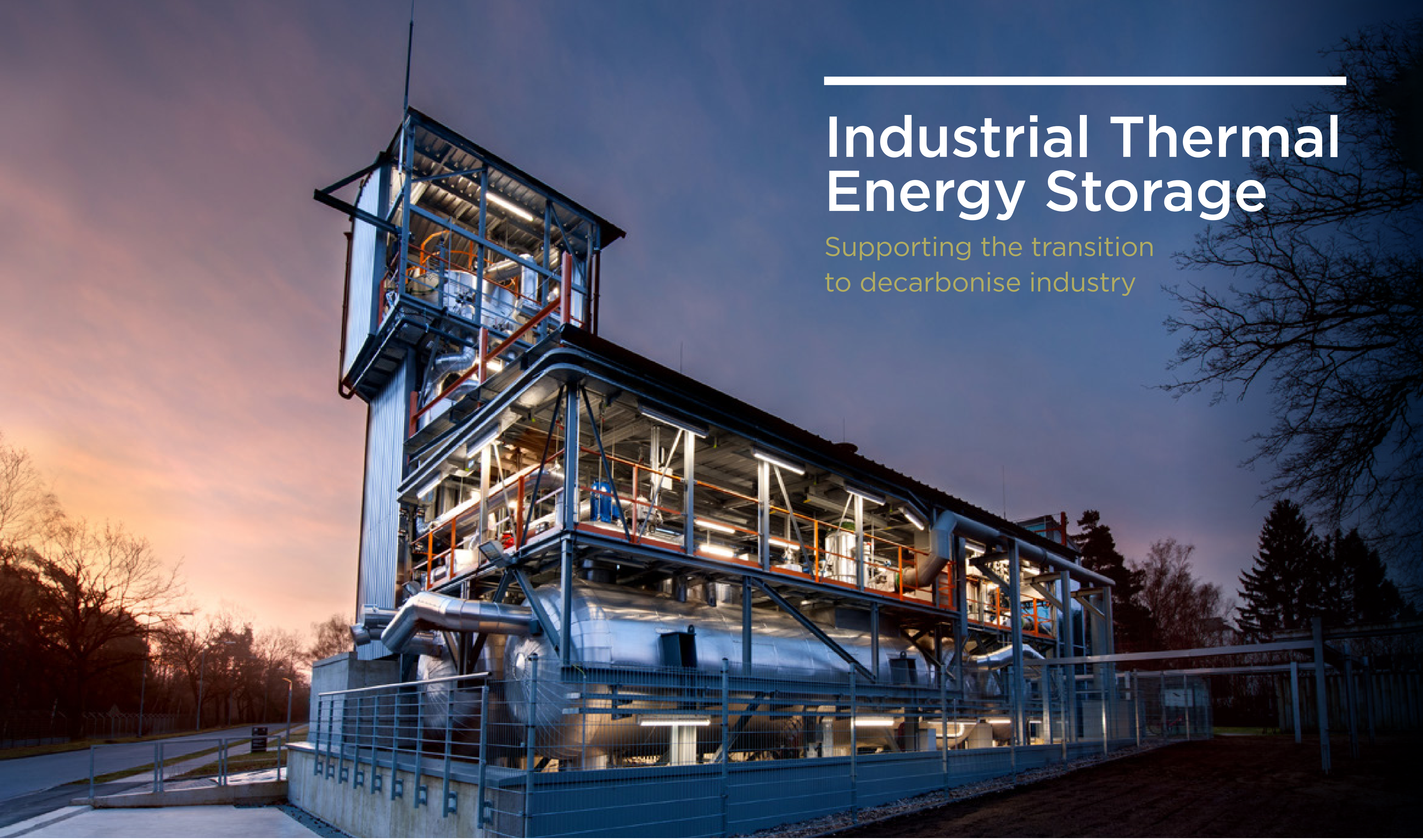


Industrial Thermal Energy Storage

Supporting the transition to decarbonise industry

EERA
European Energy Research Alliance
Energy Efficiency in Industrial Processes

Industrial Thermal Energy Storage

Supporting the transition to decarbonise industry

Authors:

Hanne Kauko, SINTEF

Alexis Sevault, SINTEF

Salvatore Vasta, CNR ITAE

Herbert Zondag, TNO

Anton Beck, AIT

Gerwin Drexler-Schmid, AIT

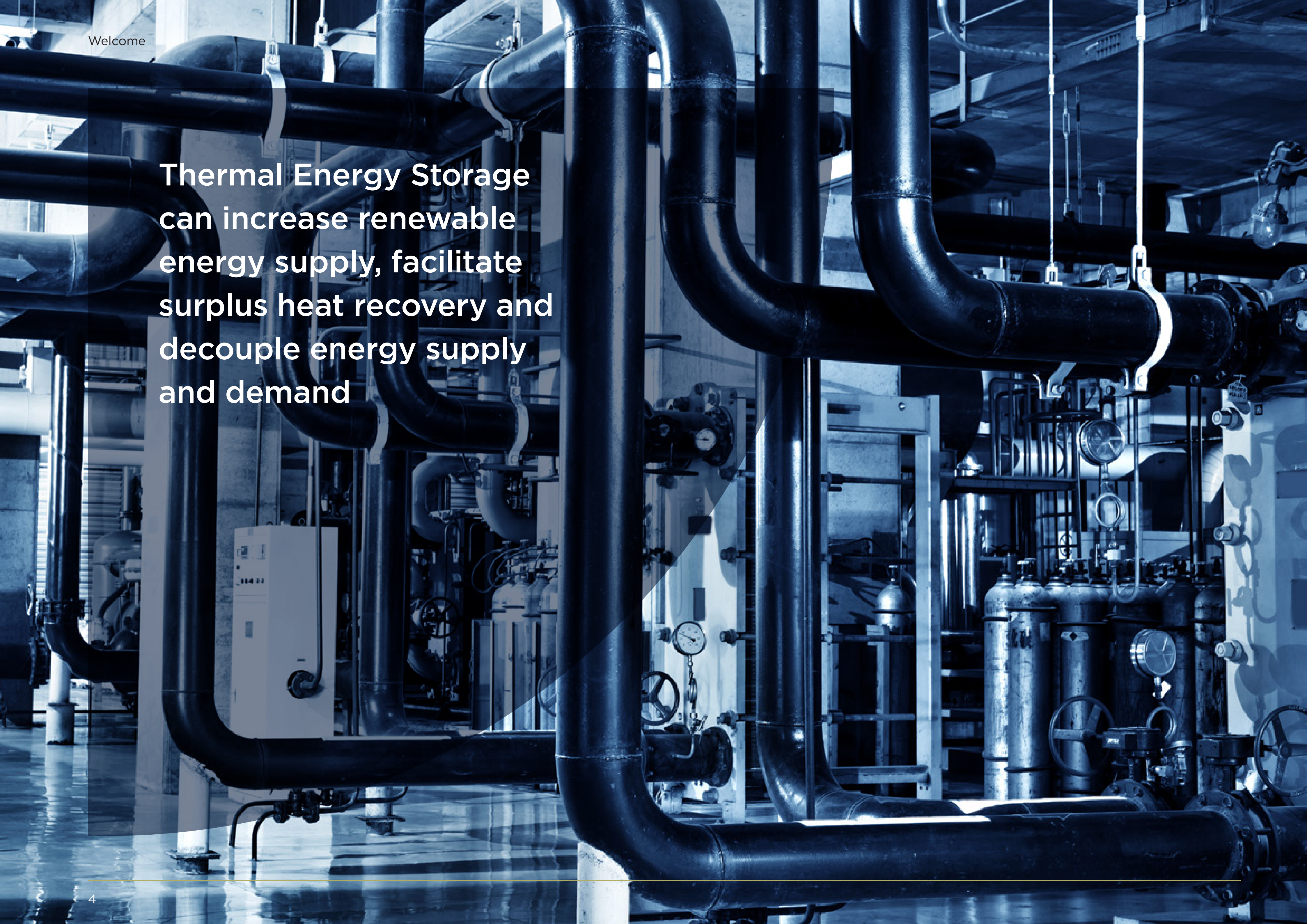
Nelson Rene García Polanco, CIRCE

Zhiwei Ma, Durham University

Tony Roskilly, Durham University

Front and back cover images kindly provided by DLR.
DLR Test facility for thermal energy storage in molten salts (TESIS).

Contents



Thermal Energy Storage can increase renewable energy supply, facilitate surplus heat recovery and decouple energy supply and demand

Executive summary

One quarter of total final energy consumption in the European Union is consumed by industry. Within that quarter, over 80% is consumed by heating and cooling processes. The continued, wide-scale use of gas, oil, coal, and other fossil fuels for industrial thermal processes leads to an estimated greenhouse gas (GHG) emission of 513 Mt CO_2 equivalent per year, which equates to around 60% of the total industrial GHG emissions and 12% of total GHG emissions in the EU. Thermal energy storage (TES) can assist in the decarbonisation of industrial heating and cooling, and at the same time increase energy system flexibility and security. The full roll-out of industrial TES could enable a potential 1,793 TWh of fossil fuel replacement by renewable energy and/or surplus heat, leading to a reduction of 513 Mt CO_2 equivalent GHG emissions per year.

Industrial TES can provide a wide array of benefits, such as catalysing an increase in the proportion of renewable energy supply, facilitating surplus heat recovery, and decoupling energy supply and demand for smart energy usage. It can also provide a means to store cheap, off-peak electricity as thermal energy, and use stored thermal energy as energy backup to support robust operation. Additionally, TES technologies help to maintain electricity grid stability and reduce congestion through the ability to shave peaks in electric and thermal loads.

TES technologies range from mature sensible heat storage and upcoming latent heat storage to cutting-edge sorption and thermochemical. However, to date the industrial application of TES is limited, mainly due to the lack of awareness and demonstration of the technology, cost, and the need to reshape existing physical process systems and interaction with energy suppliers.

This white paper highlights the potential benefits and barriers of industrial TES and indicates new solutions to overcome these barriers. It proposes future actions which aim to promote the application of industrial TES for a carbon neutral future.

To unlock the full benefits of using TES in industries, collaborative promotion and support is needed. This requires coordinated action between the stakeholders including technology developers, industry, policy makers, energy suppliers, and grid operators. The main actions are identified in the following areas:

Priority:

- Recognition of the role of TES options and benefits in industrial long-term energy and infrastructure planning.
- Develop a policy framework to deploy a portfolio of TES options, from early breakthrough to nearly commercial technology options at full scale.
- Provide support to targeted R&D programmes for TES technologies to address the identified technical barriers at regional, national and EU levels.
- Share best practices and disseminate knowledge and data actively to industry, policy makers, and other stakeholders through publications, presentations and other forms of media and engagement.

