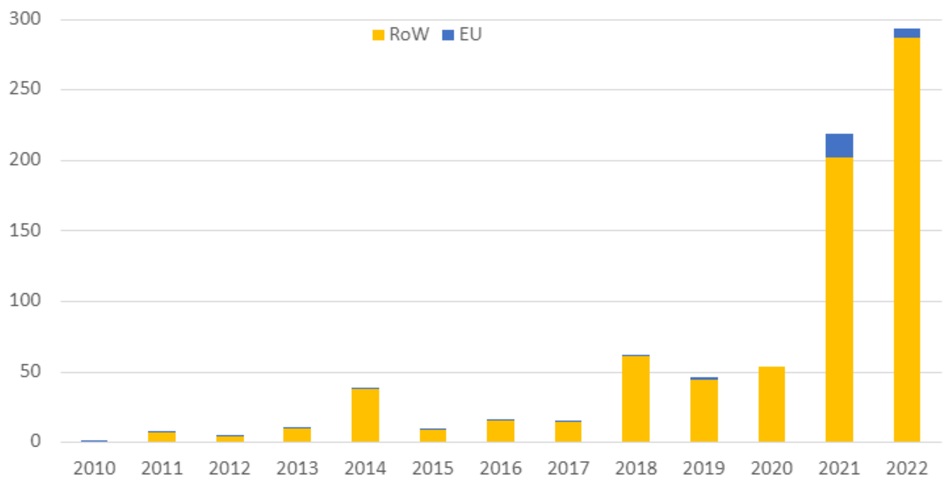
While hosting fewer VC companies, Canada leads the overall investments in TES, followed by the US, the UK, and China. VC investments in TES are driven by a limited number of ventures that account for the essential investments realised over the 2017-22 period.

The EU hosts 31% of active VC companies, but they are much younger (73 % of EU VC firms were founded since 2017 versus 36% in the rest of the world). Consequently, the EU only accounts for 2% of early stage investments (amounting to EUR 0.16 million) and 4.5% of later stages investments (amounting to EUR 23 million) over the current 2017-22 period.

Canada outruns its competitors and leads late-stage investments as it hosts the company Hydrostor (compressed air energy storage). Hydrostor accounts by itself for 51 % of the global later-stage investments realised over the 2017-22 period, in particular via a large growth equity deal in 2022.

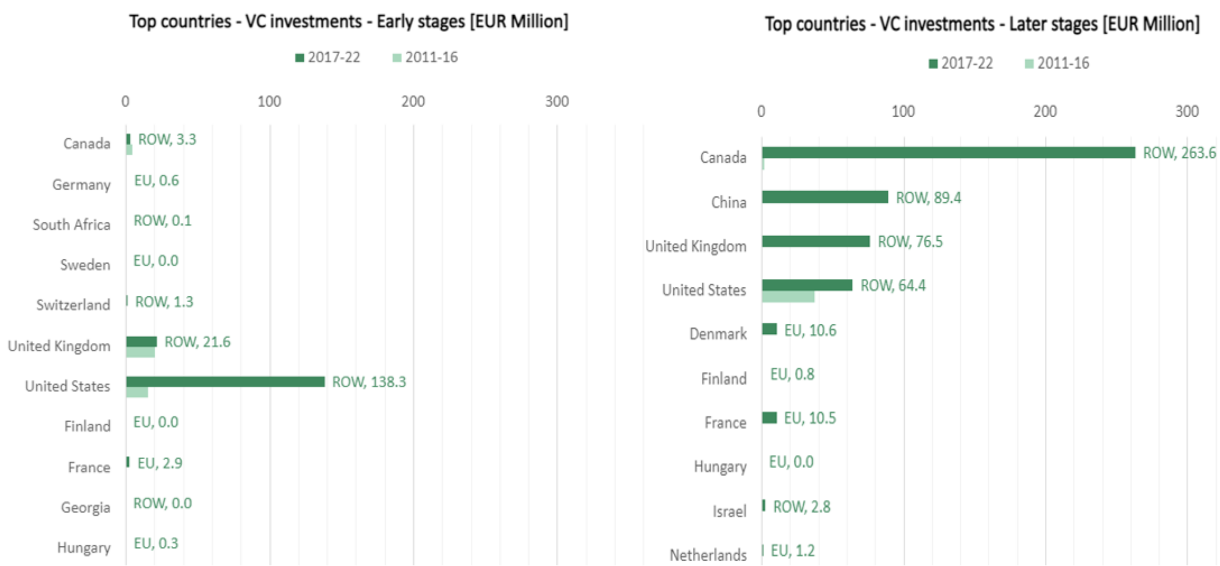
The US, however, leads in terms of early-stage investments as it hosts the company Malta (electro-thermal storage). Malta accounts for 44 % the global early-stage investments realised over 2017-22.

Figure 14. Venture Capital investments in TES related companies- Europe and RoW



Source: (JRC, 2023).

Figure 15. Venture Capital investments in TES related companies per country



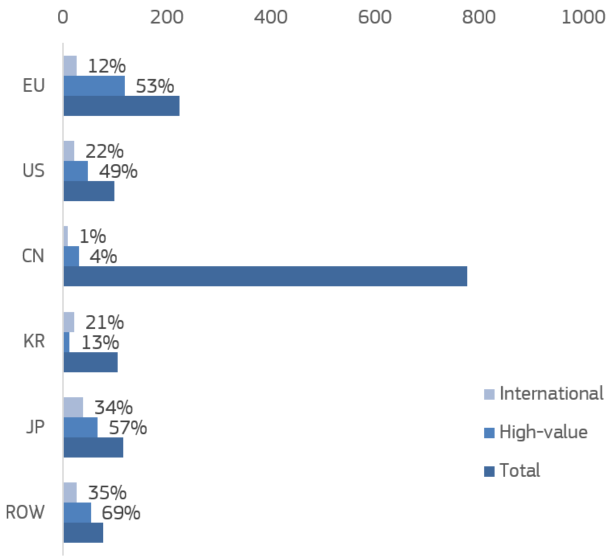
Source: (JRC, 2023).

2.6 Patenting trends

Patents are a valuable source of information that could be used to measure the research state, as they provide new knowledge that could lead to a new physical product. Figure 16 shows an analysis of the patent results for several areas. There are results about total inventions or Patent families, which are basically the total number of patents for the specific code provided as input. Another kind of invention is the high-value, which refers to patents filed in more than one patent office. Finally, there is info about international inventions, which are protected in a country different than the residence country of the applicant.

China leads the total number of patents with a total amount of 777, reaching 55% of the total inventions from 2018 to 2020. However, only 4% of the patents from China are considered high-value and only 1% are international. EU has 224 patents, and 119 are considered high-value, making the EU the one with the highest share of high-value patents, with a total share of 36%.

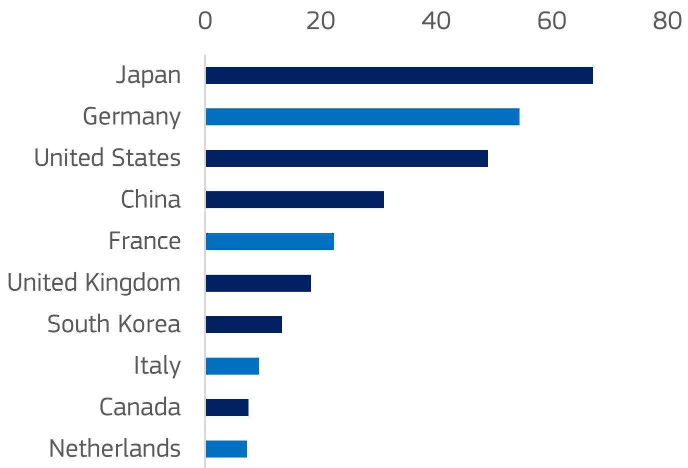
Figure 16. Number of inventions and share of high-value and international activity (2018-2020)



Source: JRC based on EPO Patstat, 2022b.

