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ECHO

EFFICIENT COMPACT MODULAR
THERMAL ENERGY STORAGE SYSTEM

D2.1 – State of the Art of TES in Europe

Project information

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Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
BHE	Borehole Heat Exchanger
CHP	Combined Heat and Power
COP	Coefficient of Performance
CIP	Common Interest Project
CTES	Chemical Thermal Energy Storage
DEC	Dissociative Evaporative Cooling
DCS	District Cooling System
EGD	European Green Deal
EfW	Energy from Waste
EU	European Union
ELP	Long-term strategy for the decarbonisation of the Spanish economy
GHG	Greenhouse Gases
GSHP	Ground Source Heat Pump
LSE	Electricity Sector Act 24/2013
LCCTE	Spanish Climate Change and Energy Transition Act 7/2021
LTES	Latent Thermal Energy Storage
NDC'S	National Determined Contributions
NIECP	National Integrated Energy and Climate Plan
PCM	Phase Change Material
SC	Spanish Constitution
STES	Sensible Thermal Energy Storage
STES	Sorption Thermal Energy Storage
SWOT	Strengths, Weaknesses, Opportunities, and Threats analysis
TCM	Thermochemical Material
TES	Thermal Energy Storage
TFEU	Treaty of Functioning of the European Union
TRL	Technology Readiness Level
TTES	Thermochemical Thermal Energy Storage
UNFCCC	United Nations Framework Convention on Climate Change

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1 Summary

Our shared planet faces a critical challenge due to our increasing energy demand, mainly sourced from fossil fuels. These resources are unevenly distributed globally, with a small portion of the population consuming the majority. Relying heavily on fossil fuels is depleting them rapidly, necessitating a shift toward sustainable energy use for the security of our resources. Concerns about climate change, evident in recent extreme weather events, emphasize the need for change. Thermal energy storage (TES) is a practical tool to address climate change by conserving energy and improving efficiency. Integrating it with local and renewable sources enhances their effectiveness. Despite proven efficiency and viability, widespread adoption requires collaboration with experts in the field. Educational initiatives are urgently needed to facilitate this transition.

Deliverable 2.1 of the ECHO project is prepared to address two important matters, including (a) analysis of state of the art in coupled storage system/renewable energy/HVAC&R applications and creation of a database with available solutions, energy system information in different countries, regulation and pricing, and (b) categorizing the need for TES in different contexts through the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis.

To accomplish the first target, the taxonomy of TES technologies was established, which is the basis for creating the dataset. In Appendix 1, this taxonomy, a scheme of the classification of different TES, organized by groups, is reported. Accordingly, a dynamic visualization platform using an online tool “Looker Studio” was provided to present TES technologies. Accessible at https://lookerstudio.google.com/reporting/1dd662a1-938f-4dd8-91a9-ef70ccdd72ab, users can filter data by TES type, application, temperature range, lifetime, efficiency, etc. The interface allows for seamless navigation and precise filtering. Users can select single or multiple items via dropdown menus, streamlining the search process for tailored insights. Regarding the second target of Deliverable 2.1, partners belonging to specific countries have been grouped and asked to complete an Excel file, which is a legal analysis on state of the art on TES in their countries (more information is presented in Appendix 2). The SWOT assessment reveals that each country showcases distinct strengths in energy policy and regulation, yet there exists untapped potential for advancement and cooperation. By addressing shared challenges and leveraging emerging trends in renewable energy and energy storage technologies, nations can collectively enhance their energy landscapes.

2 Thermal Energy Storage (TES)

2.1 Thermal Energy Storage Technologies

Within the contemporary landscape of energy systems, Thermal Energy Storage (TES) technologies assume a paramount role in mitigating the inherent intermittency of renewable energy sources. These technologies facilitate the capture and retention of surplus thermal energy generated during periods of heightened renewable energy production, subsequently releasing it during periods of diminished or absent energy generation. Diverse TES technologies exist, each meticulously designed to suit specific applications and operational demands. Prominent among these are sensible heat storage, which involves harnessing heat

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through changes in material temperature, latent heat storage that employs phase change materials for energy storage and release, thermochemical storage relying on reversible chemical reactions, and sorption TES, which involves the adsorption and desorption of gases on solid surfaces. Progress in these technologies is instrumental in achieving a sustainable and robust energy infrastructure.

2.2 Importance of Energy Storage

The pivotal role of energy storage in contemporary energy systems cannot be overstated. Serving as a linchpin, energy storage addresses the inherent variability and intermittency of renewable energy sources, such as solar and wind power. By storing excess energy during periods of abundance and releasing it during high-demand or low-generation periods, energy storage technologies contribute significantly to grid stability, reliability, and flexibility. Moreover, energy storage plays a vital role in facilitating the integration of renewable energy sources into existing power grids, fostering a transition towards a sustainable and low-carbon energy landscape. TES, though not a new technology, is gaining renewed attention in commercial and institutional buildings due to its various advantages. These benefits include lowering energy consumption and costs, reducing initial and maintenance expenses, allowing for smaller equipment sizes, providing more operational flexibility, improving indoor air quality, aiding in the conservation of fossil fuels by enhancing energy efficiency or substituting fuels, lowering emissions of pollutants or greenhouse gases, and enhancing the efficiency of equipment utilization. The multifaceted advantages underscore the growing reconsideration and increased utilization of TES in contemporary building applications [1,2].

2.3 Classification of TES Systems

The categorization of TES systems can be approached from multiple perspectives, including the nature of the storage medium, the storage process, and the intended application. Primary among these classifications is the one based on the storage medium, encompassing sensible heat storage, latent heat storage, thermochemical storage. Sensible heat storage involves the alteration of material temperature to store thermal energy, while latent heat storage leverages phase change materials for energy storage. Thermochemical storage relies on reversible chemical reactions, and sorption TES involves the adsorption and desorption of gases on solid surfaces. Another criterion for classification is based on the storage process, including sensible heat, latent heat, thermochemical, and sorption processes. Furthermore, categorization by application, such as residential, industrial, or grid-scale energy storage, provides a holistic understanding, aiding in the tailored application of TES solutions to diverse energy system requirements.

3 Latent Thermal Energy Storage (LTES)

3.1 Mechanism of LTES

The Mechanism of Latent Thermal Energy Storage (LTES) involves the strategic implementation of various storage mediums, such as Aqueous solutions (Salt hydrates), Ice, and Phase Change Materials (PCMs). It can be noted that all these materials are PCM, exploiting the same phase change mechanism. In the context of LTES, these materials act as phase change agents, enabling the storage and release of thermal energy during transitions between solid and liquid states. When surplus thermal energy is available, the Aqueous solution absorbs heat and undergoes a phase change from solid to liquid, effectively storing latent heat. Similarly, in the case of Ice, the material absorbs excess thermal energy during the phase change from solid to liquid.

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Phase Change Materials, a broad category that includes both Aqueous solutions and Ice, exhibit the ability to absorb and release substantial amounts of energy with minimal temperature change. During the discharge phase, when energy is required, these materials release stored energy as they solidify, undergoing the reverse phase change. This versatile mechanism of LTES, utilizing various storage mediums, offers an efficient and adaptable solution for addressing the intermittency of energy sources and optimizing energy utilization across diverse applications, such as solar thermal power plants and heating/cooling systems in buildings.

3.2 LTES Medium

3.2.1 Ice

Ice production techniques can be divided into two main groups namely "Dynamic" and "Static" systems. The produced ice can be used either directly or indirectly to cool down the product or system.

The direct usage generally remains within the food sector to cool down and keep refrigerated products such as fish, vegetables, meat, poultry etc. and indirect usage is generally utilized for the latent heat cooling effect for process cooling, such as ice storage, TES systems for air conditioning and process cooling as secondary cooling medium.

3.2.1.1 Static Ice Production Systems

This technique is probably the oldest in use. In principle, the ice formation and melting take place without any physical removal of the ice. The most common used techniques are as follows:

Ice on Coil:

Refrigerant or Glycol water solution at a temperature of between -4°C and -10°C is circulated within a serpentine coil, which is submerged in an insulated tank of water to form ice on it. The ice buildertank consists of a low-pressure air pump or paddle blade to agitate the system to achieve even distribution of ice melting and formation. The thickness of ice is measured by a sensor to control the operation. The relevant details can be seen in Figure 3-1.

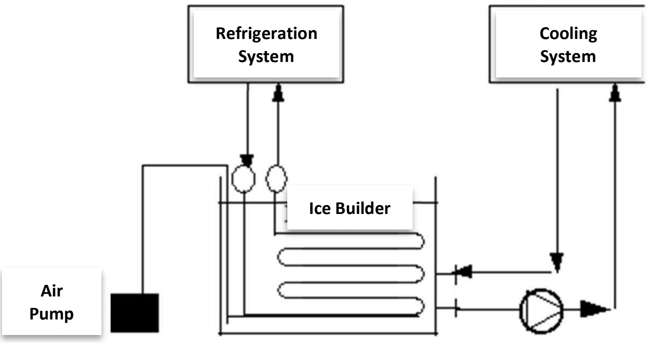

Figure 3-1: Ice builder concept [3].

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Ice Banks:

The ice bank consists of a pressurized, closely packed polyethylene tube heat exchanger. Low temperature glycol solution is circulated through the tubes, which freezes the water around them. The water in the insulated tank is almost frozen solid at the end of the charging cycle. The control of the system can be provided by the ice level sensor in the tank. The system water is circulated through the tank for both techniques, to satisfy the cooling demand (Figure 3-2).

The charging and discharging cycle can be controlled by water levels in an inventory tank, which is subject to level change due to ice expansion and contraction during the freezing and melting process respectively or byprocess fluid temperatures.

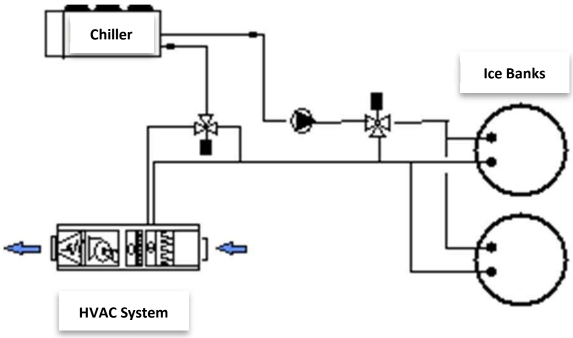

Figure 3-2: Ice bank systems encapsulated ice storage [3].

Encapsulated Ice Modules:

Encapsulated ice storage is a technique by which cool thermal energy is stored and released by means of the water (as PCM) being encapsulated using HDPE containments or small steel containers. The typical charging and discharging processes of encapsulated ice storage systems are depicted in Figure 3-3.

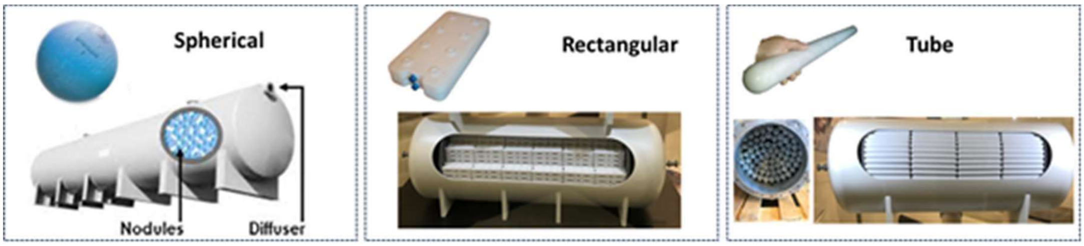

Figure 3-3: Encapsulated ice TES modules [3].

3.2.1.2 Dynamic Ice Production Systems

Ice is periodically harvested from the freezing apparatus to a storage bin and the stored energy is recovered by circulation of water through ice in the bin, to supply the chilled water system during normal operation. There are many commercially available systems in the market and the most common used systems are as follows:

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Ice Harvester:

Ice is built on a vertical surface which is the evaporator section of the refrigeration system. Water is circulated from the storage tank, over the plates until a certain thickness, normally in the region of 8-10 mm ice is formed. This freezing process takes approximately 20 minutes. The ice is harvested by means of hot-gas by-pass from the delivery port to the evaporator plates to warm the surface to about +5 °C, resulting in the ice in contact with the plates melting and falling into a sump or ice tank, to which chilled water from the system is circulated (Figure 3-4).

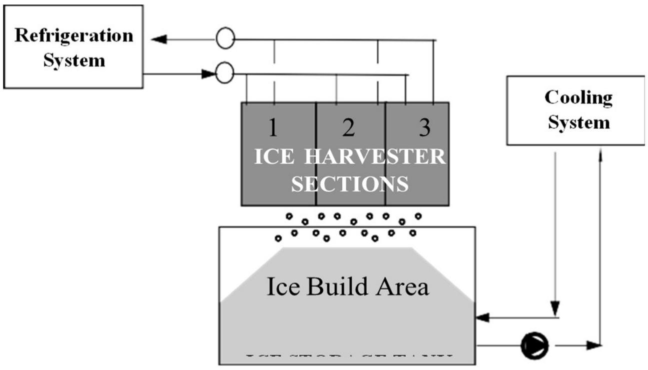

Figure 3-4: Ice harvester [3].

Tubular Ice:

In principle this technique is identical to the Ice Harvester system, the only difference being that the ice is produced within a tube rather than on the surface of plates. The storage and system applications are identical to the ice harvester techniques.

Ice Flakes:

A revolving freezing apparatus produces ice flakes continuously and the flake ice is collected at the bottom drum of the machine for later use, by means of circulating chilled water through the ice tank to satisfy the cooling demand.

Slurry Ice:

In this system a binary solution is cooled below its freezing temperature within a Falling Film, scraper, vacuum, or supercooling heat exchangers as illustrated in Figure 3-5. The refrigerant which is circulated outside the tube super cools the binary solution into millions of fine crystals which are then pumped into a storage tank for later use, or directly to satisfy the process load. During the cooling mode, warm solution is circulated through the storage tank where it is cooled by the crystallised solution and then pumped directly to satisfy the air conditioning chilled water circuit.

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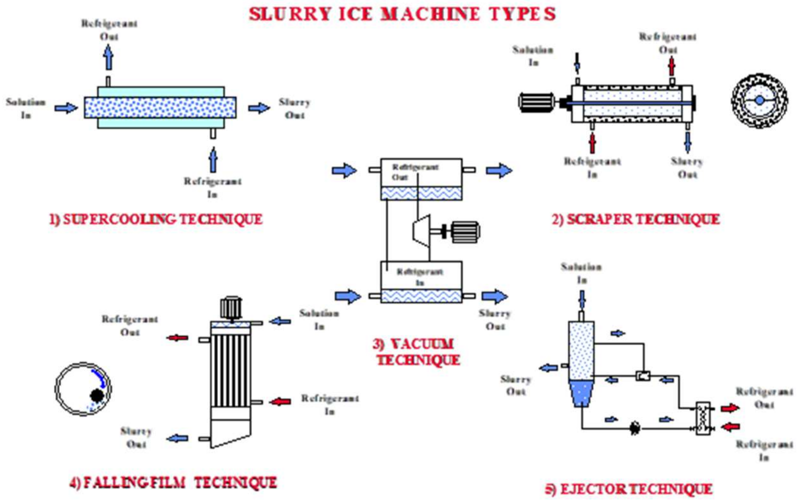

Figure 3-5: Slurry ice generator types [3].

3.2.2 Phase Change Material (PCM)

PCMs play a key role as versatile mediums in LTES systems, reshaping the landscape of energy storage technologies. These materials undergo phase transitions, maintaining a constant temperature, and exhibit a remarkable ability to absorb and release substantial thermal energy during these transitions. This feature makes PCMs particularly well-suited for applications where precise temperature control is paramount. PCMs find diverse applications, including in building construction for passive heating and cooling systems, solar TES, borehole TES, and electronic devices requiring accurate temperature regulation. The adaptability of PCMs to store and release energy within specific temperature ranges underscores their versatility across various industries. By providing a dependable and efficient means of storing thermal energy, PCMs contribute significantly to the advancement of sustainable and energy-efficient solutions, solidifying their significance in the dynamic realm of LTES systems.

The most used form of PCM exploits the heat of fusion between solid and liquid phases, although solid/solid and liquid/gas phase changes can also be used.

To be a useful PCM, a material must meet several criteria:

- Release and absorb large amounts of energy when freezing and melting.
- Have a fixed and clearly determined phase change temperature (freezing/melting point).
- Avoid excessive subcooling.
- Remain stable and unchanged over many freezing/melting cycles.
- Non-hazardous.
- Relatively unexpensive.

Aqueous solution (Salt hydrate)

Salt Hydrates are compounds of salt and water and have the advantage of high latent heat of fusion due to their high-water content. On the other hand, the salts create major disadvantages of life cycle in the form of

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phase segregation during the charging and discharging mode, which results in heavier salt settling at the bottom of the solution and consequently, the TES capacity of the solution changes. The process is progressive and irreversible.

Hydrated salts are inorganic salts that contact with water molecules and undergo a change in their crystalline structure. However, to better understand these salts, one needs to know the structure of hydrates, hydrous, and anhydrous compounds. Most aqueous salt based PCM solutions tend to either absorb moisture from the atmosphere (hygroscopic), or lose water through evaporation, and therefore they must be encapsulated in airtight/sealed containers.

In chemistry, a hydrate is a hydrated ionic compound that absorbs water molecules from its environment and contains them as part of its structure. The most known hydrates are crystalline solids. Crystalline solids lose their structure when the bound water is removed. Minerals like common table salt are crystalline solids.

In the simplest terms, a hydrous compound contains water in its structure. Hydrated salts are hydrous compounds since they have water within their crystals. The formation of hydrates occurs when ionic compounds are exposed to air and bond with water molecules. The bond happens between the cation molecule and the water molecule, making the remaining water known as the water of crystallization or water hydration.

Anhydrous compounds, on the other hand, have no water in their structure. When water is removed from a hydrate or hydrous compound, it turns into an anhydrate. The water in hydrates can be removed by either suction or heating the hydrous compound. Since Anhydrates remove water, they are mostly used in drying agents, such as paper products. They can also preserve the moisture in food and tobacco products. Commercially available hydrous & anhydrous PCM options are illustrated in Table 3-1: Aqueous PCM table [4].

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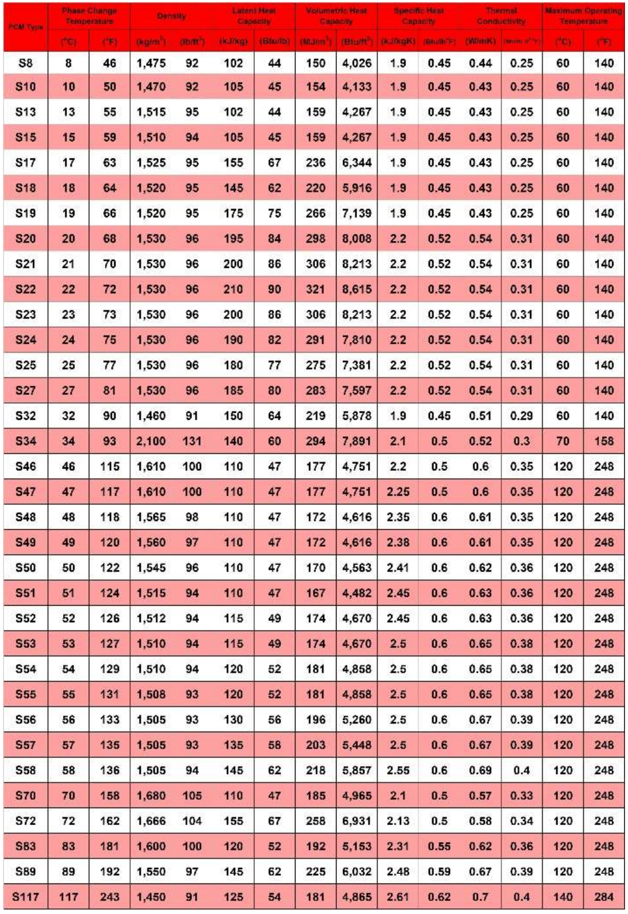
Table 3-1: Aqueous PCM table [4].



PCM Type	Phase Change Temperature		Density		Latent Heat Capacity		Volumetric Heat Capacity		Specific Heat Capacity		Thermal Conductivity		Maximum Operating Temperature	
	(°C)	(°F)	(kg/m^3)	(lb/ft^3)	(kJ/kg)	(Btu/lb)	(MJ/m^3)	(Btu/ft^3)	(kJ/kgK)	(Btu/lb°F)	(W/mK)	[illegible]	(°C)	(°F)
S8	8	46	1,475	92	102	44	150	4,026	1.9	0.45	0.44	0.25	60	140
S10	10	50	1,470	92	105	45	154	4,133	1.9	0.45	0.43	0.25	60	140
S13	13	55	1,515	95	102	44	159	4,267	1.9	0.45	0.43	0.25	60	140
S15	15	59	1,510	94	105	45	159	4,267	1.9	0.45	0.43	0.25	60	140
S17	17	63	1,525	95	155	67	236	6,344	1.9	0.45	0.43	0.25	60	140
S18	18	64	1,520	95	145	62	220	5,916	1.9	0.45	0.43	0.25	60	140
S19	19	66	1,520	95	175	75	266	7,139	1.9	0.45	0.43	0.25	60	140
S20	20	68	1,530	96	195	84	298	8,008	2.2	0.52	0.54	0.31	60	140
S21	21	70	1,530	96	200	86	306	8,213	2.2	0.52	0.54	0.31	60	140
S22	22	72	1,530	96	210	90	321	8,615	2.2	0.52	0.54	0.31	60	140
S23	23	73	1,530	96	200	86	306	8,213	2.2	0.52	0.54	0.31	60	140
S24	24	75	1,530	96	190	82	291	7,810	2.2	0.52	0.54	0.31	60	140
S25	25	77	1,530	96	180	77	275	7,381	2.2	0.52	0.54	0.31	60	140
S27	27	81	1,530	96	185	80	283	7,597	2.2	0.52	0.54	0.31	60	140
S32	32	90	1,460	91	150	64	219	5,878	1.9	0.45	0.51	0.29	60	140
S34	34	93	2,100	131	140	60	294	7,891	2.1	0.5	0.52	0.3	70	158
S46	46	115	1,610	100	110	47	177	4,751	2.2	0.5	0.6	0.35	120	248
S47	47	117	1,610	100	110	47	177	4,751	2.25	0.5	0.6	0.35	120	248
S48	48	118	1,565	98	110	47	172	4,616	2.35	0.6	0.61	0.35	120	248
S49	49	120	1,560	97	110	47	172	4,616	2.38	0.6	0.61	0.35	120	248
S50	50	122	1,545	96	110	47	170	4,563	2.41	0.6	0.62	0.36	120	248
S51	51	124	1,515	94	110	47	167	4,482	2.45	0.6	0.63	0.36	120	248
S52	52	126	1,512	94	115	49	174	4,670	2.45	0.6	0.63	0.36	120	248
S53	53	127	1,510	94	115	49	174	4,670	2.5	0.6	0.65	0.38	120	248
S54	54	129	1,510	94	120	52	181	4,858	2.5	0.6	0.65	0.38	120	248
S55	55	131	1,508	93	120	52	181	4,858	2.5	0.6	0.65	0.38	120	248
S56	56	133	1,505	93	130	56	196	5,260	2.5	0.6	0.67	0.39	120	248
S57	57	135	1,505	93	135	58	203	5,448	2.5	0.6	0.67	0.39	120	248
S58	58	136	1,505	94	145	62	218	5,857	2.55	0.6	0.69	0.4	120	248
S70	70	158	1,680	105	110	47	185	4,965	2.1	0.5	0.57	0.33	120	248
S72	72	162	1,666	104	155	67	258	6,931	2.13	0.5	0.58	0.34	120	248
S83	83	181	1,600	100	120	52	192	5,153	2.31	0.55	0.62	0.36	120	248
S89	89	192	1,550	97	145	62	225	6,032	2.48	0.59	0.67	0.39	120	248
S117	117	243	1,450	91	125	54	181	4,865	2.61	0.62	0.7	0.4	140	284

Eutectics are mixtures of two or more substances mixed in such a way as to provide the desired melting/freezing point. The mixture melts completely at the design temperature and has the overall composition in both liquid and solid phases which has the main criteria of a PCM.

Organics have low density and poor thermal conductivity. They are relatively expensive and flammable. The prime example is paraffin wax.

Clathrates (Gas Hydrates) are a mixture of chemical substances in which one chemical substance is bound inside another in a cage-like fashion. In practice, water forms the bonding structure for the clathrates for TES applications. The most commonly used clathrates are alternative refrigerants.

Solid-Solid PCMs that undergo a solid/solid phase transition with the associated absorption and release of large amounts of heat are the latest addition to PCM range. These materials change their crystalline structure from one lattice configuration to another at a fixed and well-defined temperature, and the transformation can involve latent heats comparable to the most effective solid/liquid PCMs.

Such materials are useful because, unlike solid/liquid PCMs, they do not require nucleation to prevent supercooling. Additionally, because it is a solid/solid phase change, there is no visible change in the appearance of the PCM (other than a slight expansion/contraction), and there are no problems associated with handling liquids, i.e., containment, potential leakage, etc.

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Molten-Salts; Most common material used for solar systems tends to be Molten nitrate salt (60% $NaNO_3$, 40% KNO_3), being used in commercial CSP plants around the world to provide gigawatt-hours of TES. It has a low vapor pressure, so it is not pressurized at typical storage temperatures up to ~600 ℃, and it can be pumped from one location to another.

Currently, the commercially available PCM range remains between 100 ℃ up to +1,200 ℃ as illustrated in Figure 3-6.

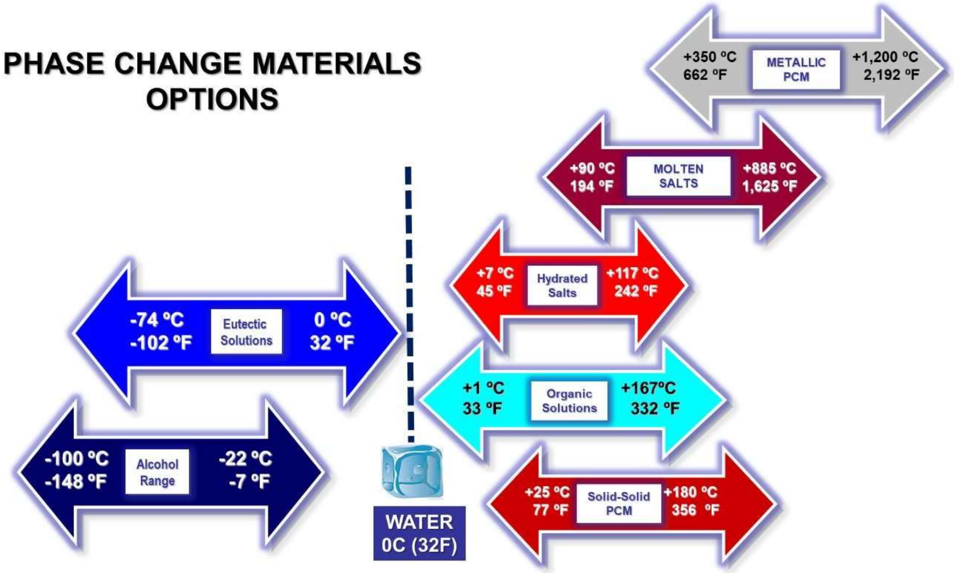

Figure 3-6: Commercially available PCM products [4].

PCMs can be broadly grouped into two categories: ***"Organic Compounds"*** (such as polyethylene glycol) and ***"Salt-based Products"*** (such as Glauber's salt). Each group of PCMs comes with advantages and disadvantages, some of which are listed in Table 3-2.

Table 3-2: PCM comparison.

Type	Advantages	Disadvantages
Organic	Simple to use Non-corrosive No supercooling No nucleating agent	Generally, more expensive Lower latent heat/density Often give quite broad melting range Can be flammable
Salt-Based	Generally cheap Good latent heat/density Well defined phase change temperature Non-flammable	Need careful preparation Need additives to stabilise for long term use Prone to supercooling Can be corrosive to some metals

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Encapsulated PCM Products:

Most aqueous salt based PCM solutions tend to either absorb moisture from the atmosphere (hygroscopic), or lose water through evaporation, and therefore they must be encapsulated in airtight/sealed containers. Although organic solutions can be exposed to air, as they are not water based, contamination and fire risk due to low flash point make it necessary for them to be encapsulated in airtight containers.

Salt based PCM solutions are corrosive and the most practical and economical method is to use plastic containers (Thermal Storage Presentation, CIBSE, 2008). However, plastic becomes soft at temperatures above 50 °C which restricts the application range to below +80~+90 °C levels.

As well as rigid plastic containers, a wide range of flexible pouches filled with various PCM solutions are produced, enabling a wide range of low-cost applications. Pouches are made using thin film and they offer good heat transfer efficiency. However, because they are prone to physical damage and puncture, some of the organic solutions are offered in powder, granule or even solid sheet forms which offer flexibility and safety.

Although plastic, and to a certain extent pouches, are economical, their heat transfer rate and/or limited temperature range restricts their wide scale use. To extend the temperature range or improve the heat transfer rate, metal containers have been extensively used for special applications.

Organic solutions are water free and can be modified in the form of dust, granules or even solid rubber forms, and they can be mixed with other products such as concrete, mortar, bricks, etc. They can also be thermoformed by simply mixing with plastic materials as part of the injection-molding process. Some of the typical encapsulation examples are illustrated in Figure 3-7.

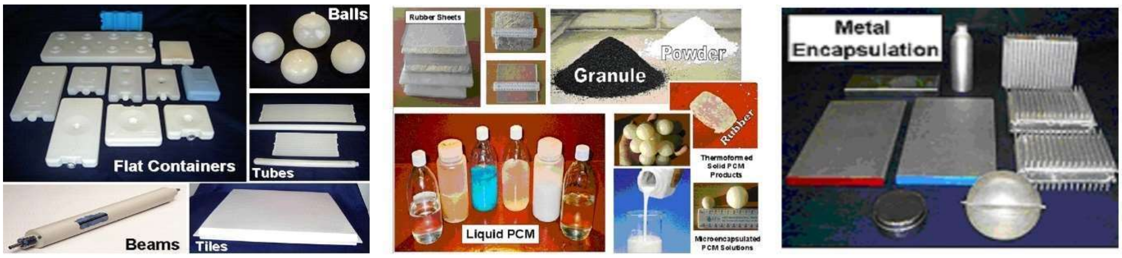

Figure 3-7: PCM encapsulation examples [5].

Organic PCM versions can be exposed to air as well as can be produced in various formats such as powder, granules or even thermoformed solid versions, as illustrated in Figure 3-8.

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Figure 3-8: PCM variations and application formats [5].

3.3 Case Studies

3.3.1 Building and HVAC Systems

Bergen Airport, T3 Energy Centre (Norway)

Most of the airports around the World stop flights over-night due to noise restriction. Therefore, the air conditioning loads are dramatically reduced. It is the case of Bergen Airport, T3 Energy Centre (Norway), where, by simply operating the installed cooling infrastructure (chillers) over- night, it is possible to build as much as 30~40% daily cooling loads by storing cold in PCM tanks. Hence, the number of chillers is reduced as much as by half by spreading the cooling load over 24 hours (Figure 3-9).

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Figure 3-9: Installed TES capacity 4 x 60 m^3 +13℃ PCM solution providing total 10,000 kWh [5].

Dekra HQ (Germany)

Office building with 62,000 m^2 floor area and high cooling demand TES application in Stuttgart / Germany is designed by Fraunhofer Institute for Solar Energy Systems ISE. Design is based on self-supply of electricity via combined heat and power (CHP), increasing renewables energies in the electrical grid and managing supply peaks and gaps with variation during the day by means of load peaks on the demand side. The electricity produced by CHP is utilized to run mechanical cooling to provide cold energy for A/C system. Surplus cooling is stored in PCM tanks, so no electricity is wasted (Figure 3-10).

Figure 3-10: Installed TES capacity 10 m^3 +15℃ PCM solution providing total 440 kWh [5].

NATIONAL THEATRE (UK)

The renovation of the National Theatre in London aimed for a significant reduction in CO$_2$ emission, and to that end it was decided to have a CHP system. Although this building houses the main shows, a fair bit of office element is also part of the building, which requires office hours building services such as water, electricity, cooling and heating all year round. On the other hand, shows take place outside of office hours, generally in the evening period. Electricity requirement is the main driving factor for the sizing and therefore 400 kWh CHP plant is installed. PCM tanks are charged using waste energy in the forms of either absorption chiller (if heat is wasted) or electric chillers (if electricity is wasted out of CHP). Then the stored cool energy is used to provide A/C for the theatre for 2~3 hours free of charge, using that waste energy (

Figure 3-11).

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Figure 3-11: Installed TES capacity, 8 storage tanks each with 8 m^3 +8℃ PCM solution providing total 2,000 kWh [5].

University of Bergen (Norway)

The renovation of the campus of Bergen University College was completed in 2014. This project covers 50.983 m^2 of occupied areas to supply 2.600 MWh heating and 1.060 MWh cooling on a yearly basis. The peak load of the system is 2.830 kW for heating load. 3.000 kW for cooling load is provided with the combined HP/chiller system complete with a PCM in order to handle the peak.

