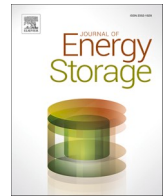




Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Research Papers

Innovation trends on high-temperature thermal energy storage to defossilize energy systems

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ARTICLE INFO

Keywords:

Innovation
Thermal energy storage (TES)
High temperature
Defossilization

ABSTRACT

The EU climate neutrality ambitious goals require breakthrough solutions and innovative products in many technological areas. The need of a transition to a more affordable energy system highlights the importance of new cost-competitive energy storage systems, including thermal energy storage (TES) for waste heat recovery, heating and cooling supply or for the increased flexibility of power systems via power to heat to power. This work focusses on technologically mature or close to market TES solutions, overviewing some of the most promising start-ups active in the sector of mid to high temperature TES for industrial heat applications or power to heat to power. It also discusses key elements to transfer these technologies to products available for market uptake. These key challenges include technical issues, such as control mechanisms, increased durability and stability of the employed materials, devices' reliability and fast dynamic performances to provide grid services or enable demand response; but also the development of new business models and novel approaches to produce revenues. Moreover, the review identifies as a key ingredient for the success in scaling up new TES products and manufacturing lines the capability to fast develop demonstration and first of a kind plants that can increase investors' trust.

Nomenclature

A-CAES	Adiabatic compressed air energy storage
BMS	Battery management system
CAES	Compressed air energy storage
CSP	Concentrating solar power
EIC	European Innovation Council
FOAK	First of a kind
IP	Intellectual property
HTF	Heat transfer fluid
HX	Heat exchanger
LAES	Liquid air energy storage
LDES	Long duration energy storage
MGA	Miscibility gap alloys
MS	Molten salts
PCM	Phase change material
RES	Renewable energy sources
SME	Small and medium enterprises
TES	Thermal energy storage
TPV	Thermophotovoltaic
TRL	Technology readiness level

1. Introduction

The Green Deal sets ambitious goals for the EU climate neutrality by 2050, pursued also by the FIT for 55 % package that increases the EU targets of renewable energy share by 2030 to 40 %, and by the Repower EU action [1] that specifically addresses the increase of energy prices, the dependence from fossil energy outside EU and the transition to a more affordable, secure, and clean energy system. The EU Strategy for Energy System Integration [2] proposes a vision to accelerate the transition toward a more integrated and clean energy system, in support of a climate-neutral economy. This approach addresses the planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures, and consumption sectors. It sets out several actions to implement the necessary reforms, including the promotion of energy storage technologies for sector coupling. The development of

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<https://doi.org/10.1016/j.est.2024.114261>

Received 31 March 2024; Received in revised form 5 August 2024; Accepted 15 October 2024

Available online 4 November 2024

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interconnected, sector coupled, and flexible energy systems is crucial to achieve these targets and to enable high penetration of intermittent renewable energy, so addressing the spatial and temporal mismatches between generation and demand. In this context, the possibility to (i) store thermal (heat and cold) and electrical energy at low cost, high density, high charging/discharging efficiency, long duration (from days to months, to better address the temporal mismatches demand/supply), and (ii) transport this energy in the form of energy carriers which are system integrated, safe and cost competitive is a key enabler for a fully decarbonized energy system. To reach these targets, it is crucial to develop a range of breakthrough solutions for thermal and electrical energy storage, that offer high round trip efficiencies and low cost in comparison to the state of the art, minimizing or avoiding the use of critical raw materials and capturing process and system integration opportunities. Energy storage can also enable smart demand response strategies and energy efficiency options, such as waste heat recovery or heating/cooling supply chain optimization for industrial, commercial, and residential sectors.

On one side, the industrial sector is a major emitter of CO₂ and greenhouse gasses, as shown in Fig. 1 (right) [3]. It is responsible for one quarter of the total final energy consumption in the EU, of which over 80 % is consumed by heating and cooling processes. The decarbonization of heating/cooling demand, in particular in the industrial sector and in the mid to high temperature range, represents one of the main challenges in the emission reduction targets [4] and sustainability development goals [5]. In particular, about 48 % of the overall energy demand is consumed as heat, and 22 % is consumed in the industrial sector [6]. 16 % of the global energy is consumed as medium to high temperature heat (at temperatures higher than 150 °C) within the industrial sector, as shown in Fig. 1 (left). The hard to abate industrial sectors are mostly responsible for such heat demand, and in particular metallic industries (iron and steel, machinery, and non-ferrous metals), chemical and petrochemical, construction and cement, pulp and paper [7]. Even in the current context of largely increasing renewable energy sources (RES) deployment, only 25 % of the global heat demand is derived from renewable sources. Thus, the global heat demand is responsible for about 26 % of the total CO₂ generation equivalent to about 14 Gton CO_{2eq} per year [8].

On the other side, the power system requires more and more daily or seasonal electricity storage to enable larger amounts of intermittent renewables to be injected into the grid, and this is particularly important in presence of not fully interconnected power systems, weak distribution and transmission networks, grid constraints, low rotating inertia of RES generators that cannot contribute to stabilize the network, limited capabilities to implement real time monitoring and control tools for optimal matching of generators and loads, or to implement demand response strategies to modulate end user demand in response to the

intermittency of the generation. While batteries and supercapacitors are well designed for very short to short duration storage, other solutions are needed to provide longer duration electricity storage, including power to heat to power solutions.

In this context, thermal energy storage (TES) technologies have the potential to be a key enabler of increased renewables penetration and industrial decarbonization. TES can decouple heating demand from the immediate thermal or electric power availability, resulting in higher system flexibility and greater reliance on intermittent renewable sources. Within the industrial context, the integration of TES units can provide a variety of services, among which: demand shifting by decoupling supply and demand and direct on-site integration of variable RES [9]; sector coupling by enabling an interlink between electricity and heating [10]; waste heat recovery [11]; and grid and network support by alleviating the strain on the electrical network and enhancing the grid flexibility and resilience [9]. TES deployment can play a major role directly toward a faster decarbonization and more rapid integration of renewables in the power sector. Indeed, TES units are also a key enabling technology and component for a variety of long duration energy storage (LDES) systems, such as adiabatic compressed air energy storages (A-CAES) [12,13] or liquid air energy storage (LAES) [14]. It has been shown that relevant installations of LDES within the power grid are and will be necessary to maximize the RES contribution at levels higher than 60–80 % without compromising the grid stability [9,15]. TES can assist in the decarbonization of industrial heating and cooling, and the full roll-out of industrial TES could enable a potential 1793 TWh of fossil fuel replacement by renewable energy and/or surplus heat, leading to a reduction of 513 Mt. CO₂ eq GHG emissions per year [16].

Today, different TES technologies and solutions are commercially available, close to market or under development. These can be divided into three main categories: sensible, latent, and thermochemical energy storage. Sensible TES stores thermal energy via a temperature change of the material, typical examples are water tanks, commonly used in low temperature residential applications, or molten salts tanks, typically used in concentrating solar power (CSP) plants. Sensible TESs are the most commercial solution, storing heat by simply changing the temperature of a material, and using as example water, thermal oil, rocks, sandstone, clay, brick, steel, concrete and molten salt. These TESs can cover a wide temperature range, with few limitations from a system integration perspective [17]. Latent TES units exploit the latent heat of storage materials and alter the phase of a substance. Latent TES is generally characterized by elevated specific energy densities, that can exceed 450 MJ/m³, leading to limited TES volume requirements. Typical materials employed include ice, paraffin, fatty acids, sugar alcohols, salt hydrates, inorganic salts, and metals. However, materials and TES design ensuring phase change containment are typically characterized by higher costs and lower technological development [18].

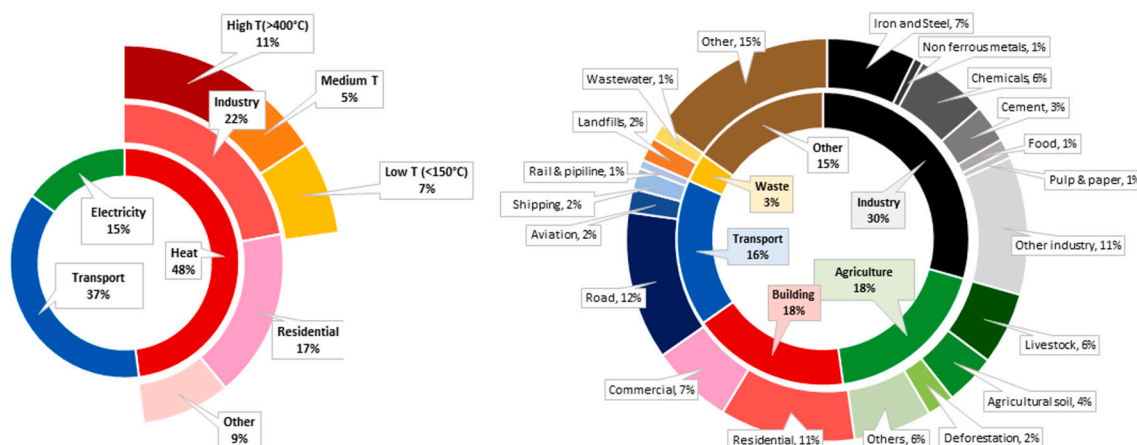


Fig. 1. (Left) Global energy consumption share; (right) Global CO₂ emission share by sector.

Thermochemical TES uses reversible endo and exothermic chemical reactions, such as sorption, chemical looping and salts hydration. Sorption TES is based on a reversible gas-solid reaction between a sorbate (gas) and a solid adsorbent or liquid absorbent, typically for temperature not higher than 200 °C [19]. The advantage of sorption TES is a very high volumetric energy density, up to 900–1300 MJ/m³ in the case of absorption, and long duration of storage with minimum losses since the charged material can be stored at room temperature. The chemical reaction TES is also based on reversible gas-solid reaction as for sorption, but the gas is now directly taken up in the crystal lattice of the solid, changing the crystal structure. These technologies present promising aspects particularly for seasonal energy storages since the storage can occur at almost ambient conditions (both temperature and pressure), thus limiting the incremental cost for larger capacity [20]. However, the technologies are still at a relatively low maturity stage and technology readiness level (TRL) and current elevated need for capital investment with long payback time might represent critical commercial barriers [21].

Previous review works include a broad overview of research activities on high temperature TES, with a specific focus on solutions suited for CSP applications [22], their operation in different specific case studies [23], and system integrations requirements [24], as well as the main aspects from a material perspective [25]. Different works addressed specific reviews on solid media based sensible TES units, such as packed beds and their design [26], specific materials development for this TES system [27], and their exploitation in the context of Carnot batteries [28,29]. Similarly, review works have been presented focusing on latent TES [30] and particularly phase change material (PCM) development [31]. However, there is a lack for comprehensive review works focused on commercially available solutions and close to market TES deployment, with the aim of highlighting the market strategies, innovation journeys, and added value of the most promising start-ups active in this sector, together with the most interesting researches focused on market creating innovations in the TES sector, and the specific policy and regulatory needs to enable their scaling up. This work aims at filling this gap whilst providing critical insights on the technological, market, regulatory and policy needs to mobilize transformational innovation in the field of mid to high temperature TES.

2. Deep tech innovation in energy storage and available support instruments

2.1. The motivation for mid- to long-duration energy storage

In future net zero electricity systems, energy storage will be required over a vast range of discharge times, from milliseconds to seasons, that cannot be provided by the same technologies. There are four main temporal intervals: (i) very-short duration storage (less than five minutes), handled best by flywheels, supercapacitors and possibly large inductors; (ii) short-duration storage (five minutes to four hours), dominated by electrochemical batteries and demand-side response actions; (iii) medium-duration storage (four to 200 h), where thermo-mechanical and hydroelectric solutions are the main options; (iv) long-duration storage (over 200 h), achieved mainly by storing energy carriers or biofuels, such as ammonia, hydrogen, biomethane or other synthetic fuels of biological or not biological origin.

Shorter duration energy storage technologies like lithium-ion batteries can handle much of the intra-day variation, like shifting midday solar power generation into the evening hours, while longer duration options are required for periods of low wind or sun that span many days. Furthermore, the increasing frequency of extreme weather events such as fires and strong storms are driving the need for the local, clean, affordable, and resilient backup power LDES systems can provide.

In the heating sector, characterized by demand seasonality of the residential demand, or batch processes of the industrial demand, the thermal storage with proper duration is a key technology to decouple

energy supply and demand, and accommodate their temporal mismatches.

A recent report from the Long Duration Energy Storage Council [32] describes how storage technologies, included in particular thermal ones, with storage duration from tens to hundreds of hours, represent a viable, cost efficient and ready solution for the decarbonization of the industrial sector, and are in some cases considered ‘an embarrassingly simple solution for industrial emissions reduction’, and technically capable to reduce these emissions by 65 %, if market and policy support is put in place.

At present, there is a range of existing mechanical, chemical, thermal, and electrical technologies for storing electrical energy adaptable from small to large scale applications, as reported in Fig. 2. Of all these technologies, only compressed air energy storage (CAES), pump hydro and chemical energy storage systems have enough commercial maturity and the ability to store energy for large scale applications over long periods of time. The first two suffer the limitation of site placement due to their geographic/geological requirements. Thus, chemical storage via hydrogen and/or derivatives (such as ammonia) and hydrocarbons offers a viable option for practical energy storage in the near term. Bearing in mind the need to reduce carbon emissions, only hydrogen and ammonia remain suitable candidates to drive the storage of large quantities of energy with flexible relocation of resources with a reduction on CO₂ emissions. Finally, movement and storage of hydrogen has proved to be more complex than for ammonia, for which a fully developed infrastructure has existed over a century, thus positioning ammonia as a strong candidate to support the concept of flexible energy storage at the largest scale [33].

However, energy storage via chemicals and energy carriers such as hydrogen and ammonia present limited round trips efficiencies, that barely can exceed 55–60 %, and appears the most promising solution for specific market segments such as aviation, maritime transport, or to substitute fossil based feedstocks in other supply chains beyond the heating/electricity demand, as in the case of fertilizers (ammonia) or biobased materials and chemicals (hydrogen combined to carbon capture ad valorization).

According to the US energy agency for innovation ARPA-E [35], the demand for energy storage and its longer duration fast accelerates at 60–70 % renewable electricity penetration. New forms of generation assets management, such as flexible inverters and dispatchable power technologies, would allow around 20 % penetration of annual energy from wind and solar in a large grid; new approaches for daily/weekly cycling, combined to grid reinforcements, highly interconnected power systems, and demand response strategies, would increase this penetration up to 60 %; and only with seasonal storage 100 % penetration would be possible.