Japan has the highest number of high-value inventions with 67, followed by Germany with 64, see Figure 17.

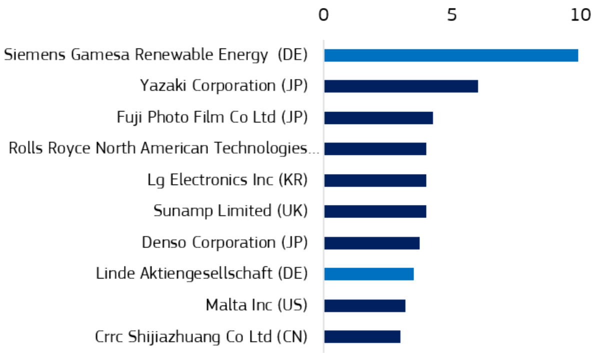
Figure 17. High-value inventions - Top 10 countries

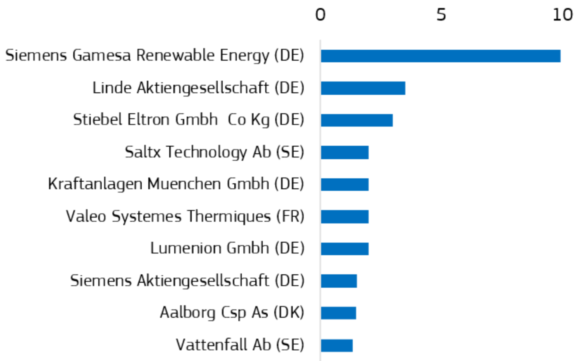


Source: JRC based on EPO Patstat, 2022b.

Another important point to mention is the patents of companies. Figure 18 shows the study's result, in which the leaders in terms of patenting companies can be seen. The results show the top 10 patenting companies in the world and the EU, displaying that the biggest company in terms of patents is Siemens Gamesa Renewable Energy from Germany with ten patents between 2018 and 2020.

Figure 18. Patenting companies in the world (left) and in the EU (right)



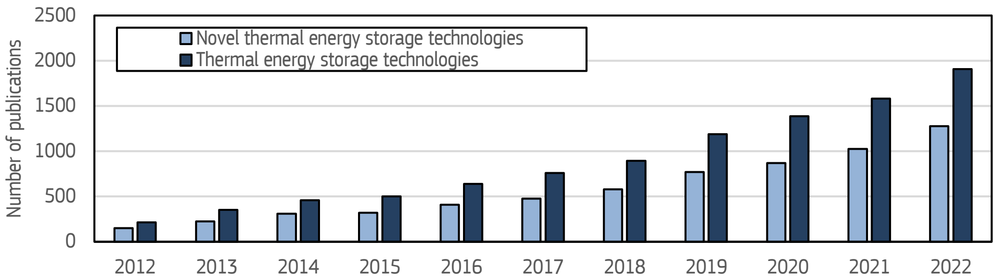


Source: JRC based on EPO Patstat, 2022b.

2.7 Scientific publication trends

TES has a positive trend in scientific publications, which serves as evidence of the growing interest in this technology. It can play a key role in global decarbonisation efforts and in achieving the EU's renewable energy targets in 2030 and 2050. Scientific publications were analysed using the tool TIM with the keywords "Thermal Energy Storage". Figure 15 shows that in 2022 there were almost 2000 scientific publications compared to only 200 in 2012. Also figure 14 presents a comparison of publications on thermal energy storage and storage technologies considered more novel.

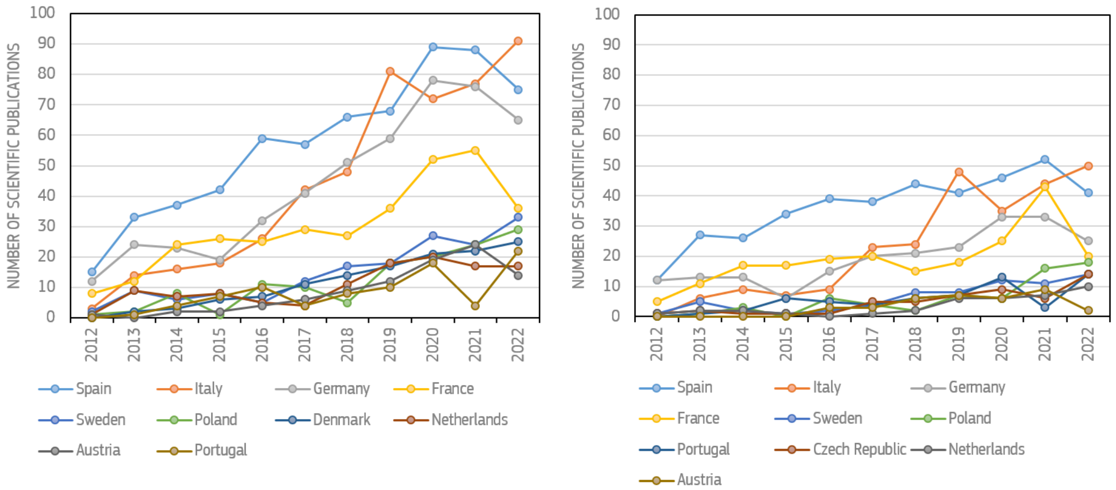
Figure 19. Number of publications in the TES field.



Source: (JRC, 2023).

A comparison of the MS scientific publications within the EU is shown in Figure 20, which exposes the analysis results with the tool TIM per MS. It follows the same approach as Figure 19, comparing all the publications of TES with the ones that can be considered novel. According to the results obtained, Spain, Italy and Germany are the MSs where more scientific publications of TES have been published. All the MS present an increasing tendency in the research of TES, with several authors from different countries interested in the topic.

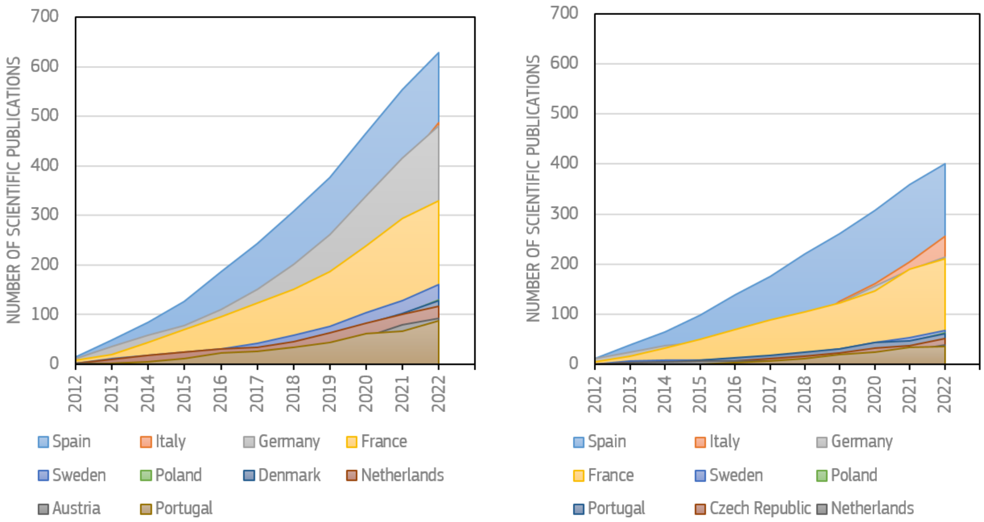
Figure 20. Publications linked to TES technologies (Left) - Publications linked to novel TES technologies (right)



Source: (JRC, 2023).