Longer term:

- Develop innovative business models based on, for example, new energy system services and a dynamic energy price structure.
- Develop clear conditions and long-term perspectives for investments in industrial TES.
- Establish independent TES materials testing institutes to support technical development.
- Activate a community sharing best practices to disseminate the advantages and successful demonstration and application of using TES in industries. This community can deliver standardised systems, disseminate information and knowledge, and as a result to help to lower financial risks.

To achieve carbon neutrality in Europe by 2050, it is necessary to decarbonise the industrial energy system

1

1. Introduction

To limit global warming to 1.5 degrees, the world must halve GHG emissions over the next decade and reach net zero carbon emissions by 2050, as foreseen by the Paris Agreement. To achieve carbon neutrality, in Europe, it is necessary to urgently accomplish the decarbonisation of the industrial energy system.

Industrial thermal energy demand, which includes, not only process heating, but also space heating, process cooling and space cooling, accounts for 80% of the total industrial energy consumption. The current industrial heating technologies are mainly reliant on the use of fossil fuels. A significant shift in the energy source for heating is therefore required to realise a CO_2 neutral industry in the EU.

TES has the potential to play a significant role in industrial energy system conversion and assist in the decarbonisation of industrial energy supply, while at the same time facilitating energy flexibility and security. Industrial TES can provide a wide array of benefits, such as catalysing an increase in the proportion of renewable energy supply, facilitating surplus heat recovery, and decoupling energy supply and demand for smart energy usage. It can also provide a means to store cheap, off-peak electricity as thermal energy, and use stored thermal energy as energy backup to support robust operation. Additionally, TES technologies help to maintain electricity grid stability and reduce congestion through the ability to shave peaks in electric and thermal loads.

In terms of the EU's decarbonisation objectives, the full roll out of TES in the EU industrial sector could enable a potential of 1793 TWh fossil fuel replacement by renewable energy and/or surplus heat and a GHG reduction of 513 Mt CO_2 equivalent per year [1, 2].

This white paper briefly outlines the energy consumption involved in industrial thermal processing, and the working principles of different TES technologies. It explains how TES can be integrated into industrial thermal processes and how it can assist industrial decarbonisation, energy system flexibility and security. The benefits of implementing TES in industries are presented, accompanied by business cases, TES costs, and several successful examples of industrial TES implementations.

The paper also explores the challenges and barriers that are currently limiting the application of TES in the industrial sector, outlining current R&D advances and new technical solutions to address these challenges. The paper concludes with proposed future actions which will strengthen the roll out of industrial TES by industrial stakeholders, with specific recommendations made for policymakers, funding agencies, and businesses as well as research institutes.

Thermal storage battery, Herøya, Norway.

Energy conservation through Thermal Energy Storage is one of the key technologies to enable the actual integration of renewables in future smart energy systems and advanced energy grids

2

2. The role of Thermal Energy Storage in industry decarbonisation and energy system sustainability

Industrial TES represents one of the key technologies that can enable the active participation of energy intensive industries in future smart energy systems. This chapter outlines the heating and cooling demand in industrial processing and the range of applications which can benefit from different TES technologies.[1]

2.1 Industrial thermal processing

Industrial energy consumption within the EU has shown a continuously increasing trend since 2015[2]. By 2019, industries in the EU were responsible for 260 Mtoe (3,026 TWh) of final energy consumption, which corresponds to almost 25% of the total final energy consumption (1,057 Mtoe/12,292 TWh) [4], with only the transport sector and domestic sector being higher.

Thermal energy demands combined account for around 80% of the total industrial energy consumption (2015 [1, 4]). As shown in Figure 1, process heating consumes 64.9% of the final energy, followed by non-thermal process (19.9%), space heating and hot water (11.2%), process cooling (3.2%), and space cooling (0.8%) [1, 4].

Industrial heating and cooling is mainly provided by fossil fuel energy sources, with Natural gas as the most dominant energy source (39%). Renewable energy sources currently provide only 10% of industrial heating and cooling by direct renewable energy use (9% biomass, 1% others). Renewable energy can also be supplied indirectly through electricity (7%) and district heating (8%) [1]. Overall, the continued dominance of natural gas, coal, oil, and other fossil fuels contributed to an estimated industrial GHG emissions of 513 Mt CO_2 equivalent (based on 2015 data [1] and CO_2 emission factors [2]), which is around 60% of the total industrial GHG emissions [3].

Within the industrial sector:

- High temperature processes (over 500 °C) consume almost 34% of the energy demand, as shown in Figure 1. Natural gas and coal are often used to achieve these high temperatures.
- Steam in the temperature range of 100–200 °C is primarily generated by natural gas and biomass.
- Lower temperature process heating (below 100 °C) is mostly provided by district heating. Space heating and hot water are mainly met by individual gas boilers or local district heating (provided by CHP).
- Industrial space and process cooling is dominantly provided by electrically driven vapour compression refrigeration.

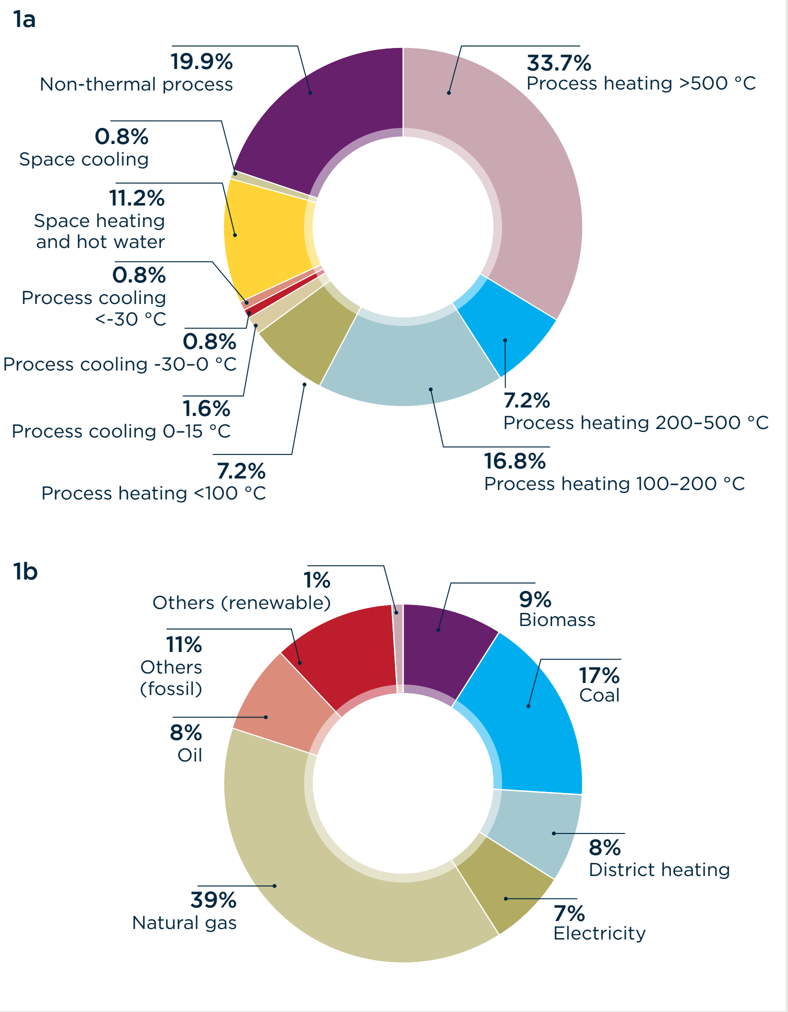


Figure 1 (a) Breakdown of final energy consumption by industries in the EU; (b) Breakdown of energy sources for industrial heating and cooling [1][2].

---

[1] The statistics, trends and recommendations in this document apply to the 27 countries now in the EU and the UK. However, the term 'EU' will be used throughout for conciseness.

[2] Not including COVID impact.

2.2 Applications of Thermal Energy Storage

Conventionally, TES has been applied mainly to balance fluctuation in thermal energy demand, as illustrated in Figure 2. By charging the TES during low-demand periods and discharging during high-demand periods, a process known as **peak shaving**, a significant reduction in implemented capacity for the heat supply or chiller system can be obtained. As the capital costs of a heat supply system are driven by its capacity, peak shaving with TES can enable a significant reduction in investment costs. In the example shown in Figure 2, the peak heating demand is reduced by 42%.

In a case where the thermal energy demand is covered by a fluctuating heat source, such as solar heat or industrial waste heat, TES can be applied to enable constant or more predictable heat production. In a process called **thermal buffering**, the TES is charged upon high availability of heat, and discharged when the heat demand exceeds the availability. This increases the security of heat supply, and reduces the demand for auxiliary heating sources, thus reducing the investment and operational costs.

For electrically driven heating or cooling systems, TES can be applied to provide load shifting i.e, the production of heating or cooling to low-price periods, thus reducing the operational costs and simultaneously alleviating the pressure on the power grid [5]. This scenario is becoming more and more relevant in a power grid with an increasing share of variable renewable energy sources.

Figure 3 illustrates an electricity-driven steam supply system powered by renewable energy, with various alternatives for steam generation and TES technologies that are relevant in industrial process heat applications [6]. Such application of power-to-heat technologies and TES paves the way for active participation of energy-intensive industries in the power market, as will be discussed in the following section.

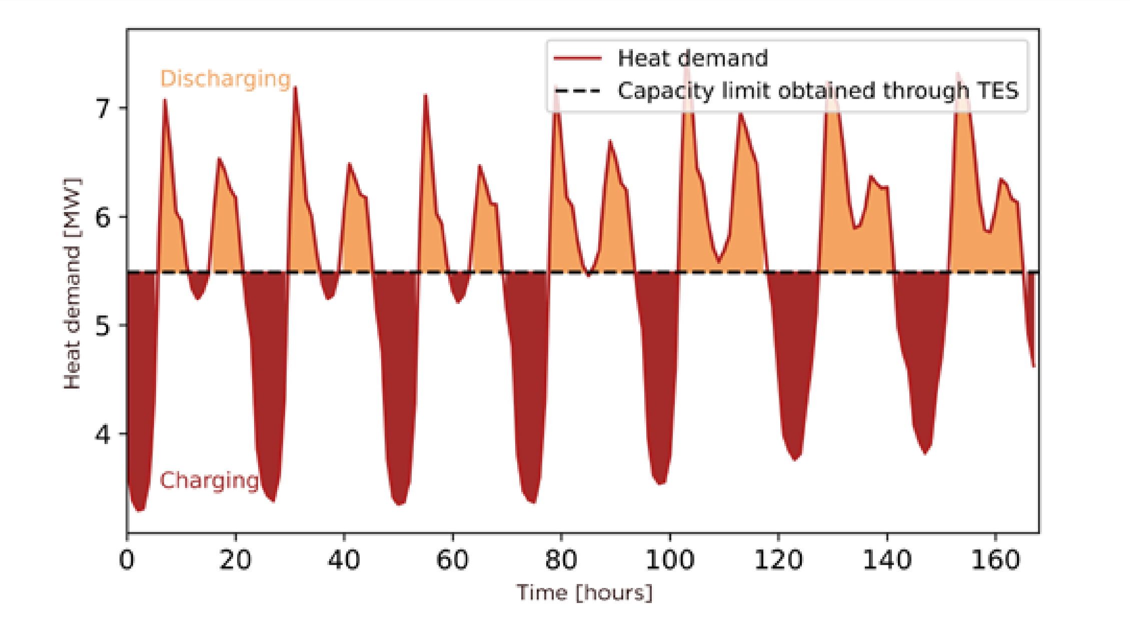


Figure 2 Peak shaving with TES: charging during low-demand periods and discharging during high-demand periods (©SINTEF).