PCM cold storage is based on 47.000 encapsulated salt-hydrate PCM elements (freezing point 10 °C), forming the FlatICE® elements. The FlatICE® self-stacking elements (500 x 250 x 32 mm) are assembled within cylindrical tanks. The stacked FlatICE® containers form a shape similar to plate heat exchangers whereby the water is ideally flowing through the tanks and is passing in between the PCM elements providing extensive heat transfer surface area. There are four tanks providing a total volume of 228 m^3.

All four tanks yield a storage capacity of 12 MWh and this stored energy in return provides 1.600 kW cooling for 7 hours. The design is based on PCM storage covering the peak cooling load on a daily basis. Overnight while the heat pumps are providing heating for the student accommodation, the waste cooling energy is stored within the PCM storage and they are charged using this waste energy. During the day PCM-TES is integrated within the chilled-water distribution loop, the designed installed chiller cooling capacity was reduced by 53% (Figure 3-12).

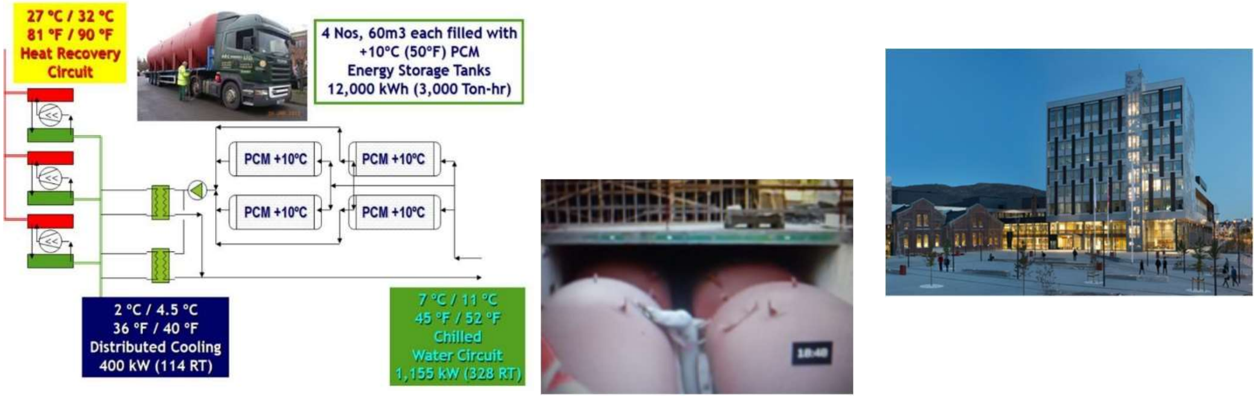

Figure 3-12: Installed TES capacity, 4 storage tanks each with 60 m^3 +10 ℃ PCM solution providing total 12,000 kWh [5].

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Norwegian University of Life Sciences (Norway)

TES bridges the time gap between energy requirement and energy use. This PCM-TES campus installation near Oslo (Norway) utilizes the installed infrastructure, and by spreading the load over a 24-hour period one can install half the number of mechanical cooling machines for the same peak loads. Like any other educational facility, the bulk of the peak load occurs once the buildings are occupied, but after office hours this large peak load subsides significantly. This campus PCM energy storage can be considered as a useful tool to spread the loads over 24 hours periods, thereby not only reducing the initial investment cost, but also offering reduced operational cost (Figure 3-13).

Figure 3-13: PCM-TES campus installation near Oslo, Norway [5].

Lusail Towers (Qatar)

Although the existing system installed in Lusail Towers in Qatar provides chilled water for the full loads of all four buildings all year round, it is essential to provide a backup system for the critical services, such as IT rooms, in case of any issues with the DCS (District Cooling Systems). During normal operation mode, +40 °C cold water provided by the DCS charges a total of 11 storage tanks, each with 18 m^3 (4,755 USG). The tanks are filled with +6.50 °C PCM encapsulated in 50 mm x 1 m long HDPE TubeICE® containers. A total of 198 m^3 TES tanks provide a stand-by cooling capacity of 7,920 kWh, giving enough time to the backup chillers to start and reach their full load operations without adding any pull-down loads of the main circuit, so the supply temperature for the cooling system is not affected. Under emergency it may take 15~30 minutes for the chillers to load and provide the full cooling capacity. It is vital to eliminate any additional thermal inertia and pull down loads from the chilled water pipework during the initial 15~30 minutes. PCM based TES absorb those short period cooling loads and effectively enable the chillers to catch up and provide vital emergency loads, without any impact on the chilled water supply temperatures (Figure 3-14).

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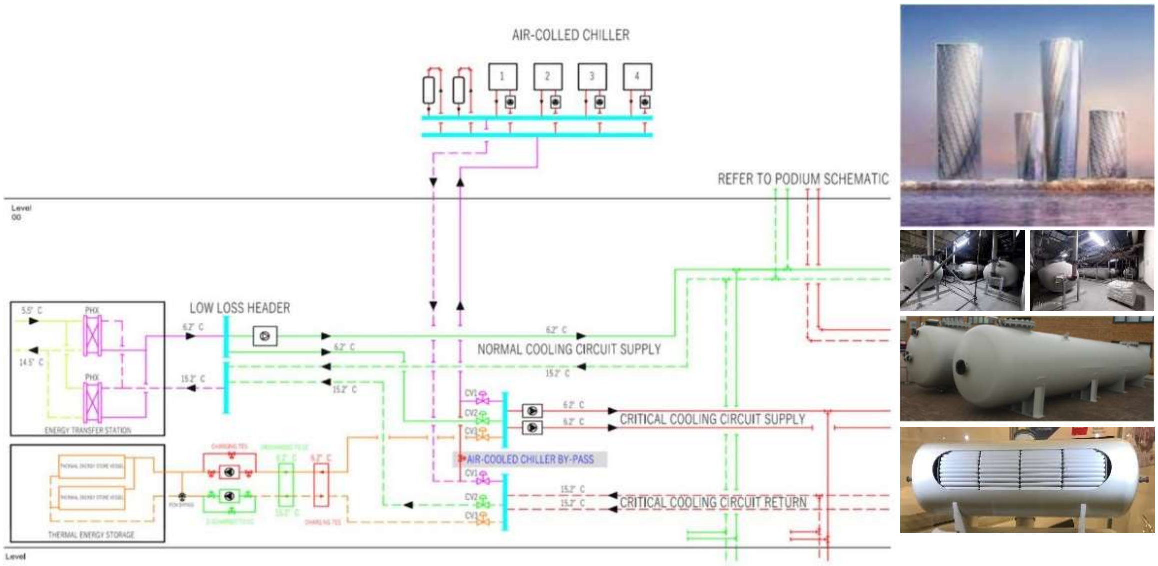

Figure 3-14: PCM-TES system installed in Qatar [5].

IT Room Back UP Passive Cooling Kits

Many high-rise buildings tend to turn off their air conditioning over weekends and holidays, if they contain banks/offices. On the other hand, IT rooms have lots of computers which would still be running over weekend / nighttime, and without any cooling they would over-heat and may shut down. To overcome this over-heating risk for individual clients in high-rise buildings, one can use an IT back- up PCM cooling module, which is charged during normal office hours utilizing the central cooling system and may provide up to 48 hours or more cooling over weekend without the need for central air conditioning system. Typical IT cooling back-up kits are illustrated in Figure 3-15.

Figure 3-15: Typical IT cooling back-up kits [5].

Sir John Laing Building Passive Cooling (UK)

Passive cooling takes advantage of the naturally occurring temperature swing between day and night. The excess coolth available at night can be stored in the PCM, which is then released during the day, absorbing

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internal and solar heat gains. Once the TubeICE® containers are filled with PCM, they weigh between 2~3 kg (4.4~6.6 lbs.) each depending on PCM type. By simply using standard 50 mm (2") pipe brackets, they can be suspended from the ceiling area to act like a heat absorbing sponge to soak up the rising heat within the enclosure.

Although it is possible to apply 12 TubeICE® per m^2 within the ceiling area, the practical limit for the passive cooling modules free area could be anywhere between 40~70% of the ceiling area since the same area is also used for other services. Using conventional bracket systems, it is possible to hang 12 TubeICE® containers per m^2 ceiling area and the overall total weight could be around 40 kg, and in return these tubes can provide anywhere between 1.7 ~2.2 kWh/m^2 energy depending on the PCM type (Figure 3-16).

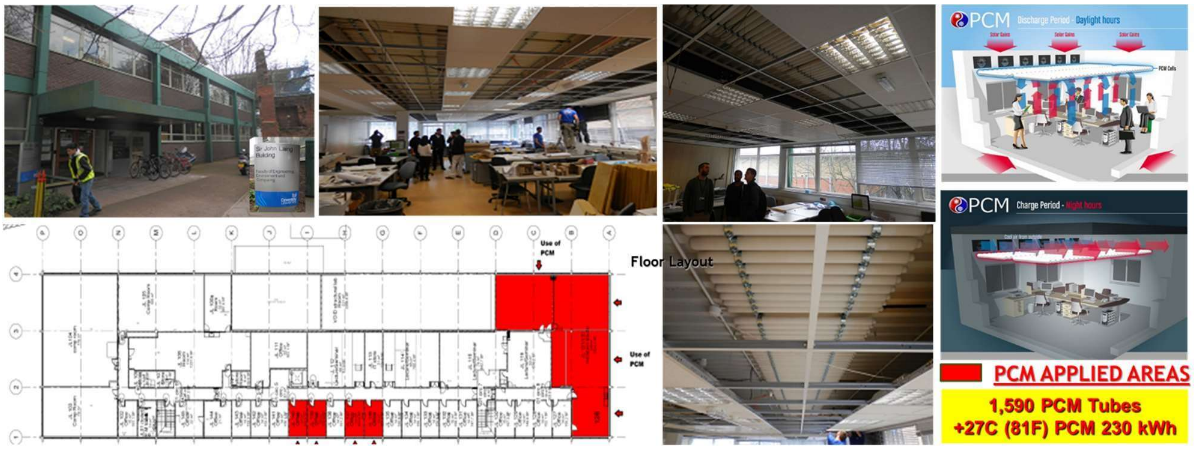

Figure 3-16: Sir John Laing building passive cooling in the UK [5].

Ventilated Roof Enhanced with PCM, Mock-up Building (Italy)

The combined application of two energy saving solutions, namely a ventilated roof and the use of PCMs, was investigated at the TekneHub Laboratory of the University of Ferrara (UNIFE). Two equivalent pitched ventilated roofs with an air gap of 4 cm and covering two identical rooms of a mock-up building were analysed (Figure 3-17). One roof was enhanced with a 0.007 m PCM layer suspended in the middle of the above sheathing ventilation (ASV) channel. A monitoring campaign under real conditions was conducted.

The structure is made by steel, and it is clad with sandwich panels both for exterior and interior walls. For what concerns the roof, which is 20° tilted with north-south oriented pitches, the steel beams are covered by a 0.03 m wooden deck and a waterproof polyolefin membrane upon which the tile supports were arranged. The two rooms set for the monitoring have both 0.04 m tiles supports, which formed the ASV, and the cladding layer made of Portoghese tiles. In one of the two roofs a 0.007 m layer of PCM in the middle of the air cavity was arranged. The layer consisted in 0.30 x 0.30 m^2 plastic containers filled in with about 0.42 kg of inorganic PCM with a melting point of about 25°C [6]. Thermophysical properties of the selected PCM are reported in Table 3-3, whilst the arrangement of PCM containers is depicted in Figure 3-17. Several sensors were installed to monitor the behaviour of the two configurations. A comprehensive and detailed description of the work is reported in Ref. [7].

Experimental results confirmed the effect of PCM in reducing peak temperatures as well as the incoming heat fluxes. Maximum temperature inside the ASV channel was reduced of up to 5°C during the hottest hours of the day, corresponding to a cut of 11.4%, while below the ASV channel and above the wooden deck the maximum temperature was 2°C lower during the day, corresponding to a reduction of 5.2%. It was up to 3°C higher during the night. Considering the incoming energy, PCM brought to an average reduction of 8% considering the whole day, that reached 15% during the hottest hours of the day. In terms of air velocity in the ASV channel, the velocity monitored below the PCM layer was the same as in the roof without PCM, while the velocity above the PCM layer was more than double.

Table 3-3: Thermophysical properties of the selected PCM.

Melting temperature °C	**Thickness** m	**Density** kg/m^3	**Latent heat** kJ/(kg·K)	**Specific heat** kJ/(kg·K)	**Thermal conductivity** W/(m·K)
25	0.007	600	100	1.80	0.60

Figure 3-17: Mock-up building (a); arrangement of PCM containers in the ASV layer of the roof (b).

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PCM Integrated Plasters, Mock-up Building (Italy)

The thermal performance of a lime-based plaster mixed with PCM granules and applied on building walls was investigated by UNIFE as potential energy refurbishment strategy. The aim was to reduce cooling energy consumption of existing – and especially historical – buildings in warm climates, like the Mediterranean one.

A monitoring activity under real conditions was carried out in collaboration with Fassa S.r.l. [8], an Italian industry leader in the production of mortars, premixed plasters, paints and thermal insulation.

An experimental set up which allowed to simultaneously monitor up to four wall samples was installed in the southern façade of an existing mock-up facility (Figure 3-18c) at the TekneHub Laboratory of UNIFE. Besides the reference sample without PCM, three different PCM configurations were examined: 10% by mass of PCM granules with a melting point of 27°C (identified as 10TK27), 10% and 30% with a melting point of 28°C (called 10AS28 and 30AS28, respectively). Thermophysical properties of the samples are reported in Table 3-4.

Each wall sample was 0.30 m x 0.30 m, and it consisted of a 0.03 m masonry tile layer covered by 0.03 m of plaster both on exterior as well as on the interior side. The wall samples were kept together by means of wooden frames and metal profiles, and they were provided with a 0.04 m insulation frame to limit the heat transfer on the edges, thus establishing a mono-dimensional heat transfer through the walls and preventing them from influencing each other (Figure 3-18a and Figure 3-18b).

Experimental results identified 10AS28 and 30AS28 as the most promising energy saving solutions. As regards 10AS28, results demonstrated that the total incoming energy during the day (9:00-20:00) was 10.6% less than the Reference when room temperature was higher than 25°C, 12.6% when room temperature was lower than 25°C and 9.9% in the critical interval 12:00-15:00. In terms of outdoor energy, on the other side, the average reduction is of 67.1%. Considering 30AS28, reductions are of 28.4% and 29.0% when room temperature was higher and lower than 25°C, respectively, of 42% in the interval 12:00-15:00 and of 95.6% in terms of outgoing energy.

Table 3-4: Thermophysical properties of the samples.

	Density kg/m^3	**Latent heat** kJ/(kg·K)	**Specific heat** kJ/(kg·K)	**Thermal conductivity** W/(m·K)
Reference	1646	-	895	0.31
10TK27	1365	14.5	1100	0.24
10AS28	1522	9.2	1100	0.28
30AS28	1321	27.6	1280	0.24

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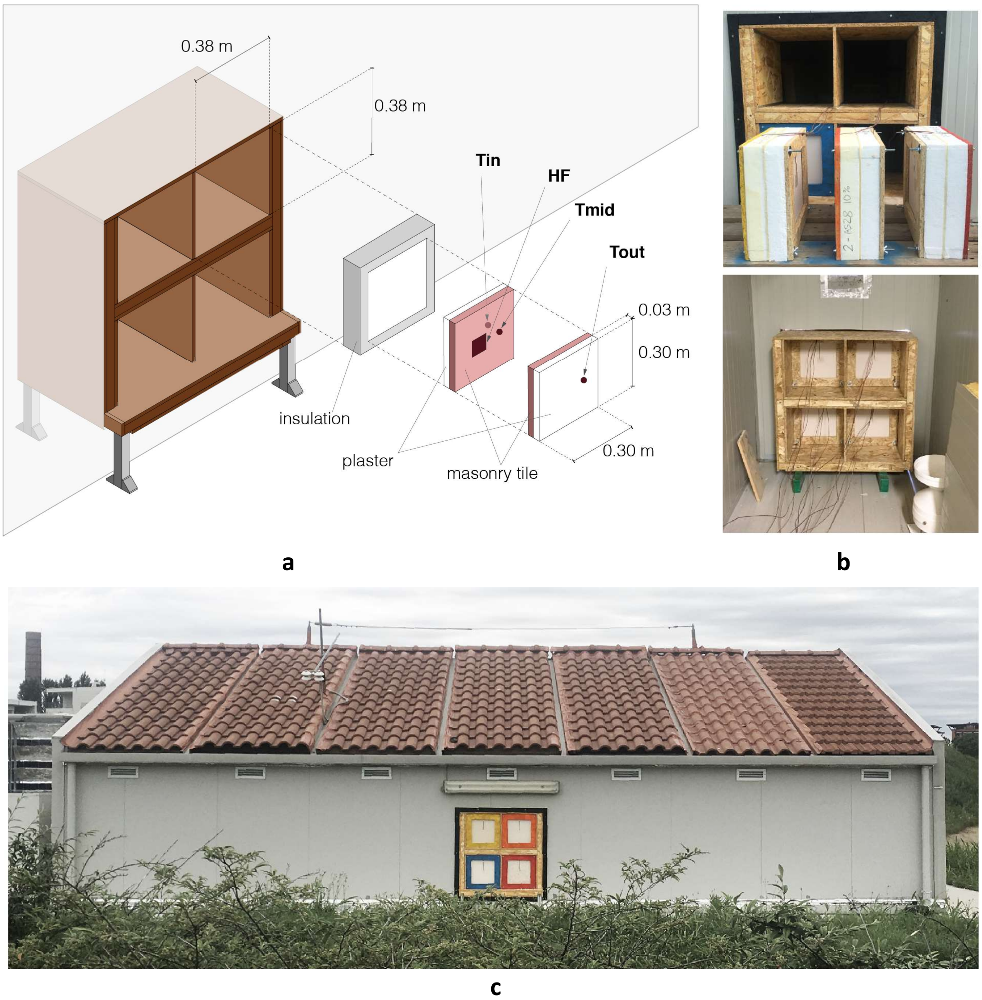

Figure 3-18: Axonometric scheme of the set-up (a), view of the samples (b) and installation in the mock-up building (c).

PCMs Enhanced Radiant Floor (Italy)

A hydronic radiant floor system enhanced with PCMs was experimentally investigated firstly at lab-scale, then at small-scale and finally at full-scale by UNIFE within the H2020 European project IDEAS [9]. Hydrated salts encapsulated in high-density polyethylene (HDPE) containers named ThinICE [10] – provided by PCM Products Ltd [11], partner of IDEAS project – were used.

Thermophysical properties of the selected PCMs [12] are reported in Table 3-5.

Table 3-5: Thermophysical properties of the selected PCMs.

PCM	Melting temperature °C	Density kg/m^3	Latent heat kJ/(kg·K)	Specific heat kJ/(kg·K)	Thermal conductivity W/(m·K)
S17	17	1525	155	1.90	0.43
S21	21	1530	220	2.20	0.54
S27	27	1530	185	2.20	0.54

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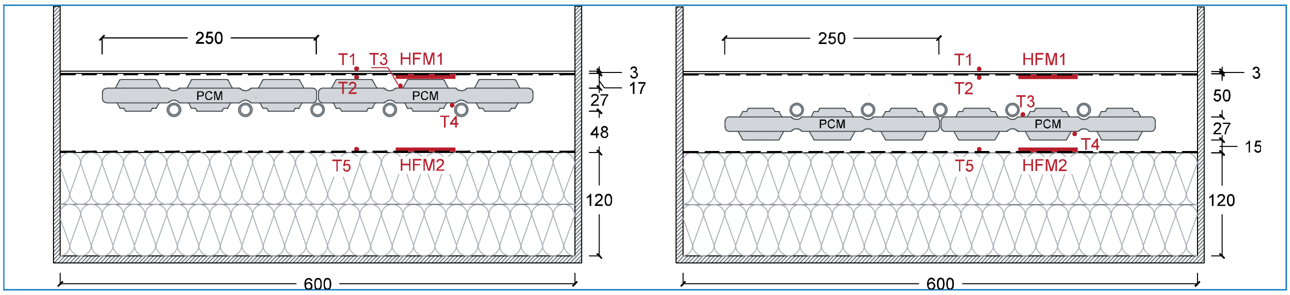
Laboratory-Scale Installation (Italy)

The impact of using dry and wet sand, as well as the effect of PCM positioned above or under heating pipes on the thermal performance of the system was investigated in heating mode through experimental tests carried out on lab-scale set-ups at the TekneHub Laboratory of UNIFE. Results were then used to calibrate a numerical model. A comprehensive and detailed description of the work is reported in Ref. [13].

The radiant floor structure consisted of 3 mm wooden finishing, 90 mm sand including piping in the middle and PCM containers placed above or under heating pipes, 120 mm insulation panel (Figure 3-19a and Figure 3-19b). 0.6 x 0.6 m lab-scale set-ups of the two different configurations were built (Figure 3-19c). Macro-encapsulated hydrated salts with a melting point of 27°C (identified as S27 in Table 3-5) were used and supply water temperature of 35°C was adopted.

Experimental results showed that the use of high thermal conduction in mortar, represented by wet sand, increased much faster the overall performance of the system in both the configurations examined. Indeed, taking into account the scenario with PCM installed above piping, it was found that heat flux in the wet sand conditions was 60% higher than in the dry sand when the system operated in steady state, and 100% higher than in dry sand when the transient mode was considered. Similarly, for the under-piping scenario, the use of wet sand allowed to achieve a heat flux through the floor surface 75% higher than the one reached by adopting dry sand. Moreover, the mean floor surface temperature for the wet sand conditions was almost 1°C higher than with dry sand.

As regards PCM position, the under-piping configuration significantly enhanced the positive effect of wet sand. Results demonstrated that the under-piping scenario achieved an increase of 75% in heat flux and a floor surface temperature 1.5°C higher compared to the system with PCM positioned above pipes. In addition, once the phase change process occurred in the containers, temperatures dropped down in 8 h rather than 6 h as it was for the above-piping scenario.



a b

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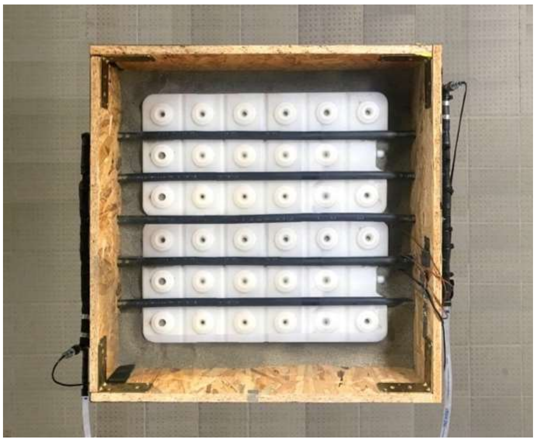

c

Figure 3-19: Radiant floor structure with PCM above (a) and under (b) piping; view of the lab-scale set-up (c).

Small-Scale Installation in Mock-Up (Italy)

The under-piping configuration experimentally investigated at lab-scale was further analysed through the installation of the small-scale IDEAS prototype (work package n.3, WP3 leader: UNIFE) in a mock-up building (10 m^2) located at the TekneHub laboratory of UNIFE.

The prototype included a multi-source water-to-water heat pump (HP, 5kW) which operated by means of two primary loops between two tanks (100 litres each one), the former on the source-side and the latter on the user-side. The system could exploit three different thermal sources (ground, sun and air) to optimise the temperature on the source-side for air-conditioning the spaces. The mock-up building consists of a central main room and two guard rooms, one adjacent on the east side and one adjacent on the west side to the main room (Figure 3-20a), having a conditioned volume of 26.00 m^3 and 6.24 m^3 (per guard room) respectively. All the zones had been already equipped with a fan coil, while the PCM integrated RF was installed in the main room in August 2020.

The radiant floor system provided both space heating and cooling and it was enhanced with ThinICE having a melting point of 27°C for the winter and 21°C for the summer period (identified as S27 and S21 in Table 3-5). The different containers were positioned to obtain three zones (which were separated by an insulation layer in order not to influence each other). The first zone on the north was made of 12 ThinICE filled with S27 and was addressed to evaluate the behaviour of a full winter solution (red area in Figure 3-20c). The second area on the south included 12 ThinICE filled with S21 and represented a full summer solution (blue area in Figure 3-20c). The last zone in the middle was composed of S27 ThinICE alternated to S21 ones, for a total of 15 PCM containers. The floor structure was composed of 7 mm laminate finishing (1) placed above a nylon sheet (2) covering the 60 mm wet sand layer (3 and 5), which included PCM containers (4). Wet sand was used so that the floor could be fully inspected. ThinICE were installed above a mortar layer (7) containing low-density polyethylene (LDPE) pipes with a pitch of 100 mm, external diameter of 16 mm and wall thickness 2 mm, positioned above expanded polystyrene (EPS) insulation (8) (Figure 3-20b and Figure 3-20c). Nylon sheets were also placed above the mortar layer (6) and under the EPS panel (9), and an underfloor mat (10) was laid over the existing sandwich panel. A comprehensive and detailed description of the work is reported in Ref. [14].

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Taking into account the cooling period, monitoring data highlighted that the PCM effect was not so relevant. However, for a proper interpretation of the results, the issues related to the starting of the prototype should be considered, i.e. the non-homogeneity of the slab, the very low performance of the building envelope and the short expertise in controlling the whole system. Results for the heating period showed that, after the installation of the insulation layer under the roof, the radiant floor was always able to ensure the setpoint temperature. However, due to its thermal inertia, overheating conditions occurred during sunny days. That is not referable to the concrete slab, but to the PCM which slowly reduced its heat flux. Nevertheless, this behaviour has not to be considered negatively, because it could be successfully exploited through a proper automation based on weather forecasts and cost of electricity, as developed in Ref [14]. Indeed, the system can benefit from a thermal inertia of around 12-18h, depending on outdoor temperature and solar radiation. Overall, the benefit of a thermal storage into the radiant floor allows a higher flexibility in the operating of the heat pump, which can be turned off/on for an interesting time length.

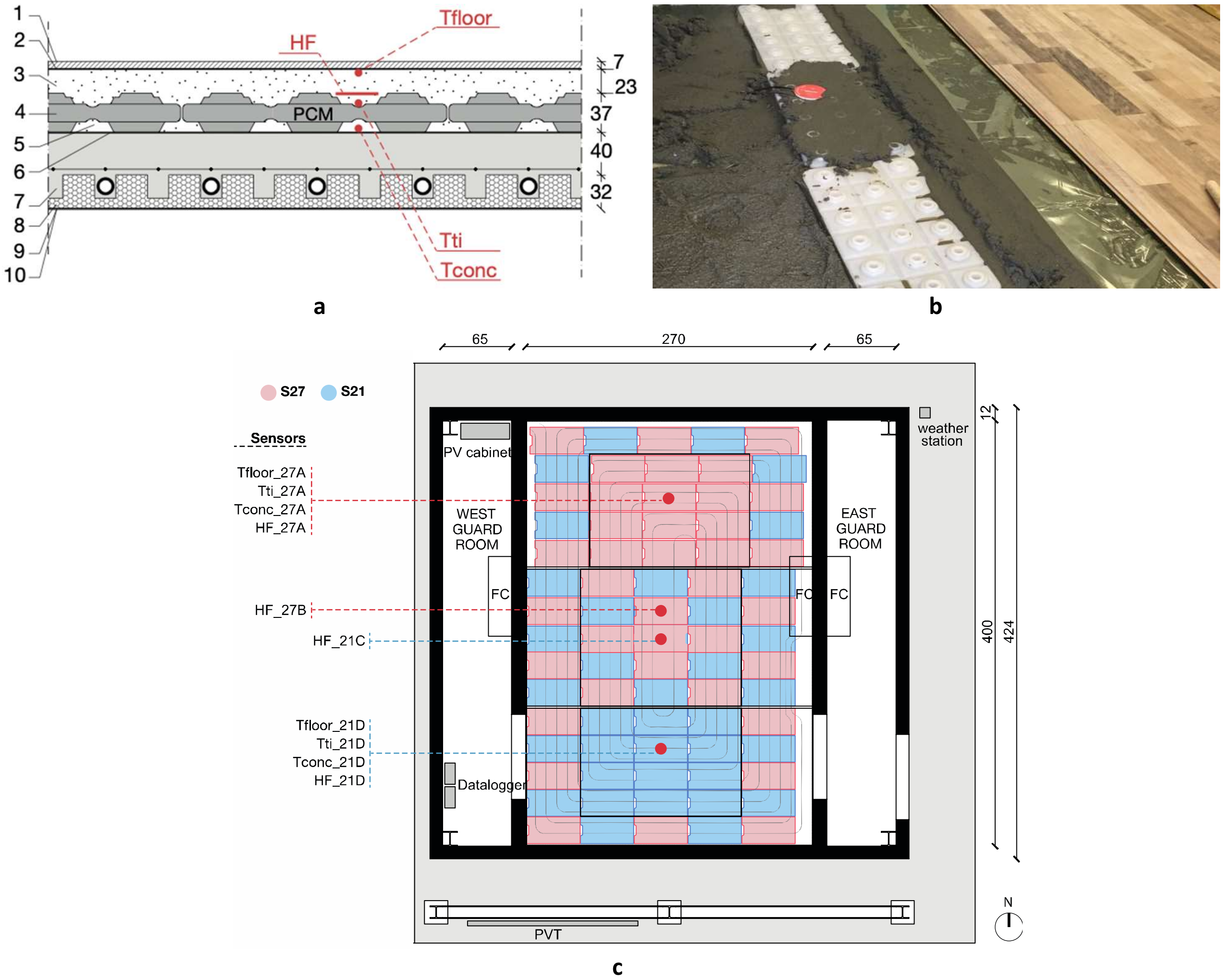

Figure 3-20: Radiant floor structure (a) and its installation (b); plan of the mock-up building with the distribution of PCM containers and sensors (c).

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Full-Scale Installation (Italy)

The final and optimised prototype of the PCM enhanced radiant floor system was then experimentally examined for the first time at full-scale within the work package n.5 of IDEAS project, focused on building demonstrators. Considering the Italian demo-case, the system was installed in the 100 m^2 snack-bar of the Department of Biomedical and Specialties Surgical Sciences of UNIFE, a vast academic complex. The space was equipped with an existing air handling unit (AHU) that was modified by integrating a new section connected to the IDEAS system, in order to be used individually or simultaneously with the novel radiant floor.

The radiant floor was composed of about 420 ThinICE with a melting temperature of 27 °C for the winter and likewise with a melting point of 17 °C for summer (identified as S27 and S17 in Table 3-5), which were positioned alternatively.

The installation required the demolition of the existing floor (20-22 cm) and the realisation of a new structure having the same overall thickness. Therefore, the coupling technology employed in the snack-bar represents a real example of renovation providing high thermal storage through the installation of PCMs in a particularly limited thickness due to existing structural constraints. The structure of the PCM enhanced radiant floor with the positioning of the sensors is illustrated in Figure 3-21a. The system is composed of a commercial vinyl flooring (1) installed over a 50 mm dry-set mortar (2). The mortar is characterised by high thermal conductivity and is improved with macro-synthetic fibre for screed reinforcement. Then, Ø16 x 2 mm piping (3) was installed above ThinICE (4) with a pitch of 80 mm (Figure 3-21d). ThinICE were positioned alternating S27 and S17 (Figure 3-21b) above a vapor barrier (5) covering a 40 mm high-density insulation panel (XPS300) (6). The panel was protected by a dump-proof membrane (7) placed between the insulation layer and an 80 mm concrete slab (8). The slab was improved with a waterproof additive and included a metal mesh. A plan of the snack-bar with the distribution of PCMs containers and the position of sensors is illustrated in Figure 3-21c.

Data showed that in summer thermal loads were absorbed by PCM during the day, thus achieving peak loads shaving and shifting. Indeed, in this way PCM reduced the cooling load to be covered by the AHU during peak price hours. Heat was then released in the night to maintain indoor temperature close to the setpoint. In winter, the radiant floor integrated with the AHU allowed to achieve 13% energy savings compared to the sole AHU. Indeed, PCM thermal storage allowed to keep AHU on for 70% less time and to maintain the setpoint temperature of 20 °C for 9 h after the switching off both the systems. Furthermore, taking into consideration the sole operation of the radiant floor, the system was able to maintain the setpoint temperature for almost 30 h after the switching off. Finally, in order to aid a proper interpretation of the achieved results, it should be considered the poor building envelope of the snack-bar where the application was conducted, which confirms the significant energy saving potential.

