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International Renewable Energy Agency

INNOVATION OUTLOOK
THERMAL ENERGY STORAGE

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The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. ***www.irena.org***

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Thermal energy storage provides the essential flexibility to integrate high shares of solar and wind power.

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ABBREVIATIONS

A-CAES	Adiabatic compressed air energy storage
ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
CAES	Compressed air energy storage
CaL	Calcium looping
CAPEX	Capital expenditure
COP	Coefficient of performance
cPCM	Composite phase-change material
CSP	Concentrated solar power
HT-cPCM	High-temperature composite phase-change material
IEA	International Energy Agency
LAES	Liquid air energy storage
LCOE	Levelised cost of electricity
LNG	Liquefied natural gas
NREAP	National renewable energy action plan
PCM	Phase-change material
PTES	Pit thermal energy storage
PV	Photovoltaic
P2H	Power to heat
R&D	Research and development
SETS	Smart electric thermal storage
TES	Thermal energy storage
TTES	Tank thermal energy storage (usually with water as thermal storage medium)
UTES	Underground thermal energy storage
VRE	Variable renewable energy
WTTES	Water tank thermal energy storage

UNITS OF MEASURE

EJ	exajoule
GW	gigawatt
GWh	gigawatt hour
GW_{th}	gigawatt thermal
K	kelvin
kJ/kg	kilojoules per kilogram
kW	kilowatt
kWh	kilowatt hour
MW	megawatt
MWh	megawatt hour
m^2	square metre
m^3	cubic metre
W/m·K	watts per metre-kelvin
°C	degree Celsius

KEY FINDINGS

The transformation of the global energy system in line with the Paris Agreement requires rapid uptake of renewables throughout all kinds of energy use. Thermal energy storage (TES) technologies can help to integrate high shares of renewable energy in power generation, industry and buildings.

This key role for TES is illustrated on subsequent pages.

- **TES technologies offer unique benefits, such as helping to decouple of heating and cooling demand from immediate power generation and supply availability.** The resulting flexibility allows far greater reliance on variable renewable sources, such as solar and wind power. TES thereby reduces the need for costly grid reinforcements, helps to balance seasonal demand and supports the shift to a predominantly renewable-based energy system.

- **The global market for TES could triple in size by 2030.** This means an increase from 234 gigawatt hour (GWh) of installed capacity in last year (2019) to over 800 GWh within a decade. Investments in TES applications for cooling and power are expected to reach between USD 13 billion and USD 28 billion over the same period. By supporting the shift to renewables, efficiency and greater electrification, TES investments can help to fulfil long-term climate and sustainability goals.

- **Molten-salt storage is commonly deployed in the power sector**. This is due to its advanced technological readiness and its application with concentrated solar power (CSP) plants. By 2030 between 491 GWh and 631 GWh of installed molten salt capacity is expected to come online. In the near-term, other TES technologies are likely to become commercially viable, including solid-state and liquid air variants that store surplus energy from CSP, solar photovoltaics (PV) and wind.

- **Global TES capacity for cooling needs to double to meet expected cooling demand in 2030**. This implies investments of about USD 560 million over the next ten years, to reach USD 2.82 billion worldwide. Phase-change material (PCM) and other TES technologies can complement cold chain applications, enabling flexibility in the cooling loads for production, storage and transportation.

- **TES use in district heating and cooling effectively decouples demand from supply, allowing energy to be stored on a seasonal basis.** District heating already incorporates sensible heat technologies such as tank TES (or TTES) and underground TES (or UTES).

- **Water tank TES (or WTTES), is already used in buildings globally.** To a lesser extent, underground TES is also used in smaller-scale installations. Ice and solid-state thermal batteries are in the early development stages for this application.

- **In industry, water tanks are coming into wider use for low-temperature heat generation and storage in conjunction with solar thermal plants**. This is seen predominantly in the mining, food and textile industries. Innovative technologies for sensible, latent and thermochemical TES are also undergoing trials to store high-grade heat.

- **Investments in technological development combined with measures to enhance market pull can unlock rapid growth in TES deployment.** Such initiatives can form part of a holistic energy policy aimed at scaling up renewables and decarbonising energy use.

TES forms a key part of the energy transition investment package available to countries for post-COVID recovery. Investments in TES, along with renewables, energy efficiency and electrification, can strengthen health and economic infrastructure, drive short-term recovery and align energy development with global climate and sustainability goals.

Renewable energy and cities
Image credit: Shutterstock

Thermal energy storage has the potential to be an important enabler of increased renewables penetration in energy systems

Solar and wind generation is variable across daily and seasonal timescales. Energy system operators can match supply and demand of energy through forms of flexibility such as energy storage. This helps to make energy systems more stable, flexible, and cheaper to build and operate.

Cold chain

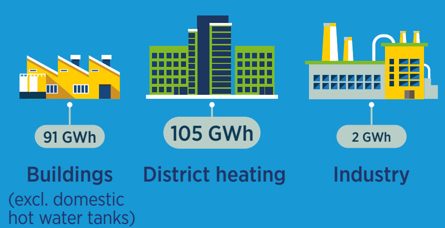
PCMs and other TES technologies can be integrated into all parts of the cold chain, enabling flexibility of cooling loads at the production, storage, and transport elements of the chain.

Industry

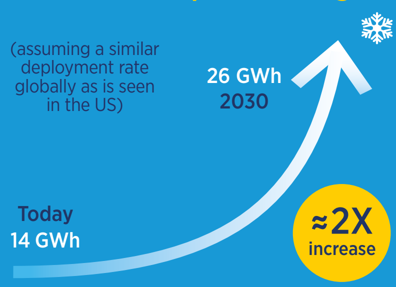
Water tanks can be used to enable on-site solar thermal generation to supply low-grade heat to industry.

Innovative sensible, latent and thermochemical technologies are being trialled to store high-grade heat.

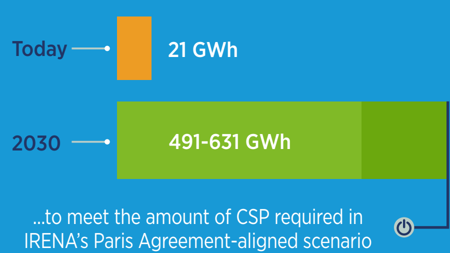
Current breakdown of TES for heat applications (excl. hot water tanks)



Significant projected increase in TES for space cooling



Required increase in molten salts for the power sector



TES technologies offer unique benefits compared to other forms of flexibility:

Demand shifting

TES can facilitate flexibility in the delivery of heat and cold, decoupling supply and demand

Variable supply integration

Heat/cold produced at times of peak supply of renewable electricity can be used to meet demand even when the sun is not shining and the wind is not blowing

Sector integration

TES enables whole system benefits through increased sector integration, allowing renewable electricity to reliably meet a greater proportion of energy demand

Network management

Increased flexibility arising through the deployment of TES can alleviate the strain on electricity networks, and can reduce the need for costly grid reinforcement

Seasonal storage

TES can enable winter heating demands to be met through thermal energy stored from sunny summer days, and cooling demands in summer to be met through cold stored from winter

Power

Molten salts are used to allow concentrated solar power (CSP) plants to discharge energy overnight.

Novel sensible technologies are being trialled for bulk stand-alone energy storage.

Buildings

Innovations using domestic hot water tanks and novel sensible, latent, and thermochemical heat batteries can integrate with heat pumps to enable flexibility of building's thermal demand.

Ice or PCM technologies can also enable flexibility of cooling loads in warmer climates.

District heating and cooling

Underground Thermal Energy Storage and novel PCM and thermochemical-based TES technologies have enabled district heating schemes that are completely powered by renewable generation, including on an interseasonal basis.

Storage that uses ice or PCMs enables demand shifting of energy demand for district cooling schemes.

Key actions required to accelerate the deployment of thermal energy storage

- Ensure a technology neutral, whole-systems approach is taken in energy systems policy making and planning, in order to address conflicting rules and regulations that arise from siloed thinking across heat, energy, and transport
- Invest more in research and development activities to help overcome the relative immaturity of some technologies
- Increase the number of TES demonstration projects in all parts of the energy system to improve stakeholder awareness of the benefits that these technologies can deliver

INSIGHTS FOR POLICY MAKERS

Thermal energy storage offers flexibility across all energy demand sectors in cities

In 2050 variable renewable energy should comprise more than 60% of power generation and thermal energy storage is one the enabling technologies for this transition.

From a power sector perspective, higher shares of variable renewable energy (VRE), mainly solar PV and wind power, are entering electricity systems every year. In 2018 around 10% of the power in global energy systems was from VRE generation. To comply with the climate targets in the Paris Agreement, IRENA estimates that VRE will see threefold growth by 2030, increasing its share to 35%, and sixfold growth by 2050, whereby VRE would provide more than 60% of global power generation (IRENA, 2020a).

With such a high share of VRE, flexibility becomes crucial to operate the overall energy system. Fundamentally, thermal storage is part of a wider portfolio of flexibility options that includes electricity storage and demand-side measures. The integration of thermal energy storage (TES) technologies is a promising solution, bringing a range of applications and merits

Over 234 gigawatt hours (GWh) of thermal energy storage act as a source of flexibility across the energy chain spectrum, from supply to demand (Figure 1).

Around 234 GWh[1] of TES is present across the globe, a crucial enabler of reliable, secure and flexible energy systems. Figure 1 depicts the key applications of TES in energy systems. From a supply-side perspective, TES can store the surplus electricity produced by solar and wind and reduce curtailment, mitigate rapid dips or spikes in output and enable capacity firming. An example of a mature TES technology is molten-salt storage at concentrated solar plants.

What is thermal energy storage?

It is the temporary storage of energy by heating or cooling a storage medium so that the stored energy can be used at a later time for power generation; a heating and cooling application. (European Association for Storage of Energy, 2017).

TES can be coupled with mechanical energy storage technologies; this provides complementary capabilities from both technologies.

Where is it used?

Today TES is tested and deployed in a variety of applications, such as utility-scale power generation, industry, district heating and cooling, buildings and cold chain logistics.

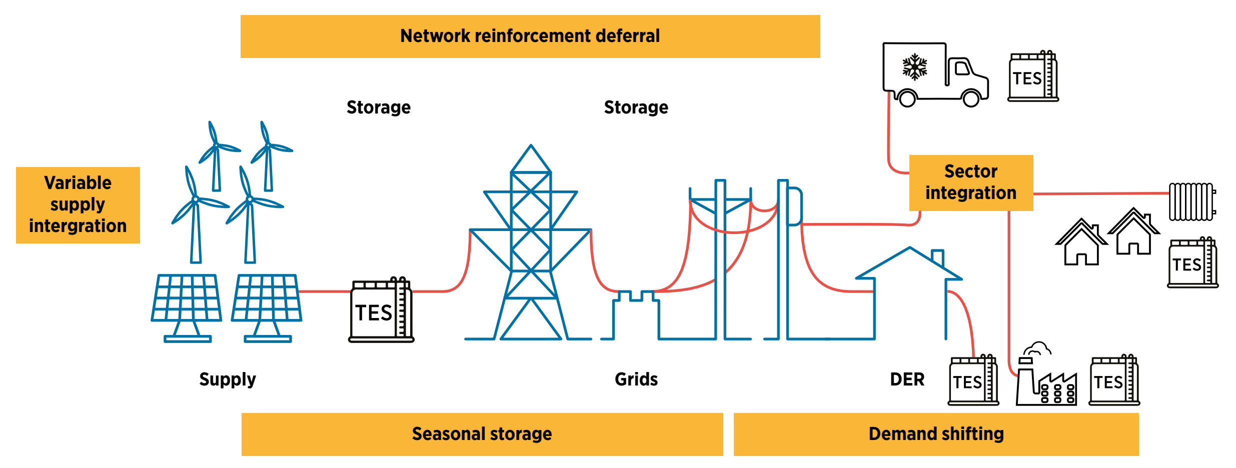
From a transmission and distribution angle, TES can help to defer or avoid the need for costly electricity network reinforcement. By enabling load shifting, it results in better utilisation of renewables, alleviates grid congestion and circumvents infrastructure investment.

A particular advantage of TES is the ability to store energy on a seasonal basis. Surplus heat produced with renewables in the summer can be retained in TES, and then used to meet heating demand during the winter period.

From an energy demand perspective, TES is capable of providing solutions for the overall energy system rather than focusing on individual vectors, such as power, heat or cold. Energy demand in end-use sectors such as buildings is strongly affected by seasonality. Thermal storage can store energy for hours, days, weeks or even months, helping to address seasonal variability in supply and demand. TES technologies such as thermal tanks (using water), solid state (using storage media such as rocks, concrete and ceramic bricks) and underground TES (UTES) can store excess power generation in summer and then supply space heating

1 Based on IRENA data collection of publicly available projects.

Figure 1: Key applications of TES in the energy sector



Note: DER = distributed energy resources.
Based on IRENA, 2019a.

during the colder seasons. Also, the other way around, chilled water tanks and UTES can be used on a seasonal basis to provide district cooling. This helps to cover electricity demand peaks when consumers require the most heating or cooling.

Moving to downstream energy, TES has the capacity to couple different sectors and improve the shape of heating and cooling loads. In a scenario that keeps the rise in global temperatures this century to well below 2°C and towards 1.5°C, the electrification of heat, cooling and transport will add a significant load to the power system. It would see an increase in electricity's share of final energy from 20% in 2017 to 49% in 2050 (IRENA, 2020a). Relying solely on power generators may stretch the energy system's resources and increase the overall cost. TES can help to improve the potential of strategies such as power to heat and cooling.

TES can help to integrate the power, heating and cooling sectors in a smart approach that benefits power as well as thermal systems.

The availability of low-cost and reliable renewable electricity is opening the door to integrate a renewable power sector with the buildings and industry sectors for a cross-sector decarbonisation strategy. For example, electricity demand for building space heating and/or cooling can be moved to lower-cost periods by charging up thermal storage during off-peak times and then discharging when required. This enables reduced grid congestion, higher renewable energy penetration and lower costs.

Industry can also benefit strongly from TES applications. It is characterised by its energy-intensive processes, and TES technologies can facilitate its wider electrification due to the wide temperature operating range in storage mediums. With the benefit of TES technologies that can reach over 500°C, such as chemical looping and solid state, the industrial sector can smartly manage its energy demand by storing low-cost energy that can be used for peak loads, also guaranteeing high-temperature heat supply for its processes (Figure 2).

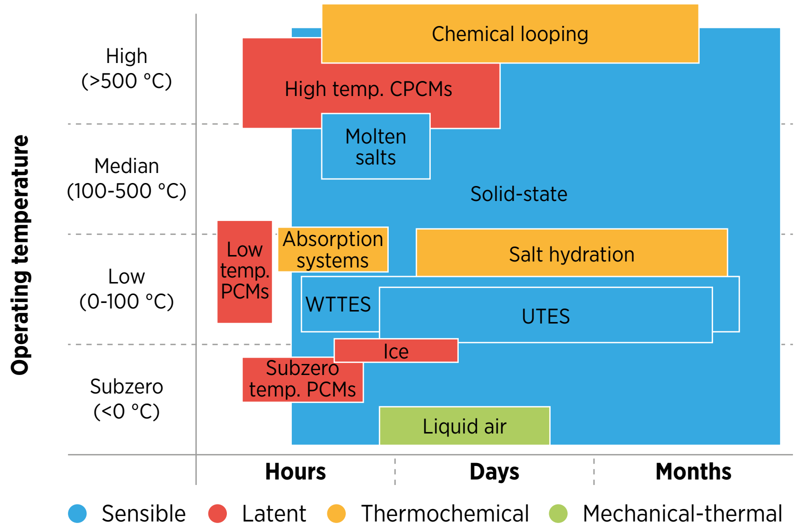
Figure 2: Operating temperatures and time ranges for TES technologies studied

What TES technologies are used in energy systems?

This report categorises thermal storage technologies into:

- Sensible
- Latent
- Thermochemical
- Coupled: Mechanical-thermal

It studies the status, benefits and innovation needs of 13 prominent TES sub technologies. Chapter 3 gives a detailed explanation of the TES sub-technologies.



Notes: cPCM = composite phase-change material; PCM = phase-change material; WTTS = water thank thermal energy storage.

TES market assessment

By 2030 TES could experience threefold growth, reaching over 800 GWh of installed capacity globally.

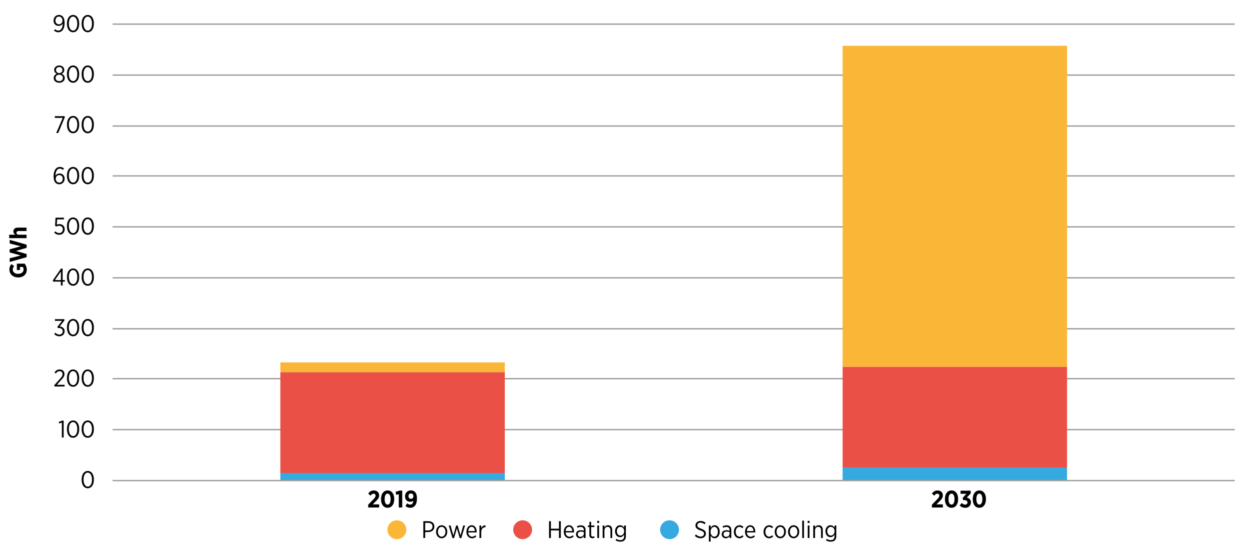
Energy systems are finding more solutions to smoothly incorporate the increasing share of renewables. For example, battery storage has emerged recently as a key source of flexibility for the power, buildings and transport sectors. All these solutions have different supply chains and applications, and the energy storage sector needs to be diversified to avoid potential bottlenecks and the concentration of risk. Special characteristics of TES, such as seasonal capability, large storage capacity, potential for higher round trip efficiency and longer life cycles, position its technologies as an attractive solution for energy markets. Figure 3 illustrates IRENA analysis, showing how over 234 GWh of TES capacity was installed globally by the end of 2019 and how IRENA's Paris Agreement-aligned Transforming Energy Scenario expects capacity to have increased threefold by 2030, reaching at least 800 GWh.

A growing business case lies ahead for TES technologies – in the next decade investment in the range of USD 12.8 billion to USD 27.22 billion is foreseen for power and cooling TES applications.

Power

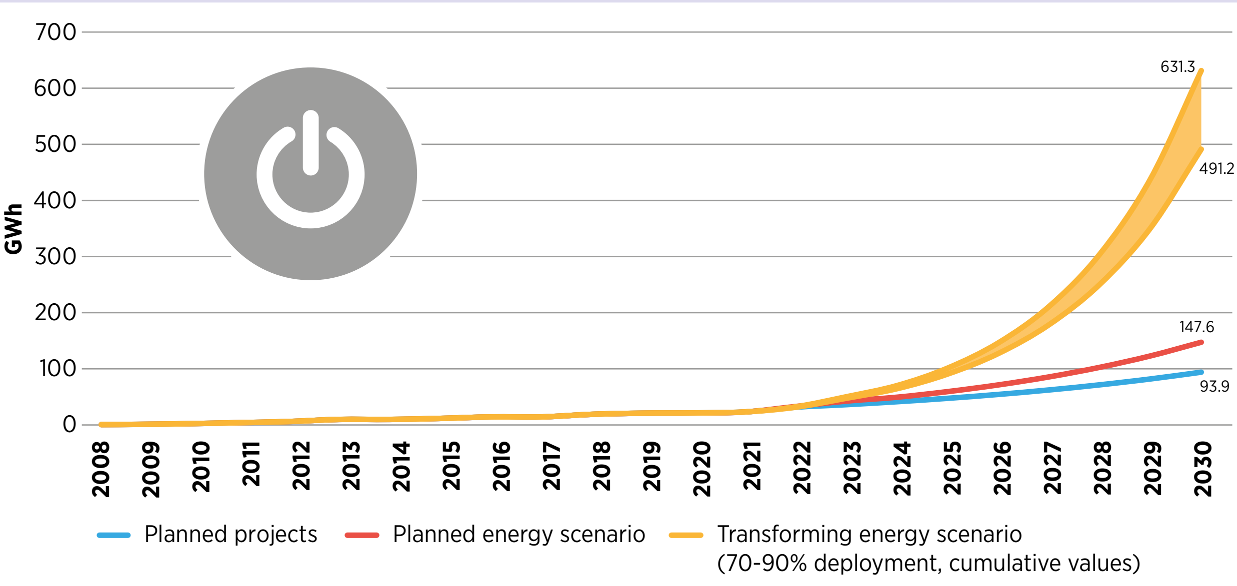
In the power sector TES is used for load shifting, capacity firming and ancillary services. Currently, molten-salt TES is the technology most used in the sector due to its advanced technological readiness and its application with concentrated solar power (CSP) plants. Molten-salt storage capacity of over 21 GWh is currently installed worldwide. In IRENA's Paris Agreement-aligned Transforming Energy Scenario, with more ambitious renewable energy growth in comparison to current trends, policies and plans, additional CSP capacity of 56 gigawatts (GW) would be needed by 2030 (IRENA, 2020a). This growth in CSP capacity, illustrated in Figure 4, would deliver a fourfold increase in installed capacity of molten-salt TES (compared to the Planned Energy Scenario), between 491 GWh and 631 GWh. The cumulative investment needed in molten-salt TES in the next 10 years is between USD 12.3 billion and USD 24.4 billion, depending on the CSP technology used.

Figure 3: Installed TES capacity projections according to IRENA's Paris Agreement-aligned Transforming Energy Scenario



Note: Heating projections are not in the scope of this analysis due to a lack of data on aquifers and small-scale distributed TES (e.g. residential water tanks). Nonetheless, growth in the installed capacity of these technologies is expected given their versatile use from short to seasonal scale.

Figure 4: Molten-salt TES installed capacity



Space cooling

Currently, out of a total of 400 TES projects identified by IRENA at the end of 2019, around 160 projects amounting to over 13.9 GWh of installed TES capacity are used for cooling in buildings and district cooling systems. This number may increase rapidly in the coming years, especially in some emerging economies where temperatures are reaching extreme levels and further advanced and large-scale cooling technologies are being adopted. TES can assist power system operators by ensuring lower system costs and higher integration of VRE via additional demand-side management capabilities.

As Figure 5 shows, an estimated doubling in global deployment of cooling TES is required to meet cooling demand in 2030, with required investment in the next ten years of about USD 560 million to USD 2.82 billion.

Heating

District heating applications make up the largest share of the current installed capacity of TES for heating, due to the use of aquifer TES (ATES) and borehole TES (BTES) with large volumes. Approximately half of current district heating projects use between-season storage (Figure 6), a special benefit that TES technologies bring to the energy system.

Figure 5: Installed and projected capacity of TES for space cooling at a global level

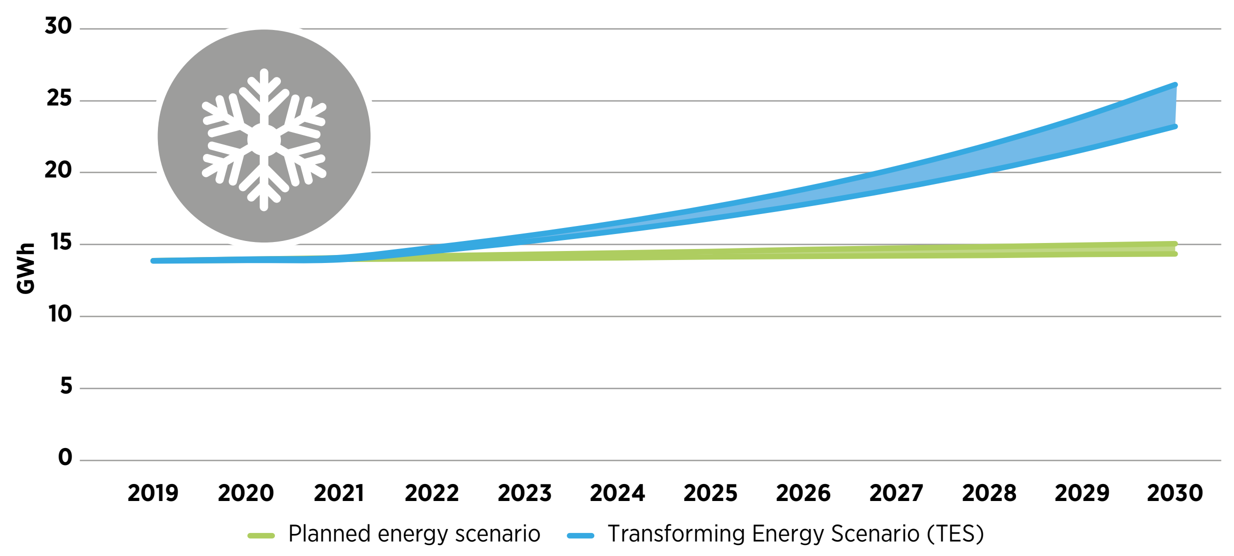
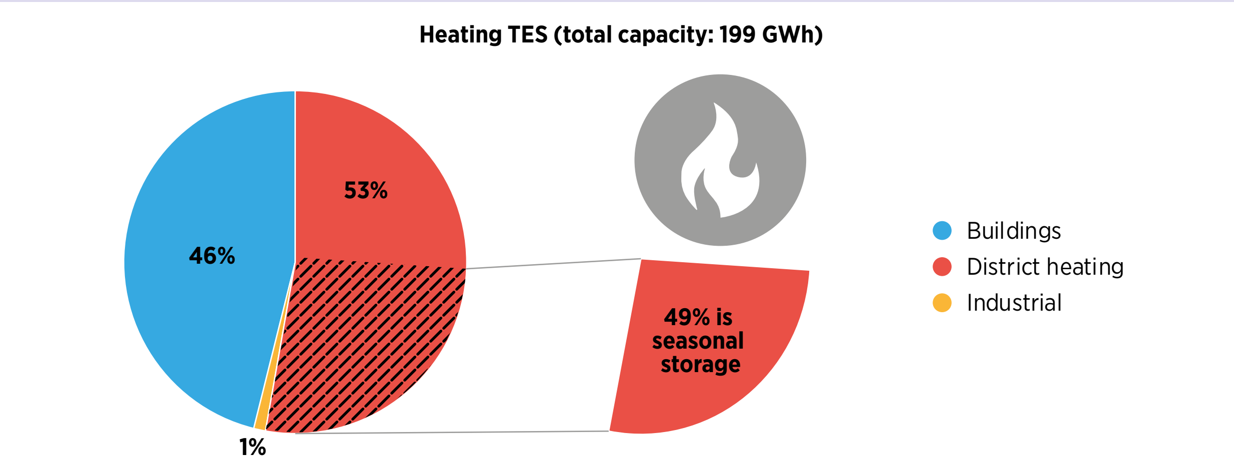


Figure 6: Installed capacity of TES for heating applications



Solar power tower

Image credit: Shutterstock

Sector applications and innovation outlook

In the energy transition, TES technologies have an important role to play, but their potential is untapped. Innovation is still needed to increase the commercial readiness of TES technologies.

TES can facilitate the introduction of higher shares of renewables and contribute to the decarbonisation of five key sectors: power, industry, district heating and cooling, cold-chain applications and buildings.

Power

The power sector has adopted TES on a commercial scale with molten-salt storage used in CSP plants. In the coming years other TES technologies may come closer to commercial levels, such as solid state and liquid air, storing surplus energy from CSP, solar PV and wind.

Molten salts are already in use today to allow CSP plants to consistently generate power by charging during the day and discharging at night. Other TES technologies, such as solid-state thermal storage using concrete, are being trialled. As the raw material in this example is inexpensive, it could reduce the capital cost of CSP applications.

Solar energy harnessed with CSP could also be stored as chemical energy through a thermochemical looping system, in which solar energy is stored for later release through a chemical reaction (Pardo et al., 2014).

Other promising TES technologies are displayed in Figure 7. As they cross the early technology readiness levels, they also have great potential to mitigate the rapid fluctuations of VRE supply and integrate growing renewables on the grid.

These systems need to achieve breakthroughs in the coming years and decades for technologies under development to successfully reach commercialisation and for the wider roll-out of molten salts.

In the coming five years, the next generation of molten salts could increase operating temperature ranges up to 700°C and improve performance, which would increase the round-trip efficiency[2] of CSP plants to over 92%. More pilot plants could emerge for solid-state storage and novel stand-alone molten-salt thermal batteries.

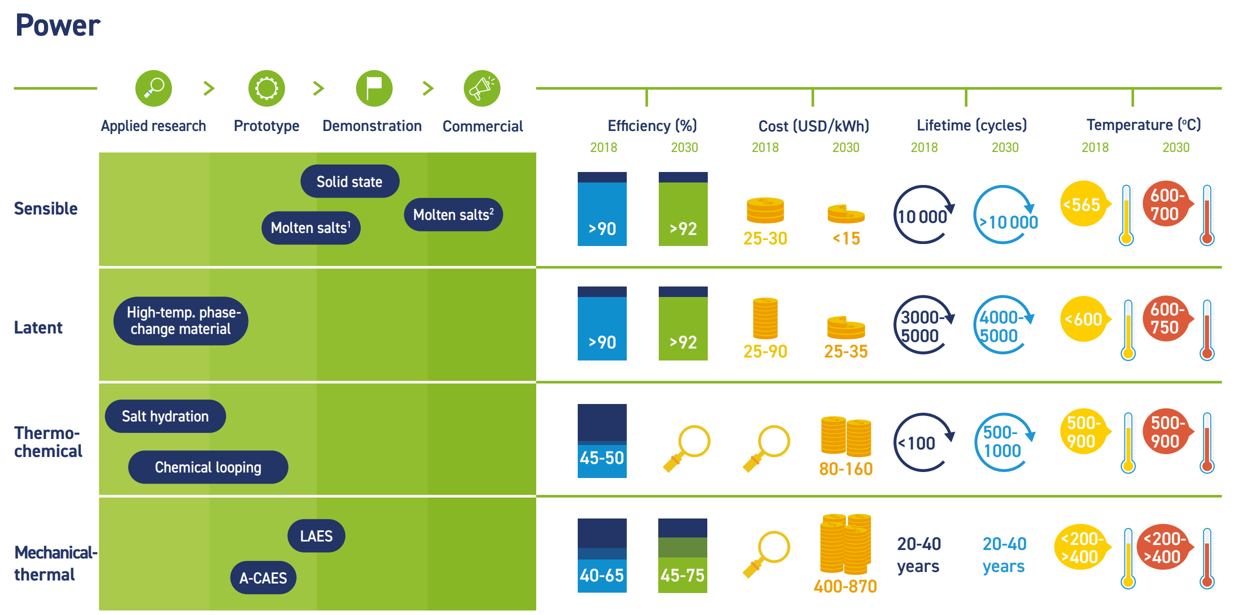
By 2030 TES costs for power generation technologies may experience cost reductions of over 50%, reaching USD 15 per kilowatt hour (kWh).

By 2030 efficiencies in liquid air energy storage (LAES), adiabatic compressed air energy storage (A-CAES) and solid-state systems are expected to have increased, enabling greater use of TES across wind and solar PV generation, and also potentially to serve as effective alternatives to molten salts in CSP.

By 2050 developments in thermochemical storage could enable much higher conversion efficiencies at CSP plants. Also, molten salt-based storage could enable fossil-fuelled power plants to be reused for renewable energy storage, saving decommissioning costs and contributing to their decarbonisation.

2 Round-trip efficiency is the relationship between energy put into storage and energy retrieved. It represents how effective the technology is at retaining and discharging thermal energy once stored. This parameter can be strongly dependent on the system working conditions (e.g. daily or seasonal).

Figure 7: TES technology status and innovation outlook in the power sector



Short term (5 years)
- Next generation of molten salts with increased operating temperature ranges and performance, improving conversion efficiencies and reducing costs of CSP plants.
- Pilots could emerge for solid-state storage and novel standalone molten-salt thermal batteries.

Long term (10+ years)
- Developments in thermochemical storage could enable much higher conversion efficiencies in CSP plants.
- Molten salt-based storage could enable fossil-fuelled power plants to be reused for renewable energy storage.

Medium term (5-10 years)
- LAES, adiabatic CAES and solid-state systems will enable greater use of TES across wind and solar PV generation, and also potentially serve as effective alternatives to molten salts in CSP.

Note: Magnifying glass means value not available due to low technology readiness level; (1) Standalone; (2) Co-located with CSP.

Thermal storage for renewables can help to decarbonise power, industry, heating, cooling and buildings.

Industry

In industry, heat production consumes significant shares of the energy used, creating a great need for decarbonisation.

TES can already be used to store low-temperature heat generated either through electrically powered heat pumps or by on-site solar thermal plants. Decoupling heat use from generation would permit flexibility and smart energy use, and would allow continuous demand to be met by intermittent renewable generation.

There is a nascent, but growing, use of water tank thermal energy storage (WTTES or TTES) in conjunction with solar thermal plants for low-temperature heat generation and storage, predominantly in the mining, food and textile sub-sectors (Figure 8). The key markets are Austria, China, France, Germany, India, Mexico and Spain (Weiss and Spork-Dur, 2019).

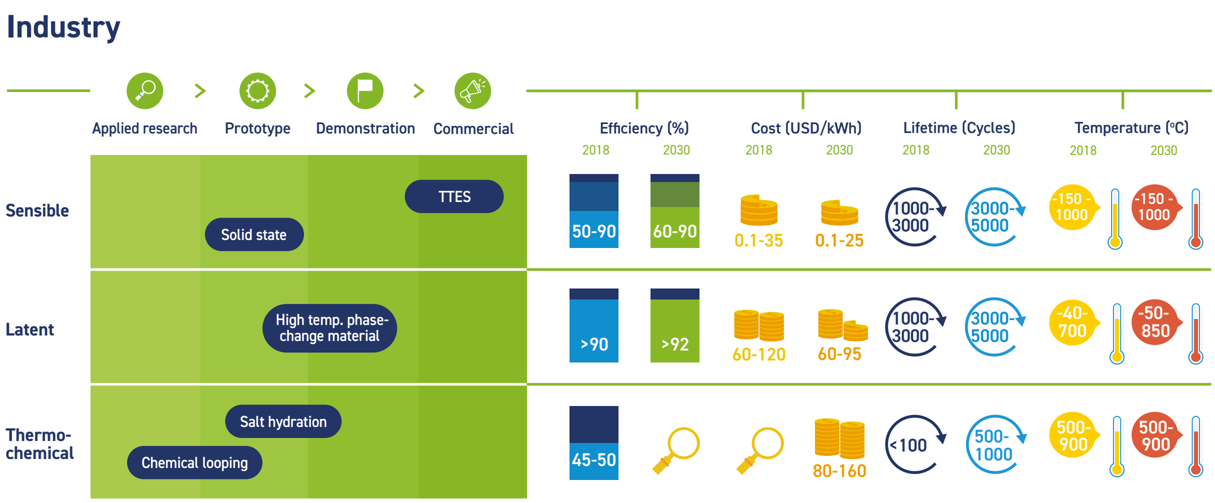
By 2030 sensible technology costs, which include TTES, are expected to drop by almost 30% from USD 35/kWh to USD 25/kWh. In conjunction with enhancements to integration, management and control of existing TTES, this could encourage greater deployment of solar thermal generation for processes that require low-temperature process heat.

In the coming decade solid-state technologies could offer a low-cost form of storage to provide both electricity and heat to industrial processes in a similar fashion to co-generation plants today.

By 2030 high energy density PCMs and salt hydration storage solutions could help to reduce the spatial footprint of TES systems, potentially expanding their range of applications. In the longer term further research is needed to understand the potential for chemical looping and other thermochemical storage systems integrated into manufacturing processes to help meet higher-temperature process heat requirements.

Water tanks are coming into wider use for low-temperature heat generation and storage in conjunction with solar thermal plants.

Figure 8: TES technology status and innovation outlook in the industrial sector



Short term (5 years)

- Cost reductions and enhancements in integration and control of existing TTES could encourage increased deployment of solar thermal generation for processes that require low-temperature process heat.

Medium term (5-10 years)

- Solid-state technologies could provide a relatively low-cost form of storage that can provide both electricity and heat to industrial processes.
- High-temperature cPCMs and salt hydration storage solutions could reduce the spatial footprint of TES systems, potentially expanding their range of applications with competitive efficiencies.

Long term (10+ years)

- Chemical looping and other thermochemical storage systems integrated into manufacturing processes alongside renewables could aid decarbonisation of processes that require higher-temperature process heat.

Note: Magnifying glass means value not available due to low technology readiness level.

Cold chains

TES technologies such as ice and other PCMs are commercially available today, and used in refrigerated vehicles and static chillers across the cold chain.

The cold chain refers to the uninterrupted supply chain required to bring products that must be stored at low temperatures from their producer to their point of consumption.

Growth in electrified refrigeration is expected to significantly increase demand on networks, especially in emerging economies with very hot climates. As these economies grow, they will have to develop cold chains in a clean and cost-effective manner.

TES could particularly support the production, storage, transport and retail segments of the cold chain, meaning TES can couple power, cooling and mobility. Another segment that could benefit is off-grid renewably supplied refrigeration, to enhance food and medicine supply chain efficiency.

There are several examples of companies serving markets in Africa, China, Europe, India and the Middle East that integrate engineered PCMs into refrigerated vehicles and containers for food and vaccine transport and/or storage. For example, researchers in the United Kingdom developed a PCM cooling system to maintain low temperatures in interchangeable road and rail containers (University of Birmingham, 2018).

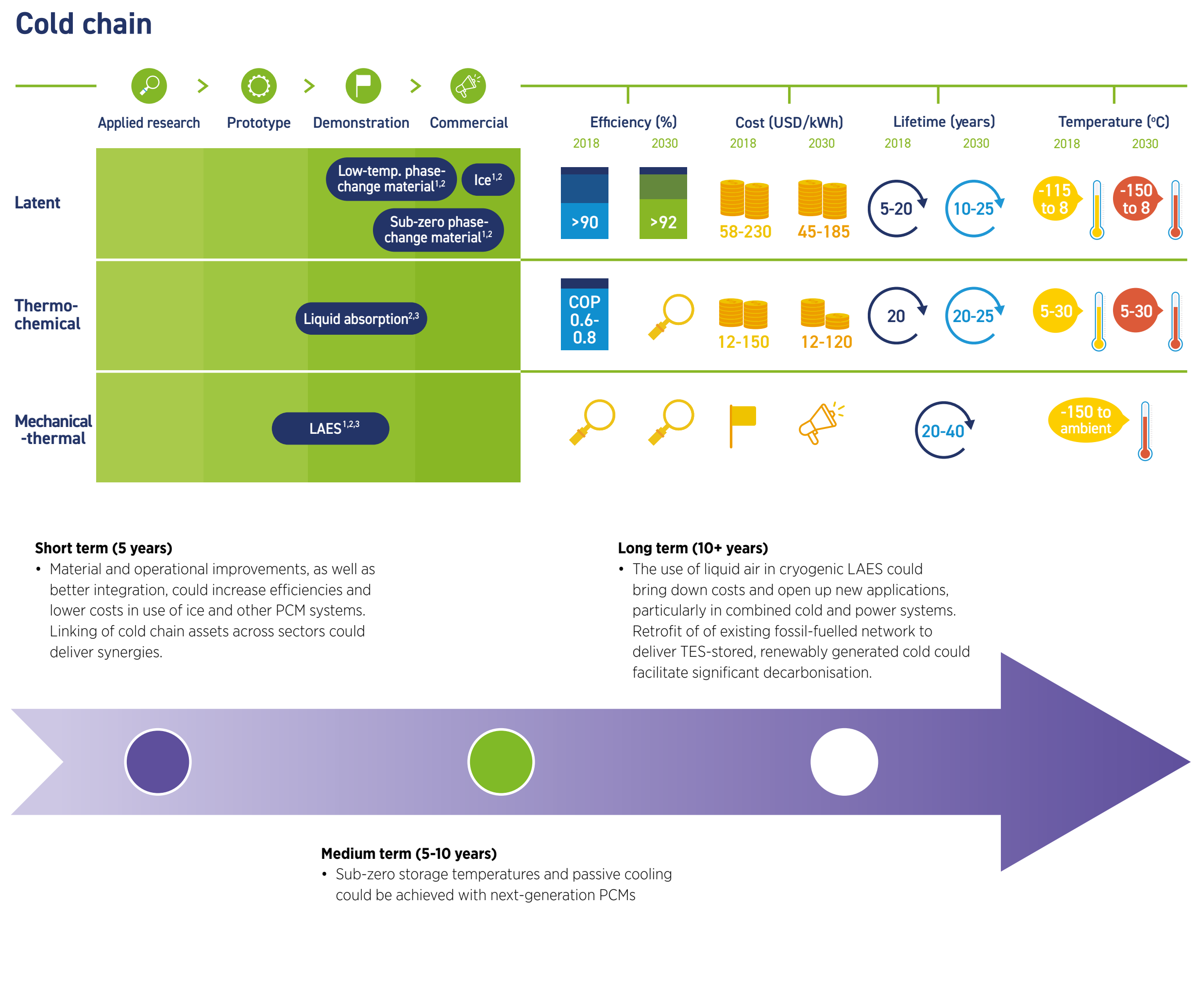
In the next five years material and operational improvements, as well as better integration, could increase efficiencies and lower costs in the use of other PCM systems (Figure 9).

In the coming decades, cooling generated from renewable thermal energy sources (such as solar and biomass co-generation) could be stored using TES, specifically absorption systems.

Due to the high energy density and minimal thermal losses seen in absorption systems, cold can be stored for both short and long timescales (such as inter-seasonally) for space cooling in the cold chain. In the longer term liquid air could be used to both power vehicles and keep them cool.

Thermal energy storage can effectively couple renewable power, cooling and mobility.

Figure 9: TES technology status and innovation outlook in the cold chain sector



Note: Magnifying glass means value not available due to low technology readiness level; Flag means demonstration stage; Megaphone means commercial stage; (1) For the storage of cold; (2) For refrigerated transportation; (3) For the production of cold.

District heating and cooling

TTES is deployed widely throughout the world and ice TES is currently used in district cooling schemes. Other PCMs and thermochemical TES technologies are on the way and expected to help decarbonise this sector.

Sensible storage technologies such as TTES and UTES are widely used in conjunction with district heating schemes today. Ice and other PCM-based solutions have also been implemented in district cooling. The key benefit of using TES in district heating and cooling is its ability to decouple heat and cold generation from consumption, giving the possibility to store energy across a range of timescales, from hourly to a seasonal basis.

In the medium term other innovative PCM and solid-state solutions could integrate high shares of renewables via power-to-heat or via seasonal solar thermal schemes, as successfully trialled in Canada, China and Europe.

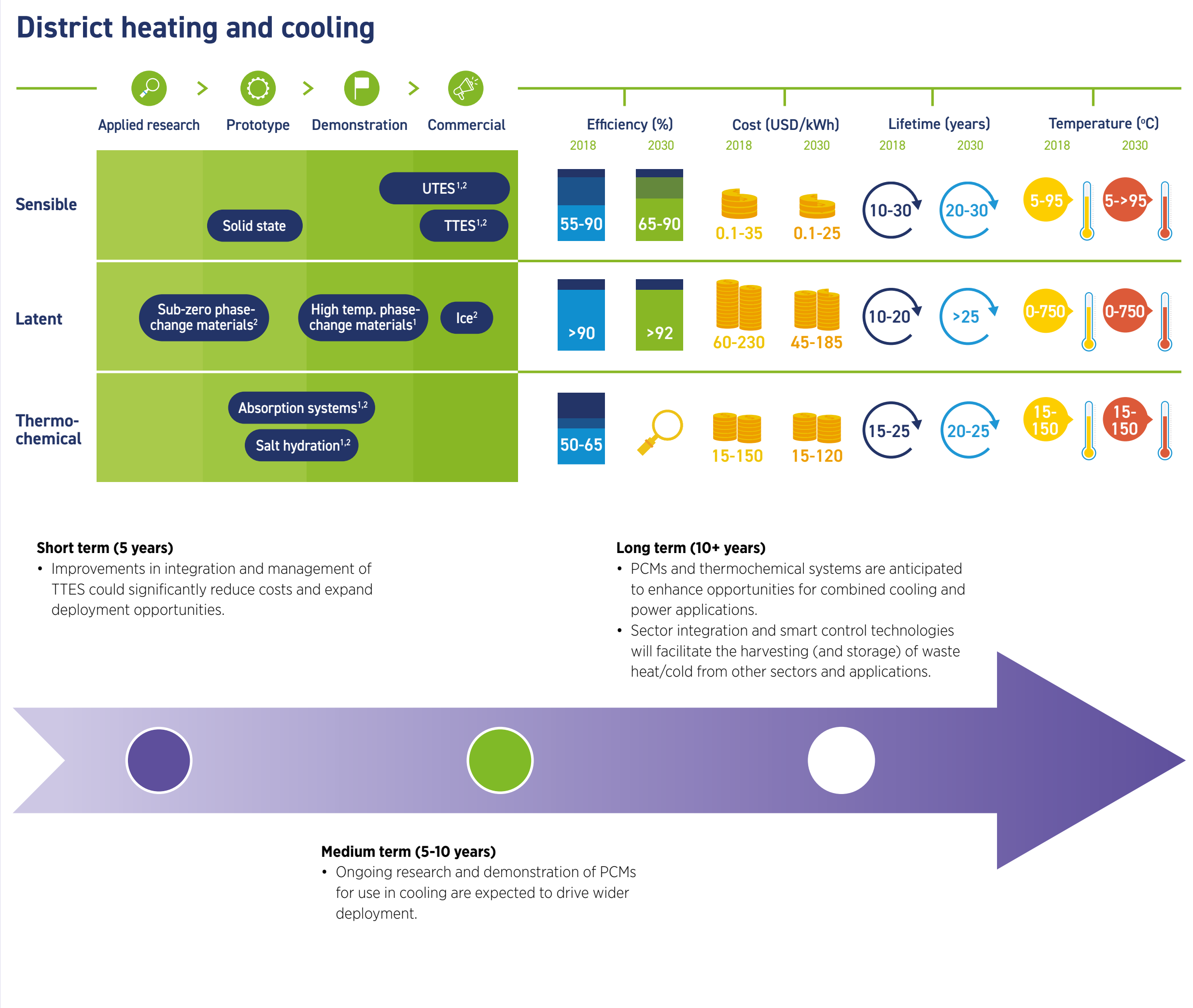
Efficiency levels of over 92% are expected for TES technologies used in industrial applications by 2030.