2.3 Thermal Energy Storage in future fossil-free industries

In many industrial applications, electrification does not require a fundamental change in the process setup, but rather a replacement of sections of the energy supply infrastructure such as fossil fuel boilers or furnaces, with electricity-based equipment. From analysis of all the fuel that industrial companies use for heating, it is estimated that 50% could be replaced with electricity using available technologies [7].

The scale of industrial process heat demands, combined with limited power grid capacity and the intermittency of renewable energy sources, calls for more energy flexibility [8]. At the same time, participating in the electricity market yields the potential for industry to reduce its energy costs and emissions. Incorporating TES is becoming both viable and necessary, allowing industry to shift their energy demand to periods when electricity prices are low.

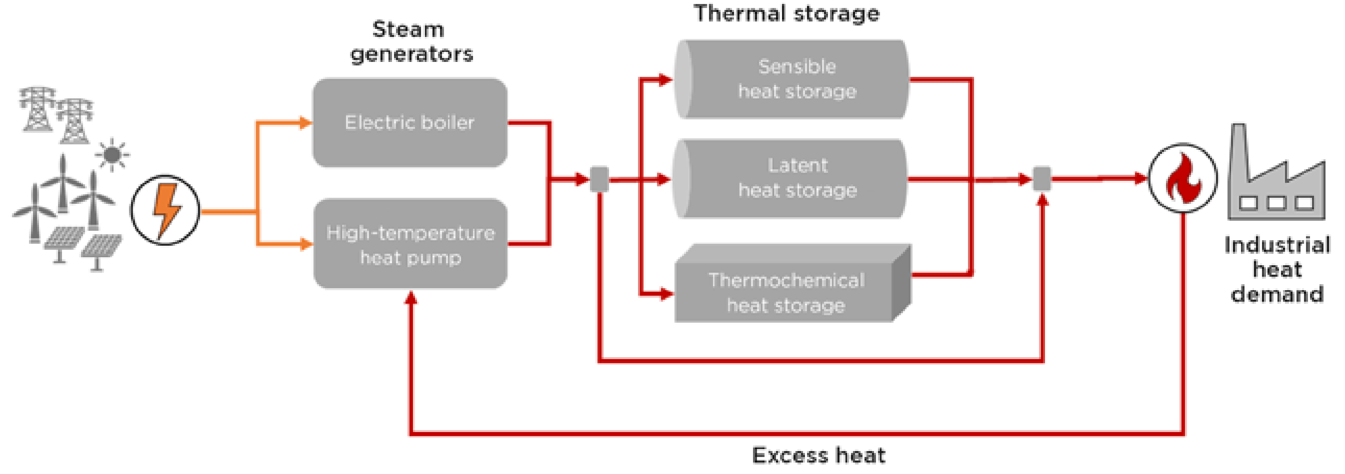


Figure 3 Electricity-driven steam supply system powered by renewable energy, with various alternatives for steam generation and TES technologies [6].

Figure 4 illustrates several classes of application of TES in future, fossil-free industries, with an active role in a renewables based power system.

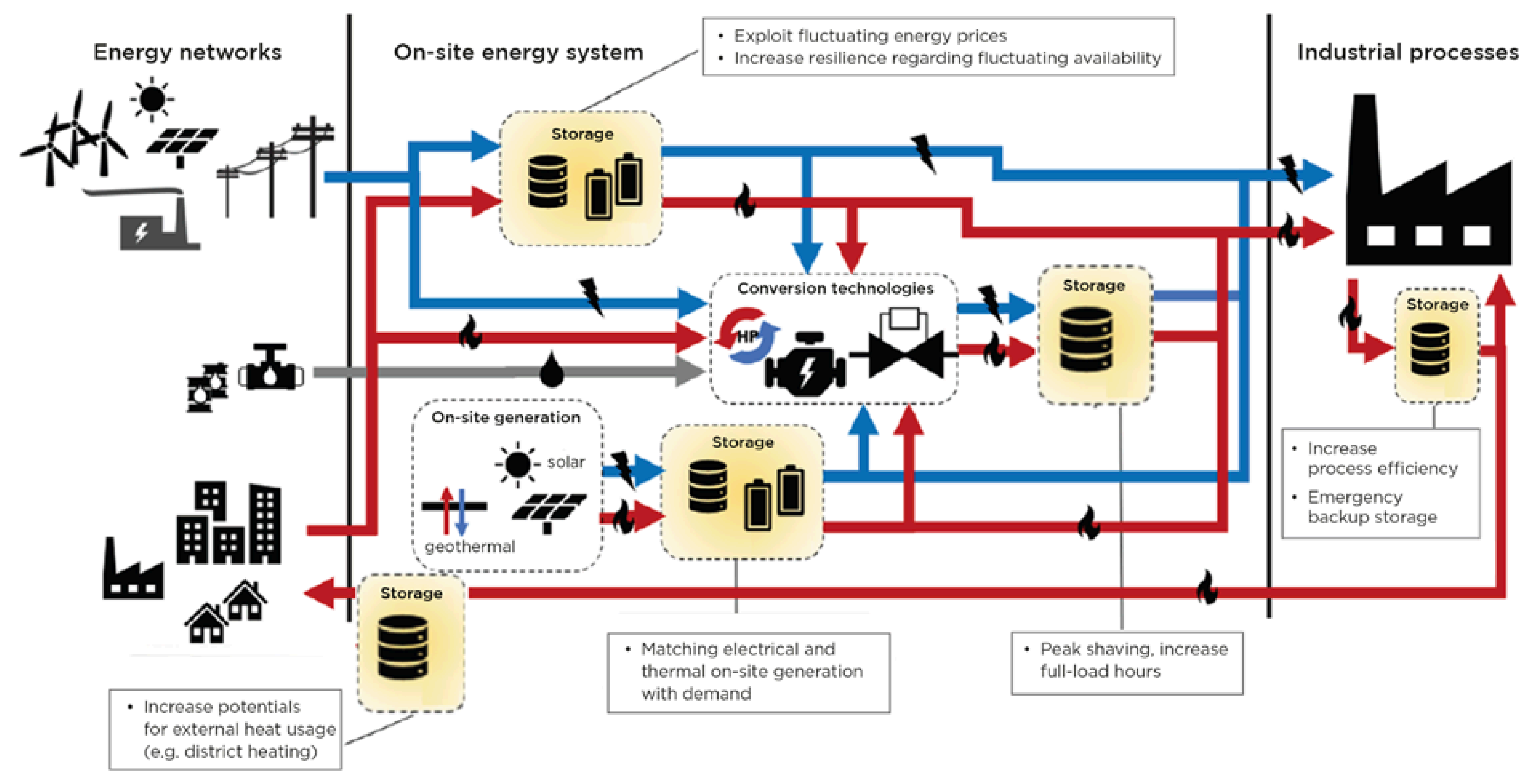


Figure 4 Industrial application scenarios of TES.

2.4 Thermal Energy Storage technologies

There are four general methods used to store thermal energy: (1) sensible heat storage, (2) latent heat storage, (3) sorption heat storage and (4) chemical reaction storage.

- **Sensible TES** stores heat by simply changing the temperature of a material to higher level for heat storage or to a lower level for cold storage. Typical sensible heat storage materials include water, thermal oil, rocks, sandstone, clay, brick, steel, concrete and molten salts.

- **Latent TES** involves a phase change (or phase transition) of the storage material. This type of material is called a phase change material (PCM). The latent heat involved in the phase change process is typically large; for example, it takes 80 times more heat energy to melt 1 kg of ice than it takes to heat up liquid water from 1 to 2 °C. Typical PCMs include ice, paraffin, fatty acid, sugar alcohol, salt hydrate, inorganic salt and metals.

- **Sorption TES** is based on a reversible gas-solid reaction between a sorbate (gas) and a solid adsorbent or liquid absorbent, typically for application temperatures below 200 °C. The sorption heat involved in this reversible sorption/desorption process is generally greater than sensible and latent heats [9]. The advantage of sorption is that heat can be stored over long periods of time with minimum heat loss, since the energy is stored in an endothermic reaction instead of a temperature rise and the (charged) material can be stored at room temperature [9].
  - o Solid adsorbents include porous-structured materials, for example zeolite, silica gel, and activated alumina, which can adsorb/desorb gases, such as water or ammonia vapour.
  - o Typical liquid absorbent materials are concentrated salt solutions, such as aqueous solutions of LiCl, LiBr and NaOH.

- **Chemical reaction TES** (also known as Thermochemical TES) is also based on a reversible gas-solid reaction, similar to sorption TES. Correspondingly, it also has the advantage of low storage loss (since the energy is stored in an endothermic reaction instead of a temperature rise), but with potentially even higher storage density and lower costs. The main difference with sorption TES is that the gas is now directly taken up in the crystal lattice of the solid, changing the crystal structure. However, this method of TES is still at a lower stage of development than sorption TES, because the material is more susceptible to mechanical degradation and agglomeration.

  Normally a solid inorganic salt and a gas are used as working pair, such as $CaCl_2$ and water vapour or $SrCl_2$ and ammonia vapour, for temperatures less than 200 °C.

  Other types of chemical reactions include hydroxide formation (e.g. $CaO/Ca(OH)_2$) and carbonation (e.g. $CaO/CaCO_3$) [10] which are used for higher temperature applications (typically in the range of 250 °C up to 600 °C). Finally, oxidation reactions are possible (e.g. BaO_2/BaO or Fe/Fe_3O_4), for temperatures ranging from 800 °C up to 1,800 °C [11].

The volumetric energy densities and application temperature ranges of various TES technologies are summarised in Table 1.