2.2. Hands on and grant giving instruments to scale up innovations

As well known, translating technologies at first of a kind stage into market ready products and early stage research into prototypes is particularly challenging. Specific support instruments are needed to facilitate the innovation journey so to overcome the two major innovation death valleys of start ups: first from proof of concept to full operational prototype and then making the prototype a product ready to meet the market needs. Europe produces world-class early-stage research, but this rarely translates into innovative products that manage to establish themselves on the market [36]. This is due to many different reasons ranging from lack of entrepreneurial scientists' mindsets, to limited fundraising opportunities. The latter is contemporary due to European limited risk-propension of private investing entities and to the need of deeptech start-ups to get not only money, so-called grant-giving support, but additional content-wise mentoring-business acceleration services, so-called hands-on support [111]. To overcome this, the European Innovation Council (EIC) was launched in March 2021 as a major novelty under the Horizon Europe Programme, building on a pilot phase from 2018 to 2020. It has a budget of over €10 billion from 2021 to 2027

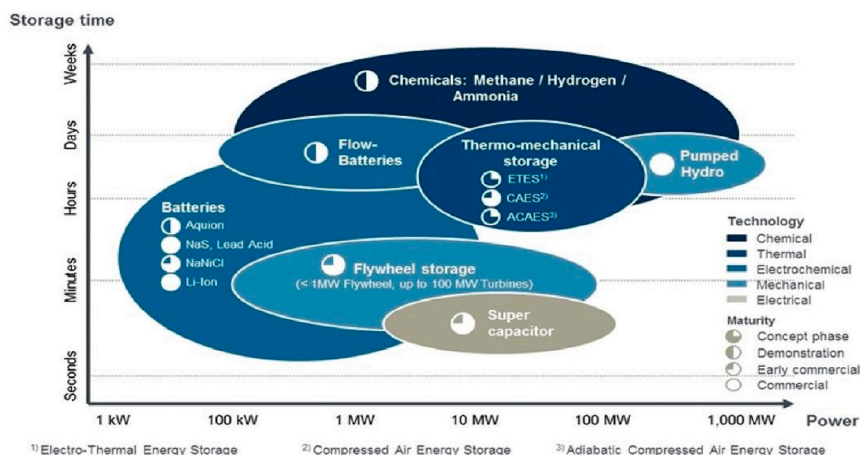


Fig. 2. Energy storage range of technologies for power systems [34].

to support game-changing deep-tech [37] innovations throughout their innovation journey from early-stage research to proof of concept, pilot plants, and the financing and scale-up of Small and Medium-sized Enterprises (SMEs).

The EIC operates through three funding schemes — pathfinder, transition, and accelerator – and calls which are either open, following a non-topic prescription, or challenge-based, following a top-down approach. One unique feature of the EIC is that, with the EIC accelerator instrument, it provides funding for individual SMEs through both grants and equity, via the EIC Fund, to derisk private investments and encourage crowd-in of other private or public investors to overcome the limited European investment risk-propension. One particularity of the EIC is as well its hands-on and content-wise approach, different from the “traditional” grants giving approach that provides money and monitoring activities, that is based on streamlining innovation through not only providing money but also the so-called content-wise external business acceleration services or via the EIC Programme Managers (PMs) actions. The EIC PMs compose and nurture portfolios of projects, sharing common topics/themes, know-how/technology, stakeholders, value chain or regulatory issues. The PMs implement the EIC portfolio hands-on approach to facilitate the innovation journey of beneficiaries by providing the necessary support to transform technologies into products, mainly at scientific-technological, marketing, business or regulatory level.

In 2022, the EIC launched the EIC Pathfinder Challenge call “Mid-to long-term and systems integrated energy storage”, which aims at developing a range of breakthrough solutions for thermal and electrical mid-long term and system integrated energy storage (MDLES), minimizing or avoiding the use of critical raw materials and capturing processes and system integration opportunities [38]. After the evaluation of the proposals, nine projects were selected based on their scientific excellence, socio-economic impact and quality of their implementation plan as well as considering a balance of complementarities and diversities among the proposals. The projects of the EIC MDLES portfolio include a broad range of technological areas to guarantee the diversification of energy storage technologies, optimize their systems integration, enable demand response strategies and capabilities to host higher penetration of intermittent renewable technologies. The overarching portfolio goal is hence to contribute to identify and accelerate the development of the most promising energy storage technologies to address the EU energy security, while contributing to other sustainability goals such as dispatchability of renewable electricity, demand side management sectors coupling, in agreement with the Repower EU and Green Deal targets. The portfolio activities will stimulate the collaboration among the projects and the networking with the innovation ecosystem to enhance the development of the EU technological

autonomy, targeting three main areas: technology, regulation and innovation (exploitation of research results or business development).

In addition, there is a layer of portfolio management and communication activities to facilitate the collaboration between the projects. The technological area is addressed by leveraging synergies between projects to speed up the technological progress, through knowledge sharing, research methodologies, multidisciplinary approaches and laboratory equipment. This dimension also includes the techno-economic and environmental comparison of the different technologies to produce high level policy feedback on the optimal routes from a system level perspective. The regulatory dimension is also particularly relevant, considering that most of the proposed solutions need public support and proper market mechanisms to be economically competitive, included capacity payments regulations and possibility to operate as prosumers (inject/withdraw energy from the grid and be remunerated for this) to reward storage assets. The standardization and certification aspects are also very important, such as the possibility to transport, store and handle heat at high temperature. The grouping of projects helps to streamline communication on their specific needs to catalyze and foster innovation, and to ensure their visibility in front of stakeholders, policymakers, regulatory and policy bodies. The creation of the portfolio is a step toward achieving the critical mass necessary to foster policy changes and to transform a technology into a market ready product. Finally, the projects work together to improve their exploitation strategies (how to develop a business out of it) and nurture entrepreneurial mindsets.

In the US, the Department of Energy (DOE) Advanced Research Projects Agency ARPA-E adopts an hands-on portfolio approach, that inspired EIC work programme approach, to support transformational research with specific challenges. ARPA-E is unique in its hiring practices and programmatic approach. Like DARPA, ARPA-E attracts talent from industry, the National Laboratories, and universities to serve as temporary program directors, so incentivizing a “move fast and break things” approach to innovation. In addition, ARPA-E's programs greatly differ from the traditional grant-giving programmatic approach in the applied and fundamental science programs. ARPA-E's programs are short, lasting only a few years, and they are highly responsive to technological innovation and market trends, which is highly conducive to innovation. ARPA-E offers open and challenge programs. Open programs solicit applications for any idea that has the potential to be transformational, while challenge programs address a specific energy challenge. ARPA-E has made significant investments also in energy storage. Similarly to EIC, but some years before, the Duration Addition to electricity Storage (DAYS) program addressed energy storage systems that could provide power to the grid for between 10 and 100 h, tackling a new set of applications like long-lasting backup power and the

integration of renewable resources on the grid. DAYS program, started in 2018, funded 11 projects to start ups and research centres, including high temperature thermal energy storage and solutions designed for coupling with flexible generation or industrial decarbonization [112].

Within Pillar II of Horizon EU, innovation in thermal energy storage is also supported by the Cluster 5 on climate, transport and energy, and in particular the destination 3, energy supply, sub-sector on energy systems, grid and storage, with a total budget of around 270 MEur in 2023–24, and focused on both research and innovation actions (RIA) and innovation actions (IA), and development of demo projects. Within Pillar I of Horizon EU, the ERC proof of concept supports the transfer of fundamental research funded by ERC early stage or advanced grants into lab scale proof of concept, and includes also projects on thermal storage. At higher TRL and outside Horizon EU, the Innovation Fund supports, with over 40 bEur total budget from the Emission Trading System (ETS) mechanism, demo plants and manufacturing facilities that contribute to limit CO₂ emissions, including energy storage, and can be a suitable tool for many innovative start ups that need to scale up their innovation. At European Member State level or at Regional level (ERDF), there are also many instruments that could support innovation in thermal storage, such as the long duration energy storage challenge launched by Sprin-D in 2023 [113].

2.3. The deep-tech innovation challenges

The development of cleantech technologies to market ready products is not a linear and standard journey: it may be very capital intensive, and affected by long commercialization times and regulatory barriers, but it is a mandatory pathway to achieve the climate goals, that cannot be addressed with the currently available technologies [39]. The deep-tech innovation journey frequently starts in a lab with the knowledge creation and then the technology development, from prototype to pilot, often tracked through the Technology Readiness level (TRL) [40]. There are many ways to exploit research results, including licensing and/or selling the intellectual property rights, but we will consider here the “venture creation” as exploitation strategy. The main challenges of a deep-tech venture can be summarized as follows:

- a) Techno-scientific: the technology development from lab to market requires the implementation of a design-build-test and learn approach [41].
- b) Team: establishing and growing venture requires the capability to identify and properly manage the right group of motivated, passionate and acknowledged talents.
- c) Business model: the overcome of the valley of death requires a business model that resonates with customers, with solutions tailored for their problems and better than competitors.
- d) Intellectual property management: the transformation of the knowledge in economic value requires the proper strategy to protect the venture intellectual property [42].
- e) Operations: an efficient but flexible operations plan is crucial to transfer a proof of concept to a prototype and then to the First of a kind (FOAK) product, addressing all the steps from permitting to building and operation, and proper management of supply chains.
- f) Navigating policy: public policies play a critical role because they can facilitate or even enable cleantech development, so it is necessary to understand the different categories of policies, regulatory frameworks and their synergic interactions.
- g) Ecosystem: an open innovation and ecosystemic approach is crucial to capture the complexity of the deep-tech innovation, engaging with key stakeholders and establishing strategic partnerships.
- h) Capital and timing: the right balance of financing options at the right time is crucial to quickly scale the venture [43].

There are different options of public and private funding, and each one has its timing mainly linked to the TRL phase. The public or

government funding is predominant at low TRL, where the technology risk is the highest, while the private venture funds will rather invest at pilot or demo phase. Most importantly, effective support to scale up a deep-tech venture is provided with “smart money”, where investors supply not only financial but also know-how resources [44]. As shown in Fig. 3, the critical fundraising phase of clean deep-tech is the FOAK (first of a kind) one, where it is more unlikely that investors are willing to intervene with their capital because it still includes the combination of high-risk and high-capital requirement so falling between company or equity growth and project finance. As shown in the examples of the next section, the cleantech ventures able to attract different investors to run the FOAK phase have a clear competitive advantage over the competitors and are almost ready for scaling up. If FOAK is successful and venture bridge to NOAK (ninth of a kind) phase then there will be typical de-risked investors such as large banks or infrastructure funds that will mainly look not at company growth but at delivered and operated projects given for granted that the technology always work.

Other studies highlight the importance of innovation in the industries with fast-developing technologies. Prieto et al. [40] showed that knowledge generation is needed but it is not enough. In particular, its transfer to the industry is essential for successful development of new products, and this is demonstrated through a case study on the development of TES systems for CSP plants. Similar conclusions have been shown in biotechnology, information and communication technology, and other high-tech sectors [46,47]. The need of the internalization of the created knowledge by the industry was also highlighted by Lim for the semiconductor and pharmaceutical industries [48].

Recent studies highlight that identifying priorities for a research and innovation agenda, a so-called targeted or challenge-based approach, enables sustainable transitions implementation [49]. A portfolio of promising interdisciplinary research and innovation targets and the stakeholder engagement facilitate multilateral communication among disciplines and institutions and the mutual exchange of perspectives, ideas, and knowledge to build future scenarios [50].

3. Thermal energy storage commercial solutions

Over the last years several start-ups have been established to propose TES solutions for industrial heat decarbonization or power grid flexibility. Such companies differ not only in terms of targeted market segments but also on the technical characteristics of their products. Table 1 overviews some of the most promising companies in mid to high temperature TES and their core technology. The following sections describe their technical solutions, market strategies, business models and some of the main techno-scientific challenges to be addressed.

3.1. Sensible solid based thermal energy storage

Sensible solid based TES are among the most mature technologies, and several companies propose similar solutions. Sensible TES technologies store heat by changing the temperature of the TES media. In this case, wide temperature differences between charge and discharge operation are important to maximize the TES energy capacity. Similarly, high density and high specific heat capacity are important characteristics for the selected TES media. Elevated thermal conductivity is required to ensure good heat transfer between the charging unit or heat transfer fluid (HTF) and the storage media. However, high thermal conductivity also causes temperature distribution and thermocline degradation during idle, which negatively affects the performance of the TES. To address this limitation, usually oversizing of the TES unit is considered, both in terms of energy capacity and maximum storing temperature. This approach might lead to higher discharge temperatures during the first phase of the discharge process, which need to be compensated by mixing, steam spraying or flashing to attain the required constant heat discharge temperature. These methods can ensure reliable operation at the expense of lowered round-trip efficiency

FOAK is the first step to *Scale*

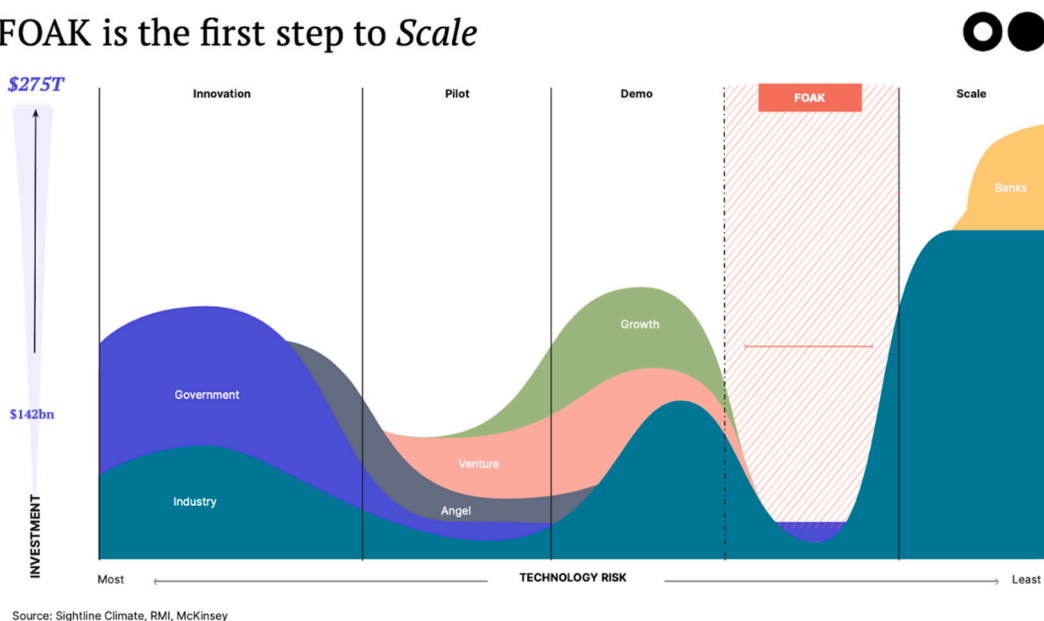


Fig. 3. FOAK is the first step to scale-up innovations [45].

and increased system complexity and capital costs. Thus, further technological improvements are needed to enhance the TES control and its system integration while guaranteeing elevated efficiency. Further advances are also required on the TES material with an even higher focus on lowering the environmental impact, also via potential waste upcycling, and cost reduction.