In the next 10 years ongoing research and demonstration of PCMs for use in cooling are expected to drive wider deployment.

By 2050 thermochemical systems could enter the demonstration phase, with prices as low as USD 10/kWh, to enhance opportunities for renewables deployment in district heating and cooling, especially in combined cooling and power applications. In this decade, sector integration and smart control technologies should intensify opportunities, particularly for facilitating the harvesting (and storage) of waste heat/cold from industrial applications (Figure 10).

Storage capacity linked to district heating and cooling networks serves to decouple their generation requirements from consumption.

Figure 10: TES technology status and innovation outlook in the district heating and cooling sector



Note: Magnifying glass means value not available due to low technology readiness level; (1) For district heating; (2) For district cooling.

Buildings

Thermal batteries based on simple TTES, solid-state or more advanced PCM technologies can be used with or without heat pumps to electrify heat.

Water TTES is widely used across the world for storing heat in buildings, while UTES is used in various cases in smaller-scale installations. PCM and solid-state thermal batteries and ice storage that replaces air-conditioning units are proven technologies, but have only been deployed on a relatively minor scale. Thermochemical technologies are also being investigated and could act as a form of distributed seasonal storage (Figure 11).

PCM-based systems have been proven to generate savings for consumers compared to gas-powered boilers, and should be the focus of more attention.

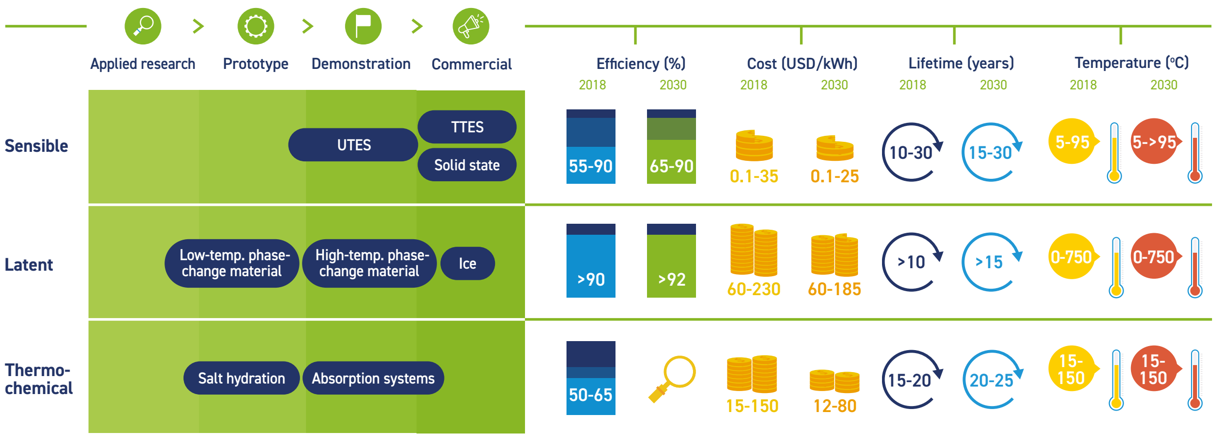
Trials of PCM thermal batteries combined with energy management systems are taking place. They could demonstrate how such batteries can use off-peak power to decarbonise heat and save consumers money. Materials are also being developed with improved thermal properties and corrosion resistance for use in tank and solid-state TES technologies; this will help to improve efficiency up to 90%, while enhanced innovations in integration and control systems will improve their cost-effectiveness.

By 2030 cost reductions and technical improvements in next-generation high- and low-temperature PCMs and composite phase-change materials (cPCMs) could help increase the deployment of latent thermal storage in buildings. On a longer-term basis research and development (R&D) activities are foreseen focusing on realising material and system improvements in thermochemical TES technologies, which could see a move into the demonstration stage.

Thermal batteries storing off-peak power can help to decarbonise heat and save consumers money.

Figure 11: TES technology status and innovation outlook in the buildings sector

Buildings



Short term (5 years)
- PCM thermal batteries combined with energy management systems are being trialled to demonstrate use of off-peak power to decarbonise heat/cooling and save consumers money.
- A development in materials to improve thermal properties and corrosion resistance in tank and solid state TES technologies could improve efficiency, and enhanced innovations in integration and control systems will improve cost effectiveness.

Medium term (5-10 years)
- Cost reductions and technical improvements in next-generation high- and low-temperature PCMs and cPCMs could help increase deployment of latent thermal storage in buildings.

Long term (10+ years)
- Research and development activities focussing on realising material and system improvements in thermochemical TES technologies could see these move into demonstration.

Note: Magnifying glass means value not available due to low technology readiness level.

Policy recommendations

Progress has been made in decarbonising the power sector, but further policy development work is required to fully address the decarbonisation challenges in heating and cooling, and in particular to further renewable energy penetration in these end-use sectors.

Key barriers to the uptake of TES across energy systems include (Figure 12):

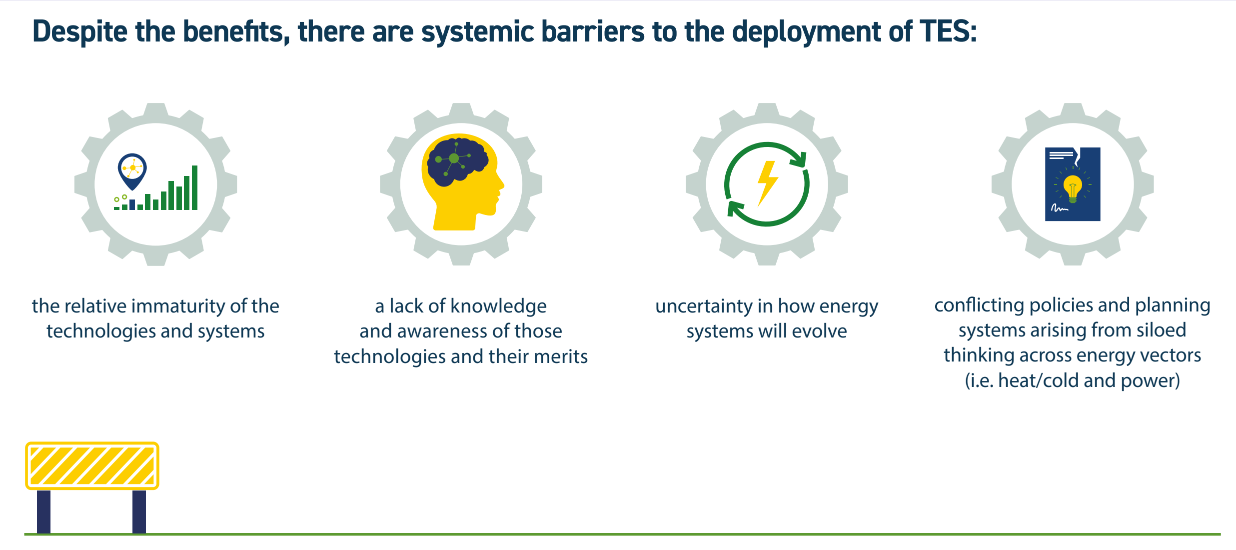
- The **lack of technology readiness** that applies to some TES technologies, and competing technologies with high TRLs (e.g. inexpensive fossil-generated heating).
- The **lack of knowledge and awareness of how TES can provide benefits** to society, the public sector and industry. This has manifested itself in a disproportional focus of R&D efforts on electrical battery storage, when thermal storage is a critical source of flexibility to enable high shares of renewable energy.
- **Uncertainty in how the future energy system will develop**, which leads to a reluctance to invest in long-term or large-scale projects.
- **Siloed thinking across different energy vectors** *(i.e. heat/cold and power)* and different sectors, leading in some cases to conflicting policies and inefficient planning. Furthermore, there is generally a lack of policy for the decarbonisation of heat compared to the power sector.

A range of technology push, market pull and enabling mechanisms can help policy makers and main actors in the sector effectively tackle these barriers and encourage the wider deployment of TES. Policy makers and other key stakeholders should consider the following actions:

- Increase the focus on decarbonisation plans for industry and the provision of heat and cold. Develop them as part of an **integrated energy policy** to realise higher levels of system benefits.
- Take a **whole-systems approach to decarbonising energy systems**, which is key to enabling a cost-effective energy transition. Consider all flexibility technologies across vectors to determine the most cost-effective pathway to a decarbonised energy system.
- **Invest more into the R&D of TES technologies**, enough to match the unique potential that they have to help decarbonise the heat, power and cooling sectors. Fund demonstrations to help build market awareness, increase consumer confidence and, of course, progress technology readiness levels.
- Looking at policy makers' broader energy policy, consider **removing fossil-fuel subsidies and introducing a price on carbon**, which would significantly improve the competitiveness of low-carbon heating systems.
- **Create market mechanisms** such as time-of-use tariffs to incentivise demand-side flexibility and help reduce consumer bills, as well as increase the utilisation of renewables. Build a market for ancillary services where participation is technology-neutral to help overcome barriers typically seen for battery storage, and provide additional revenue streams for owners/operators of TES.

3 There are also sector-specific barriers, which are addressed in detail in Chapter 4.

Figure 12: Barriers to TES deployment



Technology push and market pull, combined with key enabling mechanisms, can unlock rapid growth in thermal energy storage.

Table 1 presents other potential policy interventions relevant to advancing TES deployment in each sector.

Table 1. Overview of policy interventions that are relevant to TES in each end-use sector

Application	Regulatory/policy environment	Stakeholder acceptance	Technical performance	Financial proposition
Power	• Adopt decarbonisation policies. • Regulate heat market as part of holistic multi-vector energy regulation. • Issue energy storage mandates.	• Fund demonstration and pilots in sensible storage, and for high-temperature cPCMs, to prove technology and commercial benefits to investors and other stakeholders.	• Fund R&D, demonstrations and pilots in sensible storage, and for high-temperature cPCMs, to accelerate technology readiness level.	• Fund R&D, demonstrations and enterprise support in sensible storage, and for high-temperature cPCMs, to drive cost reductions through innovation. • Use market pull policies to drive adoption TES with collocated storage.
Industry	• Ensure decarbonisation policies do not exclude industry. • Co operate internationally to overcome fears related to competitiveness. • Remove fossil fuel subsidies to help increase value proposition of TES.	• Lead government initiatives to demonstrate technologies with industrial participants. • Support knowledge sharing and diffusion using demonstrations and "champion" organisations to reduce perceived risk of technology adoption.	• Fund R&D, demonstrations and pilots, particularly for chemical and latent storage, to accelerate development	• Fund R&D, demonstrations and pilots particularly for chemical and latent storage, to drive cost reductions through innovation. • Provide investment support and price support as market pull options once technology has been proven to help overcome financial barrier.
Cold chain	• Remove fossil fuel subsidies to help make cold-chain technologies more competitive vs a diesel alternative	• Provide knowledge sharing support around latent storage demonstrations. • Support enterprise to help companies demonstrate and communicate benefits of TES to customers to help break into/create cold-chain market.	N/A	N/A
District heating and cooling	• Improve regulatory environment for district heating and cooling more generally. • Remove fossil fuel subsidies to help increase value proposition of TES.	• Provide knowledge sharing support around latent storage demonstrations	• Provide a range of technology push support for chemical and latent storage solutions. • Provide market pull support mechanisms for chemical storage solutions.	• Improve the financial proposition of district heating and cooling with market pull mechanisms. • Provide knowledge sharing support to increase awareness of the benefit of TES.
Buildings	• Remove fossil fuel subsidies to help increase value proposition of TES. • Integrate and regulate heat and power markets. • Issue energy storage mandates, building codes, etc.	• Provide ecosystem support to boost public awareness of benefits of TES for domestic applications.	N/A	• Provide technology push support to develop low-temperature PCM and salt hydration-based products. • Provide market pull support to incentivise domestic/non-domestic consumers to purchase devices.

Note: N/A dennotes that no main needs were identified.

Application	Industry supply chain and skills	Market opportunities	Company maturity	Enabling infrastructure
Power	N/A	• Create balancing markets, time-of-use tariffs or other incentives that recognise the value that periodic storage provides to the power sector. • Introduce long-term storage revenue mechanisms like power purchase agreements to cover 24/7 demand profiles (e.g. Dubai, South Africa, Chile).	N/A	• Accelerate penetration of renewables to drive the need for flexibility solutions, such as TES.
Industry	N/A	• Create balancing markets, time-of-use tariffs or other incentives that recognise the value that demand flexibility provides, and help develop the value proposition for thermal storage (and on-site renewables).	• Introduce technology certification/recognition by trusted third parties to reduce perceived risk.	• Accelerate penetration of solar thermal generation and heat pumps in industry.
Cold chain	• Support supply chain development (e.g. LAES).	N/A	• Support enterprises and ecosystems to boost profile of new technologies such as LAES.	• Co-ordinate LAES with LNG gasification infrastructure. • Develop LAES-based cold chain.
District heating and cooling	N/A	• Provide ecosystem support to highlight benefits of TES to renewable district energy projects.	N/A	• Accelerate penetration of renewably powered district heating and cooling schemes as part of integrated systems approach.
Buildings	N/A	N/A	N/A	• Support development and penetration of heat pumps. • Ensure correct incentives in place for efficient management and adaptation of grids.

Note: N/A dennotes that no main needs were identified.

Figure 13: Recommendations for policy makers

A range of tools are available to policy makers seeking to support TES development:

Policy and planning

Invest in research and development activities and in demonstration projects can help to overcome technical challenges, build market awareness of the unique capacities of TES systems and reduce the perceived risk of deploying them.

Planning and regulatory framework

Ensure coherence of energy policy making, for example introduce carbon pricing systems, remove fossil fuel subsidies, introduce building codes to shift heating systems away from fossil fuels.

Market structure

Support the development of technology neutral market structures so that TES can compete with other sources of flexibility to provide services to energy systems.

Research and innovation

Take a whole systems approach to energy systems planning and strategy, to ensure heating, cooling and industrial energy use are accounted for in decarbonisation efforts.

Policy makers can also address sector-specific challenges with targeted interventions

Power

- Provide subsidies or other technology push interventions to improve financial value propositions and increase consumer awareness and acceptance for novel technologies
- Develop industry supply chain and skills

Industry

- Employ market pull mechanisms such as cap and trade schemes to improve the financial proposition of onsite renewables and thermal storage compared to fossil fuels
- Introduce certification schemes, media campaigns and demonstration projects to increase awareness and build trust in new technologies

Cold chain

- Address systemic barriers to energy storage in regulatory frameworks, as part of holistic energy policy
- Provide price signals for flexibility, to improve the value proposition for storage technologies
- Increase funding for R&D and demonstration projects that look specifically at TES

Buildings

- Investment support mechanisms and command and control mechanisms, *e.g.* public procurement can accelerate development of renewably powered district heating/cooling schemes
- Provide clear guidlines and regulations for planning, building standards and environmetal protection

District heating and cooling

- Increase funding for R&D and demonstrations to help accelerate technology development
- Encourage consumers uptake through media campaigns and price support mechanisms for TES or enabling infrastructure such as heat pumps
- Introduce mandatory building codes to shift away from fossil powered heating systems

Thermal power plant
Image credit: Shutterstock

1. SETTING THE SCENE

1.1 The energy transition

Globally, energy systems are undergoing a significant transition driven by decarbonisation

The manner in which energy is generated, stored, transmitted, distributed and used is changing throughout the world. Various factors are driving these changes, including moves to widen access to energy, to make energy supplies more affordable and secure, and crucially to reduce the emissions of greenhouse gas emissions associated with our energy systems. International efforts to mitigate climate change have most recently been reaffirmed in the Paris Agreement, which sets a goal to keep the global average temperature rise to well below 2°C. At the time of writing, France, Norway, Sweden and the United Kingdom have enshrined in law a commitment to achieve net-zero greenhouse gas emissions by 2050,[4] and other countries are looking to follow suit.

Looking ahead to 2050, energy system decarbonisation and whole-economy transition will be required to achieve these ambitious international climate change mitigation goals. IRENA releases regularly updated forecasts of its Transforming Energy Scenario for 2050. They envisage how global energy system transition might unfold in a manner which would facilitate the achievement of these goals. Key insights from recent reports which highlight the scale of the challenge are (IRENA, 2020a):

- The energy intensity of the global economy will need to fall by about two-thirds.
- By 2050 energy-related emissions will need to decline by 70% compared to today's levels.
- The share of electricity generated by renewables will need to rise to 86% by 2050, up from 26% today.

Energy is used in a wide range of sectors and areas of human activity, including for power generation, heating and cooling, and in industry, transport and buildings. Figure 14 summarises current global shares of greenhouse gas emissions associated with energy use in these sectors. Emission reduction forecasts for each sector are also presented, showing the decarbonisation opportunities available under the Transforming Energy Scenario.

Effectively integrating a higher share of renewables in the power sector will be a key challenge

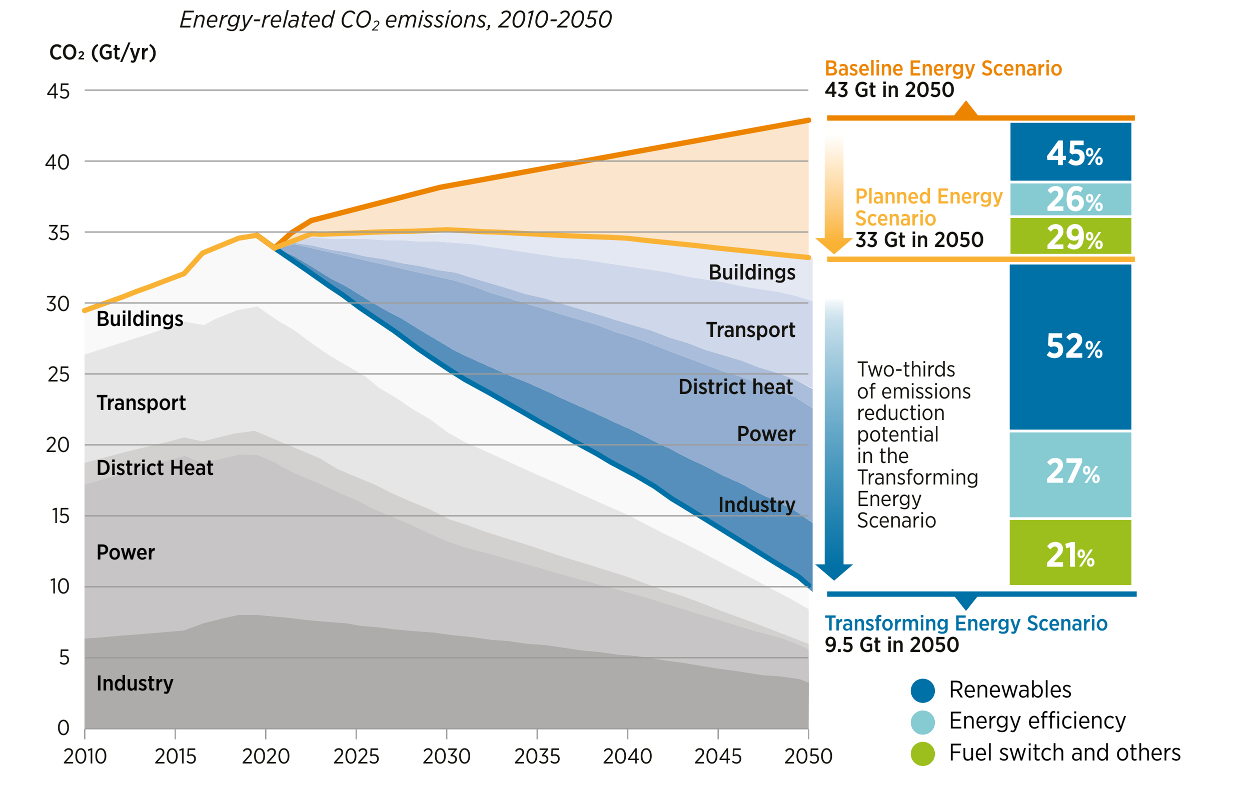
Particular focus is currently on decarbonising the **power** sector. Renewables for power generation have gained prominence due to cost reductions in technology, which both encourages and is driven by increased uptake. For example, the global average levelised cost of electricity (LCOE) from utility-scale solar photovoltaics (PV) fell by 82% between 2010 and 2019 (IRENA, 2020b). The renewable share of electricity generation accounted for 26% in 2017, but is expected to grow to 86% by 2050 (IRENA, 2020a). As such, decarbonisation of electricity production will continue to be an important priority.

Wider deployment of renewable generation technologies such as wind, solar PV and concentrated solar power (CSP) is anticipated. However, changeable weather conditions make these technologies inherently variable and intermittent (IRENA, 2017a).

Handling the variability of renewables will pose unique challenges for power system operators as they scale up, particularly ensuring effective power dispatch, system stability and security of supply. A priority in the strategic management of increasing renewables deployment will be avoiding their curtailment, where renewable generators must stop generating to meet grid balancing requirements (IRENA, 2019b).

4 Norway has a 2030 target, and Sweden has a 2045 target. The United Kingdom and France have a 2050 target.

Figure 14: Annual energy-related CO_2 emissions with itemised contribution by sector, 2010-2050



Source: IRENA, 2020a.

Decarbonising the heating and cooling sectors will be another significant challenge

Globally, half of final energy consumption is for **heat**, split evenly between space heating and industrial processes. Only 9% of global heat demand (including water heating) is currently met by renewables, compared with 26% for electricity generation in 2017 (Collier, 2018). Thus, it is important to find a sustainable and affordable way to decarbonise the supply of heat.

Space **cooling** is the fastest-growing use of energy in buildings, and this trend is especially evident in hotter countries where the economy is growing rapidly such as India, Indonesia, Brazil and countries of the Middle East. By 2050 around two-thirds of the world's households could have an air conditioner (IEA, 2018a). Given that cooling is delivered almost entirely by electricity, a key challenge to effective decarbonisation is to ensure this growth in demand is met by renewable generation, complemented by thermal energy storage (TES) systems and minimising impacts on local networks.

Electrification of other end-use sectors can help to drive decarbonisation

With ever-increasing deployment of renewables in the power sector, transitioning energy use to electricity in other sectors – including transport, buildings (heating and cooling) and industry –could contribute to decarbonisation. The electrification of other end-use sectors is part of a wider strategy known as sector integration. Electrified cooling, heating and transport (through air conditioners, heat pumps and electric vehicles, for example) can be complemented with the direct deployment of renewables to meet more complex demands, such as in industrial processes or old buildings. The exact formula for electrification vs direct renewable deployment will vary between energy systems, as a function of existing infrastructure and demand profiles.

Sector- and geography-specific decarbonisation solutions will be required

The scale of the required transition in other key energy-using sectors can be illustrated using the 2050 Transforming Energy Scenario developed by IRENA.

In **transport** IRENA analysis estimates growth in global electric vehicle (EV) numbers from 7.9 million today to 1.109 billion by 2050, and an increase in transport biofuel production from 136 billion litres/year in 2017 to 652 billion litres/year by 2050 (IRENA, 2020a). Sustained growth in EV adoption, supported by the international roll-out of supporting infrastructure, offers an opportunity to decarbonise transport. However, growth in demand for electricity may be a challenge for the power sector. Recent modelling conducted on the impacts of widespread EV roll-out in the United Kingdom towards 2035 clearly illustrates the risks that uncoordinated non-smart charging could pose to the country's electricity grid. The study found that evening peak demand could increase by 3 GW if all ten million of the forecasted vehicles were charged simultaneously, relative to a mere 0.5 GW increase if smart charging was incentivised (Aurora Energy, 2018). Strategies aiming to optimise charging behaviour will be required in the United Kingdom and in all other countries anticipating high rates of EV deployment.

Industry has been the slowest sector to move to renewable energy use, with only 13% of energy (mostly biomass) being sourced from renewables today. Given that the sector is the second-largest global emitter of energy-related CO_2, its share of renewables will need to rise significantly to help meet climate change targets (IRENA, 2020a). This scale-up will require significantly more solar thermal heat pumps for low-temperature needs, hydrogen produced from renewable electricity and scaled-up biomass deployment for medium- and higher-temperature heating needs. High-temperature demand may be met by CSP in the future. However, given the intermittency of these sources, enabling the effective integration of renewables with different industrial processes – including via fuel switching or sector integration – will be critical in this sector.

The **buildings** sector covers both commercial and residential premises encompassing around 150 billion square metres (m^2) of floor space, which is projected to increase to 270 billion m^2 by 2050. The share of renewable energy use in buildings needs to rise to 81% by 2050, with a significant increase from current levels needed in solar thermal and heat pumps (~10 times), modern cooking stoves (~12 times), biomass (~2 times) and geothermal heat (~4 times) (IRENA, 2020a). There are various priorities for increasing renewables in buildings, including scaling up heat pump deployment, effectively managing electricity demand peaks, doubling heat delivered by (renewably powered) district heating systems, and driving energy efficiency.

Energy system flexibility is needed to deliver integration of renewables across all sectors

The scale of the challenge in delivering energy system decarbonisation is clear. With VRE generation set to increase, along with a rapid rise in electrification across multiple sectors, it is critical to develop flexible energy systems to ensure the efficient integration and use of energy infrastructure. Flexibility refers to the capacity for the system to "maintain reliable and continuous service in the face of rapid and large swings in supply and demand" (IRENA, 2017b).

There are six broad categories of flexibility measures in energy system management:

- **Supply side**, in which power plants ramp up or down mainly in response to demand changes and network congestion.
- **Demand side**, where energy use varies across time, either through market actors remotely controlling certain loads, or through customers responding to price signals. These can help manage dynamic changes in output from variable generation, particularly in smart systems.
- **Market design**, which can be used to signal and reward flexibility in generation or consumption activity through effective price signals, helping to manage the system and drive appropriate longer-term investment.
- **System operation**, in which system operators make sure that supply meets demand every second by employing various balancing services. With greater amounts of VRE sources, this is becoming more complex, requiring greater sophistication in market rules, forecasting, communication and control.

- **Transmission and distribution network** operators, who manage the physical assets that connect supply to demand, have a role to play in smart system management.

- **Storage** infrastructure, which enables the storage of energy for use at a later time. Storage services can be provided by various technologies that absorb different vectors of energy (*i.e.* electrical and thermal [heat or cold]), in different storage mediums (*i.e.* electrochemical, mechanical, electrical, thermophysical or chemical). Depending on its location and use case, storage can be used to provide supply-side and/or demand-side flexibility, as well as providing additional network services that delay the need for costly network reinforcement (IRENA, 2017b).

Storage will be critical to achieving energy system flexibility

Storage has gained a lot of attention globally as a critical enabling technology for energy systems to integrate a higher share of VRE and minimise curtailment. The fundamental principle of storage is being able to absorb and store energy, and then release it when the system needs it. In doing so, storage allows for the decoupling of supply and demand, offering crucial versatility to the management of a system with a large share of VRE generation.

In a general sense, energy storage comprises the intake, storage and release of energy in a controlled manner in time and/or space. It is related to different energy vectors such as electricity, heat and synthetic fuels, including gas. Energy storage technologies are typically categorised at a high level by the energy vectors involved. Electrical storage technologies absorb electricity and release electricity. In this vector, the energy is either stored directly in an electrical form or converted into another form to be stored (*i.e.* potential, mechanical, thermal, chemical, electrochemical, electrostatic or magnetic energy). Meanwhile, TES is a technology that stores thermal energy by heating or cooling a storage medium so that the stored energy can be used later for heating and cooling applications or power generation (European Association for Storage of Energy, 2017).[5]

In addition to the diversity of storage and discharge vectors available, storage technologies range widely in scale too. As a result they can be applied across the entire extent of the energy system from power plants to residential premises, and across timescales from seconds to seasons depending on the system need.

According to the US Department of Energy's Global Energy Storage Database, pumped hydro storage accounts for 96% of the world's current storage capacity, with the rest coming from thermal storage (1.6%), electrochemical batteries (1.1%) and mechanical storage (0.9%) (US Department of Energy, n.d.). However, it should be noted that these figures do not include distributed small-scale storage, such as domestic hot-water tanks or batteries.

Electrochemical storage (batteries) has taken centre stage recently, with significant capacity added worldwide. Lithium-ion batteries have dominated recent deployment owing to rapid cost reductions. Indeed, their cost dropped by as much as 73% between 2010 and 2016 for transport applications. Forecasts for this type of storage are driven primarily by the EV market, as well as the growing deployment of wind and solar worldwide.

IRENA estimates that a 17-fold increase in deployed battery storage would be needed to manage the doubling of renewable electricity generation (IRENA, 2017a). More recent market estimates project a sixfold increase in deployment, contingent on favourable policy environments (Chediak, 2018).

Thermal storage is also gaining prominence due to the need to balance supply and demand for heating and cooling. It may also contribute to enhancing flexibility in electricity-only applications, including in thermal power plant retrofits.

This Innovation Outlook highlights the unique capacity for TES to facilitate further renewable integration globally across sectors, and to bring higher efficiency in meeting heating/cooling demand. The report prioritises 29 TES technologies, available and in development, and explains the value and benefits they can add to energy systems and disaggregated sectors in the coming decades.

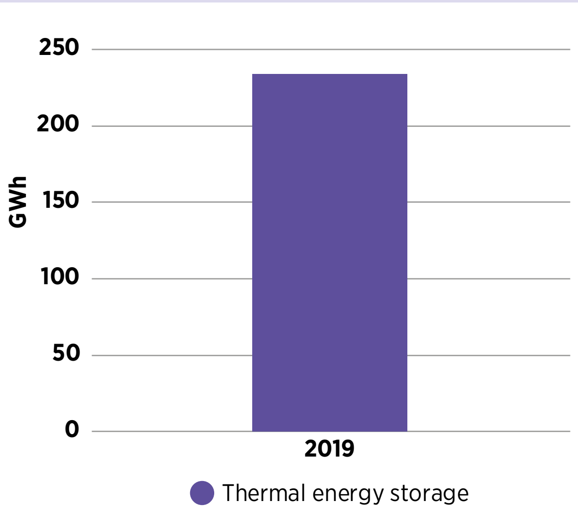
5 There are also hybrid systems where thermal storage is used in conjunction with electrical storage.

1.2 Market assessment of TES

A growing number of solutions are available to smoothly incorporate the increased share of VRE into energy systems. Electricity storage technologies have emerged as a critical source of flexibility, particularly for the power, buildings and transport sectors. However, the energy storage sector needs to diversify to avoid potential bottlenecks that might arise in the production supply chain, and to cater to a variety of end uses. Therefore, TES as a thermal solution has a clear role in providing flexibility to the power sector as well as for heating and cooling applications. Section 2.3 explains the advantages of integrating TES into energy systems.

Figure 15 shows the installed capacity of TES and other attractive storage technologies. IRENA analysis estimates that over 234 GWh of TES was installed globally at the end of 2019, a technology attracting growing attention from the private and public sectors. To give a sense of other technologies' market status, by the end of 2019 around 200 GWh of cumulative battery capacity had been installed for electromobility applications and 30 GWh of stationary battery storage applications, including utility scale and decentralised (PV rooftop) (IRENA, 2020a).[6]

Figure 15: Installed TES capacity by 2019



This section explores the TES market principally for three main sectors – power, space cooling and heating. The analysis is based on data collected by IRENA from over 430 projects and includes:

Power generation
Molten-salt technology: operational and planned molten-salt TES in Africa, the Americas, Asia and Europe. Compressed air energy storage (CAES), liquid air energy storage (LAES) and solid-state technologies.

Space cooling
Cooling TES projects, mostly located in the United States, with some large-scale projects located in warmer countries such as Jordan, Portugal and Qatar.

Heating for district systems, buildings and industry
Heating TES projects (excluding small hot-water tanks), with most of the capacity as large-scale heating TES installations in district heating systems in central and northern Europe, more specifically Denmark, Germany and Sweden.

Transport (cold chain)
Phase-change material (PCM) projects.

Power sector

TES is already being used in the power sector for load shifting and capacity firming. According to IRENA's database, molten - salt storage is the most widely adopted TES technology in this sector, due to its advanced technological readiness and its application with CSP plants. However, other TES technologies have also been used in demonstration and pilot projects within CSP and non-CSP sectors, such as solid-state material (*e.g.* ceramic or hot rocks) and PCM.

6 Installed capacity magnitudes for electrochemical and thermal technologies cannot be directly compared due to the different nature of the storage medium. This means 1 GWh of electrochemical storage is not equivalent to 1 GWh of thermal energy storage. Therefore, values are given on an informative basis to demonstrate the market status of specific technologies.

Molten-salt TES

Molten-salt storage currently accounts for the majority of installed TES capacity in the power sector, due to its coupling with CSP plants. Currently, over 21 GWh of molten-salt storage capacity is installed worldwide. By the end of 2019, the three countries with highest installed capacities are Spain, the United States and South Africa (Figure 16).

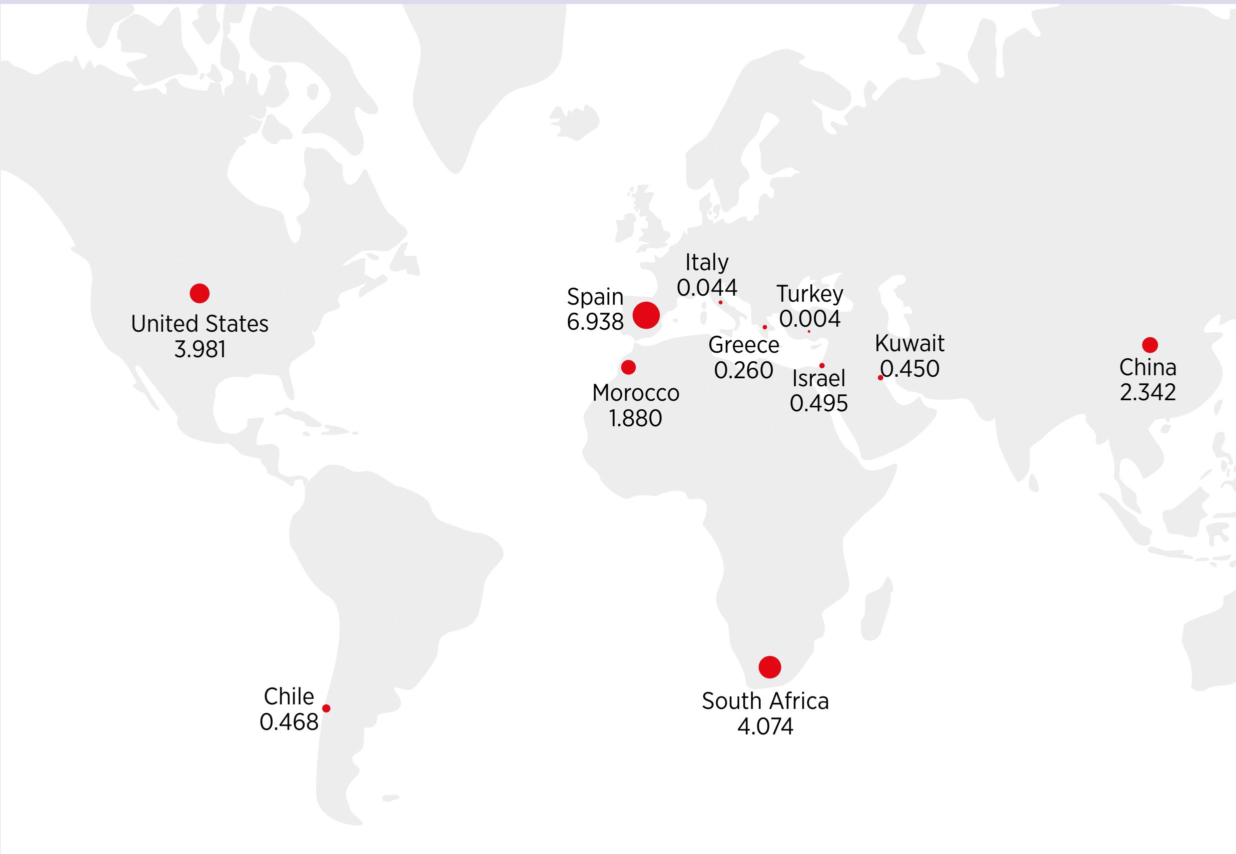
Molten-salt storage is expected to grow at a faster rate with the further installation of CSP, as the percentage of CSP plants using TES continues to increase, along with their storage capacity. Since 2014, most CSP installations have included TES (REN21, 2020).

At least 74 GWh of molten-salt TES are planned to be installed by 2030. To match the forecast CSP capacity of 20 GW by that year under current and planned policies, around 126 GWh of additional molten-salt storage capacity would be needed (52 GWh more than planned).

In IRENA's Paris Agreement-aligned Transforming Energy Scenario, with more ambitious renewable energy growth in comparison with current trends, policies and plans, 56 GW of additional CSP capacity would be needed by 2030 (IRENA, 2020a).

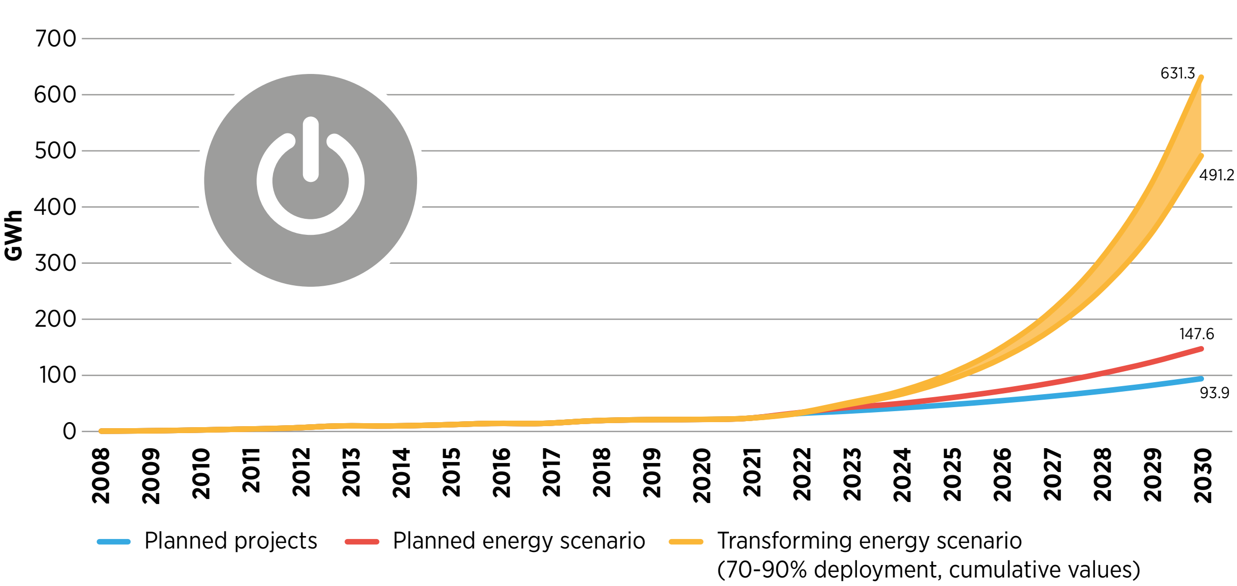
This growth in CSP capacity, illustrated in Figure 17, would deliver fourfold growth in molten-salt TES installed capacity (compared with the Planned Energy Scenario), between 491 GWh and 631 GWh. This uses a conservative estimate that between 70% and 90% of new CSP plants would be installed with molten-salt storage. This scenario requires countries to implement adequate policies (see Chapter 5) and incentives to push for such accelerated deployment of CSP and TES. It accounts for slowing of the sector due to Covid-19 and assumes that the next three years (2020-2023) constitutes the time needed to build the correct policy environment to facilitate this rate of deployment by 2030.

Figure 16: Molten-salt TES capacity installed globally (gigawatt hour)



Disclaimer: Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Figure 17: Installed molten-salt TES capacity



IRENA estimates the current installation costs for molten-salt TES to range between USD 26.1/kWh and USD 40/kWh. Assuming an 8-11 hour nominal operating capacity for TES, the cumulative investment needed in molten-salt TES in the next 10 years to match CSP capacity (according to IRENA's Transforming Energy Scenario) is between USD 12.3 billion to USD 24.4 billion, depending on the CSP technology used.

However, if costs continue to decrease for storage technologies, assuming a cost of USD 21.8-25.8/kWh by 2030, then the amount of investment needed could decrease to USD 10.2-15.7 billion.

Further growth of molten-salt storage deployment could also be seen as stand-alone bulk storage within the power sector, where there are already plans to convert decommissioned coal generation plants into storage facilities (see Section 4.1).

Space cooling

The demand for space cooling is increasing globally due to growing overall prosperity, the effects of climate change and rising global temperatures. Air conditioner sales have been rising rapidly among homeowners.

According to IRENA's analysis, energy demand for space cooling reached 8.1 exajoules (EJ) in 2016 and is steadily increasing, forecast to reach almost 11.3 EJ by 2030. Conversely, IRENA estimates that with energy efficiency measures (*e.g.* insulating and retrofitting buildings) and renewable technologies, the rate of increase could slow to reach 9.3 EJ in 2030 under the Transforming Energy Scenario. Nevertheless, this increase in demand calls for further deployment of TES for cooling to enable further flexibility and demand shifting (see Section 2.3). This can help meet cooling demand with cheaper overall system costs. Such technologies include tank thermal energy storage (TTES), underground thermal energy storage (UTES) and PCM.

Currently, out of the total of 400 TES projects identified by IRENA at the end of 2019, over 160 have been used for space-cooling in buildings and districts, amounting to over 13.9 GWh. This number could increase rapidly in the next ten years, especially in North and sub-Saharan Africa, Southeast Asia and the Middle East, where temperatures are reaching extreme levels in some regions and further advanced and large-scale cooling technologies are adopted. TES can complement this growth to ensure lower system costs and greater integration of VRE through additional demand-side management capabilities for power system operators.

Figure 18 explores two scenarios for the global growth of TES for cooling applications,[7] with the increasing demand for cooling based on two cases: one a current policies scenario, the Planned Energy Scenario; and the other a climate-compatible case, the Transforming Energy Scenario, largely based on renewable energy and energy efficiency technologies.

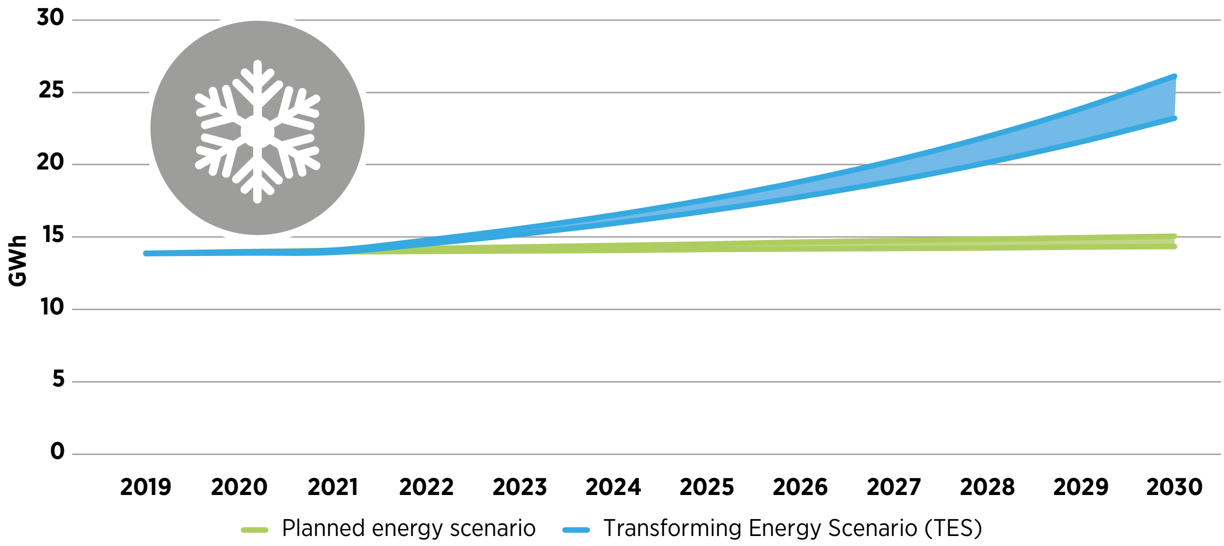
In the first scenario, TES for cooling grows at the current rate. In the Transforming Energy Scenario, global installations of TES for cooling would grow according to the ratio of installed capacity to cooling demand in the United States[8] – a country with a profile of significant deployment of cooling TES. A twofold increase in global deployment of cooling TES is required to meet cooling demands, enabling more demand-side flexibility options.