In terms of cumulative results, Figure 21 represents the number of scientific articles written in this field in the EU. Italy and Spain have the largest share of publications on novel technologies, followed by Germany and France.

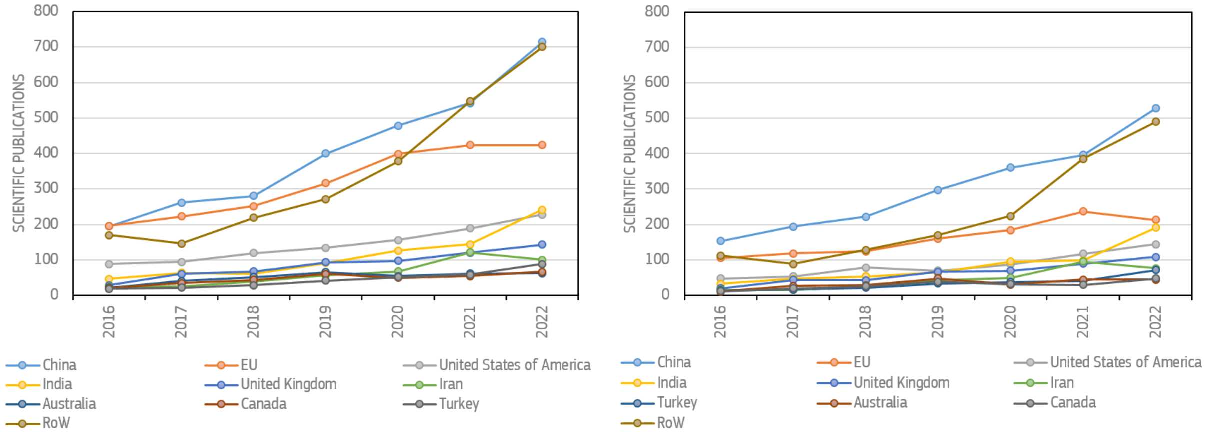
Figure 21. Cumulative Publications linked to TES technologies (Left) - Cumulative Publications linked to novel TES technologies (right).



Source: (JRC, 2023).

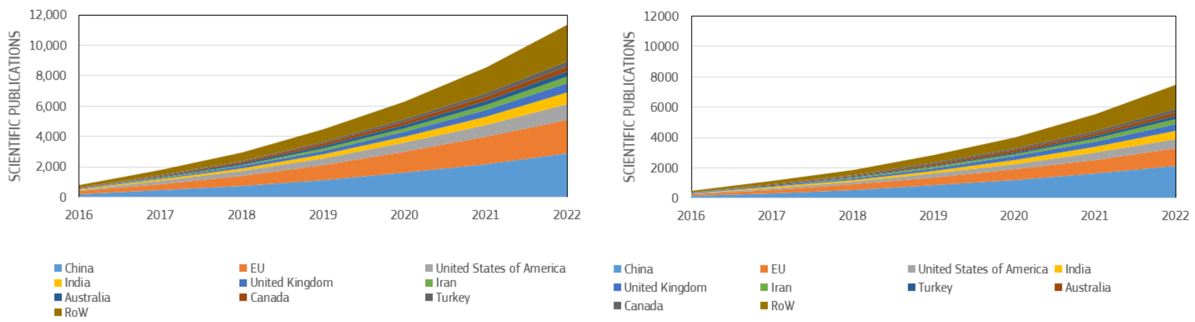
China published the most scientific publications, followed by the EU. The EU's share of research on this topic is significant. Figures 22 and 23 show the annual publications and in cumulative terms, respectively.

Figure 22. Global publications linked to TES technologies (Left) - Global publications linked to novel TES technologies (right).



Source: (JRC, 2023).

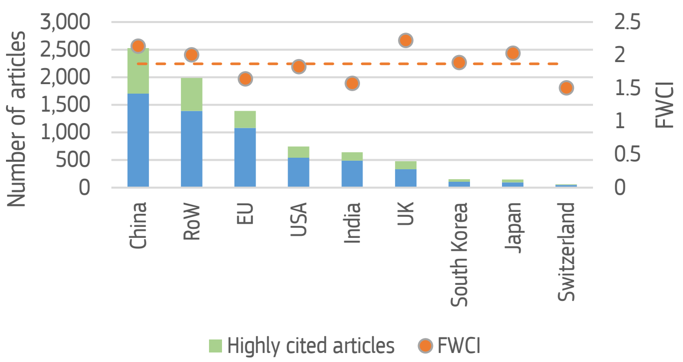
Figure 23. Global cumulative publications linked to TES technologies (Left) - Global cumulative publications linked to novel TES technologies (right).



Source: (JRC, 2023).

Another indicator to consider is the quality of the papers written and their number of citations. As depicted in Figure 24, China publishes most of the highly cited articles, indicating that the work has significant repercussions in the field. In terms of highly cited articles, the EU occupies the third position, contributing more than the USA. The UK has fewer publications but the highest Field Weighted Citation Impact (FWCI), suggesting that their articles are cited more frequently compared those of other countries. The EU, according to the FWCI, is below the average, meaning that its publications are cited less frequently than countries like Japan or USA.

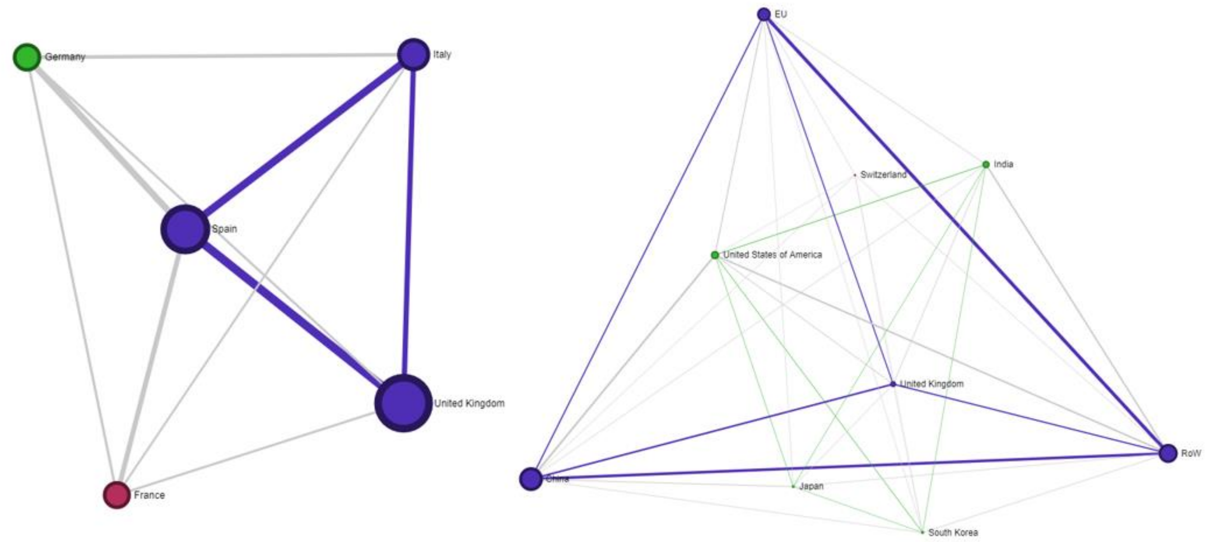
Figure 24. Number of publications and FWCI indicator



Source: (JRC, 2023).