The next paragraphs describe the main characteristics of the TES units from each of the listed companies. The section describes companies that focus both on medium-high temperature heat provision and on the power to heat to power sector to provide grid flexibility.

3.1.1. EnergyNest

EnergyNest [51] focuses on industrial heat decarbonization, specifically targeting industrial process heat and -steam. The TES is a modular containerized solution of about 2 MWh in a typical module, which is the size of a 20 feet container. On the basis of the industrial demand, several TES modules can be combined and stacked to create a TES system of any capacity (from MWh to to GWh). The core technology of the company is in the solid material, HEATCRETE®, a purposely developed high temperature concrete with high thermal capacity and thermal conductivity ensuring relevant heat transfer and energy densities, and high resistance under thermal stress. Each module is filled with several thermal elements with HEATCRETE® and embedded steel pipes for the HTF to flow and transfer heat to and from the TES media. The industrial TES unit installed at YARA International is shown in Fig. 4. The storage unit design is highly modular and simple, which ensures fast installation and limited maintenance needs avoiding major moving components. The simplicity of the system positively affects the cost and environmental impact of the TES unit manufacturing, which is primarily composed of concrete, steel and high temperature insulation. The TES unit does not include direct charging elements; therefore, the charging energy is supplied by the thermal oil which is heated by electricity, CSP/T or from waste heat. By integrating with customer application and individual processes on site, the system discharges energy on demand to the heat consumer (heat exchanger or thermal grid).

EnergyNest developed an initial pilot installation (1 MWh) at Masdar Institute Solar Platform (MISP) in Abu Dhabi, UAE in 2015. Post-operation analysis verified that there was no significant degradation of material or impact on infrastructure integrity [52], and encouraged further technology development and most importantly provided

investors trust, so that after a few years the company raised over 100 M€ funding from private and public investors, including the European Commission with the EIC accelerator instrument. A second installation is a 4 MWh TES directly connecting to the steam grid at the YARA International chemical manufacturing production facility at Porsgrunn in Norway [53], as shown in Fig. 4. The main purpose of this installation is to reduce dumping of excess steam by storing the energy and releasing it during short duration cyclic peak demand to the low-pressure steam grid. High pressure steam is condensed inside the TES heat exchanger pipes and later stored in the adjacent pressure vessel. During charging, the pressure and temperature in the TES modules and in the adjacent condensate pressure vessel increases. The TES is considered fully charged when the condensate vessel is full. During discharge, the flow direction is reverted, and the steam is produced within the TES modules (heat exchanger pipes) as the condensate evaporates and is fed to the low-pressure steam grid. To ensure a proper control of the steam delivery, steam is also produced, according to the specifications imposed by the battery management system (BMS), by flashing of the condensate vessel. The two steam lines are mixed before entering the main steam line and satisfying the user requirements. Additionally, the same embedded heat exchanger pipes are exploited during charge and discharge, which intrinsically leads to the fact that the unit cannot be operated in simultaneous charge and discharge.

EnergyNest has also recently commissioned a new installation in Avery Dennison Performance Tapes in Belgium where the TES is used to increase energy efficiency and provide flexibility to a concentrating solar thermal (CST) installation supplying heat to the industrial facility by a thermal oil heat exchanger. In this installation excess thermal energy from the CST platform (hot HTF) flows through the TES modules from top to bottom, heating up the storage material. During discharge the flow of HTF is reversed; cold heat transfer fluid (HTF) from the heat exchanger in the industrial facility flows in at the bottom of the TES and exits hot, supplying energy back to the industrial process. This plant shows the flexibility of this TES to be integrated with different fluids and different charging mechanisms.

3.1.2. Brenmiller

Brenmiller provides a patented high-temperature thermal energy storage unit, bGen™, whose main parts are shown in the cut-outs and details summarized by Fig. 5 (right) [54]. Crushed rocks are the main

Table 1
Classification and technical description of TES commercial solutions.

Company	TES technology	TRL	Max TES Temp [°C]	Storage media	Charge	Discharge	Markets	Country
Energynest	Sensible solid	8–9	400 °C	HEATCRETE®, cement	HTF in form of thermal oil or steam	HTF in form of thermal oil or steam	Industrial heat	Norway
Brenmiller	Sensible solid	8–9	750 °C	Crushed rocks	Heat recovery and electricity	Inner steam generation	Industrial heat	Israel
Kraftblock	Sensible solid	7–8	1300 °C	Ceramic pellets and bricks	Hot air	Hot air	Industrial heat	Germany
Rondo Energy	Sensible solid	7–8	1500 °C	Refractory bricks	Hot air	Hot air	Industrial heat	USA
Storworks power	Sensible solid	7–8	600 °C	Concrete	Hot air	Inner steam generation	Industrial heat	
Ecotech ceram	Sensible solid	6–7	1500 °C	Waste ceramic	Hot air	Hot air	Industrial heat	France
Caldera	Sensible solid	6–7	500 °C	Volcanic rocks	Electricity	Inner steam generation	Industrial heat	UK
Lumenion	Sensible solid	7–8	600 °C	Steel Bars	Electricity	Hot air	Industrial heat	Germany
Magaldi Power	Sensible solid	6–7	600 °C	Silica Sand	Electricity and hot air/steam	Inner steam generation	Industrial heat	Italy
Polar Energy Night	Sensible solid	6–7	1000 °C	Sand	Hot air	Steam	Industrial heat	Finland
Electrified Thermal Solutions	Sensible solid	5	1800 °C	Joule Hive™, bricks	Electricity	Gaseous	Industrial heat	USA
Echogen	Sensible solid	5–6	600 °C	Sand	Heat pump	Transcritical CO ₂ power cycle	Electricity, grid stability	USA
EnergyDome	Sensible solid	7–8	600 °C	Aluminum scrap	Heat pump	CO ₂ power cycle	Electricity, Grid stability	Italy
HighView power	Sensible solid	7–8	600 °C	–	Air liquefaction	Air Brayton cycle	Electricity, Grid stability	UK
Antora Energy	Sensible solid	5–6	2000 °C	Carbon	Electricity	TPV	Electricity, Industrial heat	USA
Fourth Power	Sensible solid	5–6	2400 °C	Graphite	Electricity	TPV	Electricity	UK
Kyoto Group	Sensible liquid	8–9	420 °C	Ternary molten salts	Electricity	External steam generator	Industrial heat	Norway
Hyme Energy	Sensible liquid	7–8	700 °C	NaOH	Electricity	External steam generator	Electricity	Denmark
Malta Inc	Sensible liquid	7–8	580 °C	Binary molten salts	Air heat pump	Air Brayton cycle	Electricity	USA
Built to zero	Sensible liquid	6	400 °C	Ternary molten salts	Electricity	External steam generator	Industrial heat	Spain
	Latent	4–5	600 °C	PCMs cascade	Electricity	External steam generator		
PUSH-CCC	Sensible liquid	4	730 °C	Carbonate and nitrate molten salts	A-CAES	A-CAES	Electricity	EIC pathfinder
1414	Latent	6–7	1200 °C	MGA	Hot air	Hot air	Industrial heat	Australia
MGA Thermal	Latent	6–7	1200 °C	MGA	Electricity	Hot air	Industrial heat	Australia
Thermophoton	Latent	4–5	1000 °C	Eutectic iron-silicon boron alloy	Electricity	TPV, hot air	Electricity, Industrial heat	Spain
M-TES	Latent	4	200 °C	Al-Sn based MGA	–	–	–	EIC pathfinder
SaltX	Thermochemical	5–6	500 °C	Calcium oxide	Steam	Steam	Electricity, Industrial heat	Sweden
RedoxBlox	Thermochemical	4–5	1500 °C	Magnesium manganese oxide	Electricity	Hot air	Industrial heat	ARPA-e project
MUSPELL	Thermochemical	4–5	400 °C	–	–	–	–	EIC pathfinder

TES media, storing up to 750 °C. The TES can be charged both thermally via embedded HTF heat exchanger pipes and electrically thanks to embedded resistive electric heaters. Such arrangement provides increased flexibility to the TES unit and decouples charge and discharge operation, also thanks to different pipes used between charge and discharge. Thus, charge and discharge can also occur simultaneously when convenient. It should be noted that when electrically driven charging is used, depending on the state of charge of the TES, the charging might occur only at reduced power. For example, when the state of charge of the TES is about 50 %, the electric heaters embedded in approximately half of the TES are surrounded by hot material; thus, these elements cannot be used for charging to avoid local overheating.

The main business cases targeted by Brenmiller are industrial heat decarbonization via power-to-heat and waste heat recovery, as well as TES integration into thermal power plants for enhanced flexibility. Brenmiller has a few running projects, among which: a demonstration unit of 1 MWh installed in Anápolis, Brazil at Fortlev integrated with a biomass plant, a 2.5 MUSD TES unit installed for New York Power Authority at SUNY Purchase College, and partially financed by the

Binational Industrial Research and Development Foundation (BIRD Energy Program) [55], a 24 MWh unit installed in Santa Barbara, Italy at one of Enel Group CHP plants, shown in Fig. 5 (left). The latter offers an interesting use case and it can provide relevant ground for further TES deployment as it demonstrates the feasibility of TES exploitation to maximize the flexibility of traditional power plant, minimize start up times, and improve responsiveness to load variation, which are all key requirements in a context with largely increasing non-flexible renewable power generation.

3.1.3. Kraftblock

Kraftblock [56] provides a solid media-based TES with maximum storage temperature up to 1300 °C, so opening wider industrial markets such as metals, glass, and ceramics production facilities. The main technological innovation of the company relies on the developed high temperature storage material in the form of purposely produced pellets or bricks, with high heat capacity and thermal conductivity. The TES unit is in the form of a horizontal flow packed bed with the HTF, primarily air, flowing through the granulated TES material and releasing or

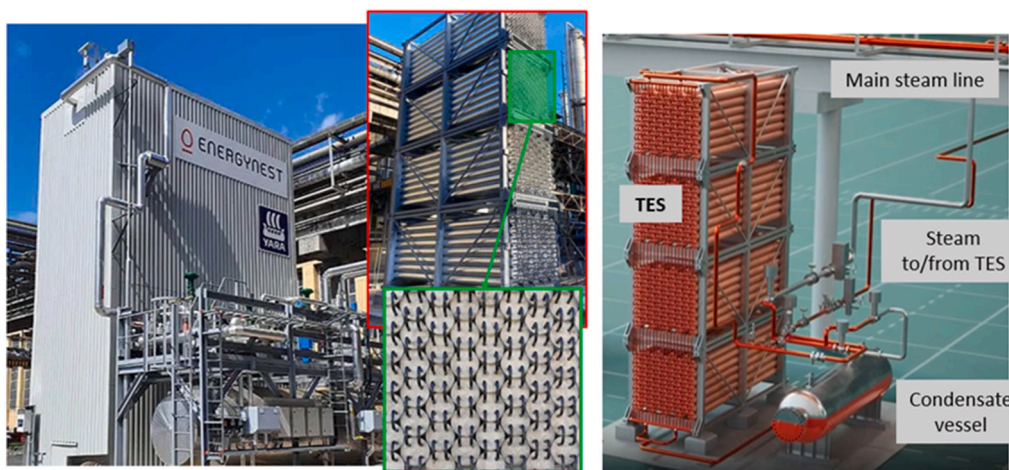


Fig. 4. Overview of the Energynest TES system including its main components and system integration [51], (left) photographs of the Energynest installation at YARA International (including details on the full TES unit before insulation and the single TES block with embedded pipes), (right) CAD illustrating the main operation of the Energynest installation at YARA International.

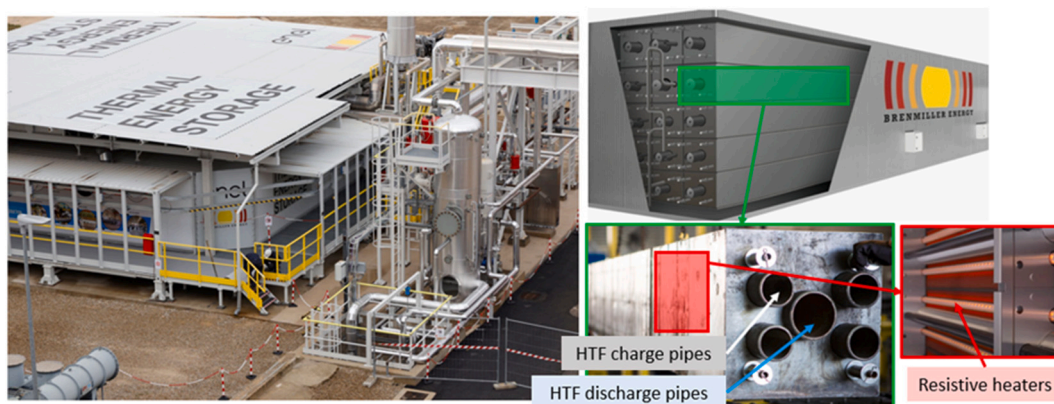


Fig. 5. Overview of the Brenmiller TES system: (left) installation in Santa Barbara Enel Group CHP plant, (right) cut out of the TES unit, single module with embedded pipes, CAD showing the inside of the module with embedded heaters [54].

absorbing heat from it. The TES unit does not include a direct electricity driven charging mechanism. Charging and discharging equipment is part of the turnkey solutions but outside of the storage to lower maintenance demand for this equipment. The high maximum temperature and thermal properties of the TES material provide high energy capacity (around 1.2 MWh/m^3). The use of cheap and recycled (up to 85 %) starting materials coupled with the simplicity of the system also ensures low capital cost and reduced environmental footprint. In some cases, the pressure drop faced by the HTF can represent an issue when packed bed TES with gaseous HTF flowing through the granular material is adopted. In addition, operational costs and auxiliary power consumption associated with fans or blowers may represent a relevant share of the total costs.