In parallel, technological advancements (*e.g.* digitalisation and improved storage capacities) and increased efficiencies are needed, as well as implementation of energy efficiency measures in buildings.

As mentioned previously, 2020-2023 will be a crucial period to implement policies that can accelerate cooling TES technologies to match the deployment rate of the US at a global scale (refer to Chapter 5).

Considering current installation costs for cooling TES technologies, an estimate of the investment needed to reach the Transforming Energy Scenario can be calculated. Taking an average installation cost of TES for district and building cooling of USD 60-230/kWh, approximately USD 560 million–2.82 billion in investment would be needed in cooling TES deployment across the next ten years for global capacity to reach similar deployment levels as the United States.

Figure 18: Installed and projected TES capacity for space cooling at a global level



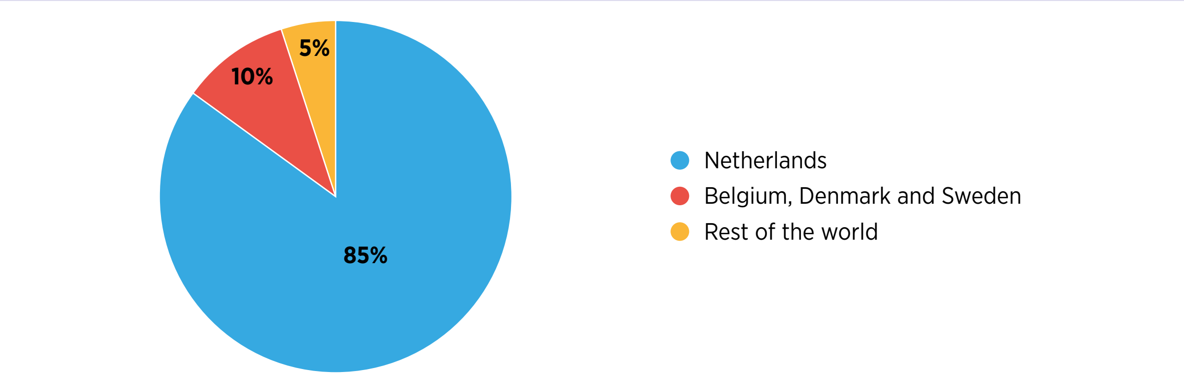
7 Projections exclude aquifer thermal energy storage (ATES) due to limitations on technical, geographical and resource data availability (see box).

8 Note that this does not imply that the United States has an optimal amount of installed cooling TES, but its high availability of project and cooling demand data allow its case to serve as a reference for increased global deployment of the technology.

Aquifer thermal energy storage

Aquifer thermal energy storage (ATES) projects have the largest storage capacities of TES projects and thus are greatly suited to seasonal storage. Currently there are over 2 800 installed ATES projects worldwide, with most located in the Netherlands and western Europe (Figure 19). These projects provide over 2.5 TWh of cooling and heating annually (Fleuchaus et al., 2018)

Figure 19: ATES projects



Source: Adapted from Fleuchaus et al., 2018.

The world's largest project is at Stockholm's Arlanda airport. The aquifer has a volume of 200 million cubic metres (m^3) and can store up to 9 GWh of energy. The same water is used on a seasonal basis for cooling and for heating purposes such as melting snow on runways and preheating ventilation systems. The project has reduced the airport's energy use by 19 GWh annually, and only uses energy from biofuels (Swedavia Airports, n.d.).

Heating for buildings, district heating and industry

The efficiency of heating systems (space and water heating) has increased rapidly in recent years, slowing the global increase in heating demand. Global heating demand reached 212 EJ in 2018 (IEA, 2019).

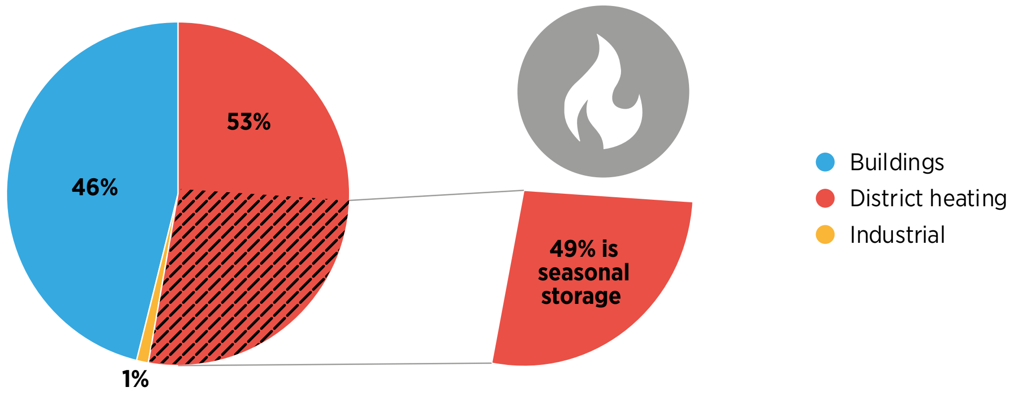
In 2019 IRENA identified over 199 GWh of medium- to large-scale TES capacity installed globally for heating in buildings, district heating and industrial processes (Figure 20). These include TTES, UTES and solid-state TES.

District heating is the largest application of currently installed TES capacity for heating, due to the use of ATES and borehole TES (BTES) with large volumes. Approximately half of the district heating projects facilitate between-season storage, a special capability that TES technologies bring to the energy system.

An increase in the share of industrial TES systems would be spurred by power sector regulations and policies aimed at integrating further renewables into the power system. This could lead to an increase in the overall capacity of installed TES for heating despite the stabilisation of heating demand worldwide. It would allow increased industrial efficiency in process heating while helping integrate renewables for a low-carbon energy system.

Due to the ubiquity and distributed small-scale nature of hot-water tank storage, the installed capacity can be hard to gauge globally. Considering the ongoing technological progress of other heat storage technologies, such as solid state and PCMs, their overall installed capacity could increase significantly, providing much-needed flexibility and demand-side management capabilities to the grid. In the United Kingdom a study projects that UK homes with electric heating will potentially need to have TES if the country were to reach net-zero carbon by 2050 (Energy Systems Catapult, 2020).

Figure 20: Installed TES capacity for heating applications (% of installed capacity)



Another study projects 5-10 GWh of TES for heat networks in France by 2030 (ATEE, 2016). This would follow the work of the leading EU countries in storage for district heating, Denmark, Germany and Sweden, which at the moment house over 60% of the world's district heating storage capacity, due to extensive use of UTES.

China is seeing the rapid uptake of various forms of heating TES, including the use of composite phase-change materials (cPCMs) to store excess renewable power that would otherwise have been curtailed and use it for clean space heating. This uptake has been driven by the will to reduce carbon emissions from coal-fired heating and declining air quality. According to Jinhe Energy, more than 1.5 GWh have been installed in the country (Jinhe Energy, 2020).

With several heating TES technologies in prototype and demonstration phases, such as solid-state and PCMs, and given the distributed nature of hot-water tank storage, information is too limited to develop global deployment projections. However, the benefits of heating TES are not going unnoticed, as evidenced by the ongoing deployment of both new and mature technologies, despite the projected decrease in heating demand. These are crucial at a time of integrating VRE into power systems and large-scale electrification, where TES can prove to be an essential provider of demand-side flexibility for more efficient and less expensive energy systems in the future (see Section 2.3).

Projections summary

Future power systems will need a combination of storage alternatives, as each has a different value proposition (in terms of storage period, energy density, market services with different response times, and operating temperatures, among others). Figure 21 shows current and future estimates for TES installation, particularly for stationary storage (used for utility-scale and decentralised PV rooftop power plants), storage for electromobility and heat.

Overall, energy storage technologies have a promising outlook. In the Transforming Energy Scenario, stationary storage is expected to grow from 30 GWh in 2019 to 745 GWh in 2030, and storage for electromobility increases from 200 GWh in 2019 to 5 065 GWh in 2030 (IRENA, 2020a).[9] Looking at TES specifically, in 2030 these technologies represent at least 800 GWh of installed storage capacity, almost tripling current capacity, taking into consideration the projections for molten salts and space cooling. It is important to emphasise that this projection only partially covers the potential of TES, as it does not leverage the future growth of heating TES projects and additional TES technologies for power generation, such as solid state. In addition, the technology readiness level of other TES solutions for industry and transport, such as PCMs and thermochemical TES (*e.g.* salt hydration and liquid absorption), is expected to develop further, allowing TES to take a higher share of the global storage market in the next ten years.

9 Installed capacity magnitudes for electrochemical and thermal technologies cannot be directly compared due to the different nature of the storage medium. This means 1 GWh of electrochemical storage is not equivalent to 1 GWh of thermal energy storage. Therefore, values are given on an informative basis for the market status of specific technologies.

Figure 21: Installed TES capacity projections

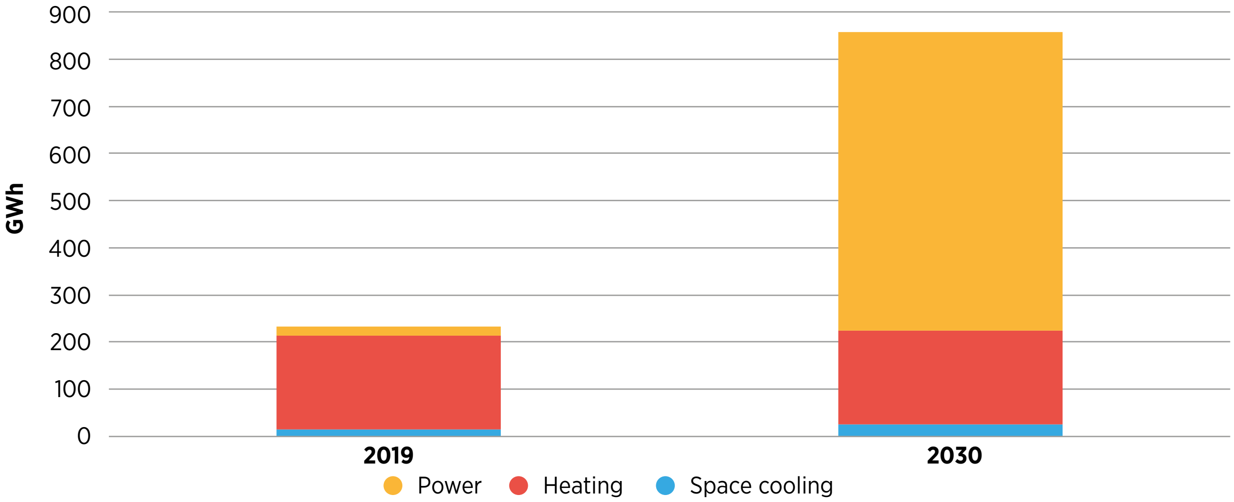
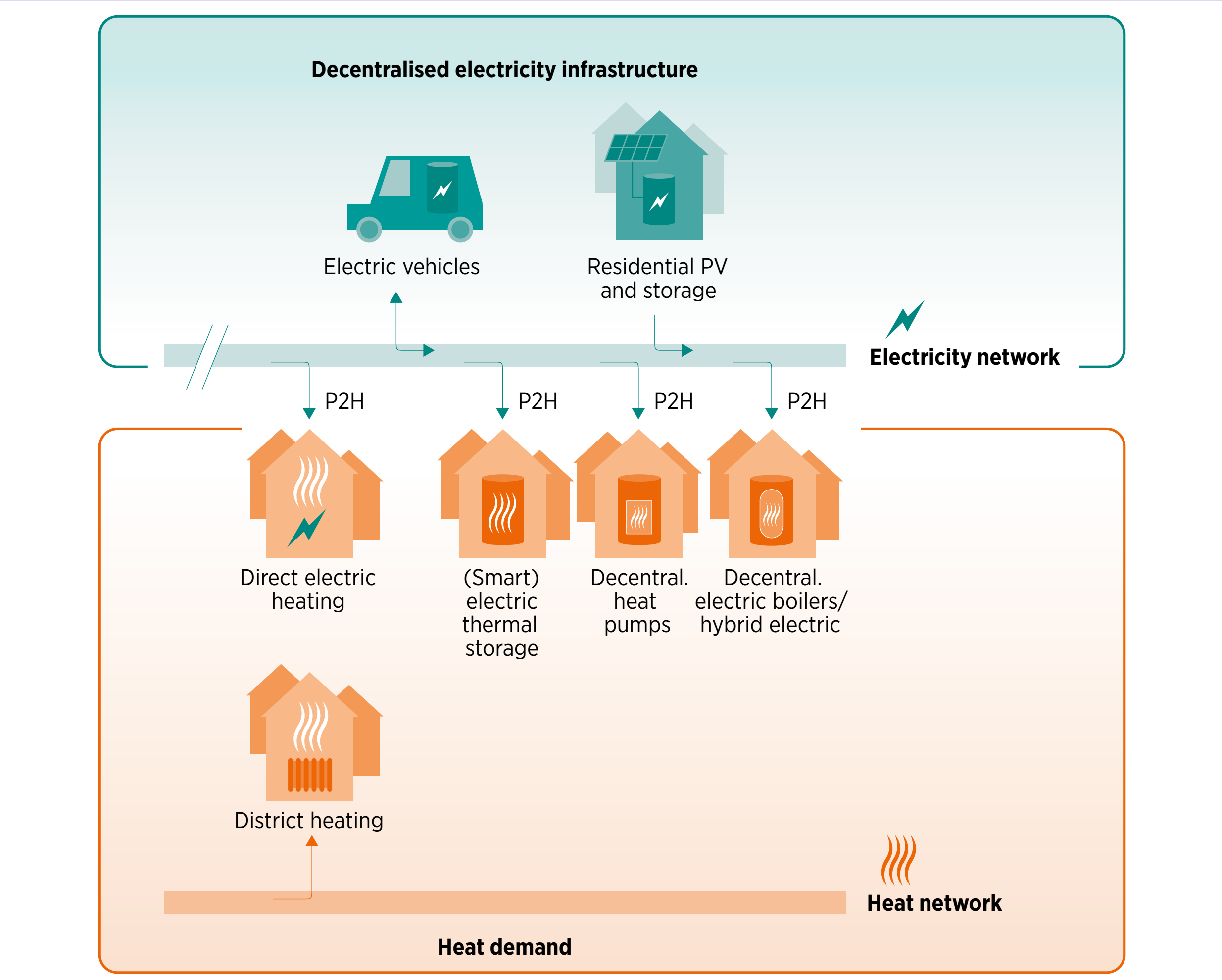


Figure 22. Overview of an integrated and decentralised electricity infrastructure to meet power and heat demand flexibly



Note: P2H = power to heat.

Source: Bloess, Schill and Zerrahn, 2018.

1.3 The role of TES in integrated energy systems

As end-use sectors in the energy system are electrified, and as renewable generation technologies are more widely deployed in sectors other than power, enhanced sector integration will contribute to realising ever more efficient energy systems. One example of coupling heat and power is the "power to heat" (P2H) concept (Figure 22), in which demand for heat is met by a range of decentralised electrified heating and storage technologies (Bloess, Schill and Zerrahn, 2018). Such approaches are sometimes referred to as "smart energy systems", in which electricity, thermal and gas grids are linked and co ordinated to leverage synergies and deliver optimal outcomes for each sector, as well as maximising efficiency for the overall system (Lund *et al.*, 2016).

TES can also help enable further options for flexibility in the heating and cooling sector. Electricity system flexibility could be enhanced using TES. Using smart controls to produce heat (or cold) at times of high supply of renewable electricity, which can then be stored using TES, could provide a useful means of balancing power supply and demand, while helping to decarbonise heat (or cold) supply. Thermal storage is also expected to be important for the electricity vector, through the optimisation of hot-water tanks for heat pump use in homes.

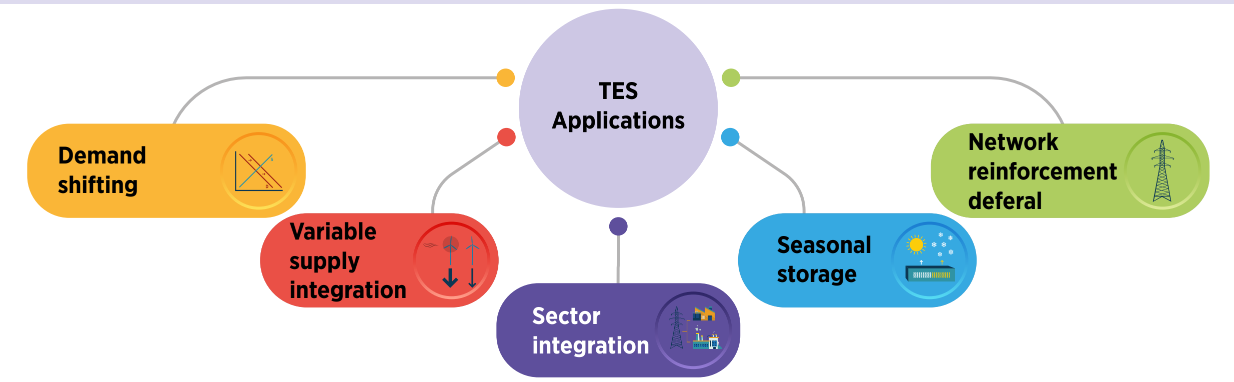
The benefits that TES can provide will vary between energy systems and their future evolution, particularly in relation to VRE deployment and the electrification of heat and transport demand. Examples of the key applications for TES are summarised in Figure 23.

Analysis conducted in different settings provides insight into the role that TES might have in increasingly integrated future systems. Here, the benefits are defined and contextualised. Further in the report are applied examples showing where and how these benefits have already been realised or where they might become increasingly relevant in the future. The exact suite of benefits offered by TES deployment will vary between differing energy systems, climates and geographies.

Variable supply integration

Thermal storage can be used to regulate the outputs from variable energy sources. This is sometimes referred to as capacity firming. It is possible to mitigate rapid dips or spikes in output, as well as longer-term variations in supply such as those which occur overnight or throughout the day. Given that solar irradiation and wind are not consistent every minute, electricity generated from these sources currently needs to be supplemented with appropriate reserves from conventional generators such as coal, gas or pumped hydro to fill in shortfalls against demand. System operators use a range of balancing tools to manage fluctuations over timescales from sub-seconds to minutes and hours. Thermal storage is not suited to providing services to meet sub-minute demands yet, such as frequency management, which electrical storage can address at much faster rates. From technical and economic perspectives, **thermal storage is suited to delivering power system balancing services across timescales of minutes/hours, and thermal demand shifting across hours**. TES technologies have long cycle lifetimes and relatively small degradations in efficiency over time compared with batteries, which reduces overall lifetime cost (Lund *et al.*, 2016).

Figure 23: Key applications of TES in energy systems



Sector integration

TES can help reduce curtailment and improve renewable energy utilisation via sector integration. This refers to linking power generation to demands in other sectors such as heat by converting excess power to heat, significantly increasing the flexibility of the energy system. As thermal demand is usually far higher than electricity demand, particularly for end-use heating applications, it is more efficient to store energy as thermal energy rather than electricity. Given the high cost-effectiveness and efficiency of TES technologies (Lund *et al.*, 2016), deploying TES could help to **decarbonise the power system** by enabling sector integration.

Heat and transport electrification will add a significant load to the power system, and relying solely on power sector assets may stretch energy system resources and increase the overall cost. TES can help to decouple heat demand and to a lesser extent that of the transport sector (through lower cooling/heating loads in vehicles) from power generation with a high share of variable generation. TES is also a critical enabling system component for effectively deploying technologies such as heat pumps, allowing their size to be optimised and efficient full load operation at lower costs. This helps to improve the potential of strategies such as power to heat (which already improves renewable integration) and so facilitate whole-system approaches.

Demand shifting

Energy demand can be shifted in time using thermal storage to better match VRE supply and reduce system strain. For example, high peak coincident loads like building space heating and/or cooling can be moved into off-peak times by charging up the thermal storage during off-peak times and then discharging when required. This enables the on-site demand pattern to stay the same while moving production of the heat or cold to more favourable times (*e.g.* low grid congestion, high renewable energy, lower price periods). Additionally, system efficiency can also be increased by charging thermal storage during times of high renewable availability and low demand, which can then be discharged at high demand periods to improve utilisation. Managing excess renewables production with storage is more efficient from a systems perspective than curtailment as it avoids energy wastage and improves the utilisation of generators, thus reducing the overall cost to consumers. Demand shifting is also a critical enabler of efficient sector integration, which otherwise would require significantly increased overall supply and network capacity to meet the same demand.

Network management

Load shifting not only helps to improve utilisation of renewables and allows them to meet a higher share of demand, but also helps defer or avoid the need for costly electricity network reinforcement. Distributed generation is putting pressure on network operators due to challenges associated with periods of high supply and low demand. Without reinforcement or increased network capacity, power must be exported out of local networks at times of peak supply. Additionally, networks are built to meet peak demand; heat and transport electrification could increase it, triggering additional investment to increase head room availability.

Network capacity is thus a limiting constraint determining the local viability of greater deployment of renewable generation assets, heat pumps and air conditioning. Without storage or other forms of demand management, networks globally will require significant reinforcement. **Demand peaks driven by heating and cooling loads can be managed effectively by thermal storage systems.** This is because the final demand is heat or cold rather than electricity.

As an example, analysis of the Latvian power system suggests that material network reinforcement could be required even under scenarios of incomplete heat electrification. This is significantly reduced when TES is used in a highly co ordinated and controlled manner to reduce the peak load (O'Dwyer *et al.*, 2018). This finding is case-specific, but offers an insight into the potential role for TES in network management.

Seasonal storage

Thermal storage can store energy for days or even months to help address seasonal variability in supply and demand. This is of particular benefit to energy systems in regions that have a significant difference in thermal loads between seasons. Surplus heat produced with renewables like solar PV or wind in the summer can be stored in TES, and then be used to supplement or meet winter heating demand. Such an initiative would reduce the need for non-renewable sources of heat during peak times. Thermal storage can also be used to store natural cold in the winter to supply space cooling during the summer season. While this particular use case does not directly aid renewables integration, it helps reduce electricity demand during peak times in the summer.

1.4 A systems approach

There is growing evidence to show the benefits of a systems approach to integrating renewables and decarbonising energy systems, in ever more cost-effective ways. For example, research in Finland has found that wind power-to-heat systems using TES can enhance decarbonisation by increasing wind-use efficiency. An integrated pilot system with heat pumps, electric boilers and TES achieved a 30% emission reduction by displacing natural gas-fired boilers against a baseline system without these assets (Kiviluoma and Meibom, 2010).

Additionally, when the share of wind and solar energy starts to increase in the energy mix, **integrating TES within power-to-heat systems can help reduce renewables curtailment.** For example, a study in the Pennsylvania-New Jersey-Maryland energy market area in the United States found that renewables curtailment could be reduced by 50-90% by using either heat pumps with thermal storage or decentralised resistive heaters with thermal storage (Pensini, Rasmussen and Kempton, 2014).

These studies demonstrate that realising the benefits of TES in a given energy system also depends upon the deployment of certain supporting assets and infrastructure. As such, a whole-systems approach to planning energy system flexibility and integration can realise untold benefits.

Case study 1: **Reducing wind curtailment through sector coupling in China**

Reducing wind curtailment using thermal storage in a district heating scheme, Xinjiang, China

A United Kingdom–China collaborative project led by the Birmingham Centre for Energy Storage, funded by the UK Engineering and Physical Sciences Research Council and the Natural Science Foundation of China, reported on a successful commercial demonstration pilot to integrate thermal storage into a district heating scheme using cPCMs in the Chinese region of Xinjiang.

The project was driven by the need to address the intermittency of renewables and network constraint challenges caused by a high penetration of renewable wind and combined heat and power district heating schemes. Local electricity demand is low in Xinjiang, and the majority of the renewable (wind and solar) generation is utilised in geographically distant load centres.

However, the low demand and network constraints meant that curtailment rates were as high as 40% in 2016. As a result, central and local government investigated routes to improve renewable utilisation rates.

Heat decarbonisation was also on the government's agenda and support was provided through feed-in tariffs. There was also high volatility in electricity prices.

A key part of their solution has been end-use coupling and converting excess renewables into heat that is stored using a thermal storage system. A 6 megawatt/36 megawatt hour (MWh) demonstration plant using high-temperature cPCMs has been operational since October 2016.

This plant charges during off-peak hours, when the price of electricity is half of what it is during normal hours. Furthermore, it is estimated that over 80% of this electricity, or over 5 000 MWh per year, is wind generation that would otherwise have been curtailed.

This facility has been successfully harnessing excess electricity from local wind generators, reducing wind curtailment, relieving network constraints and storing decarbonised heat. As a result of the success of the pilot, a further 20 plants have been constructed and are in operation across China (Ding, 2018).

Fundamentally, thermal storage is part of a wider portfolio of flexibility options. Electricity storage and demand-side measures have different merits and applications relative to TES. Other options include hydrogen, which is gaining prominence as an energy storage vector. It has the advantage of being a flexible fuel source that can be used for heating, power or transport when required. Understanding of the important role that various storage and flexibility technologies will play in future energy systems is ever increasing.

However, significant work is still required to develop, design and dispatch strategies for integrated energy systems, given the growing list of variables that are creating system complexity. A concerted effort to adopt a systems approach and identify the **right combination of infrastructure and market signals** is crucial. This will enable **efficient use cases and commercial models** of TES operation to emerge.

Integrating thermal energy storage through system-wide co-ordination reduces curtailment with solar and wind power.

2. TECHNOLOGY OVERVIEW

Thermal energy storage (TES) covers a wide range of technologies based on exploiting different fundamental scientific principles. For this report 29 TES technologies were identified and a prioritisation exercise[10] was carried out based on the following criteria:

- **Technology characteristics:** entails technology readiness level, versatility, replicability and additionality.[11]
- **Potential to overcome challenges in the variable renewable energy (VRE) sector:** enables solutions to reduce curtailment, peak shaving, system inertia and congestion in transmission grids; facilitates electrification of other sectors beyond power generation.
- **Scale:** whether the technology applies to distributed, centralised or both kinds of system.
- **Sector:** application of TES technology in power systems, industry, cold chain, buildings or district heating and cooling.

After this assessment, 13 technologies were selected as promising TES technologies that can help to integrate more VRE in energy systems.[12] This section provides an overview of these primary technologies of interest. They are classified into four groups based upon the underlying principle of their operation:

1. Sensible heat storage
   - tank thermal energy storage (TTES), using water as a storage medium
   - solid-state thermal storage (*e.g.* ceramic bricks, rocks, concrete, packed beds)
   - molten salts
   - underground thermal energy storage (UTES).
2. Latent heat storage
   - ice thermal storage
   - sub-zero temperature phase-change materials (PCMs)
   - low-temperature PCMs
   - high-temperature PCMs.
3. Thermochemical heat storage
   - chemical looping (calcium looping)
   - salt hydration
   - absorption systems.
4. Mechanical-thermal coupled systems
   - compressed air energy storage
   - liquid air energy storage.

The following section provides an overview of each group, and explains the scope of each technology and its operation principles. Further technical details on individual technologies can be found in the Appendix.

2.1 Principal types of thermal storage technology

Sensible heat storage

Sensible heat storage is the most commonly deployed and commercially advanced type of TES. It stores thermal energy by heating or cooling a storage medium (liquid or solid) without changing its phase. The amount of stored energy is proportional to the temperature change (rise or fall) on charging, within the operational temperature range, and the thermal capacity of the material.

10 More detail on the method used for prioritisation can be found in Section 7.1 in the Appendix.

11 Versatility – this is the ability of the TES to be able to fulfil multiple use cases within an energy system. Replicability – this is the ability of the TES to be used across multiple energy systems. Additionality – this is the uniqueness of the TES technology in providing the particular services.

12 Replicability – this is the ability of the TES to be used across multiple energy systems.

Sensible heat storage systems offer storage capacities ranging from 10 kWh to 50 kWh per tonne and storage efficiencies between 50% and 98%, depending on the specific heat of the storage medium and thermal insulation technologies. The working temperature range can go from -160°C to more than 1000°C (European Association for Storage of Energy and European Energy Research Alliance, 2013).

Compared to other thermal storage technologies, sensible storage offers the simplest and often cheapest form of storage (often using just water). As a result, sensible technologies are the most widespread today, appearing in the form of residential water tanks or molten-salt storage for concentrated solar power (CSP) plants (European Association for Storage of Energy and European Energy Research Alliance, 2017a).

They find application in the power sector, industry, buildings, and district heating and cooling. The main disadvantages of sensible technologies include their large physical footprint, the need for further thermal insulation with higher temperature or storage time demands, and the potential need for (energy) inputs to maintain storage at target temperatures.

The sensible heat storage technologies examined in this report are:

- TTES, using water as the storage medium
- solid-state thermal storage (*e.g.* ceramic bricks, rocks, concrete, packed beds)
- molten salts
- UTES.

Tank thermal energy storage

TTES stores thermal energy using a fluid, often water, as the storage medium. For this report, all future references to TTES refer only to systems that have water as the storage medium (as opposed to molten salts or other fluids). Water is heated or cooled via solar thermal panels, electricity, or the ambient temperature, and then delivered upon demand (Stine and Geyer, 2001). TTES represents the simplest form of thermal storage, and is the most widespread and technically mature TES technology. In terms of volume, tanks start at a few hundred litres combined with solar thermal heating for small-scale residential applications. For large applications (commercial, industrial and district heating), the size can be up to about 80 000 m³, limited by the space and the container's construction.

The systems usually provide intra-day/daily heat storage. For domestic applications, the system components are the thermal storage water tank and the water heater, dedicated to hot water production and in some cases to space heating, co generation, etc. The delivered water temperature range is normally 55-60°C. Tank-based systems have also been developed for inter-seasonal TES. Some systems proposed can store high-temperature heat, around 90°C, over 6 months with a loss of energy of less than 10% (BEIS, 2016). For large-scale applications, hot-water tanks are used for seasonal storage. They are normally charged by solar thermal technologies that heat the water up to temperatures of around 80-90°C. In these cases the heat can be extracted down to temperatures of around 10°C when heat pumps are used (IEA and IRENA, 2013).

Solid-state thermal storage

Solid-state or packed-bed storage involves the use of particulate matter to store heat, and a fluid that runs through the bed to transfer the heat in and out of the system. These systems vary in size, and a range of materials can be used. For example, ceramic bricks are used in households to store heat provided by electric heaters, and beds of rock or concrete can be used at a larger scale to store heat generated using excess electricity from a wind farm.

Solid-state technologies are simple, relatively cheap and scalable. They are used in buildings that usually require only low-grade heat. Novel materials and systems are being developed for industry and power generation applications that require higher temperature outputs.

Other natural and artificial substances have been studied as storage media, such as rocks, concrete and ceramic bricks. At higher temperatures, refractory bricks based on oxides (silica, alumina, magnesia and iron oxide feolite), carbonates (e.g. magnesite) and their mixtures are used commercially. Other materials have been considered, such as concrete with enhanced thermal properties (Xu and Chung, 2000) and industrial waste ceramic material such as Cofalit (Calvet et al., 2013).

Thermal power station

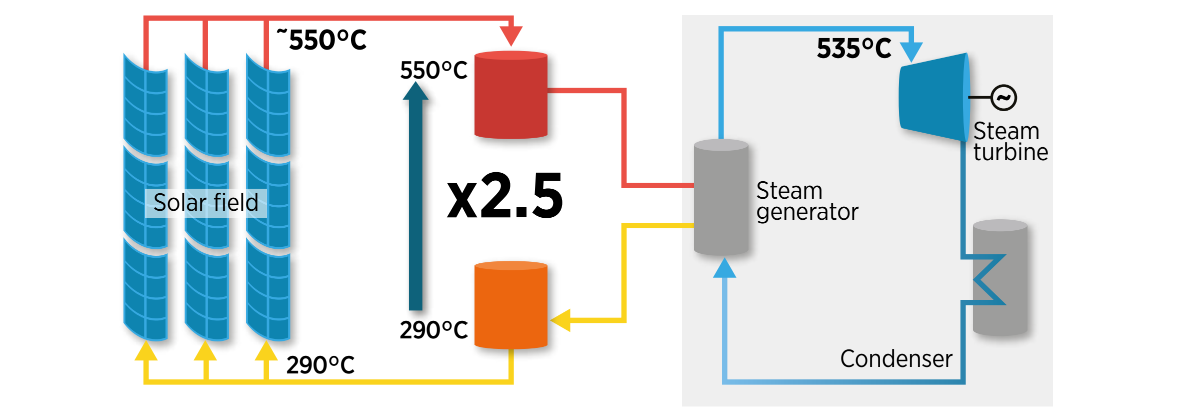
Image credit: Shutterstock

Molten salts

Salts are inorganic chemical compounds. When used for thermal storage, salts that would normally be solid at ambient temperatures are maintained at temperatures above their melting points so that they are in liquid form.

Molten salts are used for the storage of high-grade heat. However, they are vulnerable to solidifying, which can cause considerable damage to auxiliary equipment. As such, their use is limited to highly controlled environments where high temperatures are required, such as in the power sector. Here molten salts are used almost exclusively to help integrate CSP, where heat can be stored during the day and discharged at night to drive a turbine and maintain continuous electricity production (Figure 24).

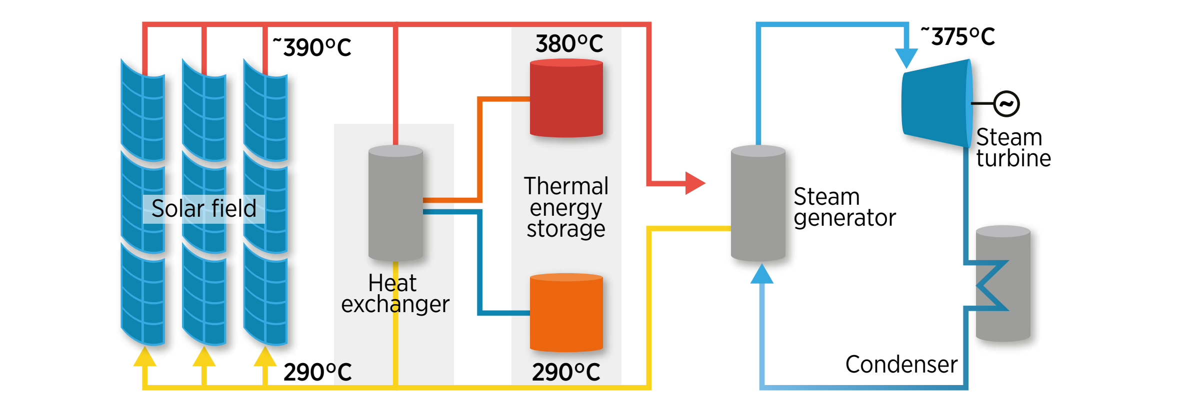
Figure 24: Direct molten-salt storage system



Source: Archimede Solar Energy, 2020.

A two-tank molten-salt storage system is one of the most common configurations used (Figure 25). The molten salt is pumped between a cold and a hot storage tank for charging and discharging. Indirect systems use a heat exchanger with a heat transfer fluid cycle, whereas in direct systems the salt is used as both the storage medium and heat transfer fluid.

Figure 25: Indirect molten-salt storage system



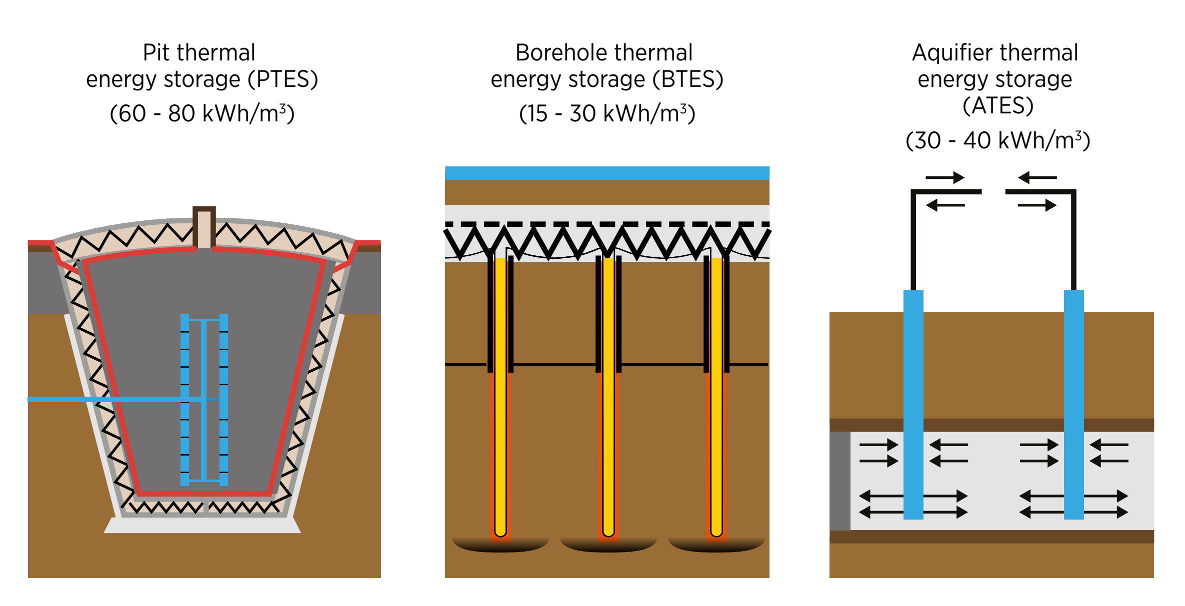
Source: Archimede Solar Energy, 2020.

Underground thermal energy storage

UTES involves heat or cold being stored underground. The storage medium can be geological strata made up of soil, sand or solid bedrock, or water in artificial pits or in aquifers. The key UTES technologies are aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES) and pit thermal energy storage (PTES) (Figure 26). A hybrid system combining PTES and BTES is also under development (European Association for Storage of Energy and European Energy Research Alliance, 2013). These technologies are relatively mature and have been in use in one form or another for centuries.

The key advantage of UTES systems is that large amounts of thermal energy can be stored across seasons; however, the efficiency of such systems is relatively low and therefore they are best deployed alongside a cheap source of thermal energy. UTES has mostly been used for district heating applications. UTES technologies can be found in some countries coupled with renewable energy sources, whereas in other areas UTES is still under demonstration or at pilot scale (European Association for Storage of Energy and European Energy Research Alliance, 2017a).

Figure 26: Underground energy storage concept



Source: European Association for Storage of Energy and European Energy Research Alliance, 2017a.

UTES can be used to store the heat from solar collectors or industrial processes, or the cold from the winter air. Then the thermal energy is used for space heating in winter or cooling in summer. Some systems use heat pumps to help charge and discharge the storage during part or all of the cycle. For cooling applications, normally only circulation pumps are used (BEIS, 2016). ATES is used to provide buildings with heating in winter and cooling in summer by using the underground water from naturally existing aquifers. ATES consists of a hot and a cold well, while PTES systems utilise underground pits insulated to reduce heat losses, and filled with gravel and water. PTES has the lowest specific cost, along with ATES. The system can be charged and discharged with heated water by direct contact or by using pipes along the gravel. PTES needs a greater volume than ATES, but has almost no geographical constraints. Finally, BTES is based on vertical heat exchangers that charge or discharge a soil mixture that presents a high specific heat, high thermal conductivity and a very low hydraulic conductivity (Gao, Zhao and Tang, 2015).

Latent heat storage

PCMs use latent heat, which is the energy required to change the phase of the material (normally solid to liquid), to store thermal energy. There are many different types and applications of PCM. This report focuses on those currently viewed as having the greatest potential for renewable energy integration for each key temperature range.

The main criterion for selecting a PCM is the phase-change temperature range needed for the application. Other thermophysical properties, such as the latent heat of fusion and thermal conductivity, should also be taken into account during selection. Figure 27 shows the classification of families of PCMs addressed in this report based on these criteria, illustrated using examples of PCM families.

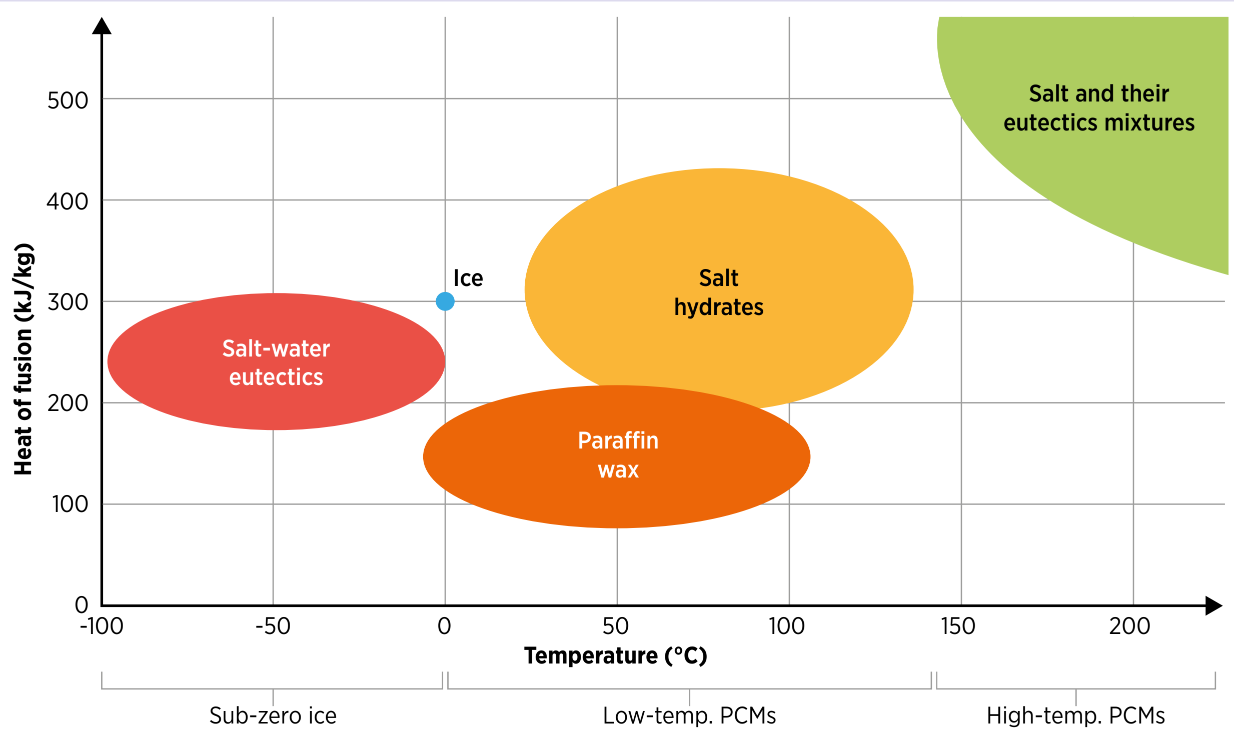
The technologies examined, and their operational temperature ranges, are outlined below:

- Sub-zero PCMs: with a congruent phase-change temperature below 0°C, *e.g.* salt-water mixtures.
- Ice: which has a phase-change temperature to water of 0°C.
- Low-temperature PCMs: with a phase change temperature of 0-120°C, *e.g.* paraffin waxes and salt hydrates.
- High-temperature PCMs: with a phase change temperature above 120°C, *e.g.* inorganic salts and their eutectic mixtures, including those stored in ceramic supporting materials known as composite PCMs (cPCMs).

Compared to sensible heat storage materials, PCMs have a higher energy density, meaning that their physical footprint is smaller. PCMs can charge and discharge at an almost constant temperature, meaning that a PCM can be specifically chosen to provide a specific output temperature according to the engineering need.

This additional control is particularly useful for sensitive applications such as in the cold chain, where drugs or food have to be maintained within narrow temperature ranges.

Figure 27: Properties of PCMs examined in this report, showing difference in heat of fusion and melting points



Note: kJ/kg = kilojoules per kilogram.

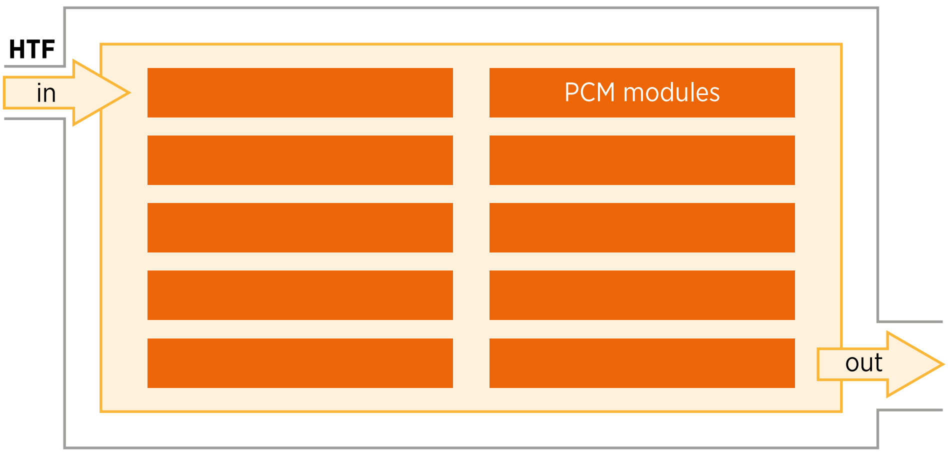
Sub-zero temperature PCMs

Sub-zero temperature PCMs are either single component or are composed of a mixture of two or more materials, such as a eutectic mixture. Eutectic mixtures are defined as a mixture of components with a specific ratio that results in the melting temperature of the mixture being lower than the melting temperatures of the individual components. Salt-water eutectics are produced by dissolving salts in water to form a solution. The component or mix of components used varies in cost, phase-change temperature, energy density and in how corrosive they are. For example, the eutectic composition of salt water has 27% NaCl dissolved in the water and has a freezing temperature of -21.1°C. Lower concentrations of salt in the water would result in a higher freezing temperature.

Sub-zero temperature PCMs are useful for applications where colder temperatures are required than standard space cooling, for example for refrigeration in the cold chain. In certain cases these are able to provide a more effective solution to using ice as the PCM.