There are a wide range of TES technologies that are applicable to a number of different industrial scenarios. The following scenarios have been demonstrated or are commercially available options (Technology Readiness Levels 7 to 9):

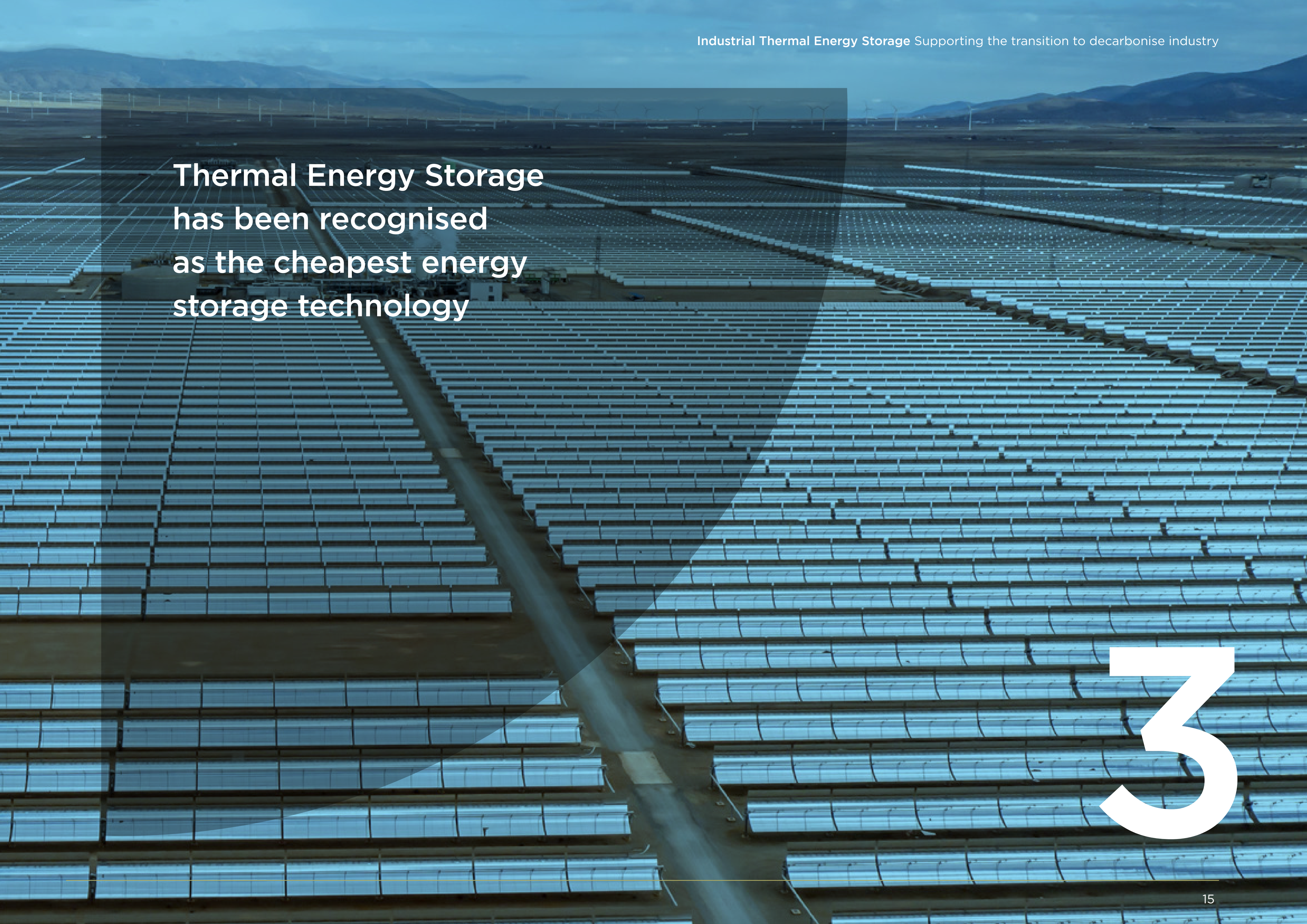
- Very high temperature storage, up to 1,400 °C, is typically achieved using porous solid materials, such as ceramics, stone or sand, with air or hot flue gas used as the heat transfer medium. Research is currently investigating the opportunity for thermochemical heat storage based on redox reactions [11].
- High temperature storage between 250–560 °C, can be achieved using molten nitrate salts or solid materials, such as concrete. Researchers are currently exploring the potential of other types of molten salt with the objective of reaching higher temperatures. Thermochemical heat storage using hydroxides (e.g., $CaO/Ca(OH)_2$) is also under investigation [10].

>>

- Medium temperature storage between 100–250 °C, typically uses process steam, combined with pressurised water storage (steam accumulators) for short-term storage (< 1 hour). Solid materials, such as concrete, are a viable option for longer time scales and high storage capacities. Research is currently being undertaken in the use of phase change materials for this temperature range.
- Low temperature storage, less than 100 °C, that is used in long-term, large-scale storage for district heating applications, is typically provided using water stored in tanks, gravel pits, aquifers or boreholes. Commercially available phase change materials are also used for this temperature range.
- Cold storage, less than 6 °C, can use different types of phase change materials. Ice is typically used for storage at 0 °C, whilst organic PCMs (e.g. paraffin) are used for higher temperatures. Salt solutions that have freezing points below 0 °C are used for cold storage at below 0 °C. Cold warehouses, take advantage of the thermal mass of the frozen product, by temporarily lowering the set-point temperature.

TES medium		Temperature range, °C	Volumetric energy density, MJ/m³	TRL
Sensible (ΔT = 50 °C)	Water	0–100	<210	High
	Steam	>100	<125	High
	Stones/ceramic/sand [12]	<1,400	<110	High
	Concrete [12]	<400	<125	High
	Molten salt, e.g. $NaNO_3$–KNO_3 mixtures [13]	150–560	<180	High
Latent (ΔT = 10 °C around melting point)	Aqueous solution, e.g. $CaCl_2$ aqueous solution, ethylene glycol aqueous solution	<0	<150	High
	Ice	0	330	High
	Organic PCMs, e.g. paraffin, fatty acids [14]	0–100	<200	Medium-High
	High temperature organic PCMs, e.g. sugar alcohol, dicarboxylic acids [14]	100–200	<200	Low-Medium
	Salt hydrate [15]	0–100	<350	Medium
	Inorganic salt and metals [16]	<1,000	<430	Medium
Sorption	Absorption, e.g. NaOH solution– water [16]	80–150	900–1,370	Low–Medium
	Adsorption, e.g. Zeolite– water [16]	80–200	170–650	Low–Medium
Chemical reaction (Thermochemical)	Type I, e.g. $CaCl_2$-H_2O, $SrCl_2$-NH_3 [16]	50–200	500–1,500	Low–Medium
	Type II, e.g. $CaO/Ca(OH)_2$ [10]	<1,000	1,000–2,500	Low–Medium
	Type III, e.g. Fe/Fe_3O_4 [11]	<1,800	3,000–26,000	Low–Medium

Table 1 Volumetric energy densities, application temperature ranges and technology readiness levels (TRLs) of different TES technologies.



Thermal Energy Storage has been recognised as the cheapest energy storage technology

3

3. Implementation of Thermal Energy Storage in industry

3.1 Benefits of industrial Thermal Energy Storage

Implementing TES in industrial energy systems can have multiple benefits, including GHG emissions reduction, energy system efficiency and sustainability improvement, cost saving and electrical grid stability improvement. These benefits are achieved through renewable energy integration, surplus heat recovery, thermal and electric peak-shaving and thermal backup.

The potential for fossil fuel savings and GHG emissions reduction through the integration of TES in the industrial energy system is summarised in Figure 5. The analysis is based on replacing the used fossil fuels (electricity and district heating have not been considered) with renewable energy and/or surplus heat integration with TES. The roll-out of industrial TES throughout the EU enables a potential of 1793 TWh [1, 2] fossil fuel replacement with renewable energy and/or surplus heat, corresponding to a GHG saving of 513 Mt CO_2 equivalent per year [1, 2]. For process and space cooling, the potential fossil fuels and GHG emissions reduction will be dependent on the carbon intensity of the purchased electricity.

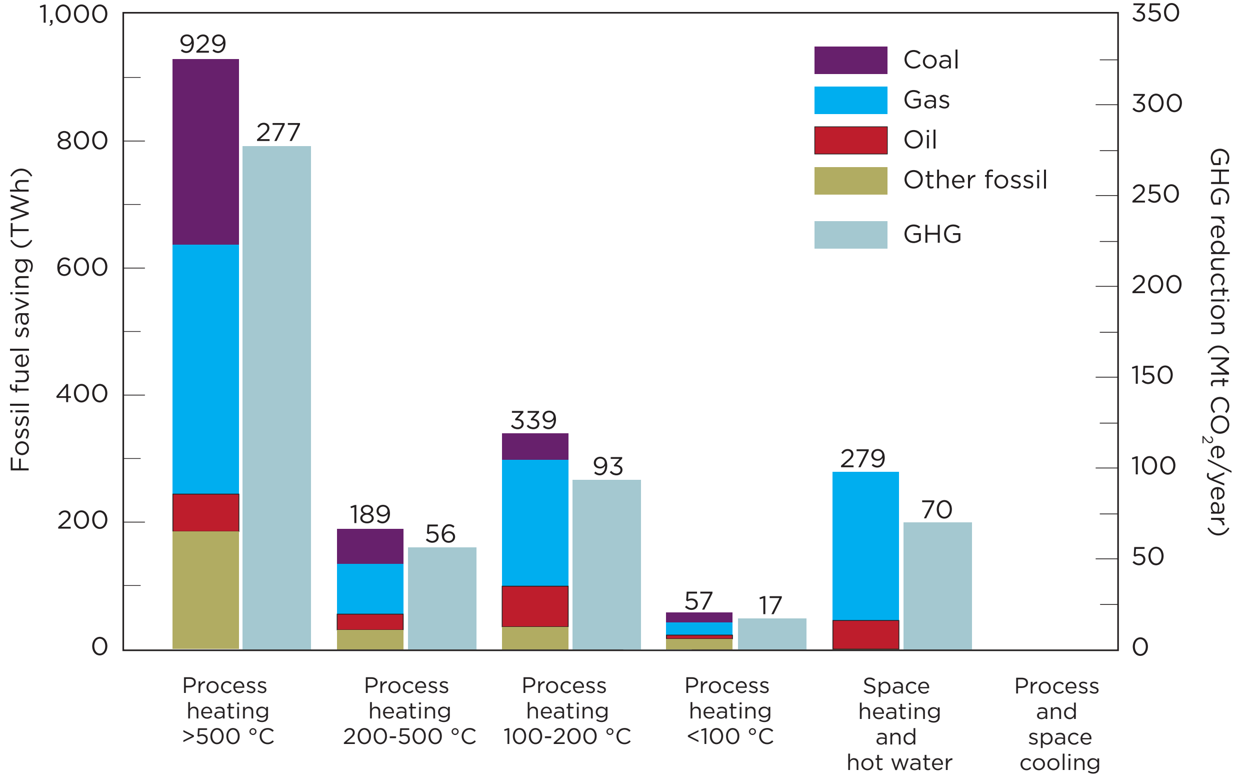


Figure 5 Fossil fuel and GHG emissions reduction through integrating industrial TES.