The main business cases pursued by Kraftblock are high temperature waste heat recovery, power to heat for industrial decarbonization, and transport of heat from places where it is discharged (flare gas in refineries, excess heat of cogeneration plants, etc.) to the heat demand, so spatially decoupling demand and supply. This can be achieved transporting the hot pellets with trucks, bypassing the needs for expensive and often infeasible heat distribution networks. However, regulatory aspects should be addressed in order to transport materials at very high temperatures, and proper insulation materials should be adopted to limit heat losses. Mobile heat storage is a strategy pursued also by other companies, such as Enetech in Poland [57], that adopts instead a phase change material (PCM) technology at constant delivered heat, and

addressing transport distances up to 30 km. Despite the advantages to decouple spatially demand and supply, the environmental impact of road transportation should be accounted for, and this option might be relevant for specific applications with low distance ranges, intermittent heat demand and/or supply and high temporal mismatch between those. These are, in fact, cases when piping might not be suited. Other types of more sustainable transportation such as ships or trains, require a much larger infrastructure which might likely not be available at the industrial site or its premises. Additionally, unless very high temperature waste heat is recovered and later transported, low grade waste heat is more likely to be techno-economically exploited for district heating network applications [58,59]. Kraftblock has been awarded an EIC accelerator grant with blended finance in 2021. They closed a €20 million investment round with Shell Ventures, Finindus, Tech Energy Ventures, Future Industry Ventures, Moore Strategic Ventures and A&G in 2023.

3.1.4. Rondo Energy

Rondo Energy focuses on power to heat and industrial decarbonization [60]. The TES unit commercialized by Rondo Energy is based on refractory bricks, with a shape optimized to maximize heat transfer area but no specifically patented solution, as shown in Fig. 6. The TES material can store heat up to $1500 \text{ }^\circ\text{C}$. The charging occurs through electric heating elements embedded within the TES bricks that can heat the TES primarily via radiative heating. During charge no air flow is needed, however limited flows might be introduced to improve heat transfer and



Fig. 6. Photograph of the refractory bricks manufactured and used as Rondo Energy TES media [60].

thermal distribution. During discharge air is blown through the brick holes and it can be heated up to 1000 °C. An AI based control system manages the air flow to ensure the desired heat delivery and temperatures. The hot air can be delivered directly to the industrial site or exploited in a steam generator to deliver superheated steam. In the latter case the outlet air is returned to the TES to limit the overall thermal losses and maximize the round-trip efficiency. As in the case of Kraftblock, this technology has the potential to be cheap and allow exploitation of largely available and non-critical material with a reliable and fully developed production and procurement chain. As previously mentioned, depending on the state of charge of the TES, the charging and discharging power can be decoupled, incurring in higher discharge power if needed.

Over the summer 2023, Rondo Energy raised 60 MUSD from investors including Breakthrough Energy Ventures, Energy Impact Partners, SCG, TITAN, Rio Tinto, Microsoft, Aramco, and Energy Impact Partners [61]. Such a round of investment came just a few months after the announcement of planning of a large-scale manufacturing plant with an annual production capacity of 90 GWh [62]. This plan is quite different from the strategy followed by other market competitors, which are rather building partnerships with equipment suppliers to operate as an assembler of the main components. However, the issue of production capacity is crucial for most of the start-ups active in this sector, where market demand is expected to increase fast, to fulfill the energy transition targets. The amount of investment needed to scale up the production processes, and achieve the consequent costs reduction and economies of scale, can be a limiting factor, in particular for EU start-ups that may face difficulties in raising equity in the EU innovation ecosystem. An interesting approach, followed by Rondo Energy but also by other competitors such as EnergyDome or Kyoto Group (presented in the Sections 3.1.13 and 3.2.1, respectively) is to involve strategic

investors that can reduce technological, operational and market risk, such as suppliers of key components or potential end users. In all cases, Rondo Energy, together with EnergyNest, EnergyDome, and some other key players listed in this overview, demonstrate strong capabilities to raise important investment rounds pursuing the 3-S golden rule of deep tech start-ups: *Simplicity* in their technology, *Speed* in the capability to develop a first of a kind (FOAK) product to convince the market, and *Scale* to convincingly address the market needs and create further markets.

3.1.5. Storworks power

Storworks power [63] proposes high temperature TES solutions relying on a proprietary concrete mixture based on fly ash which demonstrates good thermal cyclic resistance up to 600 °C. The concrete is used as the base TES media in the BolderBlocs, in which air or steam pipes are also embedded to guarantee heat transfer, as shown in Fig. 7 (right). Similarly to EnergyNest, the unit relies on non-hazardous material and simple installation limiting the potential impact at the industrial site. Unlike EnergyNest, the TES units are not directly containerized. Instead, the single concrete blocks are stacked (up to structural stability) and later enclosed by a common insulation and structure. This approach facilitates modularity, but it might present complexity of maintenance, particularly in case of major breaks. Additionally, the proposed TES system does not directly include a specific charging unit, which can be adapted on the basis of the specific application, such as for solar thermal systems.

Storworks has recently constructed a 10 MWh demonstration installation at Southern Company's Gaston coal-fired generating plant, a photograph of which is shown in Fig. 7 (left).

3.1.6. Eco-Tech Ceram

Eco-Tech Ceram [64] developed a solid media-based TES, the Eco-Stock®, which can store heat in the range 300 °C to 1500 °C. Similarly to previous solutions, the TES system is modular with a typical energy capacity per module of 2.5 MWh, and it is able to provide heat at scale between 200 kW to 3 MW, if operated at high temperatures it presents footprint around 140 kWh/m². The TES unit relies on recycled ceramics as the main TES media, and it does not include a predefined charging unit. This could limit the specific applicability of the TES and might require more site-specific engineering work.

In October 2023, Eco-Tech Ceram inaugurated an R&D demonstration unit in the Villeroy & Boch plant in Valence d'Agen, France, as part of a Horizon 2020 project (EcoStock, GA 879608) [65], aiming at demonstrating a cost-effective waste heat recovery and utilization within the ceramic industry. A photograph of the pilot installation is shown in Fig. 8.

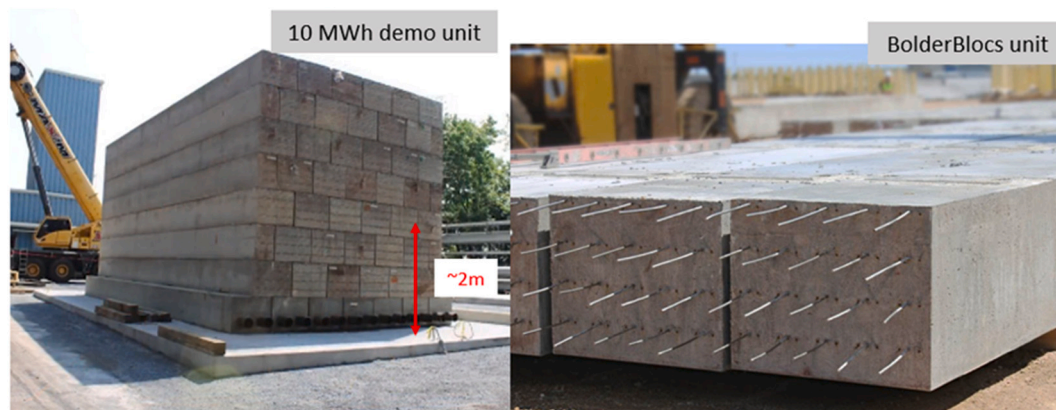


Fig. 7. Storworks concrete TES technology: (left) 10 MWh demonstration installation at Southern Company's Gaston coal-fired generating plant, (right) BolderBlocs units [63].

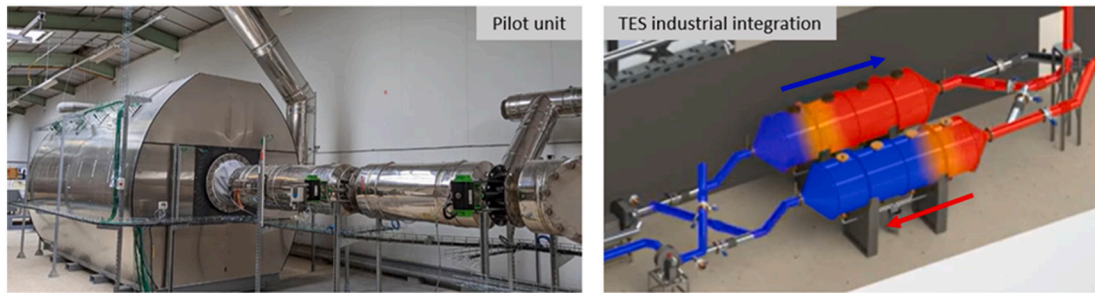


Fig. 8. (Left) Photograph of the Eco-Tech Ceram pilot installation and (right) schematics of the TES installation and its continuous working principle [64].

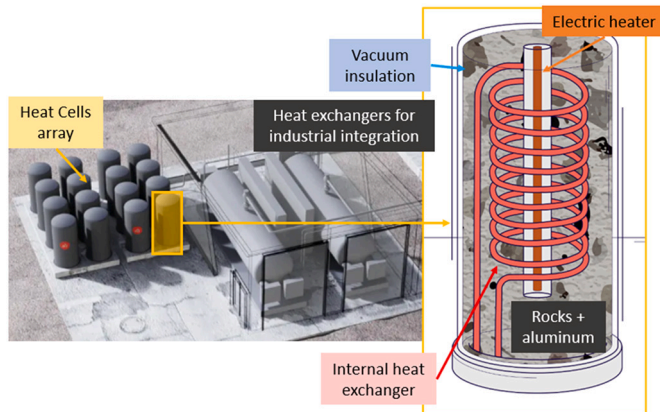


Fig. 9. (Left) Overview of the Caldera system highlighting the main components and (right) specific CAD of the main Heat Cell unit [66].

3.1.7. Caldera

Caldera is a UK company, founded in 2018, focusing on medium temperature industrial heat decarbonization [66]. The TES solution, named Heat Cell and whose main components are sketched in the CAD presented in Fig. 9, is a highly modular unit relying on simple manufacturing and mass production. The TES media, Caldera proprietary composite, is composed by a solid core of volcanic rocks, which ensures elevated availability at low cost, and aluminum, which provides enhanced thermal conductivity. Additionally, the mixing of rock and aluminum can be reversed by melting aluminum at the end of life offering potential for recyclability. The unit is charged via an embedded electric heating unit up to a maximum of 500 °C. Each Heat Cell is

enclosed in a double-walled vessel ensuring a vacuum tight insulation, which provides low thermal losses and avoids the needs for traditional insulation. During discharge, water flows through the embedded heat exchanger pipes and it is flashed into steam and transferred via a closed loop to an external heat exchanger where steam up to 10 bar and 200 °C is produced. A full TES module is made of 10 Heat Cell and it can store up to 2 MWh, while multiple modules can be stacked to increase capacity.

Caldera has been primarily supported by UK funding sources such as the Department for Energy Security & Net Zero Industrial Fuel Switching Competition and UKRI Sustainable Innovation Fund, in order to build a full-scale, industrial-size demonstrator in Southampton, which is planned to be operational by 2025.

3.1.8. Lumenion Green Energy 24/7

Lumenion is a German company founded in 2015 with the main goal of decarbonizing industrial heat in the temperature range 120–450 °C [67]. Lumenion proposes a steel and air-based TES system relying on the thermocline principle. An overview CAD of the Lumenion TES unit is shown in Fig. 10. The Lumenion storage includes carbon steel rods which are arranged within the TES to maximize the heat transfer area and energy capacity. Depending on the specific sizing, a number of rods is aligned, and a number of electric heater units is embedded within the main TES module. To charge the TES, the electric heaters are exploited to provide high temperature heat which is transferred to the steel rods via radiative and convective heat thanks to the main air flow circulated by the fan at ambient pressure. The TES is fully charged once the steel reaches its maximum temperature of 650 °C. To discharge the unit, air is circulated, still at ambient pressure, through the TES and to the outer steam generator where industrial steam is generated. The TES design is inherently modular and provides energy capacity in the range between 2

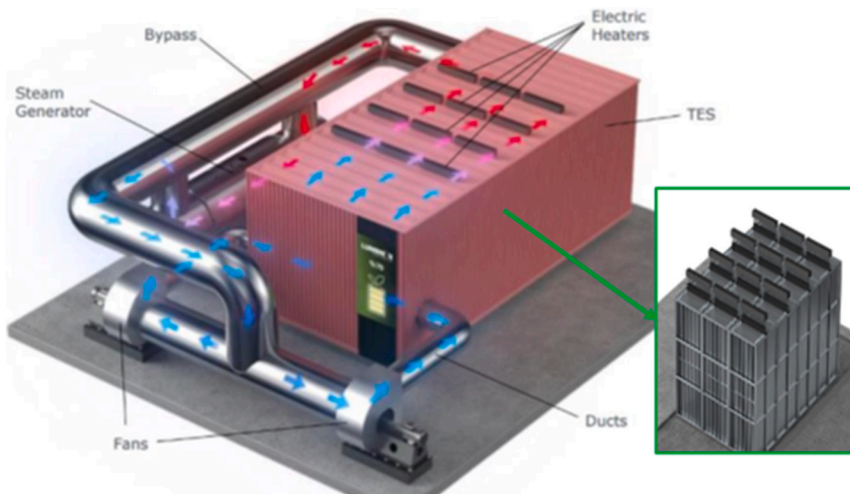


Fig. 10. CAD of Lumenion overall TES unit and its main components (steel bars and embedded electric heater) [67].

and 1000 MWh. Considering the primary use of commercially available and environmentally friendly materials which can also be recycled at the end of life, the environmental impact as well as the need for critical or strategic input materials are limited. However, this solution faces similar challenges as other thermocline-based TES. Particularly, during charge operation the power demand is dependent on the state of charge of the TES and similarly during discharge phase no constant temperature can be ensured. Also not negligible auxiliary consumptions for the fans are expected which might limit the applicability of the solution and particularly its upscaling.

Lumenion is currently building a 20 MWh unit in Friedrichsgabekoog in Schleswig Holstein, Germany, at the premises of a production site of organic frozen vegetable producer BIO-Frost Westhof GmbH. The unit will feature a 5 MW electric charging capacity and will provide up to 4 ton/h of saturated steam at 17 bar.

3.1.9. Magaldi Power

Magaldi Power developed the Magaldi Thermal Energy Storage [68], which is a sensible solid media TES based on a fluidized sand bed technology. The main TES media is silica sand which is heated up to 600 °C via an array of electrical resistors or an integrated heat exchanger, both immersed in a fluidized bed of sand, maintained thanks to a proper setting of the fluidization gas velocity. The Magaldi fluidized bed reactor and the TES concept are reported in Fig. 11. Higher operating temperatures contribute to reducing the minimum fluidization gas velocity and consequently the associated costs [69] and efficiency losses. The fluidization of sand particles increases the heat transfer, maximizing the efficiency of the system and its dynamic response to fast charging/discharging. Additionally, fluidization leads to homogeneous temperatures within the bulk of sand material during operation and it limits the requirement for elevated thermal conductivity and simplifies the control. In the discharging process, hot air or superheated steam are produced via an embedded heat exchanger. The developed TES unit has an energy footprint of about 400 kWh/m², competitive against alternative technologies which are typically in the range 200–300 kWh/m². Scalability is typically a limitation for fluidized beds since tall sand beds would cause extremely high pressure drop and fluidization auxiliary power requirements. Thus, the system can be scaled up by stacking more units either in a parallel connection (for maximum delivery temperatures up to 400 °C) or in a serial configuration (for maximum delivery temperatures up to 600 °C).