In most applications the PCM is encapsulated to avoid leakage, as shown in Figure 28. For a bulk storage unit, modules are filled with the PCM and fixed in a tank. These then cool a heat transfer fluid that flows through the tank to a specific temperature by absorbing the heat from the heat transfer fluid.

Figure 28: Bulk storage system of PCM encapsulation



Note: HTF = heat transfer fluid.
Source: Mehling and Cabeza, 2008.

Ice thermal storage

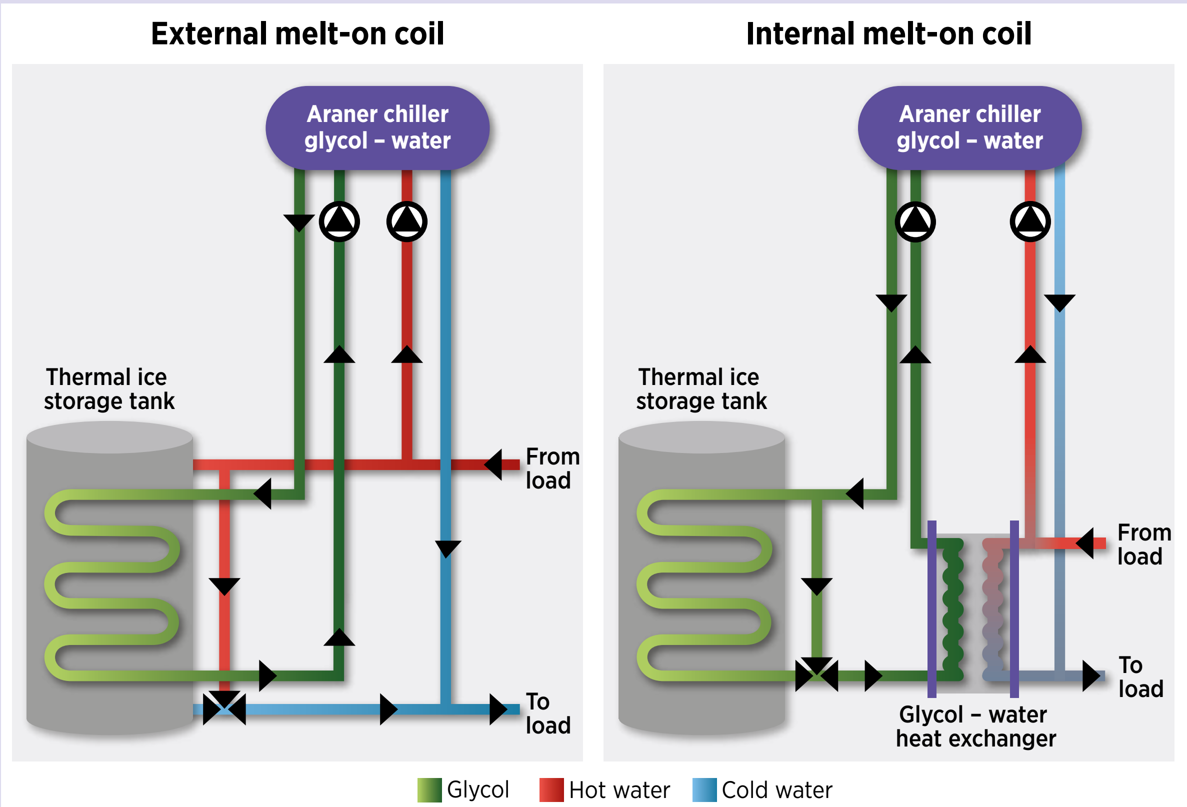
Ice has excellent material properties for cold storage, including a high heat of fusion (334 kJ/kg), good heat capacity (4.2 kJ/kg·K) and non-corrosive behaviour. As the solid form of water, ice is readily available and inexpensive. To store cold energy in ice, off-peak or renewable electricity is used to freeze water using chillers or ice generators placed above ice tanks. For discharging, the cold energy transfers via water or an additional heat transfer fluid, such as glycol.

Thermal storage using ice is commercially available for buildings and district cooling schemes. Although more expensive than chilled water tanks, it offers a lower physical footprint. Ice thermal energy storage has two typical configurations, namely as bulk ice storage and ice-on-coil storage.

For bulk ice storage systems, ice is stored in a tank filled with both chilled water and ice at freezing temperature. When charging, a pump sends the chilled water from the tank to the ice generator, and the ice falls back into the tank. In the discharging process, another pump is used to circulate the chilled water from the tank to the load, and the warm water back from the load returns to the top of the tank. Cold energy can also be stored in the form of slurry ice, which can be used as a heat transfer fluid.

For ice-on-coil storage systems, a storage tank is filled with water and a coil submerged in it. In the charging process, a chiller cools the heat transfer fluid (e.g. glycol) to a sub-zero temperature and flows through the coil, freezing the water around the coil. In discharging process, either an external loop or internal loop with a heat exchanger is used to bring the cold energy from the storage tank to the load (Figure 29).

Figure 29: Ice-on-coil system



Source: Araner, 2017.

Low-temperature PCMs

Low-temperature PCMs have a phase-change temperature from 0°C up to 120°C. Two common classes of PCM used in this temperature range are paraffin waxes and inorganic salt hydrates. Paraffin waxes have emerged as one of the key materials due to their versatility and stable chemical properties (they are non-toxic and non-corrosive). Salt hydrates such as strontium bromide have already been commercialised for domestic heating.

Commercial paraffin waxes have been studied the most due to their low cost, moderate latent heat (around 200 kJ/kg) and their wide range of melting temperatures (Jegadheeswaran and Pohekar, 2009). However, they have low thermal conductivity (0.2 watts per metre kelvin [W/m·K]) and moderate flammability, which limits their application. High thermal conductivity particles and fillers such as graphite or metal can be added to substantially increase their thermal conductivity (Karaipekli et al., 2017).

Low-temperature PCMs are especially relevant for thermal storage in buildings, as they can be integrated into domestic heating and air-conditioning equipment.

Inorganic salts as high-temperature PCMs

Some mixtures of inorganic salts have high phase-change temperatures (over 500°C). Binary and ternary mixtures of inorganic salts have been widely studied for thermal storage applications. Carbonate, nitrate, chloride and sulphate salts of alkali and alkaline metals, such as magnesium, potassium, lithium and calcium, are the main compounds used to produce eutectic mixtures (Pereira da Cunha and Eames, 2016). Notable features of molten carbonates, one of the most commonly found high-temperature PCMs alongside nitrate salts, include their chemical stability and optimal performance under a wide range of temperatures (500-800°C), making them suitable for a range of high-temperature applications. They have a high storage density; however, they are corrosive and have low thermal conductivity, which limits the charging/discharging rate.

Various methods have been proposed to solve these problems, such as the use of porous supporting materials (metal foams, porous carbon materials and ceramic structures) to avoid leakage, and the addition of high thermal conductivity enhancers such as graphite materials. Solutions that incorporate porous supporting materials are known as high-temperature composite PCMs (HT-cPCMs). HT-cPCMs are used in commercially available heat batteries for buildings, and they have also been used in demonstration projects integrating excess wind energy in district heating schemes.

Thermochemical heat storage

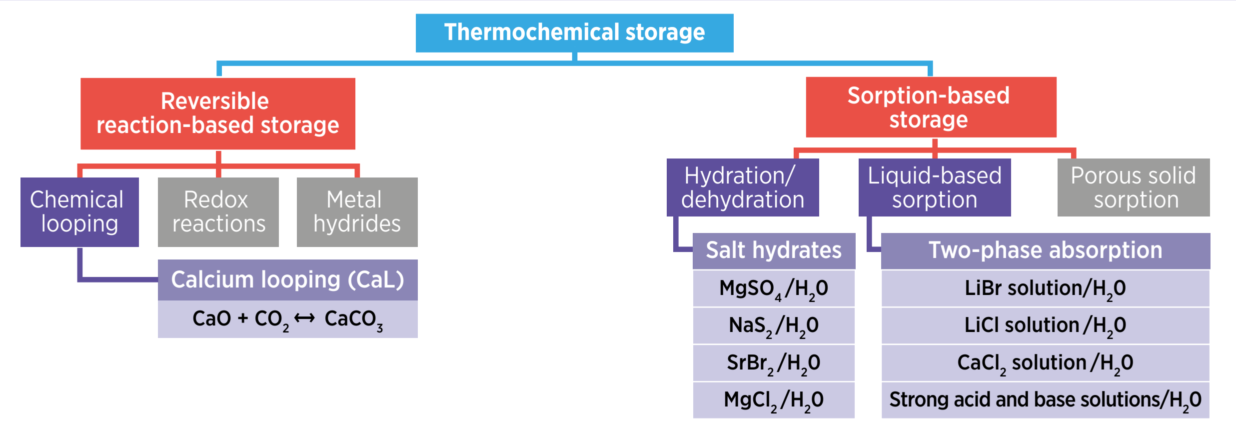
Thermochemical storage has a higher energy density than sensible and latent heat storage. It can be divided into reversible reaction-based storage and sorption-based energy storage (Aydin, Casey and Riffat, 2015). This categorisation and the relevant technology families are summarised in Figure 30.

Thermochemical systems without sorption are based on a reversible reaction of two separate chemical substances where a high amount of energy is generated as a result of an exothermic synthesis reaction (Yu, Wang and Wang, 2013).

In a sorption process, heat is stored by breaking the binding force between the sorbent and the sorbate in terms of chemical potential (Chang *et al.*, 2013).

While sorption storage can only work up to temperatures of about 350°C, thermochemical systems without sorption can operate at higher temperatures and offer higher energy storage densities. Due to the capability of the sorption systems to conserve the heat energy at ambient temperature as long as desired without heat losses, thermochemical heat storage has become a widely researched technology for seasonal energy storage at low temperature (for application in buildings).

Figure 30: Thermochemical storage methods and materials



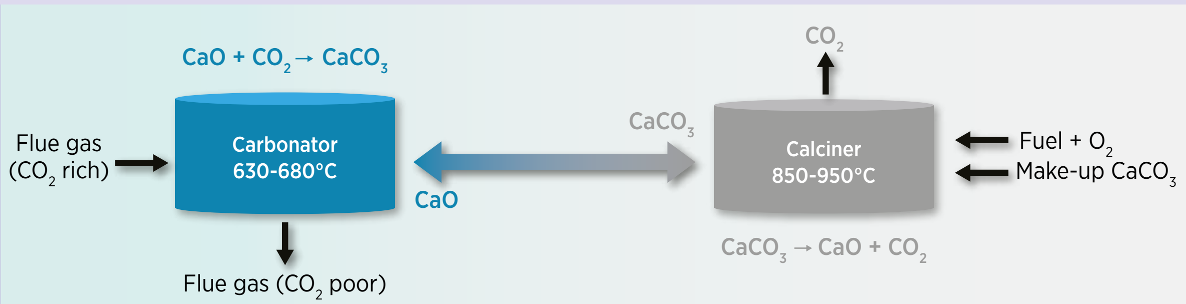
Source: Adapted from Ding and Riffat, 2012; Yu, Wang and Wang, 2013; Scapino et al., 2017.

Chemical looping

Chemical looping systems have been explored primarily as potential carbon capture technologies. One example uses the reversible reaction between calcium oxide (CaO) and carbon dioxide (CO_2) to form calcium carbonite ($CaCO_3$). This is referred to as calcium looping (CaL). In this reaction, $CaCO_3$ is exposed to large amounts of heat, breaking it down into its constituent parts (CaO and CO_2), storing the energy that was provided by the heat in the chemical bonds within the CaO and CO_2 molecules. Both CaO and CO_2 are then stored separately, acting in effect as the energy storage media.

Storage of the products could be prolonged to weeks or even months, depending on the conditions and energy demand, with no energy loss. When energy is required, CaO and CO_2 are brought back together again to form $CaCO_3$, releasing heat in the process, as shown in Figure 31.

Figure 31: CaL process scheme



Source: Adapted from Chang et al., 2013.

The advantage of the CaL system is that all materials involved are very low cost, and an extremely high energy density of 3.2 gigajoule per m^3 can be obtained (Chang et al., 2013). However, the working temperatures involved are very high (> 600°C).

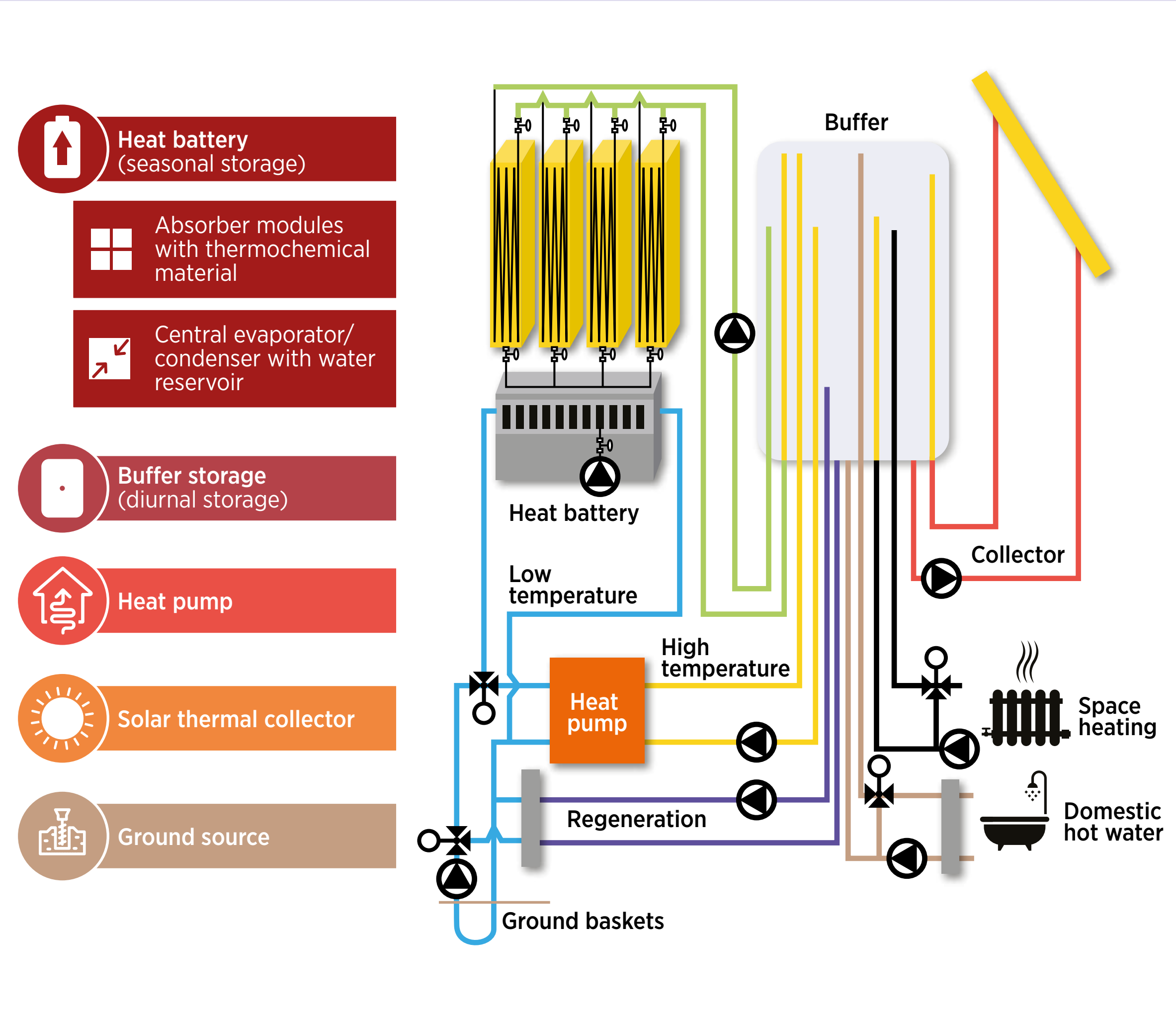
Calcium looping is being explored as a potential technology for storing energy for CSPs (European Commission, 2018), but could also be considered for other high-temperature applications such as in industry or elsewhere in the power sector.

Salt hydration

Salt hydration is a reversible process that absorbs and releases energy through the hydration and subsequent dehydration of a solid salt. The interest in using hydration reactions for heat storage applications mainly focuses on the hygroscopic salts such as magnesium chloride ($MgCl_2$), sodium sulphide (Na_2S), strontium bromide ($SrBr_2$) and magnesium sulphate ($MgSO_4$) (Yu, Wang and Wang, 2013). When heat is added the salt dehydrates, releasing water molecules that can be stored separately from the salt. When there is demand for heat, water is added to the salt, which absorbs it and releases heat. Heat batteries that exploit this process can store heat in small volumes with a minimal loss of energy over long periods of time.

These properties make hydration reactions particularly interesting for seasonal storage. Academic and industrial research is underway in Europe to develop seasonal heat batteries for use in domestic buildings in conjunction with diurnal thermal storage such as TTES, as shown in Figure 32. However, thermal storage technologies based on salt hydration present a range of challenges related to aggressive materials, corrosion issues with the containment structure, material stability and degradation/agglomeration.

Figure 32: Diagram of the CREATE demo thermal storage system



Note: Diagram shows how a seasonal heat battery based on salt hydration technology is used in conjunction with diurnal storage as well as heat pumps and solar thermal collectors.

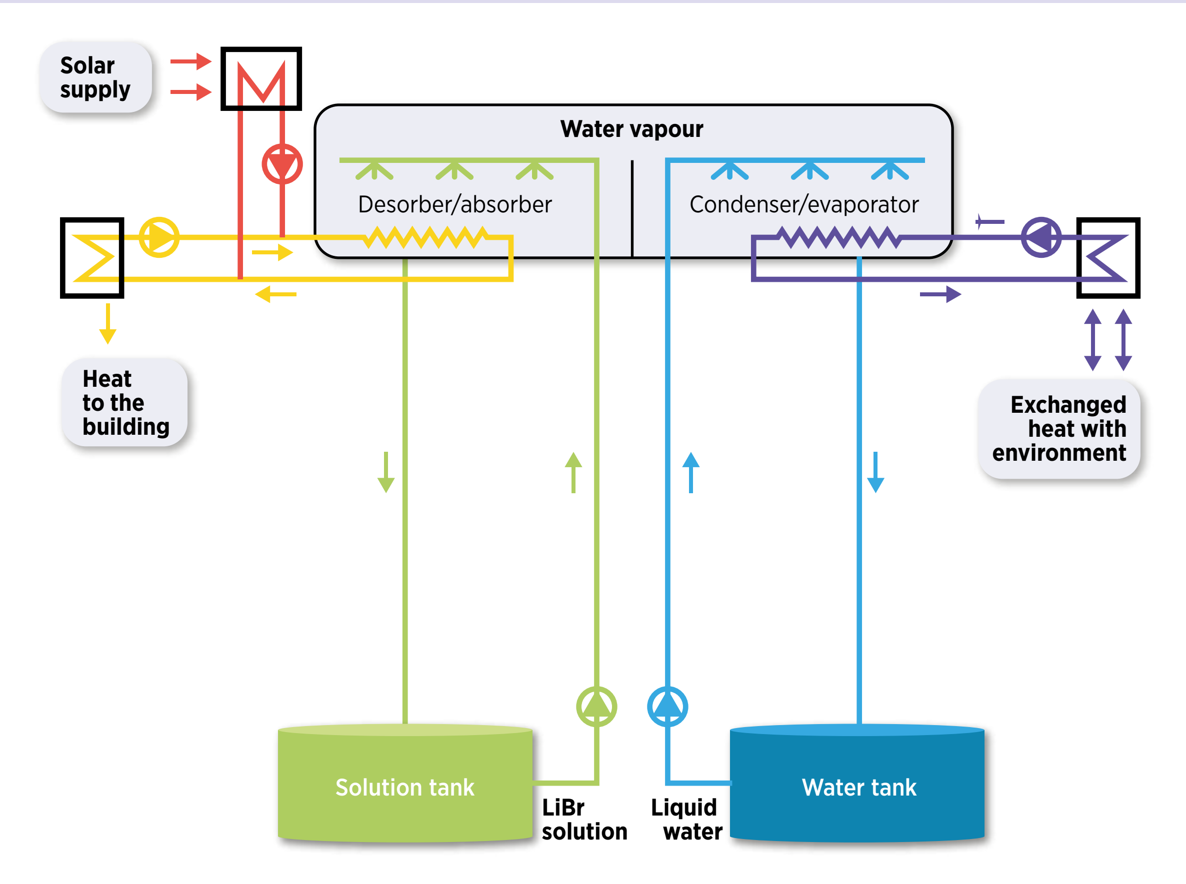
Source: CREATE, 2018.

Absorption systems

Absorption heat pumps are essentially heat pumps that are driven by a source of heat, e.g. solar thermal energy, instead of electricity. In this report we refer to absorption systems as a form of TES, in which heat/cold can be generated in real time using solar absorption heat pumps and stored for later use.

Absorption systems are based on the principle of a concentrated refrigerant solution (e.g. aqueous solutions of calcium chloride [$CaCl_2$], lithium chloride [LiCl], lithium bromide [LiBr], sodium hydroxide [NaOH], potassium hydroxide [KOH] or ammonia [Lele, 2016]) absorbing water and releasing heat in the process. The heat released is the heat of sorption, which is the energy released when water vapour is sorbed into the volume of a liquid. The system is charged through the addition of heat, causing water molecules to desorb from the refrigerant solution. This forms two products: water vapour and a more concentrated solution of refrigerant. These products can then be separated and stored until heat is required, when they can be combined again. Figure 33 shows a schematic of an absorption system with a solar thermal heat source, an absorption heat pump, and separated concentrated refrigerant and water tanks.

Figure 33: Absorption system configuration with separator reactor



Source: N'Tsoukpoe, Le Pierrès and Luo, 2013.

Absorption systems are a promising storage option because energy storage densities greatly exceed the storage density provided by water as a sensible storage technology. This is primarily because the absorption cycle is more suitable for low-grade heat utilisation, making the systems potentially useful for buildings and certain industrial applications.

Mechanical TES systems

Coupling TES systems with mechanical energy storage technologies provides complementary capabilities from both technologies. TES is used to facilitate system improvements and higher efficiencies, but these systems become highly complex (AEE INTEC, 2019).

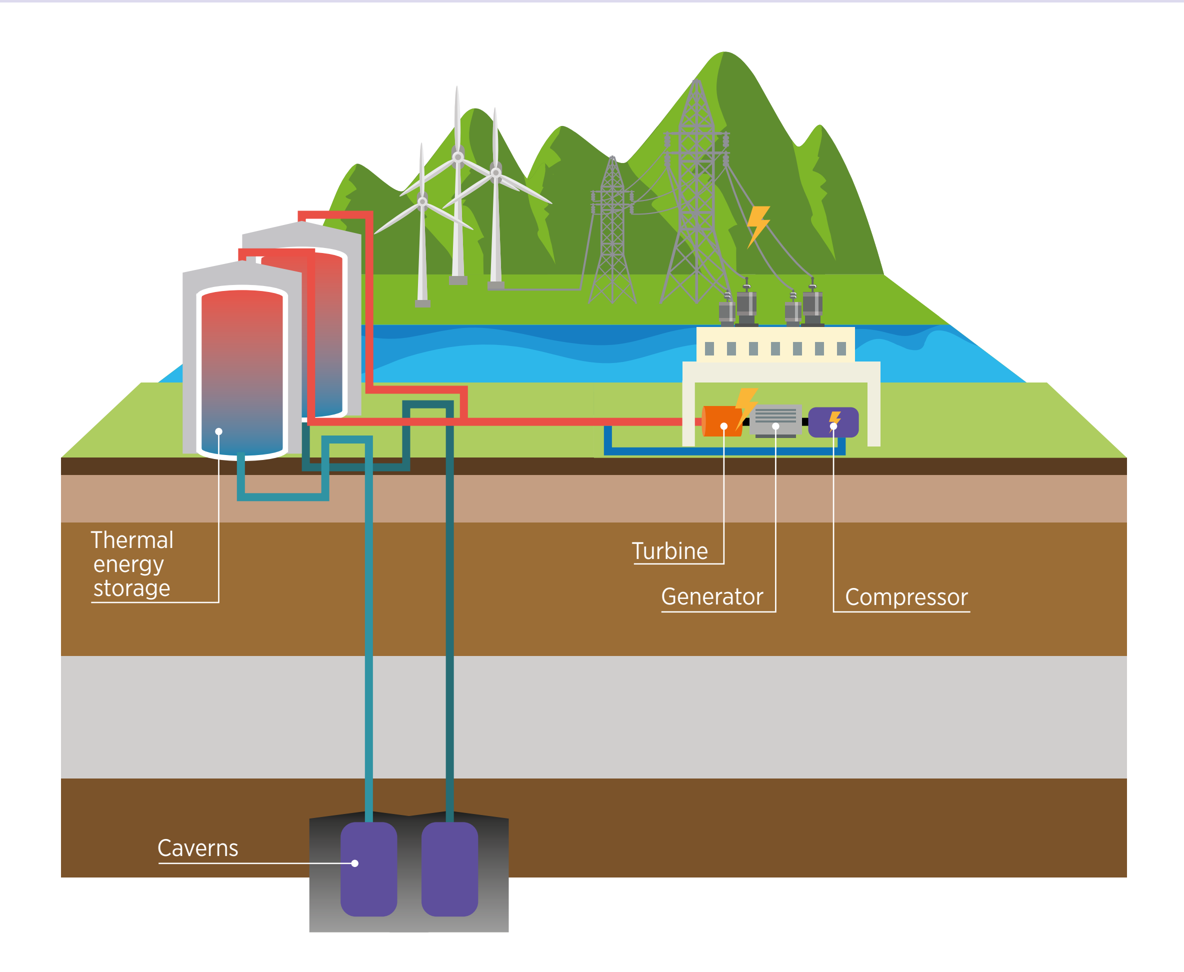
The two coupled technologies examined in this report are:

- adiabatic compressed air energy storage (A-CAES)
- liquid air energy storage (LAES).

Adiabatic compressed air energy storage

In traditional CAES, off-peak renewable electricity can be used to compress and then store air at high pressure in subterranean caverns. When electricity is needed, the pressurised air is expanded in order to drive a turbine and generate electricity. During the process, cooling units remove the heat of compression and additional heat is then required to heat up the air before the expansion. Both of these cause energy losses. A-CAES systems have been proposed to improve the overall efficiency by adding a high-temperature TES unit (e.g. pebbles, ceramics bricks or PCMs) that stores the heat of compression that would otherwise have been lost during the gas compression stage, for later use during the expansion process. Figure 34 shows a potential A-CAES site.

Figure 34: Diagram of a proposed A-CAES site

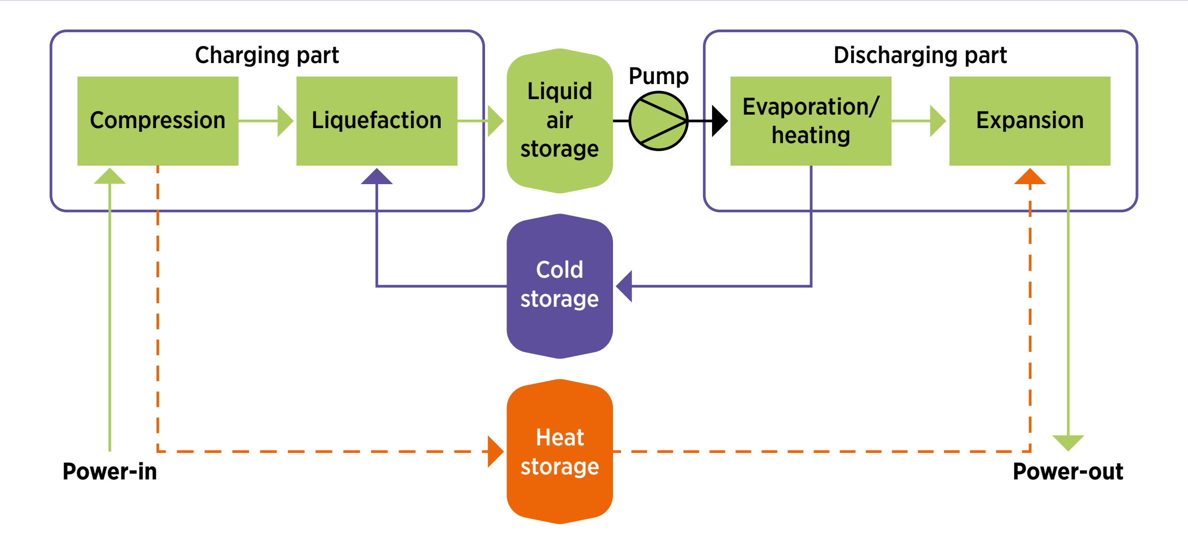


Source: RWE Power AG, 2010.

Liquid air energy storage

LAES is being developed as a novel form of energy storage that is similar to CAES in that it uses stored compressed air to later drive a turbine to release energy. However, its key difference is that the air is cooled and compressed to the extent that it liquefies, meaning it can then be stored and transported for use in other locations and applications. During charging, off-peak or renewable electricity is used to compress the air to high pressure (> 60 bar), and the heat produced during compression is stored in a heat storage system (> 300°C). The compressed air is cooled (to -145°C) by the cold storage and then liquid air (-196°C) is obtained by reducing the pressure back to ambient levels. For discharging, liquid air is returned to gas through evaporation, and part of the "waste" cold is retained in cold storage. The air is further heated by stored heat, which can be used to drive a turbine to generate electricity. This is summarised in Figure 35.

Figure 35: General system configuration of LAES for electricity generation



Source: European Association for Storage of Energy, n.d.

An alternating-current round-trip efficiency of 70% can be achieved by utilising a source of waste heat. LAES can be used as electrical energy storage, which charges and discharges electricity. The liquid air can also be used as a fuel for engines and the cold energy can be used for refrigeration (Dearman Engine, n.d.)

2.2 Key attributes of TES technologies

This section provides a high level summary of the key characteristics and technical attributes of the technologies considered in this report. Two principal criteria for choosing a specific TES technology for any application are the required working temperature range and storage duration (Figure 36). Other characteristics are also of relevance, and an overview of these characteristics is outlined in Table 2 and Table 3.

The key attributes in Tables 2 and 3 are defined below:

- The **applicable scale** refers to the ability of the TES to be used within an energy system from small- to large-scale applications at different sectors and scales in a cost-effective manner. "Small" applications refer to residential and commercial solutions that service a single building, "district/industrial" refers to a localised groups of buildings or industrial site that are connected through district heating and/or cooling networks with storage capacities at the megawatt hour level, and "utility" refers to scenarios with a large-scale requirement for thermal storage, such as for providing the heating/cooling services through a large-scale district heating/cooling network or for power generation, or both in a co-generation facility.

- The **storage period** is the possible duration each technology can store energy for prior to effective use in heating, cooling or producing electricity. It could be hours (demand shifting) or months (seasonal storage).

- **Potential vectors** refers to the form of energy input and output for each storage system.

- The **range of capacities** is the quantity of available energy in the storage system after completely charging (*i.e.* reaching the maximum working temperature of the storage tank material in sensible TES; completing 100% phase-change transition in latent heat TES; or reaching a 100% conversion rate in thermochemical energy storage). This is a function of the energy density and volume of the storage media.

- The **range of power** describes the rate at which energy can be charged and discharged from the system, and this depends on the design of the system and the technology.

- Each technology can only work in a specific **operating temperature range**, defined as estimates of the maximum and minimum working temperatures of the storage system, which is dependent on the physiochemical properties of the storage media.

- The **round-trip efficiency** is the relation between energy put in and energy retrieved from the storage, and represents how effective the technology is at retaining and discharging thermal energy once stored. This parameter can be strongly dependent on the system working conditions (*e.g.* daily or seasonal).

- The **energy density** represents the maximum amount of energy accumulated per unit volume of the storage unit. This value depends on the working conditions (maximum and minimum working temperatures).

- All storage systems experience fatigue and wear by usage, causing ageing and thermal degradation. The **lifetime** refers to either the number of years the storage unit can be expected to operate in a way that it was designed for under certain operational conditions, or it refers to the number of cycles the storage unit can perform. For example, if a storage asset is expected to undertake a full charge/discharge cycle every day, then a lifetime of 1000 cycles would mean a lifetime of roughly 3 years.

Figure 36: Operating temperatures and time ranges for TES technologies studied

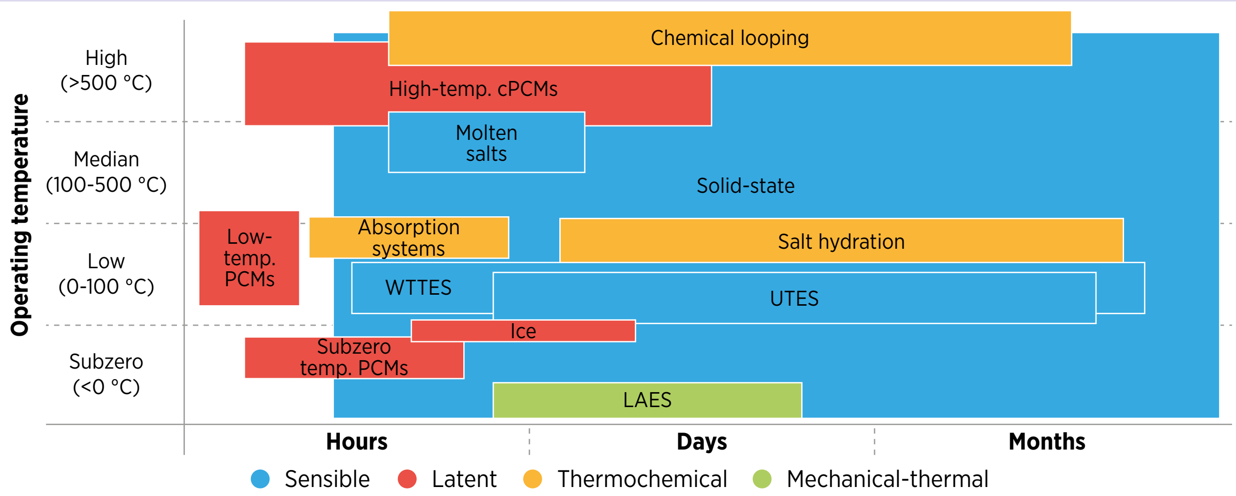


Table 2: Applicable scales, operating durations and relevant energy vectors for selected TES technologies

Type of TES	TES technology	Applicable scale			Storage period				Potential vectors					
		Small	District	Utility	Hours	Days	Weeks	Months	In			Out		
Sensible	WTTES	green	green	green	green	green	green	green	H (green)	C (green)	P (green)	H (green)	C (green)	P (red)
	UTES	green	green	green	green	green	green	green	H (green)	C (green)	P (green)	H (green)	C (green)	P (red)
	Solid state	green	green	green	green	green	green	green	H (green)	C (green)	P (green)	H (green)	C (green)	P (green)
	Molten salts	red	green	green	green	green	red	red	H (green)	C (red)	P (green)	H (green)	C (red)	P (green)
Latent	Ice thermal energy storage	green	green	red	green	green	red	red	H (green)	C (green)	P (green)	H (red)	C (green)	P (red)
	Sub-zero temperature PCM	green	green	red	green	red	red	red	H (green)	C (green)	P (green)	H (red)	C (green)	P (red)
	Low-temperature PCM	green	red	red	green	red	red	red	H (green)	C (green)	P (green)	H (green)	C (green)	P (red)
	High-temperature cPCM	green	green	green	green	green	red	red	H (green)	C (green)	P (green)	H (green)	C (green)	P (red)
Thermo-chemical	Chemical looping (calcium looping)	red	red	green	green	green	green	green	H (green)	C (red)	P (green)	H (green)	C (red)	P (green)
	Salt hydration	green	green	red	red	green	green	green	H (green)	C (green)	P (green)	H (green)	C (red)	P (red)
	Absorption systems	green	green	red	green	green	red	red	H (green)	C (green)	P (green)	H (red)	C (green)	P (red)
Mechanical-thermal	CAES	red	red	green	green	green	green	red	H (red)	C (red)	P (green)	H (red)	C (red)	P (green)
	LAES	red	green	green	green	green	green	green	H (red)	C (green)	P (green)	H (red)	C (green)	P (green)

Notes: green denotes applicable; red denotes not applicable; C = cold; H = heat; P = power.

Table 3: Key technical attributes of selected TES technologies

Type of TES	TES technology	Range of capacities	Range of power	Operating temp-erature	Round-trip efficiency	Storage period	Energy density	Lifetime (years or no. of cycles)
Sensible	WTTES	kWh to 1 GWh	kW to 10 MW	10 to 90°C	50 to 90%	Hours to months	15-80 kWh/m^3 (1)	15-40 years
	UTES	MWh to GWh	MW to 100 MW	5 to 95°C	up to 90%	Weeks to months	25-85 kWh/m^3	50 years
	Solid state	10 kWh to GWh	kW to 100 MW	-160 to 1 300°C	>90%	Hours to months	0.4-0.9 $kWh/m^3 \cdot K$ (heat capacity) (2)	> 5 000 cycles
	Molten salts	MWh to 5 GWh	100 kW to 300 MW	265 to 565°C (4)	>98%	Hours to days	70-200 kWh/m^3	> 20 years
Latent	Ice thermal energy storage	kWh to 100 MWh	kW to 10 MW	-3 to 3°C	>95%	Hours to days	92 kWh/m^3	> 20 years
	Sub-zero temperature PCM	kWh to 100 kWh	kW to 10 kW	down to -114°C	>90%	Hours	30-85 kWh/m^3	> 20 years
	Low-temperature PCM	kWh to 100 kWh	kW to 10 kW	up to 120°C	>90%	Hours	56-60 kWh/m^3	300-3 000 cycles
	High-temperature cPCM	10 kWh to GWh	10 kW to 100 MW	up to 1 000°C	>90%	Hours to days	30-85 kWh/m^3	> 5 000 cycles
Thermo-chemical	Chemical looping (calcium looping) (5)	MWh to 100 MWh	10 kW to 1 MW	500 to 900°C	45-63%	Months	800-1200 kWh/m^3	>30 years
	Salt hydration	10 kWh to 100 kWh	N/A	30 to 200°C	50% (open systems) 60% (closed systems)	Months	200-350 kWh/m^3	20 years
	Absorption Systems	10 kWh to 100 kWh	10 kW to 1 MW	5 to 165°C	COP: 0.7-1.7	Hours to days	180-310 kWh/m^3	50 years
Mechanical-thermal systems	CAES	10 to 1 000 MWh	10 to 1000 MW	up to 600°C	> 90% (thermal efficiency)	Hours to weeks	N/A	20-40 years
	LAES	MWh to GWh	10 to 300 MW	> 300°C (heat) -150°C (cold) -196°C (liquid air)	> 90% (thermal efficiency)	Hours to months	N/A	> 25 years

Notes: (1) The energy density of water TTES and UTES is based on a reference temperature at 20°C; sensible heat is not considered in the calculation of energy density of latent heat storage; (2) Energy density of solid state is determined by the operating temperature difference; energy density = heat capacity x temperature difference; (3) for "solar salt" (60% $NaNO_3$ and 40% KNO_3); (4) Only referring to calcium looping process (as opposed to other chemical looping examples); kW = kilowatt; MW = megawatt; MWh = megawatt hour; COP = coefficient of performance.

Note: N/A denotes that no main needs were identified.

3. CURRENT STATUS OF APPLICATION IN SECTORS AND OUTLOOK

This section provides an overview of how thermal storage could be used to facilitate the introduction of higher shares of renewables across five key sectors in which energy is consumed: power, industry, district heating and cooling, the cold chain, and buildings. The sector refers to the *location at which TES is deployed*, as the benefits are often shared across the system. TES can be a form of both supply-side and demand-side flexibility. The power sector sub-chapter focuses only on TES as a supply-side flexibility enabler, whereas the other sub-chapters (industry, district heating and cooling, the cold chain, and buildings) focus on TES as an enabler of demand-side flexibility and of integrating on-site renewable energy generation.

For each sector this report outlines:

- The key issues that are faced when integrating renewables and the role TES could play in helping to address these.
- Which technologies are available today to provide these benefits.
- An outlook as to what technologies may be available in the future.
- The main innovation needs to increase the commercial readiness of the technologies described.

An introductory box also summarises the principal points for each sector.

Figure 37 provides a high-level overview of how TES can be used to provide system benefits by integrating it into different sectors. These benefits are those discussed in Section 2.2 of this report.

Figure 37: Overview of the major applications of TES by sector

	Variable supply integration	Sector coupling	Demand shifting	Network management	Seasonal storage
Power	✓✓			✓	
Industry	✓✓	✓✓	✓✓	✓✓	
District heating/cooling	✓✓	✓✓	✓✓	✓✓	✓✓
Cold chain	✓✓	✓✓	✓✓	✓✓	
Buildings	✓✓	✓✓	✓✓	✓✓	✓

Notes: ✓✓ *TES technologies are available today for these applications.*
✓ *TES technologies are being developed for these applications.*

3.1 Power

TES can help facilitate ever more efficient integration of renewables in the power sector

Wind and solar PV energy are fast becoming mainstream and competitive sources of power. Although accounting for only 10% of global electricity generation in 2019, they are expected to represent the backbone of renewable energy growth: by 2050 it is projected that wind and solar PV will together account for 61% of total global electricity production (IRENA, 2020a). Given the variability and intermittency of solar and wind resources, they present challenges to the energy system that are different to other renewables such as tidal, geothermal and biomass. TES can be used to mitigate issues of variability in renewables and improve the short-term (*i.e.* non-seasonal) supply-side flexibility of the power sector.

The key use cases where TES can benefit the power sector (defined here as being up until the point of demand) are:

- **Variable supply integration:** this refers to TES co-located at the point of VRE generation, *i.e.* solar thermal in the form of CSP, and alongside wind and solar PV generation. The focus here is on assisting with the mitigation of short-term and periodic fluctuations of supply, *i.e.* cloudy periods or overnight in the case of solar power, and periods of low wind for wind energy.

- **Network management:** this refers to providing services solely to power grids, through in-front-of-meter installations of TES at the transmission or distribution level. Network management can come in the form of curtailment avoidance and network reinforcement deferral through constraint alleviation.

TES in the power sector

Role for TES

- ***Increasing the share of power generated from VRE sources, such as wind and solar, will pose challenges for balancing the power system cost-effectively.***
- ***Low-cost large-scale modular TES could potentially play a crucial role by providing bulk power management services such as load shifting, reducing curtailment and compensating for periods of non-production.***
- ***TES is critical to enable sector coupling (power to heat/cold) by decoupling availability of wind and solar from heating and/or cooling demand (explored in more detail in the other sub-chapters).***

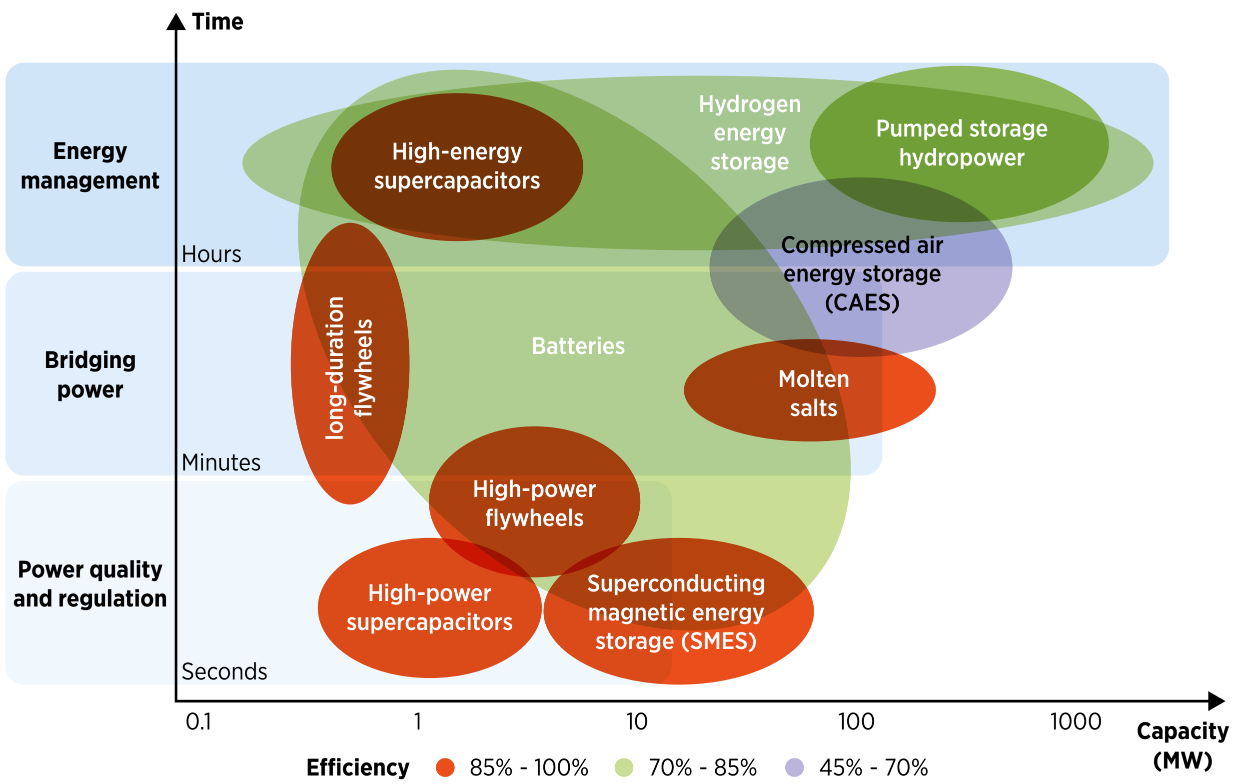
Existing use cases

- ***Molten-salt systems are deployed widely in CSP plants.***

Innovation potential

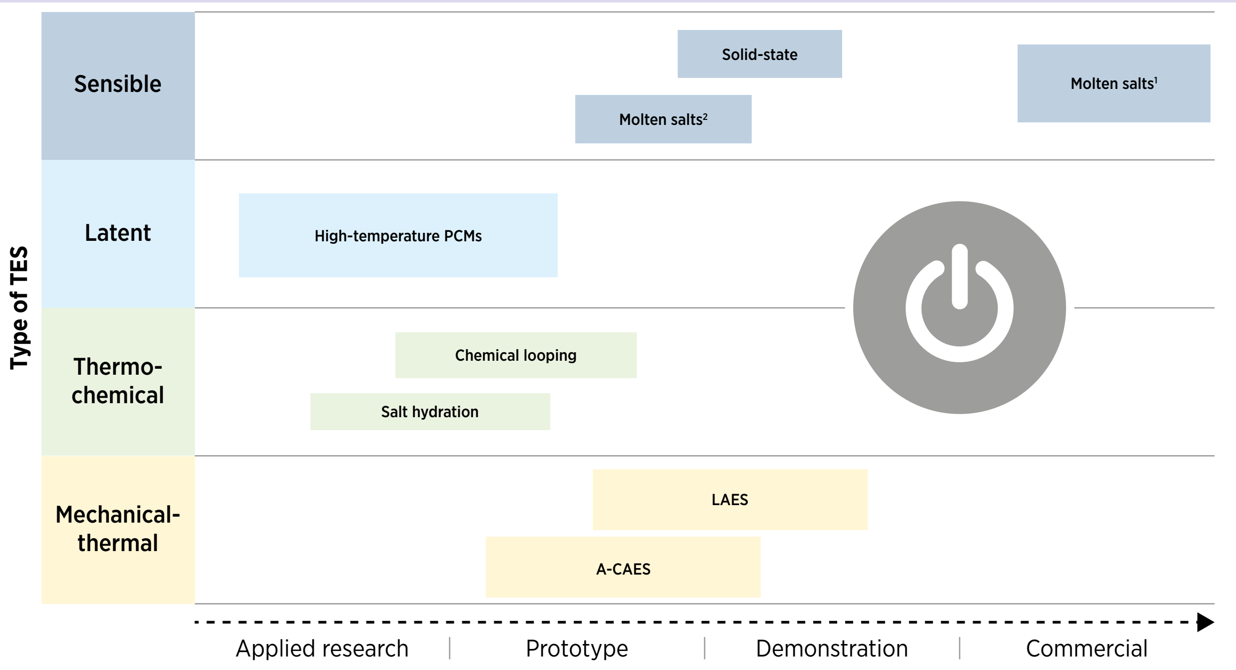
- ***Short term (5 years):** the next generation of molten salts could increase operating temperature ranges and performance, which would materially improve conversion efficiencies of CSP plants, and cost reductions will enhance feasibility of other technologies. More pilots could emerge for solid-state storage and novel stand-alone molten-salt thermal batteries.*
- ***Medium term (5-10 years):** cost reductions and developments in LAES, adiabatic CAES and solid-state systems will enable greater use of TES across wind and solar PV generation, and also potentially serve as effective alternatives to molten salts in CSP.*
- ***Long term (>10 years):** developments in thermochemical storage could enable much higher conversion efficiencies in CSP plants. Molten salt-based storage could enable fossil-fuel powered plants to be reused for renewable energy generation and storage, saving decommissioning costs.*

Figure 38: System power rating and potential discharge time at their rated capacity of various storage technologies



Source: Adapted from diagram developed by NREL.