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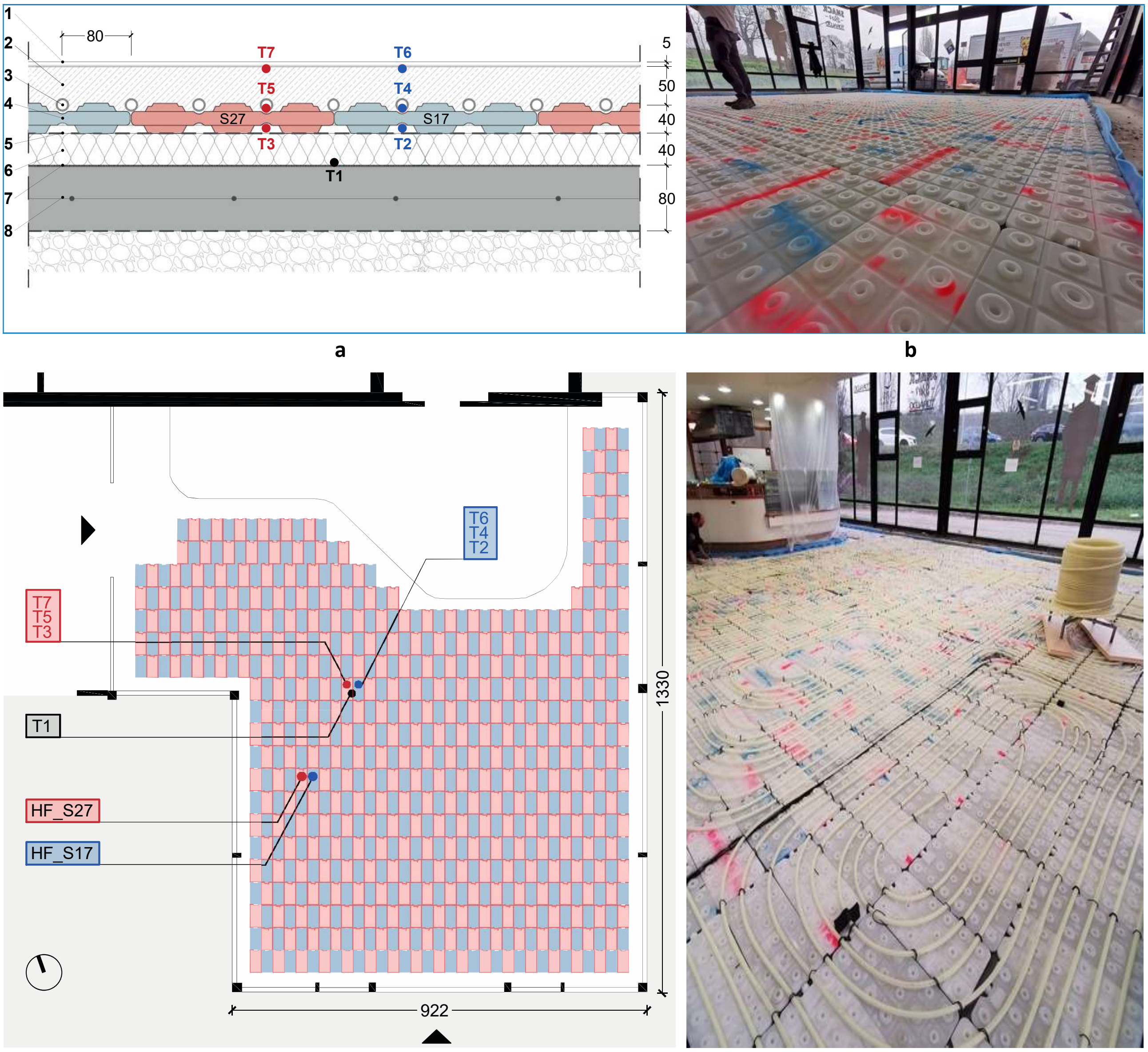

a b

c d

Figure 3-21: Radiant floor structure (a); ThinICE S27 (marked in red) alternated to ThinICE S17 (marked in blue) (b); plan of the demo-building with the distribution of PCM containers and sensors (c); Installation of the piping over PCMs (d).

Radiant Floor Mortar Integrated with PCM-Graphene (Italy)

The addition of PCMs into building materials represents a valid strategy towards the improvement of their thermal performance and therefore of the indoor comfort. However, when paraffin PCMs are used, the thermal conductivity of the mixture inevitably decreases due to the PCM low thermal conductivity. The thermal performance of a cement-based mortar enhanced with granular paraffin PCM, to improve its thermal

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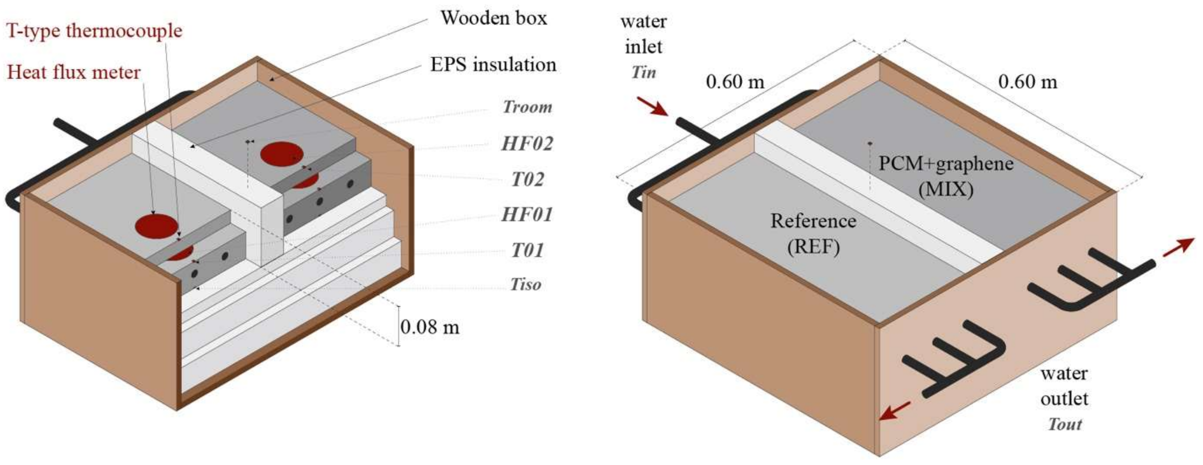
storage capacity, and integrated with hydrophobic graphene, to counterbalance the reduction in thermal conductivity, was investigated by UNIFE. Experimental tests at laboratory scale and numerical simulations were carried out to compare the behaviour of two equivalent radiant floor samples in terms of temperatures and heat fluxes.

An experimental set-up was built at the TekneHub Laboratory of UNIFE, and it consisted of a 0.6 m x 0.6 m wooden box containing two identical radiant floors divided one from the other by means of 0.06 m EPS, in which only the mortars were different (Figure 3-22). One was a reference cement-based mortar (called REF) while the other one was enhanced with 10% by mass of granular paraffin PCM and 0.2% by mass of hydrophobic graphene (called MIX). Each floor sample consisted of the following layers, starting from the bottom: 0.15 m EPS to limit as much as possible the downward heat flux, a waterproof sheet to protect the insulation layer from the wet mortar, 0.08 m of mortar in which 0.016 m polyethylene pipes were installed 0.025 m above the EPS at a distance of 0.08 m from one another. The distance between the pipes is not conventional since the experimental set-up realized in Ref. [13] was adapted for this research. A comprehensive and detailed description of the work is reported in Ref. [15].

Experimental as well as numerical results confirmed that the addition of PCM into mortars can increase its thermal capacity, and the effect are visible both on temperature and on heat flux. The addition of graphene can be seen in the velocity of the phase change which, in this case, could be identified in a melting/solidification range of only 1 K, which, compared to previous studies, is much narrower. During the first steady-state experimental test, the maximum temperature and heat flux reached in the MIX mortar at the equilibrium were 0.5 K and 15 W/m^2 lower than the REF one, while during the second unsteady-state test a more slowly decrease of the temperature was visible in the MIX mortar, which brought to a delay of more than 9h in reaching the equilibrium.



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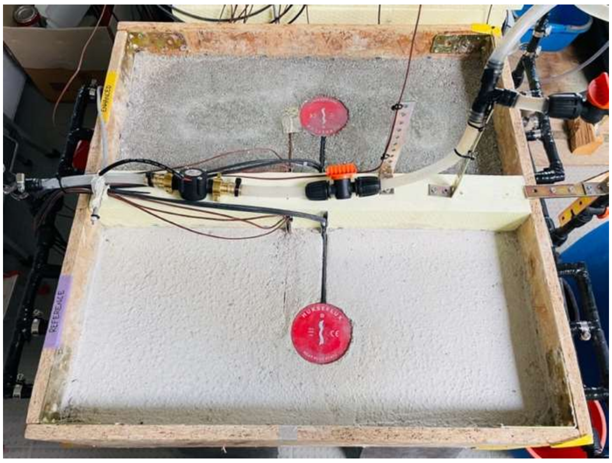

c

Figure 3-22: Experimental set-up: axonometric section (a) and axonometric view (b); reference mortar on the lower side, enhanced mortar on the upper side (c).

Water Storage Tank Enhanced with PCM-Graphene (Italy)

The thermal behaviour of a PCM-based latent heat storage enhanced with graphene oxide. The heat storage tank is composed of two PVC coaxial cylinders closed on both sides by PVC panels, and a smooth stainless-steel helical heat exchanger installed inside the smaller one at the TekneHub Laboratory of UNIFE (Figure 3-23). The coil is immersed in PCM, a commercial paraffin with a melting temperature of around 28 °C. The melting and solidification of the PCM were forced through hot or cold water flowing in the heat exchanger. The purpose is to explore the melting and solidification process by monitoring the temperature in the PCM with multiple thermocouples placed at different heights and different radial distances from the centre of the heat exchanger. Initially, the system was studied with pure paraffin. Then, two different mass percentages (i.e., 1.5% and 3%) of graphene oxide were added, whose high thermal conductivity had to counterbalance the paraffin low thermal conductivity and thus enhance the overall performance of the system. These three configurations were then compared to a reference scenario, consisting of the inner cylinder filled with pure water. The use of graphene oxide has increased the heat flux by up to 24% during heating and up to 31% during cooling compared to the pure PCM.

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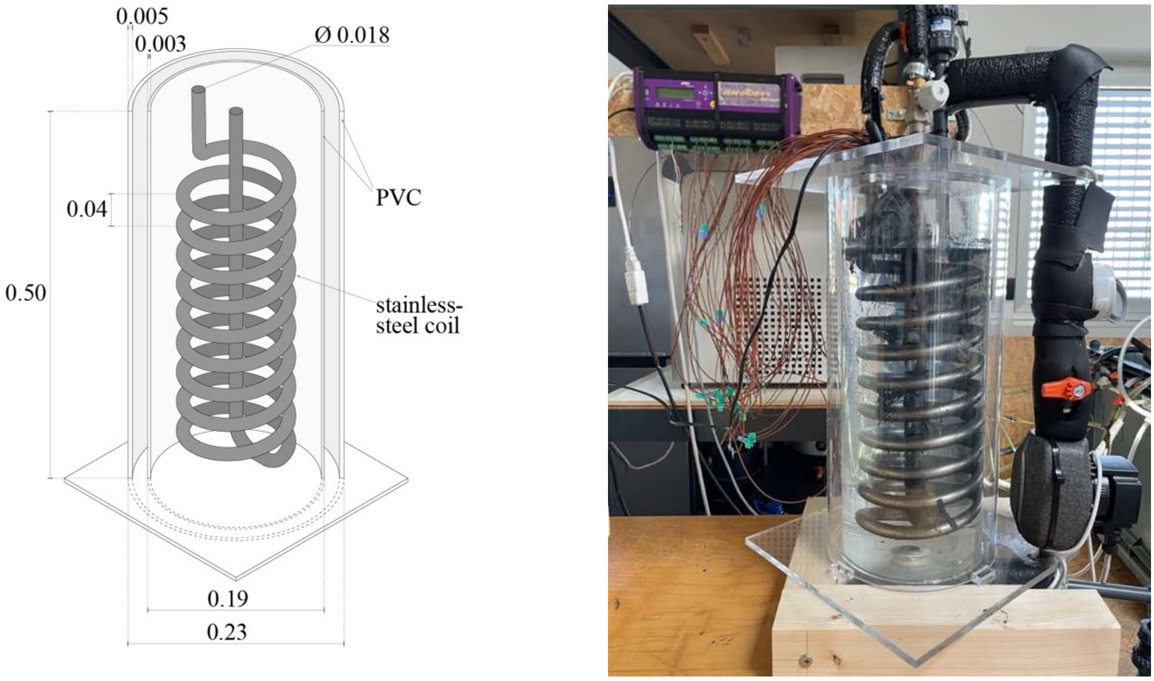

a

b

Figure 3-23: Experimental set-up: axonometric view reporting the main dimensions (a) and picture of the system with the recirculation circuit on the right side (b).

Water Storage Tank Enhanced with PCM (Italy)

Within the work package n.3 of the H2020 European project IDEAS [9] (WP3 leader: UNIFE), a small-scale prototype of the IDEAS system was installed at the TekneHub Laboratory of UNIFE, in a 38 m^3 mock-up building. The core of the system was a 5kW multi-source water-to-water heat pump (HP) that operated by means of two primary loops between two tanks (100 litres each one), the former on the source-side and the latter on the user-side. The system could exploit three different thermal sources (ground, sun and air) to optimise the temperature on the source-side for air-conditioning the spaces.

Considering the solar section, four prototypes of CPC-PV/T-PCM panels were originally foreseen in the project, but due to some issues and delays related to the COVID-19 pandemic the prototypes could not have been provided on time. For this reason, two commercial panels (2x1.6 m^2, 300 W_p) connected to an additional water storage tank integrated with PCMs were installed to exploit sun as source (Figure 3-24a). The buffer tank was characterized by a 200 l volume and it was filled with 76 cylindrical HDPE containers of PCM laid horizontally. Length and diameter of the containers were 100 cm and 5 cm, respectively. The macro-encapsulated PCMs, named TubeICE [16], were provided by PCM Products Ltd [11], partner of IDEAS project, and included: 17 containers filled with a PCM having a melting temperature of 32 °C (for summer application) (identified as S32 in Table 3-6) and 59 with a melting temperature of 10 °C (destined for winter time) (identified as S10 in Table 3-6); the water volume was around 60 l (Figure 3-24b).

An additional circulator was installed between the storage tank and the PV/T panels so that the PV/T loop could operate independently from the rest of the system and store thermal energy in the tank.

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Table 3-6: Thermophysical properties of the selected PCMs.

PCM	Melting temperature °C	Density kg/m^3	Latent heat kJ/(kg·K)	Specific heat kJ/(kg·K)	Thermal conductivity W/(m·K)
S10	10	1470	170	1.90	0.43
S32	32	1460	220	1.90	0.51

Figure 3-24: PV/T panels installed on the south facade of the mock-up with the PCM-tank on the left (a); detail of TubeICE S10 (marked in blue) and S32 (marked in red) filling the storage tank (b).

3.3.2 Shallow Geothermal Energy

Enhanced borehole heat exchangers (BHEs) with integrated PCM in Cyprus

EU Horizon project called TESSEb explored the idea of developing enhanced borehole heat exchangers (BHEs) with integrated PCM, which will take advantage of the increased underground thermal storage and maximize the efficiency of the ground coupled heat pumps (GCHP). The weakest link in BHEs is the heat transfer in the ground, which is mainly conductive, and its thermal diffusivity is low. This leads to a much slower ground thermal response than the heat pump requirements, resulting in thermal waves being transmitted into the ground through the BHEs causing lower coefficient of performance (COP) of ground source heat pumps (GSHP).

To improve the effectiveness of BHEs, integrating PCMs into the BHEs is applied in a building GSHP application in Cyprus for a small building, as illustrated in Figure 3-25. It is established that maximum PCM addition could be in the region of 35%, as above this level grout loses its mechanical properties. Employing PCMs will be an effective way to store more thermal energy in the BHEs and smooth the generated thermal wave due to PCM's latent heat capacity during phase change.

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Figure 3-25: PCM addition for geothermal borehole grout for a small building in Cyprus.

Small-Scale Prototype of the IDEAS System (Italy)

The installation of shallow ground heat exchangers enhanced with PCM integrated in the backfilling material was carried out at the TekneHub Laboratory of UNIFE in 2020, as a synergic prototype setup of two European projects: IDEAS [9], an H2020 project, and CLIWAX [17], an EFDR project. Three geothermal loops (named GHX) provide the coupling of a multi-source water-to-water heat pump (6kW) with the ground. Furthermore, two PV/T panels and a dry-cooler completed the exploitable thermal sources landscape. Finally, a control unit manages all the elements for the exploitation of the different thermal sources (Figure 3-26a).

Each line (6 m long) is composed of three novel shallow ground heat exchangers (2 x 1 x 0.015 m) (UNIFE patent EP2418439A2 [18]), installed in trenches 2.5 m deep. Three different backfilling materials were adopted: sand, assumed as the reference (identified as GHX1), a mixture of sand and paraffin-based PCM granules (identified as GHX2) (Figure 3-26b), and cylindrical HDPE containers filled in with hydrated salts (named TubeICE [16]) (identified as GHX2) (Figure 3-26c). A melting point of 8 °C was selected for the heating period, both for PCM granules (identified as A8 in Table 3-7) and hydrated salts (identified as S8 in Table 3-7), whilst a melting temperature of 27 °C was adopted for the cooling season, both for PCM granules (identified as A27 in Table 3-7) and hydrated salts (identified as S27 in Table 3-7) [12]. Both paraffins-based PCM granules and macro-encapsulated PCMs were provided by PCM Products Ltd [11], partner of IDEAS project. All the trenches were also filled in with water to increase the thermal conductivity and the heat capacity of the backfilling material. The main thermophysical properties of the different backfilling materials are reported in Table 3-7, Table 3-8, and Table 3-9. A comprehensive and detailed description of the work is reported in Ref. [19].

Results confirm that PCMs mixed into the backfilling of ground heat exchangers can affect the heat transfer by attenuating the highest temperatures in summer and the lowest in winter. Due to cost restrictions, however, the amount of PCM in each trench is limited and so is the latent heat capacity.

Monitoring data showed that in climatic zones with hot summers and cold winters, the application of PCM in summer should be preferred rather than the winter one, as water seems to be as suitable as PCM for low temperatures. However, additional considerations should be done for further real scale applications. Firstly, the decision between paraffin and hydrated salts: more stable but more expensive and with lower thermal

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conductivity the former, with higher volumetric storage capacity but phase segregation and subcooling problems the latter. Secondly, the compatibility of granules (used in GHX2) has not been deeply studied yet.

The collected data also showed good performances of the multi- source heat pump which, being able to exploit three different thermal sources at the same time or in different combinations, had winter COP always higher than 5.

As the ground source was the main focus of this work, the effect of its regeneration in summer by means of air and its recharge in winter by means of sun were highlighted. However, the effect of the PCM seemed to be quite limited. The reasons are to be found in the total length of each loop, which is only 6 m, the limited amount of material per trench to keep the costs down, the installation of the loops which converge into the same buffer tank and, lastly, the thermal properties of the PCM, especially the granules, that are characterised by low thermal conductivity. On the basis of this last consideration, further developments of the research might involve the improvement of the PCM thermal properties to investigate whether enhanced-PCM might bring to further improvements.

Table 3-7: Thermophysical properties of GHX1 backfilling material (sand).

	Heating	Cooling	Unit
Dry sand	8.3	8.3	t
Water	2.5	2.5	t
Wet sand UTES (10K)	171.0	171.0	MJ

Table 3-8: Thermophysical properties of GHX2 backfilling material (PCM granules).

	Heating	Cooling	Unit
Dry sand	6.1	6.1	t
Water	1.8	1.8	t
Wet sand UTES (10K)	126.5	126.5	MJ
PCM type	A8	A27	°C
Melting point	8	27	°C
Specific heat	2.16	2.22	kJ/(kg·K)
Latent heat	180	250	kJ/kg
PCM mass	174	89	kg
Product mass	348	178	kg
PCM STES	3.8	2.0	MJ
PCM LTES	31.3	22.2	MJ

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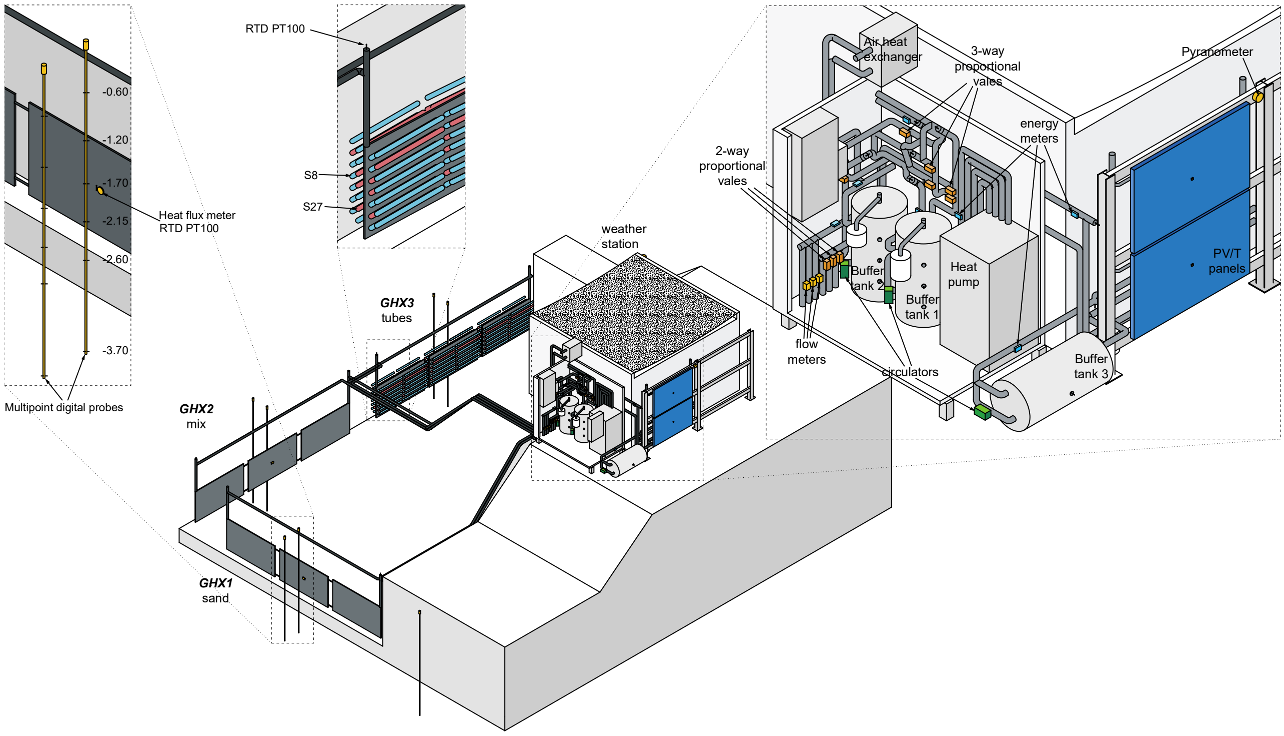
Table 3-9: Thermophysical properties of GHX3 backfilling material (macro-encapsulated PCM).

	Heating	Cooling	Unit
Dry sand	7.6	7.6	t
Water	2.3	2.3	t
Wet sand UTES (10K)	156.5	156.5	MJ
PCM type	S8	S27	
Melting point	8	27	°C
Specific heat	1.90	2.20	kJ/(kg·K)
Latent heat	130	185	kJ/kg
PCM mass	241	120	kg
Number of containers	112	56	–
PCM STES	4.6	2.6	MJ
PCM LTES	31.3	22.2	MJ



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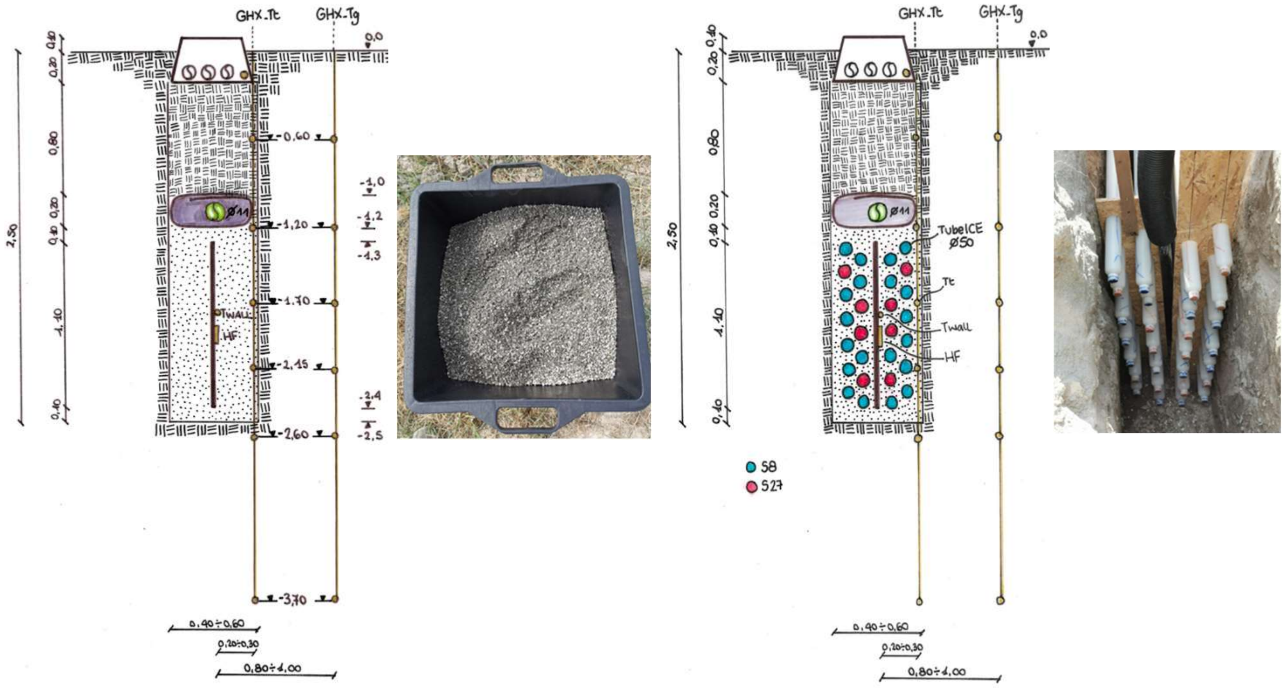

b c

Figure 3-26: Axonometric scheme of the system (a); section of GHX1 and GHX2 with detail of sand mixed with PCM granules (b), section of GHX3 with detail of PCM containers (c).

3.3.3 Solar Energy and Passive Heating & Cooling

The most common and widespread application of PCM remains within the solar power generation plants, as the molten salts are used for storing solar energy at a high temperature. Molten salts can be employed as a TES method to retain thermal energy. These systems are based on salt melting at 131 °C and kept in liquid state at 288 °C in an insulated "cold" storage tank. This stored energy is recovered by pumping the liquid salt through panels in a solar collector, where the focused sun heats it to 566 °C. It is then sent to a hot storage tank. When electricity production is required, the hot molten salt is pumped to a conventional steam-generator to produce superheated steam for driving a conventional turbine/generator. Various eutectic mixtures of different salts are used, such as sodium nitrate, potassium nitrate and calcium nitrate. They are the most commonly used mixture due to their lower cost than other alternatives for solar installations. A typical installation is illustrated in Figure 3-27.

Exploitation of solar energy can be enhanced by using PCMs at lower temperatures, too, as explained below. In addition, this section also delves into the utilization of solar energy for passive heating and cooling. Harnessing the sun's energy through strategic design and architectural features enables efficient temperature regulation within buildings, reducing reliance on traditional heating and cooling systems while promoting sustainability. By integrating passive solar techniques, structures can optimize comfort levels and minimize environmental impact, contributing to a more energy-efficient future.

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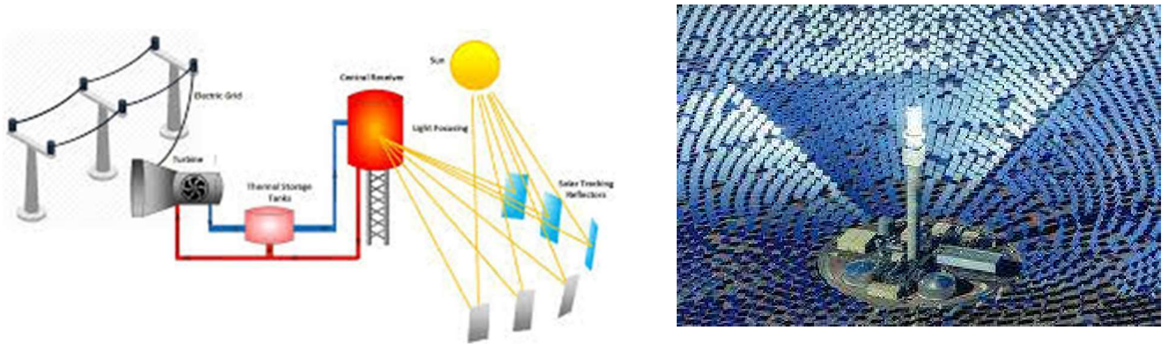

Figure 3-27: Typical concentrated solar TES concept [5].

FIFA 2022 World Cup Solar Stadium (Qatar)

Parabolic solar collectors generate significant hot oil which drives absorption chillers during day-time, storing cooling from these chillers in PCM-TES tanks. Nearly 5 MWh of free energy is stored during daytime and can be later used as a cooling source by the stadium cooling system for the duration of the football games, which would be around 2~3 hours and generally played in the evening when the ambient gets slightly cooler.

As the PCM-TES tank’s stored energy is equal to the full cooling load for the over-night game, once the game finishes TES tanks are completely depleted and ready for the next day charging. Operational data for the demonstration stadium clearly proved that a large-scale cooling can be achieved using only the sun energy off grid operation as illustrated Figure 3-28.

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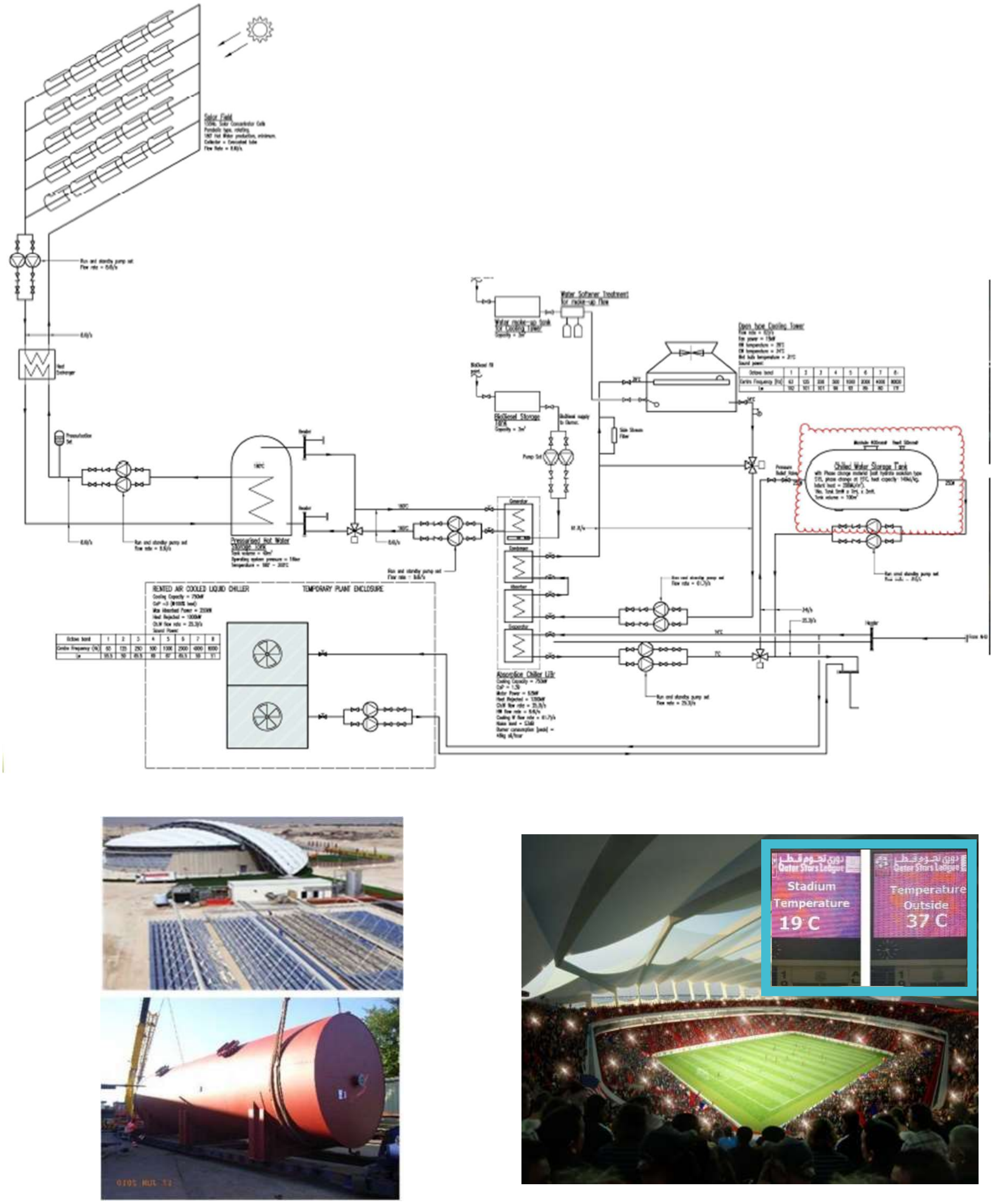

Figure 3-28: Solar large scale off-grid cooling application in Qatar [5].

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<u>**Underfloor Heating PCM-Based TES Concept**</u>

Encapsulated PCM containers filled with 27~32 °C PCM are ideal to store any excess energy and overcome any overheating. This TES capability provides a useful tool to store any free energy, such as solar, as well as shifting the loads from peak to off-peak periods for any domestic or commercial heating applications. A typical installation is illustrated in Figure 3-29. Thin PCM containers are designed to house any standard underfloor heating pipes within the built-in grooves. Once the pipes are laid down over the PCM containers, any standard floor levelling compound can be poured over the pipes to level the floor. Any screen and floor finishing materials can be applied like any standard underfloor installation. As the PCM material temperature is fixed, this TES within the floor mass will keep the floor temperatures steady, irrespective of the incoming heating water supply temperatures.