In March 2023, Magaldi started the construction of a 13 MWh MGTES unit, in collaboration with Enel X, at the food production plant of IGI, in Buccino, Italy [70].

3.1.10. Polar Night Energy

Polar Night Energy [71] is a Finnish start-up who proposes a sand-

based TES unit primarily dedicated to heat decarbonization. The sand can store energy in a maximum temperature range between 600 °C to 1000 °C. The TES is charged primarily through electricity input, when it is available at low cost, an external electric heater heats an HTF which circulates in a closed loop embedded in the sand pile. During discharge, the same HTF loop is connected with an external heat exchanger which can then deliver heat in the form of hot water, steam or hot air up to 400 °C. A photograph of the pilot installation and a CAD summarizing the main components are shown Fig. 12. Considering the specific system configuration, charge and discharge operation cannot occur simultaneously, and their power range needs to be about the same to avoid major off-design operation of the main components during either charge or discharge.

3.1.11. Electrified Thermal Solutions

Electrified Thermal Solutions [72] is a spin-off from Massachusetts Institute of Technology developing a TES unit, named Joule Hive™, based on proprietary electrically and thermally conductive bricks. This thermal energy storage system can provide heat for industrial applications up to 1800 °C and attain round trip efficiencies of about 95 %.

The Joule Hive TES is composed of a stack of electrically conductive firebricks in an insulated steel container and an electrical balance of plant. During charging, electricity runs directly through the bricks and heats them by Joule effect up to 1800 °C. During discharge, a gaseous HTF flows through the bricks' channels removing heat from the bricks. Thus, the main difference in comparison to alternative brick solutions such as Rondo, is represented by the charging mechanism. The Joule Hive TES electric bricks are arranged and stacked in a pattern with traditional firebricks enabling fast charging and more uniform temperature distribution. Each Joule Hive is a containerized unit, and several containers could be stacked at the industrial site to provide the needed capacity. As highlighted before, refractory brick-based TES solutions can leverage on a fully developed main material production and supply chain with elevated affordability. However, in this specific case, the manufacturing of electrically conductive bricks might rise additional challenges.

3.1.12. Echogen

Echogen [73] is a US company providing a pumped TES based on transcritical CO₂ cycles and targeting power grid flexibility applications. During charging, a set of CO₂ turbomachinery is used in a heat pump cycle gathering low grade heat from a cold TES, upgrading it to higher temperature, and transferring it to a high temperature TES. During discharge, the loop is operated reversely and high-grade heat is used to heat up the CO₂ which then evolves in a Brayton cycle producing power and finally cools down the cold TES. The integrated system is primarily aimed at power generation, however high temperature heat and cooling

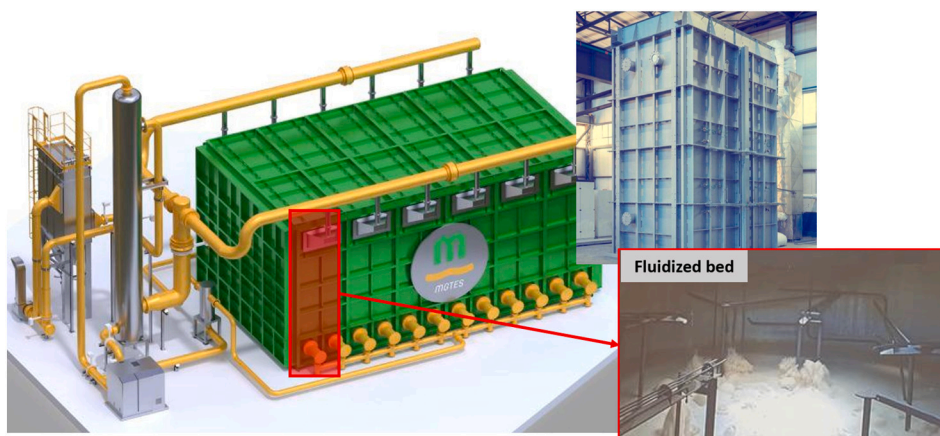


Fig. 11. CAD of the Magaldi Power TES unit, photograph of the pilot installation [68] and photograph of the fluidization within the sand bed.

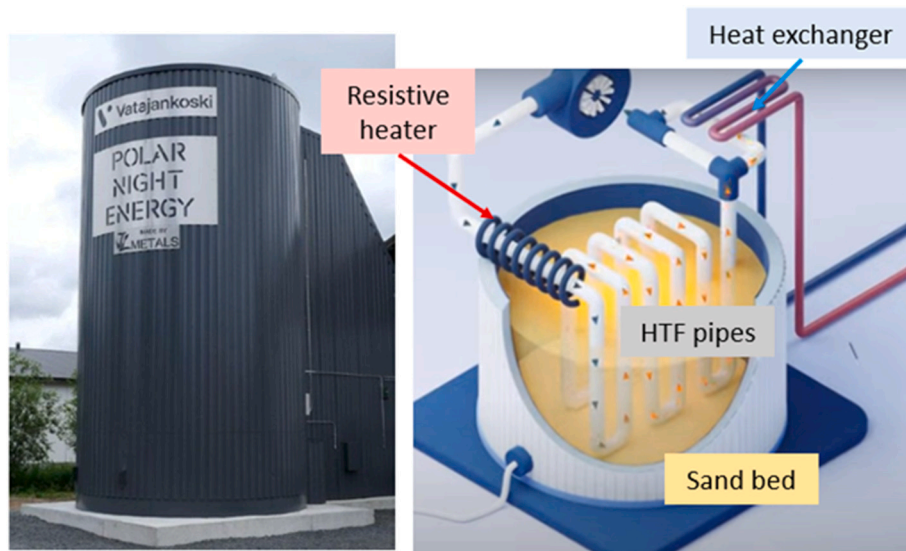


Fig. 12. (Left) Photograph of the Polar Night Energy demonstration unit and (right) schematic drawing of the system including its main components [69].

could be also considered as potential products and services offered, and a TES is needed to operate the system.

The proposed system relies on sand-based TES on the hot side. According to the latest public information from Echogen, the hot TES is made by a fluidized bed of sand in which the main heat exchanger pipes for the CO₂ are embedded. Fluidization air is used to maximize the heat transfer and homogenize temperature within the TES. Fluidization is used only during operation, and to limit the associated auxiliary consumption the TES is extended primarily horizontally, limiting the height of the bed that needs to be fluidized. Scaled up configuration foreseen silos for hot particle storage and fluidized bed heat exchangers between sand and CO₂. The cold TES is instead based on a water/ice bath with an embedded heat exchanger. The choice of a sensible TES media for the high temperature TES and a PCM based cold TES aligns with the cycle requirements. Particularly, on the hot side during both charge and discharge the CO₂ requires large temperature differences; while on the cold side CO₂ evaporates during charge and condensate during discharge, both processes occurring at isothermal conditions.

The exploitation of a heat pump during charge operation offers higher efficiencies than resistive electric heaters, and the expected round trip efficiency of the full system is around 60 %. However, it should be noted that CO₂ power cycles are not yet fully commercial, and few demonstration sites have recently been commissioned or are under construction. Similarly, the use of CO₂ in different heat pumps applications among which large scale district heating units as well as high temperature systems is a wide topic of R&D. This type of technology is also known as Carnot Battery, or pumped heat storage, or pumped thermal electricity storage. Among the others, the IEA Energy Storage TCP Task 36 [74] classified the different technologies and applications for Carnot Batteries, including the various TES adopted, and critical assessed the technology competitiveness and research challenges, policy

feedback and regulatory amendments needed.

3.1.13. Energy Dome

Energy Dome [75] is a rapidly growing company from Italy which proposes an innovative long-duration energy storage (LDES) solution, with a sweet spot between 8 and 24 h of storage duration, for power grid decarbonization. The technology integrates CO₂ based turbomachinery, high temperature TES, and other storage units (dome and vessels for liquefied CO₂), as described in Fig. 13. This makes such technology more integrated than the previous one and possibly more complex. However, the exploitation of CO₂ Brayton cycles can ensure several advantages over competitive LDES relying on commercial steam Rankine cycles, among which higher thermodynamic efficiency, compactness and responsiveness. CO₂ is operated in a closed thermodynamic transformation between its gaseous and liquid phase. During charge, CO₂ is compressed, cooled down firstly by passing in a sensible TES (a packed bed TES made of steel scraps), which recovers the thermal energy produced by the compression for later use, and later the CO₂ is further cooled to ambient temperature by a water based heat exchanger (HX) and finally stored at ambient temperature in its liquid phase. During discharge, the CO₂ warms up by passing through the TES and exploiting the previously recovered thermal energy, evaporates, and expands, turning a turbine to generate electricity, finally CO₂ is stored at ambient pressure in a dedicated dome. The full technology is patented and uses only water, steel, and CO₂. The liquid CO₂ is stored at ambient temperature limiting the costs and auxiliaries consumption, thus making this technology less expensive than compressed or liquid air energy storage. This specific technology is targeting grid stabilization ensuring a large variety of services; however, the TES is an integral and fundamental part of it without which the target round trip efficiency of 75 % would be difficult to achieve. Considering the specific requirements of

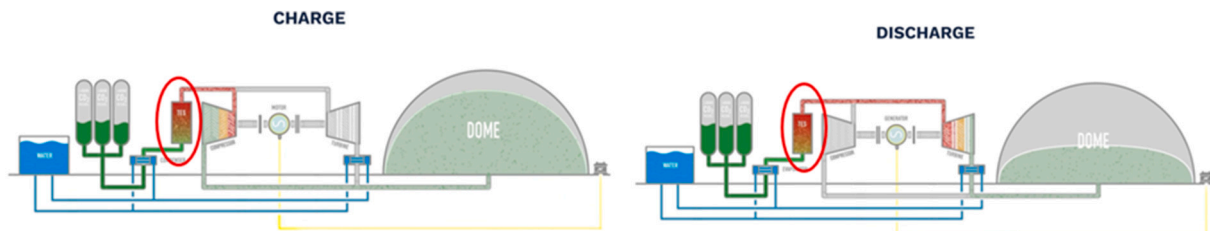


Fig. 13. Energy Dome technology overview during charge (left) and discharge (right) operation [75].

this technology, a sensible TES where a large temperature differential can be allocated efficiently seems the most relevant choice. Steel scrap as a filling material in a packed bed configuration might not represent the best solution since the elevated thermal conductivity might affect the thermocline stability. However, if the CO₂ is contained within pipes running through the material (which might be a relevant solution considering the elevated pressure of the CO₂ at the TES), the elevated thermal conductivity is a specific need that justifies the steel scrap. This technology can offer time and load shifting, physical inertia, frequency primary, secondary and tertiary reserve thanks to the inertia of the turbomachinery units.

During the first half of 2022 Energy Dome built its FOAK project, a 2.5 MW - 4MWh plant in Sardinia, Italy. This FOAK successfully convinced investors and contributed to de-risking the technology and entering the main commercial phase. At the end of 2022, Energy Dome has been awarded 17.5 M€ by the EIC via the Accelerator program. Over the spring and summer 2023, Energy Dome closed a set of Series B financing rounds totaling about 55 M€. The main investors included: Eni Next, Neva SGR, Japan Energy Fund, Barclays' Sustainable Impact Capital, CDP Venture Capital, 360 Capital, Novum Capital Partners, Gruppo Brixia and Elemental Excelerator, Innovation Development Oman Investments, and Vopak Ventures. By the end of 2023, Energy Dome also received a project-level grant commitment of up to 35 M€ from Breakthrough Energy Catalyst and up to 25 M€ from the European Investment Bank. This capital will be used to complete Energy Dome's 20 MW, 200MWh CO₂ Battery™ project under development in Ottana, Sardinia, Italy (planned operation by the end of 2024).

3.1.14. Highview Power

Highview Power [76] is a UK company delivering LAES for grid flexibility applications. As for Echogen and Energy Dome, the TES unit is not the main product, but it represents a key instrumental component to ensure relevant performance to the full system.

The full system is composed of a charging unit powering an industrial liquefier to produce liquid air during off-peak periods, vessels for liquid air at cryogenic temperatures and low pressure; and a power recovery unit where the liquid air is pumped to high pressure, gasified, heated, and expanded in a gas turbine to produce power [77]. Hot and cold TES are added to increase the round-trip efficiency of the system. The cold TES is charged during the power production and the gas expansion, and the stored cold energy is used in the liquefaction process to increase its efficiency. Similarly, the hot TES stores the heat generated during air compression. A schematic CAD of the system in which the main sub-components of the system are highlighted is shown in Fig. 14.

Highview Power established a demonstration site at the Pilsworth Landfill facility in Manchester, which is now in operation since 2021 demonstrating balancing services capabilities such as the short-term

operating reserve supporting the grid during winter peaks. The project was developed together with Viridor, a recycling and renewable energy company and partially financed by the UK government by 8 M€. Currently, a 50 MW/300 MWh plant is under construction at Trafford Energy Park near Manchester. The next projects will be still located in the UK and each will be 200 MW/2.5 GWh capacity primarily aiming at providing flexibility to the planned massive increase of wind installation within the country. Similar projects are also under establishment in Australia.

3.1.15. Antora Energy

Antora Energy [78] main target is providing modular TES as grid flexibility assets and power to heat to power solutions. The TES is a sensible solid media, U-shaped graphite blocks, with electric heater included in the main cavity which heats up the media via thermal radiation up to 2000 °C. The heat to power transformation is also based on radiative heat transfer from the TES block to a thermophotovoltaic unit (TPV). High temperature process heat could also be provided if the heat to power unit is removed for a purposely designed heat exchanger.

The very high temperatures targeted by the TES impose challenges and limitations from a material and insulation perspective. The TES material must guarantee elevated thermal conductivity, heat capacity and thermal stability. TPV are becoming more and more commercial solutions, however their operation at high temperature still needs further R&D effort and demonstration [79]. In the case of direct production of process heat, further challenges arise from the design of the heat exchanger, which needs to be based on radiative heat from the TES blocks. The control and BMS represent fields for further development. Particularly, the thermal radiative process within the TES and between the TES and the TPV surface is complex to control and might require physical obstructions and purposely designed optics to modify the view factor, which would also negatively affect the overall performance and increase costs. Alternatively, the control needs to act downstream of the TES unit also lowering the round-trip efficiency of the unit.