3.2 Business cases for industrial Thermal Energy Storage

The potential benefits of TES are clear, however, adoption within industry is sluggish, lagging far behind the contribution it could make. Potential business cases are outlined in the following:

1) **Industrial process heating or cooling:** Depending on climatic conditions, industrial solar thermal systems can also be used, typically in combination with daily/weekly TES. Typical examples are solar heating of batch processes in the food industry, e.g. related to cooking, pasteurising, scalding and evaporation.
   a. **For high temperature process heat demand (250–1,400 °C)**, typically electric heating in combination with heat storage in porous solids could be used, similar to that used for high temperature Carnot batteries [17].
   b. **For medium temperature hot water and process steam demand (up to 200 °C)**, multiple options exist:
      i. Industrial heat pumps in combination with TES [18].
      ii. Depending on climatic conditions, industrial solar thermal systems can also be used, typically in combination with daily/weekly TES.
   c. **For industrial cold storage (<6 °C)**, refrigeration systems (e.g. chillers or air conditioning), can provide low-temperature energy to a sensible or PCM cold storage to overcome peaks in cold demand at the start of a new cooling batch/period and to exploit low-cost renewable electricity.

2) **Industrial surplus heat utilisation:**
   a. Short-term storage, in which surplus heat from batch processes is used to preheat a new batch, to reduce energy input and increase energy efficiency. The storage temperature level varies and hence the most suitable TES technology, depending on the surplus heat available (e.g. in exothermic batch processes in the chemical industry that need a sufficient starting temperature, such as polymerisation or alkoxylation). Short-term storage can also improve the potential of utilising fluctuating industrial surplus sources for district heating [19, 20].
   b. Long-term storage, in which surplus heat from an industrial process is stored to provide space heating during winter for the industrial site itself or for export to a district heating network. This requires storage temperatures in the range of 70–120 °C or alternatively an upgrade of the heat stored at lower temperatures or to supply heat customers with low temperature demand.

3) **Industrial backup storage** serves as an uninterruptible thermal supply (UTS) in case other heating options fail. This requires fast response time and high reliability. Today, industry mostly relies on gas-fired boilers as backup. Instead, storage can be used in the form of a backup steam supply, avoiding steam boilers that otherwise would have to be available in standby mode. Steam accumulators are available commercially, while PCM and thermochemical storage options are of interest for future development. For higher temperature options, porous solids would be available, with high temperature PCM and thermochemical material as future options.

4) **For industrial electricity demand**, in addition to batteries, thermal options can provide low-cost solutions to meet the future need for high-power, high-capacity and long-duration storage. Implementation of such TES solutions at industrial sites would have several advantages as these TES systems can deliver both electricity and process heat. Several technologies need to be developed:
   a. High temperature Carnot batteries [18], using electric heating to store heat in porous solids to 800 °C.
   b. Medium temperature Carnot batteries [21], using a heat pump to convert electricity to heat up to 200 °C. To increase the coefficient of performance, industrial surplus heat may be used as a heat source for the heat pump.
   c. Adiabatic compressed air systems, requiring high temperature heat storage (typically using ceramic porous solids).

3.3 Cost of industrial Thermal Energy Storage

The capital cost of TES includes the costs of storage materials, containers, heat exchangers, pump, fittings and installation. These costs vary widely, depending on storage size and material. Generally, the specific TES capital cost (per kWh) reduces with increasing storage size.

The International Renewable Energy Agency [23] has published key objectives for industrial TES, including cost (€/kWh) and lifetime (in cycles) as presented in Table 2. The payback period, which is normally prioritised by industrial investors, is currently long, e.g. 3–4 years for a steam accumulator for surplus heat recovery, and up to 11 years for mobile TES systems (e.g. a trailer or a cargo ship filled with PCMs for surplus heat recovery for swimming pools or district heating) [22]. However, this may change as fossil fuel costs continue to increase.

- Sensible heat storage is the most established and cheapest TES method. The cost of sensible storage materials, e.g. water and gravel, are very small compared to other system components. Therefore, the capital cost of sensible TES is dominated by the container, heat exchanger and installation costs. Further reduction in these costs is difficult, although standardisation could reduce installation and integration costs. Large scale TES using water tanks can be less than 1.3 €/kWh and 120–150 €/m^3 [5].
  Borehole and aquifer TES are also established technologies, mostly for building applications combined with solar thermal or heat pump technologies, but can also be used for industrial low temperature heating or cooling. Underground TES is possible to implement at very large scale and investment costs can be lower than 0.5 €/kWh [5].
- Latent TES has not yet been widely used in industrial applications, even though there is no significant technology barrier to deploy it. The cost of latent TES generally remains higher than sensible TES. The most cost effective PCMs are approximately 50 €/kWh [5] and this will likely reduce in the near future due to the expansion of the market.
- Sorption and chemical reaction TES have the potential of very high energy storage density, experience minimal energy loss, while also being cost effective. These storage materials are generally cheap. However, these types of TES systems are currently in the early stages of development and not yet commercially available. Hence it is impossible to estimate their cost, although it is expected that this could be similar to latent TES in the future.

	Sensible			Latent			Sorption & Chemical reaction		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (Eur/kWh)	0.09–31	0.09–22	0.09–13	53–106	53–84	53–71	Research	Pilot scale 80–160	Demonstration <80
Lifetime (cycles)	1,000–3,000	3,000–5,000	5,000–7,500	1,000–3,000	3,000–5,000	5,000–7,500	<100	500–1,000	1,000–3,000

Table 2 Foreseen objectives of capital cost and lifetime cycles of sensible, latent, sorption and chemical TES for industry [23].

3.4 Examples of Industrial Thermal Energy Storage

Examples of the successful application of TES are introduced below. :

Case 1: Packed bed TES applied to a steel recycling plant – RESlag project

In steel recycling, a significant amount of surplus heat is wasted in the exhaust gases from an electric arc furnace (EAF). Aiming to increase energy efficiency and reduce the primary energy cost of operation, CIC EnergiGUNE has demonstrated a packed bed TES for surplus heat recovery at ArcelorMittal in Spain, Figure 6 [23, 24]. Steel slag, a low-cost by-product produced in the same plant, was used as the storage material. The pilot system was installed at a capacity of 1 MWh, corresponding to 1/10 scale of the full plant. The storage volume is 3 m^3 and uses approximately 6 tons of steel slag. The exhaust gas from the EAF is at 1,200 °C and is used to heat air, which is subsequently used to heat the packed bed TES to 700 °C. The stored heat can be used for scrap pre-heating, steam production or other recycling plant applications. The project estimated that the full usage of 2.9 Mton slags in EU steel industrial for surplus heat recovery would lead to 71 kg CO_2 reduction per ton of produced steel. Since steel production generated on average 1.85 tons CO_2/ton steel [25], this amounts to a CO_2 reduction of about 4%.

Case 2: Solar-water TES applied to a brewery process

Hofmühl Brewery in Eichstatt, Germany, uses the Merlin ‘gentle brewery’ process which requires heating for the evaporation process. An area of 835 m^2 of evacuated tube solar collectors were installed with two series-connected 55 m^3 water storage tanks by Solarbayer GmbH, Figure 7. The system is capable of storing pressurised hot water up to 115 °C and enables the smart utilisation of heat at different temperatures; it can supply 90 °C hot water for the bottle washer, 60–90 °C preheating for brewing and domestic hot water and 45–65 °C for space heating. The solar TES system replaced a gas boiler, increasing the share of renewable energy in the plant and reducing carbon emissions, energy consumption and operating costs.

Figure 6 CIC Energigune packed bed TES at the ArcelorMittal steel recycling plant [23, 24].

Figure 7 Solar-water TES in Hofmühl Brewery, Germany [26].

Figure 8 Emulsion, bitumen and water storage tanks in Colas, Switzerland SA [22, 27].

Case 3:
Sensible TES for road construction sector

Bitumen and emulsion mixtures used for road construction must be heated to be delivered in a liquid state. To increase the share of solar energy in the process heating system, Colas Switzerland SA installed a 70 m^3 bitumen tank, two 50 m^3 emulsion tanks and a 27 m^3 water tank to store the solar heat for construction work and for space heating and hot water supply for an onsite building, Figure 8. High vacuum flat plate solar collectors are used to produce heat which is stored at 160–200 °C in the bitumen product to keep it liquid and at 60–90 °C in the emulsion tanks and the water storage, with a gas boiler for backup when solar energy is not available. The system delivered 18.2 MWh heat between April–October 2015. The estimation showed an average annual heat supply of 22.4 MWh which is 58% of the site heat demand.

Case 4:
Molten salt TES for Concentrated Solar Power (CSP)

Molten salt is widely used for thermal energy storage in CSP to ensure the continuous operation of the plant during the night and during periods of low solar radiation. The Andasol Solar Power Station (28) in Spain is a 150 MW CSP station which is the EU's first commercial plant using parabolic troughs, Figure 9. During the daytime, part of the solar heat is stored using 28,500 tons of molten salt (a mixture of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3)), resulting in a temperature rise of the molten salt from 290 °C to 390 °C. The stored energy is used to provide the necessary heating to operate the power plant at night or during overcast periods for up to 7.5 hours. Separate tanks are used for the hot and the cold molten salt to ensure a stable heat charge and discharge with a constant thermal store temperature.

Molten salt TES also has very promising applications for high temperature industrial process heating. A concept for a modular, scalable system is being developed by the Norwegian company Kyoto Group [29].

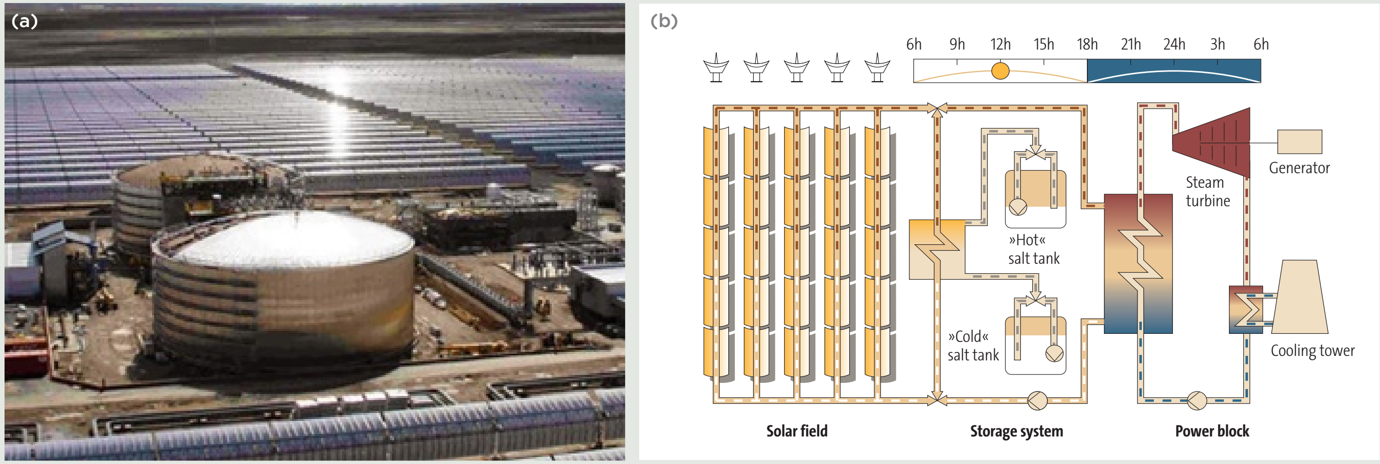


Figure 9 (a) Molten salt TES in Andasol Solar Power Station; (b) the system layout (daytime operation) [28].