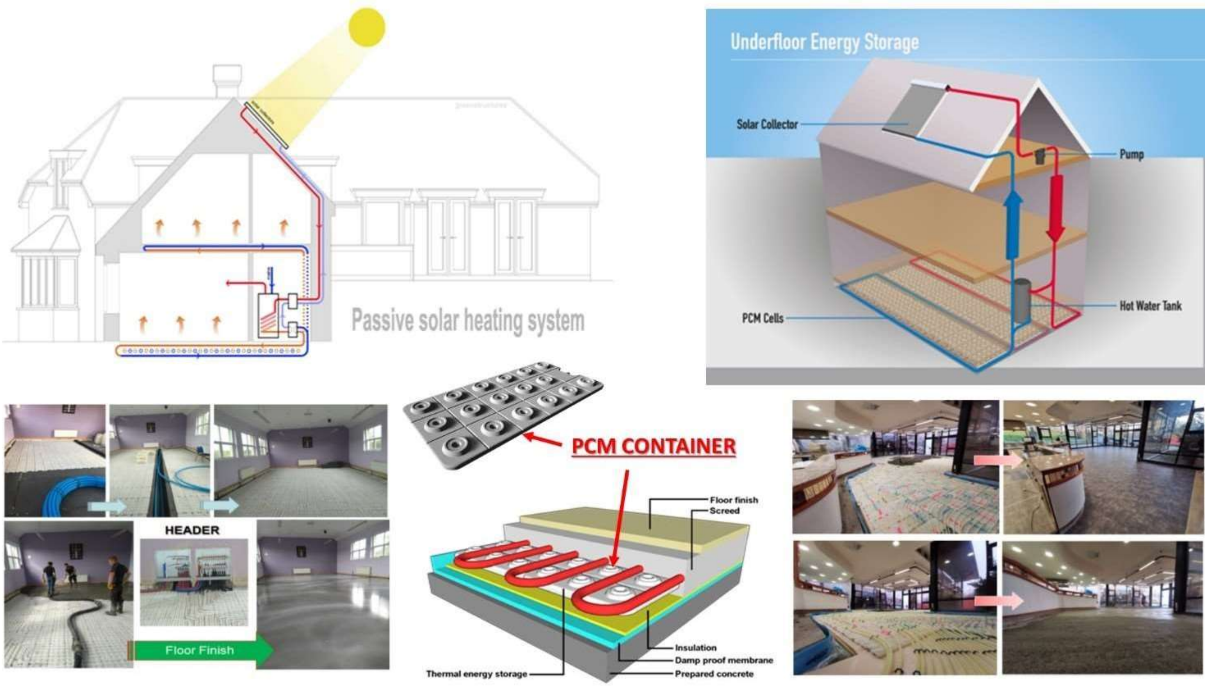

Figure 3-29: PCM-based free underfloor heating concept [5].

3.3.4 Industrial Applications

<u>**Steel Production and Recovery of Waste Heat (Netherlands)**</u>

Waste heat in the steel industry refers to the excess heat generated as a byproduct of various industrial processes. A project at the steel production in Ijmuiden (Netherlands) demonstrates the potential to fully utilize the energy potential of the waste heat of the facility. A full-scale implementation throughout the facility shows impressive results: an installed 500 MWh TES can yield annual savings of 2.3 million GJ of natural gas (65 million Nm^3) consumption and eliminate 130,000 tons of CO_2 emissions, with a return of investment in less than three years.

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Heat transport application

Apart from in-situ waste heat recovery systems, the most common application of PCM materials remains within the heat transport application, whereby the waste energy from an industrial process such as foundry, steel / ceramic etc. is utilized to melt the PCM in a road tanker and the waste is stored with the tanker tank. The most common material used as PCM is Sodium Acetate. It melts at 53 °C and as it sub-cools well below the ambient temperature before freezing, it remains as liquid during transport and therefore even with minimal insulation heat losses are very little. Once the tanker arrives to delivery point, the PCM is triggered to activate it, and even at ambient temperature liquid PCM immediately goes back to the original freezing point at 53 °C, and the heat generation is recovered via heat exchanger and transferred into the delivery process, as illustrated in Figure 3-30.

Once the tanker's tank is completely depleted i.e., turned to solid PCM, it returns to original heat source and using the heat the content is melted using waste heat for the next delivery. As this process is repeatable, it shuttles backwards and forwards between the energy source and energy use locations. As the heat is wasted from one process and very valuable for the end user, this application not only makes economic sense, but environmentally it is a very attractive application. Currently applied both within the EU but the largest use tends to be in China.

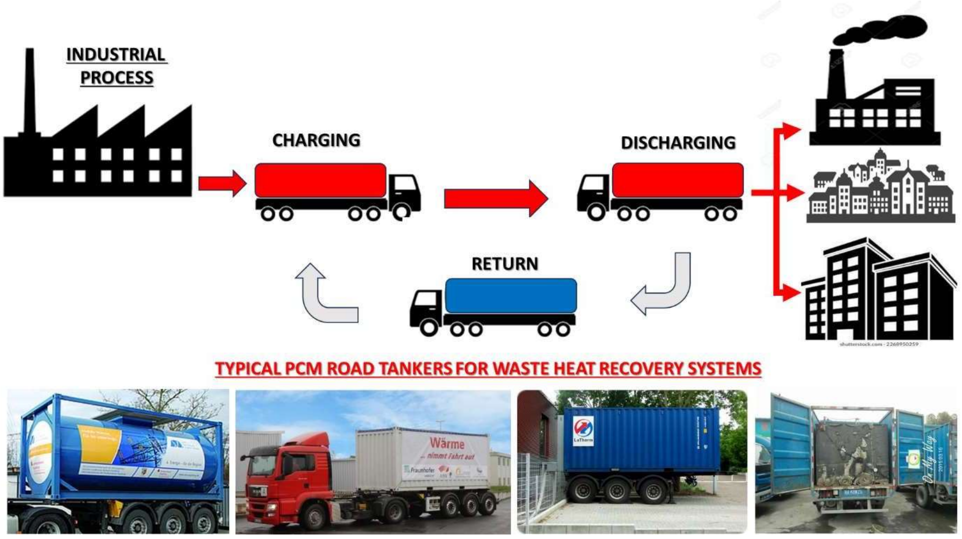

Figure 3-30: Waste heat recovery and transfer applications [5].

4 Sensible Thermal Energy Storage (STES)

Designers all over the world have developed over the years different techniques and many unique applications, but the main design criteria remain "full" or "partial" storage.

Full Storage systems shift the total cooling/heating load to the off-peak period, and the cooling/heating source is never used during the peak period to achieve the maximum economy. This type of system results in a smaller cooling/heating source but a larger storage volume.

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Partial Storage system utilizes the cooling/heating source during the peak periods to reduce the initial storage capacity. This type of system is widely used to limit demand during the peak period. This technique is called “Demand Limiting”. The excess capacity is supplemented by a TES source to stay below the maximum electrical demand limit. Any of the above techniques can be used either over a daily cycle (daily partial/full storage) or longer period of weekly or seasonal (weekly partial/full storage).

In principle, Full Storage provides the most economical running cost with a penalty of larger initial investment cost and volume (space) requirement. Partial Storage cost is relatively cheaper in comparison with full storage, but the running cost may be higher.

Both the above techniques can be applied for either an existing system or a new installation. The practical applications show that if a TES system is applied carefully in full consultation with the utility companies, the existing system modification cost can be recovered in a very short time depending on the application, and a new installation can be provided within the same budget limits as conventional systems.

4.1 Mechanism of STES

As the sensible heat capacity for a given material is fixed, the temperature rise or drop for the application dictates the TES capacity. Typical application examples for most commonly used STES material are illustrated in Figure 4-1 and in Figure 4-2 for water and building materials, respectively.

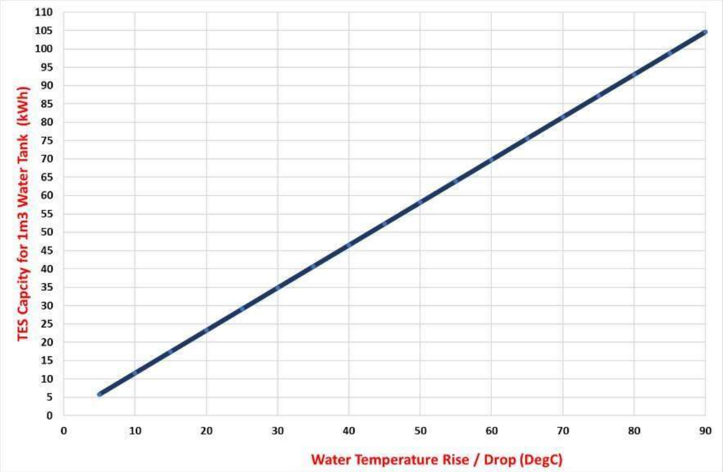

Figure 4-1: 1m^3 water tank’s STES capacity against various temperature rise/drop [5].

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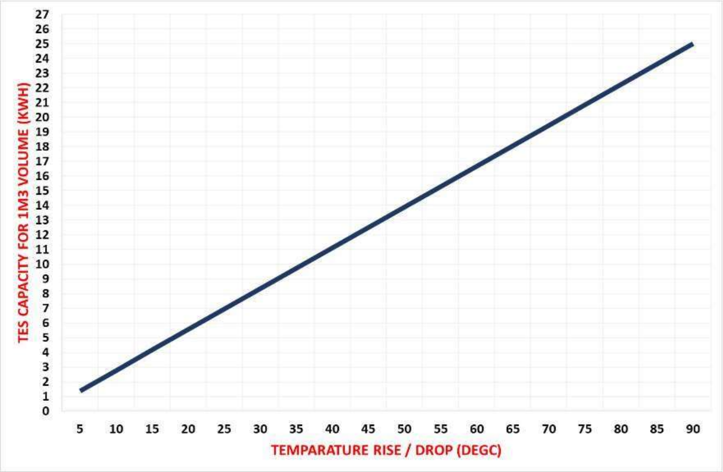

Figure 4-2: 1 m^3 building materials STES capacity against various temperature rise/drop [5].

4.2 STES Medium

Sensible thermal energy storage (STES) is the most straightforward and widely used method of TES. It simply means the temperature of some medium is either increased or decreased. The materials are generally inexpensive and safe such as a water tank, but materials such as molten salts or metals can be heated to higher temperatures and therefore offer a higher storage capacity. One of the other options is known as a packed-bed (or pebble-bed) storage unit, in which some fluid, usually air, flows through a bed of loosely packed material (usually rock, pebbles or ceramic brick), to add or extract heat.

However, STES storage capacities are limited by the specific heat capacity of the storage material, and the system needs to be properly designed to ensure energy extraction at a constant temperature for a practical application. STES is the well-established, mature and widely applied TES solution due to its simple operation and reasonable cost. However, it suffers from the low-energy storage density achieved compared to latent heat TES options. In this approach, the energy transfer (as heat) to and from the storage medium, that can be liquid (water, oil, etc.) or solid (sand, rock beds, brick, etc.), results in the corresponding change (increase or decrease) of the medium’s temperature.

4.2.1 Water

Water has the advantages of universal availability, low cost and transport ability over other systems. In principle, the simplest TES is a water tank which can store hot or cold water during the off- peak periods and be withdrawn during the peak periods. There are many application techniques of water storage, but the main criteria can be described as “mixing the return water with the stored volume in such a way to provide uniform supply temperature to the system”.

Different water storage types for both short-term and long-term heat storage are introduced as well as basic design rules for water stores. Both water STES systems can be considered for chilled water, solar domestic hot water systems and for solar combined systems for space heating/cooling and domestic hot water applications. It is vital to aim for a low heat loss by reducing thermal bridges and thermal stratification through a suitable heat storage design or by using inlet stratifiers for an STES design.

The following techniques have been successfully applied commercially throughout the world:

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Labyrinth Method:

This system was developed by Japanese Engineers and has been successfully applied in commercial buildings since 1950. Water flows back and forth through high and low apertures in adjacent cubicles in order to minimize the temperature swing for the supply water.

Temperature Stratification:

The return water from the system can float normally above the stored chilled water and the same principle is applicable for a +45 °C water supply which can successfully float above +39 °C return water, since the density difference is much larger.

Flexible Diaphragms:

The natural temperature stratification can be replaced by a sheet of coated fabric diaphragm which is anchored securely at the mid-point of the tank, this floats up and down depending on the water supply and return volumes and as a result the diaphragm dramatically improves storage and constant supply temperature accuracy.

Empty Tank Concept:

The Empty Tank concept can be described as the installation of as many tank sections which can be used to pump chilled water back and forth between the numbers of compartments. This technique provides an excellent separation of temperature for HVAC applications.

4.2.2 Steam

Steam TES is based on having a steam accumulator, which is an insulated steel pressure tank containing hot water and steam under pressure. It can be utilized to smooth out peaks. Steam accumulators may take on a significance for energy storage in solar or any waste heat thermal energy projects.

A typical application is the district heating steam accumulator tower on the Churchill Gardens Estate, Pimlico, London, United Kingdom. The installed plant is based on utilizing once used waste heat pipes from Battersea Power Station on the opposite side of the river Thames, as the installation shows in Figure 4-3.

Figure 4-3: Steam STES installed in the UK [5].

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Charging Process:

The tank is about half-filled with cold water and steam is blown in from a boiler via a perforated pipe near the bottom of the drum. Some of the steam condenses and heats the water. The remainder fills the space above the water level. When the accumulator is fully charged, the condensed steam will have raised the water level in the drum to about three-quarters full and the temperature and pressure will also have risen.

Discharging Process:

Steam can be drawn off as required, either for driving a steam turbine or for process purposes (e.g., in chemical engineering), by opening a steam valve on top of the drum. The pressure in the drum will fall but the reduced pressure causes more water to boil, and the accumulator can go on supplying steam (while gradually reducing pressure and temperature) for some time before it must be re-charged.

4.2.3 Solid (Stones/Ceramic/Sand/Concrete)

STES includes storing heat in liquids such as molten salts and in solids such as concrete blocks, rocks, or sand-like particles.

Solid thermal storage has been used in several commercial and demonstration facilities. In 2011, Graphite Energy developed a 3 MWe CSP plant in Lake Cargelligo in New South Wales, Australia, that used graphite blocks in the receivers on top of multiple towers. The graphite blocks in the receiver, irradiated by concentrated sunlight, served as both the storage system and boiler to generate steam for power production.

EnergyNest, based in Norway, developed a concrete-based TES system that consists of an array of modular pipes filled with concrete and steel tubes as illustrated in Figure 4-4.

Figure 4-4: Concrete STES module installation [20].

The tubes carry heat transfer fluid that can heat the concrete when charging and extract heat from the concrete when discharging to power a turbine/generator or provide process heating. The system can charge/discharge in ~30 minutes and the stored energy can last for several days, with less than 2% heat loss per 24 hours for large-scale systems.

Siemens Gamesa in Germany has developed a 130 MWht Electric Thermal Energy Storage (ETES) system, which comprises rocks stored in a building. Air is resistively heated using electricity (when price is low) and passed directly through the bed of rocks. The rocks are heated to ~600 °C, and, when needed, air is passed through the hot rocks to heat steam for a Rankine power cycle. The 130 MWht demonstration plant became operational in 2019, and the company is planning a design for a 30 MW commercial pilot plant.

Storage heaters work by storing heat generated by cheaper night-time electricity and releasing this heat during the day. All called night storage heaters come in many shapes and sizes, but all storage heaters will use bricks or energy cells, as they are sometimes referred to as, to store heat.

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Most storage heaters are wall-mounted and look a bit like radiators as illustrated in Figure 4-5. They use electricity to heat up a “bank” of ceramic or clay bricks inside them overnight. A storage heater is an electrical heater which stores thermal energy when switched on and releases the heat when switched off. It stores the heat by using heat retaining bricks. The bricks are typically made from clay bricks, water containers, ceramic materials (grog) or more specialist materials such as Feolite. All these materials function well for storing and retaining heat.

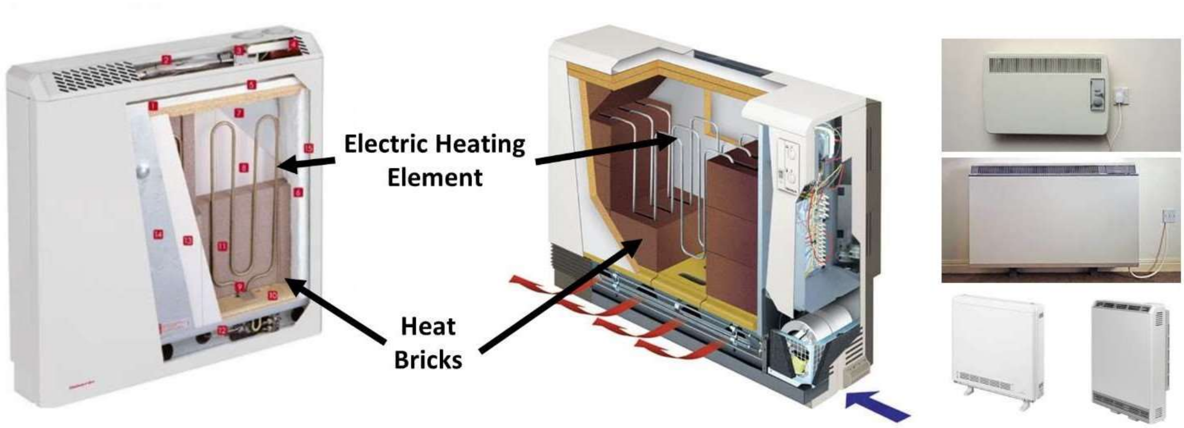

Figure 4-5: Storage heater examples [5].

4.3 Case Studies

4.3.1 HVAC Systems

In Heating, Ventilating and Air Conditioning systems (HVAC), sensible TES are normally employed. In general, there are three main HVAC services that require TES, namely cooling, heating and hot water requirements, whether they are produced via primary energy source or secondary/waste energy sources, as illustrated in Figure 4-6. The storage medium is formed usually by water or water-glycol mixtures.

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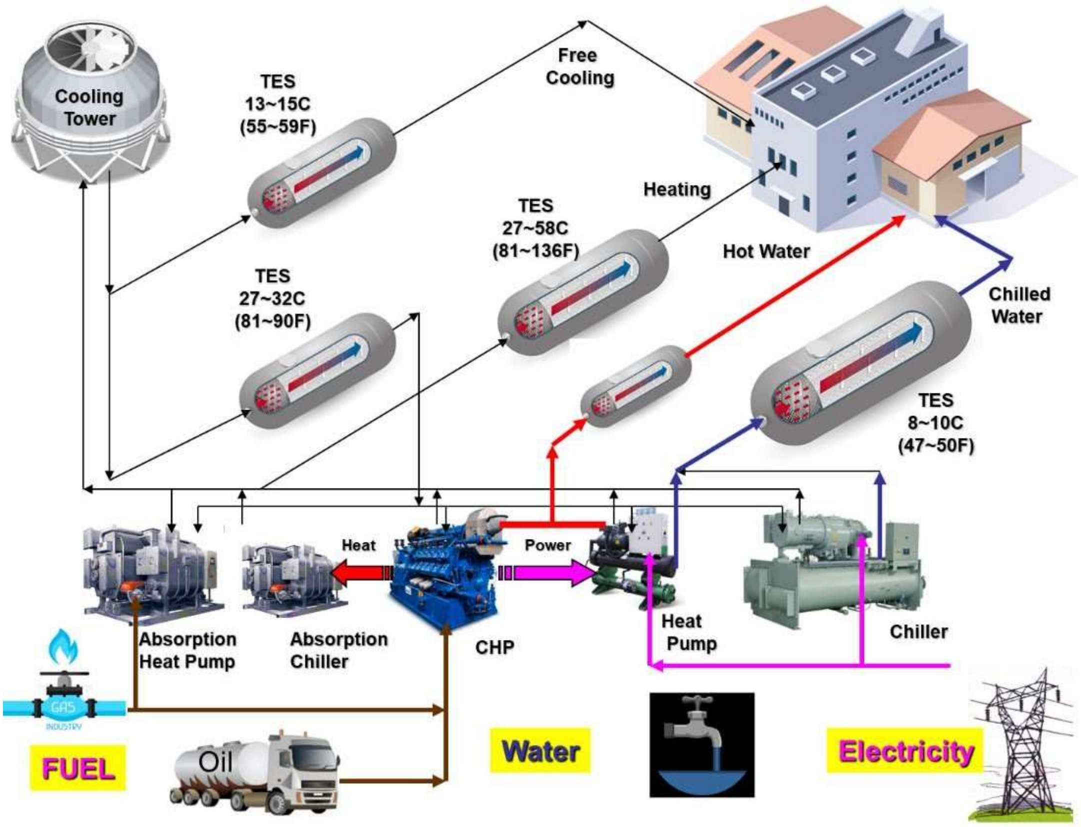

Figure 4-6: Built environment HVAC services for TES [5].

4.3.2 Solar Energy

The most common application examples for STES can be described as the conventional solar hot water production for domestic or commercial applications, as illustrated in Figure 4-7, where thermal solar applications heat water.

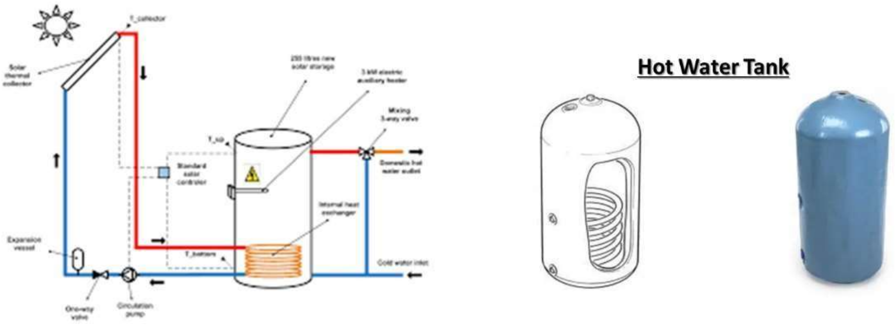

Figure 4-7: Solar hot water STES for domestic applications.

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The Royal Wolverhampton Hospital Heating TES (UK)

An interesting application of STES for solar energy exploitation has been built in Royal Wolverhampton Hospital (UK). As the system relies on heat pumps heat recovery and due to fluctuating cooling and heating load profiles, it was essential to balance the load so neither cooling nor heating energy from the heat pumps are wasted, as illustrated in Figure 4-8. To this end, cool PCM tanks are installed, and on the hot side, a simple 90 m^3 STES tank is added to the system, providing 930 kWh TES capacity. In this way, while the cool PCM tanks are charged, the waste heat is stored in these STES tanks as a byproduct. The installed system operates around 13~14 COP level i.e., putting 1 kWhe electric power, 13~14 kW combined heating and cooling is energy generated. As the hospital needs both heating and cooling loads all year round, the overall efficiency of the system reduces the operating cost significantly.

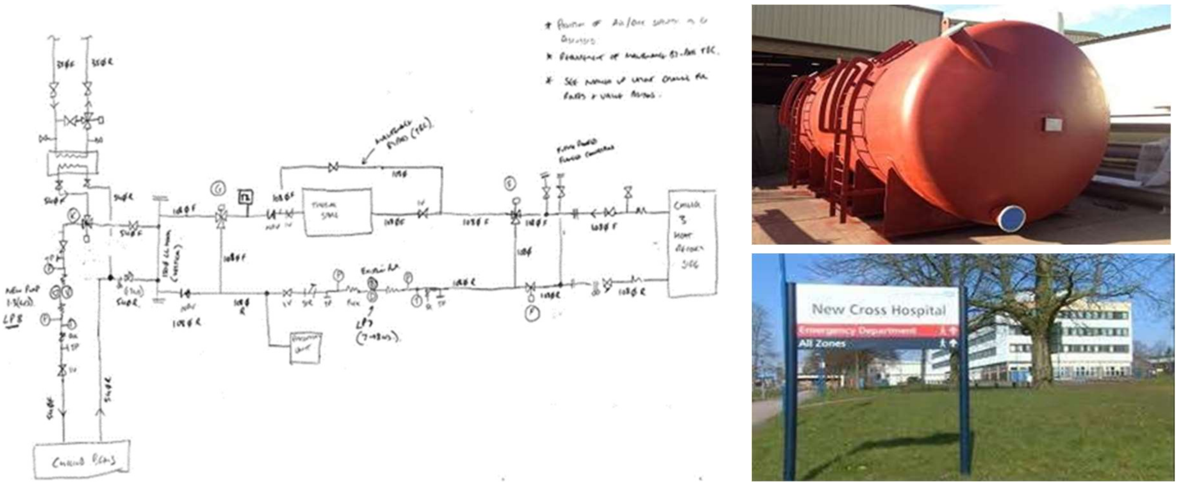

Figure 4-8: UK hospital warm TES application [5].

Snack-Bar of the Department of Biomedical and Specialties Surgical Sciences, University of Ferrara (Italy)

The experimental system IDEAS, developed within the H2020 European project IDEAS, was installed by UNIFE in the Italian building demonstrator in 2021. The Italian demo-case was identified in the 100 m^2 snack-bar of the Department of Biomedical and Specialties Surgical Sciences of UNIFE, a vast academic complex located in Ferrara, Italy.

The core of the system is represented by the 25kW multi-source water-to-water heat pump (HP), which operates by means of two primary loops between two tanks, one on the source-side (named BF1, 800l), and one on the user-side (named BF2.1 and BF2.2, 2x500l). On the source-side, the system operates between three thermal sources (ground, sun, and air) to optimise the temperature in BF1 in order to provide the snack bar with space heating/cooling.

Besides the geothermal section, 14 PV/T panels, 2 CPC-PV/T panels and a dry-cooler (AHX) completed the exploitable thermal sources landscape. Finally, a control unit manages all the elements for the exploitation of the different thermal sources, as illustrated in Figure 4-9.

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The commercial solar section (PVTc) is composed of n. 14 PVT panels (400Wp), one of which is not connected with the hydronic loop due to leakages. Each panel has 80 cells and therefore an active surface of 1.947 m^2, whilst the gross panel surface is around 2.19 m^2; the azimuth is around 17°, equal to that of the building pitched roof.

During summer period, the section was cooled during the day to increase the electrical photovoltaic conversion and heated during the night to de-superheat the ground section. For the highlighted period (July and August), the cooling activity accounted for 890kWh_t, whilst the heating for 340kWh_t. Consequently, the temperature just occasionally achieved values over 60°C, even with high solar irradiance (>800W/m^2).

Monitoring data showed that the cooling mode allowed a net increasing of 7.6% in peak power conversion. In terms of efficiency, the cooled panel achieved 14.3%, whilst the not-cooled one 13.3%. Furthermore, the cooling of PV/T panels is only functional to increase the peak power (+7.6%) and not to increase the energy production.

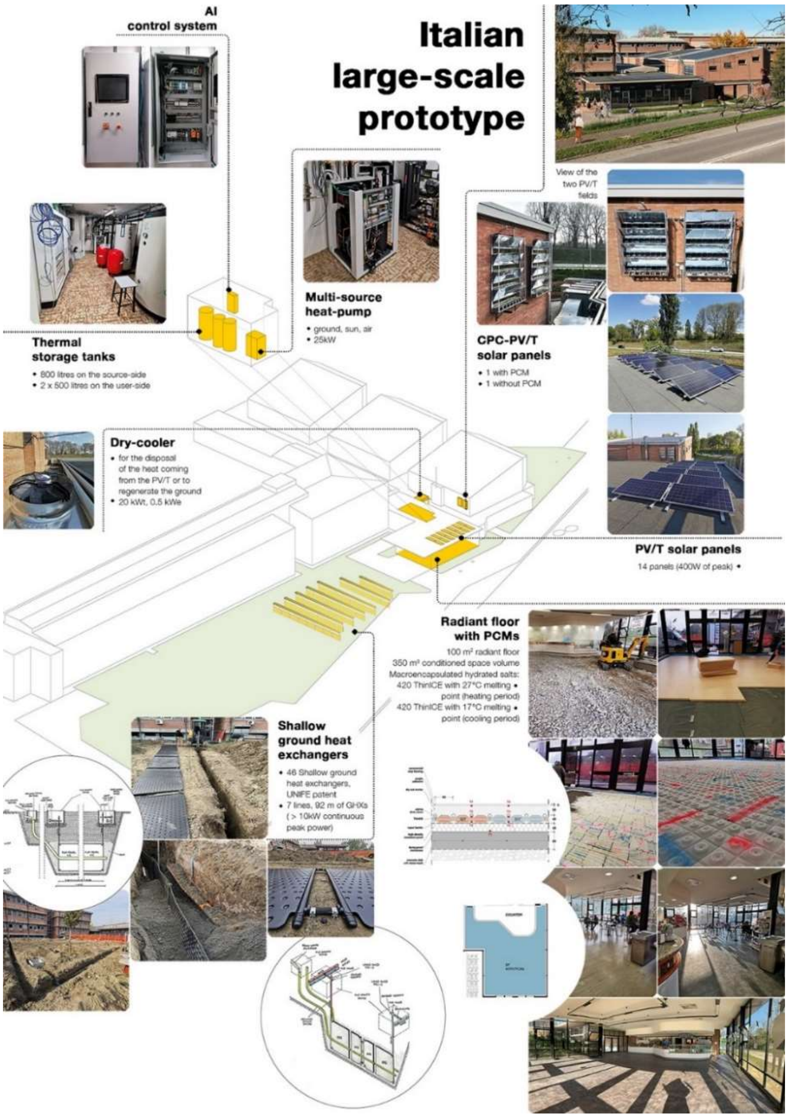

Figure 4-9: Axonometric scheme of the full-scale installation of the IDEAS system [9].

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4.3.3 Industrial Processes

Thermal Energy Storage with Concentrating Solar Thermal (CST) Technologies in a Brewery (Spain)

CST technologies use mirror configuration to reflect and concentrate the sun's direct normal irradiance (DNI) into a receiver to heat a high temperature fluid. Solar energy is stored in hot oil storage units and this stored heat energy can be used to create steam, driving a turbine to generate electricity, or directly as heat purposed for heavy industries, known as Solar Heat for Industrial Processes (SHIP). The stored energy of STES enables production possible at night and during cloudy periods, or at any time heat is required.

Furthermore, STES makes the process more flexible and dispatchable in the form of solar energy. The system illustrated in Figure 4-10 is based on 30 MW CST Plant in a brewery in Spain, covers 55% of the heat demand with the remaining 45% covered by other energy sources.

Figure 4-10: Spanish brewery solar TES system [21].

Although on-site heat recovery STES can be very attractive as long as there is a gap between the waste energy availability and energy use, generally most of the industrial processes tend to be 24hr daily cycles and utilized simultaneously. Hence, they offer very little opportunity and economic sense for CAPEX or OPEX for TES systems and waste heat, directly recovered and utilized.

One potential application could be waste heat recovery at high temperatures to be delivered to a different location where the heat has a high value, such as district heating. Due to the large temperature difference, large amounts of energy can be transported in each tanker and making round trips economically viable.

4.3.4 District Heating and Cooling

Sand-based system for seasonal storage (Finland)

A system exploiting sand sensible heat will provide district heating to the city of Kankaanpää in western Finland. It has 100 kW of heating power and 8 MWh of energy capacity. Finnish utility Vatajankoski and Finland-based startup Polar Night Energy have switched on a sand-based high-temperature heat storage system, as illustrated in Figure 4-11.

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Figure 4-11: Sand-based STES installation in Finland [22].

The storage is embedded in a 4 m x 7 m high steel container and can store electricity in the form of heat for several months, at temperatures ranging between 500 °C and 600 °C. Vatajankoski utility uses the heat provided by the storage to enhance the temperatures of the waste heat from the servers before the heat is fed into the district heating network.

Chilled Water TES (US)

Pepco Energy Services (PES) provided an energy services performance contract project to the State of North Carolina, and selected DN Tanks to build a 2.7 MG stratified chilled water TES tank on the state capital campus in downtown Raleigh. The precast, prestressed, wire-wound concrete TES tank is at the heart of this significant energy savings project. Coupled with a new high efficiency packaged chilled water plant, this TES tank can deliver 96 MWh of cooling capacity. The system is the primary chilled water source for 325,000 m^2 in 20 buildings (Figure 4-12).

Figure 4-12: Chilled Water STES in the US [4].

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4.3.5 Shallow Geothermal Energy

BTES for heating and cooling (Canada)

An underground borehole thermal energy storage (BTES) system was installed at the University of Ontario Institute of Technology (UOIT) in Oshawa, Canada, for heating and cooling four new campus buildings with a total cooling load of 7,000 kW. The system comprised 370 boreholes, each 200 meters deep, and included the installation of five temperature monitoring boreholes. The water-filled borehole heat exchangers (BHEs) were opted for over the grouted BHEs, resulting in enhanced efficiency and ensured borehole longevity. The BHEs, arranged on a 4.5 m grid, covered an area of 7,000 m^2, with a total volume of 1.4 million m^3. A schematic flow chart of the BTES system was presented in Figure 4-13, and technical specifications for the chiller and two heat pumps were listed in Table 4-1. Figure 4-14 displayed a site view during the construction of the BTES system at UOIT's well field, showcasing borehole grids and interconnected piping.