Finally, the relationships between authors from the EU and the rest of the world and between EU member states, were analysed using the TIM tool. Figure 25 shows the significance of collaborations between countries. Important collaborations were found between authors from Spain, Italy and United Kingdom in the field of the most novel TES technologies. Moreover, EU and China have significant collaborations and also the highest number of scientific publications, which means that a large part of the research in terms of novel TES technologies is hold by EU and China.

Figure 25. Links in terms of publications between MS and regions



Source: (JRC, 2023).

3 Value Chain Analysis

The TES technologies are diverse and there is no common procedure of how to define or analyse its value chain. Logically, the novel TES technologies currently have a minor presence in the market and thus limited value chains. Furthermore, data on different materials used for heat storage are missing and thus not described in this section. However, an example from a Horizon 2020 funded project called "HEAT-INSYDE", which investigates a sorption-based solution, made a value chain analysis for their technology mentioning all the stakeholders involved in the development.[34]

3.1 Turnover

No data is available regarding turnover for the novel TES technologies. There are, however, some data for conventional TES technologies.

Turnover typically denotes a company's earnings during a specified timeframe. Nonetheless, for a more comprehensive view of the sales associated with TES technologies, there is an analysis conducted by Precedence Research.[35] According to the study, the market size of TES technologies amounted to USD 23.7 billion in 2021, with sensible TES constituting approximately 85% of this market. Notably, the industrial segment claimed a substantial 40% share of the market. When considering the specific applications of stored thermal energy, TES dedicated to power generation dominated with a 60% market share in 2021.

3.2 Gross value added

There is no data on the gross value added of the novel TES technologies.

3.3 Environmental and socio-economic sustainability

The environmental impact and sustainability of various TES solutions hinge on the specific technology employed. For example, for sensible storage solutions like water tanks or underground TES, the materials used are quite similar to those used in other heating technologies, such as domestic hot water tanks or geothermal heat pumps.

Sensible TES, such as water tanks, have an impact on the environment, primarily through the production of the tank itself. Furthermore, energy consumption may arise from transportation and chemical treatment linked to the production and installation of the tank. The tank is generally made of reinforced concrete, stainless steel or plastics, all common materials which also are associated with high carbon emissions or adverse environmental effects. In terms of the storage medium, namely water, the adverse impact is minimal or even zero.

PCMs vary significantly in terms of sustainability. Some PCMs could have a negative effect on the environment. For example, a PCM like octadecane needs a significant amount of energy to be produced. To address this problem, bio-based PCMs could play a key role, as they could contribute to a sustainable development and to a lower dependency of fossil fuels or any type of energy source. The energy needed to produce octadecane is 10 times higher than to produce a bio-based PCM (Aridi & Yehya, 2022). Another aspect to take into account is the material that can encapsulate the PCM. Usually the capsules are made of carbon steels, copper, stainless steel or aluminium. These materials could be corroded by the PCMs they contain, which could lead to environment impacts as these fluids can be harmful in the environment.

Furthermore, there is a risk ATES influences the groundwater. Nevertheless, the expected modifications in the water composition should not be high enough to make this water not suitable for drinking. (Possemiers, Huysmans, & Batelaan, 2014) (Bonte M. , Stuyfzand, Berg, & Hijnen, 2011).Concerning social aspects, it's hard to define an exact social cycle in technologies that are not already widespread in the market or that basically use similar procedures than other technologies, such as district heating or heating facilities in buildings. However, there are activities, e.g., in the production cycles of the PCMs that add an order of magnitude of the social impact, e.g. bio-based PCMs in agricultural practices, indicating how society could be affected. Poor management of such processes could impact negatively the quality of life of the people working in the sector (Aridi & Yehya, 2022).

[34] https://www.heat-insyde.eu/

[35] https://www.precedenceresearch.com/thermal-energy-storage-market

3.4 Role of EU Companies

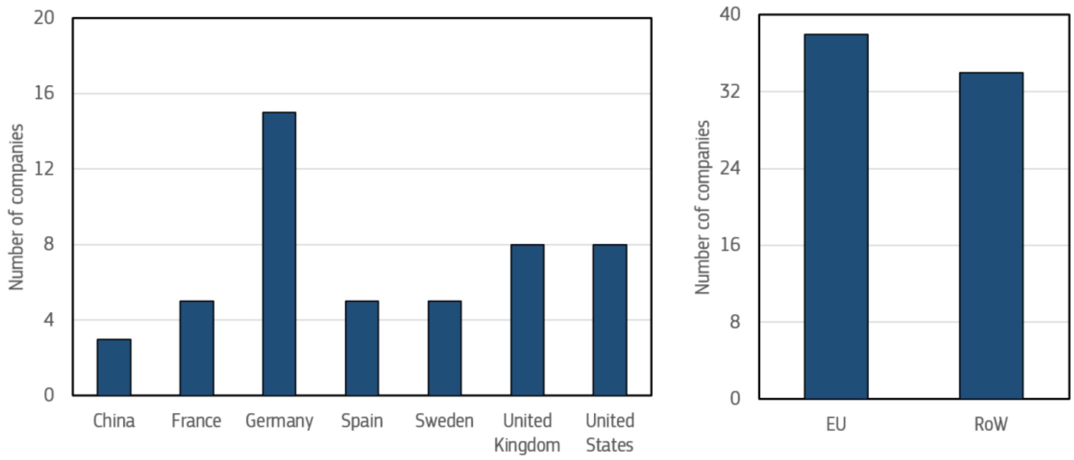
Companies linked to TES could represent different markets, given that thermal energy can be stored for both electricity production or for thermal uses like district heating or domestic hot water in buildings. The companies analysed in this chapter provide TES solutions or are associated with it, despite the different end-uses.

Companies such as LAPESA[36] or CHROMAGEN[37] are well-known for solutions storing sensible thermal energy stored in water tanks, usually for domestic hot water and for thermal inertia in HVAC facilities.

Some companies included in the count are not storing thermal energy themselves but they are associated with this technology. This is the case for non-technologically mature TES technologies, such as sorption-based solutions or adiabatic compressed air TES.

Figure 26 shows the number of TES companies by country or region, illustrating that Germany has a higher number of companies linked to TES compared with countries like the USA or China. Furthermore, the EU has more TES companies than the rest of the world combined.

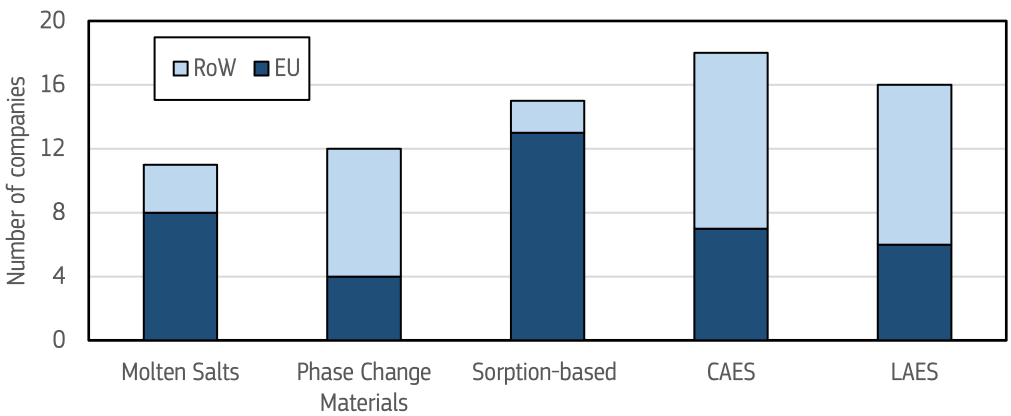
Figure 26. List of TES companies by country or region



Source: (JRC, 2023).