The company has recently launched its first commercial-scale system with a pilot project installation at their facility in Fresno, California. The current plan is to move toward full commercial scale and market sales by 2025. Their innovation journey started from a first 8 MUSD grant from ARPA-E within the DAYS program in 2018, followed by a 14.5 M USD from the ARPA-E SCALEUP program in 2024, with the aim to unlock commercial-scale manufacturing for the Antora heat to power technology. The start up has raised a total of \$230 million in funding from Decarbonization Partners, Breakthrough Energy Ventures, Lowercarbon Capital, and other investors.

3.1.16. Fourth Power

Fourth Power [80] also relies on the power to heat to power

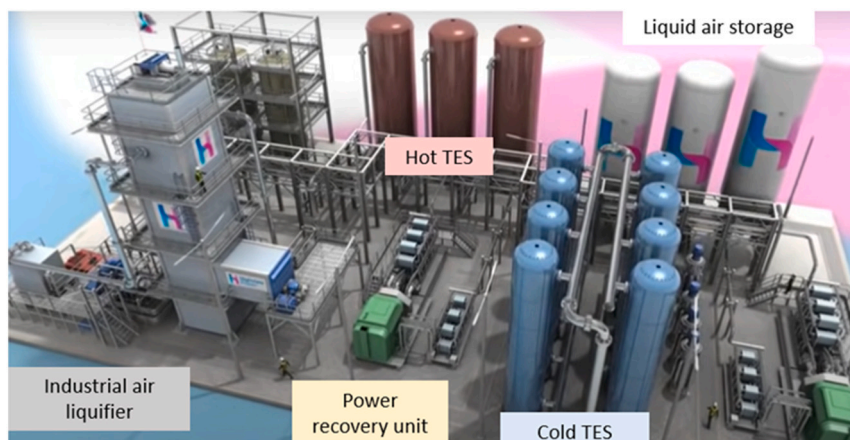


Fig. 14. Overview of Highview Power energy storage system and main subcomponents [76].

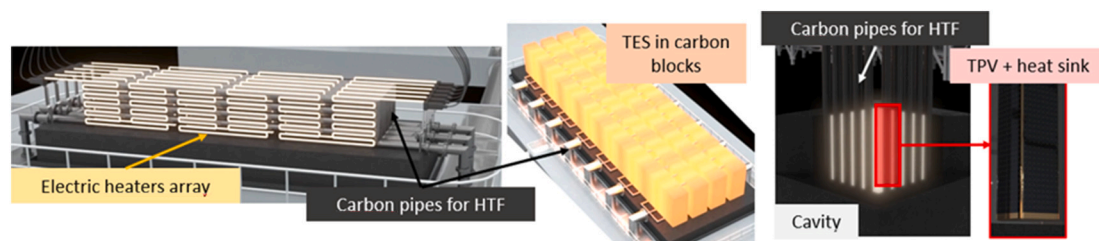


Fig. 15. Overview of the main components (CAD drawings) of the solution developed by Fourth Power [80].

approach and focuses primarily on flexibility solutions for the grid aiming at costs in the range 10–20 USD/kWh and 0.5 USD/W. The main elements of the full system are shown in Fig. 15. The unit is charged via embedded electric heaters which glow at about 2500 °C and by thermal radiation transfer the heat to a set of carbon piping in which tin is used as HTF. The tin is heated from about 1900 °C to 2400 °C. The tin is circulated to the main TES block which is composed of graphite blocks with embedded pipes for the HTF to flow through and release heat to the carbon. The carbon blocks are enclosed in an Argon filled atmosphere to avoid oxidation. In discharge, tin is circulated in the embedded pipes and extract heat from the carbon blocks. The power is generated via purposely designed TPV based units. Each unit is a cavity, formed by an array of carbon pipes carrying the liquid metal, filled with intense light. The TPV cells are installed within the cavity on a water-based heat sink to reduce their operating temperature to almost ambient, mirrors on the back of the TPV also ensure that the light that passes through the TPV is circulated back to the hot region and further exploited for power production. The TPV can be moved out from the cavity rapidly by actuators thus ensuring a fast response time. The water from the hot sink is cooled in an air-cooling unit.

Fourth Power, founded in 2022, is backed by Breakthrough Energy Ventures and has recently raised a 19 MUSD Serie A to scale up their solution. The current plan is to build a 1 MWh pilot at MIT Bates Lab aiming for its full commissioning within the next two years.

3.2. Sensible liquid media based thermal energy storage

Sensible liquid TES are among the most commercial technologies, leveraging the experience and supply chain development from the CSP industry in which massive TES tanks filled with molten salts (MS) are commonly used. In sensible liquid-based TES, energy is stored in the increase or decrease of temperature of the media which is always kept in its liquid form. The wide deployment at large scale of molten salts TES units in CSP plants provides to this technology a competitive advantage in terms of market confidence with respect to solid media-based solutions. However, it should be highlighted that molten salts-based TES suffer from some drawbacks. Solar salts, traditionally used in CSP plants, have an elevated freezing temperature (around 258 °C) and relatively low maximum operating temperature up to about 580 °C [83]. This limits the operating range for the unit and imposes relevant heat tracing and anti-freezing solutions on the cold side. Typical molten salts also present relevant corrosiveness, which implies the use of specific piping and tanks material. Additionally, in different CSP plants the hot MS tank has been the cause of major maintenance. Indeed, the hot tank is subjected to elevated thermal deformation and stresses at the walls and bottom due to the natural interaction with the salts. Finally, the main components used to produce solar salts are a major commodity commonly used as fertilizers, which might raise future social and environmental issues and demand for a considerate exploitation of them. The different companies currently proposing molten salts based systems are all trying to address some or all of the above challenges exploiting different salts mixtures, downscaling the TES units which also enables increased modularity whilst reducing the impact of thermomechanical stresses.

The next paragraphs describe the main characteristics of the sensible liquid media based TES units provided by the companies identified in this work.

3.2.1. Kyoto Group

Kyoto Group [84,85] focuses on medium temperature industrial heat decarbonization and power to heat applications, exploiting a liquid media based sensible TES. Specifically, ternary YARA MOST [86] salts (a ternary mixture based on potassium-nitrate (KNO₃), sodium-nitrate (NaNO₃), and calcium nitrate (Ca(NO₃)₂), with a mass ratio of 43 wt %, 15 wt% and 42 wt%, respectively) are used up to 415 °C. The salts are stored in dedicated tanks of >8 MWh, connected to provide the required capacity (between 16 and 120 MWh). The system is charged via a molten salts electric heater, which is also in a modular arrangement with charging capacity in the range 10–30 MW. The discharge occurs by flowing the hot molten salts into a molten salts-based steam generator, where steam is produced in the temperature range 170–400 °C at a discharge capacity up to 20 MW. This storage technology offers a footprint of about 250 kWh/m², comparable with the previously listed solid media-based solutions. The operability and control of this type of TES technology is simpler than for solid media-based TES. Indeed, most of the control can be based on adjusting the salts flow rate. To operate the full system, the modular TES arrangement demands the installation of an additional TES tank beside the main required TES capacity for the industrial user. The TES tanks are always either at the minimum or maximum MS working temperature and the TES state of charge is determined by the salt level in the different tanks. At full charge, all TES units except one are full of hot MS, the additional tank is fully empty. In discharge operation the hot MS are drained from one of the TES units (the coldest one to prevent further thermal losses), sent to the steam generator and then stored cold in the initially empty tank. Once all the MS are drained from the starting hot tank, this will become the ‘new’ empty tank and discharge can process modifying the valves arrangement such that hot MS are collected from a new tank. Similarly, during charge the cold MS is pumped from one TES tank through the electric heating unit and back to the initially empty tank.

Kyoto Group inaugurated in August 2023 their first demonstration project and commercial contract for Heatcube thermal battery solution under a battery leasing (BaaS) arrangement with Aalborg Forsyning in Denmark [87]. The installed TES has a capacity of 18 MWh, provided by about 150 tons of molten salts. The installation also has a charging capacity of 5 MW and a discharging capacity of 4 MW, the produced steam is fed to the local district heating network. Fig. 16 (left) shows the pilot installation including its main components. The installation has provided ground for validating the full unit, has well as its possible participation in fast frequency downward regulation market attaining activation time of the electric heater to start consuming 5 MW below 90 s. Currently, Kyoto Group is moving forward with a set of commercial projects at KALL Ingredients Kft an Hungarian food processing factory, whose commissioning is planned by the end of 2024, and at Klingele a German paper and packaging manufacturing plant. Fig. 16 (right) shows the rendering of the commercial unit.

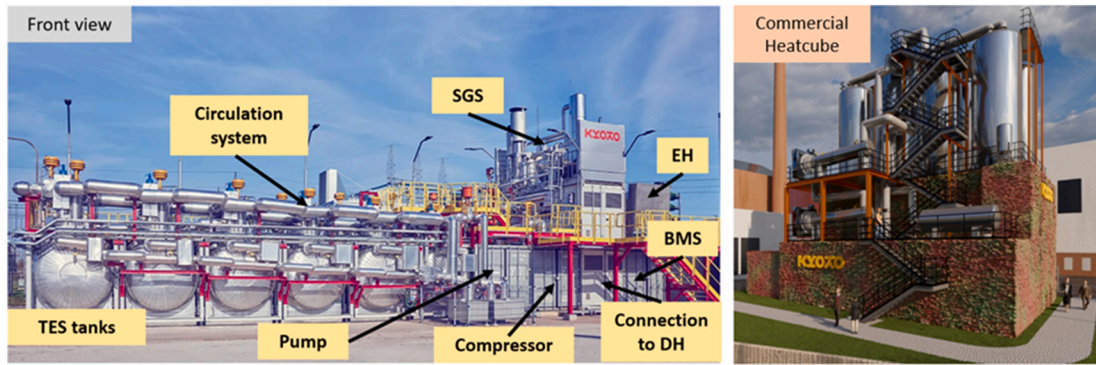


Fig. 16. (Left) Photograph of the KYOTO's installation at Norbis park, including its main components and (right) rendering of the commercial unit under construction in Hungary at Kall plant [84].

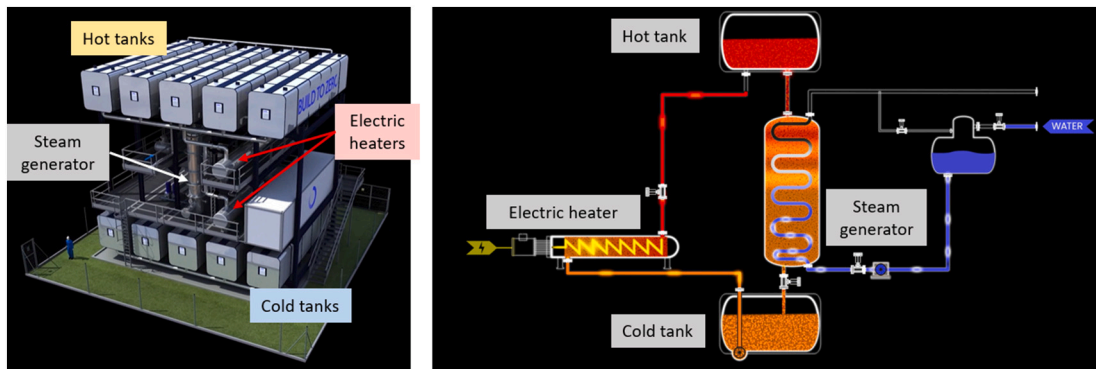


Fig. 17. (Left) Rendering providing an overview of Build to Zero ThermalBox® with main components, (right) simplified schematics of the ThermalBox® system and operation [93].

3.2.2. Built to zero – sensible solution

Build to zero is a Spanish start up [93] focusing on decarbonization of industrial processes via a molten salts based thermal energy storage

and power to heat solution, Thermalbox. The ThermalBox system is shown as a rendering, also highlighting its main components, in Fig. 17. The unit features an in line electric tubular heater heating molten salts

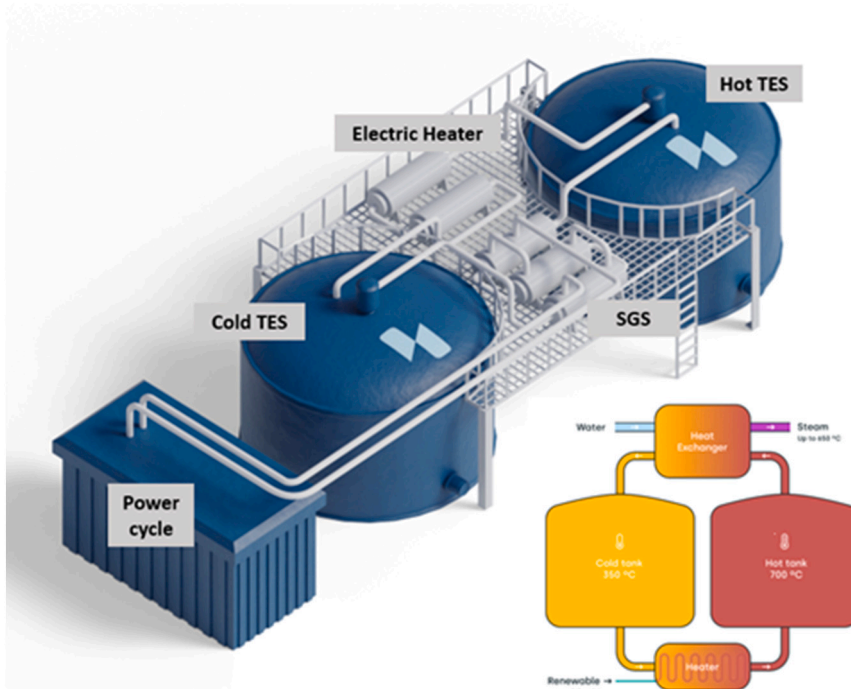


Fig. 18. Overview of the Hyme Energy TES system and its main subcomponents [88].

from 180 °C up to 400 °C. The hot salts are stored in the top tanks whilst the cold salts are stored in the bottom tanks. The system relies on gravity during the discharge operation. The hot salts flow from the top to the bottom tanks via a vertical once through steam generator for low to mid pressure superheated steam. The system is modular, and the storage capacity can be increased by adding tanks (both cold and hot) when needed. The first project from Build to Zero is expected to have comparable footprint to the other sensible technologies presented around 150 kWh/m². The ThermalBox® is designed for 4 to 12 h of storage capacity, it can operate flexibly intraday with no limitations on charge or discharge cycles. The gravity-based operation can provide relevant advantages avoiding the need for expensive hot salts pumps and potentially simplifying the piping system, while still relying on control valves for load adjustment. From a structural perspective, the support structure to keep the hot tanks above the other components might be a challenging unit requiring very robust solutions with potential large impact on the final costs.