Figure 39. Commercial readiness of technologies applicable to the power sector in 2018



Notes: (1) Co-located with CSP; (2) Standalone.

Figure 38 maps various storage technologies and what role they play in the power system. Generally speaking, most battery technologies can help with power quality and regulation, or provide bridging power services, due to the combination of their capacities and response durations. However, excluding pumped hydro and CAES, there are few storage technologies that can play an energy management role for the system, and both pumped hydro and CAES are constrained to specific geographic locations.

There is an opportunity for thermal storage technologies (molten salts, LAES, CAES/A-CAES] and solid-state TES) to provide energy management services to the system, primarily due to the potential for low-cost scalability of the storage technologies. These technologies are generally not commercially available at present, but their innovation potential is outlined below.

TES technologies are at varying stages of development and deployment in the power sector

Figure 39 shows that the only form of TES currently used commercially in the power sector is molten salts.

Current status

Co-located with concentrated solar power

Molten salts are used in CSP plants to improve their thermal power utilisation efficiencies. Molten-salt TES is used with CSP to store thermal energy during the day, which can subsequently be discharged to power a turbine and generate electricity during the night.

Molten salts have been used in CSP plants for more than 20 years (Bundesverband Energiespeicher, 2017). **There are currently 93 CSP plants operating worldwide. About half of those (47%) are currently integrated with a TES system** (Pelay *et al.*, 2017). A further 39 plants with molten-salt storage are either under construction, under contract or under development in Australia, Chile, China, India and the Middle East, accounting for over 70% of the pipeline of all CSP projects.

A range of other TES technologies are being developed with applications in the power sector in mind. Figure 39 summarises them. Near- to long-term potential and expected future deployment of these technologies in key applications within the power sector are discussed below.

Future outlook

Co-located with CSP

Operators of CSP plants that use **molten-salt** TES technologies face several challenges. These include:

- The high cost of the molten salts used as storage media.
- The need for a substantial amount of backup energy in order to minimise the risk of the salt freezing.
- Reliability issues with the TES system, due in part to the corrosive nature of the molten salts.
- Concerns around parasitic use, and cost of antifreeze and circulation pumping.

The total installed cost for CSP plants with four to eight hours of thermal storage capacity range from USD 3183/kW to USD 8645/kW. Projects with eight hours or more of thermal storage capacity show a narrower range, between USD 4077/kW and USD 5874/kW (IRENA, 2020b). One of the main objectives of lowering the LCOE of CSP is to reduce the cost of the thermal storage asset employed by the plant.

Furthermore, to improve the overall economics of the plant, one of the principal objectives is to increase the operating temperature. High operating temperatures improve the thermal-to-electric efficiencies of CSP plants. The current restriction on plant operating temperature is the functional temperature range of the TES materials used. For example, thermal stability limits of molten-salt TES materials limit maximum operating temperatures to 565°C.

For higher-temperature operation very specific thermophysical properties are required of the TES materials, including low melting points (to increase working temperature range), high heat capacities and high thermal conductivity, as well as high thermal stability. As a result, research is being conducted primarily in China and the United States to develop next-generation thermal storage materials for CSP.

Table 4: Main objectives for technological innovation of TES with CSP

Attribute	Sensible			Latent			Thermochemical		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (USD/kWh)	25-30	< 15	< 12	25-90	25-35	< 12	Research level	Pilot scale, 80-160	Demon-stration, <80
Efficiency (%)	>90	>92	>95	>90	>92	>95	40-50	(1)	
Energy density (kWh/m³)	70-200	(2)		30-85			800-1200		
Lifetime (years or cycles)	< 10 000	> 10 000		3 000-5 000	4 000-5 000	5 000-10 000	< 100	500-1 000	> 1 000-3 000
Working temperature (°C)	< 565	600-700	> 700	< 600	600-750	700-850	500-900		500-1 000

Notes: (1) Value not available due to low technology readiness level; (2) Value dependent on the material selection.

Expected and targeted innovation requirements for such materials are listed in Table 4. These are influenced by the US Department of Energy's SunShot programme, which focuses on encouraging innovation in molten-salt material science. The key objective of this programme is to reduce the cost and corrosiveness of the molten salts, but also to explore the potential for other types of thermal storage for CSP applications.

Solid-state concrete storage could offer a cheaper alternative to molten salts for CSP applications, as concrete as a raw material is inexpensive. Furthermore, concrete storage operates at almost ambient pressure, thus no pressure vessels are needed, reducing capital costs further. Moreover, it benefits from good mechanical properties, and is non-toxic, inert and non-flammable. In a typical concrete TES system, pipes are embedded in a concrete block to exchange heat between the block and a heat transfer fluid.

Unfortunately the lifetime of these assets is currently limited due to their maximum working temperatures, and spalling at high temperature, which causes cracks after repeated cycles of thermal expansion and contraction (Alva *et al.*, 2017). Lifetimes are expected to improve through R&D activities (Table 4).

Two projects are being developed in China that will use solid-state formulated concrete as its thermal storage device, as part of a wider deployment of 20 CSP demonstration projects in the country (Kost, 2017).

Solar energy harnessed using CSP could also be stored as chemical energy through the endothermic oxidation reaction in a **chemical looping** system, in which solar energy is stored for later release through a chemical reaction (Pardo *et al.*, 2014). Calcium carbonate is the thermochemical material of choice due to its high energy density (4 400 megajoules per m^3 (MJ/m^3)) and operating temperature (800-900°C) (Prieto *et al.*, 2016). This high operating temperature enables the development of next-generation high-efficiency solar energy conversion systems. Research is underway studying several configurations to investigate the benefits of integrating chemical looping with CSP (Alovisio *et al.*, 2017).

In 2015, 5 GW of CSP capacity was installed globally, but this number could to grow to 309 GW by 2050 provided that ambitious policy frameworks are implemented (IRENA, 2020a). Based on this assumption, and CSP requiring thermal storage with a ~8-hour storage period, there could be a market demand for 633 GW/2 472 GWh of thermal storage for CSP by 2050.

Co-located with wind and solar PV

Solid-state sensible storage in the form of rocks can be used to store renewably generated electricity through resistive heating or via upgrading with a heat pump. In these applications, rocks are electrically heated to high temperature. The stored heat can later be used to drive a steam or gas turbine to generate electricity.

The round-trip efficiency of this approach can theoretically only reach ~50% due to the efficiency of the steam turbine. However, the overall cost is potentially very low due to the use of cheap highly scalable TES materials and integration with existing infrastructure, such as steam turbines and generators from thermal power plants that are no longer operational (Siemens Gamesa, 2017). The key use case is therefore long-duration storage coupled locally with power generation assets, with expected storage timescales of at least 24 hours (Collins, 2018).

A Siemens Gamesa 1.5 MW/30 MWh demonstration project that uses rocks as a form of solid-state storage began construction in Germany in 2017, co-located with an industrial site. It uses resistive heating, with the stored heat discharged using a steam turbine (Deign, 2017). Separately, Stiesdal are working on a 5 MW/120 MWh system in Denmark in which a heat pump will be used to upgrade stored heat, which will be discharged in an air-based system resembling a gas turbine. This will provide storage for wind generation for up to 24 hours (Collins, 2018).

Estimating the future market size, costs and potential of thermal storage is challenging, whether co-located with solar PV or wind plants, or stand-alone to provide grid services. Most of the technologies being investigated are still at early stages of commercial readiness (Figure 39). Representative projections based on available data are presented in Table 5.

Stand-alone

A-CAES can help manage grid loads by storing energy as pressurised air when demand is low, and releasing it to produce electricity when demand increases. Currently CAES is limited in where it can be located due to the lack of technology-specific underground studies for this application (*e.g.* the requirement for appropriate geological environments in the form of underground caverns). However, tunnel boring machine and micro-tunnel boring machine development could bring cost disruption and reduce the geological constraint.

Only two commercial-scale CAES plants are operational: the 290 MW plant in Huntorf, Germany, built in 1978 and a 110 MW McIntosh plant in the United States built in 1991. They have both been used for peak shaving, load levelling, storing off-peak energy and frequency control. Similar to pumped hydro plants, they have a high CAPEX but long lifetimes, are able to provide bulk storage capabilities, and are not able to respond as quickly as electrochemical batteries. A new 330 MW CAES plant is being developed in Northern Ireland, and a demonstration project for next-generation A-CAES has been developed in Switzerland.

Table 5. Key objectives for technological innovation of TES with solar PV and wind generation

Attribute	Sensible			Latent			Mechanical-thermal		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (USD/kWh)	20-45	commer-cial	commer-cial	25-95	25-35	< 12	demon-stration	400-870	150-260
Efficiency (%)	> 90	> 92	> 95	> 90	> 92	> 95	40-65	45-75	50-80
Energy density (kWh/m³)	0.4-0.9 kWh/m³·K (heat capacity)			50-85			2-70		
Lifetime (years or cycles)	> 5 000	5 000-7 500	7 500-10 000	3 000-5 000	4 000-5 000	5 000-10 000	20-40 years		
Operating temperature (°C)	up to 600			< 600	600-750	700-850	< 200 to > 400 (heat) -150 (cold)		

LAES is a developing technology that can provide similar services to CAES, but is comparatively less geographically constrained. A LAES demonstration project has been completed in the United Kingdom, and commercial projects are in development in North America (Sampson, 2018). The developer, a UK-based company, has claimed that their modular solution can achieve a levelised cost of storage of USD 140/MWh for a 200 MW plant with a 10-hour duration.

Both LAES and CAES can store large amounts of energy at a low cost when compared to conventional Li-ion batteries, but with slower response times. Both technologies can be installed at the transmission or distribution level to overcome network constraints, reduce renewables curtailment, defer the need for network reinforcement, and also provide other ancillary services such as black start. In the current market, LAES and CAES can be used to create revenue through energy arbitrage (selling energy stored at off-peak times when energy demand is high), but this does not currently generate sufficient value to recoup the capital investment.

A limitation of LAES is the speed at which it can be switched on to access these markets. LAES is able to respond within ~30 seconds if operated in SpinGen mode, enabling the provision of some frequency regulation services, but cannot respond at the sub-second level achieved by electrochemical storage. However, the world's first hybrid flywheel, supercapacitor and LAES system is in development, seeking to tap into higher value markets including the UK National Grid's enhanced frequency response and firm frequency response (Holder, 2017).

Molten salts are also being proposed for novel forms of stand-alone bulk thermal storage systems known as Carnot batteries. For example, there are concepts being developed in Germany that combine a molten-salt storage asset with the infrastructure from an existing (and decommissioned) coal plant. Excess power is converted using a heat pump and then stored as heat, before being converted back to power using the turbine from the coal plant. However, the steam cycle in coal plants has efficiency limits of about 40%.

To tackle this constraint, a US project has developed novel turbine and heat exchanger equipment that could raise the efficiency to about 60% (SolarPACES, 2019). This project looks to use a four-tank system, with two sets of hot storage for the molten salt and cold storage for the coolant. Utilising four tanks allows operation over a broader temperature range, which in turn increases the power and efficiency of the overall thermal storage device (Freund, 2019). Concepts for a 10 MW/80 MWh and 100 MW/1 000 MWh system have been developed; however, it is likely to be several years before the first pilot is constructed.

3.2 Industry

Heat demand in energy-intensive industry will be difficult to decarbonise; TES can help

The wider industrial sector is responsible for a third of global emissions and is the second-largest emitter of energy-related CO_2. The industrial sector uses more delivered energy than any other end-use sector, and does so in several ways:

- Generating process heat (hot water, steam and direct heat applications) at various temperature levels on-site by burning fuels.
- Generating electricity and process heat on-site via a co-generation plant.
- Importing process heat from a district heat network.
- Importing electricity from the grid.
- Generating electricity and/or process heat using solar PV and/or solar thermal plants.

On-site process heat production accounts for 74% of total industrial energy use. Process heat can be classified into three types of heat: low-temperature heat (below 150°C), medium-temperature heat (150-400°C) and high-temperature heat (above 400°C).

Industry is the biggest laggard in the integration of renewables, with only 14% of final energy consumption in the sector from renewable sources. The majority of renewable heat today is from biomass, and the solar thermal capacity installed in the industrial sector worldwide is small (< 1 gigawatt thermal [GW_{th}]), and is restricted to low-temperature heat production as shown in Table 6.

TES in industry

Need for TES

- *The majority of energy used in industry is for process heat production, so the potential exists for decarbonisation through TES deployment in conjunction with renewables.*
- *Decoupling heat use from generation would permit flexibility and smart energy use, and would facilitate the meeting of continuous demand with intermittent renewable generation, thus reducing waste and disruption.*
- *TES could be used to store low-temperature heat generated either through electrification of heat with heat pumps or by on-site solar thermal plants.*
- *Medium- and high-temperature process heat is current hard to generate using renewable resources, but there may be a role for latent and thermochemical TES solutions in the future to help facilitate the integration of renewables.*

Existing use cases

- *There is a nascent, but growing, use of water TTES in conjunction with solar thermal plants for low-temperature process heat generation and storage.*

Innovation potential

- ***Short term (5 years):*** *cost reductions, awareness-raising and enhancements in integration, management and control of existing TTES could encourage increased deployment of solar thermal generation for processes that require low-temperature process heat.*
- ***Medium term (5-10 years):*** *solid-state technologies could provide a relatively low-cost form of storage that can provide both electricity and heat to industrial processes. High energy density HT-cPCMs and salt hydration storage solutions could reduce the spatial footprint of TES systems, potentially expanding their range of applications. Improved integration and management will also enhance efficiencies.*
- ***Long term (> 10 years):*** *chemical looping and other thermochemical storage systems integrated into manufacturing processes alongside renewables could aid decarbonisation of processes that require higher-temperature process heat.*

Meanwhile, decentralised renewable electricity generators have been utilised in industry to mitigate risks from variable grid supply, to overcome grid access issues (for example in remote operational contexts), to hedge against fuel price increases, and also to a lesser extent for decarbonising operations (Philibert, 2017).

Renewable energy use to meet industry needs may grow over fourfold, whereby renewables would reach a 62% share by 2050 from 13% in 2017.

Pathways towards a future with wider decarbonisation of the industrial sector comprise: deployment of solar thermal generation and heat pumps for lower-temperature heat processes; and the greater use of biomass for on-site co-generation plants that can generate medium- and high-temperature heat. Under the IRENA Transforming Energy Scenario the share of electricity in industrial sector energy use is expected to increase to around 65% in 2050 (IRENA, 2020a).

Table 6. Renewable technologies in industry

Renewable source	2015	2050[1]
Solar thermal installed capacity	0.1 GW_{th}	134 GW_{th}
Geothermal heat	0.02 EJ/yr	4.11 EJ/yr
Biomass heat	8 EJ/yr	20.2 EJ/yr
Heat pumps	0.2 million units	80 Million units
Hydrogen derived from renewables	N/A	7 EJ/yr

Note: (1) The 2050 values correspond to a Paris Agreement-aligned scenario, based largely on renewable energy sources and steadily improved energy efficiency.

Note: N/A dennotes that no main needs were identified.

Source: IRENA, 2018.

Various issues arise when attempting to integrate renewables either for electricity generation or direct heat input in industrial processes. These include:

- Industry is a for-profit enterprise in a competitive global marketplace, and therefore requires low-cost energy.
- Industrial actors are generally risk averse and so new technology integration and the threat of disruption pose barriers to renewables deployment.
- The variability of renewable sources of heat and electricity do not match well with the need for continuous supplies of power or process heat for some industrial applications.
- The geography of existing plant infrastructure can be limiting, either due to sun/wind availability or grid restrictions.
- For high-temperature processes (>400°C), no feasible technical and commercial model currently exists to directly use heat from solar thermal assets. This limits renewables integration into processes requiring high temperatures, especially where demand is variable over time (Muster-Slawitsch *et al.*, 2016).

TES deployment could help address these issues. **The key use case is the decoupling of heat demand from the supply of heat or electricity**, and thereby helping to integrate higher shares of renewables.

Different TES technologies are suited to helping decouple different temperature classifications of heat from their source.

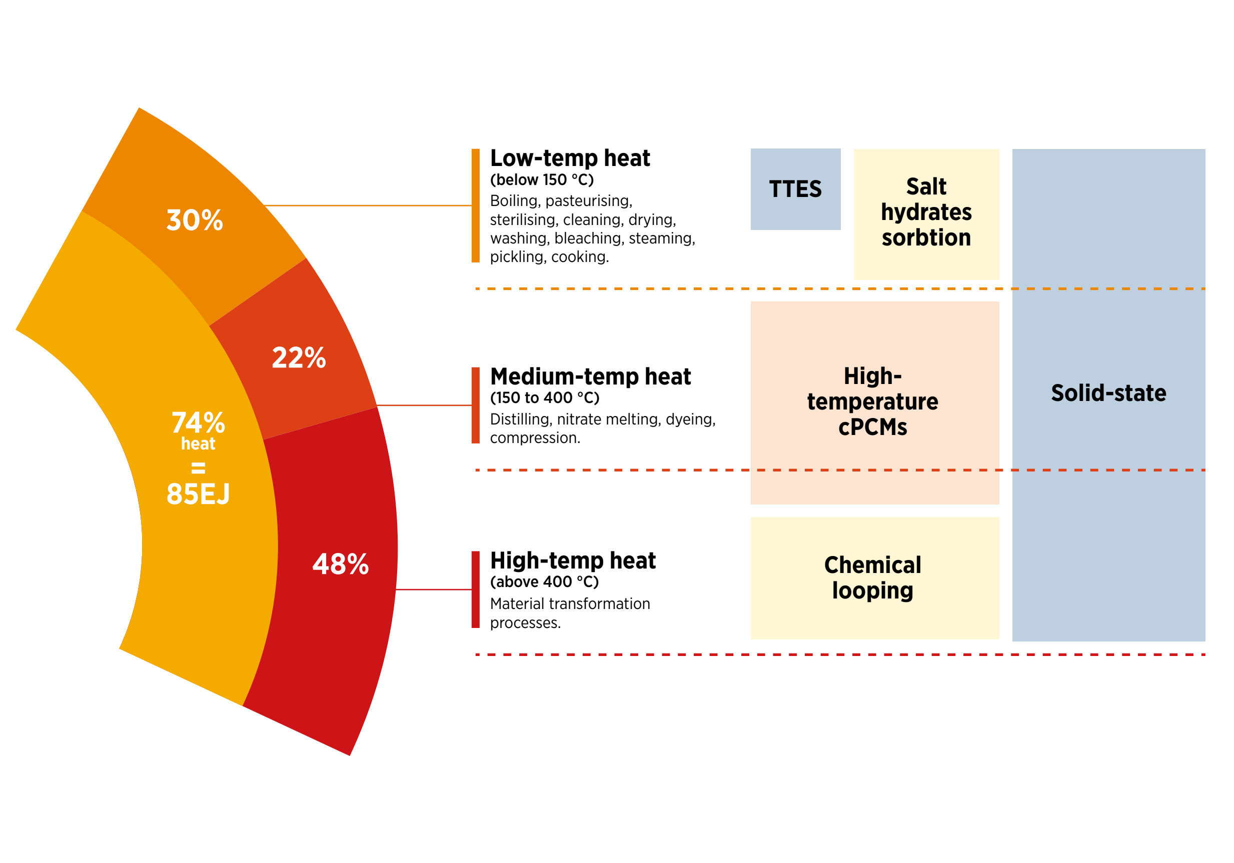
In low-temperature processes and manufacturing applications, TES can be used to store heat generated from on-site variable solar thermal plants and heat sourced from heat pumps powered by variable renewable power. In medium- and high-temperature applications, TES can be used in conjunction with biomass-powered co-generation plants to decouple the supply of heat and electricity to the industrial plant. These use cases would enable higher utilisation of either imported or on-site renewable electricity and heat generation.

In markets where there is a variable cost of electricity (*e.g.* as a result of time-of-use tariffs, or from temporally sensitive grid charges), TES could also be used in conjunction with heat pumps to shift demand and provide cost savings to industrial sites.

A range of TES technologies are relevant for industrial applications, now and in the future

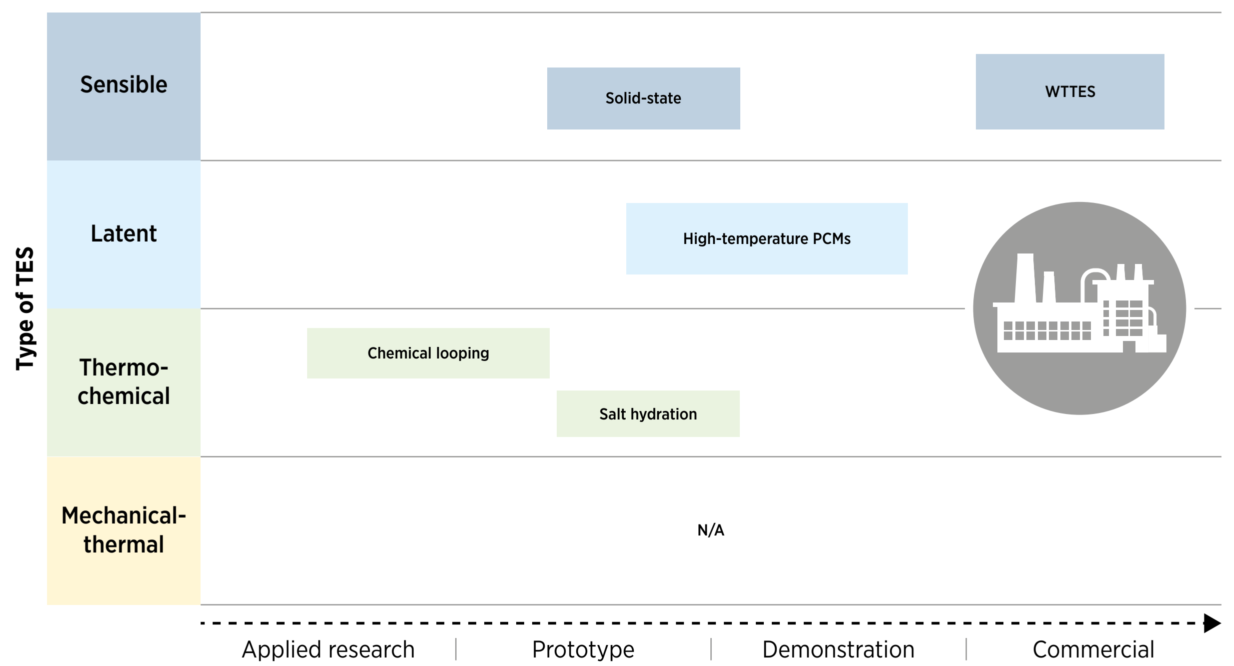
Based on their relative stages of development or deployment (Figure 41) and differing ideal operational temperature ranges (Figure 40), the full suite of TES technologies finds differing applications in the sector. Current use cases, potential future deployment and innovation needed to facilitate wider use are summarised below.

Figure 40. Technologies applicable in the industrial sector by operating temperature range



Source: Adapted from Solar Payback, 2017.

Figure 41. Commercial readiness of TES technologies for application in the industrial sector



Current status

For industrial processes at low temperatures (< 90°C), the heat collected from solar thermal collectors can be used as an alternative heat source to replace the use of hydrocarbon fuels. Due to the intermittency of solar energy, storing heat in **water tanks** is a good option for managing thermal demand, to ensure the stability of energy supply for industrial processes.

A small but growing amount of solar thermal heat is being used for industrial processes, predominantly in the mining, food and textile sub-sectors. By the end of 2018 there were 741 solar thermal plants for industrial processes installed worldwide, with a total thermal capacity of 567 megawatts thermal (Weiss and Spork-Dur, 2019). The main markets are Austria, China, France, Germany, India, Mexico and Spain. The International Energy Agency (IEA) Solar Heat for Industrial Processes (SHIP) database lists about 50% of all such plants as having a form of short-term TTES using water as the storage medium (Figure 42).

Future outlook

Salt hydration also provides an alternative for integrating solar energy in low-temperature industrial processes. The main advantages of this technology are the high heat storage capacity and the possibility of storing heat over long periods with almost no heat losses. Currently salt hydration has been tested in industry through integration into waste heat processes, such as heat recovery or heat transformation and reintegration (Richter *et al.*, 2018). There is also 0.5 MW/10 MWh salt hydration battery being piloted in a district heating scheme in Berlin, which could be of a scale applicable to the industrial sector.

Solid-state technologies are also being looked at across the energy system as a method for storing bulk energy in a cost-effective way. One example being piloted by a utility in Germany is a system that uses steel to absorb regional generation peaks of excess renewables, stores the energy as heat at temperatures of up to 650°C, and can then output both heat and electricity at a 2:1 ratio or just heat by itself.

This 2.4 MWh storage pilot plant is being co-financed by the European Regional Development Fund for use in a district heating scheme at an apartment block in Berlin, and it has projected heat storage costs of USD 22-34/MWh.

In the case of medium-temperature applications, **high-temperature cPCMs** have been proposed for industrial applications such as waste heat recovery and also for coupling with solar energy systems. Compared with sensible energy storage technologies, cPCMs can provide a more compact system due to their higher energy density, which is useful when space constraints need to be considered. The system can store solar energy to satisfy the later heat needs of the industrial site. Industries such as cement production and manufacturing of non-metallic materials may become end users of this technology.

Chemical looping could potentially be used to increase the share of renewables in the manufacturing sector, where there is a need for high temperatures (above 400°C) (Miró, Gasia and Isa Cabeza, 2016). Thermochemical systems commonly require higher temperatures to initiate the energy storage, but conversely provide higher temperatures on the release of that energy. They are still at the basic research stage of development. Chemical looping in the form of high-efficiency calcium looping technology has been trialled in Taiwan as a carbon capture method for the cement industry (ITRI, 2014). However, chemical looping specifically aimed at better integrating renewables in industry is not yet at this stage.

Technical innovation is required for TES to fully contribute to decarbonisation in industry

Table 7 provides a summary of the key metrics for innovation in TES technologies, materials science and systems engineering for industrial applications.

Figure 42. Locations of plants that use water as a medium for short-term thermal storage

Source: AEE INTEC, 2019.

Disclaimer: Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Table 7. Key objectives for technological innovation in TES for industry

Attribute	Sensible			Latent			Thermochemical		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (USD/kWh)	0.1-35	0.1-25	0.1-15	60-120	60-95	60-80	Research level (1)	Pilot scale, 80-160	Demon-stration, < 80
Efficiency (%)	50-90	60-90	70-90	> 90	> 92	> 95	40-50	(2)	
Energy density (kWh/m³)	0.4-0.9 kWh/m³·K (heat capacity)			50-85			800-1 200		
Lifetime (years or 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
Working Temperature (°C)	-150-1 000			-40-700	-50-950		500-900		500-1 000

Notes: (1) Research level: still at an early stage, material development; (2) Value not available due to low technology readiness level.

Common development and innovation objectives across the different TES technologies are:

- Develop TES materials that are more suitable for use in industrial processes based on properties such as operational temperature ranges and discharge power.
- Develop systematic approaches for designing TES systems to better integrate renewable technologies in industrial process. Enhanced system modularity could be used to address issues of scale. Design and engineering priorities will focus on the efficiencies of heat transfer systems, for example.
- Develop advanced control and operation systems for TES, to ensure storage is stable and flexible for high-tariff industrial processes.

A range of more applied development and innovation needs are now explored for each technology family.

Sensible

Although sensible heat storage is used widely in a range of applications, and over a wide temperature range, research challenges still exist. Natural variations in the thermal characteristics of solid-state materials limit their utility, caused by geological aspects such as the proportion of minerals and impurities existing in the rock (Meier, Winkler and Wuillemin, 1991).

Limited research has been done on their thermophysical properties and mechanical behaviour at elevated temperatures, and this is a future focus area. Currently (even) lower-cost systems using recycled waste materials are proposed, offering sustainable options with improved performance (IRENA, 2014). These new options need to be studied further. Specifically, the compatibility between the storage material and the system heat transfer fluid has to be analysed, insulation materials need to be improved, and specific use cases need to be developed.

In systems employing **tank** storage with solar heating, control and management of the heating system is the main challenge. Using solar energy for industrial heating is currently limited due to changing solar irradiance through weather conditions, time of day and seasonality. The key to managing these challenges in future systems with enhanced TTES deployment will be advanced control and metering systems to manage generation, storage and use of energy.

Latent

High-temperature cPCMs offer the potential to meet storage needs for higher-temperature industrial processes, improving on currently deployed sensible materials. Given their comparatively high costs, initial development will focus on achieving material and efficiency improvements to deliver economies of scale. They face similar integration challenges to sensible materials, and indeed these are exacerbated by their relatively early stage of development and deployment. Demonstration projects are needed to prove the performance of the system under different operational conditions and working temperature ranges, and to better investigate systems integration approaches for these technologies.

Thermochemical

The challenges and opportunities of **chemical looping** in industrial settings are similar to those described in the previous section on their use with CSP. Calcium looping presents the greatest solar energy hybridisation potential due to its high energy density (Pardo *et al.*, 2014). However, other chemical reactions could be also applied to industrial processes at high temperature, such as lead oxide (PbO) and copper oxide (CuO) looping (Cao and Pan, 2006). Since the application of this technology is less developed for industrial processes, new reactions should be investigated to adapt to specific sector requirements. Chemical looping is at an early stage of development when it comes to solar heat for industrial processes. Further research and pilot demonstrations are required that focus on its integration with solar systems, in particular examining control systems and measures required to manage high-tariff heat demand for industrial processes.

Salt hydration is also at an early stage of development for applications in the industrial setting. The storage material and application strongly affect the performance, cost, stability and utility of these systems. Therefore, first steps must focus on evaluating the merits of using existing working salt pairs by studying their material properties in operation conditions. Salt hydrates might find application in next-generation industrial heat pumps. Such heat pumps, sometimes referred to as chemical heat pumps, are typically used for space heating and cooling, refrigeration, low-temperature steam production, cleaning, drying, and evaporation and distillation processes in various manufacturing processes. Heat pumping technology is used to "upgrade" the temperature of wasted heat (or heat produced in solar thermal generation) to a level where it can be either reused or stored (Wongsuwan *et al.*, 2001).

Conventional pumps operate on absorption or vapour compression technologies. If salt hydration TES systems were developed to compete with the incumbent heat pump technologies, this could improve system efficiencies through better integration. The principal challenges are optimising reactor design and integrating the sorber components to facilitate ideal heat and mass transfer. It is anticipated that R&D activities, as well as collaborative industrial deployment studies, could realise significant efficiency improvements.

3.3 Cold chain

The **cold chain** is the uninterrupted supply chain required to get products which must be stored at low temperatures from the producer to the point of consumption. Perishable food and vaccines are good examples of such products. Cold is used at each stage of the chain to keep these products fresh. It is estimated that energy used for refrigerating food accounts for 8% of global power usage, and is responsible for 2.5% of global GHG emissions, when including both direct and indirect emissions. It also represents a sizable cost: for example, energy accounts for 11% of the production value added for dairy products (Dallemand *et al.*, 2015).

TES in the cold chain

Need for TES

- *TES can help integrate renewables across all parts of the cold chain (production, transport, storage and retail, and consumption) by increasing the demand-side flexibility of refrigeration loads. This could reduce the need for investment in network reinforcement and permit the generation of cold at times of peak supply of renewably generated electricity.*
- *Growth in electrified refrigeration will increase demand on networks, especially in emerging economies. TES could support development of off-grid renewably supplied refrigeration in developing countries, to enhance food and medicine supply chain efficiency.*
- *TES can be used to displace diesel-powered refrigeration in cold-chain transport, and can help to couple the transport, cold chain and power sectors.*

Existing use cases

- *Ice and other PCMs are in use variously in refrigeration in vehicles and static chillers, replacing diesel and other fossil fuel generators.*

Innovation potential

- ***Short term (5 years):*** *material and operational improvements, as well as better integration, could increase efficiencies and lower costs in use of ice and other PCM systems. Linking of cold chain assets across sectors could deliver synergies.*
- ***Medium term (5-10 years):*** *sub-zero storage temperatures and passive cooling could be achieved with next-generation PCMs.*
- ***Long term (>10 years):*** *the use of liquid air in cryogenic LAES could bring down costs and open up new applications, particularly in combined cold and power systems. Retrofit of existing fossil fuel refuelling network to deliver TES-stored renewably generated cold could facilitate significant decarbonisation.*

The cold chain is typically made up of the following parts:

- **Production:** cold storage at the site of production, *e.g.* at a dairy, fishery, fruit farm.
- **Transport:** cold storage during transport from the site of production to the site of retail or storage.
- **Storage and retail:** cold storage at warehouses and retail sites run by distributors (*e.g.* a supermarket chain).
- **Consumer:** cold storage up until the point of use in the form of refrigeration, in homes and workplaces.

The cold chain is very well established in developed countries, with most cooling requirements met by electrified grid-connected refrigerators. However, diesel generators are frequently used to power warehouses without grid connections, and in refrigerated trucks and other vehicles.

There is a critical difference between developed and emerging economies. For example, in Europe the embedded energy in all food consumed accounts for over 25% of the EU-27's total final energy consumption (Dallemand *et al.*, 2015). By contrast, developing countries often have limited or no established functional cold chain. However, the demand for cold storage is increasing in developing countries with burgeoning populations and growing economies. This is particularly true in countries experiencing rapid urbanisation, with shifts in lifestyles and diets reflected in energy consumption profiles. For example, between 1995 and 2007 domestic refrigeration ownership in China's urban population increased from 7% to 95% (Birmingham Energy Institute, 2015). Also, the hygiene requirements of the food sector in developing countries is driving the increasing demand for cold chain energy .

Growing demand for cold chain services has significant impacts upon global energy systems, including:

- **Continuous high-tariff electrical demand from electrified refrigeration.** Ensuring product freshness requires constant energy-intensive cooling. With most refrigeration being electrified, this places demand on existing electricity networks, and growth in demand will require increasing deployment of renewables to maintain the pace of decarbonisation.
- **In developing countries**, which often have **weak grids and frequent power cuts**, especially **in rural areas** where agriculture is located, the introduction and **development of cold chains is even more challenging**. Increasing cooling loads onto these grid types will present additional problems for grid operators in these environments.
- The **continued transition from diesel-powered to electrical cooling in cold storage centres and refrigeration vehicles will result in the need for efficient peak-load management in electricity grids**. Cooling load peaks typically occur during summer when temperatures are hottest and when the energy system is already under strain from other demand.

Deploying TES could contribute to addressing these challenges in the global cold chain

Using TES to decouple the production of cold from electrical supply at peak demand could have substantial benefits for electricity system operators. It could help to reduce the reliance on thermal plants during peak hours, reducing system costs and lowering emissions. Using TES to reduce peak demand for cooling could help to **defer network reinforcement**. Where relevant, cold storage with the aid of solar powered absorption chillers or solar PV panels can contribute to **addressing challenges associated with poor grid reliability** by providing decentralised sources of decarbonised cold.

In grids with a high penetration of renewables, the addition of TES provides an opportunity to absorb excess renewable production and use it for cooling, helping to reduce curtailment (and subsequent curtailment payments) and improving the utilisation of renewable generation. As a result, **sector coupling** between the transport and power sectors is possible by employing thermal storage in refrigeration vehicles and displacing diesel-powered fridges (in addition to electrifying the vehicles themselves), or using liquid air to power vehicle auxiliary systems while providing cooling at the same time.

In a future where electric vehicles may be the norm, having a thermal storage system on board could increase the range of the vehicles by reducing power demand for air conditioning.

Existing use cases demonstrate the scope for TES to aid renewables deployment in cooling

Several companies that serve markets in Africa, China, Europe, India and the Middle East have integrated engineered PCMs into refrigerated vehicles and containers for food or vaccine transport and/or storage.

It is estimated that almost 30% of food is lost globally as a result of cooling limitations in the cold chain (Food and Agriculture Organization of the United Nations, 2015).

However the global cold chain is expanding. The total capacity of refrigerated warehouses in 2016 was 600 million m^3, with an annual growth rate of 4.2% (GCCA, 2016). Furthermore, the global refrigerated vehicle fleet stood at 4 million in 2015, and could grow to 18 million by 2025 (Birmingham Energy Institute, 2015). An anticipated 31 GW of extra power generation is expected to be needed to supply the projected increase in fridges in developing countries (Birmingham Energy Institute, 2015). TES can play a role in ensuring that these power needs are met by renewable generation sources.

Case study 2. **Thermal storage for freight containers**

World-first cold storage freight container

Academics based at the University of Birmingham (UK) Centre for Energy Storage recently collaborated with a Chinese rail haulage maintenance and manufacturing company to demonstrate a PCM-based cooling system on board interchangeable road and rail units. The system maintained storage temperatures at the target of between 5°C and 12°C for up to 120 hours.

The cold storage containers were transported 35 000 kilometres on road, and a further 1 000 kilometres on rails, across a range of climatic zones.

The project team has noted that other haulage and transport companies have expressed an interest in the studied container. Storage temperatures are maintained more consistently in the new container than in mechanical alternatives. Further, as the containers do not need a power supply, they can be more effectively transported between different transport types, such as rail to road in this case (University of Birmingham, 2018).

Case study 3. **Smart refrigeration providing demand-side management services at commercial retail sites**

Smart refrigeration in retail sites provides peak-shaving service in the United States

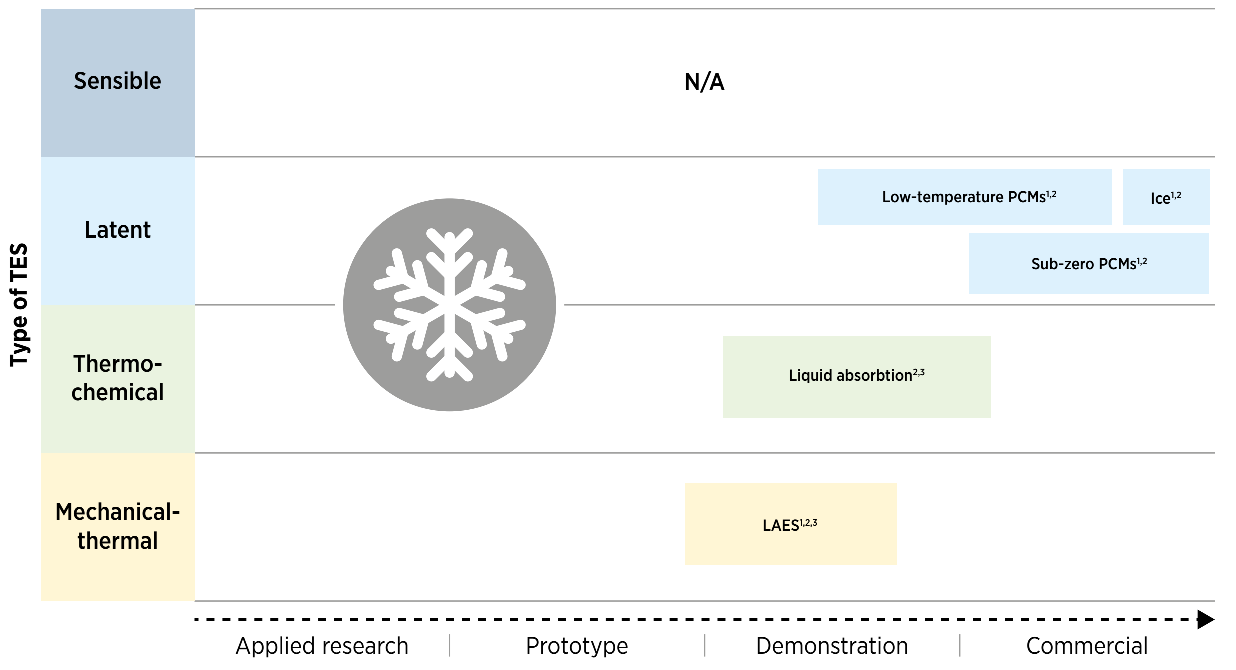
An innovative company in the United States is using PCMs to provide energy management solutions for supermarkets and commercial buildings with high refrigeration-based energy loads.

Their product is a refrigeration battery that works by storing low-cost off-peak electricity in a frozen saltwater solution at night, then, during peak hours, when electricity and demand charges are highest, the system discharges to provide cooling.

This significantly reduces peak load for the building. A cloud platform evaluates the energy use and electricity rates to optimise system operation and maximise savings. In this way, operational costs from electricity bills, and business risks are reduced.

To date this product has been deployed twice at pilot scale for two major US supermarket chains. This example of TES integration in retail cooling is a world first (Axiom Cloud Inc., n.d.).

Figure 43. Commercial readiness of TES technologies in the cold chain



Notes: (1) For the storage of cold (2) For refrigerated (3)For the production of cold.

Other TES technologies are at various stages of deployment in the cold chain

Based on their relative stages of development or deployment (Figure 43), a range of TES technologies find differing applications in the cold chain sector. Current use cases, potential future deployment and innovation needed to facilitate wider use are summarised below.

Current status

Ice can partially or fully replace the operation of refrigeration units at peak hours, using off-peak or on-site renewable generation to convert water to ice. When cooling is required, thermal energy is extracted from the cold store using a heat transfer fluid and is absorbed by the ice.

Sub-zero and low-temperature PCMs can be used to store cold energy from room temperature down to -114°C (PCM Products, n.d.).The cold could be generated from renewable electricity by electrical chillers or solar absorption systems.