In Figure 27, the companies are classified according to the type of technology they are linked, including both technologically mature (Molten Salts and PCM) and non-technologically mature TES technologies (Sorption-based, CAES and LAES). Note that these technologies should not be compared among themselves, because one type represents companies working with that technologically mature technologies while others are research and demonstration projects.

Figure 27. List of companies by technology



Source: (JRC, 2023).

[36] https://lapesa.es/es
[37] https://chromagen.com/

3.5 Employment

Employment from novel thermal storage technologies is not possible to evaluate due to lack of data.

3.6 Energy intensity and labour productivity

The lack of data makes it difficult to assess.

3.7 EU Production Data

Codes to identify the technologies could not be identified for the novel thermal storage technologies, as they use common materials used for several heating facilities. Another approach to find codes for the chemical products used in these technologies, such as molten salts or PCM, was also unsuccessful as specific codes for these technologies are not defined.

4 EU Market Position and Global Competitiveness

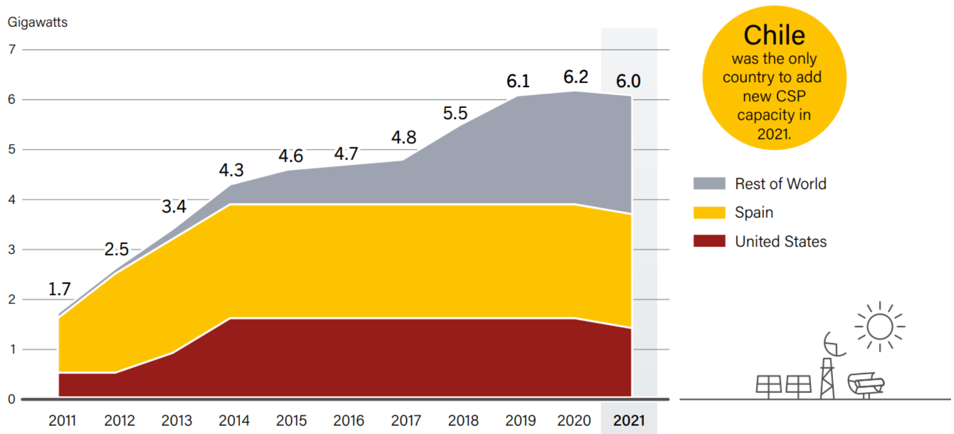
This chapter describes the market of the TES technologies, where data is available.

4.1 Global & EU market leaders

Molten salts thermal energy storage co-located with CSP plants have achieved commercial stage since 2010. Given its dependency on solar thermal energy, MSTES growth is directly correlated to the growth of CSP plants. Since 2014, only two out of 25 completed CSP plants did not incorporate TES[38]. Furthermore, it is estimated approximately 23 GWh of TES, mostly based on molten salts, an 18.5 GWh addition compared to 10 years prior[38]. Projected capacity based on planned MSTES installations is a total of 94 GWh by 2030. However, if it is assumed that all forecasted CSP capacity of 20 GW by 2030 will be accompanied by molten salt storage, this total goes up to approximately 148 GWh of installed MSTES capacity by 2030, an increase in capacity of around 547% (IRENA, 2020). The 491 to 631 GWh projection in graph 2 shows IRENA's Transforming Energy Scenario, which is aligned with the climate targets under the Paris Agreement (IRENA, 2020).

There is a significant pipeline of new projects focusing on molten salt TES together with CSP plants. In 2022, a CSP project in Chile entered commercial operation with a 10 MW capacity and 17.5 hours of TES[38]. China has 30 CSP projects underway that will be developed together with over 12 GWh TES systems and are to be completed by 2024, all of which are to be constructed by Chinese state-owned enterprises[39]. However, total installed CSP capacity has slightly decreased between 2020 and 2021, as it is represented in Figure 28. Figure 28 also shows how the capacity installed is distributed, where Spain and the US have the highest capacity installed of CSP (which can use molten salts as TES technology). The decrease of capacity installed in 2021, is due to a growth smaller than total decommissioning previewed for that year, falling from a total of 6.2 GW to 6 GW capacity worldwide. In its current state, future growth of molten salt as a TES is reliant on the growth of CSP. However, current research may decouple this dependency to some extent, where for example, stand-alone bulk storages converting decommissioned coal plants into storage facilities (IRENA, 2020). Expansion of molten salt applications beyond the power sector, such as for industrial purposes, may also play a key role.

Figure 28. Capacity installed of CSP, most of them with molten salts as TES



Source: (REN21, 2022).

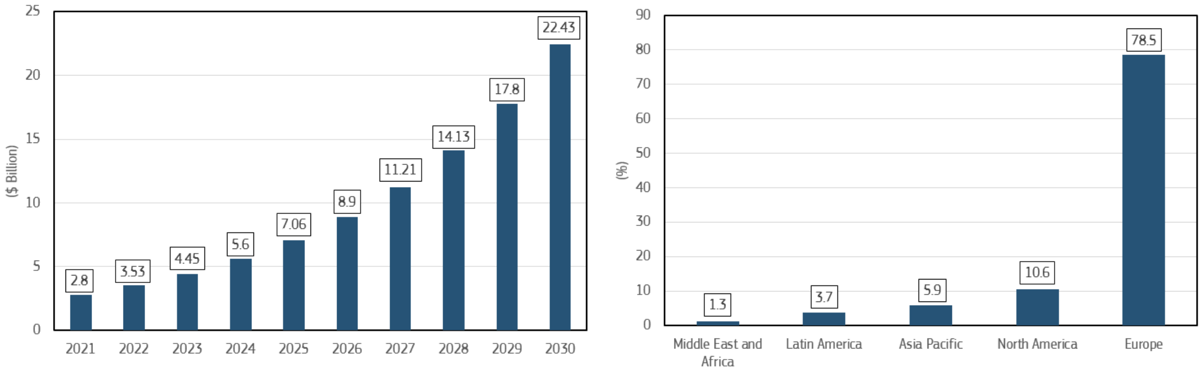
Some of the leading companies operating in the molten salt for TES market are:

- In the EU: Acciona (Spain), Engie (France), SENER Group (Spain), TSK Flagsol (Spain), Torresol Energy (Spain), MAN Energy Solutions (Germany), Siemens (Germany) and Linde group (Germany)
- In the rest of the world: Yara International (Norway), ACWA Power (Saudi Arabia) and BrightSource Energy (Israel)

[38] https://www.ren21.net/wp-content/uploads/2019/05/GSR2022_Full_Report.pdf
[39] China now has 30 CSP projects with thermal energy storage underway - SolarPACES

A study from Precedence Research[40] shows that the molten salt global market amounted to a USD 2.8 billion in 2021. According to their projection, the market in 2030 will reach USD 22.43 billion, as shown in Figure 29a. The EU is the region with the largest market share of molten salts, accounting for 78% (figure 29b) of the global market in 2021, with Spain as the biggest contributor.

Figure 29. Market size of molten salts (left) and market shares of molten salts market (right)



Source: (Precedence Research, 2023).

Solid media thermal energy storage. The market for this technology still under a low stage of development, with some pilot and first commercial projects. Some companies working with this technology are:

- In the EU: Kraftblock and KAM (Germany).
- In the rest of the world: Energy NEST (Norway), 1414 (Australia), Brenmiller (Isreal), Rondo (US) and Lumenion.