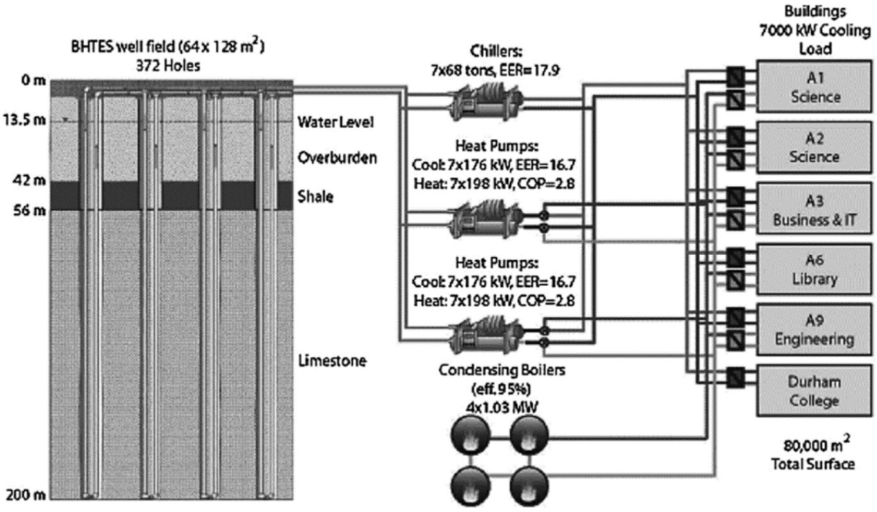

Figure 4-13: Schematic flow diagram of the BTES in Canada [23].

Table 4-1: Design values for heat pumps [23].

Total heating/cooling loads	1,386/1,236 kW
For heating	
Load water	
Entering/leaving water temperatures	41.3/52 °C
Source water	
Entering/leaving water temperatures	9.3/5.6 °C
For cooling	
Load water	
Entering/leaving water temperatures	14.4/5.5 °C
Source water	
Entering/leaving water temperatures	29.4/35 °C
COP$_{design}$ for heating/cooling	2.8/4.9

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Figure 4-14: A site view during construction of the BTES in Canada [23].

Snack-Bar of the Department of Biomedical and Specialties Surgical Sciences, University of Ferrara (Italy)

The full-scale installation of the experimental IDEAS system, developed within the H2020 European project IDEAS [9], was carried out by UNIFE in the snack-bar of the Department of Biomedical and Specialties Surgical Sciences, a vast academic complex located in Ferrara, Italy (Figure 4-9). A detailed description of the system is reported in the previous section 4.3.2, among solar energy case studies. In this facility, STES has been exploited, too.

Horizontal ground heat exchangers (GHXs) so called Flat-Panels (2 x 1 x 0.015 m) (UNIFE patent EP2418439A2 [18]) were used to provide the coupling of a 25kW multi-source water-to-water heat pump (HP) with the ground. N. 7 lines composed of almost 6 Flat-Panels per line were installed in the green area in front of the snack bar, on the south side, for a total of 46 Flat-Panels (92 m of GHXs) (> 10 kW continuous peak power) as illustrated in Figure 4-15. A comprehensive and detailed description of the work is reported in Ref. [24].

Monitoring data from end-May 2022 to January 2023 showed that the system exchanged with the ground the following thermal energies: +11570 kWh in heating the ground (summer) and –6880 kWh in cooling the ground (summer in de-superheating service, winter).

Data regarding the heating period and collected from end-November 2022 to February 1st 2023 demonstrated that 4410kWh$_t$ were extracted by the GHX panels in around 67 days, which represents a daily average thermal energy of 65.8 kWh$_t$/d, thus a daily average thermal power of 67 W$_t$/panel. As a consequence, the thermal performance per metre of panel is around 34 W$_t$/m, which is comparable with the more expensive vertical boreholes. Since the average air temperature was 7.0°C and that into the source buffer tank (BF1) was around 8.8°C (which represents the blended temperature between the working fluid leaving the geothermal field and that processed by the heat pump), this technology shows good performance, especially when compared to the installation costs and the absence of the common freezing issues of air heat exchanger.

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Considering the cooling period, data collected from July 6th to September 2nd showed that around 3800 kWh_t were relieved into the ground in 58 days, as generated at the condenser by the HP compressor activity. Around 1610 kWh_t were then removed from the ground in the same period during nighttime, by means of the AHX and PVTc different action, and therefore dissipated in air convection and sky radiation.

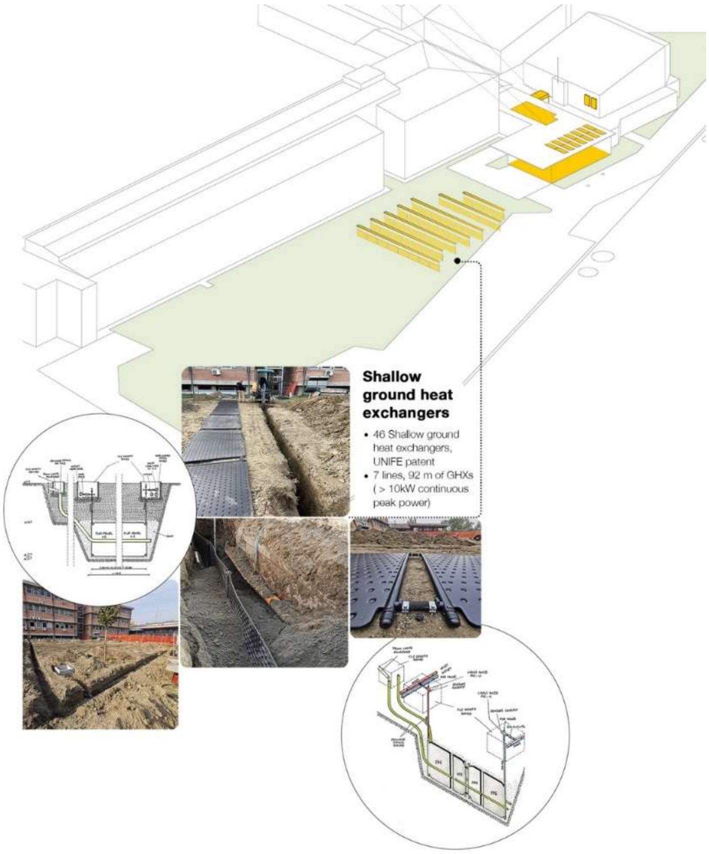

Figure 4-15: Axonometric scheme of the full-scale installation of the IDEAS system [24].

TekneHub Laboratory, University of Ferrara (Italy)

A common air-to-air heat pump was modified by coupling a geothermal closed loop, composed by innovative horizontal ground heat exchangers, via a plate heat exchanger. The work was carried out within the EFDR project HEGOS. The goal was to perform a dual-source heat pump system (DSHP) able to switch between air and ground according to the more profitable temperature. The DSHP can represent a smart solution to overcome the disadvantages of a single-source heat pump, as it offers the most suitable thermal source, reduces the frosting issue during winter (air-source heat pumps) and it allows to reduce drastically the length of the ground heat exchangers (ground coupled heat pumps), which are the most relevant installation cost of a geothermal heat pump.

The prototype is composed of a common air-to-air heat pump, a geothermal closed loop, and a novel kit for coupling the air-source heat pump with the closed loop. The kit links the refrigerant circuit with a plate heat exchanger coupled with the closed loop, and automatises the switching between air and ground by means of a control unit which pilots valves according to rules based on air-ground temperature and air humidity.

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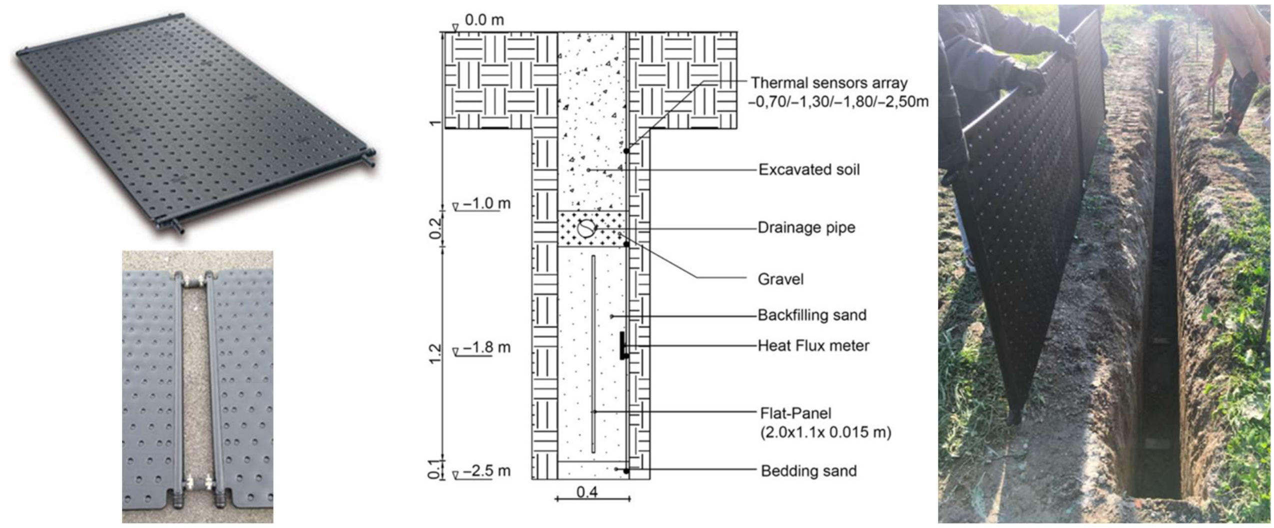
A novel shallow ground heat exchanger, named flat-panel (FP) (UNIFE patent EP2418439A2 [18]), was used for the installation at the TekneHub Laboratory of UNIFE, due to its higher performance in comparison with similar shallow and horizontal ground heat exchangers. Moreover, its flat shape (2 x 1 x 0.015 m) allows installations in narrow trenches, minimizing the digging and therefore the overall costs.

The geothermal closed loop was composed of three pairs of FPs, which were edgeways buried in a trench 2.5 m deep and 0.4 m wide, backfilled with washed sand. A gravel layer with a dedicated irrigation system was laid at the FP top to soak the trench on demand and improve soil thermal performance. Soil resulted from digging was used to cover (Figure 4-16). A room (48 m^3, 16 m^2) of the TekneHub Laboratory was devoted to test the experimental air-conditioning system with the novel DSHP. The complex is a recent one-storey building (2014).

The prototype operated for the whole wintertime 2017–18, for testing the behaviour and to support parametric rules to be implemented in the control system (PLC), according to the length of the geothermal closed loop. The temperature difference between air and ground is the main parameter that controls the closed loop length; the higher the difference, the shorter the length and therefore the lower the installation cost, but also the overall energy saving. Another important parameter is the threshold temperature for activating the dual functionality, because it anticipates or delays the ground depletion; the higher the threshold, the quicker the depletion of the ground.

Even if the DSHP prototype showed better performance than the original air-to-air heat pump, the extra-cost of the revamping kit only partially justified the starting investment, although increases the indoor comfort when hard weather conditions occur. If the starting point is a ground source heat pump, the DSHP allows a shorter ground heat exchanger and therefore lower installation costs.



a b c

Figure 4-16: View of the flat panel with detail of hydraulic connections (a); cross section of the trench (b); installation in trench (c) [25].

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5 Chemical Thermal Energy Storage (CTES)

Chemical Thermal Energy Storage (CTES) materials exploit the heat generated or acquired during exothermic and endotermic chemical reactions. They are usually referred to as Thermochemical materials (TCMs) and they can be divided depending on the reaction involved, as detailed below.

5.1 Thermochemical Thermal Energy Storage (TTES)

Thermochemical thermal energy storage (TTES) may yield a reasonable heat storage capacity without producing any thermal losses during the storage period. The working pairs of various salt options are incorporated in high porous structured carrier materials, whereby utilizing a reversible chemical reaction. This takes advantage of strong chemical bonds to store energy as chemical potential. Compared to STES and LTES, this theoretically offers higher energy density with minimum energy loss during long-term storage due to the temperature-independent means of storage.

5.1.1 Mechanism of TTES

TTES is a promising storage technology, especially at high temperatures (> 700 °C), as it allows for the storage of heat through chemical reactions of thermochemical material (TCM), for example, the breaking/reforming of bonds. A conceptual illustration of TTES is shown in Figure 5-1.

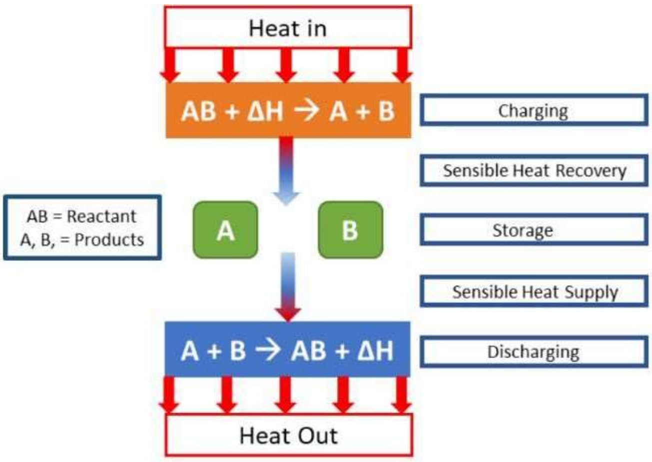

Figure 5-1: TTES processes.

The thermochemical storage reaction of TCM can be described as AB + ΔH ↔ A + B format. In this equation, Reactant AB is dissociated into Products A + B via the introduction of heat, which creates an endothermic reaction. The individual products can be stored separately for an indefinite amount of time, so if and when the thermal demand is required, A + B is recombined as an exothermic reaction, releasing heat back into the process. TTES is performed by working endothermic and exothermic chemical reactions of TCM in a cycle. The working principles of this technology are as follows:

Charging period: An endothermic chemical reaction of TCM is performed by using heat during the off-peak periods or when the renewable energy source is active.

Storing period: The TCM compound obtained in the charging period is kept in a container that provides steady condition for the TCM compound.

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Discharging period: The stored TCM is allowed to exothermic reaction and heat is produced. The energy requirement is met with the heat produced.

State-of-the-art:

TTES is based on reversible chemical reactions of TCM according to the following equation, where the dehydration reaction (charging phase) is endothermic, and the hydration reaction is exothermic (discharge of heat).

$$\Delta\text{Hreac}$$

$$Salt \cdot yH_2O\ (s) \rightarrow Salt(s) + yH_2O\ (g)$$

The forward and the reverse reactions may take place in different steps at different temperature levels, where intermediate hydrate phases can occur. The chemical reaction of TCM in a TTES may also follow this equation:

$$\Delta\text{Hreac}$$

$$AB \rightarrow A + B$$

In most of the reported processes, solid sorbents are arranged in packed beds. Pure water vapor is applied in closed cycles while water vapor contained in wet air is applied in open cycles. Sorption TCM can be classified in adsorption TCM like zeolite/water or selective-water- sorbents/water and absorption systems. The working pairs of TCM incorporated in TTES system including silica gel/water, magnesium sulfate/water, lithium bromide/water, lithium chloride/water, and NaOH/water have been considered the most prominent TCM for achieving increased heat storage capacity.

The challenge associated with solid adsorption seasonal storage is, in general, the need for a huge amount of adsorbent and, consequently to huge heat exchangers and, therefore, an excessively expensive machine. By using the high porous structured carrier TCM dispersed with the reactive material inside, the heat and mass transfer processes can be improved. Besides, the incorporation of chemical heat pumps working on the principles of chemical sorption processes can help acquire enhanced heat storage capacity even at very high temperatures, where the conventional heat pump does not need to be suited for the desired purpose.

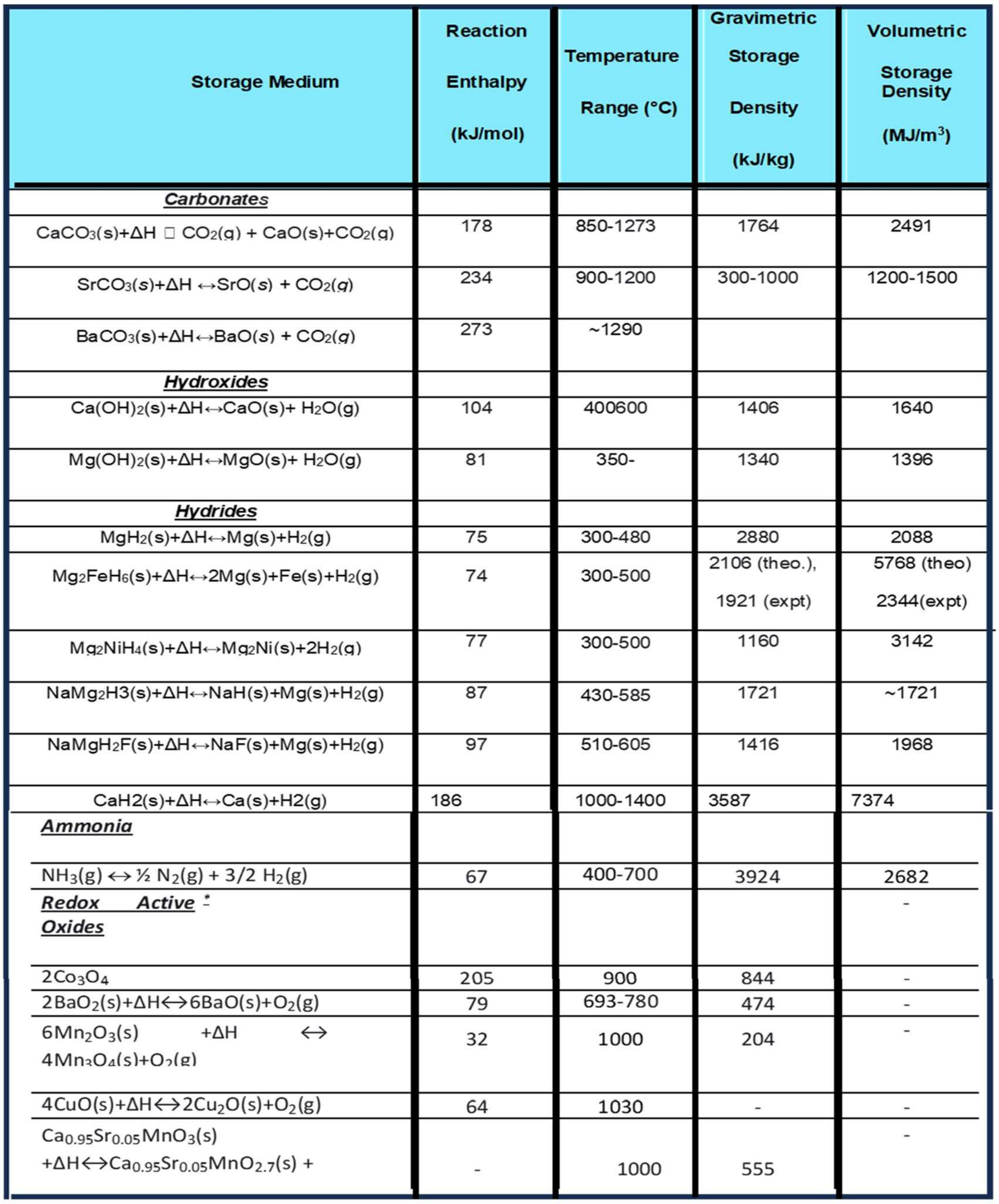
TTES can be considered an energy-efficient approach that offers a wide opportunity for conserving primary energy sources as well as reducing greenhouse gas emissions. When compared to STES and LTES, in theory TTES using TCM may yield the highest heat storage capacity without producing any thermal losses during the storage period.

Furthermore, TTES, if blended with long-term seasonal TES techniques, can still result in enhanced thermal performance of the storage system without sacrificing energy efficiency and environmental sustainability.

5.1.2 TTES Medium

A variety of potential TTES processes exist, though no TCM has been implemented on an industrial scale. TTES can be applicable over a wide range of temperatures and conditions. Heat source, the type of power cycle, operating temperature, and receiver configuration all influence the selection of a candidate TCM. Table 5-1 lists the most promising TTES reactions by type, reaction temperatures, enthalpies, and gravimetric storage energies. The operating temperatures and storage densities are representative values, but can differ depending on operating conditions, such as pressure, as well as the morphology of the solid species.

Table 5-1: TCM options [5].



Storage Medium	Reaction Enthalpy (kJ/mol)	Temperature Range (°C)	Gravimetric Storage Density (kJ/kg)	Volumetric Storage Density (MJ/m^3)
Carbonates				
$CaCO_3(s)+\Delta H$ □ $CO_2(g) + CaO(s)+CO_2(g)$	178	850-1273	1764	2491
$SrCO_3(s)+\Delta H \leftrightarrow SrO(s) + CO_2(g)$	234	900-1200	300-1000	1200-1500
$BaCO_3(s)+\Delta H \leftrightarrow BaO(s) + CO_2(g)$	273	~1290		
Hydroxides				
$Ca(OH)_2(s)+\Delta H \leftrightarrow CaO(s)+ H_2O(g)$	104	400600	1406	1640
$Mg(OH)_2(s)+\Delta H \leftrightarrow MgO(s)+ H_2O(g)$	81	350-	1340	1396
Hydrides				
$MgH_2(s)+\Delta H \leftrightarrow Mg(s)+H_2(g)$	75	300-480	2880	2088
$Mg_2FeH_6(s)+\Delta H \leftrightarrow 2Mg(s)+Fe(s)+H_2(g)$	74	300-500	2106 (theo.), 1921 (expt)	5768 (theo) 2344(expt)
$Mg_2NiH_4(s)+\Delta H \leftrightarrow Mg_2Ni(s)+2H_2(g)$	77	300-500	1160	3142
$NaMg_2H3(s)+\Delta H \leftrightarrow NaH(s)+Mg(s)+H_2(g)$	87	430-585	1721	~1721
$NaMgH_2F(s)+\Delta H \leftrightarrow NaF(s)+Mg(s)+H_2(g)$	97	510-605	1416	1968
$CaH2(s)+\Delta H \leftrightarrow Ca(s)+H2(g)$	186	1000-1400	3587	7374
Ammonia				
$NH_3(g) \leftrightarrow \frac{1}{2} N_2(g) + 3/2\ H_2(g)$	67	400-700	3924	2682
Redox Active** ** ***Oxides				-
$2Co_3O_4$	205	900	844	-
$2BaO_2(s)+\Delta H \leftrightarrow 6BaO(s)+O_2(g)$	79	693-780	474	-
$6Mn_2O_3(s) +\Delta H \leftrightarrow 4Mn_3O_4(s)+O_2(g)$	32	1000	204	-
$4CuO(s)+\Delta H \leftrightarrow 2Cu_2O(s)+O_2(g)$	64	1030	-	-
$Ca_{0.95}Sr_{0.05}MnO_3(s) +\Delta H \leftrightarrow Ca_{0.95}Sr_{0.05}MnO_{2.7}(s) +$	-	1000	555	-

Although the above theoretical TCM may exist, finding a suitable heat exchange process is the main challenge to get the heat in and out of the system. Many of the current TCM offer great advantages but also some drawbacks, and the comparison between the main TCM is illustrated in Table 5-2.

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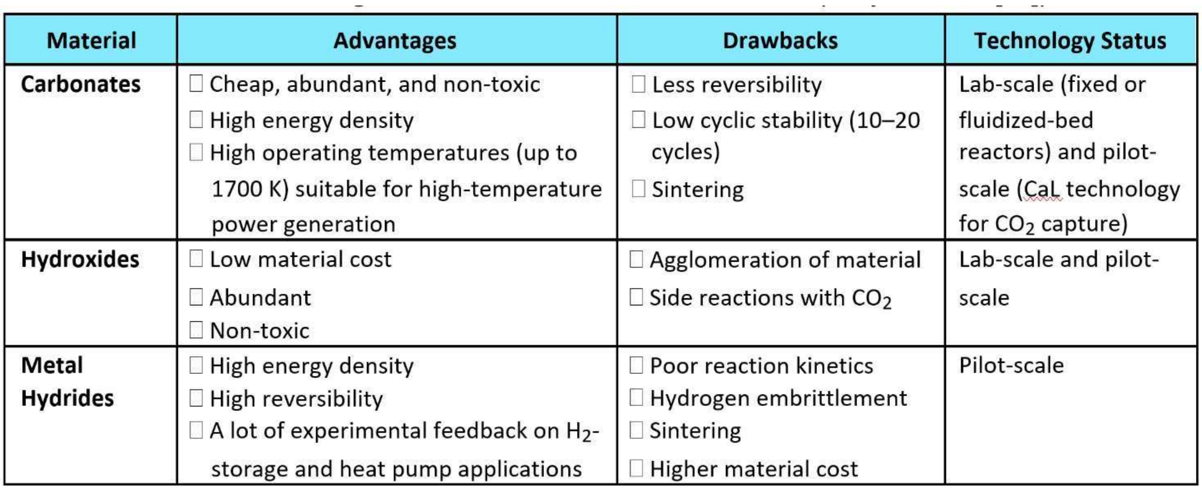
Table 5-2: Comparison of TCM.



Material	Advantages	Drawbacks	Technology Status
Carbonates	☐ Cheap, abundant, and non-toxic ☐ High energy density ☐ High operating temperatures (up to 1700 K) suitable for high-temperature power generation	☐ Less reversibility ☐ Low cyclic stability (10–20 cycles) ☐ Sintering	Lab-scale (fixed or fluidized-bed reactors) and pilot-scale (CaL technology for CO_2 capture)
Hydroxides	☐ Low material cost ☐ Abundant ☐ Non-toxic	☐ Agglomeration of material ☐ Side reactions with CO_2	Lab-scale and pilot-scale
Metal Hydrides	☐ High energy density ☐ High reversibility ☐ A lot of experimental feedback on H_2-storage and heat pump applications	☐ Poor reaction kinetics ☐ Hydrogen embrittlement ☐ Sintering ☐ Higher material cost	Pilot-scale

As already said, although a variety of potential TTES processes exist, no TTES system has yet been implemented on an industrial scale. Several bench-scale and pilot-scale demonstrations have been reported, and one of the most-developed TTES systems is the ammonia-based reaction, which has been studied for over 40 years, most notably at Australian National University (ANU). When heat is required, the gases are reacted to re- synthesize NH_3 in an exothermic process similar to the industrial Haber-Bosch process.

However, most of the TTES applications require very high heat for the generation and there has been many developments and studies carried out to develop low temperature (50~90 °C) generation TCM, but so far, no commercial application / product emerged. Some of the most promising commercial low temperature generation TCM are summarized in Table 5-3.

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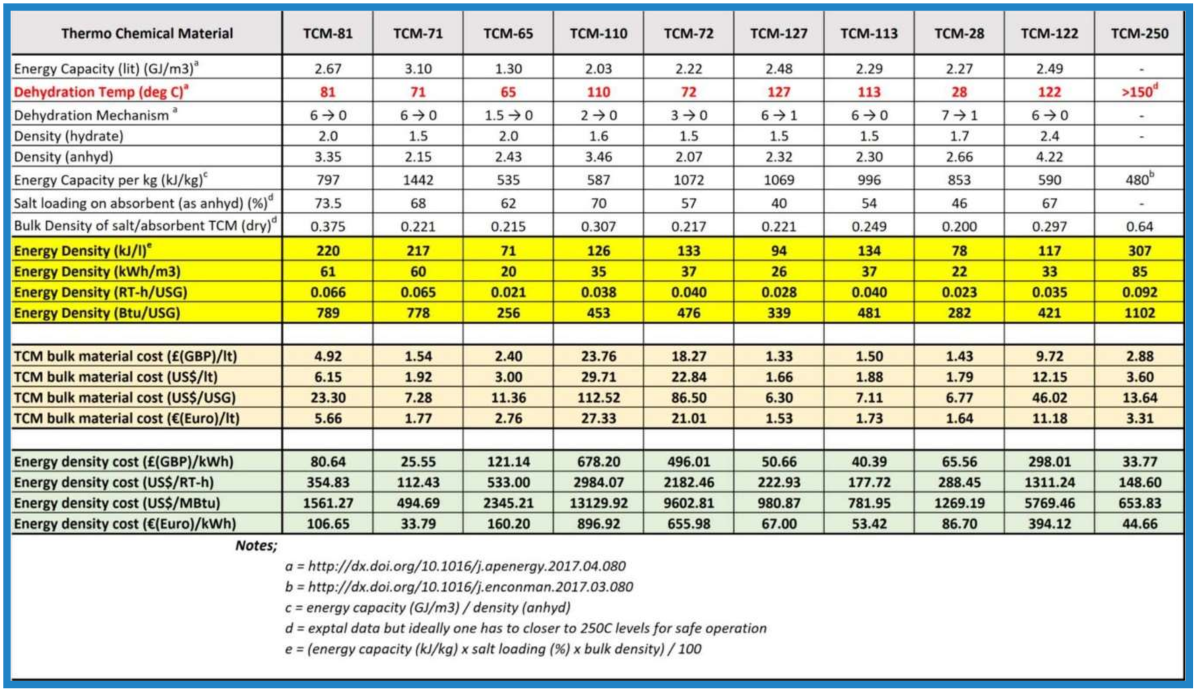
Table 5-3: Low temperature commercial TCM options [5].



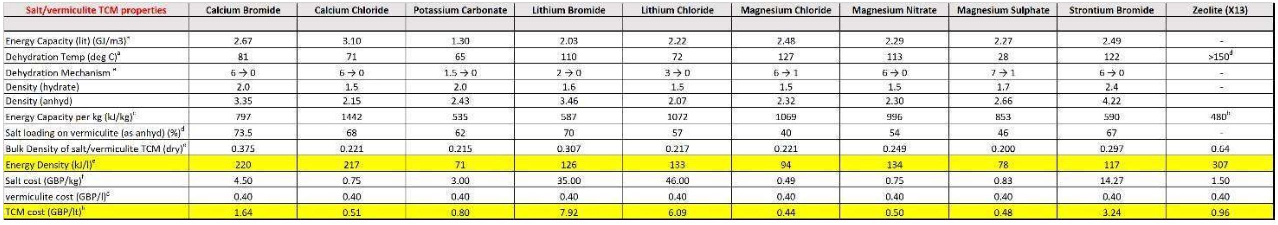
Thermo Chemical Material	TCM-81	TCM-71	TCM-65	TCM-110	TCM-72	TCM-127	TCM-113	TCM-28	TCM-122	TCM-250
Energy Capacity (lit) (GJ/m3)[a]	2.67	3.10	1.30	2.03	2.22	2.48	2.29	2.27	2.49	-
Dehydration Temp (deg C)[a]	**81**	**71**	**65**	**110**	**72**	**127**	**113**	**28**	**122**	**>150[d]**
Dehydration Mechanism [a]	6 → 0	6 → 0	1.5 → 0	2 → 0	3 → 0	6 → 1	6 → 0	7 → 1	6 → 0	-
Density (hydrate)	2.0	1.5	2.0	1.6	1.5	1.5	1.5	1.7	2.4	-
Density (anhyd)	3.35	2.15	2.43	3.46	2.07	2.32	2.30	2.66	4.22	
Energy Capacity per kg (kJ/kg)[c]	797	1442	535	587	1072	1069	996	853	590	480[b]
Salt loading on absorbent (as anhyd) (%)[d]	73.5	68	62	70	57	40	54	46	67	-
Bulk Density of salt/absorbent TCM (dry)[d]	0.375	0.221	0.215	0.307	0.217	0.221	0.249	0.200	0.297	0.64
Energy Density (kJ/l)[e]	**220**	**217**	**71**	**126**	**133**	**94**	**134**	**78**	**117**	**307**
Energy Density (kWh/m3)	**61**	**60**	**20**	**35**	**37**	**26**	**37**	**22**	**33**	**85**
Energy Density (RT-h/USG)	**0.066**	**0.065**	**0.021**	**0.038**	**0.040**	**0.028**	**0.040**	**0.023**	**0.035**	**0.092**
Energy Density (Btu/USG)	**789**	**778**	**256**	**453**	**476**	**339**	**481**	**282**	**421**	**1102**
TCM bulk material cost (£(GBP)/lt)	**4.92**	**1.54**	**2.40**	**23.76**	**18.27**	**1.33**	**1.50**	**1.43**	**9.72**	**2.88**
TCM bulk material cost (US$/lt)	**6.15**	**1.92**	**3.00**	**29.71**	**22.84**	**1.66**	**1.88**	**1.79**	**12.15**	**3.60**
TCM bulk material cost (US$/USG)	**23.30**	**7.28**	**11.36**	**112.52**	**86.50**	**6.30**	**7.11**	**6.77**	**46.02**	**13.64**
TCM bulk material cost (€(Euro)/lt)	**5.66**	**1.77**	**2.76**	**27.33**	**21.01**	**1.53**	**1.73**	**1.64**	**11.18**	**3.31**
Energy density cost (£(GBP)/kWh)	**80.64**	**25.55**	**121.14**	**678.20**	**496.01**	**50.66**	**40.39**	**65.56**	**298.01**	**33.77**
Energy density cost (US$/RT-h)	**354.83**	**112.43**	**533.00**	**2984.07**	**2182.46**	**222.93**	**177.72**	**288.45**	**1311.24**	**148.60**
Energy density cost (US$/MBtu)	**1561.27**	**494.69**	**2345.21**	**13129.92**	**9602.81**	**980.87**	**781.95**	**1269.19**	**5769.46**	**653.83**
Energy density cost (€(Euro)/kWh)	**106.65**	**33.79**	**160.20**	**896.92**	**655.98**	**67.00**	**53.42**	**86.70**	**394.12**	**44.66**

Notes;

a = http://dx.doi.org/10.1016/j.apenergy.2017.04.080
b = http://dx.doi.org/10.1016/j.enconman.2017.03.080
c = energy capacity (GJ/m3) / density (anhyd)
d = exptal data but ideally one has to closer to 250C levels for safe operation
e = (energy capacity (kJ/kg) x salt loading (%) x bulk density) / 100

As these low temperature TCM will require absorbent materials and the most common TCM as absorbent tend to be vermiculite (sometimes perlite) and Table 5-4 highlights the possible combination of various salts which reacts with moisture to generate heat.