Case 5:
Steam accumulator

Steam is widely used in industrial heating processes, typically at 140 °C (3.5 bar), 160 °C (6 bar), 180 °C (10 bar), or even 210 °C (18 bar). Steam requirement often varies with time and a single steam boiler sometimes cannot meet this fluctuating demand. In this case, a steam accumulator can be used during low demand periods to provide steam for heating processes when utilisation is high. During accumulator charging, more steam than needed is generated and the surplus steam is injected into a mass of water for storage, increasing the pressure and temperature of the stored water. During discharge, flash steam is generated as the pressure of the stored water is reduced.

At a large poultry processing plant in Orkanger, Norway, a 175 m^3 steam accumulator has been implemented, Figure 10 [30]. The plant is located in an area where the electricity price is strongly influenced by the high share of variable wind power, and with the help of a smart control system, the steam accumulator will be applied to store steam from an electric boiler during periods with low power prices and to deliver steam to the plant when the demand is high.

Case 6:
Solid sensible TES for steam grid balancing

A solid sensible TES system is under construction at a Yara chemical plant in Herøya, Norway, to balance their steam grid, shown in Figure 11. The ThermalBattery™ system is designed, manufactured and installed by EnergyNest [31]. The plant has a continuous steam demand produced by a CHP-plant and gas boilers. Steam is used in several processes at different temperature levels, and therefore there are three steam grids at different pressure levels. The high-pressure steam at 34 bar is currently discharged in times of imbalances. The TES material, Heatcrete, is a specially developed high-conductivity material [32] and is used to store heat from the high-pressure steam grid in low demand periods. The stored heat is released to the middle and low-pressure steam grids to optimise production. Four ThermalBattery™ modules, with a total 4 MWh capacity, are used to achieve 10 charge/discharge cycles per day. The integration of TES allows (1) energy saving by avoiding producing large amounts of steam; (2) increasing electricity output from a CHP-plant; (3) enhancement of the energy supply security as the gas boilers can be used as backup; (4) a reduction of 8 tons CO_2 emissions per day.

Figure 10 Steam accumulator (175 m^3) implemented at a large poultry processing plant in Orkanger, Norway [30].

Figure 11 Four module ThermalBattery™ before insulation and cladding, during assembly at site in Norway [31].

There is no doubt that the uptake of Thermal Energy Storage technologies will increase and take a significant share of the energy storage market

4

4. Challenges and barriers

The main objective for energy efficiency measures in the process industry has traditionally been to reduce energy use and thereby cost. TES technologies have huge potential in improving surplus heat recovery and significantly reducing energy use. Despite these benefits, interest in exploiting TES has remained relatively low.

In recent years, there has been a rapid change of focus by industry towards reducing its carbon footprint and increasing the use of renewable energy sources in the power grid and industrial processes. As a consequence, many companies are seeking to move away from fossil fuel based process heat production systems, with fuel switching to low carbon hydrogen or electrification. The usage of TES will be beneficial in providing resilience to the fluctuation of renewable energy sources.

4.1 Technical challenges

Each TES technology has its specific area of application, particularly in terms of temperature range and cycle duration. The overall goals for technological development are, however, the same for all technologies: low cost, high efficiency charging/discharging cycles, compactness through high energy storage density, and long lifetimes. The common challenges are, the proximity of the heat sources and sinks, the demand for new components and effective operational strategies.

Table 3 introduces the technical challenges for the different types of TES: sensible, latent, sorption and thermochemical.

Section 3.4 shows that some innovative TES technologies have been, and are, currently being demonstrated at either pilot or full-scale within industrial processes, providing evidence of their benefits. Given that these projects have been successful, there is no doubt that TES technologies uptake will increase and take a significant share of the energy storage market. This will be accelerated through addressing the above technical challenges and upscaling the production of TES technologies to reduce their specific costs.

High temperature PCM TES prototype at TNO Laboratory, Petten, Netherlands.

Technology	TES	TRL	Main identified technical challenges	Main applications
Sensible heat storage	Liquid (tank)	9	• Increase volumetric thermal density, therefore reduce space requirements • Reduce high temperatures, pressures, and corrosion for molten salts • Reduce heat losses due to lack of compactness	Hours to days duration of heat or cold storage, where a cheap solution is required, and space-availability is not a challenge
Sensible heat storage	Solid	7	• Increase low gravimetric and volumetric thermal density, therefore reduce space requirements and system weight • Improve heat exchange process	Hours to days duration of heat or cold storage, where a cheap solution is required, and space-availability is not a challenge
Sensible heat storage	Underground (borehole/aquifer)	7	• Reduce very large area requirement • Reduce dependence on specific geological conditions • Reduce high heat losses • Reduce long start-up time • Increase limited temperature range	Large-scale seasonal heat storage under 90 °C where close-to-free heat is available for charging periods
Sensible heat storage	Pit	7	• Reduce space demand at the surface • Improve storage efficiency and impact of temperature levels and the general quality of stratification	Large-scale weeks to months heat storage under 60–80 °C where close-to-free heat is available for charging periods
Latent heat storage	Phase Change Materials (PCM)	4–7	• Increase heat transfer rates, limiting the charge/discharge rates • Improve the process of standardisation and commercialisation of PCMs • Reduce the need for a customised solution for each application • Increase PCM durability (number of cycles) • Improve the purity of thermal storage materials required	Hours to days of heat or cold storage where a compact unit is required
Sorption heat storage	Absorption and adsorption heat storage	6–8	• Increase materials commercially available for applications above 200 °C • Improve efficiency through utilising cold energy produced • Reduce gap between charging and discharging temperatures	Hours to months of heat storage where space availability is a challenge
Thermochemical heat storage	Chemical heat storage (e.g. salt-based reactions)	4–6	• Increase durability and stability of materials • Eliminate agglomeration/lumping issues • Reduce gap between charging and discharging temperatures	Hours to months of heat storage where space availability is a challenge

Table 3 Technical challenges related to the different TES technologies.

4.2 Non-technical barriers

Typical non-technical barriers include: a lack of awareness of the potential of the technology, lack of knowledge of implementation and operation, high costs, or lack of incentives that support its uptake. Additionally, often a company investing in the technology may not be the one that obtains the greatest benefits, for example, load shifting might not benefit the owner of the TES but rather the grid operator, depending on the power pricing scheme.

The identified non-technical barriers are represented below (Figure 12), divided into four categories: market, operational, financial, and legislative.

The share of renewable energy sources supplying the power grid is increasing rapidly, and the demand for removing fossil energy sources is more urgent than ever. One of the main non-technical barriers is the lack of awareness of TES solutions, particularly as a means of providing flexibility at the interface with a renewable energy-based power grid. In general, the benefits of TES compared to battery technology, including lower costs, suitability for large-scale applications, longer lifetime, and use of common and abundant materials, as well as the minimal environmental impact of most TES technologies.

Integration and operation of TES is more complex compared to batteries, with thermal power, temperature, and pressure demands needing to be considered. Until recently, variability in electrical power prices has been low, reducing the viability of investments in adopting TES, however, this is now changing with the potential future introduction of power tariffs and increasing energy price variation. These factors support the further demonstration that TES can provide an increased return on investment, both financially and environmentally.

Market	Operational	Financial	Legislative
Lack of awareness on the potential of TES as a source of flexibility and security of supply	Lack of research and demonstration projects: industry needs to be convinced that technology works	High investment costs	Lack of procedures for certifying the reliability of the technology
The size of the current market limits the reduction in prices	Lack of sufficiently competent engineers for TES systems	Lack of incentives specifically directed at TES	Lack of legislation on the usage of new TES materials and systems in terms of transportation, operation and environment
Lack of standardised products and integration practices	Lack of TES materials databases with uniform KPI metrics	Lack of business models where ownership of the infrastructure is not at the demand side (energy-as-a-service)	Lack of legislation that supports new business models and local sharing of energy resources
		Energy costs mainly dependent on the amount of energy, not peak power	
		Lack of energy price structures to support sharing energy resources and increased use of local energy resources	

Figure 12 Non-technical barriers hindering the implementation of TES.

The low carbon transition and the sustainable use of energy are the most pressing challenges of the modern society

5

5. New technical solutions

5.1 Recent trends and innovations in Thermal Energy Storage technologies

The cases described in Chapter 3 demonstrate a growing interest in the application of TES, with collaborative research solving some critical issues and reducing costs. Recent trends and innovations in TES for industrial exploitation of renewable energy are mainly related to the development of advanced storage materials and configurations, as well as the implementation of established technologies on an unprecedented scale to fit industrial applications. The development of advanced simulation tools to improve and accelerate the design and implementation of integrated energy systems with TES, also provides greater opportunity for efficient exploitation.

Solid sensible heat storage

Solid sensible TES provides a robust and safe means for storing high-temperature heat. Solid TES technologies that have been gaining interest lately include concrete storage and packed bed storage. The Norwegian company EnergyNest has developed and demonstrated a modular TES system based on specially developed high-conductivity concrete, called Heatcrete®. The technology was recently implemented in the steam grid of a chemical plant in Norway, as discussed in Chapter 3. Other foreseen applications of this technology are at the Austrian brick manufacturer Senftenbacher [33] and the Dutch Sloecentrale combined cycle power plant [34].

Packed bed storage using rock, slag-based materials or sand is finding new applications within the Carnot battery concept, which will be discussed in more detail in the following section. In the SIEMENS Gamesa's Carnot battery pilot plant [35], a packed bed basalt rock storage at 740 °C is used. The storage has a thermal capacity of 130 MWh and a heating power of 30 MW. Packed bed TES is also used for surplus heat recovery at the ArcelorMittal steel recycling plant in Spain, discussed in Chapter 3.

PCM heat storage

PCM materials can provide heat at constant temperature, which makes PCM very interesting for applications such as industrial steam storage. A new development in PCM heat storage is the increasing interest in high temperature PCM materials, with melting temperatures above 100 °C, such as nitrate salt eutectics, dicarboxylic acids, sugar alcohols and even metal PCMs [36].