Build to Zero has been awarded in June 2024 an EIC accelerator grant with blended finance.

3.2.3. Hyme Energy

Hyme Energy [88] is a spinoff, established in 2021, of the nuclear technology company Seaborg Technologies [89]. The main idea was to exploit the extensive research on molten salts for nuclear reactors which led to new insights on sodium hydroxide chemistry and its potential use as TES media.

Hyme Energy is deploying a LDES solution mostly aimed at providing electricity and balancing services for the grid by storing heat in high temperature molten sodium hydroxide based two tanks arrangement. The tanks can operate in the temperature range 200–350 °C and 600–700 °C for the cold and hot unit respectively, depending on the specific sodium hydroxide salt based mixture used. The Hyme Energy system is sketched in the CAD in Fig. 18. The choice of this salt provides elevated heat capacity and high stability at high temperature (up to 700 °C), as well as almost no supply limitation but it also shows high corrosiveness toward typical steel. Thus, the main challenge and IP of the company relies on the specific corrosion control system. Hyme Energy is not pursuing modular TES units but rather large scale two-tanks installations thus simplifying control, reducing piping, and focusing on larger scale installations. The charging is provided by an independent electric heater, while the discharge is provided via a molten salts-based steam generator which fed a typical steam cycle. The coupling with a steam cycle represents a benefit for the company since steam cycles are well-known in the industry and widely deployed with established supply chain. However, steam cycles, due to their economy of scale, limit the scalability of the unit which requires large installation to attain cost-competitive performance. This limitation might be crucial at the initial commercialization stages since elevated CAPEX and limited bankability might hinder the commercial applications. Also, steam cycles partially limit the flexibility and responsiveness of the unit in terms of ramping and load control, though they can provide spinning reserve and grid ancillary services. Thus, further development can be foreseen in coupling of this TES unit with different power cycles. Such pathways might largely improve the perspective of this type of technology.

The first installations from Hyme Energy are under constructions, as they received funding from the EU (Horizon Europe 2LIPP project [90] and recently EIC accelerator blended finance) and the Danish energy Agency. Hyme Energy is building and will commission in the first half of 2024 a pilot and proof of concept facility (1 MWh) in Semco Maritime facilities in Esbjerg, bringing the solution to TRL6 but still lacking full functionality and lifetime optimization. Hyme Energy will then build a 10–20 MWh demonstration storage plant to partially replace a fossil-based boiler in Bornholm, with a planned start of operation in 2026. The storage plant will be installed within the existing power plant and integrated into its operations. The demonstration unit will serve to validate all components and control system and will supply power, high

temperature steam as well as ancillary services contributing to the flexibility of the CHP plant. Hyme Energy has also recently received funding from the EIC Accelerator program to support the construction of this demonstration unit.

3.2.4. Malta Inc.

Malta Inc. [91] is a US company with legal entities established both in Germany and Spain. Malta value proposition is similar to Hyme Energy providing long duration energy storage for grid balancing, load shifting and renewable stabilization. Malta technology included two TES units at high and low temperature, an air Brayton based heat pump unit for charging of the system and an air Brayton based power cycle for discharging, as from Fig. 19. The hot side TES is made of typical binary solar molten salts two tanks unit, operating between 580 °C and 280 °C, while the cold TES is based on water glycol. Malta core development is represented by the charging unit, a turbomachinery-based heat pump. However, the storage is instrumental for the full system to ensure its operation and critical for its control. The larger the temperature differential that the two TES units provide, the higher the overall efficiency attained by the power cycles, which overcompensates for the decrease in performance for the heat pump. Besides the TES units, to ensure overall cost-competitiveness and elevated efficiency, the development of purposely suited heat exchangers is crucial. To this aim, Malta together with DLR, Alfa Laval and Siemens Energy have recently received funding from the German Government for the development and testing of advanced HX units [92]. This development is deemed not only for Malta purposes but also for the potential integration of additional heat streams and a more comprehensive heat integration in other TES solutions (particularly the ones deploying molten salts). It should be noted that the TES and HX are fundamental components of this technology; but the turbomachinery units have represented key challenges over the last years. In particular, the initial technology proposed by Malta was relying on reversible turbomachinery operating with CO₂. Their development has never reached a fully commercial stage and today still puts several risks which led the company opting for decoupled charge and discharge turbomachinery trays operating air. Such a choice causes higher installation costs and system complexity; however, it guarantees a more reliable operation, which is crucial at an early commercial stage. Thus, future development will likely look also at the turbomachinery units aiming at attaining the original system concept.

Over the last years, Malta Inc. has collaborated with the Southwest Research Institute (SWRI), USA, in building and commissioning a first pilot facility to validate their technology [114]. In 2022, Malta Iberia Pumped Heat Electricity Storage S.L.U. has been awarded an Innovation Fund Project Development Assistance Agreement by the European Commission and the European Investment Bank to pursue a 100 MW – 1 GWh energy storage facility in Spain. This funding will hopefully provide the ground for a first commercial installation from one of the first companies pursuing LDES.

3.2.5. PUSH-CCC – EIC Pathfinder Project

As an example of an innovative project targeting some of the challenges of the above commercial solutions, the PUSH-CCC project “Pushing the limits of large-scale energy storage: optimized combined cycle CAES” [81], funded by the EIC pathfinder instrument within the portfolio on mid- to long-duration energy storage, aims at developing up to TRL4 an isobaric adiabatic Combined Cycle CAES. The proposed system includes a high-efficiency thermal storage technology specifically designed for hard-rock bedded caverns. Specifically, the project targets the development of a sensible TES in cascade configuration with different media depending on the temperatures: carbonate salts at high temperature (around 730 °C), nitrate salts at mid temperature (around 550 °C) and pressurized subcooled hot water at low temperature (below 275 °C). Carbonates salts-based TES have been quite widely studied and the main challenges to be faced are related to salt stability and corrosion [82]. Pressurized water tanks are commercial units, with relatively low

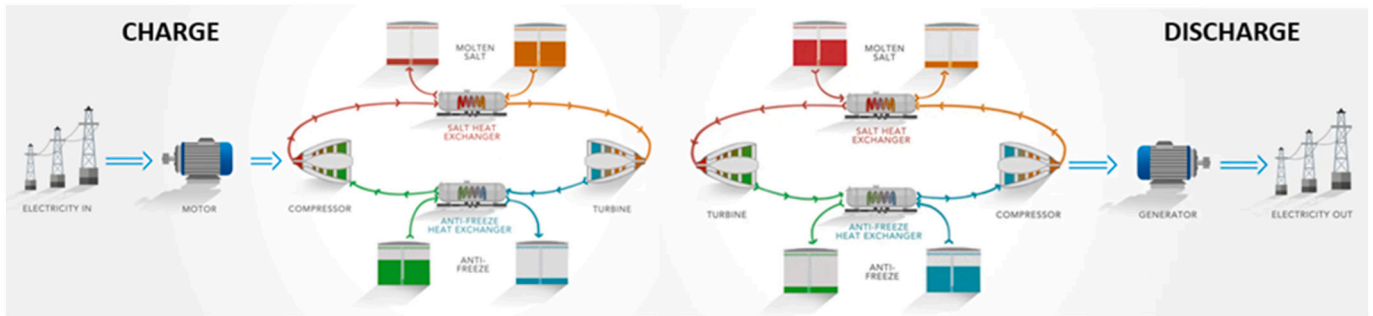


Fig. 19. Overview of Malta Inc. technology and main operation during (left) charge and (right) discharge operation [91].

costs, below 150 °C; however, the project aims at storing at much greater temperatures and consequent pressures of about 64 bar, which imposes major challenges. To this extent the project also aims at developing purposely designed hard-rock bedded heat exchangers. These HXs are meant to operate with the low-pressure fluid inside the pipes and the high-pressure fluid in the hard rock shell, which can withstand higher pressures. Provided that the rock bed can sustain the needed working conditions, the pipes can be manufactured with lower thicknesses and reduced costs. The proposed solution can be very relevant for the specific application, however, larger efforts in understanding its scalability and applicability in different geological frameworks would be needed.

3.3. Latent heat-based thermal energy storage

Latent heat-based TES represents a commercial solution for residential applications (both for cooling and heating needs). However, their development at high temperatures is more limited. The main challenges are represented by the cost and availability of the phase change materials (PCM) and the scalability of the TES unit. Additionally, latent heat TES are very effective when limited temperature differences are expected during operation, which might often not be the case in the context of industrial processes. Latent based TES typically offer elevated energy densities leading to limited footprints with respect to sensible TES. This feature is normally a major advantage particularly in the industrial context where footprint is a key limitation. However, when land is available, latent heat-based TES are hardly cost-competitive. It should be highlighted that the current limited cost-competitiveness is also caused by an earlier stage of development of the technology. Thus, further R&D effort and initial demo facilities could largely contribute to bringing down the costs.

The next paragraphs describe more in details the main characteristics of selected latent heat based TES units Considering the highlighted need

for additional R&D effort, examples of EIC financed projects, typically targeting TRL lower than 5 and innovative solutions addressing some of the main challenges, are also reported.

3.3.1. Build to zero – latent solution

Even if Build to zero [93] is currently focusing on liquid sensible solutions, a longer term development plan includes the adoption of a PCM based TES solution. The main idea in order to overcome the limitations caused by the specific melting temperature of the PCM is to set the single TES units in a cascade arrangement with stratification in the melting temperature of the different units, thus exploiting different PCMs. Fig. 20 shows a sketch of a potential industrial development of the system with different TES units arranged in a cascade. Additionally, the inclusion of elements based on recycled metallic materials within the main bulk of PCM is foreseen to enhance the effective thermal conductivity of the unit. Indeed, limited thermal conductivity is known to be a limiting factor for non-metallic based PCMs, limiting the maximum power that can be extracted or delivered to the TES during operation [94]. The proposed solution is technically very relevant and could tackle some of the main challenges for further deployment of PCM based TES. However, it is yet far from full commercial or first industrial size demonstration stage. In order to keep pursuing this technical solution, Build to zero has received funding from the Horizon Europe program (HYBRIDplus project [95]) and is collaborating with major Spanish universities (University of Sevilla and Lleida) toward a full development of the TES technology and its validation up to TRL5. Further TRL improvement and relevant demonstration will be needed to foster this technology.

3.3.2. 1414 Degrees

1414 Degrees [96] is an Australian company developing high temperature TES for industrial process heat decarbonization. Their core

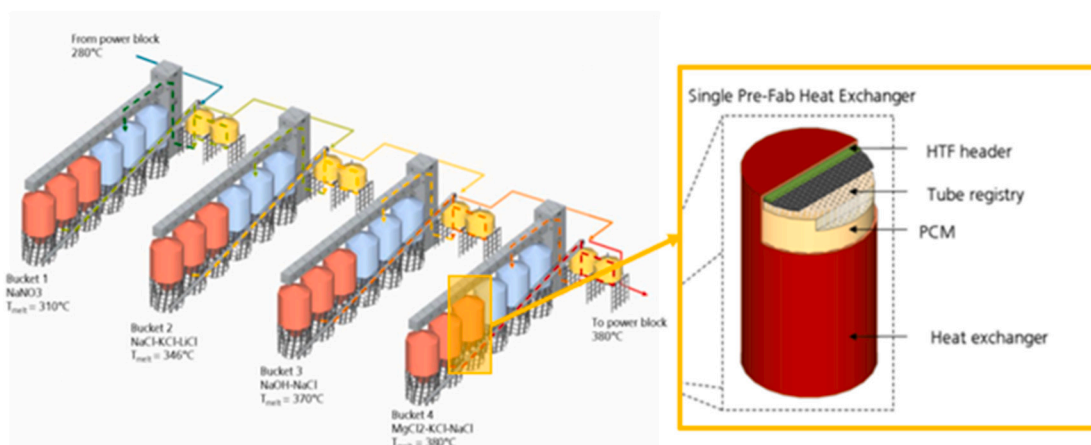


Fig. 20. Overview of the cascade PCM system developed by Build to Zero: (left) TES cascade arrangement, (right) cut out of the single TES unit [94].

technology and IP relies on the TES material, SiBrick™, which is made of a solid matrix (based on Si) permeated by high temperature PCM [97], leading to what is called a shape stabilized PCM TES material [98]. The proprietary TES material can store and deliver heat at up to 1000 °C. With respect to alternative TES units, able to store and deliver heat up to these temperatures (i.e. refractory brick based), 1414 Degrees technology can offer higher energy density and lower footprint which might result in crucial competitive advantages in the industrial context.

Over the last years, 1414 Degrees main technological focus has been on the development and validation of the TES material. The company has recently commissioned a pilot complete TES unit, SiBox®, installed within their facility in Adelaide and shown in Fig. 21. The main commercial step is today represented by the Aurora Energy Project, Port Augusta in South Australia's Upper Spencer Gulf. The project, a joint venture between 1414 Degrees and Vast, includes the deployment of a 140 MW/280MWh stationary BESS, 70 MW Solar PV, 150 MW CSP, and SiBox thermal energy storage.

3.3.3. MGA Thermal

MGA Thermal [99] is an Australian clean energy company also aiming at grid and industrial heat decarbonization via PCM based TES deployment. The core of the company is represented by the TES material, blocks that consist of a purpose-invented material called Miscibility Gap Alloy (MGA), whose overview of the manufacturing process is summarized in Fig. 22 (left). Metal alloy particles are dispersed throughout a matrix material. During charge the blocks are heated up and only the metallic alloy melts. The matrix has a higher melting point; thus, it stays solid keeping the molten particles in place and distributing the heat. Similarly, to 1414 Degrees solution these blocks can deliver heat at a constant temperature while remaining solid making the unit easily scalable. Fig. 22 (right) shows a rendering of the full installation.

Considering the core part of the TES unit its bricks, MGA Thermal decided (pursuing a strategy similar to Rondo Energy) to invest in upscaling its production line and over the summer 2023 announced the commissioning of its 3rd generation automated production line, which is capable of manufacturing over 1 MWh of MGA Blocks every day (about 1000 blocks per day). This commissioning has been facilitated by 8.25 M AUD funding, including investors such as Main Sequence, Varley Holdings, Melt Ventures, New Zealand Climate Venture Capital Fund, Pollination Group, and Understorey Ventures. During the last months of 2023, MGA Thermal is commissioning its first demonstration unit which has received 1.26 M AUD in funding from the Australian Renewable Energy Agency (ARENA). The demonstration has a target thermal capacity of 5 MWh for 500 kW thermal power in discharge. In October 2023, the company has temporarily suspended operations at its pilot plant in Tomago after a dangerous heat build-up, with temperature going much higher than the maximum design point of 700 °C (up to 1200 °C), [100]. This incident shows the need to further investigate and enhance the control systems and operation of this technology.