Table 5-4: Vermiculite with various salt solutions data [5].



Salt/vermiculite TCM properties	Calcium Bromide	Calcium Chloride	Potassium Carbonate	Lithium Bromide	Lithium Chloride	Magnesium Chloride	Magnesium Nitrate	Magnesium Sulphate	Strontium Bromide	Zeolite (X13)
Energy Capacity (lit) (GJ/m3)[a]	2.67	3.10	1.30	2.03	2.22	2.48	2.29	2.27	2.49	-
Dehydration Temp (deg C)[a]	81	71	65	110	72	127	113	28	122	>150[d]
Dehydration Mechanism [a]	6 → 0	6 → 0	1.5 → 0	2 → 0	3 → 0	6 → 1	6 → 0	7 → 1	6 → 0	-
Density (hydrate)	2.0	1.5	2.0	1.6	1.5	1.5	1.5	1.7	2.4	-
Density (anhyd)	3.35	2.15	2.43	3.46	2.07	2.32	2.30	2.66	4.22	
Energy Capacity per kg (kJ/kg)[c]	797	1442	535	587	1072	1069	996	853	590	480[b]
Salt loading on vermiculite (as anhyd) (%)[d]	73.5	68	62	70	57	40	54	46	67	-
Bulk Density of salt/vermiculite TCM (dry)[e]	0.375	0.221	0.215	0.307	0.217	0.221	0.249	0.200	0.297	0.64
Energy Density (kJ/l)[e]	220	217	71	126	133	94	134	78	117	307
Salt cost (GBP/kg)[f]	4.50	0.75	3.00	35.00	46.00	0.49	0.75	0.83	14.27	1.50
vermiculite cost (GBP/l)[g]	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
TCM cost (GBP/lt)[h]	1.64	0.51	0.80	7.92	6.09	0.44	0.50	0.48	3.24	0.96

5.1.3 Case Studies

5.1.3.1 HVAC Systems

As a retrofit, a UK house heating is converted to TTES concept (as illustrated in Figure 5-2), whereby the low temperature (70~90 °C) regeneration TTES is absorbed in vermiculite and dried out using solar thermal collectors. Once it is regenerated using a conventional humidifier, it is activated, and the reaction creates heat which is transferred into the house using small fans as part of the solar heating system. As the process is reversable, this regeneration i.e., drying and hydrating process can be repeated. Although this installation utilized solar thermal collectors, the same process can be activated using heat pump or off- peak electricity.

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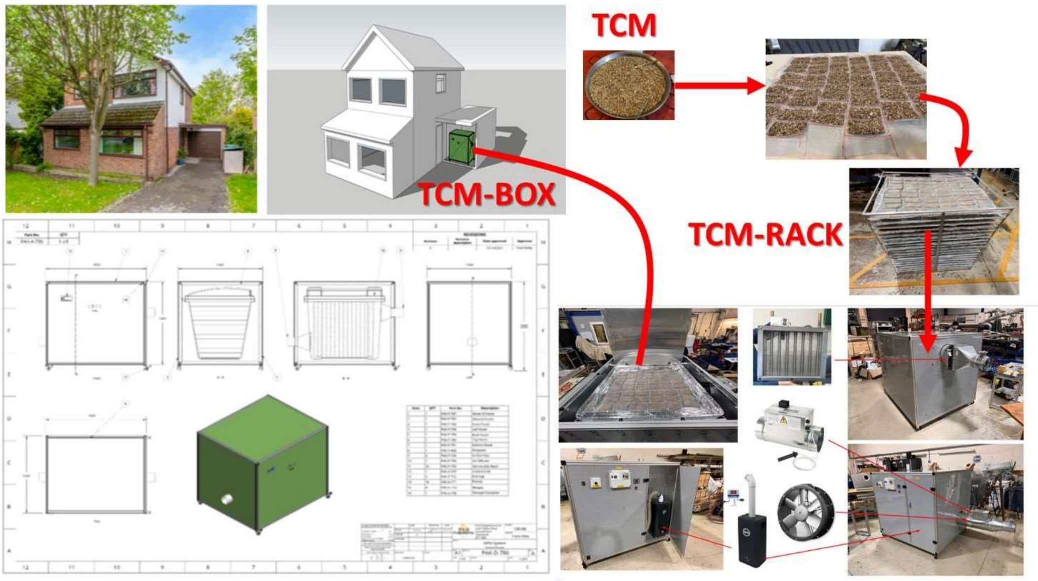

Figure 5-2: UK House TTES heating conversion [5].

5.1.3.2 Solar Energy (water harvesting)

TTES can be utilized as a practical solar driven solution for atmospheric water harvesting. TCM captures the moisture present in the atmosphere, offering a sustainable and environmentally friendly approach to address water scarcity. The system’s core innovation lies in its ability to efficiently extract moisture from the air via highly absorbent TCM, converting it into clean, consumable water. This is achieved through a combination of advanced methods that ensure optimal water collection. The technology is designed to be energy-efficient, primarily operating on solar power. This not only reduces operational costs, but also minimizes the environmental footprint, making it a green solution for water procurement.

The device functions by harnessing the potential of two key technologies. The first technology focuses on the efficient storage of atmospheric moisture, while the second is geared towards the adsorption process, ensuring that the collected moisture is free from contaminants and suitable for consumption. Each process is done in individual boxes interconnected as illustrated in Figure 5-3. The cold is stored by PCM freezing during night, and moisture is adsorbed in the TCM, while during daytime the sun extracts the stored moisture/water from TCM and heats the air which passes over cold PCM plates, where the water condensates and is collected at the bottom. Together, these technologies (PCM and TCM) work in tandem to provide a consistent and reliable source of clean water.

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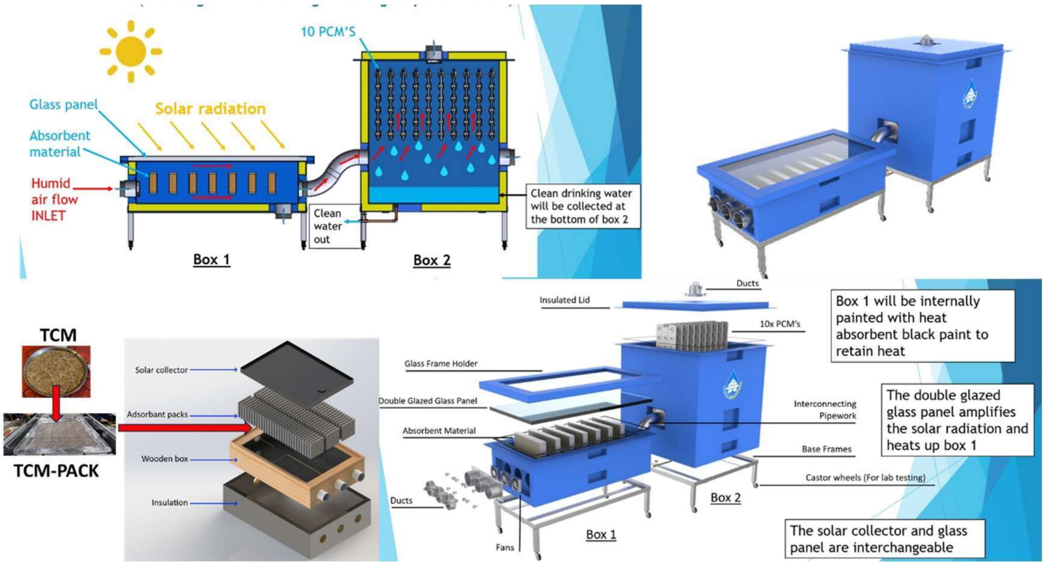

Figure 5-3: TTES solar application [5].

5.1.3.3 Industrial Processes

Not only due to the high temperature energy utilized in industrial processes, but also to non-stop continuous production of the industrial production areas, TTES offers far better opportunities for these applications. Heat generated by the production can be utilized in three ways, as illustrated in Figure 5-4. Firstly, internally one-to-one direct heat recovery without any storage, where heat from one production side can be directly transferred to another part of the plant, for direct usage. However, if there is a gap between the energy availability and energy use, a TES system is required. They can be STES or LTES, but the lowest heat losses can be achieved with TTES systems, that makes them ideal for long-term storage of any waste energy.

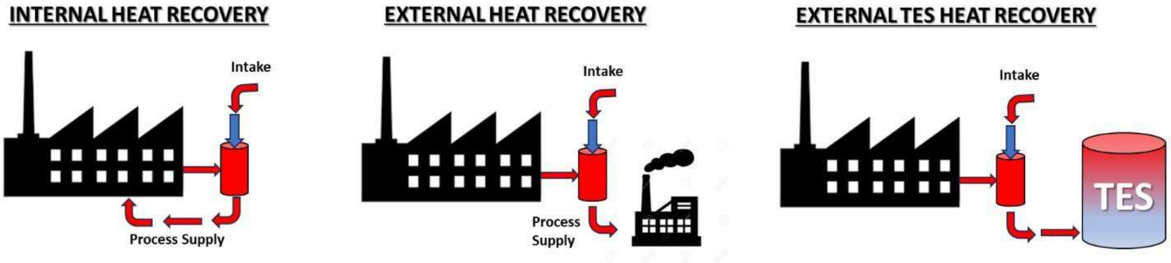

Figure 5-4: Industrial energy recovery [5].

In particular, if the energy from the process is required to be transported, as illustrated in Figure 5-5, similarly to what already seen for PCM, the light weight of TCM makes them ideal, since as lighter the energy storage material, as higher the energy density can be transported within the road weight limits. Considering the relatively low cost of TCM combined with low-cost tanker design, TTES offers a significant opportunity for transporting waste thermal energy from one process to another location. First applications of this solutions have been demonstrated in Germany using a zeolite within a road tanker.

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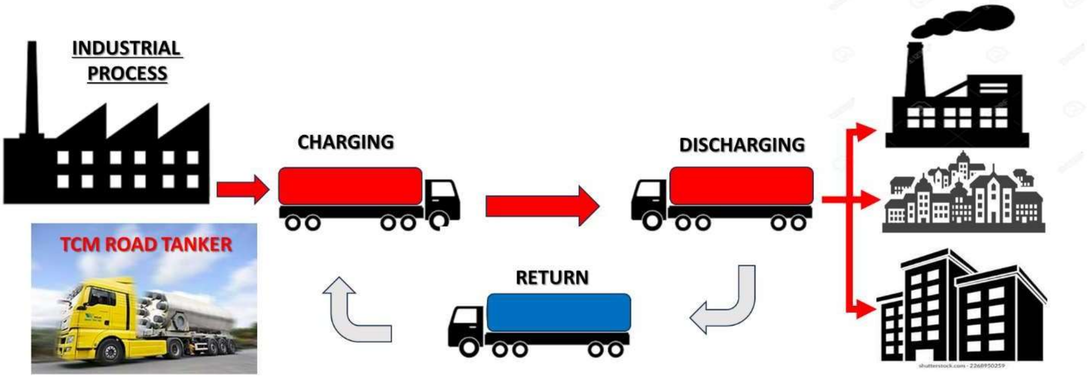

Figure 5-5: TTES tanker heat recovery process [5].

5.1.3.4 Waste Heat Recovery

An example of waste heat recovery is provided by a Swedish company exploring a large-scale energy storage technology based on dried salt, aiming to discover how surplus electricity generated by wind power and solar power plants can be stored as heat in dried salt. As the energy stored in salt can be kept for weeks or months until it is needed without any heat losses, it offers a cost-effective long-term TES option. Salt is retained in sealed containers and by simply adding water to the dry salt (calcium oxide), the salt turns into calcium hydroxide. The water starts a chemical process, which generates heat, and the temperature will rise to approximately 120 °C. If you add hot steam instead of water to the salt, the steam temperature will rise up to 500 °C. A typical application example is illustrated in Figure 5-6.

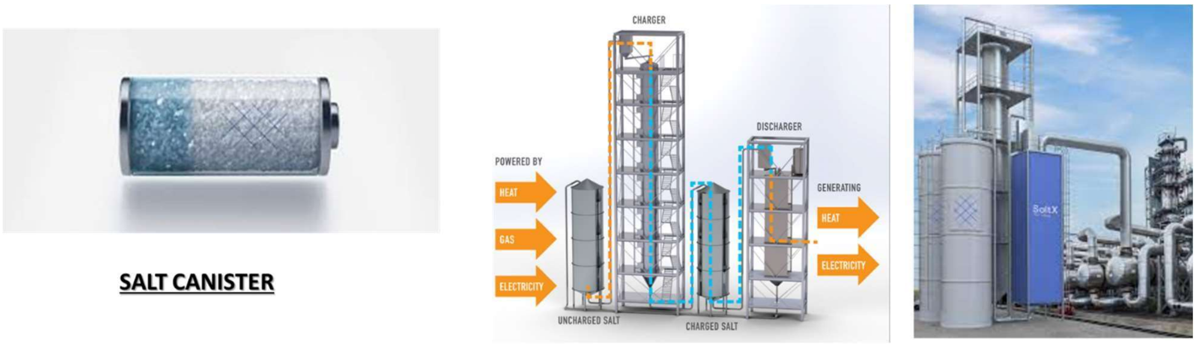

Figure 5-6: Salt based TES systems [26].

5.1.3.5 Electrical Vehicles

Figure 5-7 shows the schematic of a proposed system of heat storage and production in an electrical vehicle. The adsorption reactor stack consists of multiple modular adsorption units, each layer of which can be independently controlled by an individual valve to produce heat when required. These adsorption units can be utilized sequentially to avoid the consumption of substantial sensible heat at the onset of energy discharge and to achieve a rapid temperature increase of the supply air. The initiation of the adsorption reaction in each modular unit is controlled by opening the corresponding valve between that modular unit of the reactor and the evaporator. The implementation of such a valve control has been previously studied and

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demonstrated to enable precise control over the flow of working gas passing through selected layers of the unit.

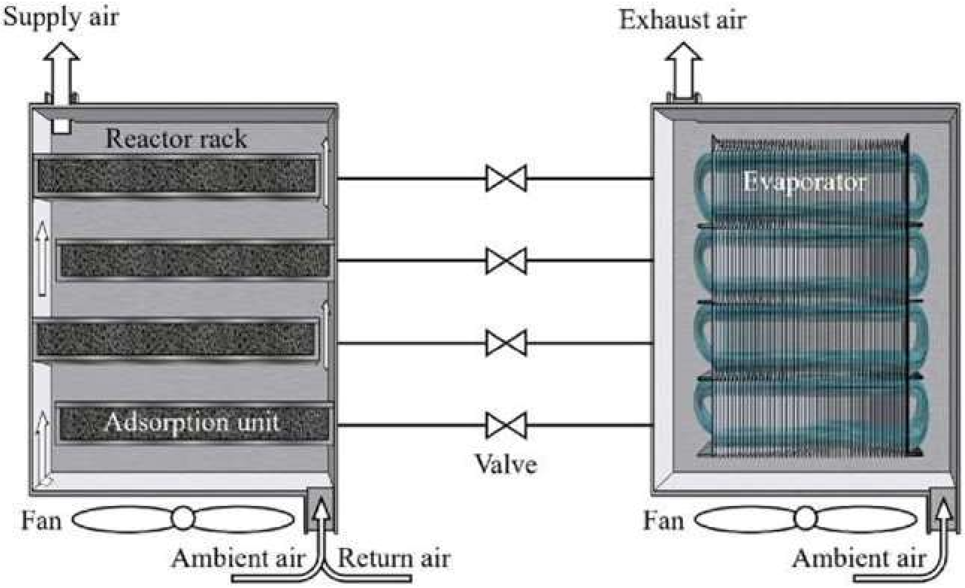
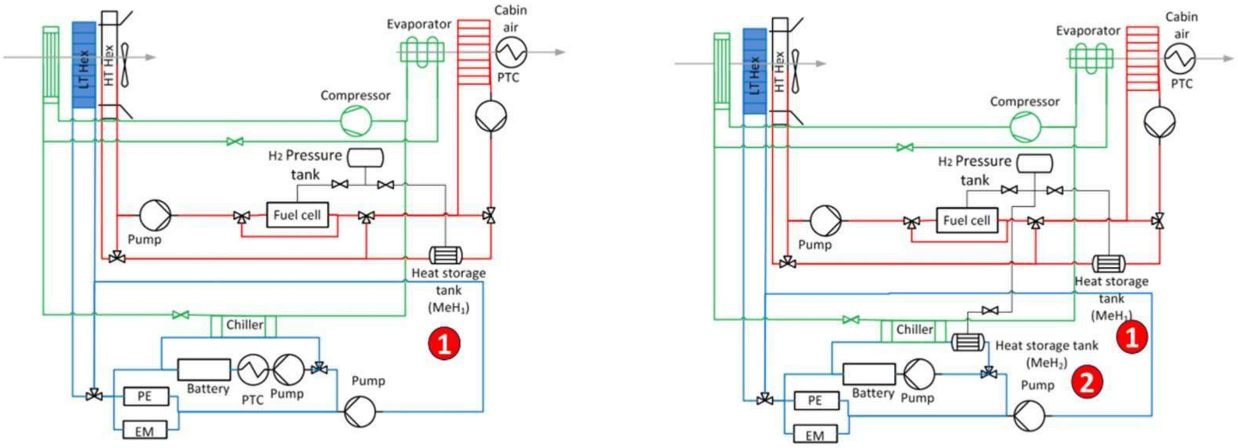


Figure 5-7: EV car cabin heating concept [5].

Fuel cell electric vehicles have the advantage over battery electric vehicles, because they produce higher waste heat, which can be used for heating purposes. When the fuel cell is activated, the generated waste heat is around 40 % of the consumed fuel power and can be used for the cabin and battery heating. However, at the beginning of vehicle operation, there is not sufficient waste heat for the preheating of the battery, cabin and even the fuel cell itself. This lack of waste heat is usually covered by a positive temperature coefficient (PTC) heater, which converts the electricity from the battery into heat, and consequently the electric range is considerably reduced. Waste heat recovery concept with one or two TTES tanks containing TCM are presented in Figure 5-8.



Single Heat Storage Tank

Double Heat Storage Tank

Figure 5-8: Fuel cell car heat recovery TTES concepts [27].

Thermochemical reactors are operated independently and are connected via a hydrogen pipe to a hydrogen pressure tank. The choice of different metal hydride TCM is very important to allow the coupling between both reactors and to generate heat and cold in different places without the use of the hydrogen pressure tank and the fuel cell as hydrogen sink when the fuel cell is deactivated.

5.2 Sorption Thermal Energy Storage (STES)

5.2.1 Mechanism of Sorption TES

Always amongst TCMs, we can consider Sorption Thermal Energy Storage. In this case, sorption-based systems are classified, in relations to the reactants involved in the reaction, into sub-groups (1) solid adsorption, (2) liquid absorption, (3) chemical reactions, and (4) composites formats, and they all have certain pros and cons for specific applications. Some of the potential chemicals for Sorption TES applications are highlighted in Figure 5-9.

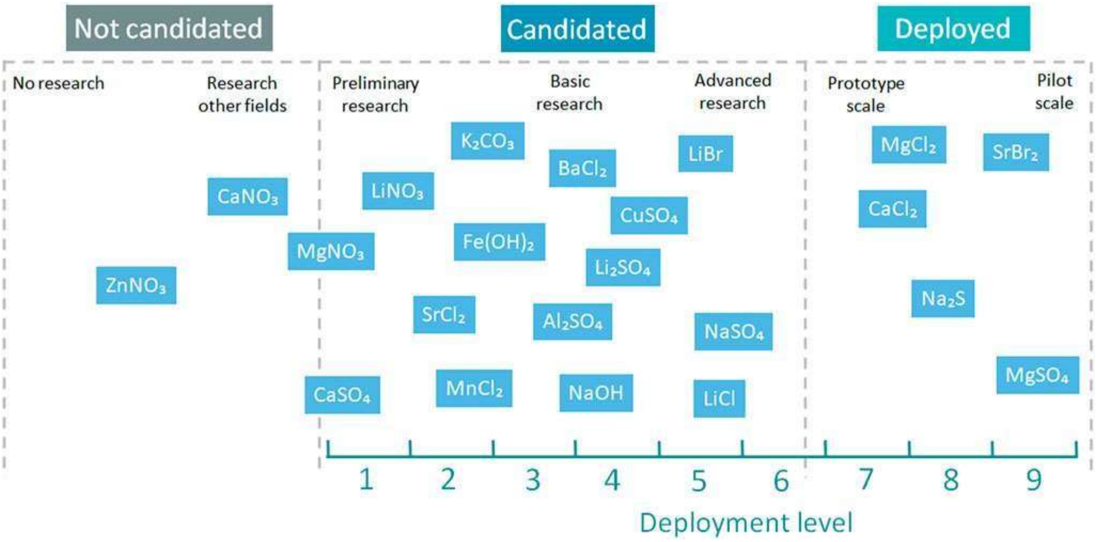


Figure 5-9: Potential solution materials for sorption TES [5].

Sorption storage material manufacturing routes to market:

All the solutions covered in the previous figure must be applied as a product, and therefore they require some base form to apply, whether in powder, film, absorbent based. The challenges at the material level significantly influence the manufacturing strategies, which at the same time limit the technology.

There are several technologies that can be applied to house the proposed salts, and at present the manufacturing routes are divided between conventional manufacturing procedures (shaping and insertion in a binder) and emerging manufacturing procedures (nano-alternatives, encapsulation, and extrusion). All these procedures are summarized in Figure 5-10. Little has been carried out on large-scale manufacturing of thermochemical materials, and most work is still at laboratory scale levels (from grams to kilos). The fact is that there is still no agreed approach in the manufacturing process at the laboratory scale, not to mention large scale manufacturing.

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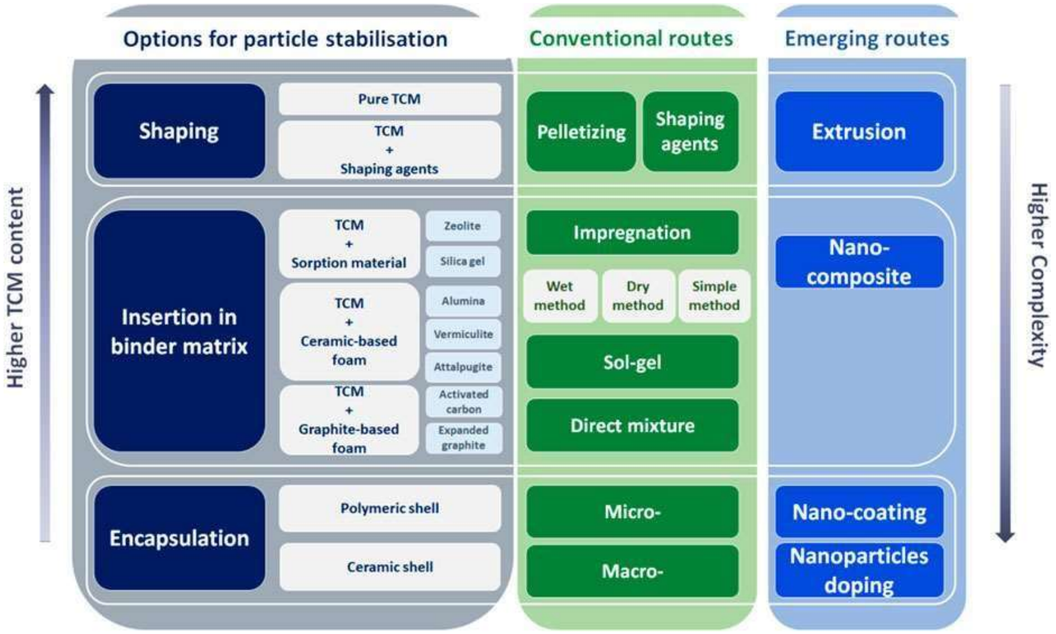

Figure 5-10: TTES materials manufacturing routes.

5.2.2 Sorption TES Medium

Sorption TES is a promising technology for effectively utilizing renewable energy, industrial waste heat and off-peak electricity owing to its remarkable advantages of a high energy storage density and achievable long-term energy preservation with negligible heat loss. It is the latest TES technology in recent decades and remains in the laboratory investigation stage.

Sorption TES system has prominent advantages, including a high storage density arising from the large bonding force between the sorbent and sorbate, as well as the feasibility of long-term energy preservation with ignorable heat loss once the sorbent and sorbate are separated.

Sorption materials are the basis for developing sorption energy storage systems, and the main selection criteria is as follows [70]:

- Good thermal stability and mechanical strength
- High sorption capacity
- Large energy storage density
- Low charging temperature
- High thermal conductivity / heat and mass transfer
- Non-toxicity, non-corrosiveness
- Environmentally acceptable
- Low cost

Some of the most common TCMs which were applied/considered for Sorption TES applications are given below.

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Sulphates-Based Options:

Magnesium Sulfate

Magnesium sulfate is one of the TCMs that accounts for higher energy density and is widely studied for seasonal storage as it offers theoretical energy of up to 2.8 GJ m^{-3}. However, the use of magnesium sulfate powder is difficult in a storage reactor because the particles rapidly form agglomerates during dehydration/hydration cycles, thus liming gas transfer and causing reversibility issues and low temperature lift, resulting in poor system performance.

Calcium Sulfate

Calcium sulfate is mostly used in industrial processes (limestone–gypsum flue gas desulfurization (FGD), production of phosphoric acid or phosphate fertilizers) and has not been boarded to thermochemical storage. As a binder and building material, the main focus of use remained in hydration–dehydration processes of calcium sulfate for chemical heat pumps due to high heat density, negligible expansion in hydration, long-term storage of the absorbent and products, and low heat loss.

Copper Sulfate

Copper sulfate ($CuSO_4$) is a salt hydrate material and has the advantage of relying on low-temperature heat source of 60–85℃. Hence, it is ideally suited to be driven by solar energy or other low temperature renewable energy heat source as low as (55–85 ℃), allowing the activation energy of 25.053 kJ/mol.

Aluminum Sulfate

Aluminum sulfate hydrated salt offers attractive dehydration temperature and high enthalpy of hydration/dehydration, which made it to be considered one of the most promising TTES materials. It can be applied for working temperatures between 50 and 150 ℃.

Other Sulphates

Li_2SO_4 and Na_2SO_4 have not shown significant reversibility under 100 ℃, when subjected to a heating rate of 10K min. Furthermore, acute toxicity and, like all lithium materials, limited lithium resources limit the use of these materials even if we ignore the high cost.

Carbonates-Based Options:

Potassium Carbonate

Potassium carbonate in theory may offer as high as energy density of well above 1.3 GJ/m^3 with a hydration temperature above 50 ℃, dehydration temperature below 120 ℃, and a melting point above the dehydration temperature. It offers low volume change while acceptable corrosive levels. Its wide availability, reasonable capacity for water uptake, and energy density at low temperatures (below 100 ℃), while better stability than other salts that show higher energy density attributes,

Bromides-Based Options:

Strontium Bromide Hexahydrate

Strontium bromide is the promising salt along with magnesium sulfate for solar cooling and heat storage in a closed process, or seasonal storage of solar energy in an open process. The high enthalpy ($\Delta H^{\circ} r = 67,400$ J·mol^{-1}G) and density of hexahydrated strontium bromide (2.386 g/cm^3) allow the salt to reach a high energy storage density. In addition, its high melting point enables a charging/discharging melting-free process. Its

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theoretical energy storage is very high with 628 kWh/m^3, small scale trials achieved scale 400 ~ 531 kWh/m^3 energy density. It may be possible to operate around a temperature ranging from 80°C to 90°C, which is sufficient to ensure the dehydration from hexahydrate to monohydrate without incongruent dissolution of water vapor in the solid phase, given the melting point.

Lithium Bromide Monohydrate

Most studies of this material targeted the use as an adsorption system for solar heating. However, lithium bromide can also be considered for ‘open’ TES interseasonal systems, the reaction by water sorption without bringing the salt to the solution. The energy storage is estimated to be around 1.1 and 2.8 kJ/g in the temperature range from 30 °C to 140 °C.

Zinc Nitrate Hexahydrate

Theoretical energy density of around 1.5–1.7 GJ/m^3 and a dehydration–hydration temperature range that meets the common heat recovery system requirements. The thermal decomposition of zinc nitrate indicated that dehydration starts at 30 °C, which is accompanied by the melting at 35 °C. According to them, dehydration occurs in three consecutive steps that finish at 120 °C. The decomposition of nitrate groups starts at 75 °C and ends at 265 °C, forming ZnO as the final product.

Calcium Nitrate Tetrahydrate

Calcium nitrate tetrahydrate is one of the most commonly used inorganic salts, given its high latent heat and low melting point. The salt melts at around 40~45 °C forming a saturated solution that with increasing temperature becomes unsaturated. Until the boiling point, the salt does not lose water, while above 135 °C, the solution starts losing water.

Lithium Nitrate Trihydrate

Lithium nitrate trihydrate has also been studied as a potential candidate for TTES. One of the main problems and reasons for not being extensively studied, as with all lithium materials, is their use limitation due to lithium resources.

Chlorides-Based Options:

LiCl, $MgCl_2$, and $CaCl_2$ are highly hygroscopic and form a solution in a closed system, which is referred as deliquescence, resulting in salt segregation, corrosion in sorption reactors, and deterioration of heat and mass transfer of sorbents. Calcium chloride and magnesium chloride exhibit high energy density at the desired operational temperatures, but magnesium chloride suffers from thermal decomposition and HCl formation and deliquescence below 40 °C.

Calcium Chloride

At present, $CaCl_2$ has been already applied for air dehumidification in buildings. Calcium chloride also has the potential to be used as a PCM, given its melting point of around 30 °C. For sorption applications, it shows a tendency for agglomeration.

Magnesium Chloride

It is a promising potential of seasonal heat storage option in terms of energy density and charging/discharging temperature. However, the main issues with magnesium chloride are the instability and decomposition over cycles. Especially at ambient temperatures, it tends to overhydrate into a solution, which causes inhomogeneous dehydration. Furthermore, the chlorides decompose into magnesium hydroxy chloride involving a release of hydrochloric acid above 150 °C.

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Lithium Chloride

It is widely used as desiccant solution in commercial rotary dehumidifiers. It is a hygroscopic salt with high chemical stability, and equally shows significant potential for sorption TES with its large water sorption capacity. However, since it is a highly hygroscopic salt, it is likely to turn into a liquid solution when in contact with water vapor. In theory it may offer an energy density of 2.08 GJ/m^3 in an open system and 1.36 GJ/m^3 in a closed system.

Strontium Chloride

The high energy storage density of 2.6 GJ/m^3 offers a great potential for TTES material which can be regenerated at 90 °C levels and release 80% of its energy storage capacity at this level of low-grade heat.

Barium Chloride

The $BaCl_2$-H_2O system is one of the few hydrates that has been demonstrated to undergo fully reversible dehydration–hydration reactions. Dihydrate to monohydrate and monohydrate to anhydrous salt reactions are commonly observed to proceed in a stepwise manner; however, under moderate vacuum conditions the reactions overlap, and dihydrate reacts directly to form the anhydrous salt.

Hydroxides

Hydroxides, such as $Fe(OH)_2$, have been considered as potential TCMs for solar seasonal storage. The operating range is between 60 °C and 250 °C, and the energy storage density is higher than 1 GJ/m^3. It could be an option, but so far very little experience and trials have been carried out on this material. Although it is abundant and easy to mine, there is a lack of technical/practical applications. Consequently, it requires further developments.

Sulphides

It offers a large energy density of 2.66 GJ/m^3, but it is highly corrosive and reactive with the risk of outgassing. The physical instability involves phase transitions of sodium sulphide hydrate salts at a temperature of 49°C, a phase transition of the nonahydrate salt to the pentahydrate salt occurs while simultaneously a solution of sodium sulphide forms. At a temperature of 83°C the pentahydrate structure partially dissolves while it forms a solution of sodium sulphide. Moreover, the environmental issues due to the toxicity of the salt hydrate and its by-products such as hydrogen sulphide should not be overlooked.

Some popular salt candidates' respective properties are summarized in Table 5-5, including volumetric energy density, the deliquescence relative humidity (DRH) at 25 °C, dehydration temperature and cost level. $CaCl_2$ is one of the most promising sorbents with the advantages of easy availability, low cost, high sorption rate, good chemical stability, low corrosiveness, and non-toxicity. Comparatively, $MgSO_4$, LiCl, $MgCl_2$, $SrBr_2$ and $SrCl_2$ are the preferred salt hydrates for TAHS systems owing to their high theoretical volumetric energy storage densities (i.e., >2.1 GJ/m^3). By adopting high energy-density hydrates, less volume is required for storage, which could be beneficial for domestic TAHS applications. In particular, $SrCl_2$, which exhibits the highest theoretical energy density of 4.9 GJ/m^3, is a relatively new salt used in thermochemical heat storage research.