Substantial research has been undertaken in recent years to improve the thermal conductivity and thus the rate of charging/discharging of PCMs by adding conductive filler materials [37]. This has led to a more compact and cheaper storage system since less heat transfer surface area (e.g. metal fins) is needed.

Furthermore, new high-temperature resistant encapsulating materials are being developed [38], increasing the application potential of high-temperature PCM.

Thermochemical and sorption energy storage

Thermochemical energy storage is a very promising technology for industrial high-temperature applications. The storage period is independent of heat losses and the heat release is controllable with respect to time, temperature and power level.

Composites of thermochemical and sorption materials are also being developed, which is promising for high energy density and long-term stability. R&D is investigating the benefits of using salt-in-porous host matrix composite materials and their innovative preparation techniques [39], aiming to increase energy storage density and enhance the sorption/reaction stability and longevity. In addition, coating technologies are developed to protect thermochemical materials from agglomeration or pulverising.

The feasibility of such a technical solution has been demonstrated by the Swedish company SaltX Technology, who haves developed a nano-coated salt for use in a thermochemical energy storage system called EnerStore. This salt demonstrates a high number of charging and discharging

>>

cycles with low-cost material [40]. The principle is based on the thermochemical reactions between calcium oxide and water/steam. The storage system consists of two tanks as shown in Figure 13.

During charging, calcium hydroxide in the first tank is heated up to 500 °C, which leads to evaporation of the water and therefore drying of the salt. Dry salt (calcium oxide) remains in the first tank while the water is condensed and stored in the second tank, representing the charged state of the storage system. For discharging, water or steam is added to the salt, resulting in a chemical reaction, converting calcium oxide to calcium hydroxide, releasing heat at 450 °C. A SaltX system has been demonstrated in a Power-To-Heat pilot that was built at the Vattenfall CHP plant in Berlin in the winter of 2018/19 and has been in use since March 2019, delivering thermal energy into the long-distance heating network of Berlin [41]. It has a storage capacity of 10 MWh and is charged with electricity from the grid. The overall Power-To-Heat efficiency reached is 72% to 85%, with a theoretical maximum of 92%. The discharge rate and level can be controlled with high precision.

Advanced simulation

The development of simulation models can effectively support the implementation of TES in integrated industrial energy systems with thermal energy storage. Simulation studies are important because they allow the reliable and rapid design of TES systems and sensitivity analysis for innovative configurations. For example, in the field of latent heat storage, a simulation-based system design performance evaluation has been recently presented [42, 43].

In particular for industrial thermochemical heat storage systems, modelling is helpful in the design and development stages, since operational kinetics of thermochemical reactions for reactor and process design can be predicted by advanced non-parametric models [44]. Moreover, the efficiency of the overall system can be increased by the integration of sorption units as part of hybrid sorption/compression chillers. Such a solution can allow an increase of exploitation of renewable energy sources by combined thermal and electrical energy, especially for low-temperature TES applications, such as food processing [45].

Figure 13 SaltX thermochemical energy storage system [40].

Figure 14 SIEMENS Gamesa's Carnot-battery thermal storage pilot plant in Hamburg [35].

5.2 System integration studies

Power-to-Heat-to-Power

Electrification of industrial processes has become an important focus for research and applications, because of the CO_2 reduction targets and increasing shares of solar and wind energy in the electricity supply. However, powering a wide range of industrial processes by electricity rather than through the combustion of fuels creates issues related to intermittent electricity supply and grid capacity, a challenge which can be addressed through energy storage [46]. So far, there has been a lack of location-independent, cost-effective storage systems, capable of absorbing and releasing large amounts of electrical energy with minimal losses. To fill this gap, PXP (Power-to-X-to-Power) systems are proposed as a promising solution. PXP systems convert electrical energy into other forms of energy (such as compressed air, thermal energy and/or hydrogen), which can be stored efficiently and reconverted into electrical power when needed.

A low-cost option for Power-to-X-to-Power is Power-to-Heat-to-Power, also known as Carnot battery solutions [17, 21]. These batteries convert electricity into heat during the charging process and store the energy in the form of heat. During the discharging process, the stored heat is converted back into electricity. In addition, part of the stored heat can be used directly for industrial process heating. An example of such a concept has been recently implemented by SIEMENS. The SIEMENS Gamesa's Carnot battery thermal storage pilot plant in Hamburg, shown in Figure 14, went into operation in summer 2019 and is operated by Hamburg Energie GmbH [35]. The plant uses packed bed basalt rock storage charged with air via an electric heater and a blower. The stored heat is converted back into electricity using a steam Rankine cycle, with a reported Power-to-Heat-to-Power efficiency of 45% and a maximum of 1.5 MW electrical power.

Retrofitting existing power plants

Integration of TES can also contribute to the phase-out of existing fossil fuel power plants run. This applies in particular to coal power plants that are under pressure to close down as part of national CO_2 reduction plans.

The study I-Tess focuses on TES integration in existing power plants as part of Germany's transition to a coal-free energy supply [47]. The project aims to use existing storage concepts, with an electric heater powered by surplus electricity when available. When there is a lack of available electricity, the system uses steam cycles from existing coal power plants for the heat-to-power conversion.

The German Aerospace Centre, DLR, the University of Applied Sciences FH Aachen and the RWE Power AG are working on the StoreToPower project, a pilot plant to develop a heat storage power plant in Rheinisches Revier [48]. The plant will combine an existing coal power plant with high-temperature storage, including an electrical heater and steam generator, to deliver about 10% of the steam used in the steam cycle of the coal power plant, possibly extending the system to a storage only system after the end of coal utilisation.

SIEMENS Gamesa is one of the leading organisations working on the retrofitting of coal power plants, through the integration of a standalone system for providing electricity, heat or process steam with fluctuating renewable electricity as the input [49]. A prototype storage system, using basalt that is heated to 740 °C, has been demonstrated at the scale of 30 MW, as mentioned above. This storage enables the repurposing of a fossil fuel power stations to energy storage plants by employing the existing turbomachinery as part of the storage concept. At the same time, it can be used to provide heat for industrial processes.

The examples listed above illustrate the considerable interest and investment in thermal energy storage systems, with particular regard to industrial applications and the retrofit to existing power plants. The number of studies currently underway and the organisations involved in this research demonstrate how different technologies can be successfully integrated into existing industrial processes.

While further development of Thermal Energy Storage technologies would enhance their take-up by industry, a major bottleneck is the lack of knowledge on their potential applications and benefits

6

6. Proposed actions

Despite the huge potential of TES in the renewable energy transition, wide-scale uptake is still slow. A major bottleneck at present is the lack of knowledge on their potential applications and benefits. This has led to an exclusion of TES options in business model development and long-term implementation which has hampered further adoption and advancement of industrial TES. To overcome this, and allow for greater exploitation in order to contribute to industrial decarbonisation, multiple parallel actions are recommended. These activities involve many different stakeholders, such as Policy Makers, R&D Institutes, Developers, Contractors, Investors and others. A distinction is made between actions that should start immediately, mainly focusing on demonstration and awareness (pre-commercial phase P), and actions that should start in the near term, related to the starting of the commercialisation phase (commercial phase C).

6.1 Policy actions

- Recognise that electrification of industrial processes strongly enhances the need for heat storage, since most of the energy demand in the process industries is in the form of thermal energy. (P)
- Provide support to the demonstration and scale up of innovative and commercially promising industrial TES technologies and business models in various industrial processes on regional, national and EU levels, to encourage greater adoption of technologies which have been shown to be potentially beneficial in their applications. (P)
- Provide support to targeted R&D programmes for TES technologies to address the technical barriers identified in Chapter 4 on regional, national and EU levels. (P)
- Take full account of the potential advantages of TES in comparison with other forms of energy storage, including the abundance of available and recyclable materials, lower costs when scaled up, and low carbon-footprint. (P)
- Provide support to the dissemination of best practices for industrial TES, essential for knowledge sharing and the wider implementation of the technology. (P)
- Ensure energy efficiency, storage and flexibility are embedded as an integral part of EU, national, regional, and local energy transition plans. (P)
- Develop clear conditions and long-term perspectives for investments in industrial TES to support longer term investment. (C)
- Establish independent TES materials testing institutes to support technical development. (C)

PCM-based heat storage system at the SINTEF/NTNU ZEB Laboratory, Trondheim, Norway.

6.2 Technical actions

- Conduct R&D projects on TES, focusing on the technical barriers identified in Chapter 4. (P)
- Undertake techno-economic studies of the benefits of TES and its applications (P), including:
  - Use of TES in renewable power-to-heat (hot/cold)-to-power applications (Carnot batteries)
  - Use of TES in renewable power-to-heat (hot/cold), to match fluctuating electricity supply to electrified industrial heat demand
  - Use of solar thermal and geothermal storage to satisfy fluctuating heat demand
  - The recovery, storage and use of industrial surplus heat
  - Use of thermal storage in cooling and the industrial cold chain
  - Use of thermal storage as a reliable backup in case of failure of other heating technologies
- Identify and share applications in which TES has an advantage (economic, environmental, operational) over other forms of energy storage (batteries or hydrogen). (P)
- Develop and operate TES demonstration projects and provide open access results and data. (P)
- Share best practices and disseminate knowledge and data actively to industry, policy makers, and other stakeholders through publications, presentations and other forms of media and engagement. (P)
- Develop accessible TES materials databases with uniform KPI metrics. (C)
- Work with regulators, professional bodies and industry to develop standardised TES systems. (C)

6.3 Business actions

- Promote and develop new business models to support the exploitation of TES. (C)
- Promote and develop dynamic price structures, adjust the energy system regulatory framework, tariffs, and taxation to accommodate TES and energy flexibility. (C)

Multiple parallel actions are recommended, these involve policy makers, R&D Institutes, EPC Contractors and energy suppliers