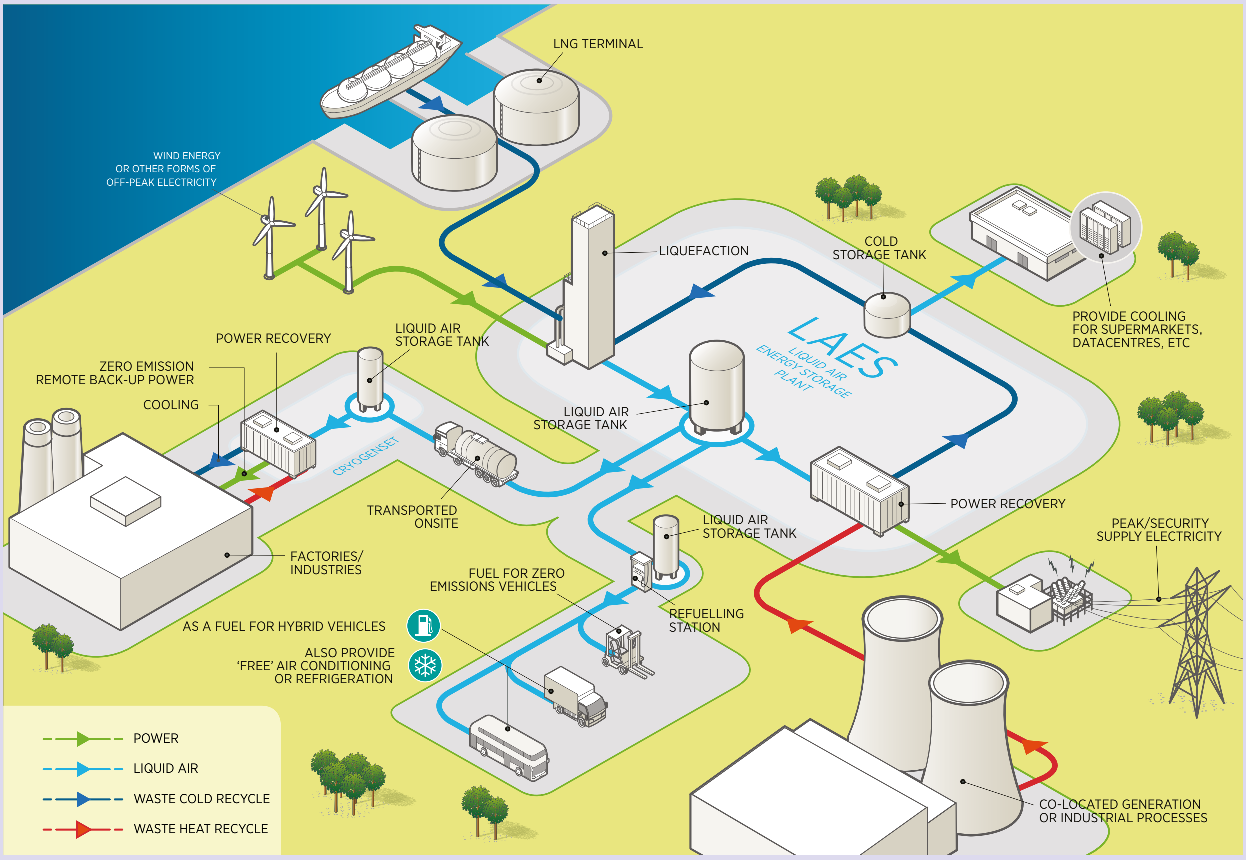
Normally the PCM is encapsulated in modules or containers and can be used as backup or replacement for refrigeration systems at peak hours, or to directly provide cooling by installing it in the cold storage container (Oró *et al.*, 2012). For refrigerated trucks or aeroplanes, PCM modules can either be built into the vehicle walls or the air conditioner unit.

PCMs have been developed that keep refrigerated vehicles maintained at a constant temperature for up to 72 hours (Huang and Piontek, 2017). In static applications PCMs have also been shown to help reduce the physical size of storage required by up to 40% for solar absorption cooling systems, reducing system costs (Hirmiz, Lightstone and Cotton, 2018). PCMs provide a higher energy density than ice, and therefore require less space, making them more appropriate for refrigerated vehicles since space (and weight) would ideally be minimised.

Future outlook

Less mature technologies show great promise in the cold chain. Their potential is outlined below, and the next section provides insight into innovation challenges that will need to be addressed before these solutions can become more mainstream.

Figure 44. A vision for the use of LAES in the integrated cold chain of the future



Source: Birmingham Energy Institute, 2015.

Cold energy generated from renewable thermal energy sources (such as solar and biomass co-generation) could be stored using **absorption systems**. Due to the high energy density and minimal thermal losses seen for these systems, cold could be stored for both short and long timescales (such as inter-seasonally) for space cooling in the cold chain.

Liquid air produced using electricity from renewable sources could be used in the future to store cold. The air is liquefied via cooling to -192°C. The liquid air can then later be used to provide space cooling on or off site, or indeed on board refrigerated vehicles. Alongside release of cold, there is a volume expansion associated with converting the air back to gas, which can drive engines and produce emission-free power.

Figure 44 depicts a LAES plant that integrates renewable generation with liquid air for transport and grid applications.

Material and system innovations will help deliver TES solutions fit for the future cold chain

A summary of the key metrics for innovation is shown in Table 8, while Table 9 shows the anticipated materials science and systems engineering development priorities for TES systems used in cold chain applications.

Table 8. Key metrics for technological innovation of TES in the cold chain

<table>
<tr><th rowspan="2">Attribute</th><th colspan="3">Latent</th><th colspan="3">Thermochemical</th><th colspan="3">Mechanical-thermal</th></tr>
<tr><th>2018</th><th>2030</th><th>2050</th><th>2018</th><th>2030</th><th>2050</th><th>2018</th><th>2030</th><th>2050</th></tr>
<tr><td>Cost (USD/kWh)</td><td>58-230</td><td>45-185</td><td>35-140</td><td>12-150</td><td>12-120</td><td>< 95</td><td>demon-stration</td><td colspan="2">commercial</td></tr>
<tr><td>Efficiency (%)</td><td>> 90</td><td>> 92</td><td>> 95</td><td>COP 0.6-0.8</td><td colspan="2">(1)</td><td colspan="3">N/A</td></tr>
<tr><td>Energy density (kWh/m³)</td><td colspan="3">30-92</td><td colspan="3">180-310</td><td colspan="3">78</td></tr>
<tr><td>Lifetime (years or cycles)</td><td>5-20 years</td><td>10-25 years</td><td>10-30 years</td><td>20 years</td><td>20-25 years</td><td>> 25 years</td><td colspan="3">20-40 years</td></tr>
<tr><td>Operating temperature (°C)</td><td>-115 to 8</td><td colspan="2">-150 to 8</td><td colspan="3">5-30</td><td colspan="3">-150 to ambient</td></tr>
</table>

Note: (1) Value not available due to low technology readiness level; N/A dennotes that no main needs were identified.

Table 9. Key material and system innovation needs for TES technologies used in cold chain applications

TES technology	Innovation needs
Ice	• Research new operation strategies such as full storage or partial storage • Reduce localised ice formation during charging to increase charging rate and efficiency
Low-temperature and < 0 °C PCMs	• Improve thermal conductivity; avoid corrosion and supercooling • Pursue novel composite with low-cost materials • Minimise phase segregation through development of anti-corrosion container materials • Explore the use of cold storage at sub-zero temperatures
Absorption System	• Address crystallisation properties and the difficulties on the working pairs separation • Research alternative sorbents to increase absorption rate • Decrease temperature of driving heat source • Research new configurations to increase absorption rate of the double-effect absorption system • Enhance efficiency, reduce the space for the network components and avoid corrosion
LAES	• Optimise the design of cryogenic engine • Reduce operating cost by using liquid air instead of liquid nitrogen • Work with equipment manufacturers to revise the design of some off-the-shelf components to reduce costs • Develop new applications such as emergency backup power, supermarkets and data centres

Latent

For **sub-zero temperature PCMs**, costs can be reduced by developing new eutectic mixtures of inorganic salts using lower cost components. For example, it is possible to replace lithium chloride (> USD 250/kg) with sodium chloride (< USD 20/kg), resulting in a cost reduction of the overall mixture. Currently sub-zero temperature PCMs are mainly used in food storage or cooling in transport refrigeration units, but other applications and use cases are worth consideration.

Refrigeration trucks with PV panels and PCMs have been already proposed, as they have an important advantage over battery systems in that they weigh less. However, this option is geography dependent, as the intermittency of renewables and solar irradiation plays an important role in their feasibility (Li and Zheng, 2016).

Corrosion of the container is another issue that most of the inorganic materials present. This could lead to poor thermal performance and also leakage of the salt mixtures in use. Suitable container and coating materials have to be carefully selected to minimise the corrosion and extend device lifespans (Ferrer *et al.*, 2015), and these are the subject of R&D activities.

The EU-funded project FRISBEE is investigating which PCMs are best suited to different temperature ranges in the cold chain. It has generated a software tool that evaluates the thermophysical properties of a large number of salt hydrates and water alcohol solutions that are suited to a phase-change temperature of between -60°C and 6°C. Furthermore, it has looked into reducing and controlling the capsule morphology of the PCM to the nanoscale so that they can be more easily incorporated for food packaging.

Thermochemical

The material pairs used in **absorption systems** determine their operational temperature ranges and system efficiencies (Hui *et al.*, 2011). Both parameters must be optimised to enhance system feasibility. New absorption pairs are in development to achieve wider working temperature ranges and improve process efficiencies. Although a high energy storage density of the materials has been demonstrated (Ibrahim, Al-Sulaiman and Ani, 2018), the system design and performance need to be tested to ensure that these systems can provide long lifetimes. Further understanding of the system and demonstrators are needed to prove the technology under real-world conditions.

Mechanical-thermal

Currently liquid nitrogen is the most common cold "vector" used for providing cooling in the cold chain. However, liquid air provides a potentially cheaper alternative due to the fact that no gas separation process is required in its production.

Currently the most studied cold-chain application for **LAES** is the cryogenic engine for refrigerated transport. Truck demonstrators have been designed and are being tested to prove economic viability. Different applications for LAES are also being explored that require flexible cooling and power. For example, LAES systems (integrated with cold storage to keep the efficiency at reasonable levels) are anticipated for use in in emergency power and cooling backup systems for supermarkets and data centres (Dearman Engine, no date).

3.4 District heating and cooling

District heating and cooling systems use a network of insulated pipes to deliver heat or cold to multiple buildings from a centralised generation source, rather than having individual boilers or chillers in each building. The final users tend to be domestic or commercial premises with space heating/cooling and or water heating/cooling requirements, although some district energy facilities can additionally service industrial energy demand. This type of energy generation and distribution results in lower emissions and costs through efficiency gains, and provides scope for integrating renewables into urban centres at scale.

A wide range of heating/cooling technologies are deployed as district assets, including co-generation plants, conventional boilers, waste incinerators, piped waste heat from industrial sources, solar thermal plants, heat pumps and geothermal energy.

As mentioned, district heating/cooling schemes can enable efficiency gains and by this contribute to the decarbonisation of the sector. Ideally, they also facilitate the use of renewable generation assets. However, as with other sectors discussed thus far, this comes with challenges.

Key challenges include:

- A mismatch between VRE output and demand loads, across a range of timescales from hours to seasons.

TES in district heating and cooling

Need for TES

- *TES technologies can enhance efficiency in district heating and cooling across a range of timescales from short (hourly) to long (seasonal), to provide flexibility, to better match supply of heat/cold to demand, and to take advantage of renewably generated off-peak electricity.*
- *District heating/cooling plants with TES can be designed and sized to meet average load, rather than requiring capacity to meet peaks in demand, reducing their capital cost.*

Existing use cases

- *TTES is deployed widely throughout the world.*
- *UTES is in use in some countries, but is subject to the suitability of the subsurface environment.*
- *Ice produced using renewable electricity is currently used in some district cooling schemes.*

Innovation potential

- ***Short term (5 years):*** *improvements in integration and management of TTES could significantly reduce costs and expand deployment opportunities. Development of high-temperature cPCMs, following successful demonstration in China, could see material and systems improvements enhancing competitiveness.*
- ***Medium term (5-10 years):*** *ongoing research and demonstration of PCMs for use in cooling is expected to drive wider deployment.*
- ***Long term (>10 years):*** *PCMs and thermochemical systems with increased cost-effectiveness and higher efficiencies are anticipated to enhance opportunities for renewables deployment in district heating and cooling, especially in combined cooling and power applications. Sector integration and smart control technologies will intensify opportunities in this regard, particularly facilitating the harvesting (and storage) of waste heat/cold from other sectors and applications.*

- Determining pricing schemes for heating and cooling.

- Low and inefficient utilisation of generators caused by variable load.

- The inability to ramp up VRE generators to meet demand peaks. Meeting peak demand requires supporting technologies like boilers, which increases system costs.

TES deployment in district heating/cooling could contribute to addressing these challenges

The key benefit of using TES in district heating/cooling is the opportunity to decouple heat/cold generation from consumption. In almost every example discussed here, the principal use case for TES is in utilising peak supply of renewable energy to store heat/cold for use at a later point when demand outstrips supply, whether that is over short or long timescales.

In solar thermal district heating schemes, TES can be used to store surplus heat supply, which can be discharged during times of low solar irradiance such as during night-time, or even over the winter. In addition to covering periods of low solar irradiance, TES allows the modulation of heat output to meet varying demand and better balance the local network. These features help to deliver low-cost decarbonised heating. Europe has over 200 solar district heating schemes, primarily in Austria, Denmark, Germany and Sweden (Solar District Heating, 2018).

UTES are the primary type of TES used in these cases, particularly pit thermal energy storage (PTES). By including seasonal storage, high deployment rates of solar thermal generation (up to 90%) become feasible (Han, Wang and Dai, 2009).

District heating schemes that source energy from variable wind and solar PV have been trialled in China, Denmark, Russia, Sweden and United States (United Nations Environment Programme, 2015; Xiong *et al.*, 2016; Werner, 2017). These schemes have tested different approaches to meeting heat demand using renewable electricity, for example by heating water using heat pumps or resistive heating. There is significant scope for TES to assist in making these schemes more feasible through enhancing generator utilisation.

Integrating TES into a VRE-powered district heating system can enable the system to avoid curtailment by continuing to generate in periods of peak supply.

“Excess” energy can be stored as heat for later use when heat demand picks up. In this case, TES contributes to the delivery of low-cost decarbonised heating (Liu *et al.*, 2017).

In **co-generation district heating schemes**, as deployed in China, Denmark, Germany, Italy, Sweden and the United Kingdom (United Nations Environment Programme, 2015), **short-term TES can be used to help meet daily peaks in demand**. This enables deployment of smaller-scale co-generation systems that can run continuously at full capacity (rather than oversized plants peaking to meet demand), enhancing system efficiencies and utilisation rates. Similar benefits are seen in **geothermal district heating schemes, where utilisation can be improved by facilitating constant generation and meeting variable peak demand with TES**. Geothermal heat accounted for less than 1% of the sources of energy for district heat schemes internationally in 2014. They are at present primarily utilised in Iceland and France, with other smaller-scale projects elsewhere in Europe (Werner, 2017). Geothermal schemes are restricted by the availability of local geothermal heat sources. However, it has been estimated that 25% of Europe’s population could be supplied by geothermally powered heat through urban district heating schemes (Connolly *et al.*, 2012).

Similar to district heating, **cooling loads also tend to be variable across seasons and TES helps to improve the utilisation of the generation source**. TES enables constant generation of cold, whilst helping to meet variable loads. In the case where electric chillers are used in district cooling, TES also helps reduce the peak electricity load on the networks by moving production to other times when overall demand is lower. This can help to avoid expensive network reinforcement or expansion by shaving peak load. District cooling systems coupled with cold storage allow a reduction in cooling capacity of 15-50%, as well as reducing the need for auxiliary components, with improved overall system performance due to more efficient utilisation of compressors (Cecca, Benassis and Poeuf, 2010).

Adding thermal storages to district heating or cooling schemes enables the system to meet a wider range of heat loads and to integrate renewable energy sources with differing generation profiles. TES effectively enables decoupling of how the heat or cold is generated from how it is consumed.

This is critical when the scheme provides a continuous supply of heat and cold to a wide variety of customers and also has to integrate renewable generation sources that are variable in nature, such as solar thermal. This means that renewable generators can be run when they are available, stored at times of low demand and then discharged during times of higher demand and low supply, thereby increasing the utilisation of generation.

Key use cases show that TES is already facilitating renewables deployment in district heating/cooling, and will continue to do so in the future

UTES technologies are commonly deployed alongside district heating and cooling schemes in China (Nordell, 2000), **North America** (IEA, 2014) **and northern Europe**. Seasonal storage schemes using BTES have been trialled in Canada and Denmark, and there are several projects being developed in the Tibet region of China.

There are an estimated 80 000 district heating schemes globally. The majority of these schemes operate in colder climates, with high implementation rates in northern China, northern Europe and Russia. For example, district heating supplies 51% and 34% of the heat demand in Denmark and Poland respectively (Werner, 2017). District heating schemes are most applicable in dense urban or industrial areas, in countries with cool climates. Renewable district heating projects primarily use biomass or co-generation; however, there have been demonstration projects in Canada and Denmark that use solar thermal panels to supply heat.

UTES can be used for both district cooling and heating schemes, but its utility can be limited by strict geographical and geological constraints. ATES requires the presence of an aquifer, whereas BTES can be limited by the quality of the subsurface.

Where ATES is not appropriate, closed-loop BTES can be implemented (Mott MacDonald, n.d.). UTES can be used for both seasonal and short-term cold and heat storage (Sarbu and Sebarchievici, 2018).

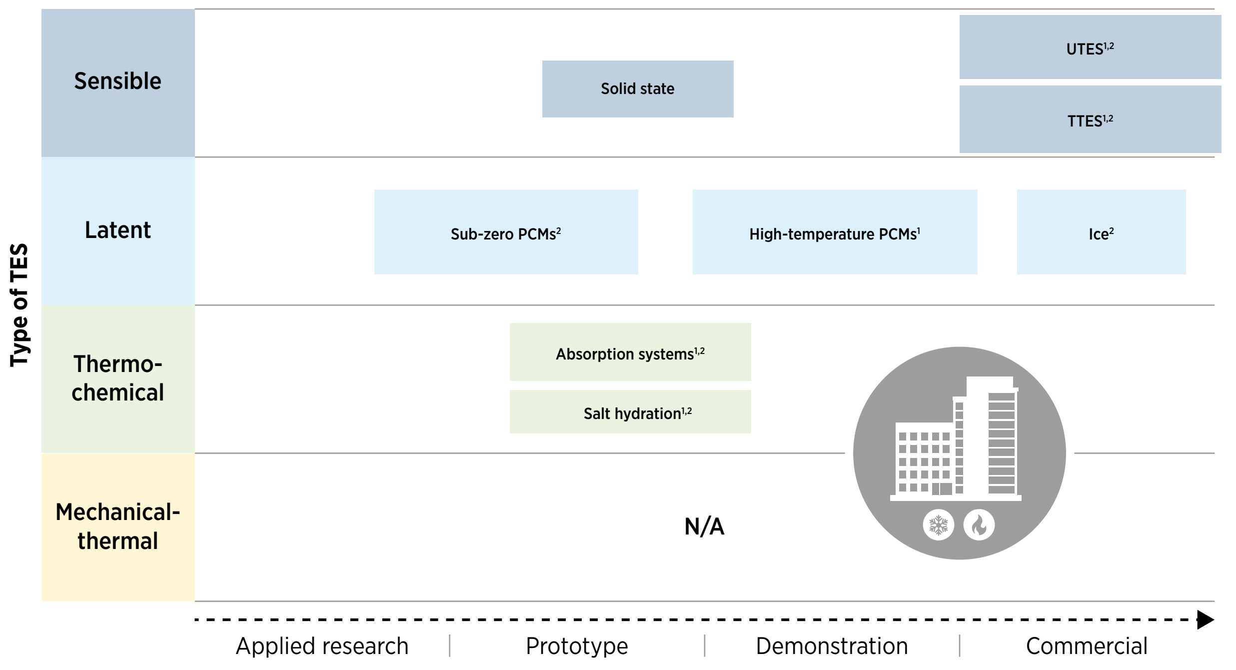
The majority of district cooling is delivered in the Middle East and the United States, with schemes also operating in Australia, Europe and Japan (Cecca, Benassis and Poeuf, 2010; Paksoy, 2013; JCU, 2014; Asian Development Bank, 2017; IRENA, 2017c). In the United Arab Emirates over 20% of the total space-cooling load is met through district cooling (IRENA, 2017c). There is an emerging market in China, with 833 projects reported across the country in 2013 (Paksoy, 2013). The primary users are service-sector and residential buildings for space cooling (Werner, 2017) **Typically schemes will employ either chilled water tanks or ice as a form of cold storage**, as well as absorption chillers (Asian Development Bank, 2017).

District cooling schemes are found across a range of latitudes, implying its deployment is largely independent of climate (IRENA, 2017c). Short-term cold storage using ice is typically deployed where there is a variable power supply and cooling load. Ice storage has a high energy density, making it preferable for use in urban areas as it only requires 25% of the space needed by chilled water tanks (FVB Energy, n.d.). UTES can be used to provide long-term cold storage, but is restricted in its applicability by the subsurface environment.

Various TES technologies are deployed in district heating and cooling

Figure 45 summarises the state of TES deployment in district heating/cooling. These are discussed by technology category below.

Figure 45. Commercial readiness of TES technologies for district heating and cooling.



Notes: (1) For district heating; (2) For district cooling.

Current status

Large **water tanks** are utilised regularly in district heating. They consist of well-insulated systems, with reduced heat losses and an extended effective storage period. The water is heated up during periods of off-peak electrical demand or using solar collectors. When the heat is required the storage is discharged. These large-scale water tanks can be located above or below ground, depending on the needs of the scheme.

Chilled water tanks are the most common thermal storage option for district cooling, using large concrete and steel tanks with reported volumes in this application of up to 150 000 m^3 (Somarriba, n.d.). In these systems, excess solar energy from periods of high irradiation can be used to cool down the water, for example using an absorption chiller (Hasnain, 1998; BEIS, 2016).

UTES technologies are also deployed in conjunction with heat grids to integrate low marginal cost heat sources, such as geothermal and solar thermal heat, for seasonal storage. Heat can be stored at temperatures up to 100°C, with heat being upgraded for use by heat pumps. For district cooling, UTES usually works with a temperature difference of around 6°C.

Ice has been widely used as a cool TES material due to its high latent heat of fusion. It is produced by electricity from renewable sources, or a solar absorption process to freeze water to ice. The heat transfer fluid (commonly water or glycol) transfers the cold energy though pipelines to supply cooling to residential blocks or office buildings.

Case study 4. **Solar-powered district heating scheme with seasonal storage**

Seasonal BTES allowed district heating scheme to supply near 100% renewable heat in Canada

Drakes Landing was a technical demonstration project that utilised solar thermal energy and seasonal UTES for a district heating scheme supplying a residential community of 52 houses in Alberta, Canada. It was born out of the desire to improve the efficacy of seasonal storage for district heating.

A total of 1.5 MW of solar thermal capacity installed on the garages of each house captured solar energy during the summer before storing it underground using BTES. In winter months, during periods of high heating demand, heat was extracted from the stores and distributed to each home.

The project enabled the provision of almost 100% of space heating from local solar thermal generation. Through effective energy storage, the project demonstrated that the problem of seasonal mismatch between supply of renewable energy and the demand for heat could be resolved. As a result, each household's GHG emissions were reduced by more than 80% per annum.

There are several non-technical barriers to its replication. The financial risk is currently a critical one.

In Canada the availability of cheap gas dampens the potential market demand for seasonal storage schemes. In other countries such as Denmark, where energy prices are increasing, other seasonal thermal storage projects for district heating schemes have sprung up (*e.g.* Vojens).

It is expected that such a project would have to be about 8-10 times larger to be commercially viable. In order to make the system more commercially attractive, it is therefore necessary to bring down costs. However, the BTES only accounted for 10-20% of the total cost of the system, implying that it is the cost of the solar thermal collectors that are hindering the spread of similar projects.

Drakes Landing's scheme was operated by a gas utility, but was also reliant on a housing developer. Bringing together diverse stakeholders can also be difficult, as no one party wants to shoulder the burden of the financial risk. In this case it was taken on by government, suggesting there may be a role for public-sector intervention in future projects (Sibbitt, B. *et al.*, 2015).

Future outlook

PCMs based on eutectic mixtures of salts and water with melting temperatures of around 7-8 °C could be used instead of chilled water or ice storage. The charging efficiency is higher than ice storage due to a higher charging temperature, and the required tank volume is significantly reduced compared to those containing chilled water.

High-temperature PCMs could be successfully implemented for district heating applications. The high storage density and higher thermal conductivity of the systems enables the storage of large amounts of energy in a smaller storage volume, when compared to sensible technologies.

This storage technology could be used for both the short and long term in district heating, coupled with renewable energy systems such solar thermal and wind. A first-of-its-kind 6 MW/36 MWh **high-temperature cPCM demonstration plant** has been operational since September 2016 in northern China. More details about this project can be found in Case study 1.

Thermochemical storage provides several key advantages over other types of storage. The energy density of such systems is about three to six times higher compared to other TES systems like TTES, reducing spatial requirements. Furthermore, thermal losses are minimal, and it may be possible to transport the thermochemical storage systems for remote use.

Salt hydrates sorption systems have been studied in demonstration projects for use in the residential and commercial sectors to cover the demand of a stand-alone building. They could be potentially implemented in district networks, coupled to a solar collector or co-generation plant as a source of energy to heat the hydrated salt. The system would be charged in summer for the purpose of stored heat to be used during the winter season, to cover the hot water and heating demand in the network.

Absorption systems are a promising technology because they can be pumped and used as the working heat transfer fluid in a district network. This permits the use of heat sources far away from the service location. Absorption systems have been applied in the refrigeration sector for a long time, but are a promising candidate when it comes to district cooling. Absorption heat pumps can be used to provide refrigeration and space conditioning from low-grade heat (solar collectors) within a district heating infrastructure. Absorption systems allow cooling loads to be shifted temporally, so that the system can take advantage of ambient conditions that are more amenable to efficient refrigeration operation.

Enhanced efficiencies in TES will continue to improve the feasibility of co-deployed district heating and cooling

Table 10 shows a summary of the key objectives for technological innovation within components of TES for district heating and cooling.

Sensible

There are no standard designs for **UTES** installations. Each facility is unique as it is designed for the particular location and application, although the component pumps, pipes and heat exchangers are standard industrial products. Therefore, UTES cannot be industrially commercialised in the traditional sense (Nielsen, 2003). Besides that, one of the main challenges facing UTES systems are their possible environmental impact as they can threaten local ecosystems. Currently several studies are being undertaken to understand the environmental effect of ATES systems. Scientists need to study the impacts of UTES on groundwater, and cross-sectoral subsurface planning is required to minimise negative conflicts between UTES and other subsurface interests (Bonte, 2015).

New systems using temperatures in the range of 40 - 90°C need to be further studied, as they can store heat from power plants, industrial processes, geothermal or solar energy and later on be used as back-up capacity to be released at high demand. Higher temperatures result in higher system heat losses, and the scaling and clogging of the components of the system due to particles, gas bubbles, bacterial growth and precipitation of minerals. Component corrosion also needs to be tested to better predict the lifetime of the installation. For higher-temperature storage the use of water-based storage systems is limited. That presents a serious challenge to making UTES more efficient for seasonal storage. Therefore, other candidate storage media with high specific heat, thermal conductivity and low cost need to be selected and studied (RHC-Platform, 2012).

Case study 5. **Salt hydration thermal storage being prototyped for a Berlin district heating scheme**

Demonstration of salt hydration thermal storage system enabling co-generation flexibility

A 0.5 MW/10 MWh sorption-based storage solution was piloted during in 2019 at a co-generation plant in Berlin, Germany. The sorption system was charged at times of excess power supply, either from the grid or from the co-located co-generation plant. When required, heat was then discharged from the plant into Berlin's district heat network.

This project was intended to decouple the production of heat from the production of electricity, for example in situations when heat is required but there is no need for the power supplied by the co-generation plant.

The technology uses nano-coated salts to minimise salt degradation issues and maintain optimum efficiencies after high numbers of charge cycles (Vattenfall and SaltX Techonolgy, 2019).

Table 10. Key objectives for technological innovation of TES for district heating and cooling

Attribute	Sensible			Latent			Thermochemical		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (USD/kWh)	0.1-35	0.1-25	0.1-15	60-230	45-185	35-140	15-150	Pilot scale 15-120	Demon-stration 10-80
Efficiency (%)	55-90	65-90	75-90	> 90	> 92	> 95	50-65	(1)	
Energy density (kWh/m^3)	15-80	(2)		30-90			120-250		
Lifetime (years or cycles)	10-30 years	20-30 years	> 30 years	10-20 years	> 25 years	> 30 years	15-20 years	20-25	> 30
Operating temperature (°C)	5-95	5 to > 95		0 to up to 750			15-150		

Notes: (1) Value not available due to low technology readiness level; (2) Depends on working temperature range.

Furthermore, there is a need for research on hybrid UTES systems to increase capacity, efficiency and alignment with renewable heat production technologies. Optimised control of UTES is also required to improve energy savings and reduce the use of back-up systems (European Association for Storage of Energy and European Energy Research Alliance, 2017b).

Considerable gains are to be had in TTES by increasing the size of the tanks and improving system standardisation. The cost of TTES can be reduced from USD 486/m^3 for a 300 m^3 hot-water tank, toUSD 123/m^3 for a 12 000 m^3 hot-water tank (BEIS, 2016). System efficiency improvements are anticipated, perhaps through new approaches to increase and maintain stratification. This would reduce running costs.

Thermal stratification can lead to longer operating hours and thus a significantly greater utilisation of solar collectors, thereby reducing the use and cost of auxiliary energy. Recent developments propose new methods to increase stratification, such as minimising the mixing and turbulence of water entering a stratified thermal storage tank (Al-Habaibeh, Shakmak and Fanshawe, 2017). These improvements could result in storage efficiency being increased by significant margins, between 6% and 20% (Han, Wang and Dai, 2009).

Other improvements are also being sought, such as optimisation of the internal heat exchanger and the internal free convection in water tanks, as well as through minimising the heat losses due to parasitic heat convection in pipes.

Latent

The innovation needs of **high-temperature cPCMs** focus on improving thermal cycling stability, corrosion and structural instability that can cause leakage of the PCM. Further research on novel composites and systems is needed to make this technology fully competitive. The performance of system cycling and the overall system over time must be analysed prior to further commercialisation, to ensure adequate system lifespans. The main focus of innovation is on novel integration systems that improve the charging/discharging rate, and materials science research to improve component compatibility and reduce maintenance costs. These innovations would bring this technology from demonstration level to commercial stage at larger capacities.

In **sub-zero temperature PCMs**, a primary technical challenge of the currently utilised salt mixtures is phase segregation[13] during the charging and discharging processes. These systems can also be prone to supercooling[14] and corrosion.

13 The effect that phases with different components are separated from each other, and cause a loss in enthalpy of solidification.

14 The effect whereby the temperature is lower than melting point, but the material does not start to solidify.

These factors currently reduce the cyclability performance and increase the maintenance cost of the system.

Different strategies have been proposed to overcome these problems, such as adding cross-linked material to keep the salt in solution or adding a material to increase its viscosity (Li *et al.*, 2013). However, most of the solutions are at lab-bench testing stage in terms of development and there is no best approach for all of them. To avoid or minimise the corrosion of the container, a selection process has to be carried out and in some cases encapsulation or coatings must be used (Ferrer *et al.*, 2015).

Similar to the other PCMs, the heat transfer rate is limited during the charging and discharging process due to the moving liquid-solid boundary and the low thermal conductivity. The heat transfer rate can be improved by increasing the heat transfer area (*e.g.* using metal fins) and adding high thermal conductivity material additives (*e.g.* graphite, particles) (Oró *et al.*, 2012).

Ice formation during the charging process is the key challenge for ice storage, which may affect the system's performance by decreasing the charging rate and efficiency. For instance, during the charging process of an ice-on-coil thermal storage system, the ice starts to grow from the surface of the coil and the charging efficiency decreases due to the low thermal conductivity of the growing ice itself. Different approaches are proposed to tackle this issue, such as adding fins or rings to the coil.

The performance can also be optimised by applying different operation strategies, *e.g.* a full storage strategy and partial storage strategy (Yau and Rismanchi, 2012).

Thermochemical

High investment costs are currently impeding development of thermochemical TES for district heating/cooling. There are also issues associated with the corrosiveness of the chemicals used, and concerns from potential adopters regarding the safety of the systems given their relative complexities.

The seasonal storage capacity of thermochemical TES systems makes these potentially very attractive options for district heating and cooling applications. Significant development in materials chemistry will be required to realise the potential for these systems, however. For **salt hydration** systems, primary development activities focus on enhancing the activity and durability of the salts used while attempting to maintain their compatibility and safety characteristics. In **absorption systems**, similarly, the utility of the salts used is key, and researchers are seeking to enhance their stability and energy densities.

Various configurations for coupling thermochemical TES systems with renewable generators have been proposed for district heating and cooling applications, based on salt hydration (heating) and absorption (cooling) systems.

Case study 6. **Transporting charged TES materials from charging site to point of demand**

H-DisNet

The European Union "Intelligent Hybrid Thermo-Chemical District Networks" (H-DisNet) project is seeking to evaluate a particularly innovative approach to integrating thermochemical TES into district heating/cooling. The project partners are investigating a "hybrid" smart transport system for charged TES materials, in which partially hydrated/dehydrated salt solutions pumped around a distribution network can be utilised remotely to release stored thermal energy, for heating or cooling. The project involves simulation and control research to afford better management of thermochemical TES infrastructure, alongside three demonstration projects in Germany, Switzerland and the United Kingdom (KU Leuven, 2018).

3.5 Buildings

The buildings sector covers both commercial and residential premises, encompassing around 150 billion square metres of floor space. Energy is used in buildings for space heating, space cooling, hot water and cooking. With 3% annual global growth in the building footprint predicted for the foreseeable future, total energy consumption in the sector is expected to rise (IEA, 2017).

As such, decarbonisation efforts will need to intensify in the future, and increased adoption of buildings-scale renewables generation is anticipated.

The main challenges impeding further renewables deployment in buildings focus on managing potential peaks in electricity demand and ensuring that energy supply (including heating/cooling) and varying demand can be matched efficiently. Driving constant improvements in energy efficiency will be a priority in managing demand. Further global focus will be required on scaling up heat pump deployment while doubling heat delivered by district heating systems powered by renewables.

TES in buildings

Need for TES

- *In cold climates TES can support heat pump deployment by adding demand-side flexibility, reducing potential peaks and the need for network reinforcement, and increasing the utilisation of off-peak renewable generation.*
- *In warm climates TES can help reduce issues associated with the duck-curve, by shifting cooling loads and decreasing system stress as a result.*
- *Decentralised heat/cold storage could also reduce grid dependency and enhance security of energy supply in buildings in areas where the grid is weak or unreliable.*

Existing use cases

- *Water TTES is widely used across the world for storing heat in buildings.*
- *PCM and solid-state thermal batteries, and ice storage that replaces air-conditioning units are proven technologies, but have only been deployed on a relatively minor scale.*
- *UTES has been used in various cases, with the utility of smaller (individual building) scale installations being studied.*

Innovation potential

- ***Short term (5 years):*** *PCM thermal batteries combined with energy management systems are being trialled. Trials could demonstrate how such batteries can use off-peak power to decarbonise heat and save consumers money. A development in materials to improve thermal properties and corrosion resistance in TTES and solid-state TES technologies could improve efficiency, and enhanced innovations in integration and control systems will improve cost-effectiveness.*
- ***Medium term (5-10 years):*** *Cost reductions and technical improvements in next-generation high- and low-temperature PCMs and cPCMs could help increase deployment of latent thermal storage in buildings.*
- ***Long term (> 10 years):*** *R&D activities focusing on realising material and system improvements in thermochemical TES technologies could see them move onto demonstration.*

Given that cooling is delivered primarily through electricity, ever-increasing electricity demand will be another energy system challenge. This will be particularly so during peak demand (of which cooling is already a significant contributor). Matching renewable electricity (especially solar) to cooling needs that last beyond daytime will be a priority.

The buildings sector is projected to increase to 270 billion m^2 by 2050. On the residential side this is due to rising populations and incomes, leading to preferences for more space per person, and fewer people per household, particularly in developing countries (Global Alliance for Buildings and Construction, 2016). For example, India has forecast demand for 20 billion m^2 of new residential building space by 2030, equating to a change in residential building energy consumption from 1.9 EJ in 2005 to 8.12 EJ in 2030 – a 450% increase (Global Buildings Performance Network, 2014).

According to IRENA analysis, 36% of buildings energy consumption is currently met by renewables, including local use of biomass for space heating and cooking purposes. This fraction will need to rise, and increasing the roll-out of decentralised building-scale renewables may be one key solution. By 2050 the share of renewables could rise to 77% driven by a significant increase in solar thermal and heat pumps from current levels (~10 times higher compared to 2015 levels), with sizeable increases in the uptake of modern cooking stoves, biomass (around double compared to 2015 levels) and geothermal (~6 times higher compared to 2015 levels) (IRENA, 2018).

Space cooling is the fastest-growing use of energy in buildings and this trend is especially evident in warmer developing countries, where economies are growing rapidly. As they continue to grow, more and more citizens will have access to cooling equipment and energy use is expected to rise proportionally. For example, 50 million air-conditioning units were bought in China in 2010 (equating to half the entire US stock) (Cox, 2012). In 2016, 6% of total energy use in buildings was for space cooling, which was predominantly met by electricity.

Estimates by the IEA project the energy needs for space cooling to triple by 2050, which raises the cooling share of total electricity use to 30% and almost triples its share in total buildings energy use (IEA, 2018b). By 2060 worldwide energy use for space cooling is expected to overtake that of space heating (Isaac and van Vuuren, 2009).

Thermal storage could play a significant role in buildings, helping to integrate renewables. TES can help deliver sector coupling through the electrification of heat and can contribute towards meeting the increase in cooling demand.

Building-scale TES could contribute to meeting or shifting peak demand

The electrification of heat and the increase in cooling demand will result in analogous issues. **Decoupling** the production of heat and cold from the discharge of heat and cooling allows the shaving of the respective load peaks. This would lessen system reliance on peaker plants, and **reduce curtailment** of renewables to lower overall system costs. This would be a key benefit in areas/energy systems that have high VRE penetration. For heating this is applicable both diurnally and seasonally. It is also more effective to store excess energy from renewables as thermal rather than electricity, which makes TES more effective than batteries to reduce the mismatch between load and variable generation (Lund *et al.*, 2016).

The increase in electricity demand is also likely to cause significant strains on local networks. Domestic TES can help reduce this strain and **delay the need for grid reinforcement**.

There is significant scope for a range of TES technologies to be deployed directly in buildings

TES technologies and systems with different operational temperatures and requirements can meet a range of needs in the buildings sector. Mature TES technologies have been deployed at building scale for many years. In the future these are likely to be supplemented by the newer solutions currently under development. The state of development and deployment varies between the technologies (Figure 46), and this is discussed in detail below.

Case study 7. PCM thermal batteries with smart energy management to enable integration of off-peak renewables

Thermal batteries using PCMs provide cost and carbon savings to UK households compared to gas boilers

In the last decade the United Kingdom has seen significant progress in decarbonising its power system. However, only 16% of final household energy consumption is electricity – 81% is heat. The fact that 90% of UK homes rely on gas heating means that, overall, domestic heating results in 25% of the country's total carbon footprint. Therefore if the country wants to achieve its recently declared goal of net-zero emissions by 2050, a significant challenge will be how to decarbonise domestic heat.

Thermal batteries that use PCMs could form part of the solution. One such battery uses an inorganic salt hydrate, sodium acetate, which has a phase change temperature of 58°C. The PCM technology has been engineered so that it can run 41 000 cycles without any degradation. The thermal battery has four times the energy density of a water TTES, and is non-toxic and non-flammable.

Over a 15-year time period, which is less than half the potential lifetime of the battery, the battery can deliver heat at about USD 0.05/kWh, which is considerably less expensive than the equivalent energy stored in an electrochemical battery. Given that the lifetime is expected to be considerably longer, and degradation impacts are negligible, the thermal battery is a much more cost-effective solution for providing energy for heat than electrochemical batteries.

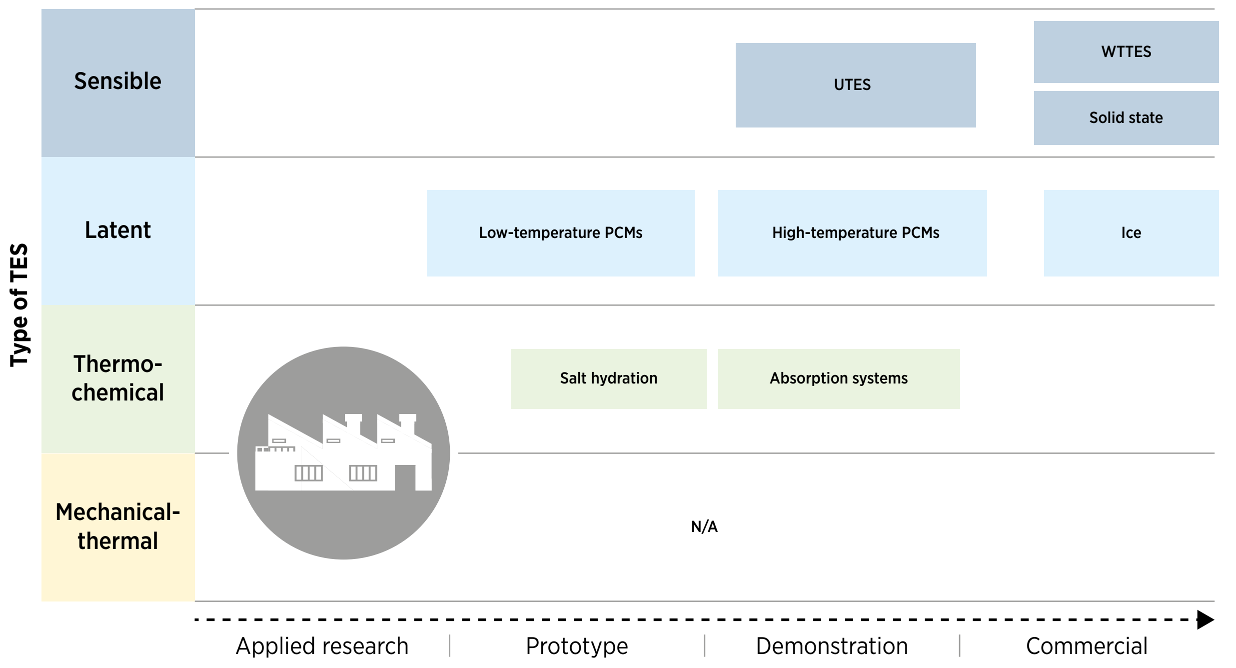
The latest battery is claimed to be 60-90% cheaper than the cheapest Li-ion alternative, per unit of energy stored.

The technology can be used in conjunction with rooftop PV, grid electricity or using a heat pump. It has been involved in several trials. The first, which involved seven households, started in 2013 and has shown how household heating running costs are 50% lower compared to a gas-powered boiler. The next generation of batteries was trialled on a larger scale across 600 households in Scotland, 404 of which had rooftop solar PV included. It has shown that the majority of the tenants saved money.

In 2019 the UK government announced that it was awarding USD 2 million to fund a trial for the developer of the battery technology to work with an energy supplier to allow domestic customers to heat their homes with low-cost renewable electricity during off-peak times, enabled through the use of the supplier's energy management platform. This pilot aims to demonstrate the feasibility of smart electric central heating on the mass market.

Such a system could be critical to the future of the United Kingdom's domestic heating plans, as the UK government announced in 2019 that it would ban gas heating in new houses by 2025. It shows how TES can be used to increase demand-side flexibility, something that will be critical to supporting grid stability if the widespread electrification of heat takes off (Sunamp Ltd, 2019).

Figure 46. Commercial readiness of TES technologies for use in buildings



Current status

Traditional **water tanks** for residential and commercial use have a typical water capacity between 100 and 1 000 litres (Lanahan and Tabares-Velasco, 2017). Water TTES is based on the heating or cooling of water during periods of off-peak electrical demand or excess electricity from solar collectors. The heat can later be delivered and distributed to the facility during peak periods of demand (Alva, Lin and Fang, 2018).

Various examples of electric hot-water storage have been reported in countries around the world. Examples from Australia, France and New Zealand have demonstrated the capacity for this use of TES to assist with the management of local electricity network congestion by reducing residential peak demand. In 2014 a 5% annual peak reduction was achieved this way in France (IEA, 2014).

Thermal energy has been stored within **ceramic bricks** at temperatures up to 70°C in residential storage heaters since the mid-20th century. Modern versions of these appliances, smart electric thermal storage (SETS) heaters, use a low-cost ceramic brick storage medium heated up by means of an electrical resistance at temperatures up to 700°C.

SETS devices have been installed in tens of thousands of residential properties globally (European Association for Storage of Energy and European Energy Research Alliance, 2017b).

Meanwhile, **ice storage** has recently been developed in California for residential use, aiding utilities by diminishing the "duck curve". Devices that are based on ice storage are also commercially available throughout North America and in India, primarily envisaged for use in commercial buildings. Other low-temperature PCMs also find application in buildings. In most cases, the **ice** and **sub-zero temperature PCMs** are encapsulated in modules, with heat transfer fluid used to supply the cold from the modules to the load. These systems can be used to back up or replace refrigeration systems, or to provide air conditioning in residential or commercial buildings (European Association for Storage of Energy and European Energy Research Alliance, 2013).

Focusing on heat, **domestic PCM heat batteries** have been trialled successfully and are commercially available in the United Kingdom. The encapsulated PCM can be charged by electrical heating or the heat exchanged through a heat transfer fluid (such as hot water from solar thermal and cold air from air conditioning).

Case study 8. Municipality introduces domestic TES to reduce household bills and increase wind utilisation

Canadian municipal programme provides discounted TES, resulting in increased utilisation of local wind

Summerside is a town on Prince Edward Island in Canada with a population of 15 000. Summerside's utility is municipally owned. It owns and operates 21 MW of local wind capacity that supplies roughly half of the town's electricity demand. The administration became frustrated that at times of low demand they were not realising the full potential of their generation by having to sell excess electricity onto the grid at low prices. Meanwhile, almost 80% of the town's heat demand was met by expensive and energy-intensive oil space heating.

In 2013 the town implemented the "Heat for Less" programme, which encouraged residents to replace oil-based heating appliances in residential properties with either electric thermal storage technology (using ceramic bricks) or time-of-use electric water heaters (TTES) at discounted rates. On the utility side, a smart grid network was developed to co ordinate real-time control of load.

The customer could purchase the TES device outright, rent it, or engage in a 5, 7 or 10 year lease-to-own scheme. The municipality manages the assessment and installation of the device, reducing the burden on the consumer.

In total 366 storage devices, ranging from 3 kW to 80 kW, have been delivered across 238 locations, with 75% of the TES for residential customers. Commercial customers also signed up to the programme, resulting in the addition of 3 MW/13.5 MWh of storage.