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Table 5-5: Some popular salt candidates' respective properties [28-34,71].

Salts	Volumetric Energy Density	DRH at 25°C	Dehydration Temperature	Cost
	GJ/m^3	%	°C	
K_2CO_3	1.3	43	93	Low
$CaCl_2$	2.2	28	45	Low
$LiNO_3$	1.8	13	93	Moderate
$MgCl_2$	2.1	33	>150	Moderate
$SrBr_2$	2.2	60	90	High
LiCl	2.4	11	65.6	High
$MgSO_4$	2.8	92	>120	Moderate
$SrCl_2$	4.9	12	61	Moderate

5.2.2.1 Absorption

Due to the high energy storage density and long-term storage capability, absorption TES is attractive for the utilization of solar energy, waste heat, off-peak electricity, and etc. In recent years, absorption TES has been intensively studied from thermodynamic cycles, working pairs, and system configurations for various purposes due to its potential high energy density. Most promising working pairs including water-based working pairs, ammonia-based working pairs, alcohol-based working pairs, and others are under consideration.

5.2.2.2 Adsorption

The physical process of sorption in general is characterized by the take-up and accumulation of one material by means of a second material. The aggregate state of the second material is solid or liquid. The accumulation of a material on a surface is called adsorption. In the case of the accumulation in the liquid phase the process is called absorption. Adsorption and absorption are exothermal processes. The release of the material is called desorption which is an endothermic process.

Adsorption storage systems use a combination of two different materials. One is the adsorbent as the solid material (e.g., zeolite) and the other one is the adsorbate as the gaseous material (e.g., water vapor).

Adsorption heat storage is nearly free of heat losses over a long period of time. After charging, the storage tank can cool down to ambient temperature, but the energy stored remains constant as long as the two materials (adsorbent, adsorbate) are kept separate.

The main components of an adsorption storage unit are the adsorber storage reactor with an internal heat exchanger, an external heat exchanger, an evaporator, and a condenser. A typical combination of Zeolite and Silica Gel combination might have an energy storage density between 180 kWh/m^3 and 220 kWh/m^3.

Closed-cycle adsorption system:

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In a closed-cycle system heat exchangers are embedded within the adsorbent to transfer heat from the heat source to the load. These systems typically operate at low pressure. During charging, the storage reactor is heated to release water vapor, which is condensed and stored in a separate vessel. The heat from the condenser is either rejected to the surroundings or may be used to meet the load. To discharge the system, the stored water is transported to an evaporator where a low temperature source provides the energy for evaporation. The evaporated water passes through the storage reactor where it is re-adsorbed by the adsorbent thereby releasing its energy.

Open-cycle adsorption system:

In an open-cycle system the heat exchangers are external to the integrated storage reactor. During charging, the heated air stream is circulated through the storage reactor to desorb water vapor. To discharge the system, moist ambient air is passed through the storage reactor. It exits the storage reactor as warm dry air which is passed through a load-side heat exchanger. There is no condenser or evaporator. The advantages of the open cycle are that: there are fewer components, the system operates at atmospheric pressure, and the heat exchangers do not scale with the volume of the storage. The disadvantage is that a source of warm moist air is required during the heating season.

5.2.2.3 Composite Thermochemical Material (TCM in matrix)

In addition to employing pure salt hydrates in thermochemical adsorption heat storage (TAHS) systems, composite adsorbent materials have been gaining increased research interest in recent years, which could address salt deliquescence-related issues. A composite adsorbent material is also called a ‘salt in the porous matrix’, in which a hygroscopic salt is embedded in a host matrix. Typically, the composite material is synthesized through the impregnation of the matrix with an aqueous salt solution [35]. A number of studies have been performed on adopting composite materials in TAHS systems, which could be beneficial for short-term and even seasonal energy storage in domestic and industrial applications. It is noteworthy that the energy storage performance of a synthesized composite material varies depending on the host matrix and the immersed salts, which implies the importance of optimal material selection and composition. Typically, a host matrix has a large pore volume with a mesoporous structure (e.g., an ideal pore size range of 2-50 nm), which can facilitate salt impregnation and benefit the kinetics of moisture migration [36]. Additionally, the structural stability of the host matrix is also an essential factor for consideration to ensure stable multicyclic performance [37].

Silica gel (SG) is the most commonly used host material, with features of chemical inertness, toxic-free, long life, low abrasion, low cost, and great feasibility under different conditions [38,39]. Extensive studies have been conducted on SG-based composites with various hygroscopic salt combinations for low-grade heat storage applications. For instance, Courbon et al. [40] synthesized a composite of SG-$CaCl_2$ (43 wt%), which demonstrated a high volumetric energy storage density of 211 kWh/m^3 (i.e., with adsorption reaction at 30 °C and desorption reaction at 80 °C). Their results reveal that the SG-$CaCl_2$ composite can be feasible for the TAHS systems by integrating solar thermal collectors. On the other hand, they also assessed the feasibility of an SG-$SrBr_2$ composite for the solar-assisted TAHS system, which provided a similar volumetric energy storage density of 203 kWh/m^3 as the SG-$CaCl_2$ composite [41].

Zeolite (Z) presents a regular nanoporous structure. Zeolites have been favorable host matrices with impregnation with different salts. Among various types of zeolites, synthetic zeolite 13X, with the largest permeability and high stability, offers outstanding suitability for thermochemical energy storage applications [42-44]. Whiting et al. [45] characterized two different zeolite-based composites, including Z-$MgSO_4$ (15 wt%)

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with an energy density of 970 kJ/kg and Z-$MgCl_2$ with an energy density of 1173 kJ/kg. The Z-$MgCl_2$ composite presented better heat storage performance, owing to the higher storage density of $MgCl_2$ and the blocking issue in the host matrix caused by the $MgSO_4$ particles. Researchers also found that one of the main challenges for zeolitic composites is their comparatively high dehydration temperatures (i.e., >120°C) for integration with low-grade heat sources and high costs [46].

Vermiculite (V) is a natural and non-toxic mineral. Structurally, vermiculite is a mixed-layered silicate crystal. The environmentally friendly vermiculite has been widely used as an active carrier for adsorbents, filter aids, chemicals, and fertilizers. As the host matrix, the lightweight vermiculite allows the reaction process to be more easily controlled and supplies energy when necessary [47-49]. For instance, Casey et al. [50] examined the V-$CaCl_2$ composite with a volumetric energy storage density of 290 kWh/m^3 and a charging temperature of 90 °C, which could be suitable for domestic thermal energy storage applications. The characterization analysis carried out by Jarimi et al. [51] suggested that the vermiculite-based composites are appealing for long-term energy storage in building applications, owing to the features of flexibility, availability, low cost and low charging temperature below 80 °C. Brancato et al. [36] observed a slower reaction kinetic in the vermiculite-based composites (i.e., impregnated with LiCl and LiBr, respectively) compared with the SG-based composites. They reported that the V-LiCl composite has a volumetric energy density of 111 kWh/m^3 and a desorption temperature of 90 °C.

5.2.3 Case Studies

5.2.3.1 Solar Energy

Sorption-based long-term TES

Research on a liquid sorption storage process is carried out with the working pair sodium hydroxide (NaOH)/water. This activity has started in 2002 with a first laboratory testing plant funded by the Swiss Federal Office of Energy (SFOE), followed by a pilot storage plant in an EU-funded FP7 project COMTES in 2013-2016.

Recently, a novel heat and mass exchanger has been developed and tested. Optimization on power density is ongoing along with research on understanding the basic phenomenon of absorption from a gaseous into a liquid phase. In the frame of the Swiss Competence Center of Energy research “Heat and Electricity Storage” (SCCER HaE) and an SFOE Pilot and Demonstration project this research is followed by an upscaling process of the heat and mass exchanger along with its integration in the NEST research and innovation platform and ehub demonstrator. As part of participation in the combined IEA SHC Task 58 / ECES Annex 33 material characterization and evaluation along different scales, from materials to systems, is further carried out (Figure 5-11).

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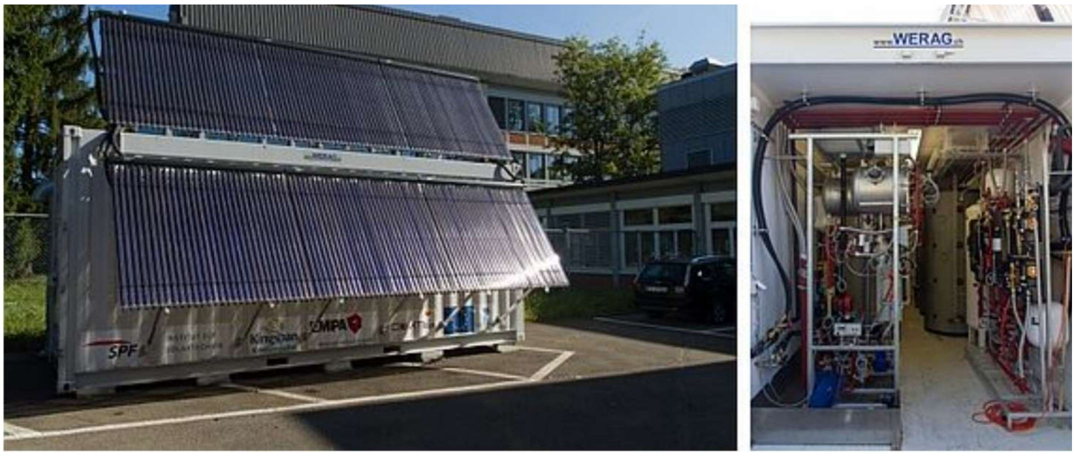

Figure 5-11: Pilot-scale storage plant combining long-term sorption storage and short-term sensible de- signed to cover yearly energy demand of a low-energy single family home [52].

5.2.3.2 District Heating and Cooling

Figure 5-12 clearly indicates that there are significant opportunities as part of a district energy systems for both cold and warm TES and sorption TES could be a useful tool towards this aim due to very low heat losses. However, so far no commercially viable option has emerged, and most studies have remained in academia and small trial installations.

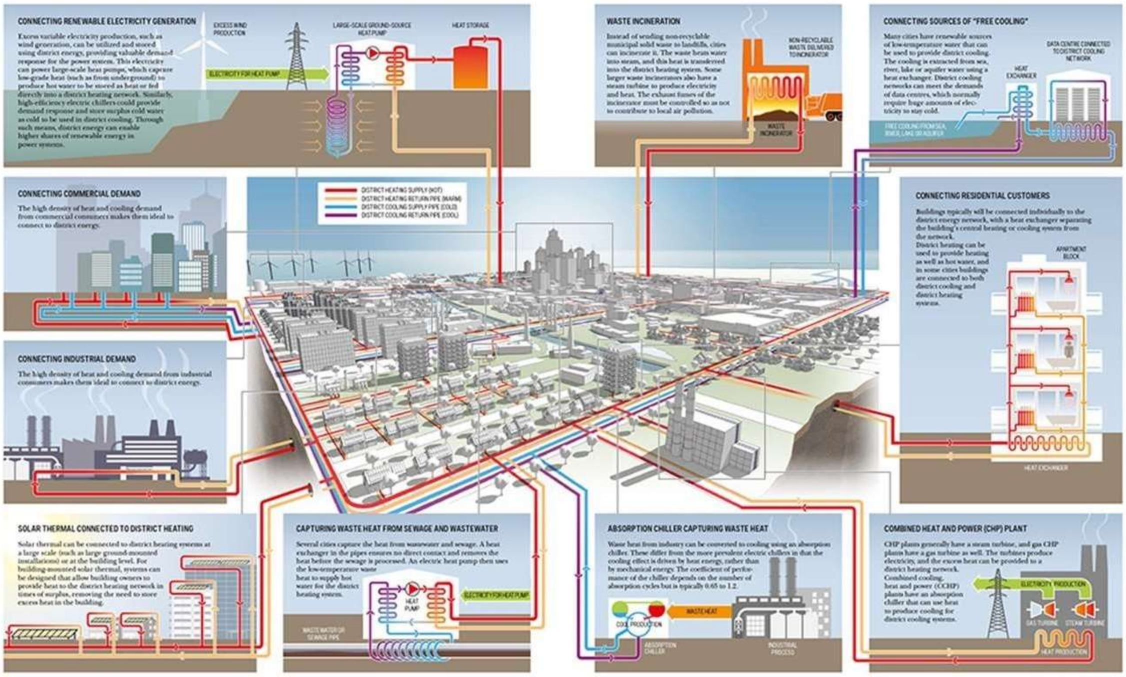

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Figure 5-12: TES possibilities around a district energy system [53].

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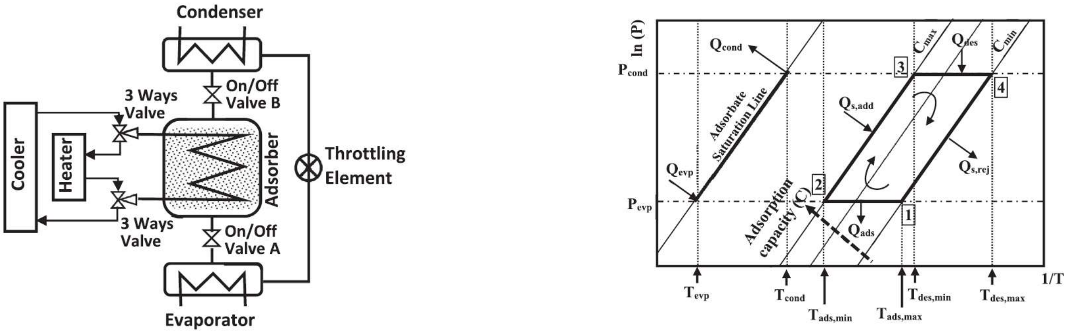
5.2.3.3 HVAC Systems

A recent review has been published [54], showing case studies of sorption materials applied to cooling systems for building applications.

Absorption machines are well known technologies, and several commercial systems are already present since long time in the market. They mainly operate with $H_2O/LiBr$ or NH_3/H_2O. For cooling purposes, they can operate between 80 °C and 120 °C. The cooling capacity for commercial machines ranges from 10 kW to over 1 MW.

Adsorption cooling systems are less common in commerce, although present in literature since quite long time. A typical adsorption system includes an evaporator, an adsorber, a condenser, a throttle, a heater, and a cooler, as shown in Figure 5-13a. The adsorber is packed with solid adsorbent material while the evaporator is charged with the adsorbate material (refrigerant). The adsorption system is derived by consequent actions demonstrated on the thermodynamic cycle represented in the Clapeyron diagram, see Figure 5-13b. Adsorption action occurs when the solid adsorbent material is cool and relatively dry, reducing surface vapor pressure than the adsorbate vapor pressure. This yields a strong attraction to the adsorbate vapor generated in the evaporator due to the evaporator's appropriate designed pressure conditions. Adsorption action continues until the adsorbent material is loaded with the maximum possible adsorbate capacity (namely saturation limit).



a b

Figure 5-13: Schematic of an adsorption cooling systems (a) and corresponding Clapeyron diagram (b) [54].

Examples of adsorption systems working pairs are:

1- Physical adsorption pairs: NH_3/activated carbon, ethanol/activated carbon, silica gel/water, and zeolite/water.
2- Chemical adsorption: NH_3/metal chloride, hydrogen/metal hydrides, and water/metal oxides.
3- Composite adsorption working pairs: silica gel/water and chlorides, methanol/silica gel and chlorides, NH_3/ chlorides, porous media, water/zeolite, and foam aluminum.

Commercial machines are based on silica gel/water and the cooling capacity ranges from 4 kW to 1 MW.

The last type of cooling technology is the Dissociative Evaporative Cooling (DEC) technology, which may operate in two ways as shown in Figure 5-14. The cooling capacity of commercial machines based on DEC range from 2 to 300 kW.

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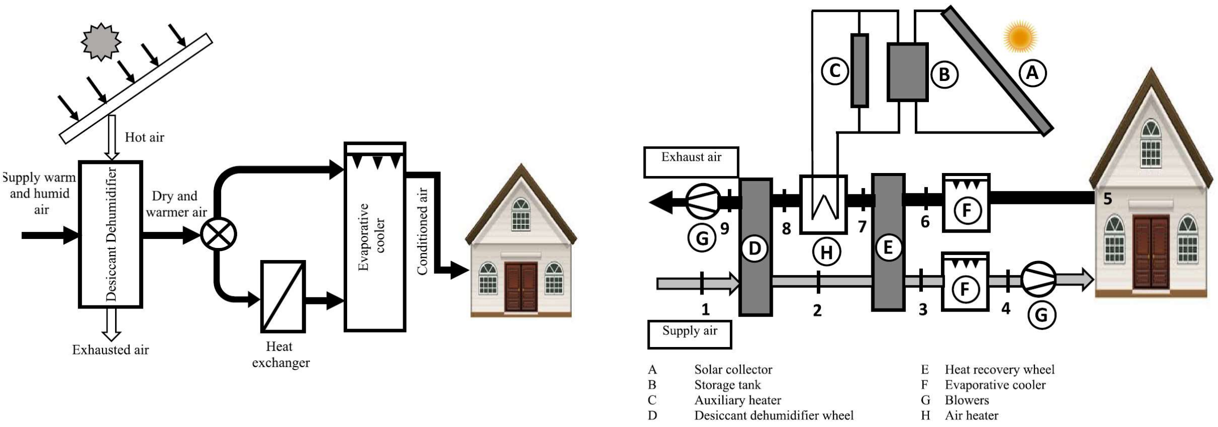

a b

Figure 5-14: Generic lay-out of the Dissociative Evaporative Cooling (a) and schematic of a DEC with solid desiccant wheel (b) [54].

As for thermal storage in buildings, laboratory scale tests have been developed in [55], where a high-powered energy dense zeolite thermal heat storage system using water vapor sorbate has been analyzed. The specification requirements of the system are to supply a heating power of 2 kW during 2 h to shave the electricity peak loads in a house. The open reactor has been designed, built, and instrumented with temperature sensors, chilled mirror hygrometer and airflow meter. Several tests have been carried out both during hydration – heat release – and dehydration – heat storage. Tests have also been carried out for different flow rates, relative humidity, and temperatures of hydration. The results show that the reactor can supply a constant power of 2.25 kW during more than two hours, namely 27.5 Wkg^{-1} of material.

Longer test has been performed in [56] as shown in Figure 5-15. The closed sorption storage system was designed to cover the domestic hot water and space heating demand of a single-family house with a heating demand of 30 kWh/m^3 and a living area of 140 m^2. The system consists of a collector area of about 12 m^2 of evacuated tube collectors, cylindrical tanks each filled with 1 m^3 of zeolite 13XBF. Additionally, there is a conventional stratified storage with 660 l and a hot water tank with a volume of 80 l for short term storage for space heating and domestic hot water, respectively.

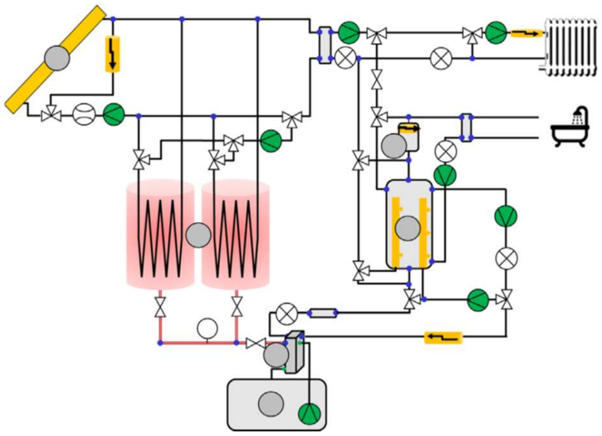

Figure 5-15: Scheme of the demonstration system with all important components and hydraulics used in [55].

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The system reliably worked during the full automated operation and the potential of the technology could be proved. During this period a solar fraction of 83.5% could be achieved due to the optimized control strategy. The application of the charge boost mode enabled a significant increase of the energy density, acting on the water concentration in terms of $g_{H2O}/g_{zeolite}$. As a result, the energy density results in a total energy density of 178 kWh/m^3.

A recent review on Low temperature sorption storage systems [57] has highlighted the following points.

- Research at material level is still needed to find a suitable active material with sufficient energy density, hydrothermal stability and cyclability in system operating conditions. Composite materials are promising but further research on host/active material working pairs is still necessary.
- Modular reactor layouts, especially in open systems, must be preferred to limit the pressure drops that in turn increase the auxiliary systems consumption. Separate reactors with efficient material transport systems can further increase the system performance by decreasing the overall reactor thermal mass.
- To make future research on sorption heat storage comparable, common key performance indicators should be adopted by the research community. For example, energy density at different research stages should be calculated defining a common reference temperature. Moreover, together with the energy density, the appropriate volume should be specified, which depends on the research scale (material, reactor, system).
- Economic considerations should be taken into account from the earliest stages of the research. Materials cost can already provide indications of the profitability of a future system in an intended application. When increasing the scale, all the components and auxiliary systems should be considered for the cost estimation.

6 Comparative Analysis of the Various TES Technologies

6.1 Technology readiness levels (TRLs)

The readiness or maturity of TES technologies is assessed based on the technology readiness level (TRL), a standardised reference value firstly introduced by NASA in 1974 and then adopted by the U.S. Department of Energy in 2011 [58] for evaluating the commercial readiness of a given technology. The TRL indicator includes nine levels of development:

- TRL 1 – basic principles observed.
- TRL 2 – technology concept formulated.
- TRL 3 – experimental proof of concept.
- TRL 4 – technology validated in lab.
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- TRL 7 – system prototype demonstration in operational environment.
- TRL 8 – system complete and qualified.

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- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).

TRL phases one to three are considered to be the ideas levels. The basic research has been done, the fundamental concept investigated, and a proof of concept developed. In TRL phases four and five represent the prototype level, the technology has been developed and approved in a laboratory or in another relevant environment. In TRL phases six and seven, the technology finds itself at the validation level, with demonstrations of its capacity occurring at a relevant operational environment. The final TRL phases eight and nine involve the production level. The technology is complete and approved and proved to work in its operational environment.

6.1.1 Latent Thermal Energy Storage (LTES)

Latent TES systems have achieved TRLs ranging from 7 to 9, indicating a high level of maturity and readiness for commercial deployment. This TES technology has undergone extensive laboratory testing and field demonstrations. However, further development is required to face crucial issues and achieve widespread commercial deployment.

One of the main challenges in assessing the TRL of latent TES is the need to address technical barriers such as PCM leakage, thermal cycling stability, and integration technologies. TRL strongly depends also on the field of application. Indeed, latent TES for building applications, both for cold and heat storage [59], has reached high TRL and has been put on the market in the last years. Similarly, integration of PCMs in the building envelope has been already proposed at market level, even if its economic feasibility is not completely proven, which is hindering its widespread application [60]. There are ongoing activities aiming at the optimization of materials also at low-medium temperature, for building applications [61-63]. Nevertheless, there are fields of application in which the latent TES technology is still at low TRL. For example, in high temperature applications, such as concentrated solar power and industrial plants, this technology is considered promising, but not yet completely developed for commercial application.

Significant advancements have been made in the field of latent TES, particularly in materials science and system design. Researchers have focused on developing PCMs with enhanced thermal properties and improved cycling stability. Moreover, innovative encapsulation techniques have been developed to prevent PCM leakage and ensure long-term durability. These advancements have contributed to the improved performance and reliability of latent TES systems, bringing them closer to commercial viability.

Despite the progress made, latent TES technologies face several challenges that hinder their TRL progression. One of the key challenges lies in optimizing PCM properties to achieve higher energy storage density and faster charging/discharging rates. Additionally, ensuring the scalability and cost-effectiveness of latent TES systems remains a formidable task.

6.1.2 Sensible Thermal Energy Storage (STES)

Sensible TES is a well-established technology already on the market for several years, with high TRLs in various applications. The TRL of sensible TES typically ranges from 7 to 9, indicating a high level of maturity and readiness for commercial deployment. These systems have undergone extensive testing and validation in real-world applications and in diverse sectors such as district heating, concentrated solar power, and industrial processes, demonstrating their reliability, effectiveness, and commercial viability.

Steady research and development efforts focused on improving thermal efficiency, durability, and cost-effectiveness with the aim to further elevate the TRLs of sensible TES technologies. The main development

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activities in the sensible storage field are focused on high temperature applications, such as concentrated solar power plants, for power production [64]. Indeed, for a temperature range between 200°C and 500°C, or even above, materials such as rocks and molten salts become promising, since they can withstand these temperatures, keeping their mechanical and thermo-physical properties almost unaffected. For such systems, efforts are devoted towards the proper material selection and reactor design, to optimize the TES performance [65]. For this reason, the TRL of solid materials (like stones, ceramic, sand, concrete) and molten salt still ranges between 5 or 6 and 9.

Furthermore, the integration of sensible TES systems with renewable energy sources such as solar and wind power holds immense potential for positioning them as key components of future energy systems.

6.1.3 Chemical Thermal Energy Storage (CTES)

6.1.3.1 Thermochemical Thermal Energy Storage (TTES)

Assessing the TRL of thermochemical TES technologies requires evaluating factors such as reaction kinetics, material stability, and system efficiency. The TRL of thermochemical TES systems ranges from 4 to 6. At this stage, thermochemical TES systems have undergone laboratory-scale demonstrations and proof-of-concept studies, showcasing their potential for practical applications.

However, despite the interesting features, namely, high theoretical storage density and long-term storage ability, thermochemical TESs are not yet at a sufficient TRL to be considered ready for the market. Further research and development are required to address technical challenges and enhance system performance before widespread commercial deployment can be realized. Especially for integration in buildings there are already several examples of promising prototypes, which can be operated both as daily and seasonal TES [66]. Nevertheless, further efforts are needed to make them ready for widespread application.

Among the main challenges hindering TRL progression there is the optimization of reaction kinetics to achieve fast charging and discharging rates. Additionally, the stability and durability of materials under cyclic operation remains a significant concern. Moreover, the complexity and cost of system integration pose challenges to the widespread adoption of thermochemical TES technologies.

For these reasons, progress focused on developing new reaction systems, optimizing reactor designs, and improving system efficiencies. Researchers have explored a wide range of chemical reactions and materials to identify suitable candidates for energy storage applications. Additionally, innovations in reactor engineering and heat transfer processes have contributed to improving the overall efficiency and reliability of thermochemical TES systems.

6.1.3.2 Sorption Thermal Energy Storage (STES)

Sorption TES systems have achieved TRL ranging from 5 to 7. At this stage, sorption TES systems have transitioned beyond laboratory-scale demonstrations and undergone preliminary testing in real-world applications. While not yet fully mature for widespread commercial deployment, sorption TES technologies have demonstrated promising performance and potential for various applications, including decentralized cooling and heating systems [67].

Assessing the TRL of sorption TES technologies requires considering factors such as adsorption/desorption kinetics, energy density, regeneration efficiency, and material compatibility.

Advancements in sorption materials, system design, and integration have significantly contributed to the progression of sorption TES TRLs. Researchers have focused on developing innovative sorbent materials with

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improved adsorption/desorption kinetics, higher energy storage density, and enhanced cycling stability. Moreover, novel system configurations and control strategies have been developed to optimize the overall efficiency and reliability of sorption TES systems [68].

Despite considerable progress, sorption TES technologies face several challenges that impact their TRL progression. One of the primary issues regards the optimization of sorbent materials to achieve an even higher energy storage density and faster adsorption/desorption rates. Moreover, ensuring compatibility and stability of sorbent materials in different operating conditions represents a critical issue. Finally, the complexity of system integration and scalability poses challenges for the widespread deployment of sorption TES technologies in various applications.

6.2 Cost Considerations

The market analysis indicates a dominance of STES due to its affordability and versatility. However, advancements in LTES and CTES could shift the market dynamics, offering enhanced storage capacities and efficiencies. While STES currently leads in market penetration and cost-effectiveness, the evolving landscape of LTES and CTES technologies holds significant promise for advancing TES solutions, potentially transforming the energy storage sector with improved performance and cost-efficiency. To provide a more detailed analysis of the costs associated with various TES technologies we examine deeper into each TES type: STES, LTES, and CTES, as follows:

Sensible Thermal Energy Storage (STES):

Cost Range (EUR/kWh): 0.1 – 50. This wide range indicates that STES can be very cost-effective but can also escalate depending on the specific materials and scale of the system.

Investment Cost (EUR/kW): 3400 – 4500. This investment cost is relatively moderate, making STES a viable option for both small-scale residential and large-scale industrial applications.

Operation and Maintenance (O&M) Cost (EUR/kW/y): 70 – 250. The ongoing maintenance and operational costs are manageable, which contributes to the popularity of STES in various sectors.

Latent Thermal Energy Storage (LTES):

Cost Range (EUR/kWh): 8 – 50. While generally more expensive than STES, LTES offers higher energy density, which can justify the higher cost in applications where space is a constraint.

Investment Cost (EUR/kW): 6000 – 15000. The higher investment cost reflects the complex technology and materials (e.g., PCMs) used in LTES, which are crucial for its efficient operation.

O&M Cost (EUR/kW/y): 120 – 750. The maintenance and operational costs are higher, likely due to the need for specialized equipment and potential replacement of PCMs.

Chemical Thermal Energy Storage (CTES):

Cost Range (EUR/kWh): 8 – 100. CTES systems exhibit a broad cost range, reflecting the diversity of materials and processes involved, from simple reactions to more complex systems requiring advanced materials.

Investment Cost (EUR/kW): 1000 – 30000. This range is quite wide, indicating that CTES can vary significantly in complexity and scale. The higher end of the range is likely associated with cutting-edge systems employing novel materials and reactions.

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O&M Cost (EUR/kW/y): 20 – 1500. The operational costs for CTES are notably variable, suggesting that some systems are relatively straightforward to maintain, while others may require extensive and costly maintenance protocols.

Cost comparison of various TES technologies is presented in Table 6-1. In addition, Table 6-2 shows more detailed cost comparison between STES and LTES.

Table 6-1: Cost comparison of various TES technologies [69].

Technology	Cost (EUR/kWh)	Investment Cost (EUR/kW)	O&M Cost (EUR/kW/y)
STES	0.1 – 50	3400 – 4500	70 – 250
LTES	8 – 50	6000 – 15000	120 – 750
CTES	8 – 100	1000 – 30000	20 – 1500

Table 6-2: More detailed cost comparison between STES and LTES [5].

	LATENT HEAT THERMAL ENERGY STORAGE	**Cost (€/kWh)**
1	Ice	15~20
2	Static Ice Production Systems	15~20
3	Dynamic Ice Production Systems	30~35
4	Phase Change Material (PCM)	35~50
5	Shallow Geothermal Energy	50~70
6	Solar Energy	60~90
7	Industrial Applications	60~120
8	Molten Salt System	40~65
	SENSIBLE HEAT THERMAL ENERGY STORAGE	
1	Water	10~15
2	Steam	30~35
3	Solid (Stones/Ceramic/Sand/Concrete)	20~30
4	Molten Salt	50~65

In summary, the choice of TES systems depends heavily on the specific needs and constraints of the application. While STES emerges as the most economically feasible option, particularly when prioritizing affordability over energy density, LTES presents a compelling alternative for scenarios where space constraints or enhanced efficiency are crucial factors. Furthermore, CTES showcases promising advancements in TES technology, offering potential long-term solutions for energy storage challenges. However, its widespread adoption is hindered by substantial costs and intricate maintenance demands. Ultimately, a nuanced understanding of these trade-offs is essential for informed decision-making in implementing TES solutions across various industries and contexts.

6.3 Environmental Impact

The environmental impact of TES technologies, and in particular of the ECHO TES, will be largely studied in WP7. Therefore, the intention of this section is to give an overview and preliminary thoughts about it.

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To correctly understand the environmental impact of TES technologies, a **life cycle approach is needed**. Life Cycle Analysis (LCA) is a methodology standardized by the ISO 14040 series for assessing the environmental impacts of a system under analysis, taking into account all the life cycle stages: from the raw material extraction, the transport of them, the manufacturing or production, installation, use and maintenance and including the end of life.

To make comparisons in LCA terms, the definition of a common functional unit is needed. Only systems that have the same functional unit can be compared. In LCA context, a functional unit is a quantified performance of a product system for use as a reference unit. Therefore, the functional unit provides a reference from which input and output data are normalized.

In the specific field of TES technologies, it is common to think that this reference would be a single TES system. However, TES technologies have different performance at use stage that would stay masked if the comparison is made per technology. On the other hand, a reference that allows highlighting the technology that generates less impact in manufacturing together with a great performance, is needed. For the TES technologies, **the most used functional unit is the storage of 1kWh**. Those TES technologies that are able to storage 1kWh at a lower impact will be considered the most suitable. On the other hand, there are studies that define the functional unit as **1kWh delivered**. The functional unit to be applied in ECHO project will be defined in WP7.

Depending on the system under analysis and in close relationship with the functional unit definition, the scope of the environmental impact assessment must be defined. Within the scope, the system boundaries of the assessment are established. The system boundaries define what must be included in the analysis and what is out of scope and are described for each of the life cycle stages. For the LCA of WP7 it is expected that a **cradle to grave approach** will be followed. This means that all life cycle stages of the TES technology will be considered in the assessment. The specific boundaries of each life cycle phase will be defined in upcoming steps of WP7.