Low-temperature PCMs. Several projects are working to reduce low-temperature PCMs' cost and increase their thermal efficiency, as well as to widen the applicability of the technology. TES for buildings is the most promising area, yet its potential for industrial processes and waste heat are also being explored. Examples of TES projects for buildings are found at the Chalmers University of Technology in Sweden, and the University College of Bergen in Norway[41].Some of the most prominent companies in the market for PCM use in TES include:

- In the EU: Rubitherm Technologies GmbH (Germany), Axiotherm GmbH (Germany), PCM Technology (Netherlands), and va-Q-tec AG (Germany).
- In the rest of the world: Phase Change Energy Solutions (US), PCM Products Ltd (UK), Pluss Advanced Technologies (India), PureTemp LLC (US), Sunamp Ltd (UK), ISU Chemical Co., Ltd (South Korea), Croda Europe Ltd. (UK), Hangzhou Ruhr New Material Technology Co., Ltd. (China), and Boca PCM (Hong Kong).

High-temperature PCMs. A couple of ongoing research activities are also exploring the potential of high-temperature PCM. For example:

The City-zen EU programme has received EU funding to develop roadmaps for low-carbon cities[42]. One of their projects consisted of developing a programme for the city of Grenoble, France. Part of this project was to couple solar thermal heat to a centralized PCM storage with a capacity of 180 kWh, helping to peak demand and decarbonize district heating[43].

An operational demonstration plant utilizing HT-PCM for district heating has been in place since 2016 in the region of Xinjiang in China (IRENA, 2020), harnessing electricity from wind energy that would otherwise have been curtailed. With a storage capacity of 36 MWh, the power-to-heat project uses PCM at a working temperature of around 700°C and has a thermal efficiency of around 95%[44]. Despite of these demonstration

[40] https://www.precedenceresearch.com/molten-salt-thermal-energy-storage-market
[41] Applications-of-Thermal-Energy-Storage-in-the-Energy-Trenasition-Annex-30_Public-Report.pdf (iea-es.org)
[42] City-zen | New urban energy (cityzen-smartcity.eu)
[43] interactive_final-deliverable-book.pdf (cityzen-smartcity.eu)
[44] Fact Sheet (eera-energystorage.eu)

projects, as previously mentioned, the technology still has to cover some ground before it enters commercial scale.

Although some pilot projects are in place with demonstration capacity, the technology is still being developed and not many companies offer high temperature PCM as TES yet. Compared to the list for the low temperature counterpart, only three of those companies also claim to provide the high temperature option: PCM Products Ltd[45] (UK); PureTemp LLC[46] (US); and Boca PCM[47] (China). However, the technology has the potential to become impactful for the industrial, district heating and building sectors, in the medium-term horizon.

According to the results of Fortune Business[48], the global PCM (Sub-zero, low and high temperature) market size in 2019 amounted to around USD 1.16 billion in 2019, with a projection of reaching USD 4.17 billion in 2027. This market includes PCMs that are linked to cold chain purposes, HVAC technologies, buildings, construction materials, as well as TES.

Reversible-based reaction thermal energy storage. The technology is in the beginning of its innovation curve, with most work focused on applied research or prototype development. A few projects developed pilot scale plants, but a market is not yet formed around this technology. The novel solution of calcium looping utilization has a significantly higher TRL in its application for carbon capture (7-8), as different projects have researched such application in the cement industry to lower its carbon footprint[49]. However, calcium looping utilization in TES is far earlier in its development.

The SOCRATCES project is among the few projects piloting the utilization of calcium-looping for TES, from a CSP source. The Australian company Calix is backing this SOCRATCES project[50]. The company has experience in carbon capture through calcium looping as they lead a consortium in the LEILAC project to implement carbon capture processes in the cement industry[51]. The SOCRATCES project is being piloted as a hybrid CSP-electric LEILAC unit from Calix[52].

Sorption-based thermal energy storage. The development of the technology varies depending on the sorption-based method. While HEAT-INSYDE develops a compact battery for residential buildings, Vattenfall and SaltX technology developed a large-scale pilot thermochemical energy storage plant based on salt hydration at Berlin's Reuter CHP plant.[53] This salt battery has a total storage capacity of 10 MWh and served as a prototype for district heating TES scheme. Following the project in Berlin, SaltX is currently developing another pilot project near Stockholm, also based on salt hydration. Their partners on this new project are Sumitomo SHI FW & Calix Limited, ABB & Alfa Laval.[54]

The companies relevant on this segment vary significantly depending on the sorption type and material of choice. The technology has a strong prospect to penetrate the building and district heating and cooling sectors. Industrial waste heat recovery and process heat also create potential market applications for the technology. Some of the relevant companies from different points of the value chain are listed below.

Adiabatic Compressed Air Energy Storage. The growth of this technology is mainly driven by the necessity of a storage system that works like a battery to integrate with renewable energy. Several projects have been completed or are underway exploring this technology. The Swiss company ALCAES built in 2016 the first Advanced Adiabatic-CAES pilot plant in the world.[55] The plant has a capacity of 1 MWh, operates with an air compression temperature of 550 °C and a round-trip efficiency of above 72%. The company also states it achieves a ramping up time of less than five minutes, and the lowest CAPEX per kWh among all storage technologies.[56] In 2013, RWE, Ed. Züblin and General Electric carried the ADELE project, developing an A-CAES facility in Stasfurt, Germany. The project had facility had 200 MW of power and a storage size of 1 GWh. The project, however, was discontinued in 2016 (King, Jain, Bhakar, Mathur, & Wang, 2021).

[45] https://www.pcmproducts.net
[46] GLOBAL AUTHORITY ON PHASE CHANGE MATERIAL® - PureTemp
[47] PCM | pcm-tes.com
[48] https://www.fortunebusinessinsights.com/phase-change-materials-market-104848
[49] Reaching new heights with CO2 capture at cement plants | Research and Innovation (europa.eu)
[50] Project SOCRATCES Targeting low cost / low carbon energy supply - Calix | Because Mars is for quitters
[51] Cement | Industries | Reducing CO2 Emissions by Project LEILAC (calix.global)
[52] Calix backs 'calcium looping' energy storage - Australian Manufacturing Forum (aumanufacturing.com.au)
[53] Vattenfall to test salt-based power storage technology | Reuters
[54] Installations - SaltX Technology
[55] Pilot Plant (alacaes.com)
[56] Concept (alacaes.com)

China has four active A-CAES projects. Ticc-500 is a demonstration project that was built in 2014 having a 0.5 MW of power and 0.5 MWh of storage capacity (King, Jain, Bhakar, Mathur, & Wang, 2021). A second demonstration project was developed by the Chinese Academy of Sciences and was deployed in 2015, in Bijie City (King, Jain, Bhakar, Mathur, & Wang, 2021). The demonstration plant has a 2.8 MW charge and 10 MW discharge, having 40 MWh of storage capacity. In late 2022, a commercial A-CAES facility was built in Jintan, China.[57] The project is led by the state-owned company China Huaneng Group.[58] The facility uses mined salt caverns for its storage system, having a generating capacity of 60 MW and a total storage size of 300 MWh. Finally, it is reported that in 2019 China commissioned an A-CAES project to be developed in Feicheng.

The project aims to repurpose salt and coal mine caverns and is expected to deliver 1.25 GW in power generation capacity, with a total storage size of 7.5 GWh (King, Jain, Bhakar, Mathur, & Wang, 2021).