Additionally, at a material level the use of potentially reactive components (such as aluminum graphite – used in the matrix) when in oxidizing environments or in contact with water leads to additional complexity and risks. Thus, further material-based research might be required to prevent similar issues.

3.3.4. Thermophoton – EIC Transition

Thermophoton [101] is a company developing an innovative Power-to-Heat-to-Power energy storage technology to decarbonize both the heat and electricity sectors. Thermophoton was started in 2021 as a result of two EU projects (AMADEUS [102] funded by EIC Pathfinder which developed the proof of concept of the technology and NATHALIE [103] from EIC Launchpad). Thermophoton technology, leveraging also the key exploitable results of the EIC Transition project Thermobot [104], stores electricity by melting boron-silicon alloys, and particularly eutectic iron-silicon boron alloy [105], at temperatures over 1000 °C and recovering this heat back to electricity on demand using TPV. The technology takes advantage of the low cost, the high energy density of silicon alloys, the simplicity and compactness of TPV to produce a system that is compact, scalable, modular, and without noise or moving parts. All these are relevant advantages for industrial installations. The overall solution presents different potential advantages; however, scalability and demonstration in real industrial environment are deemed to foster its application.

3.3.5. M-TES – EIC Pathfinder Project

As an additional example the EIC Pathfinder project addressing some of the key challenges, M-TES “Metallic phase change material-composites for Thermal Energy management based on Self-encapsulated microstructure” [106] aims at developing advanced solutions for Miscibility Gap Alloys and metallic PCM based TES. The M-TES project explores the possibility of producing self-encapsulated granules, form-stable metallic PCM using Al–Sn mixtures (targeting a working temperature around 200 °C). Of particular interest industrial waste Al is investigated as a starting point for the solid matrix, such upcycling of waste materials is also in line with increased circularity concepts and solutions.

3.4. Thermochemical energy storage

Thermochemical energy storages (TCES) are the least developed technology with limited examples of commercial solutions or companies trying to bring the technology to market. More R&D is currently ongoing with different solutions being investigated up to TRL 5, particularly for long duration and seasonal energy storages. Indeed, the costs associated with this technology are typically higher for shorter duration (i.e. daily cycles) but, also considering a potential learning curve over the next years, could become cost competitive for LDES targeting monthly and seasonal durations.



Fig. 21. 1414 Degrees PCM-based storage system pilot installation in Adelaide [96].

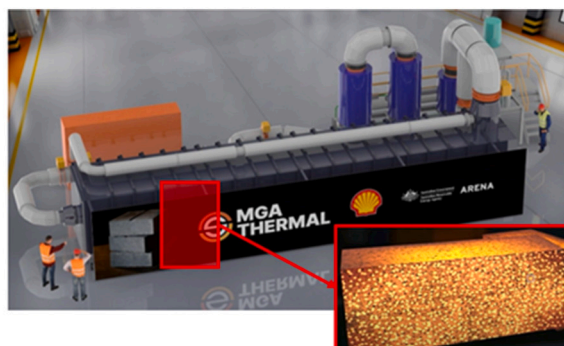


Fig. 22. (Left) Overview of the manufacturing of the MGA bricks and (right) rendering of the MGA TES unit including a cut-out representative of the bricks [99].

The next paragraphs describe more in details the main characteristics of the TES units from each of the identified companies. Considering the highlighted need for additional R&D effort, examples of EU and USA projects, typically targeting TRL lower than 5 and innovative solutions addressing some of the main challenges, are also reported.

3.4.1. SaltX Technology

SaltX Technology [107] is the main company providing TCES for industrial heat and grid decarbonization. The main working principle behind the TCES is sketched in Fig. 23. The company has been developing solutions for energy storage as well as for decarbonization and electrification of the limestone and cement industries. Such a double focus has been possible thanks to the fact that both processes share some of the main chemical reactions and physics.

SaltX Technology initial focused on the development of TCES solutions with nano-coated salts and sorption technologies, in this line they built two pilot facilities in Berlin and Stockholm. Realizing that the cost-competitiveness and market potential of the storage unit alone would be difficult to attain, the company focus shifted toward the electrification of the calcination process for lime and cement. A first electric arc-based calcination pilot has been built together with ABB and an Electric Calciner Research Center (ECRC), an industrial test and research plant for electric calcination, is planned to open by the end of 2023 in Hofors, Sweden.

In the context of TCES, electrification of the calcination process is interesting because in this process, materials are heated to high temperatures in order to alter their properties through a chemical reaction and this process has the potential to function as a charging reactor for the storage unit. Such process occurs in a kiln which can use renewable energy and create quicklime also facilitating the CO₂ capturing. The kiln features a plasma burner which enables very precise and concentrated temperatures [108], as shown in Fig. 23 (right). This technology is under

development in the context of an industrial partnership between SMA Mineral and SaltX Technology, which formed ZEQL.

3.4.2. RedoxBlox

RedoxBlox [109] is a project financed by ARPA-e (with an award of 4.9 MUSD) currently ongoing and led by the Michigan State University (together with Spartan Innovations, Ansaldo Energia, Siemens Energy, Evolved Energy, and Martin Energy). RedoxBlox is developing zero-carbon thermochemical energy storage in which electricity is used to resistively heat a packed bed of magnesium manganese oxide pellets to 1000–1500 °C. A CAD of the TCES unit is shown in Fig. 24. At this temperature the pellets undergo a highly endothermal chemical reaction that releases oxygen gas and stores the heat in the form of chemical energy and sensible heat. To discharge the system, air is passed through the pellet bed, which consumes oxygen from the air, reverses the reaction, and releases heat to the oxygen-depleted air. The project aims at minimizing the production costs for the magnesium-manganese chemical pellets at about 600–800 USD/ton (1.8–2.4 USD/kWh_{th}), whilst maximizing the energy density, with a storage capacity of 25 MWh that could be stored in a standard 40 ft container.

The main challenges to be addressed are represented by ensuring a uniform heating in the bed avoiding local hot-spots, fabricating heating elements capable of delivering the required temperature with limited degradation over multiple cycles and managing the high temperature air flows and associated auxiliaries and pumping requirements.

3.4.3. MUSPELL – EIC Pathfinder Project

The “MUSPELL: Mid-to-long-term TESS with heat pump capability” [110] is a project financed by the EIC Pathfinder in 2022. The project is developing a TES system including thermochemical and latent TES in cascade arrangement, as summarized by the schematics shown in Fig. 25. The TCES covers the high temperature range (up to 400 °C),

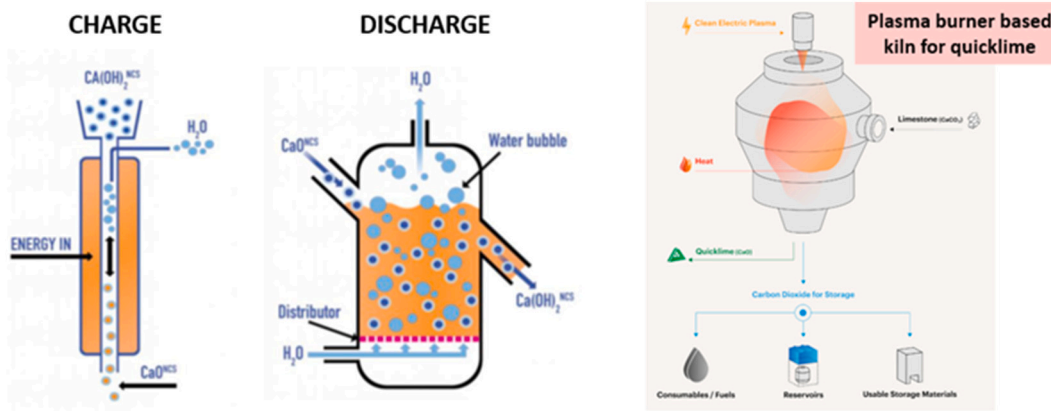


Fig. 23. (Left) Schematic overview of TCES proposed by SaltX during charge and discharge operation and (right) the plasma burner-based kiln from ZEQL [107].

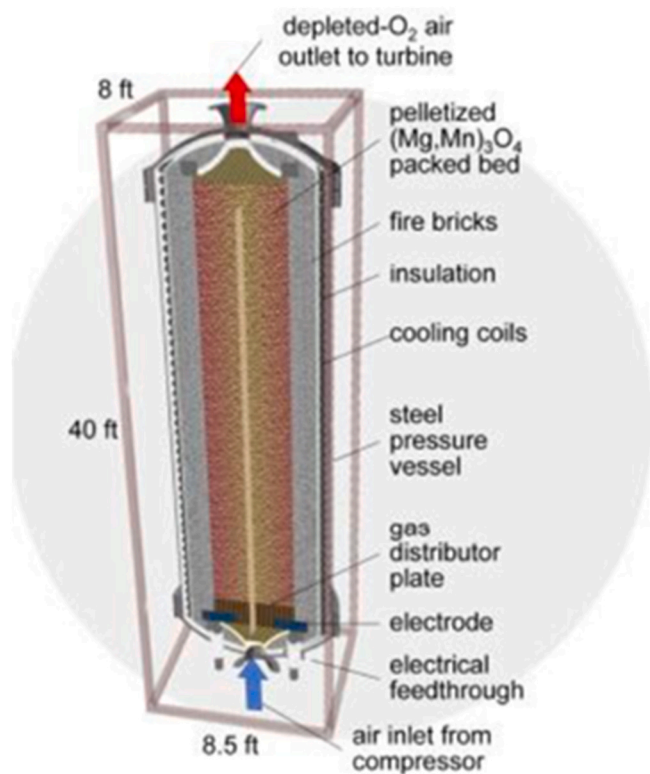


Fig. 24. CAD showing an overview of RedoxBlox technology [109].

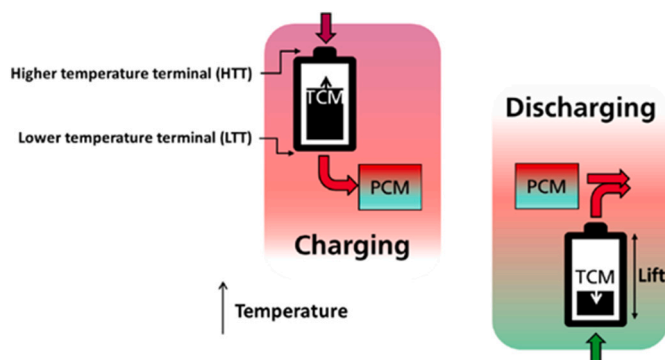


Fig. 25. General operating principle of the MUSPELL TES solution [110].

while the PCM unit covers the lower temperature range ($<100\text{ }^{\circ}\text{C}$). The cascade arrangement also includes an embedded heat pumping system. During charging, heat is consumed by the TCM module for the desorption (separation of the working fluid – water – from the TCM) at higher temperature and released at lower temperature (as water vapor which can be condensated), where it can still be charged into a PCM heat storage. During discharging the temperature levels of the TCM module are shifted to upgrade heat from a lower temperature level to a useful higher temperature level at which also the PCM module is discharged allowing the TESS to discharge in total more heat than initially used for charging.

The solution investigated in this project shows great potential; however, the development is still at a limited TRL thus still requiring large R&D effort to reach full commercialization. Particularly, effort would be needed to upscale the solution and the overall system. Also cost reduction and industrial acceptance will be critical challenges to be faced particularly when targeting the low temperature range ($<100\text{ }^{\circ}\text{C}$) and district heating network integration.

4. Conclusions

This work presents a comprehensive review of commercially available solutions or promising innovations at lower TRL for high temperature thermal energy storage dedicated to industrial heat applications or power to heat to power. The aim of the work is to highlight the readiness of different alternatives, summarize the specific technological and research challenges to scale up the different solutions, and provide useful insights on the key elements to transfer these technologies to products available for full market uptake, via exemplary experiences of successful start-ups.

The proposed overview highlights that most of them involve sensible heat-based TES and primarily solid media units. Several of the above solutions can already be implemented in full industrial context and could already provide relevant contributions toward decarbonization of the industrial sector. More innovative solutions adopting latent heat are getting closer to market, while lower TRL development is still ongoing for thermochemical units. These technologies do not imply the use of critical or scarce raw materials, in several cases adopt circular approaches in the use of recycled products and can strongly contribute to the energy transition goals as well as to the strategic EU need for technological autonomy.

Key technical challenges for TES technologies include control mechanisms, increased durability and stability of materials, and device/system reliability. The applications in power to heat to power present further technical challenges in the dynamic response needed to match the grid requirements.

The business case of these TES solutions is reinforced by the high fluctuation of electricity prices, due among the others to the increasing penetration of intermittent renewable electricity generation, and high costs of fossil fuel, which are the benchmark solution to match the heating demand. However, an improvement of the business cases and novel approaches to produce revenues from TES units are crucial to foster innovation. Promising opportunities include ‘storage as a service’ business models, combining demand aggregation, sectors coupling, flexible generation management with storage assets.

As appears from this overview and from the described case studies, the key ingredients for success in scaling up innovations in TES, as in several other cleantech sectors, include the capability to develop a FOAK demo plant that can increase the trust of investors and enable sufficient fund raising to scale up the production and further reduce costs and improve performance. In addition, a clear planning ahead attitude is crucial, and the successful entrepreneurs should look at the first entry markets where their products can produce revenues and win against competitors at short term, but at the same time identify future markets and get a long-term vision on customer needs and trends.

Author statement

The views expressed in this publication are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission.

CRediT authorship contribution statement

Antonio Marco Pantaleo: Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization. **Silvia Trevisan:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Francesco Matteucci:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Luisa F. Cabeza:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project was partially funded by the European Union's Horizon Europe Research and Innovation Programme under grant agreements 101083899 (SHARP-sCO₂), 101136000 (SCO2OP-TES), 101084182 (HYBRIDplus), and 101103552 (SUSHEAT). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EISMEA or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

This work was partially funded by the Ministerio de Ciencia e Innovación - Agencia Estatal de Investigación (AEI) (PID2021-123511OB-C31 - MCIN/AEI/10.13039/501100011033/FEDER, UE and RED2018-102431-T). The authors would like to thank the Catalan Government for the quality accreditation given to their research group GREiA (2017 SGR 1537). GREiA is a certified agent TECNIO in the category of technology developers from the Government of Catalonia. This work is partially supported by ICREA under the ICREA Academia programme.

Data availability

Data will be made available on request.

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