Through the utilisation of "wrong-time" renewables, 24% of the energy that was previously sold to the grid was kept in the community and the capacity factor of the wind assets was increased by a percentage point.

While utility income was increased as a result of the intervention, the real winners were the consumers, who on average saved CAD 1300 per year per household using the ceramic brick thermal storage and CAD 200 per year using the TTES.

In addition, 400 tonnes of CO_2 were avoided in 2015 as a result of the reduction in oil heating and backup diesel generation.

The provincial government, which also owns several wind farms, published its 10-year energy strategy in 2017, in which it states its desire to follow Summerside's example and roll out TTES and ceramic brick-based heaters across the rest of the province (Wong, Gaudet and Proulx, 2017).

Future outlook

Large-scale **UTES** has been utilised in the residential and commercial sectors for district heating and combined heating and cooling, as highlighted in the previous section. Currently some studies are testing smaller-scale low-cost BTES systems linked with solar collectors for greenhouses or single buildings (Başer, Lu and McCartney, 2016).

Furthermore, **high-temperature cPCMs** could be used to store large amounts of heat in relatively small storage volumes for residential and commercial applications. They would also use tanks similar to current boilers, but with much smaller size requirements.

Salt hydration can potentially store heat from the sun, both for the long term (seasonal) and the short term (diurnal), to overcome demand fluctuations in the residential and commercial sectors. Solar collectors, solar panels or co-generation plants can be used to charge the sorption system in summer to provide hot water and heating to the building in winter.

The technology is at an early stage of deployment in the buildings sector, but it has shown great potential given that its theoretical energy density is 5-10 times higher than traditional heat storage techniques such as water tanks (van Essen *et al.*, 2010).

Different integration schemes have been proposed according to the storage material, system and application needs (Mette, Kerskes and Drück, 2012): integration into a building's ventilation system (MonoSorp project [Bales *et al.*, 2007]), integration into a buildings ventilation wall (SolSpaces project), or integration into a solar thermal combi system with a separate reactor and material reservoir (CWS-NT-concept).

In the case of integration into a building's ventilation system, the heat store is designed to be integrated into a building with a controlled ventilation system and with heat recovery using solar collectors as a renewable energy source. The other option is to integrate the sorption unit within the building's wall. The proposed system divides the sorption store into several segments by separating absorption and desorption, which has the advantage of reducing the storage amount. Integration into a solar thermal combi system entails a reservoir material and a reactor where the charging/discharging takes place.

Absorption cooling systems are a novel form of thermochemical heat storage that can help integrate renewables in buildings.

Large-scale heat-driven absorption cooling systems are available in the market for industrial applications, but the concept of a solar-driven system for air-conditioning applications is relatively new.

Solar thermal cooling can reduce energy needs during peak periods in summer by replacing electrically driven air-conditioning systems with thermally driven air conditioning. The absorption cycle is more suitable for low-grade heat utilisation and allows faster heat and mass transfer rates than other sorption systems.

Innovation in materials science and system integration will see TES capacities improve

Table 11 shows a summary of the key objectives for technological innovation within components of TES for buildings.

Sensible

The main challenges of **UTES** for residential and commercial applications is scaling down the system designs. For small-scale applications, the undersized BTES volume will result in greater heat losses and inefficiencies (Lanahan and Tabares-Velasco, 2017). Moreover, the high capital cost for the construction of BTES highlights the importance of numerical simulations to ensure economic and thermodynamic feasibility.

Table 11. Key objectives for the technological innovation of TES for buildings

Attribute	Sensible			Latent			Thermochemical		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (USD/kWh)	0.1-35	0.1-25	0.1-15	60-230	60-185	60-140	15-150	Pilot scale 12-80	Demon-stration < 80
Efficiency (%)	55-90	65-90	75-90	> 90	> 92	> 95	50-65	(1)	
Energy density (kWh/m³)	15-80	(2)		30-135			120-250		
Lifetime (years or cycles)	10-30 years	15-30 years	20-30 years	> 10 years	> 15 years	> 20 years	15-20 years	20-25 years	> 30 years
Operating temperature (°C)	5-95	5 to > 95		0 to up to 750			15-150		

Notes: (1) Value not available due to low technology readiness level; (2) Depends on working temperature range.

Several studies have illustrated the efficiency benefits associated with coupling BTES and solar collectors in smaller-scale systems. A study on an installation for a greenhouse predicted an 80% operational efficiency, with an expected payback time of 14 years (Gao, Zhao and Tang, 2015).

Follow-up pilot projects could be used to test BTES designs and performance for other building and commercial applications.

The **integration of PCMs into water tanks** to increase the energy density of domestic hot water storage is a current topic of research. Hot water/PCM hybrids have significant potential and are likely to emerge in the medium term (Mette, Kerskes and Drück, 2012). Incorporating PCMs can help to overcome challenges associated with the space constraints and the weight of traditional water tanks, which otherwise restrict their utility.

As regards systems efficiency, new approaches to improve and maintain stratification and reduce system running costs are needed. Recent developments propose new methods to increase stratification, such as minimising mixing and turbulence of water entering stratified thermal store tanks (Al-Habaibeh, Shakmak and Fanshawe, 2017). Another approach is to use a smart thermostatic control strategy that enables the prediction of required water amounts, to maintain customer comfort while reacting to variations in the electricity network (Gelažanskas and Gamage, 2016). This system operates with a demand response according to consumption forecasts (Davis, 2014).

Smart control systems can produce both up and down regulation, as well as increase water heater efficiency. System changes that include optimising the integration of the internal heat exchanger, internal free convection in water tanks and the heat losses due to parasitic heat convection in pipes also warrant further study to assess the potential for new designs with higher efficiencies.

Several projects are being carried out that aim to take the newly commercially available small-scale sorption chillers and combine them with solar water tanks for space heating and cooling (Reda *et al.*, 2017).

A high proportion of VRE power generation creates both new opportunities and ideal conditions for the integration of **SETS** heaters using ceramic bricks.

SETS systems have been proposed to deliver services for demand-side management, enabling the increased penetration of low-carbon energy sources (*e.g.* wind and PV) at both a local and national level. Several studies have simulated and optimised the use of decentralised TES with SETS heaters for renewables penetration (Ali, Ekström and Lehtonen, 2017; Di Fresco, 2018). They noted the opportunity to co ordinate these systems to embed an interconnected TES network.

Latent

Similar to other PCMs, the low thermal conductivity of **low-temperature PCMs** limits the heat transfer rate and hence hinders their wider commercial deployment. Following similar approaches as described previously, the heat transfer rate can be improved by increasing the heat transfer area with fins and designed structures, expanding the conductive matrix in which the PCM is embedded, or by adding materials of high thermal conductivity to the matrix (*e.g.* carbon nanotubes) (Karaipekli *et al.*, 2017). However, most of the solutions are only tested at lab scale and there is no common approach to all eutectics. Development will focus on testing these strategies in real conditions.

Currently some low-temperature systems are fully commercialised and available, but the investment cost is very high. Further studies are required to scrutinise their long-term performance and reliability at system level. Reducing the cost of individual components, as well as developing new cost-effective approaches to whole TES system design, will be key priorities.

As noted in previous sections of this report, **high-temperature cPCMs** need to be developed and further research is required to improve their storage properties and composite stability over cycling. Furthermore, the common limitations of inorganic PCMs related to supercooling, leakage, cyclability and corrosion also have to be overcome when integrating high-temperature cPCMs.

As for other applications, hurdles must be overcome before high-temperature cPCMs can be commercialised. They include improving compatibility between the construction material and the storage media, lowering the integration cost (especially for short-term applications) and identifying new integration systems to compete with other traditional technologies (sensible heat).

Thermochemical

In **salt hydration** systems, the temperature range and user conditions are similar to district heating. Technical details on materials in development are available in the Appendix.

The storage material strongly affects the performance and cost of such a heat storage system according to some economic studies for various applications (typically, about 30 % of the total investment cost) (Lele, 2016).

Further work is required to optimise the properties of the materials used, particularly in regard to thermal conductivity, and also to study their durability over long periods of cycling. It is predicted that these systems will become realistic options for long-term heat storage in the future (Mette, Kerskes and Drück, 2012), although research into system integration is needed. Limited research effort has so far been devoted to sizing these systems to establish real-world applicability, a priority for commercialisation.

The innovation needs of **absorption systems** are the same as those presented in the district cooling section, given that the storage media used in this technology are the same for both applications. As previously noted, commercialisation of the technology remains limited due to system complexity and the cost of maintenance. Therefore, new absorption cycles need to be investigated and system design improved.

System complexity and maintenance costs must be reduced to open the way for commercial applications.

4. POLICY INTERVENTIONS TO ACCELERATE DEPLOYMENT

Chapter summary

***Key system-level barriers** to the uptake of TES across the energy system include:*

- *The lack of technology readiness for some TES technologies and the presence of competing technologies (e.g. inexpensive fossil-generated heating).*
- *The lack of knowledge and awareness of how TES can provide benefits to society, the public sector and industry. This has manifested itself in a disproportional R&D focus on battery storage, when thermal storage can provide significant benefits to energy systems with high heating or cooling loads.*
- *Uncertainty in how the future energy system will develop, which leads to a reluctance to invest in long-term or large-scale projects.*
- *Siloed thinking across different energy vectors (i.e. heat and power) and different sectors, leading in some cases to conflicting policies and inefficient planning. Furthermore, there is generally a lack of policy for the decarbonisation of heat compared to the power sector.*

Policy makers can implement a range of technology push, market pull and enablers to encourage the uptake of TES. The precise combination of these, as indeed with the combination of relevant TES technologies, is dependent on the characteristics of the energy system.

*The main **technology push** interventions involve:*

- *Investing more into R&D of TES technologies, enough to match the potential that they uniquely have to facilitate the decarbonisation of the heat, power and cooling sectors.*
- *Funding demonstrations to help build market awareness, increase consumer confidence and progress TRLs. The supply chain is mature for some technologies, but those with the most potential for integrating higher shares of renewables are generally at a lower technology readiness level.*

*The main **market pull** interventions involve a greater emphasis on heat decarbonisation, incentivising flexibility and unlocking ancillary services markets for thermal storage:*

- *Removing fossil fuel subsidies and introducing a price on carbon to significantly improve the competitiveness of low-carbon heating systems.*
- *Encouraging mechanisms such as time-of-use tariffs to incentivise demand-side flexibility and help reduce consumers' bills, as well as increase the utilisation of renewables.*
- *Ensuring participation in ancillary services is as technology neutral as possible to help overcome barriers typically seen for battery storage, and provide additional revenue streams for owners/operators of TES.*
- *Adopting a long-term view on the development and deployment of TES, and providing incentives that de-risk such projects for investors.*

***The principal enablers** required to facilitate the uptake of TES in energy systems are:*

- *Taking a whole-systems approach to decarbonisation of energy systems, which is essential to enabling a cost-effective energy transition. All flexibility technologies should be considered in studies to determine the most cost-effective pathway to a decarbonised energy system.*
- *Implementing strategies as part of an integrated energy policy in order to reduce the instances of conflicting energy policies, and help to realise higher levels of system benefit.*
- *Raising awareness across industry, the public sector and consumers to communicate effectively the benefits of TES.*

The make-up of energy systems differs from country to country, in both their stage of development and overall characterisation. Therefore, the appropriateness of thermal storage technologies is highly context specific, as are the interventions to accelerate their deployment. The approach that policy makers take must be part of an integrated strategy steered by whole-systems thinking.

This section provides an overview of the following:

- Key barriers limiting the uptake of TES solutions.
- Support mechanisms available to policy makers to facilitate TES development.
- Support needs for TES across each sector, as well as examples of tried and tested interventions.

4.1 System-level barriers to the uptake of TES

Knowledge and awareness in society, public sector and industry

In general, the focus of climate change mitigation efforts falls on electricity, transport and sometimes agriculture, but rarely are heat or cold a priority, even though they account for approximately 50% of EU member states' annual energy consumption. This could in part be due to the challenges associated with the decarbonisation of heat (and cold). In the absence of a focus on heat/cold decarbonisation, relatively little investment is made in relevant development activities and demonstration projects.

Demonstrator projects typically work to reduce perceived risk around given technologies and thus encourage future investment. Demonstration activity is also useful in pre-emptively identifying potential technological and system pitfalls, and in contributing to recognition among relevant stakeholders and general public groups. In the absence of an evidence base developed through demonstration activities, installation and operating costs for new technologies such as TES are likely to be higher, and investments in these opportunities considered higher risk. There also appears to be limited reporting of demonstrator outcomes for TES installations. Collecting case studies for this report proved to be very challenging.

Relative immaturity of TES technologies

Many different TES technologies, particularly latent and thermochemical, have not been upscaled or proven at commercial levels, as described in detail in Chapter 4. These systems still stand at the early or middle technology readiness stages, where cost reductions would be needed for their widespread adoption. In the near term, the focus should be on providing demonstration support, developing investment mechanisms, and the establishment of supply chains and strategies for a smooth integration of TES in energy systems.

Uncertainty in future energy system mix

There is a level of uncertainty in how the challenge of decarbonisation will be resolved. For example, it could be addressed by deploying significantly increased levels of (variable) renewable energy. Equally, it could be resolved through much higher levels of nuclear power generation, which is non-variable. It is unclear what combination of technologies will make up the future energy mix. The shape of future energy systems will guide the types of TES (or other forms of energy storage) that are utilised, given the differing storage needs (timescale, location, temperature range etc.) associated with differing energy technologies.

It is not feasible to identify a single policy recommendation to solve this uncertainty, especially given that the composition of the future energy system will vary by country, by changes in governments, by increasing or decreasing costs and a variety of other factors. However, further analysis and modelling of energy systems would be beneficial, identifying the various scenarios that may or may not occur from varying perspectives, *e.g.* least cost, lowest CO_2 emissions.

Limited recognition in policy and regulation

As covered in previous sections, global decarbonisation of the heating and cooling sectors has not kept pace with that of electricity systems. This is in part due to the comparatively limited attention paid by policy makers to heating and cooling decarbonisation roadmaps and strategies, relative to electricity. TES technologies for heat and cold vectors, like other potential decarbonisation solutions in these sectors, have not benefitted from policy support to the extent enjoyed by storage technologies in the power sector. In 2016 only 21 countries had renewable energy regulatory incentives and mandates that involved a solar heat obligation or a technology-neutral heat obligation. There were 29 other countries that had different heating or cooling policies.

More effort is clearly needed to address heating and cooling, acknowledging the challenge of meeting the level of effort required when heating and cooling policy will need to vary by sector, country and infrastructure type in order to overcome specific barriers.

On a positive note, the European Union's revised Renewable Energy Directive specifically recognises the challenges surrounding renewable heating and cooling. Subsequently, it has set an ambitious target of a 1.3% annual increase in renewable heating and cooling, starting in 2021.

Many countries have regulated energy markets for electricity and gas. Market regulators were typically established to ensure that competition between market participants delivers value for consumers, by preventing the formation of potentially exploitative monopolies. However, there is no equivalent regulated market for the generation, distribution or supply of heat (or cold). Notably, multiple actors from industry in the United Kingdom support the future regulation of heat networks under the supervision of a regulator (either current or newly formed) (The Association for Decentralised Energy, 2018).

Furthermore, looking to the future, there is expected to be a much greater level of cross-sector interaction between energy vectors as a result of sector coupling (Energy Technologies Institute, 2017). If policy makers react to the interaction and competition between vectors by taking a whole-systems approach to policy and regulation, this would provide an opportunity to create a level playing field for TES amongst other technologies.

Some TES technologies are also not widely recognised in environmental or planning and building standards regulatory regimes. TES is a relatively new infrastructure type, which may experience a public backlash in the absence of robust regulation. Therefore, regulation should be in place to ensure that these systems are designed in the best way to minimise the environmental impacts of TES installation and the technology itself.

Conflicting policies

In some cases, fossil fuel subsidies undermine efforts and progress towards low-carbon technology deployment (Matsuo and Schmidt, 2017). For example, diesel subsidies could severely limit the incentives for countries and their industries to invest in TES, reducing the scope for facilitating higher levels of renewable energy penetration.

Competing technologies

Various types of energy storage (electrochemical batteries, for example) can provide services similar to TES in the current power system. If further innovation in batteries (particularly Li-ion) continues to drive down prices, partly due to the rapid deployment of electric vehicles, this situation may set a complex cost-competitiveness scenario for TES technologies.

Heat pumps may supply a proportion of heat through electricity at a domestic level, but it is yet to be seen whether this technology can alone meet the challenges of heating provision. At domestic and industrial levels, renewable heating and cooling will be required at different scales, meaning TES might be in a better position to provide possible pathways.

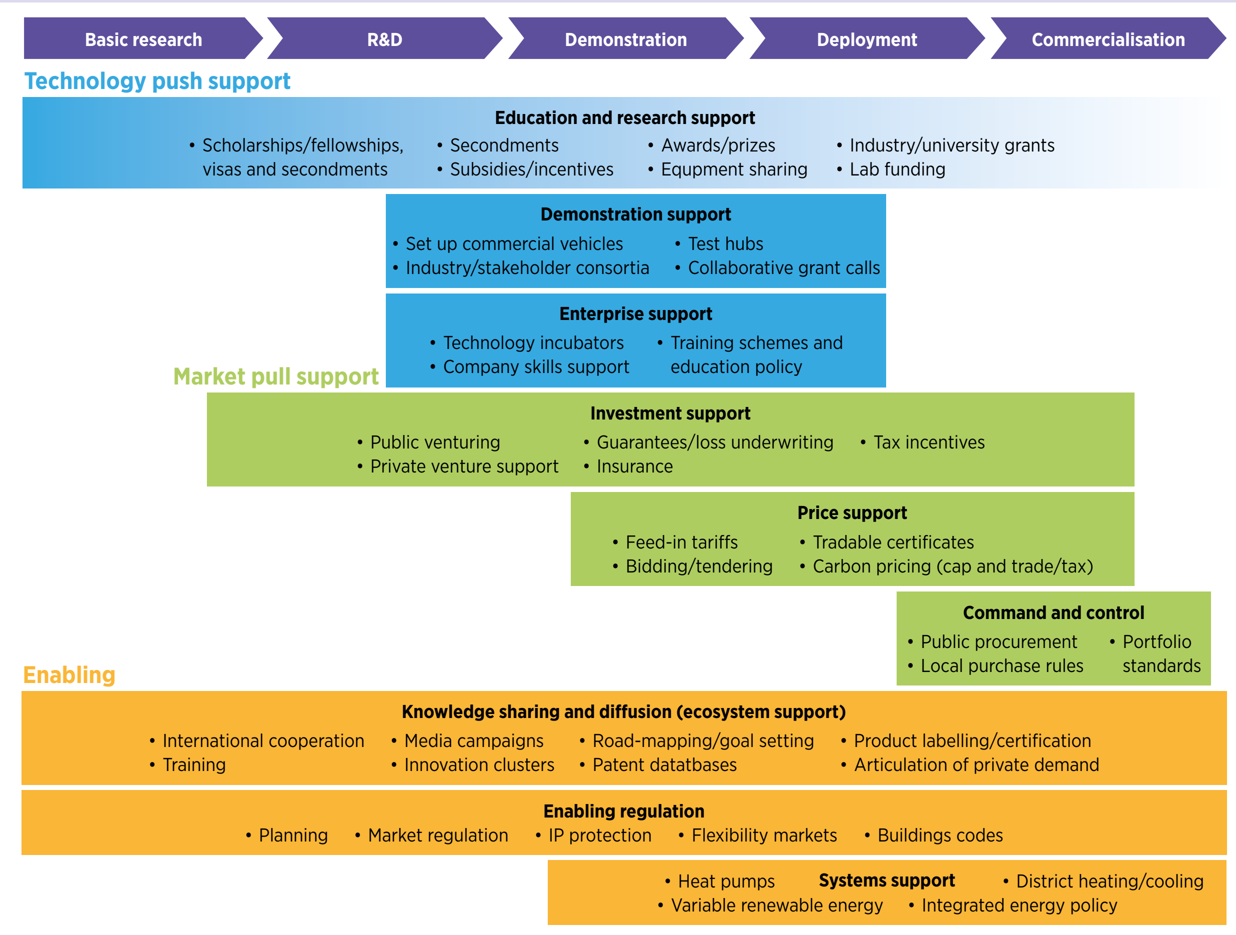
Similarly, there might also be an increased level of competition from alternative heat decarbonisation technologies.

For example, hydrogen gas could theoretically use existing underground gas network infrastructure already installed in some countries and provide an alternative vector to natural gas. This example demonstrates the need for the adopted solution to be adapted to the local context.

4.2 Available support mechanisms

A range of interventions are available to policy makers to help accelerate the deployment of TES technologies in target sectors. These measures cover all stages of development, from the R&D stage, through demonstration, to commercial deployment. The highlighted interventions are listed in Figure 47, classified as technology push support, market pull support and overall enabling regulation and ecosystem support.

Figure 47. Menu of policy options for advancing the commercialisation of TES technologies



Technology push

Technology push support is generally implemented near the beginning of a technology venture's commercialisation journey as the technology itself is being developed. It can be categorised into education and research support, demonstration support, and enterprise support.

- **Education and research support** focuses primarily at the early stage of the commercialisation journey, and includes interventions such as the provision of scholarships, visas and secondments, lab funding, industry and university grants, and the founding of academic awards and prizes.

- **Demonstration support** focuses on testing unproven technologies in laboratory and operational environments through mechanisms such as test hubs, joint industry projects, funding for pilot-scale demonstrations, innovation competitions, etc.

- Technology developers are often spin-outs from academic institutions, large companies or technical experts with little experience in commercialisation. Once the technology has been demonstrated to work, the journey towards commercialisation begins. This requires an entirely different skillset of developers who up to this point may only have had technical expertise. As such, **enterprise support** in the form of technology incubators, training schemes and education policy, or company skills support can help technology start-ups begin to build or improve upon their commercial offering.

Market pull

Market pull support is provided once a technology has been proven, to try to make it commercially competitive and achieve successful levels of deployment. Support can be classified into investment support, price support, and command and control support. These support mechanisms tend to be more relevant once the technology has been proven technically and commercially.

- **Investment support** involves providing various forms of capital for commercial ventures, through mechanisms such as public or private venturing or by reducing costs via tax incentives, loss underwriting and insurance.

- **Price support** includes a range of mechanisms that can help improve the competitiveness of a technology with an additional source of revenue for technology implementers, helping to de-risk the financial proposition of the technology to investors. Mechanisms include feed-in tariffs, tradeable certificates, carbon pricing or cap and trade schemes, and bidding and tendering support (*e.g.* contracts for difference).

- **Command and control** mechanisms use a top-down approach to pull technologies to market using measures such as public procurement, local purchase rules and portfolio standards.

Case study 9. **Technology push interventions for LAES in the United Kingdom**

LAES in the United Kingdom

The liquid air storage industry in the United Kingdom has been subject to examples of all three technology push support approaches. In 2013 the Birmingham Centre for Cryogenic Energy Storage and the Birmingham Centre for Thermal Energy Storage were established with a GBP 13.6 million grant from UK industry and the Engineering and Physical Sciences Research Council – an example of education and research support. An enterprise seeking to bring these technologies to market was assisted by a grant-funded clean-tech incubator, aiding the development of commercial skills and a business strategy. Demonstration support has been provided consistently, most recently in 2018 for a 5 MW/15 MWh LAES project near Manchester that is being built with the support of about GBP 10 million of government grant funding (Innovate UK, 2020).

Case study 10. **California demonstrates market pull intervention with mandate for energy storage**

California Storage Mandate

One example of policy directly encouraging energy storage through market pulls techniques is the California Storage Mandate in the United States. Initiated in 2013 by the California Public Utilities Commission, the requirements were that the three largest investor-owned utility companies in California should add 1.3 GW of energy storage to their portfolios by 2020. It is possible that California's ambitious target of deriving 50% of the state's electricity from renewable sources has resulted in more energy storage projects being planned or announced. However, this renewable electricity target is coupled with an effort from state legislators to resolve storage-related complexities, including how energy storage is classed and regulated (Hill and Williams, 2016).

Enablers

Policy makers have a range of enabling interventions available to them to benefit a technology either directly or indirectly. These measures are relevant at various stages of the commercialisation journey.

- **Knowledge sharing and diffusion (ecosystem support)** are essentially awareness raising through different means. Examples include media campaigns, training workshops, road-mapping, product labelling or certification, publicly accessible patent databases, and reports such as this. Interventions such as these can help to increase market demand, increase stakeholder acceptance and provide clarity to investors.

- Policy makers can introduce **enabling regulation** to help provide clarity and de-risk the financial proposition of technologies to investors. Policy makers can reduce barriers or even provide incentives by improving planning regulation, introducing building codes to phase out fossil-powered boilers, regulating markets (*e.g.* by removing regulatory conflicts, creating a regulated heat and power and flexibility markets, or with decarbonisation policies), or by protecting intellectual property.

  New EU regulations that will be in place from 2021 requires national energy and climate plans, in which EU member states will have to establish a trajectory for the penetration of renewable energy sources in heating and cooling to 2021-2030. This will also require an assessment of the need to build new infrastructure for district heating and cooling produced from renewable sources.

- **Systems support** involves interventions that support the growth of renewables and other infrastructure, which can be viewed as an indirect intervention for the development of TES technologies, as demand for thermal storage is likely to increase depending on the penetration of enabling infrastructure. For example, the penetration of heat pumps and hot-water tanks is seen as a key enabler for TES technologies across several sectors (buildings, industry, district heating and cooling).

A long-term planning horizon is required, which can take the form of long-term power purchase agreements or "storage capacity lease" agreements. Using Jordan as an example, in 2018 a proposal was submitted for an energy storage system of 30 MW import and export power and 60 MWh useable energy capacity. Financed and managed by a private developer and structured on a long-term off-take agreement (15 years), financiers and investors could now view project financing of energy storage systems as more viable. This is due to the maturity of the energy storage system market, technology improvements, decreasing costs and a stable market of engineering, procurement and construction contractors.

4.3 Key barriers and recommendations for each sector

This section discusses barriers to TES adoption in the use sectors overviewed in Chapter 3. It proposes potential policy interventions relevant to each sector. These should be viewed as complementary measures to the generalised "menu of policy options" presented in the previous section.

Power

Globally there is limited recognition of energy storage or indeed heating/cooling systems in energy market regulations. Regulation in the power sector is typically based on models that were envisaged for centralised production of baseload power with passive consumers. Growth in distributed variable generation and the rise of the "prosumer" has changed the way power market participants interact, and regulatory frameworks are not generally keeping pace. Storage technologies are impeded by several challenging quirks of regulation, including a lack of classification and instances of potential double-charging for power at the point of storage and use.

Policy makers should **address these regulatory barriers to energy storage** to provide clarity to the wider market as to the prospects for storage penetration in power systems.

In Europe policy makers have already addressed the regulatory barriers to energy storage by providing clarity on the wider market and the prospects for storage penetration in power systems (Table 13). Looking specifically at TES, it is essential that policy makers evaluate and amend regulatory frameworks using whole-system perspectives, so that power and heat markets are not siloed.

Current market structures also restrict TES commercialisation. **Price signals for the provision of flexibility** are needed to improve the value proposition of TES technologies. However, governments should be mindful of the need to avoid the high levels of volatility in electricity prices associated with VRE. Taking curtailment as an example, if it is invisible to the wider market, there is little to no incentive to address it or better integrate the VRE generators. If price volatility in markets with high levels of intermittent renewable penetration is made visible, this strengthens the economic case for deployment of storage.

European Union Renewable Energy Directive

A multinational example of integrated policy is the European Union's 2009 Renewable Energy Directive. All EU member states were required to create a National Renewable Energy Action Plan (NREAP), which outlined their respective targets for renewable energy to be achieved by 2020. As a related policy, all member states then adopted decarbonisation targets for transport, for electricity and for heat. Table 12 shows the NREAP targets of three member states. Since the adoption of NREAPs, most member states have adopted relevant policy measures towards achieving their stated renewable energy deployment aims.

Table 12. A snapshot of the NREAPs of three EU member states, showing targets for renewable penetration in each sector for 2020

Sector\Country	Germany	Sweden	France
Electricity	37%	63%	27%
Heating and cooling	15%	62%	33%
Transport	13%	14%	10.5%

Source: IEA and IRENA, 2018.

Table 13. Identification of barriers to energy storage deployment at EU level

Barrier	Solution
Ownership rights unclear	Clarification of ownership rights
Value streams	High level of reward for ancillary and grid services
Curtailment	Elimination of the ability to curtail renewable energy sources, *e.g.* solar, wind
Pricing	Ensure that pricing of thermal energy reflects demand and/or scarcity

Source: Westgeest, 2017.

Case study 11. **Market reform helps to reduce renewables curtailment in China**

Averting curtailment in China

China has recently reformed its market conditions to better account for renewables curtailment. In 2016 the Chinese government introduced Document 625, a policy that sought to address high levels of curtailment of renewable generation (Xuan and Dupuy, 2016). The key feature of the policy is the introduction of a guarantee that grid companies will purchase renewably generated output first (before generation from fossil fuel plants) for a minimum number of hours. The National Energy Administration and the National Development and Reform Commission plan the allocations. In previous years in China, curtailed renewable generators were not in receipt of any payment or compensation for lost revenue, which arguably made the renewables sector unattractive to investors. However, through the introduction of Document 625, renewable generators could expect to receive a curtailment compensation fee from non-renewable generators or grid companies, depending on the reason for their curtailment.

Information on the technical and financial performance of thermal storage solutions for non-CSP renewable power is currently limited due to the relatively small number of demonstration projects. However, several demonstrations that will test the technical and commercial feasibility of TES in these applications are either in development or in construction. **More funding for research and demonstration projects** is required to drive innovation and reduce costs further across all technologies analysed in this report, and ecosystem support can help to ensure learnings from these demonstrations are well documented and shared.

Industry

Decision makers in industry typically prioritise improving revenues over reducing costs, and place a significant emphasis on payback time. Furthermore, due to the absence of policies aiming to price externalities such as CO_2 emissions, and in some cases the availability of fossil fuel subsidies, there is a **weak financial proposition for TES deployment** to help integrate renewables in industrial environments.

For example, in Mexico the solar heat for industrial processes market has potential, but the need for upfront investment and the lack of loan schemes has been a barrier to adoption. As a result, other more commercially attractive investments can push renewable energy with (or without) TES down the list of priorities. **Market pull interventions** such as cap and trade schemes that provide incentives to industry to invest in renewables/TES over a specific timeframe could help to increase levels of interest.

Risk aversion is another key barrier to decarbonisation efforts in the industrial sector, particularly with regard to potential deployment of new capital-intensive technologies. Decision makers are typically reluctant to risk disrupting revenue streams by adopting novel technologies and approaches without adequate assurance of success. Even if the benefits of adopting the technology are understood conceptually, there is reluctance for any one organisation to be the first to move.

Ecosystem and technology push support can help **build trust around certain technologies**, for example by introducing certification schemes administered by a trusted third party, or via government-sponsored demonstration projects.

It can be helpful to target innovative companies for whom this barrier would perhaps be less significant. These organisations are often large customer-facing companies who have a dedicated sustainability division (*e.g.* major car manufacturers), and an interest in the kudos associated with successful decarbonisation initiatives. Such activities can contribute to increasing **awareness** of the opportunities offered by thermal storage, especially for technologies that are not yet commercialised. By **making clear the potential benefits of TES in the industrial sector**, and providing ecosystem support to share learnings with relevant market participants, policy makers could help accelerate the uptake of TES.

Cold chain

Significant growth in energy demand is foreseen in the cold chain. It is important that systems-thinking approaches are used to ensure policy making and regulation encourage decarbonisation in this vital sector.

Historically one of the main barriers to the development of cold chain technologies, including thermal storage, has been a lack of R&D investment. However, since 2015 a range of initiatives have been led by government (*e.g.* the EU CryoHub), education facilities (*e.g.* the UK Thermal Energy Research Accelerator), and philanthropy (*e.g.* the Kigali Cooling Efficiency Program).

The latter initiative is looking to mobilise finance for solutions such as thermal storage in the context of the cold chain.

Technology push interventions such as these are needed to accelerate the commercialisation of TES technologies for the cold chain. Ideally these types of initiative should be managed concurrently to achieve synergies, such as those realised in LAES development in the United Kingdom. As highlighted previously, **grant funding for R&D activities *and* demonstration projects** for LAES in the country have showcased capabilities of the technology, and also helped **develop the industry supply chain and skills**.

Much of the growth anticipated in the cold chain will occur in developing countries. The technologies required to decarbonise cooling are currently associated with significant capital expenditure costs. The cold chain is particularly important in agriculture, and a key barrier in deploying TES and renewable cooling assets will be the **limited economic resources of small-scale farmers**. Another barrier is **stakeholder awareness and acceptance of cold chain TES**.

Medium-sized and large farmers who do have the resources to invest in thermal storage without subsidies are largely unfamiliar with the technologies, and indeed may be agnostic or hostile to technological innovation if it risks disrupting revenue streams. The same fears are apparent at the other end of the cold chain, for example among food retailers, as there is limited awareness of the capabilities of these technologies.

Case study 12. **Technology push and market pull interventions to develop a clean cold chain in India**

Agricultural cold chain in India

Interventions in India have found success in supporting early adoption of TES solutions in agriculture. The Indian government provides subsidies to farmers for investments in equipment, which currently cover thermal storage technologies. This is an example of a price support mechanism. TES manufacturers have also been trialling lease-to-own propositions in the country. Such schemes can encourage farmers to try out these new technologies, without the risks and reservations associated with an upfront investment. Policy makers can also build upon the impact of demonstrations such as these using a combination of technology push and market pull interventions, and through ecosystem support such as media campaigns, knowledge sharing and international co operation. This can communicate the benefits of adopting thermal storage technologies to a wide range of stakeholders (University of Birmingham, 2017) .

District heating and cooling

While demonstrations have proven the technical feasibility of the equipment and infrastructure, investment costs and the high degree of perceived risk currently discourage developers from prioritising these solutions. This is further compounded by the complex map of stakeholders involved in district heating/cooling projects, including developers, local authorities, utilities, consumers and housing associations. It is labour and resource intensive for developers to manage relationships with these disparate groups.

Projects can be accelerated with **investment support mechanisms and command and control mechanisms**, *e.g.* through public procurement. **Additionally, clear guidelines and regulations for planning, building standards and environmental protection will assist in facilitating projects** that deploy TES alongside a district heating/cooling asset.

The current EU strategy on district heating and cooling is for it to be flexible, allowing for the more rapid integration and deployment of renewable energy sources (European Commission, 2016). UTES technologies can provide significant storage capabilities with limited covered ground area, and are relevant for these infrastructure types. **A subsurface presence invariably requires specialist planning permission**, however, and policy makers can remove barriers to project progress and assist developers in managing relevant stakeholders by ensuring planning procedures are robust.

Market demand for renewable district heating (and any accompanying TES) can be limited by convenient and cost-effective fossil fuel alternatives. Recognising the externalised costs of continued fossil fuel use would help to level the playing field. Price support mechanisms (*e.g.* carbon taxes) that form part of wider enabling regulation frameworks can help drive competitiveness of renewably powered district heating.

Buildings

Utilities will require support from policy makers to facilitate solutions that manage the increasing share of renewables and electrification solutions in buildings.

TES assets could aid in managing building-scale energy demand, but they are not yet cost-competitive options. There is a **lack of consumer awareness and market demand** for novel thermal storage (heat and cold) in buildings. The availability of **cheap electricity or gas** and a **lack of price signals** (*e.g.* time-of-use tariffs) have restricted consumer demand for thermal storage beyond traditional non-smart water tanks. For commercial buildings energy is typically a small fraction of the total cost of the business, and rarely seen as a strategic issue compared to other parts of the cost structure more central to a business.

Policy makers could assist with **funding for R&D and demonstrations** to prove the system benefit, ecosystem support such as **media campaigns** to encourage consumer uptake and **price support mechanisms** to enhance feasibility. Policy makers can also provide systems support by **encouraging the uptake of heat pumps**, or ensuring that **grid operators are properly incentivised** to manage grids efficiently rather than investing in grid reinforcement as the default.

Reliance on incumbent technologies and established infrastructure has limited decarbonisation efforts in heating and cooling in many countries. Nonetheless, moving away from gas boilers towards renewable heat would help to drive demand for thermal storage, and thus help to deal with intermittency issues. From a buildings perspective, decarbonisation of heat is being considered through direct renewable heating (*e.g.* rooftop solar thermal panels), clean hydrogen or the electrification of heat.

Wider adoption of these solutions can be achieved through **mandatory building** codes defined by national or sub-national authorities. For example, In June 2017 the Norway Ministry of Climate and Environment announced a ban on the use of oil and paraffin to heat buildings from 2020. This ban will cover old and new buildings, publicly owned facilities as well as private homes and businesses. Some of the alternatives outlined include heat pumps and wood chip burning stoves, whose deployment is set to rise significantly.

4.4 Key barriers to wider TES deployment

Table 14. Overview of key support needs that are relevant to TES in each end-use sector

Application	Regulatory/policy environment	Stakeholder acceptance	Technical performance	Financial proposition
Power	• Fragmented, siloed energy regulation. • No regulation of heat or cold.	• Commercial CSP plants at a scale of 100 MW have provided awareness and confidence to international power project developers and contractors. More effort should be made on lender and consumer awareness.	• Utility-scale thermal storage technologies (for non-CSP use) are at an early stage of development • Technical performance of molten-salt TES is proven in over 10 years' operating track record at utility-scale in multi-GW CSP plants.	• The commercial feasibility of non-CSP utility-scale storage technologies has yet to be demonstrated.
Industry	• Fragmented, siloed energy regulation. • No regulation of heat or cold. • Limited subsidy for installation of non-power assets.	• Risk-averse decision makers likely to prioritise revenue-neutral solutions, including incumbent fossil fuel alternatives.	• Many promising technologies are at an early stage of development and are not yet ready for widespread deployment.	• Commercial trials have not yet proven the financial proposition for anything other than TTES. • High CAPEX of projects prohibitive. Return on investment needs to be high for renewable energy projects to be considered.
Cold chain	• Fragmented, siloed energy regulation. • No regulation of heat or cold.	• Agriculture and food retail stakeholders often quite risk averse. No one wants to be the first to move. Failure can spoil perishable products and disrupt revenue generation.	N/A	N/A
District heating and cooling	• Planning permission can be complicated to obtain for UTES technologies. • Fragmented, siloed energy regulation. • No regulation of heat or cold.	• Technical/ commercial /environmental performance of latent technologies for district heating has only recently been proven, so limited stakeholder awareness and acceptance of these technologies.	• Only a small number of demonstrations of next-generation high-temperature cPCM-based storage.	• Renewable district heating/cooling schemes with or without storage have high upfront costs, which limit attractiveness.
Buildings	• Planning permission can be complicated to obtain for UTES technologies. • Lack of building codes to encourage/force take-up of alternatives to fossil fuel-powered heating systems. • Fragmented, siloed energy regulation. • No regulation of heat or cold.	• Consumer awareness is low for both domestic and non-domestic thermal storage (heat and cold).	• Still relatively low TRLs for low-temperature PCMs and chemical storage-based solutions for heating/cooling applications.	N/A

Note: N/A denotes no main needs were identified.

Application	Industry supply chain and skills	Market opportunities	Company maturity	Enabling infrastructure
Power	N/A	• Lack of value placed on flexibility provision reduces opportunities for storage, including TES.	• Engineering, procurement and construction (EPC) companies have competitively matured with the implementation of 17 GW of molten-salt TES systems for CSP plants.	• Limited CSP uptake associated with low demand for molten-salt TES.
Industry	• Supply chain for TES is relatively undeveloped due to the current early stage of commercialisation of the technologies.	• Industry tends to be revenue driven, and investment in cost-cutting measures is often a second-order priority. • Renewables integration is low in industry in part due to a lack of customer demand – this impacts the interest in TES as a result.	• Preference for established equipment suppliers to avoid technology risk can make it difficult for early-stage businesses to break into the sector.	• Very limited adoption of renewable technologies in industrial environments.
Cold chain	• Supply chain relatively undeveloped due to emerging technology, especially for LAES.	• Small-scale farmers in developing countries face financial barriers, impeding TES adoption.	• Manufacturers and other businesses involved in TES are new market entrants (especially for PCMs, LAES).	• Cold chains need to be complete – the lack of a functional cold chain compounds issues. • Lack of reliable power infrastructure in developing countries is a driver for TES, so improving power infrastructure could reduce the value proposition of TES.
District heating and cooling	N/A	N/A	N/A	• Barriers including high upfront costs, perceived financial risk, resource-based constraints, the urban environment and existing incumbent network.
Buildings	N/A	• Cheap gas in many countries mean demand for thermal storage and renewable heat is low. • Cheap electricity means that demand for thermal storage (instead of using AC) for cooling is limited.	N/A	• Sunk costs in gas infrastructure may slow move to electrification of heat. • Heat pumps are still relatively scarce in European and North American developed countries where thermal demand is highest.

Note: N/A denotes no main needs were identified.

Table 15. Overview of policy interventions that are relevant to TES in each end-use sector

Application	Regulatory environment	Stakeholder acceptance	Technical performance	Financial proposition
Power	• Decarbonisation policies. • Regulation of heat market, as part of holistic multi-vector energy regulation. • Energy storage mandates.	• Funding demonstration and pilots in sensible storage, and for high-temperature cPCMs, to prove technology and commercial benefits to investors and other stakeholders.	• Funding R&D, demonstrations and pilots in sensible storage, and for high-temperature cPCMs, to accelerate technology readiness level.	• Funding R&D, demonstrations and enterprise support in sensible storage, and for high-temperature cPCMs, to drive cost reductions through innovation. • Market pull policies to drive adoption of TES with co-located storage.
Industry	• Ensuring decarbonisation policies do not exclude industry. • International co operation to overcome fears related to competitiveness. • Removing fossil fuel subsidies to help increase value proposition of TES.	• Government-led initiatives to demonstrate technologies with industrial participants. • Knowledge sharing and diffusion support using demonstrations and "champion" organisations to reduce perceived risk of technology adoption.	• Funding R&D, demonstrations and pilots particularly for chemical and latent storage, to accelerate development.	• Funding R&D, demonstrations and pilots particularly for chemical and latent storage, to drive cost reductions through innovation. • Providing investment support and price support as market pull options once technology has proven to help overcome financial barrier.
Cold chain	• Removing fossil fuel subsidies to help make cold chain technologies more competitive vs a diesel alternative.	• Provide knowledge-sharing support around latent storage demonstrations. • Enterprise support to help companies demonstrate and communicate benefits of TES to customers to help break into/create cold chain market	N/A	N/A
District heating and cooling	• Improve regulatory environment for district heating and cooling more generally. • Removing fossil fuel subsidies to help increase value proposition of TES.	• Provide knowledge-sharing support around latent storage demonstrations.	• Provide a range of technology push support for chemical and latent storage solutions. • Provide market pull support mechanisms for chemical storage solutions.	• TES helps decrease the LCOE for district heating and cooling. While the financial proposition of district heating and cooling can be improved further and benefit from market pull mechanisms, knowledge-sharing support can also increase awareness of the benefits of TES.
Buildings	• Removing fossil fuel subsidies to help increase value proposition of TES. • Integrated, regulated heat and power markets. • Energy storage mandates, building codes, etc.	• Provide ecosystem support to boost public awareness of benefits of TES for domestic applications.	N/A	• Technology push support to develop low-temperature PCM and salt hydration-based products. • Market pull support to incentivise domestic/ non-domestic consumers to purchase devices.

Note: N/A denotes no main needs were identified.

Application	Industry supply chain and skills	Market opportunities	Company maturity	Enabling infrastructure
Power	N/A	• Creating balancing markets, time-of-use tariffs, or other incentives, that recognise the value that periodic storage provides to the power sector. • Need for long-term storage revenue mechanisms like power purchase agreements to cover 24/7 demand profiles (*e.g.* Dubai, South Africa, Chile).	N/A	• Accelerating penetration of renewables will drive the need for flexibility solutions, such as TES.
Industry	N/A	• Creating balancing markets, time-of-use tariffs, or other incentives, that recognise the value that demand flexibility provides, and helps develop the value proposition for thermal storage (and on-site renewables).	• Technology certification/ recognition by trusted third party can reduce perceived risk.	• Accelerating penetration of solar thermal generation and heat pumps in industry.
Cold chain	• Support supply chain development (*e.g.* LAES).	N/A	• Enterprise support and ecosystem support can boost profile of new technologies such as LAES.	• Co ordination of LAES with LNG gasification infrastructure. • Development of LAES-based cold chain.
District heating and cooling	N/A	• Ecosystem support to highlight benefits of TES to renewable district energy projects.	N/A	• Accelerate penetration of renewably powered district heating and cooling schemes as part of integrated systems approach.
Buildings	N/A	N/A	N/A	• Support for development/penetration of heat pumps. • Ensure correct incentives in place for efficient management and adaptation of grids.

Note: N/A denotes no main needs were identified.

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6. TECHNICAL APPENDIX

6.1 Methodology behind technology selection for innovation outlook

As thermal storage technologies sit across a vast family of different types of technology, we developed a method to help focus the report on those most relevant for energy systems with a high share of renewables globally.

As a first step, we gathered a long list of 29 technologies from the literature across different types, readiness levels and applications. To help prioritise these to a core set of technologies for detailed analysis, we developed a prioritisation framework to draw up a short list. The framework was used to map the following attributes across the different technologies to help qualify the thermal energy storage (TES) technologies with the most impact:

- **TES type** – this broadly classified the technology into one of four groups: latent, sensible, chemical or coupled
- **Sub-category** – this identified a specific sub-group, such as redox or hydration/dehydration within chemical TES, to help further distinguish between them.
- **Technology readiness level (TRL)** – a standard TRL metric was used to identify the technical maturity of each TES technology (an addition metric of commercial readiness level was also used later in the study to identify development needs).