The Canadian Hydrostor is the company with most A-CAES projects developed and planned. The first project developed by the company was in 2015, a demonstration facility in Toronto that was the world's first A-CAES system connected to the grid.[59] Also in Canada, the Goderich had the first commercially contracted A-CAES facility completed in 2019. The facility has a 1.75 MW output and 2.2 MW charging rate, with a capacity of 10 MWh. After Goderich's success, the Canadian government aims to have more A-CAES facilities and is supporting Hydrostor with at least USD 3.2 million fund a new 300-500 MW development.[60] The StrataStore consortium includes Hydrostor and EDF Energy, and it plans to transform an existing gas storage site into an A-CAES facility in England.[61] The Silver City Energy Storage project[62] is being developed in New South Wales, Australia. The project developed by the Canadian company received a USD 45 million from the Australian Renewable Energy Agency.[63] The facility size is expected to be of 200 MW, with a total storage capacity of 1.6 GWh which would provide 8 hours of storage; and a lifetime of over 50 years. Furthermore, the company also shares that the project will generate around 750 jobs. The project is expected to be completed in 2024.[64] The Pecho Energy Storage Center[65] is a utility scale A-CAES project being developed in California. The project will be able to provide 400 MW with a total storage size of 3.2 GWh and 8 hours of total storage time. Hydrostor's last A-CAES project in the pipeline is its largest yet. Another project to be developed in California, the Willow Rock Energy Storage Center[66] is projected to support 500 MW, with a storage capacity of 4 GWh, having a storage time of 8 hours. Like the Australian and the first Californian projects, Hydrostor expects to generate 750 jobs for the facility's development.

Several other companies participate on the technology's value chain. Below is a list of some companies involved in the development of A-CAES:

- In the EU: MAN Energy Solutions (Germany), Siemens Energy (Germany), Alfa Laval (Sweden), Geostock (France), Meridiam Infrastructure Partners (France), Ed. Züblin (Germany), RWE (Germany).
- In the rest of the world: Hydrostor (Canada), ALCAES (Switzerland), Baker Hughes (US), Hanwha Power Systems (South Korea), Therco-Serck (UK), Exchanger Industries (Canada), Lane Power & Energy Solutions (US), Agapito Associates (US), General Electric (US), China Huaneng Group (China), China National Salt Industry Group (China).

Liquid Air Energy Storage. The technology in question is currently not widespread in the market. Highview Power is the main company gaining the market as a developer, with few other upcoming developers trailing. Highview Power, besides developing the previously mentioned demonstration project in the UK in 2018, has announced several upcoming projects. The company is developing a commercial scale plant facility in Yorkshire, having 200 MW of power and up to 2.5 GWh of storage capacity. A third project in the UK, building a 50MW/300MWh facility in Manchester, is now being developed, and is part of an 18-site-plan to be deployed throughout the UK.[67] Outside of the UK, the company has set out a plan to build seven facilities throughout

[57] China's first salt cavern for compressed air energy storage goes online – pv magazine International (pv-magazine.com)
[58] Company Overview - CHINA HUANENG GROUP (chng.com.cn)
[59] Toronto A-CAES Facility – Hydrostor
[60] Advanced compressed air energy storage project gets funding help from Canadian government - Energy Storage News (energy-storage.news)
[61] Strata-Store
[62] Silver City Energy Storage
[63] ARENA funding for 2 renewable energy storage projects | energy.gov.au
[64] Broken Hill Energy Storage - Infrastructure Pipeline
[65] Pecho Energy Storage Center – Hydrostor
[66] Willow Rock Energy Storage Center – Hydrostor
[67] Plants | Highview Power

Spain, with an aggregate capacity of 2 GWh and total investment of USD 1 billion.[68] The first of these investments will take place in the Canary Islands and it will have 50 MW of power and a storage size of 300 MWh[67]. In 2021 was announced that Highview Power would develop together with Energía Latina SA Enlasa a LAES facility in the Atacama region, Chile.[69] The facility is planned to have 50 MW of power and 500 MWh of storage, offering 10 hours of storage. The project is estimated to cost around USD 150 million. Another relevant announcement relates to the Danish offshore wind company Orsted and Highpower View studying the value of co-locating offshore windfarms and LAES, to transform excess offshore wind power into liquid air, reducing curtailment and further decarbonizing the grid.[70]

Phelas is a German start-up company which is developing Aurora, a new modular container design for a LAES system. This new system comprises of an internal heat management, a custom cooling process and a simplified liquification process.[71] The company has recently announced a long-term commercial partnership with Wien Energie to push the technology into commercial stage.[72] Another company bringing innovative solution in the field is Innovatium.

The Scottish company developed a liquid air battery known as Prisma. Each battery stores up to 150 kWh and has over 25 years of lifespan.[73] The battery can be applied in a company level, and a demonstration project is currently running at one of Aggregate Industries' cement facilities.[74] Pintail Power is an American company who created Liquid Air Combined Cycle, a patented LAES technology. The company states that their system can deliver a 10 GWh storage capacity with longer durations – up to several days.[75]

LAES is verging to commercialisation stage and as mentioned before it utilizes several off-the-shelf components, making it have an established value chain of technology suppliers. Other characteristics of this technology that eases its deployment is the fact that it doesn't rely on specific geological characteristics to be developed, having no geographic restriction. Furthermore, the technology uses no form of critical resources, being less reliant on specific suppliers of those natural resources.

Below is a non-comprehensive list of companies working on LAES:

- In the EU: MAN Energy Solutions (Germany), Phelas (Germany), Endesa (Spain), Linde Group (Ireland), Messer Group (Germany), and Wien Energie (Austria).
- In the rest of the world: Highview Power (UK), Enlasa (Chile), Hitachi (Japan), Viridor (UK), General Electric (US), Sumitomo (Japan), Baker Hughes Company (US), Heatric (UK), Samad Power (UK), and Mitsubishi Heavy Industries (Japan).

Pumped Heat Electricity Storage (PHES). The market of this technology is in start-up phase, with some first pilots being enacted. Companies identified are:

- In the EU: MAN Energy Solutions (Germany).
- In the rest of the world: SynchroStor (UK), Echogen Power Systems and Malta (US).

4.2 Trade (Import/export) and trade balance

The data available is not enough to make an analysis about TES trade. In terms of materials used, like aluminium, stainless steel or copper, there is no exclusive data for TES technologies. When it comes to chemicals used as PCM, no codes have been identified for specific chemical species.

[68] Spain may host 2 GWh of liquid air storage – pv magazine International (pv-magazine.com)
[69] Highview Power unveils plan for first 500MWh liquid air storage project in Latin America - Energy Storage News (energy-storage.news)
[70] Offshore wind giant Ørsted turns to liquid air energy storage | RenewEconomy
[71] Energy Storage (phelas.com)
[72] Wien Energie and phelas sign partnership for Long Duration Energy Storage
[73] PRISMA | Liquid Air Battery Technology | Compresed Air Production (innovatium.co.uk)
[74] Aggregate Industries | Building A Sustainable Future
[75] Liquid Air Combined Cycle – Pintail Power

4.3 Resource efficiency and dependence in relation to EU competitiveness

There are currently no significant shortages associated with the materials used in TES. Various resources and materials can be employed in technology, contingent upon specific requirements. However, one material, aluminium, stands out as the preferred choice for its suitability in sensible, latent, and thermochemical TES facilities.

Aluminium is derived from bauxite, a mineral that the EU typically sources through imports. In the 2023 EU list of critical raw materials, aluminium is classified as one of the critical materials. This designation underscores the EU's acknowledgment of aluminium's vital significance across multiple sectors including TES. Aluminium has a supply risk of 1.2 on a scale of a maximum rating of 5.0, indicating a relative low level of supply risk (European Commission, 2023).

Furthermore, aluminium has an economic importance rating of almost 6, where tungsten is the critical raw material with the highest rating of almost 9, signifying the relative high economic importance of aluminium in the EU (European Commission, 2023). Guinea is the primary supplier of aluminium to the European Union, accounting for 62% of the EU's domestic aluminium production during the extraction phase, mainly through bauxite mining. Finally, EU imports 89% its aluminium (bauxite) from non-EU countries.