7

7. References

1. Tobias Fleiter et al. Heat Roadmap Europe. Deliverable 3.1 – Profile of heating and cooling demand in 2015.
2. Koffi, B., Cerutti, A., Duerr, M., Iancu, A., Kona, A. and Janssens-Maenhout, G., 2017. Covenant of mayors for climate and energy: Default emission factors for local emission inventories. Joint Research Centre (JRC).
3. European Environment Agency. EEA greenhouse gases – data viewer. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (accessed: Sep. 16 2022)
4. Eurostat. Energy Balances. 2021.
5. BEIS. Evidence gathering: Thermal energy storage (TES) technologies.
6. Beck, A., Sevault, A., Drexler-Schmid, G., Schöny, M., & Kauko, H. (2021). Optimal selection of thermal energy storage technology for fossil-free steam production in the processing industry. Applied Sciences, 11(3).
7. Roelofsen, O., Somers, K., Speelman, E., & Witteveen, M. (2020). Plugging in: What electrification can do for industry. McKinsey & Company.
8. IEA. (2019). World Energy Outlook 2019. Paris: IEA
9. N'tsoukpoe, K.E., Liu, H., Le Pierrès, N. and Luo, L., 2009. A review on long-term sorption solar energy storage. Renewable and Sustainable Energy Reviews, 13(9), pp.2385–2396.
10. Pardo, P., Deydier, A., Anxionnaz-Minvielle, Z., Rougé, S., Cabassud, M. and Cognet, P., 2014. A review on high temperature thermochemical heat energy storage. Renewable and Sustainable Energy Reviews, 32, pp.591–610.
11. Solid, Enabling circular energy [Online]. Available: https://teamsolid.org/ (accessed: Sep. 16 2022)
12. Singh, H., Saini, R.P. and Saini, J.S., 2010. A review on packed bed solar energy storage systems. Renewable and Sustainable Energy Reviews, 14(3), pp.1059–1069.
13. Nunes, V.M.B., Lourenço, M.J.V., Santos, F.J.V. and de Castro, C.N., 2019. Molten alkali carbonates as alternative engineering fluids for high temperature applications. Applied Energy, 242, pp.1626–1633.
14. Sharma, A., Tyagi, V.V., Chen, C.R. and Buddhi, D., 2009. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable energy reviews, 13(2), pp.318–345.
15. Kenisarin, M. and Mahkamov, K., 2016. Salt hydrates as latent heat storage materials: Thermophysical properties and costs. Solar Energy Materials and Solar Cells, 145, pp.255–286.
16. Lizana, J., Chacartegui, R., Barrios-Padura, A. and Valverde, J.M., 2017. Advances in thermal energy storage materials and their applications towards zero energy buildings: A critical review. Applied Energy, 203, pp.219–239.
17. https://en.wikipedia.org/wiki/Carnot_battery (accessed: Sep. 16 2022)
18. de Boer, R., Marina, A., Zühlsdorf, B., Arpagaus, C., Bantle, M., Wik, V., Elmegaard, B., Corberan, J.M. and Benson, J., 2020. Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat.
19. Knudsen, B.R., Rohde, D. and Kauko, H., 2021. Thermal energy storage sizing for industrial waste-heat utilization in district heating: A model predictive control approach. Energy, 234, p.121200.
20. Kauko, H., Rohde, D., Knudsen, B.R. and Sund-Olsen, T., 2020. Potential of thermal energy storage for a district heating system utilizing industrial waste heat. Energies, 13(15), p.3923.
21. Dumont, O., Frate, G.F., Pillai, A., Lecompte, S. and Lemort, V., 2020. Carnot battery technology: A state-of-the-art review. Journal of Energy Storage, 32, p.101756.
22. Gibb, D., Seitz, A., Johnson, M., Romani, J., Gasia, J., Gabeza, L.F., and Gurtner, R., 2018. Applications of thermal energy storage in the energy transition – Benchmarks and developments. IEA ECES Annex 30 report.
23. International Renewable Energy Agency. Innovation outlook, Thermal Energy Storage. 2020.
24. Ortega-Fernández, I. and Rodríguez-Aseguinolaza, J., 2019. Thermal energy storage for waste heat recovery in the steelworks: The case study of the REslag project. Applied Energy, 237, pp.708–719.
25. https://worldsteel.org/wp-content/uploads/Climate-and-the-production-of-iron-and-steel-presentation-2021_Asa-Ekdahl-2.pdf (accessed: Nov. 11 2022)
26. Brewing beer with solar heat [Online]. Available: https://www.solarthermalworld.org/sites/default/files/brewing_beer_with_solar_heat.pdf (accessed: Sep. 16 2022)
27. Bunea, M., Hildbrand, C., Duret, A., Eicher, S., Péclat, L. and Citherlet, S., 2016. Analysis of a medium temperature solar thermal installation with heat storage for industrial applications. Energy Procedia, 91, pp.601–610.

28. The parabolic trough power plants Andasol 1 to 3 [Online]. Available: http://large.stanford.edu/publications/power/references/docs/Andasol1-3engl.pdf (accessed: Sep. 16 2022)
29. Holo, G., 2021. First thermal battery ordered for commercial pilot to decarbonizing industrial heating [Online]. Available: https://www.kyoto.group/news/kyoto-group-orders-first-thermal-battery-for-commercial-pilot-decarbonizing-industrial-heat-usage (accessed: Sep. 16 2022)
30. Mona Strande, 2019. Will produce chicken utilising artificial intelligence and waste heat (Original title: Skal produsere kylling med kunstig intelligens og spillvarme.) Teknisk Ukeblad, 27. Nov 2019.
31. https://energy-nest.com/applications/ (accessed: Sep. 16 2022)
32. Hoivik, N., Greiner, C., Tirado, E.B., Barragan, J., Bergan, P., Skeie, G., Blanco, P. and Calvet, N., 2017. Demonstration of EnergyNest thermal energy storage (TES) technology. In AIP Conference Proceedings (Vol. 1850, No. 1, p. 080011). AIP Publishing LLC.
33. EnergyNest's thermal storage to replace natural gas at Austrian manufacturing plant [Online]. Available: https://www.energy-storage.news/energynests-thermal-storage-to-replace-natural-gas-at-austrian-manufacturing-plant/ (accessed: Sep. 16 2022).
34. First major power plant worldwide assesses use of Thermal Battery – EnergyNest [Online]. Available: https://energy-nest.com/first-major-power-plant-worldwide-assesses-use-of-thermal-battery/ (accessed: Sep. 16 2022).
35. 2nd Life for Power Plants using Electric Thermal Energy Storage (ETES) [Online]. Available: https://www.siemensgamesa.com/en-int/products-and-services/hybrid-and-storage (accessed: Sep. 16 2022).
36. Inés Fernández, A., Barreneche, C., Belusko, M., Segarra, M., Bruno, F., and Cabeza, L.F., 2017. Considerations for the use of metal alloys as phase change materials for high temperature applications. Solar Energy Materials and Solar Cells, 171, pp.275–281.
37. Zhang, P., Xiao, X. and Ma, Z.W., 2016. A review of the composite phase change materials: Fabrication, characterization, mathematical modeling and application to performance enhancement. Applied Energy, 165, pp.472–510.
38. Tudor, A.I., Motoc, A.M., Ciobota, C.F., Ciobota, D.N., Piticescu, R.R. and Romero-Sanchez, M.D., 2018. Solvothermal method as a green chemistry solution for micro-encapsulation of phase change materials for high temperature thermal energy storage. Manufacturing Review, 5, p.4.
39. Yu, N., Wang, R.Z. and Wang, L.W., 2013. Sorption thermal storage for solar energy. Progress in Energy and Combustion Science, 39(5), pp.489–514.
40. https://saltxtechnology.com/ (accessed: Sep. 16 2022).
41. SaltX Berlin pilot plant shows very promising results! [Online]. Available: https://helioscsp.com/saltx-berlin-pilot-plant-shows-very-promising-results/ (accessed: Sep. 16 2022).
42. Beust, C., Franquet, E., Bédécarrats, J.P. and Garcia, P., 2020. Predictive approach of heat transfer for the modelling of large-scale latent heat storages. Renewable Energy, 157(C), pp.502–514.
43. Varvagiannis, E., Charalampidis, A., Zsembinszki, G., Karellas, S. and Cabeza, L.F., 2021. Energy assessment based on semi-dynamic modelling of a photovoltaic driven vapour compression chiller using phase change materials for cold energy storage. Renewable Energy, 163, pp.198–212.
44. Birkelbach, F., Deutsch, M. and Werner, A., 2020. The effect of the reaction equilibrium on the kinetics of gas-solid reactions—A non-parametric modeling study. Renewable Energy, 152, pp.300–307.
45. Palomba, V., Dino, G.E. and Frazzica, A., 2020. Coupling sorption and compression chillers in hybrid cascade layout for efficient exploitation of renewables: Sizing, design and optimization. Renewable Energy, 154, pp.11–28.
46. Deason, J., Wei, M., Leventis, G., Smith, S., & Schwartz, L. C., 2018. Electrification of buildings and industry in the United States: Drivers, barriers, prospects, and policy approaches. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).
47. Herrmann, U., Schwarzenbart, M., and Dittmann-Gabriel, S., 2019. Speicher statt Kohle: Integration thermischer Stromspeicher in vorhandene Kraftwerksstandorte. EnergieForum, vol. 71, no. 4, pp.42–44.
48. Arnold, W., Giuliano, S. and Koll, G., 2022. StoreToPower Phase I. Electricity storage in high temperature thermal storage power plants. Public final report.
49. Parnell J., 2022. How Siemens Gamesa Could Give Coal Plants a Second Life [Online]. Available: https://www.greentechmedia.com/articles/read/how-siemens-gamesa-could-give-coal-plants-a-second-life (accessed: Sep. 16 2022).

Thermal Energy Storage offers significant benefits towards net zero, including the abundance of available and recyclable materials, lower costs when scaled up, and low carbon footprint

8

8. Contacts


Dr Hanne Kauko and **Dr Alexis Sevault**
SINTEF, P.O. Box 4760 Torgarden,
NO-7465 Trondheim, Norway
e: Hanne.Kauko@sintef.no
e: Alexis.Sevault@sintef.no

Dr Salvatore Vasta
Advanced Energy Technology Institute (ITAE)
“Nicola Giordano”,
Salita Santa Lucia Sopra Contesse, 5,
98126 Messina ME, Italy
e: Salvatore.Vasta@itae.cnr.it

Professor Herbert Zondag
TNO, Westerduinweg 3,
1755 LE Petten, Netherlands
e: Herbert.Zondag@tno.nl


Dr Anton Beck and **Dr Gerwin Drexler-Schmid**
Austrian Institute of Technology,
Giefinggasse 4, 1210 Vienna, Austria
e: Anton.Beck@ait.ac.at
e: Gerwin.Drexler-Schmid@ait.ca.at

Dr Nelson Rene García Polanco
CIRCE, Dinamiza Business Park,
Ranillas Avenue 3D Building,
1st Floor. 50018, Zaragoza, Spain
e: nrgarcia@fcirce.es


Dr Zhiwei Ma and **Professor Tony Roskilly**
Durham Energy Institute, Durham University,
Stockton Road, Durham, DH1 3LE
e: Zhiwei.Ma@durham.ac.uk
e: Anthony.p.Roskilly@durham.ac.uk

The writers wish to thank the EERA Joint Programme Energy Storage and particularly Karin Rindt (CTU/CVUT), Francesca De Giorgio (CNR), and Francesco Mercuri (CNR) of the Sub Programme 3 “Thermal Energy Storage” for their support in producing this white paper and to DLR, Brenmiller Energy, EnergyNest, SaltX, Lumenion and SIEMENS Gamesa for their generosity in allowing the use of these images.

EERA
European Energy Research Alliance
Energy Efficiency in Industrial Processes

Durham University

TNO innovation for life

SINTEF

AIT AUSTRIAN INSTITUTE OF TECHNOLOGY

circe