In addition to the basic attributes above, we developed four specific metrics to help capture how globally applicable these TES technologies might be for renewables integration to ensure the short list was broadly relevant to IRENA's membership countries. These were:

- **Versatility** – this is the ability of the TES to be able to fulfil multiple use cases within an energy system.
- **Replicability** – this is the ability of the TES to be used across multiple energy systems. Energy systems differ in the extent to which they are centralised/distributed, their market structures, their climate zone/geography, etc. As a result, some TES technologies might only have use to particular systems and so not be broadly applicable.
- **Additionality** – this was to capture the uniqueness of the TES technology in providing the particular services. It was used to capture the extent to which the TES can provide a unique solution to a problem that another form of energy storage cannot solve as cost-effectively or at all.
- **Industry focus** – this refers to the current state of attention the technology is receiving through private or public research or project funding.
- **Renewables integration** – we describe at a high level what the use cases this TES could support for renewables integration. To qualify this factor, we used the IEA's renewable energy integration challenges, such as variable output, uncertainty of output and geographical dependence. These were then analysed at a high level for each of the 29 technologies to determine if they offered solutions for one or more of these challenges that present barriers to high renewables penetration in energy systems globally.

In addition to the above, we also mapped at a high level where there was high potential for further innovation to reduce costs and improve performance, based on expert input from the University of Birmingham.

These factors above were mapped with either quantitative inputs (such as TRL) or red/amber/green (for versatility, replicability etc.) for each of the 29 technologies in the long list. Then prioritisation was undertaken to short list technologies based on the following:

- mid-range TRL and above
- medium–high level of interest from industry
- one or more use cases supporting renewable energy integration
- amber or above on average for global energy system applicability attributes
- medium–high potential for further innovation.

Using these filters, we then developed the final short list that consisted of 13 different technologies from the 29 in the long list. It is possible that there are other technologies that meet these criteria that have not been covered in detail in this report, but a detailed analysis of options was undertaken as outlined above to arrive at the list of focus technologies.

This section provides further technical detail on the technologies described in the report. Included is further detail on relevant system components, materials and configurations, as appropriate. The technologies are divided based upon the principle of operation underpinning their function:

1. Sensible heat storage.
2. Latent heat storage.
3. Thermochemical heat storage.
4. Mechanical-thermal coupled systems.

6.2 Sensible thermal storage

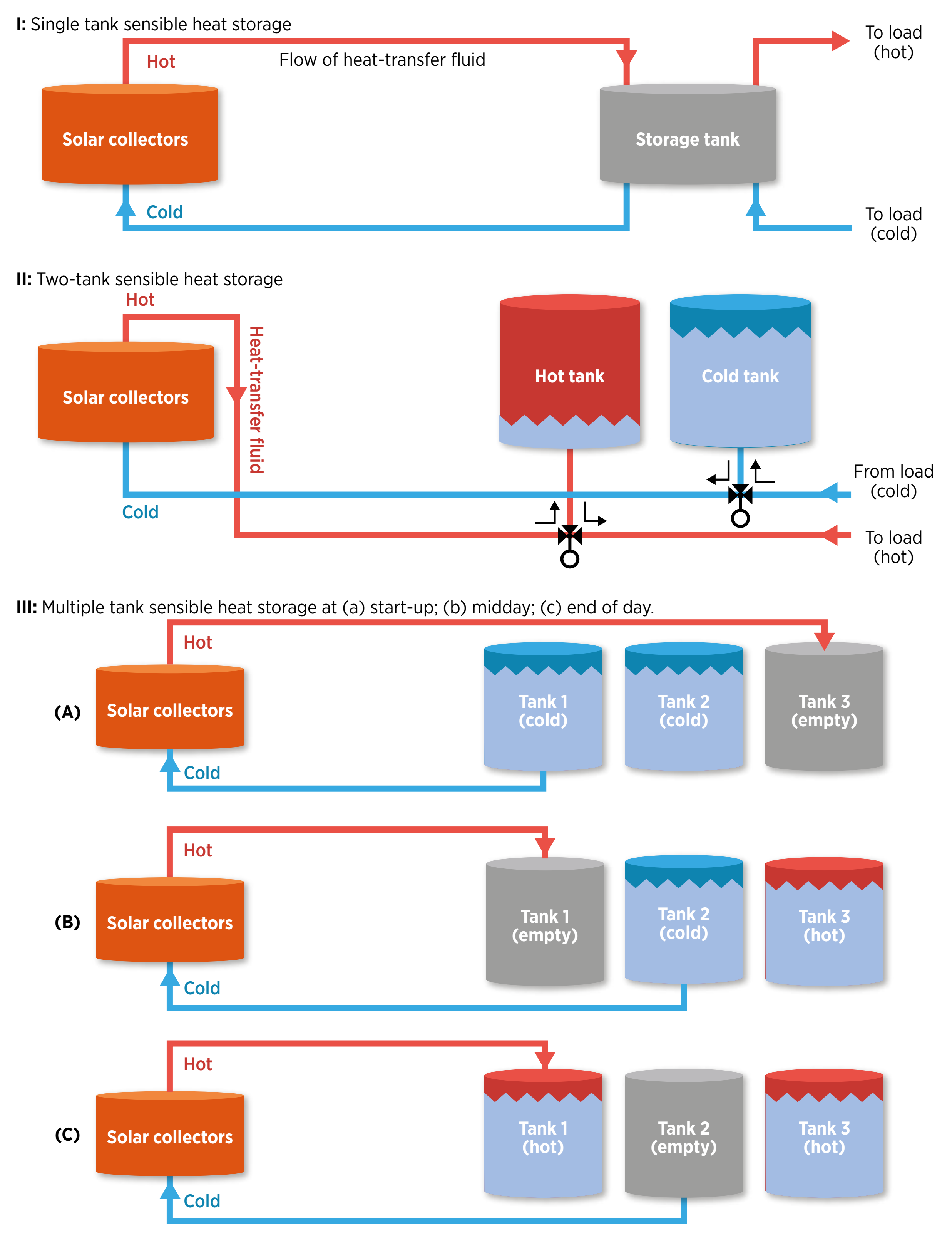
Sensible heat storage systems consist of a container for the storage medium and equipment for the charging and discharging processes. The type of container depends on the working temperature range, the chemical compatibility with the storage material and the effective thermal insulation needed, and constitutes an important element of the total TES system cost.

Tank thermal energy storage

In TTES, thermal energy is stored using a fluid, often water. Application-relevant aspects of TTES system configuration are highlighted here.

The tanks are highly scalable. Tanks with small volumes of a few litres combined with solar thermal heating can be used for small-scale residential applications. For large applications, (commercial, industrial and district heating), the tanks can scale up to millions of cubic metres, limited only by the space available. Different configurations can be used (single tank, two tanks and multiple tanks), as shown in Figure 48. One tank is the simplest form of storing thermal energy. Cold fluid contained in an insulated tank is heated, reaching an average temperature between the starting storage tank and the heat transfer fluid temperature. In a two-tank system, both tanks must have the capacity to hold all the fluid, so the total volume is twice the sensible material volume.

Figure 48. Different water tank configurations



Source: Stine and Geyer, 2001.

Solid state

Solid materials as sensible TES can be utilised from cryogenic temperatures up to 1000°C (Xu and Chung, 2000). Both natural and artificial substances have been studied as storage media, such as rocks, pebbles, concrete and ceramic bricks. For small-scale applications (domestic and commercial) ceramic bricks working at temperatures up to 700°C are used. The system components are: the heat storage material, high-performance insulation (to avoid heat losses) and a fan to drive heat from the storage medium to point of use. These systems are typically charged overnight, and have a smart control to manage the level and timing of charge/discharge processes.

Molten salts

The most common salts used are HITEC ternary salt (53% of potassium nitrate [KNO_3], 7% of sodium nitrate [$NaNO_3$], and 40% of sodium nitrite [$NaNO_2$]), and a binary salt mixture named "solar salt", composed by 60% of sodium nitrate ($NaNO_3$) and 40% of potassium nitrate (KNO_3) (European Association for Storage of Energy and European Energy Research Alliance, 2017a).

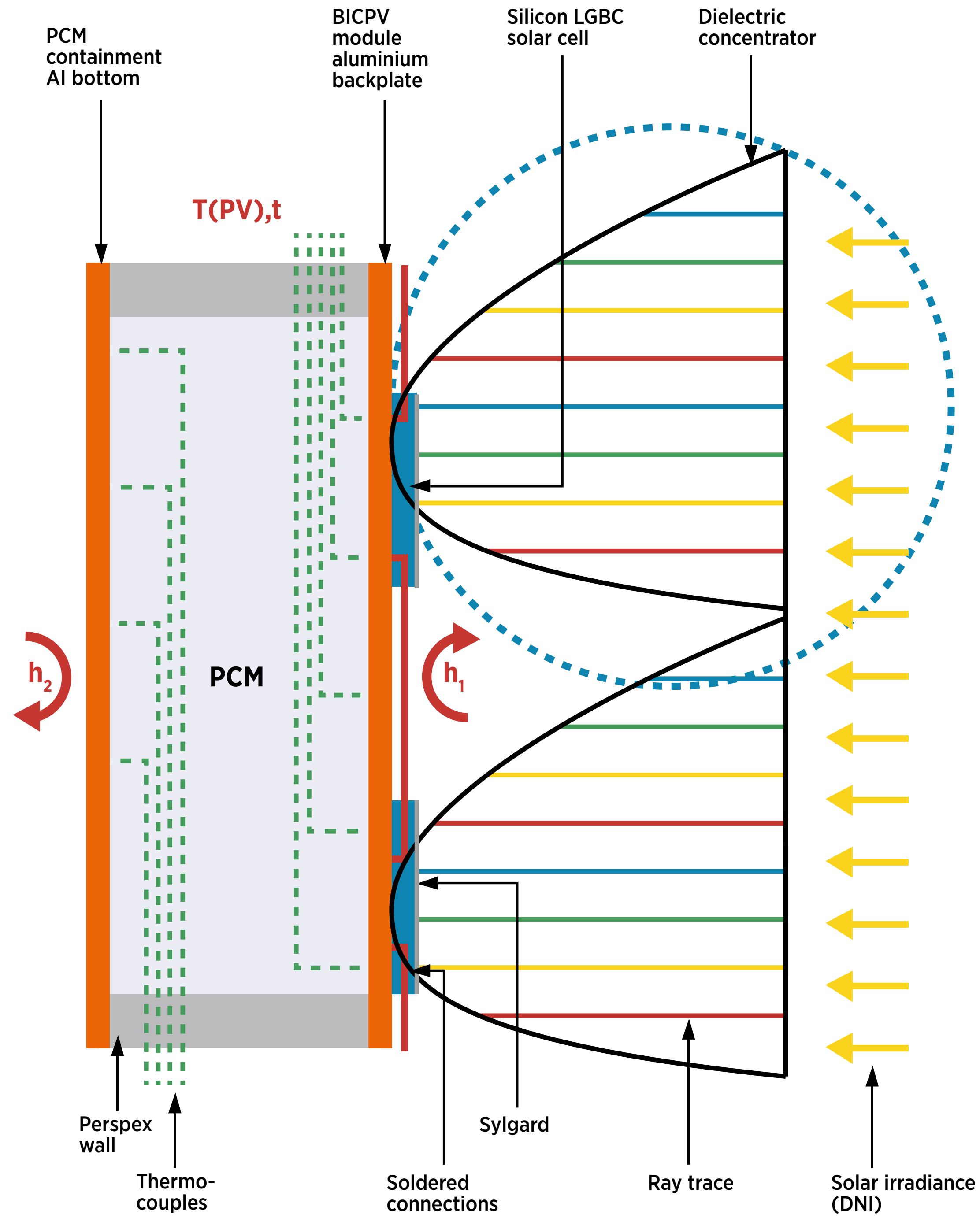
6.3 Latent thermal storage

Low-temperature phase-change materials

Several phase-change materials (PCMs) are in use with phase-change temperatures from 0 up to 120°C. As regards organic materials, paraffin is the most commonly used formed of wax at room temperature and chemically consisting of hydrocarbons with alkanes C_nH_{2n+2}. The melting point increases with the number of carbon (Fatih Demirbas, 2006). Laboratory-grade paraffin waxes, tetradecane and hexadecane and their binary mixtures are mainly used (Farid et al., 2004). As regards inorganic materials, salt hydrates such as strontium bromide ($SrBr_2.xH_2O$) have already been commercialised for domestic heating.

Encapsulation or using shape-stabilisation (prepared by PCM integration into supporting material and microencapsulating PCMs in shell) are the most common forms of paraffin used. Recently emerging integration of photovoltaic (PV) and PCM system concepts for temperature control offers an opportunity to extend its usage to building-integrated concentrated photovoltaic (BICPV) systems. Employing PCMs passively keeps the BICPV unit's temperature within a safe operating range and can also collect rejected heat for possible regeneration (Sharma et al., 2016) (see Figure 49).

Figure 49. Concept of a BICPV–paraffin system



Source: Sharma et al., 2016.

High-temperature composite phase-change materials

High-temperature composite PCMs (cPCMs) have working temperatures defined by their PCM melting point. For medium-temperature applications (working temperatures around traditional molten salts) and high-temperature applications (temperatures higher than the current concentrated solar power storage systems), binary and ternary mixtures of inorganic salts have been widely studied for thermal storage applications as heat transfer fluid (HTF) and TES materials. Nitrate, chloride and sulphate salts of alkali and alkaline metals, such as magnesium, potassium, lithium and calcium, are the main compounds used to produce medium temperature eutectic mixtures (Pereira da Cunha and Eames, 2016). Some composite material candidates proposed in the literature are shown in Table 16. Notable features of molten carbonates include their chemical stability, safety and optimal performance under a wide range of moderate (500 - 600°C) and moderate-to-high temperature (600 - 800°C) conditions, which makes them suitable for CSP applications.

6.4 Thermochemical heat storage

Chemical looping

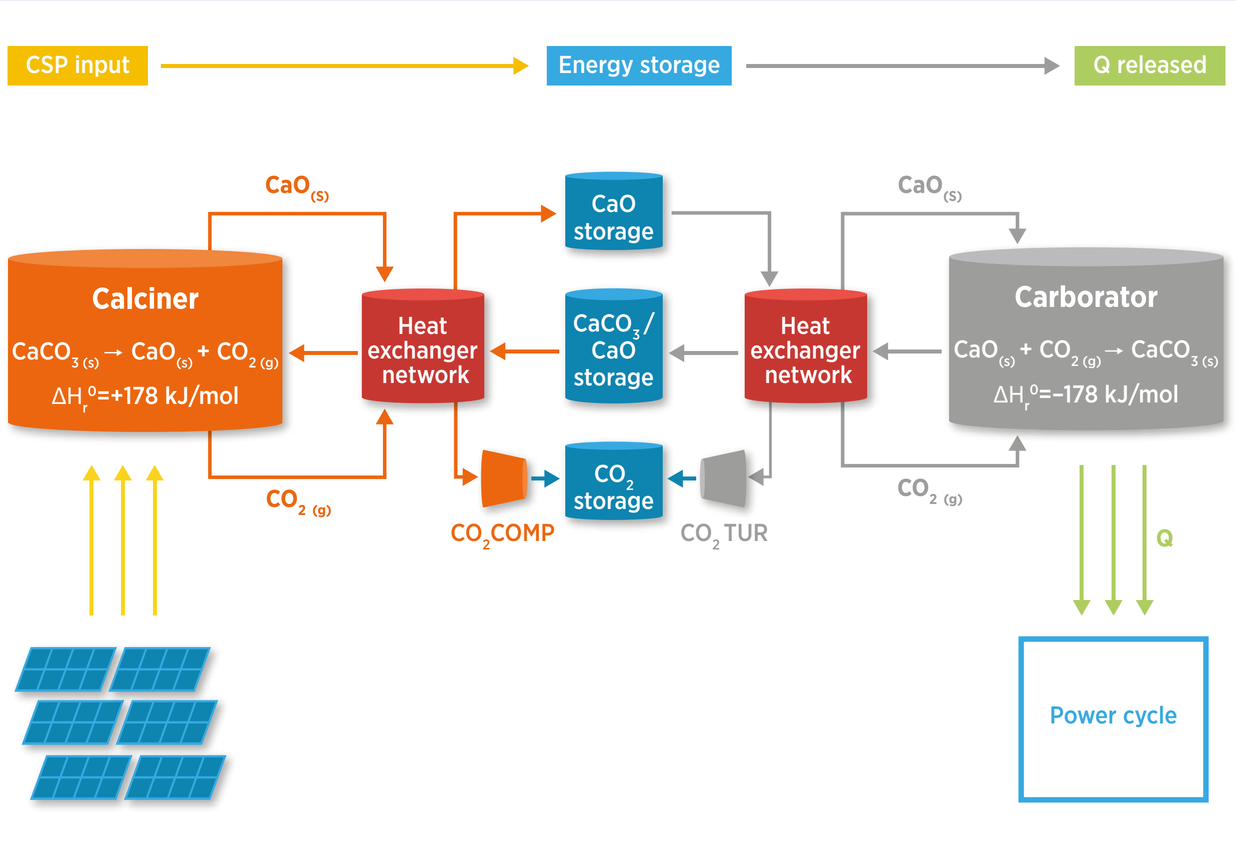
Integration of the calcium looping (CaL) process and CSP has been previously analysed by other authors considering several schemes. Tregambi et al. (2015) proposed a configuration where $CaCO_3$ calcination is assisted by CSP. Zhai et al. (2016) analysed several schemes in which CSP served to recover energy in the CO_2 capture system. Edwards and Materić (2012) studied a CSP-CaL integration in which the heat produced in the carbonator reactor is used for power generation through a CO_2/air open cycle. Muñoz-Antón et al. (2015) analysed the integration of a close-to-critical regenerative CO_2 Brayton cycle over a CSP power plant without storage, to achieve a higher cycle efficiency. Alovisio et al. (2017) explored several conceptual configurations to maximise the performance of the CSP-CaL integration, mainly focusing on power cycle integration in the carbonator zone. An example of CSP-CaL configuration is shown in Figure 50.

Table 16. Inorganic composites proposed in the scientific literature

PCM	Ceramic matrix	High thermal enhancers	Outcomes	Ref.
Eutectic carbonate ($LiNaCO_3$)	Microstructure of MgO	Natural graphite and carbon nanotubes	Thermal conductivity over 4.3 W/(m·K) and energy storage density over 530 kJ/kg	(Alonso et al., 2016)
Eutectic nitrates ($NaKNO_3$)	N/A	Expanded graphite	Thermal conductivity up to 51.5 W/(m·K) and energy density up to 80 kJ/kg.	(Giannuzzi et al., 2017)
Eutectic chlorides ($MgCl_2$-KCl)	N/A	Expanded graphite and graphite paper	Thermal conductivity: 12.7 W/(m·K) Energy density: 205 MJ/m^3	(Giannuzzi et al., 2017)

Note: N/A dennotes that no main needs were identified.

Figure 50. CSP-CaL integration for thermochemical energy storage



Source: Alovisio et al., 2017.

Salt hydrates sorption

The interest in using hydration reactions for heat storage application mainly focuses on the hygroscopic salts such as magnesium chloride ($MgCl_2$), sodium sulphide (Na_2S), strontium bromide ($SrBr_2$) and magnesium sulphate ($MgSO_4$) (Yu, Wang and Wang, 2013). The priority properties of thermochemical storage materials (TCMs) are high energy density, high sorbate uptake, low charging temperature and high thermal conductivity. The most promising TCMs and the projects where they have been studied are listed in Table 17. Magnesium sulphate has been the most assessed material by researchers (Paulik, Paulik and Arnold, 1981; van Essen, Zondag, et al., 2009; Ferchaud et al., 2014; Posern et al., 2015; Kallenberger et al., 2016) due to its high energy density and low cost. Nevertheless, most of the studies conclude that pure magnesium sulphate is quite difficult to use practically because of its low power density and poor cyclability.

Two different configuration systems can be used depending on the application requirements: closed and open systems (Figure 51). An open system exchanges mass and energy with the environment, and operates typically at ambient pressure (Ferchaud, 2016). Closed systems exchange only energy with the ambient environment, and are normally evacuated to enhance sorbate transport (van Essen et al., 2010). Depending on the storage media, the demand conditions and the system location, either an open or a closed system is selected. An open reactor can be more versatile compared to a closed system as it can be operated at atmospheric pressure. It also has a more compact system and more effective heat and mass transfer. Also, the energy efficiency of the open system has been reported to be 19% higher than the closed system (69% open system and 50% closed system) (Abedin and Rosen, 2012).

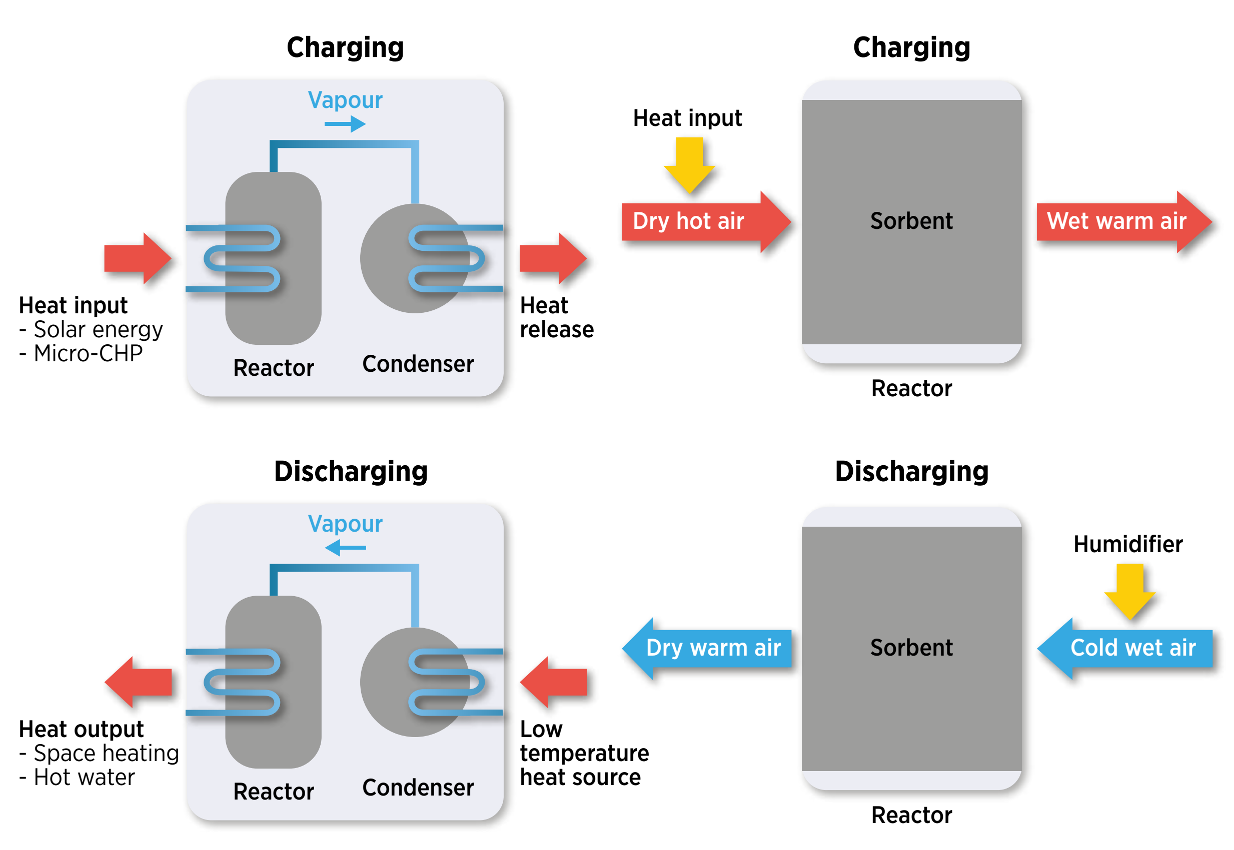
Table 17. TCM materials proposed by researchers for seasonal storage applications

Material	Theoretical energy density (kWh/m³) (Trausel, De Jong and Cuypers, 2014)	Prototype energy density (kWh/m³)	Charging temperature (°C)	Discharging temperature (°C)	Price (USD/1 000 kg) (Trausel, De Jong and Cuypers, 2014)	Research level (Fopah-Lele et al., 2016)	Projects
$MgSO_4 \cdot 7H_2O$	476	N/A	122-150	30	87	Reactor scale (lab scale)	N/A
$MgCl_2 \cdot 6H_2O$	750	140 (5 H_2O)	117	35	174	Reactor scale (prototype)	N/A
$CaCl_2 \cdot 6H_2O$	200	60	95	35	131	Reactor scale (theoretical study)	SOLAUTARK project
$SbBr_2 \cdot 6H_2O$	635	60	70-80	35	2 708	Reactor scale and prototype	PROMES, SOLUX prototype

Note: 1 EUR = 1.13 USD; N/A denotes that no main needs were identified.

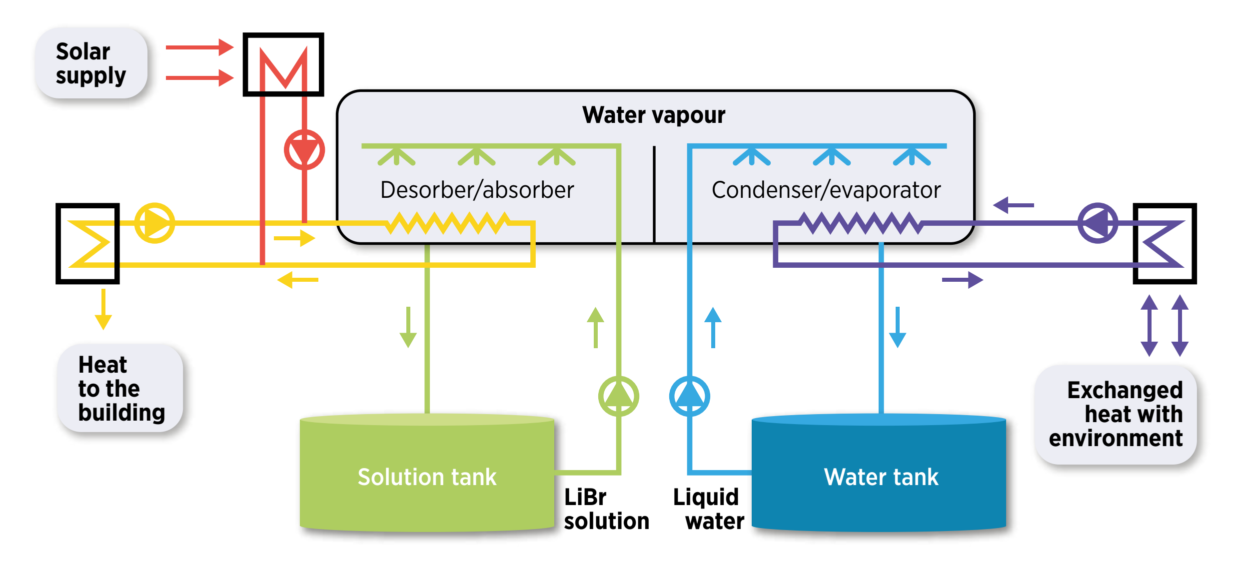
Source: van Essen, Cot Gores, et al., 2009.

Figure 51. Configuration of closed (a) and open system (b) for salt hydrates



Source: Lele, 2016.

Figure 52. Process configuration with separator reactor concept



Source: N'Tsoukpoe, Le Pierrès and Luo, 2013.

Absorption systems

In absorption systems, there is one loop for concentration solutions and diluted solutions and another loop solely for sorbate. These systems work by shifting the concentration of a solution from weak to strong, and vice versa, by absorbing and desorbing a sorbate. As shown in Figure 52, the strong solution becomes a weak solution after it absorbs the sorbate from the evaporator. The weak solution becomes strong solution after it evaporates the sorbate from the base solution and condenses in the condenser after being heated up in the generator (Lele, 2016).

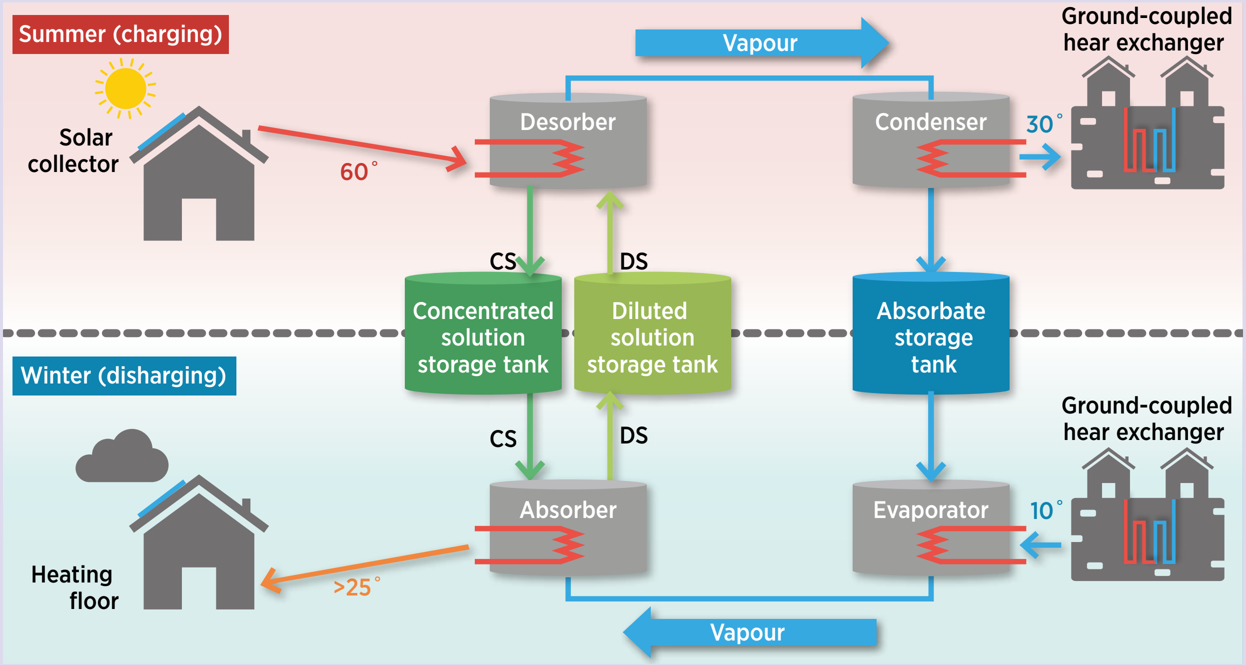
Performance of an absorption refrigeration system is critically dependent on the chemical and thermodynamic properties of the working fluid (Sarbu and Sebarchievici, 2013). The main requirements of absorbent/refrigerant combination are that they must have a margin of miscibility within the operating temperature range of the cycle, and the mixture should also be chemically stable, non-toxic, and non-explosive (Sarbu and Sebarchievici, 2013). Materials recently investigated include aqueous solutions of calcium chloride ($CaCl_2$), lithium chloride (LiCl), lithium bromide (LiBr), sodium hydroxide (NaOH), potassium hydroxide (KOH) and ammonia (Lele, 2016).

The most common working fluids are water/NH_3 and LiBr/water (Sarbu and Sebarchievici, 2013). For space conditioning and other requirements for chilling fluid temperatures of 40°C or higher, water/lithium bromide is the most common solution. For lower temperatures, ammonia/water is typically used. Many challenges do exist, such as crystallisation possibilities of the H_2O/LiBr pair and the difficulty in the separation of the NH_3/H_2O pair. Thus, the investigation of alternative solvents is still a relevant topic to increase adsorption rate, enhance efficiency (COP), decrease the temperature of the driving heat source and improve absorber performance by enhancing absorption rate (Ibrahim, Al-Sulaiman and Ani, 2018).

Absorption systems are composed of seven major components: a desorber and an absorber, a condenser and an evaporator, two solution storage tanks (diluted and concentrated solution) and an absorbate storage tank (Figure 53). The system operates in the charging mode when solar heat is available and in the discharging mode in heating demand periods.

Absorption systems can be used for multiple applications such air conditioning and refrigeration, and can be integrated with solar energy technologies for long-term solar thermal storage for buildings space heating. This is summarised in Figure 53 (N'Tsoukpoe, Le Pierrès and Luo, 2013).

Figure 53. Absorption storage system scheme



Notes: CS = concentrated solution; DS = diluted solution.

Source: N'Tsoukpoe, Le Pierrès and Luo, 2013.

6.5 Mechanical-thermal energy storage systems

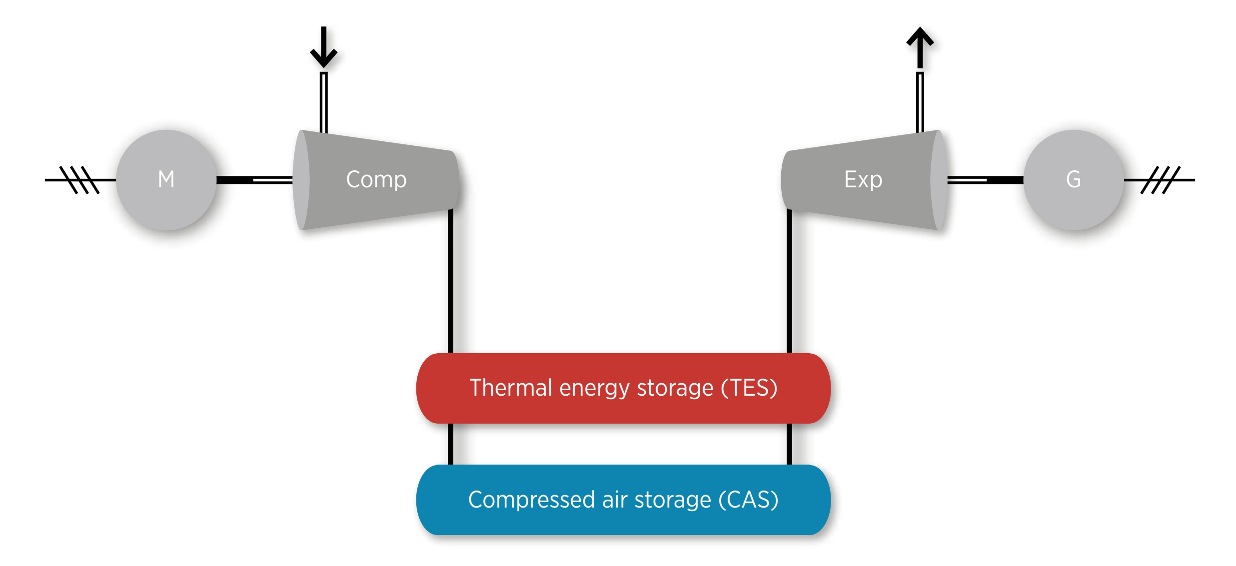
TES for adiabatic compressed air energy storage

Adiabatic compressed air energy storage (A-CAES) systems have been proposed to improve the overall efficiency of CAES by adding a high-temperature TES unit that stores compression heat, which would have otherwise been lost during the gas compression stage, for later use during the expansion process.

A-CAES can be broken down into three parts (see Figure 54), i.e. charge, storage and discharge. For charging, one or more electrical motors drive compressors to pressurise the air (> 75 bar). For storage, compressed air storage stores air at high pressure and TES stores the compression heat during the charging process. For discharge, an expender drives the electrical generator. TES could be installed inside compressed air storage to avoid the use of a high-pressure vessel, and this type of system is called advanced adiabatic compressed air energy storage (AA-CAES).

CAES operates as a battery that charges and discharges electricity. It can be scaled up easily; however, caves are normally used to reduce the cost of storage, so there are typically geographical limitations.

Figure 54. Adiabatic CAES with TES



Source: Yu, Wang and Wang, 2013.

TES for liquid air energy storage

Compared to CAES, liquid air energy storage (LAES) has higher energy density and no geographical limitation. The efficiency of LAES can be further improved up to 90% or higher by integration with a waste heat source (Li, 2011). LAES can be used as electrical energy storage to charge and discharge electricity. The liquid air can also be used as a fuel for engines and the cold energy can be used for refrigeration (Dearman Engine, n.d.).

For charging, an electric motor is connected to compressors for compression, and an expander is used for liquefaction. For discharging, a cryo-pump and evaporators are used for evaporation and heating, and air turbines are connected to a generator and driven by expansion. For storage, there is liquid air storage; cold storage; and heat storage (e.g. thermal oil and/or PCMs). Heat exchangers are used to transfer the cold and heat between compressed air and TES. For the systems that are integrated with waste heat from another process, it is not necessary to store the heat from compression for use in the discharging process.

Back up information for the executive summary

Upstream - From (supply) power sector perspective:

- Impact on the systems –demand, capacity/peak, load profile, grid investments.
- Flexibility – can these loads / technologies become a sources of flexibility? How?

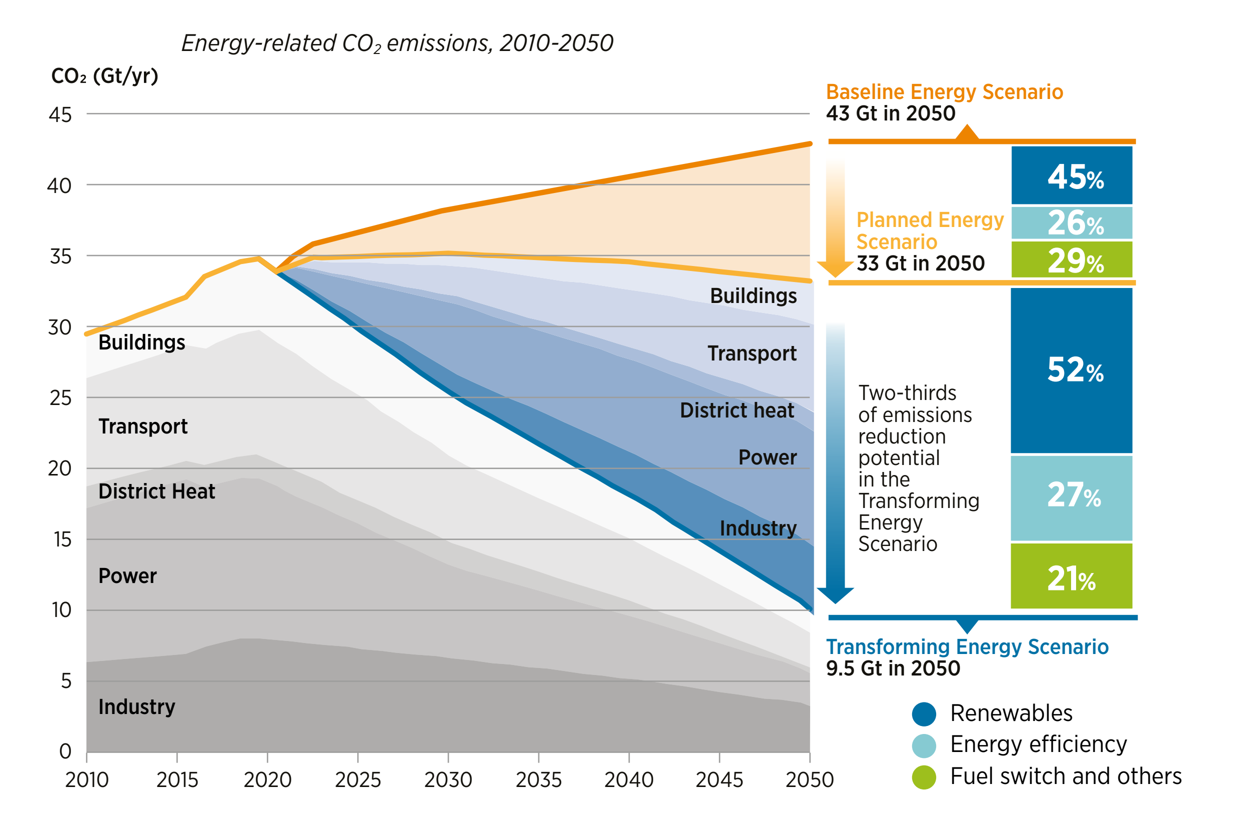
Downstream - From a (demand) coupling and service perspective:

- What infrastructure and other aspects need to be considered today for a successful electrification tomorrow?
- How to enhance the business case for each application? (systemic approach; *e.g.* ToU tariffs?)

Start with the role of TES:

- Provide flexibility to energy systems from a supply side perspective.
- Shape cooling and heating loads from a demand-side perspective.
- Enabler for sector coupling, electriricty, gas, heat cooling.

Figure 1 Appendix: Annual energy-related CO_2 emissions, 2010-2050 (Gt/yr)



Source: IRENA, 2020a.

- Short-term and long-term flexibility (from minutes to seasonal).

Energy systems globally are undergoing a significant transition driven by decarbonisation. The energy sector is responsible for a large share of global emissions, having less than 43 GT CO_2 per year. The power sector is here where the focus of decarbonisation efforts has taken place. However, decarbonisation of other sectors such as heating and cooling for buildings, industry, and district heating and cooling schemes is both critical and has seen less progress. According to IRENA projections, renewable power, considering storage systems, and electrification of end-use sectors can provide over 90% of the energy related CO_2 emission reduction required by 2050.

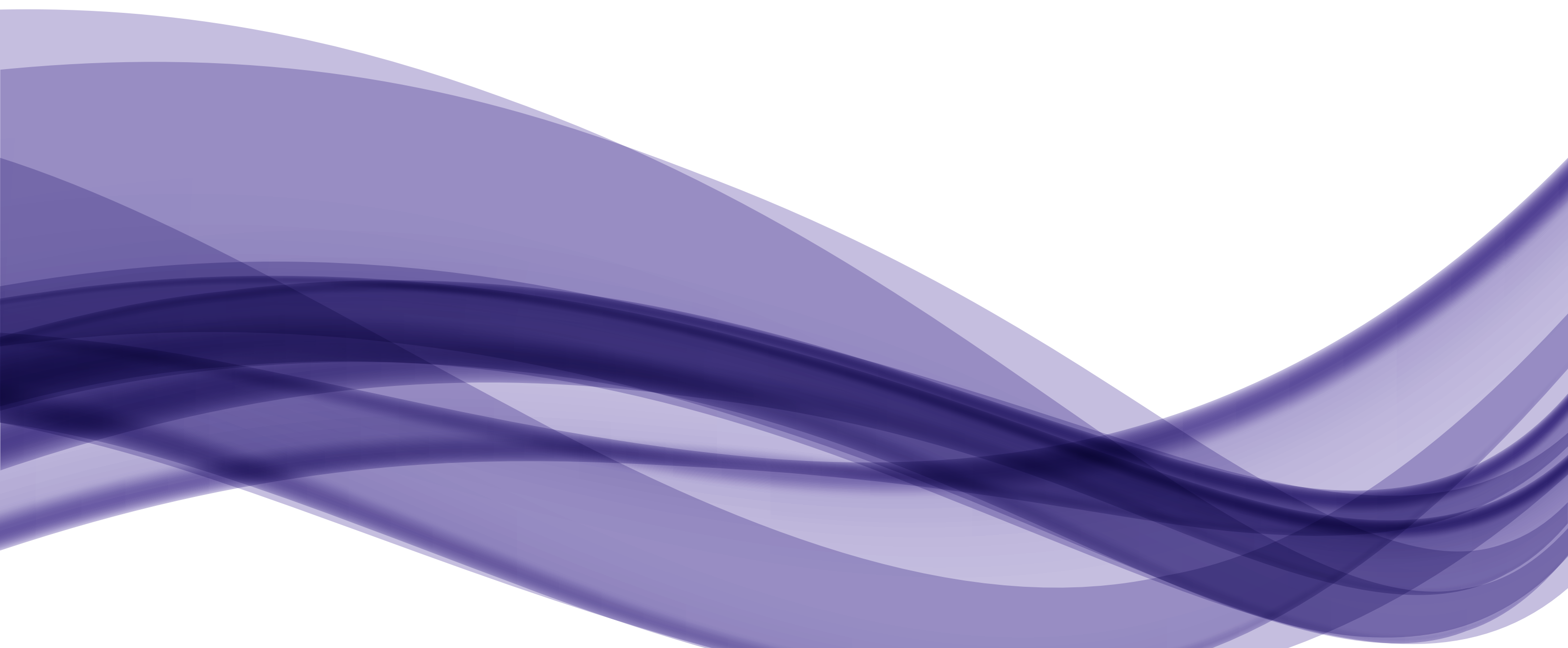
Furthermore, energy system flexibility is needed to deliver integration of renewables across all sectors, and energy storage is one of several key technological solutions to providing system flexibility by higher VRE integration enabling end-use sector integration, demand shifting, deferral of costly electricity infrastructure. Some storage technologies are also able to store their energy cost-effectively for long durations, making them suitable for seasonal storage.

Thermal storage technologies are broad in their technical characteristics, and their various qualities mean they can be applied to meet from hours to even months storage needs.

There are several thermal storage technologies and they are mainly categorised by the underlying physical principle of how the specific material stores and discharges energy. These different technologies also have different temperature ranges in which they can operate, all the way from sub-zero to greater than 500°C, and it is this operating temperature range which defines the applications they can be used in. This report studies 13 TES sub technologies and the value and benefits they can add to energy sectors.

Table 18. TES technologies and energy sectors

Integrating with renewable generation	**CSP** Sensible: Molten salt PCM: Inorganic salt composite TCS: Chemical looping	**Wind/PV** Coupled: CAES, LAES	**Solar thermal** Sensible: TTES, UTES TCS: Chemical looping, Salt hydrates, Absorption systems
Using at district level (large scale)	**District heating** Sensible: TTES, UTES PCM: inorganic salt composite TCS: chemical looping	**District cooling** Sensible: TTES, UTES PCM: Ice TCS: absorption system	**Industries** Sensible: Pebbles/ceramics bricks PCM: Inorganic salt composite TCS: Chemical looping, Salt hydrates
Using at consumer level (small scale)	**Cold chain transport** PCM: Ice, Eutectics Coupled: LAES	**Commercial** PCM: Ice, Eutectics, Paraffin TCS: Absorption systems	**Residential** Sensible: TTES, UTES, pebbles/ ceramics bricks PCM: Paraffin TCS: Salt hydration



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