In applications of high-temperature TES, stainless steel is another essential material. Stainless steel is an alloy composed of various elements, with its constitution dependent on specific compositions. Key constituents within stainless steel include chromium and iron. Additionally, nickel holds a pivotal role as a critical raw material, as defined by the European Critical Raw Materials Act. (Carrara, et al., 2023).

In terms of supply risks, chromium, iron and nickel have 0.7, 0.5 and 0.5 respectively, indicating relative low levels of risks for the EU (European Commission, 2023) (Carrara, et al., 2023). The economic importance of these materials are rather high, with chromium, iron and nickel have 7.2, 7.0 and 5.7 respectively.

Russia stands as the primary source of nickel for the EU during the processing phase, contributing 29% of the supply. 55.5% of the chromium imports come from South Africa, while Australia accounts for 36.6% of the EU's iron supply. It's essential to note that the country where these materials are extracted doesn't necessarily align with the country where they undergo processing. (Carrara, et al., 2023).The IR of Chromium, Iron and Nickel is 7% (Extraction phase), 77% (Extraction phase) and 75% (Processing phase) respectively (European Commission, 2023). These results show also the importance of imports for these materials.

5 Conclusions

Thermal energy storage can make a significant contribution to achieving the European Union's climate goals. For a wide range of applications, established solutions are available. For example, water tank storage is the go-to solution for optimising heating efficiency & flexibility in district and individual heating. For solar power plants, molten salts have been on the market for several years, but they are still subject to research in an effort to mitigate degradation and corrosive effects and to achieve further reductions in cost.

In the industrial sector, novel markets are opening up, because of the increasing need to electrify industrial heating and increase waste heat recuperation. The ability to provide ancillary services by combining thermal storage with power-to-heat could further stimulate these markets, provided an efficient remuneration scheme is in place.

Mid-to-long-term storage is a market worthy of attention, through Compressed Air Energy Storage, Liquid Air Energy Storage and Pumped heat electricity storage, for example. These are all concepts in which thermal storage plays a central role through sector coupling.

Although an increasing number of start-ups is creating a thermal storage market, further research is required to develop next-generation storage with lower costs, higher energy density and seasonal storage, a task which novel thermo-chemical storage aims to tackle.

Novel thermal energy storage technologies are under continuous development and scientific research. For example, thermochemical thermal energy storage is still under validation. New technologies with more thermal energy storage density are being explored to maximise the level of energy stored. More research and investment is needed in order to increase the low TRL of novel technologies, and to make them cost-effective.

In terms of capacity installed, the main issue is the lack of data and the uncertainty around estimations. However, by using the data available and making some assumptions, an order of magnitude has been ascertained for each technology. For instance, data about concentrating solar-thermal power plants that use molten salts are shown in chapter 2.2, and an estimation is made of Europe's thermal energy storage capacity in domestic hot water tanks.

Data about costs is limited, and has been obtained from pilot projects and actual facilities. For that reason, it represents an order of magnitude and should not be generalised for all the facilities of the same technology.

Scientific research is led by China, with several contributions involving authors from Europe. Overall, European authors make a high proportion of contributions to scientific publications. However, more scientific study is required in order to bring the most novel technologies to market, at an affordable cost to the final user.

Public investment in novel TES technologies leads in terms of thermal energy storage technology funding. Latent thermal energy storage has received the most funding from Horizon Europe, with more than 20 EUR million in 2022. The US, Canada and UK lead in terms of private investment via venture capital. The contribution of Europe via Venture Capital is much lower than these three combined.

Technology markets have been analysed where data is available. However, the definition of each market is weak as there is considerable crossover, with technologies capable of being used either for the power grid or for the heating and cooling grid, supporting heating production or electricity production. Taking this into account, Europe leads the molten salts market, with a share of almost 80%. This market is predicted to increase by more than 700% in 2030. This is an indicator of the potential of novel TES technologies, whose efficiency is directly linked to the share of renewables. For example, for the market of molten salts, the storage of the thermal energy from the sun in concentrating solar-thermal power plants is crucial for producing electricity. Therefore, efforts are necessary to reduce the cost and increase the lifetime of molten salts to contribute to meeting the EU's energy targets for 2030 and 2050. Moreover, the integration of phase change material in several sectors could also be key in this regard. Phase change materials could be integrated into construction materials, modifying their thermal characteristics, and lowering the energy demand of new buildings. On the other hand, high-temperature phase change materials could help to store the heat from industry where, for example, it can be used as waste heat in district heating networks.

However, Thermal Energy Storage technologies are the key to matching thermal energy grids with power grids. Excess electricity could be stored in the form of heat by using solid media solutions or Compressed Air Energy Storage technologies, which is an indicator of the technology's potential.

Finally, Thermal Energy Storage technologies are a solution for the integration of renewable energy production and waste heat. Several issues have been identified with data availability, but the potential of these technologies is clear in terms of the levels of thermal energy that they can store.

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List of abbreviations and definitions

A-CAES	Adiabatic Compressed-Air Energy Storage
ATES	Aquifer Thermal Energy Storage
Austria	AT
Belgium	BE
BTES	Borehole Thermal Energy Storage
Bulgaria	BG
CAES	Compressed-Air Energy Storage
Croatia	HR
CSP	Concentrated Solar Power
Cyprus	CY
Czechia	CZ
Denmark	DK
ES	Energy Storage
Estonia	EE
ETES	Electro Thermal Energy Storage
Finland	FI
France	FR
Germany	DE
Greece	EL
HTPCM	High-Temperature Phase Change Material
Hungary	HU
Ireland	IE
IS	Ice Storage
Italy	IT
JRC	Joint Research Centre
kW	kilowatt
kWh	kilowatt-hour
LAES	Liquid Air Energy Storage
Latvia	LV
Lithuania	LT
LTES	Latent Thermal Energy Storage
LTPCM	Low-Temperature Phase-Change Material
Luxembourg	LU
Malta	MT
MSTES	Molten Salts Thermal Energy Storage
Netherlands	NL
PCM	Phase-Change Material
Poland	PL
Portugal	PT
RBRTES	Reversible-Based Reaction Energy Storage
Romania	RO
SBTES	Sorption-Based Thermal Energy Storage
Slovakia	SK
Slovenia	SI
Spain	ES

SMTES	Solid Media Thermal Energy Storage
STES	Sensible Thermal Energy Storage
Sweden	SE
SZTPCM	Sub-Zero Temperature PCMs
TCTES	Thermo-Chemical Thermal Energy Storage
TES	Thermal Energy Storage
TPTES	Tank-Pit Thermal Energy Storage
TTES	Tank Thermal Energy Storage
UK	United Kingdom

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Annex 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)*
	Installed capacity & energy production	*(IRENA, 2020), (Cabeza, Mehling, & Romaní, Installed Capacity of Thermal Energy Storage, 2022) & (European Commission, Directorate-General for Energy, Andrey, C., Barberi, P., Nuffel, L., 2020)*
	Technology costs	*(IRENA, 2020) & (Yang, Liu, Kramer, & Sun, 2021)*
	Public and private RD&I funding	*(IEA, 2023)*
	Patenting trends	*JRC own analysis*
	Scientific publication trends	*JRC own analysis*
Value chain analysis	*Turnover*	*No data available*
	Gross Value Added	*No data available*
	Environmental and socio-economic sustainability	*(Aridi & Yehya, 2022), (Possemiers, Huysmans, & Batelaan, 2014) & (Bonte M. , Stuyfzand, Berg, & Hijnen, 2011)*
	EU companies and roles	*JRC own analysis*
	Employment	*No data available*
	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*	*(IRENA, 2020)*
	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)	*(European Commission, 2023) & (Carrara, et al., 2023)*

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