To report the environmental impact, a set of indicators or environmental impact categories is provided. The most common indicator is the **global warming potential (GWP)**, measured in kilograms of CO_2 equivalent. There are standards focused in this category and are commonly known as “Carbon Footprint”. In the field of energy technologies, a relevant indicator that must be considered is the **primary energy (PE)**, divided into renewable and non-renewable and measured in MJ. Even though the GWP and the PE are the most used indicators, in ECHO project it is expected to calculate several more. Considering a complete set of indicators will allow us to make comparisons with a broader perspective and will allow us to identify hot spots or conclusions that with only two indicators it is not possible to identify. For example, beyond the GWP and the PE, the impact of the phase change materials (PCMs in the case of ECHO) will be characterized thanks to the consideration of indicators like **abiotic depletion of resources** among others. When comparing, it is important to note that it will be difficult to find a TES technology that will comply with the lowest impact in all the environmental impact categories studied. This makes the consideration of a complete set of indicators more interesting and needed to provide more detailed conclusions and, thus, to work in to being more accurate in defining environmental impact reduction strategies.

A specific state of the art regarding LCA methods, studies, etc., of storage is being conducted in the context of task 7.2. This state of the art will have, as a result, the methodology to analyze the environmental impact of TES technology under development in ECHO project. The methodology will include the functional unit, the scope and system boundaries, the indicators, etc., to be considered in the analysis.

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Preliminary conclusions of the state of the art in progress in WP7 show that electrical storage has been deeply studied in LCA terms, while only few studies exist in the thermal storage context. The information included in these studies will be needed to obtain information with which to be able to make the analysis needed to make comparisons. Other preliminary conclusions regarding thermal storage include:

- In general, numerical studies on thermal energy storage systems focus on solar energy and PCMs. Recently we can see a new trend focusing on thermal systems applied to buildings.
- Most of the reviewed articles on thermal storage refer to STES and LTES. PCMs related to thermal energy storage show the highest number of research studies, while thermochemical systems are scarce.
- In the case of thermochemical systems, the most studied area focuses on the development of new compounds to achieve the required energy density, high temperature applications in concentrated solar power plants and their application to buildings for seasonal storage.
- The research gaps identified in the CTES studies are related to LCA studies on materials and systems, application of sorption technologies, optimisation techniques and environmental/economic analysis of sorption systems.

6.4 Selection Criteria for TES Systems

The selection of TES systems is a nuanced process influenced by a diverse set of criteria tailored to the distinct requirements of various applications.

Primary considerations include the intended **application environment**, distinguishing between residential, industrial, or grid-scale contexts. The **scale of storage**, encompassing both capacity and power output, must align with the dynamic energy demands and supply fluctuations of the system. The **thermophysical attributes of the storage medium**, such as heat capacity, thermal conductivity, and phase change characteristics, significantly impact system efficiency. **Economic factors**, comprising initial and operational costs, must be carefully balanced to ensure cost-effectiveness over the system's lifecycle. **Compatibility with existing or planned energy infrastructures** and the **environmental impact** of the chosen technology are also pivotal considerations. A holistic evaluation of these criteria is indispensable for the optimal selection of TES systems, ensuring their alignment with application-specific needs, and contributing to enhanced energy efficiency and sustainability.

6.4.1 Scale of Storage and Application Environment

The application environment is a crucial consideration when selecting TES systems. Depending on whether the system is intended for residential, industrial, or grid-scale contexts, different requirements and constraints must be taken into account.

Small-scale TES systems are typically designed for localized applications, such as **residential buildings, small commercial establishments**, or **individual industrial processes**.

In these cases, the following key factors are attentively considered:

- space availability: in residential contexts, as well as in small commercial ones, space destined for installing TES systems is often limited. Thus, compact and space-efficient designs are preferred;
- cost-effectiveness: affordability is crucial for small-scale applications. TES systems should offer a reasonable return on investment through energy savings and reduced utility bills;

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- ease of installation and maintenance: homeowners and small entrepreneurs seek TES systems that are easy to install and require minimal maintenance to ensure hassle-free operation;
- integration with existing HVAC systems: compatibility with existing HVAC systems is essential for seamless integration without significant modifications;
- energy storage capacity: the TES system should have adequate storage capacity to meet the thermal energy demand of the targeted application, especially during peak periods;
- flexibility: these systems should offer flexibility in operation, allowing users to adjust energy storage and discharge based on varying demand patterns.

Differently, **medium-scale** TES systems cater to larger applications such as **district heating and cooling networks**, **medium-sized industrial facilities**, or **community-based energy projects**. The selection criteria for medium-scale TES systems include:

- storage capacity and rate: these systems must strike a balance between storage capacity and the rate of energy transfer to meet the diverse energy demands of medium-sized applications effectively.
- scalability: these systems should be scalable to accommodate future expansions or changes in energy demand, ensuring long-term viability and adaptability;
- compatibility with infrastructure: medium-scale TES systems should integrate seamlessly with existing infrastructure, including heat distribution networks or industrial process systems;
- reliability and durability: reliability is paramount for medium-scale applications to minimize downtime and maintenance costs and ensure uninterrupted operation. TES systems must also exhibit durability to withstand operational demands over extended periods;
- lifecycle cost: considerations such as initial investment costs, maintenance expenses, and operational efficiency contribute to assessing the lifecycle cost of medium-scale TES systems;

Large-scale TES systems serve **utility-scale applications**, **grid stabilization initiatives**, and **centralized industrial processes** requiring substantial thermal energy storage capacities. Thus, when selecting large-scale TES systems the following aspects are evaluated:

- high storage capacity: large-scale TES systems must offer significant storage capacities to support utility-scale energy storage requirements, grid stabilization, or industrial processes with high thermal energy demands;
- fast response time: rapid response capabilities are essential for large-scale TES systems to provide grid ancillary services, stabilize renewable energy integration, and meet fluctuating demand patterns;
- grid compatibility: these systems should comply with grid interconnection standards and regulatory requirements to ensure seamless integration with the existing power infrastructure;
- cost-effectiveness: large-scale TES systems must demonstrate competitive capital costs and operational efficiency to justify their deployment on a utility scale;
- sustainability: environmental considerations, such as the use of eco-friendly storage materials and energy-efficient operation, are crucial for large-scale TES systems to align with sustainability objectives.

6.4.2 Thermophysical Attributes of the Storage Medium

The selection of an appropriate storage medium is a critical aspect of designing effective TES systems. Thermophysical attributes such as heat capacity, thermal conductivity, and phase change characteristics significantly influence the performance and suitability of TES systems for specific applications.

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In TES systems, a high **heat capacity** is desirable as it allows for the storage of large amounts of thermal energy, thus for high energy storage densities. Materials with high heat capacities, such as water and certain PCMs, are commonly used in TES applications. Water, for instance, has a high heat capacity, making it an excellent medium for storing thermal energy in both sensible and latent heat TES systems. PCMs, on the other hand, can store significant amounts of energy through phase transition.

The efficient heat transfer between the storage medium, heat source, and heat sink depends on **thermal conductivity**. Materials with high thermal conductivity facilitate rapid charging and discharging cycles, minimizing energy losses and improving system efficiency. Metals like copper and aluminum exhibit high thermal conductivity and are often used in heat exchangers and other components of TES systems to enhance heat transfer rates.

PCMs exhibit unique thermophysical properties, undergoing phase transitions (e.g., solid to liquid or vice versa) at specific temperature ranges. These **phase change characteristics** enable PCMs to store and release large amounts of energy at nearly constant temperatures, making them ideal for TES applications. During the phase transition, PCMs absorb or release latent heat, providing a highly efficient means of energy storage. The selection of PCMs depends on their melting and solidification temperatures, which should align with the temperature requirements of the TES system's operating conditions.

Finally, also the **stability and compatibility** of the storage medium are essential aspects in TES system design. The storage medium must exhibit thermal stability over numerous charging and discharging cycles to ensure long-term performance reliability. Compatibility with other system components, such as containment vessels, piping, and insulation materials, is also essential to prevent material degradation and ensure system integrity. Additionally, the storage medium should be compatible with the operating conditions and environmental factors of the intended application to minimize the risk of corrosion, degradation, or leakage.

6.4.3 Economic Factors

Economic considerations play a crucial role in the selection of TES systems. Initial investment, operational costs, and return on investment (ROI) must be carefully evaluated to ensure the economic viability of the chosen solution.

One of the primary economic factors influencing the selection of TES systems is the **capital cost** involved in procuring and installing the system. This includes the cost of TES equipment, such as storage tanks, heat exchangers, insulation materials, and control systems, as well as installation expenses. The capital cost varies depending on the scale of the TES system, technology used, storage capacity, and specific application requirements. Stakeholders must conduct cost-benefit analyses to assess whether the initial investment aligns with the expected returns in terms of energy savings, operational efficiency, and potential revenue streams.

Operational costs encompass expenses incurred during the day-to-day operation and maintenance of TES systems. These include energy consumption for charging and discharging processes, maintenance activities, system monitoring, and personnel costs. The operational costs of TES systems depend on factors such as system efficiency, energy losses during storage and retrieval, frequency of maintenance interventions, and the complexity of control and monitoring systems. Stakeholders must evaluate the operational costs alongside potential energy savings or revenue generation opportunities to determine the overall economic viability of TES systems over their lifecycle.

Conducting a **lifecycle cost analysis** is essential for comprehensively evaluating the economic feasibility of TES systems. Lifecycle cost analysis considers the total cost of ownership over the entire lifespan of the TES

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system, including initial investment, operational costs, maintenance expenses, replacement or upgrade costs, and salvage value. By accounting for all relevant costs and benefits over time, stakeholders can make informed decisions regarding the economic viability and sustainability of TES systems compared to alternative energy storage technologies or conventional energy management approaches.

Finally, Assessing the **ROI** and **payback period** is crucial for determining the financial attractiveness of TES systems. ROI measures the profitability of investing in TES systems by comparing the net benefits (e.g., energy savings, revenue generation) with the initial investment. The payback period indicates the time required for the accumulated savings or revenues to offset the initial investment costs. Stakeholders often use ROI and payback period analyses to assess the economic viability of TES systems and prioritize investment decisions based on financial returns and risk tolerance levels.

6.4.4 Compatibility with Existing or Planned Energy Infrastructures

One of the primary considerations in selecting TES systems is their compatibility with existing energy infrastructures. Whether in residential, commercial, industrial, or utility-scale applications, TES systems must seamlessly integrate with the prevailing energy systems to ensure efficient operation and minimal disruption. Compatibility encompasses various aspects, including:

- **thermal compatibility**: TES systems must align thermally with existing or planned energy generation and distribution systems. Compatibility in terms of temperature requirements, heat transfer mediums, and thermal storage capacity is crucial to facilitate efficient energy transfer and utilization;
- **system interconnectivity**: TES systems should feature compatible interfaces and control mechanisms to integrate seamlessly with existing energy infrastructures. Compatibility in communication protocols, data exchange formats, and control signals enables effective coordination and synchronization between TES systems and other energy components;
- **operational synergy**: compatibility with energy infrastructures extends beyond technical aspects to operational synergy. TES systems should complement the operation of energy generation, distribution, and utilization systems, contributing to overall system reliability, stability, and efficiency. For example, TES systems can help mitigate peak demand periods, optimize renewable energy integration, or enhance grid stability through coordinated operation with existing energy infrastructures;
- **scalability**: compatibility considerations also include the scalability of TES systems concerning existing or planned energy infrastructures. TES systems should be scalable to accommodate future expansions, changes in energy demand patterns, or the integration of additional renewable energy sources. Scalability ensures long-term compatibility and adaptability, enabling seamless integration into evolving energy systems;
- **flexibility**: flexible operation and configuration options enhance compatibility by accommodating diverse energy infrastructures and operational scenarios. TES systems should offer configurable storage capacities, charging and discharging profiles, and operating modes to adapt to varying energy demand patterns and system requirements. Flexibility promotes versatility and interoperability, facilitating integration with existing or planned energy infrastructures across different applications;

6.4.5 Environmental Impact

The environmental impact of TES systems, including resource utilization, potential for pollution or emissions, and their carbon footprint, is an essential consideration in the selection process.

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- **resource utilization**: TES systems utilize various materials for TES, including PCMs, molten salts, and chilled water. Assessing the environmental impact involves evaluating the availability and sustainability of these resources. Opting for abundant, renewable, or recycled materials can minimize resource depletion and environmental damage;
- **emissions**: during the lifecycle of TES systems, emissions may occur from manufacturing, operation, and disposal phases. Evaluating the emissions associated with TES systems involves considering factors such as energy consumption during production, greenhouse gas emissions, and air pollutants. Selecting TES technologies with lower emissions and higher energy efficiency can reduce environmental impact;
- **energy efficiency**: energy efficiency is a key criterion in assessing the environmental sustainability of TES systems. Higher energy efficiency means reduced energy consumption and lower environmental burden. TES systems with efficient thermal storage and retrieval processes, as well as minimal energy losses, contribute to overall energy conservation and environmental protection;
- **lifecycle assessment (LCA)**: conducting an LCA helps evaluating the environmental impact of TES systems throughout their entire lifecycle, from raw material extraction to end-of-life disposal. Considering factors such as energy consumption, emissions, resource depletion, and waste generation enables stakeholders to make informed decisions regarding TES system selection. Opting for TES systems with favorable lifecycle profiles can minimize environmental harm;
- **recyclability and reusability**: TES systems should be designed considering recyclability and reusability to minimize waste generation and resource depletion. Materials used in TES systems should be recyclable, and systems should be easily disassembled for component reuse or recycling at the end of their lifecycle. Promoting circular economy principles ensures sustainable resource management and reduces environmental impact;
- **ecological footprint**: assessing the ecological footprint of TES systems involves considering their impact on ecosystems and biodiversity. Factors such as land use, habitat disruption, and water consumption should be evaluated to minimize adverse effects on the environment. Choosing TES systems with minimal ecological footprint and implementing eco-friendly practices can mitigate environmental degradation;

7 Visualization Tool of the TES Technologies (Dataset)

In the context of Task 2.1, a visualization tool of the available TES technologies was created. The software used for this purpose is *Looker Studio*. The entire dataset is visible to the user, who can filter the data according to different parameters such as the type of TES system, the application, the temperature range, the efficiency, etc.

The tool is available at the link https://lookerstudio.google.com/reporting/1dd662a1-938f-4dd8-91a9-ef70ccdd72ab

The home page shows a brief description of the tool, as in Figure 7-1. On the left-hand side, the user can navigate through different labels: *Instructions* displays the home page, *TES DATASET* contains the raw data, the *Data Analysis* section allows to filter the data, and the last section consists of different graphs related to each numerical parameter.

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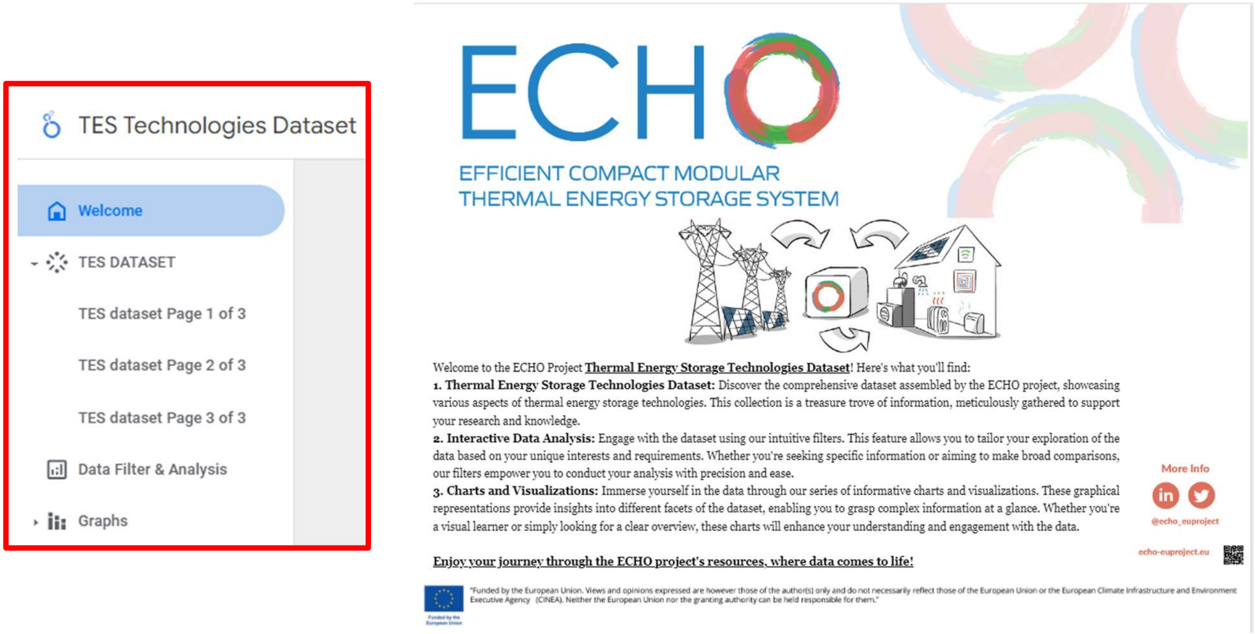

Welcome to the ECHO Project <u>Thermal Energy Storage Technologies Dataset</u>! Here's what you'll find:

1. Thermal Energy Storage Technologies Dataset: Discover the comprehensive dataset assembled by the ECHO project, showcasing various aspects of thermal energy storage technologies. This collection is a treasure trove of information, meticulously gathered to support your research and knowledge.

2. Interactive Data Analysis: Engage with the dataset using our intuitive filters. This feature allows you to tailor your exploration of the data based on your unique interests and requirements. Whether you're seeking specific information or aiming to make broad comparisons, our filters empower you to conduct your analysis with precision and ease.

3. Charts and Visualizations: Immerse yourself in the data through our series of informative charts and visualizations. These graphical representations provide insights into different facets of the dataset, enabling you to grasp complex information at a glance. Whether you're a visual learner or simply looking for a clear overview, these charts will enhance your understanding and engagement with the data.

Enjoy your journey through the ECHO project's resources, where data comes to life!

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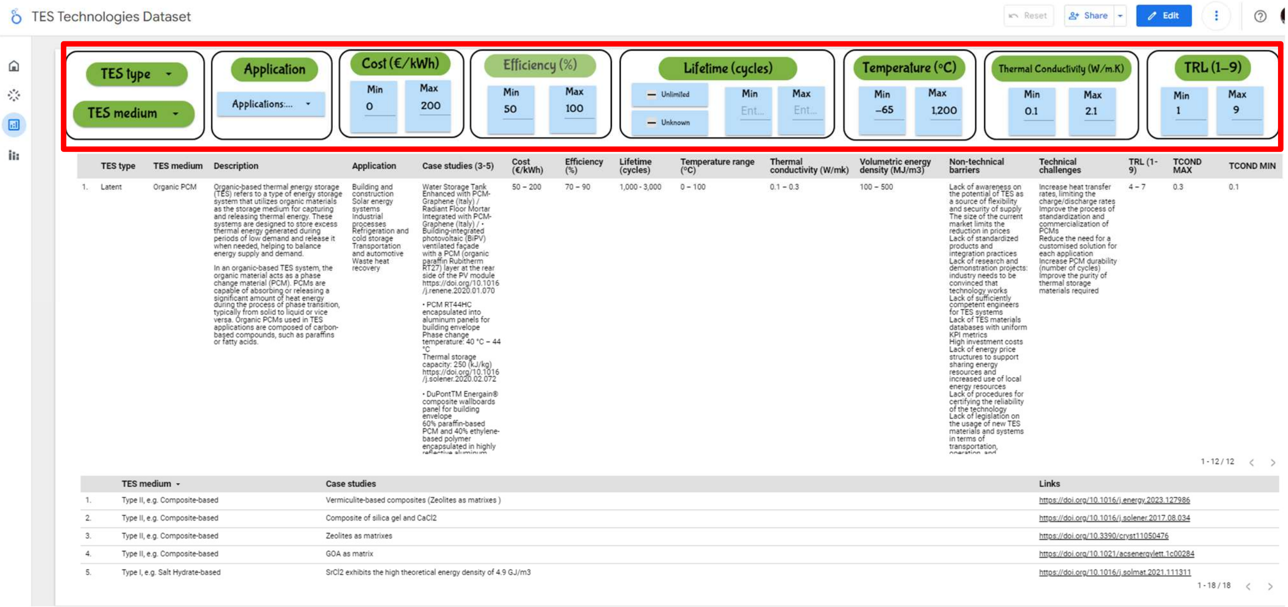
Figure 7-1: Home page of the ECHO dataset.

In the data filter & analysis section (Figure 7-2), the user can apply multiple filters. These can be found in the upper part of the page, and include:

- TES type
- Medium
- Application
- Temperature range [°C]
- Cost [€]
- Lifetime [number of cycles]
- Efficiency [%]
- TRL
- Volumetric energy density [MJ/m^3]
- Thermal conductivity [W/m/K] (applicable to LTES).



	TES type	TES medium	Description	Application	Case studies (3-5)	Cost (€/kWh)	Efficiency (%)	Lifetime (cycles)	Temperature range (°C)	Thermal conductivity (W/mk)	Volumetric energy density (MJ/m3)	Non-technical barriers	Technical challenges	TRL (1-9)	TCOND MAX	TCOND MIN
1.	Latent	Organic PCM	Organic-based thermal energy storage (TES) refers to a type of energy storage system that utilizes organic materials as the storage medium for capturing and releasing thermal energy. These systems are designed to store excess thermal energy generated during periods of low demand and release it when needed, helping to balance energy supply and demand. In an organic-based TES system, the organic material acts as a phase change material (PCM). PCMs are capable of absorbing or releasing a significant amount of heat energy during the process of phase transition, typically from solid to liquid or vice versa. Organic PCMs used in TES applications are composed of carbon-based compounds, such as paraffins or fatty acids.	Building and construction Solar energy systems Industrial processes Refrigeration and cold storage Transportation and automotive Waste heat recovery	Water Storage Tank Enhanced with PCM-Graphene (Italy) / Radiant Floor Mortar Integrated with PCM-Graphene (Italy) / • Building-integrated photovoltaic (BiPV) ventilated façade with a PCM (organic paraffin Rubitherm RT27) layer at the rear side of the PV module https://doi.org/10.1016/j.renene.2020.01.070 • PCM RT44HC encapsulated into aluminum panels for building envelope Phase change temperature: 40 °C – 44 °C Thermal storage capacity: 250 (kJ/kg) https://doi.org/10.1016/j.solener.2020.02.072 • DuPontTM Energain® composite wallboards panel for building envelope 60% paraffin-based PCM and 40% ethylene-based polymer encapsulated in highly	50 – 200	70 – 90	1,000 - 3,000	0 – 100	0.1 – 0.3	100 – 500	Lack of awareness on the potential of TES as a source of flexibility and security of supply The size of the current market limits the reduction in prices Lack of standardized products and integration practices Lack of research and demonstration projects: industry needs to be convinced that technology works Lack of sufficiently competent engineers for TES systems Lack of TES materials databases with uniform KPI metrics High investment costs Lack of energy price structures to support sharing energy resources and increased use of local energy resources Lack of procedures for certifying the reliability of the technology Lack of legislation on the usage of new TES materials and systems in terms of transportation,	Increase heat transfer rates, limiting the charge/discharge rates Improve the process of standardization and commercialization of PCMs Reduce the need for a customised solution for each application Increase PCM durability (number of cycles) Improve the purity of thermal storage materials required	4 – 7	0.3	0.1

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	TES medium	Case studies	Links
1.	Type II, e.g. Composite-based	Vermiculite-based composites (Zeolites as matrixes)	https://doi.org/10.1016/j.energy.2023.127986
2.	Type II, e.g. Composite-based	Composite of silica gel and CaCl2	https://doi.org/10.1016/j.solener.2017.08.034
3.	Type II, e.g. Composite-based	Zeolites as matrixes	https://doi.org/10.3390/cryst11050476
4.	Type II, e.g. Composite-based	GOA as matrix	https://doi.org/10.1021/acsenergylett.1c00284
5.	Type I, e.g. Salt Hydrate-based	SrCl2 exhibits the high theoretical energy density of 4.9 GJ/m3	https://doi.org/10.1016/j.solmat.2021.111311

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Figure 7-2: Data filter & analysis section.

The filters *TES type* and *TES medium* work in the same way. The user can select one or more items through the dropdown list, as shown in Figure 7-3. If all items are selected but the user would like to only select one option, the button *ONLY* can be clicked.

Figure 7-3: TES type filter.

The filter *Application* consists of a dropdown list as well, but only one option can be selected, as shown in Figure 7-4. To show the results, the filter must be activated by clicking on the purple *Application* button. Once activated, the button color becomes darker.

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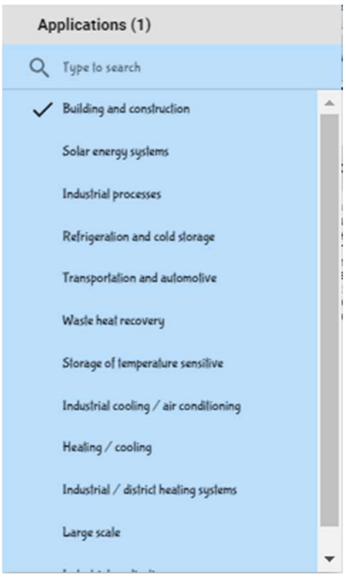
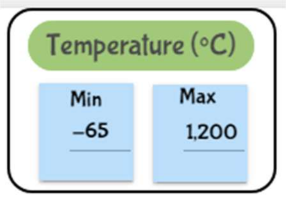


Figure 7-4: Application filter.

All the other filters allow the user to insert a range for the chosen parameter, showing then the TES technologies characterized by values included in it.

For example, the steps for setting a temperature range between 5 °C and 65 °C are as follows:

1. Insert the desired minimum temperature in the entry box *Filter Temp min*.
2. Insert the desired maximum temperature in the entry box *Filter Temp max* (Figure 7-5).



Min –65

Max 1,200

Figure 7-5: Temperature range.

3. Activate the filter by clicking on the purple *Temperature* button (Figure 7-6).

Figure 7-6: Activation of the filter.

4. The records are now filtered, showing technologies that can operate in the selected temperature range.

To remove all filters, the user can click on *Reset*, in the upper part of the window.

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Finally, the *Lifetime* filter can be used by following the procedure described above, and/or by selecting the checkboxes *Unlimited* or *Unknown*, as shown in Figure 7-7.

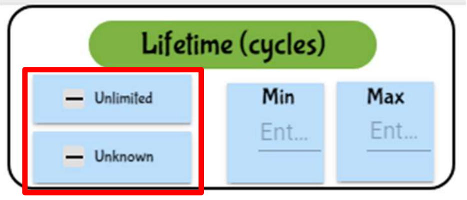

Figure 7-7: Lifetime filter.

In the *Graphs* section, the user can find different pages. Each page corresponds to a TES parameter, including TRL, temperature range of operation, cost, efficiency, lifetime, volumetric energy density, and thermal conductivity (Figure 7-8).

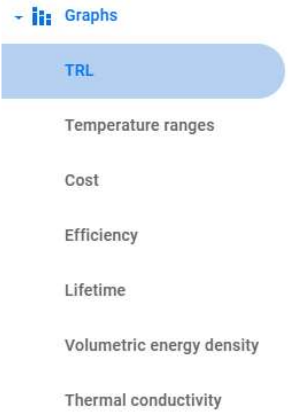

Figure 7-8: Pages in the graphs section.

For each parameter, a graphical representation in the form of a table is displayed, showing the values that can be taken by that parameter for each TES technology. Each row is related to a certain medium or mechanism (e.g. concrete, organic PCMs, absorption, etc.): the correspondent range of values is represented by one or more adjacent colored cells. The numerical values can be read in the first row of the table. The technologies belonging to the same TES type (sensible, latent, or chemical) are represented with the same colors.

These graphs are useful to give the user a clear overview of the difference among the various technologies regarding these relevant parameters, thus allowing an easier comparison between them.

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8 Energy Policy Scenarios of TES Systems Across European Union (EU)

8.1 EU Storage Regulation

8.1.1 Preliminary Considerations

Before drawing up this report, it is useful to provide a brief contextualization of the climate crisis situation which, a priori, would justify the origin and development of the ECHO project and whose consideration could well merit recognition as a project of common interest (PCI) in view of its technical characteristics.

Today, there is no State in any region of the world that remains impassive to the adoption of progressive climate policies aimed at decarbonizing their economies, either “de iure”, i.e. due to the fulfilment of their commitments under the regulatory framework for climate change in international law and, consequently, the incorporation of these rules into their respective legal systems; or "de facto", in order to provide solutions to the increasingly frequent occurrence of extreme weather events, whether immediate or mediate, which are forcing States to legislate to adapt to climate change, in order to keep their sovereignty intact.

In view of the abovementioned, on 28 November 2019, the European Parliament declared a climate and environmental emergency. This declaration urges both the European Commission and the other Member States of the European Union (EU) to adopt urgent and necessary measures aimed at reducing greenhouse gases (GHG), bearing in mind that climate change requires a global solution involving all sectors of society and the economy, including industry, in a socially balanced and sustainable manner, as the proposal for urgent change can only come about within the framework of a global agreement common to all. Following this statement, on 11 December 2019, the European Commission presented the European Green Deal (EGD), which is consolidated as the EU’s strategy to achieve climate neutrality by 2050. It is worth mentioning that all the sources mentioned in this section can be found in the Documentary References. Its adoption in December 2019 fits perfectly with the “Strategic Agenda of the Union for 2019-2024”, previously adopted by the European Council on 20 June 2019, and with the current Regulation establishing the Multiannual Financial Framework (MFF) 2021-2027, which provides for 30% funding for climate action, which means that the determination that Member States’ national recovery and resilience plans funded under the Recovery and Resilience Mechanism (RRM) “should contribute to the green transition with measures representing at least 37% of the plans' allocations”.

Given the path that European climate policy is taking, to achieve the transformation of the EU economy towards a sustainable future, as envisaged in the EGD, it will be required a redefinition of the climate ambition for 2030 and 2050 and, consequently, intervention in the following current policies: (i) energy; (ii) industry; (iii) production and consumption; (iv) infrastructure, construction methods and energy efficiency of buildings; (v) transport; (vi) food; (vii) preservation and restoration of ecosystems and biodiversity; and (viii) elimination of pollution. In the ECHO project, different areas of intervention intersect, specifically the following: energy, industry, production and consumption, and infrastructure, construction methods and energy efficiency of buildings.

More specifically in the field of energy, renewable energy sources - wind, solar, hydro, ocean, geothermal, biomass and biofuels - are alternatives to fossil fuels that help to reduce GHG emissions, diversify energy supply and reduce dependence on volatile and unreliable fossil fuel markets (in particular oil and gas). European legislation aimed at promoting renewable energies has evolved significantly over the last fifteen years. In 2021, renewable energies accounted for 21.8% of the EU’s gross final energy consumption. In 2023, the co-legislators increased the EU renewable energy target for 2030 to 42.5%, with the aim of reaching 45%.

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In addition, among the measures envisaged under the “Fit for 55”, the EU Commission proposed a first revision of the Energy Efficiency Directive to adapt its energy efficiency targets to the Union’s new climate ambition and incorporated into legislation the principle of the primacy of energy efficiency as a pillar of the Energy Union. In accordance with this principle, Member States must ensure that energy efficiency solutions, including demand-side resources and system flexibility, are assessed in major planning, policy and investment decisions.

In line with the abovementioned considerations, Directive 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources and repealing Council Directive (EU) 2015/652, provides for further simplification and shortening of administrative procedures for granting authorizations for renewable energy plants, including power plants combining different renewable energy sources, heat pumps, co-location energy storage, including electrical and thermal installations, as well as assets necessary for the connection of such plants, heat pumps and storage to the grid. It also indicates that it is necessary to integrate renewables into heating and cooling networks in a coordinated and harmonized manner, in order to ensure the achievement of the Union's ambitious climate and energy targets for 2030 and its goal of climate neutrality by 2050, while taking into account the 'do no harm' principle of the European Green Deal and without prejudice to the internal division of competences within Member States.

For its part, the European Strategy for Energy System Integration, published by the European Commission in July 2020, provides the necessary framework for the green transition, setting out a new comprehensive vision for energy system planning that takes into account the interrelationships between the different energy vectors, with the aim of designing a decentralized, flexible and optimized energy system that exploits the many benefits of clean and innovative technologies. Systems to provide such flexibility include storage in its various forms, daily, weekly, or seasonal.

Considering the sectoral regulatory framework and Spain’s membership in the EU, the country is obligated to adhere to European regulations and adhere to the EU’s decarbonization plans to ensure compliance with international and regional laws. Furthermore, it is possible to note that Spain already has an Energy Storage Strategy, which identifies the main challenges for the deployment of storage and a vision that implies a new paradigm for the energy system, the objective of which is climate neutrality and the exploitation of the opportunities that this change of model entails.

In preparing this report, it will be assumed that all EU policies covered by the EGD will affect the ECHO project in terms of the technical characteristics of the project. This will be described in more detail in the section of this report dealing with the legal framework, feasibility of the project and the SWOT analysis.

8.1.2 Purpose of the Research

The purpose of this report is twofold. Firstly, it will determine whether or not the ECHO Project is viable in legal terms, considering its position in the energy and energy efficiency of buildings sector. Secondly, it will identify potential legal threats, barriers or obstacles to its deployment in the sector, as well as identify strengths and potential alliances in the regulatory environment.

This is a broad objective that will have to take into account multiple cross-cutting factors and the sectoral interrelationship described in the contextualization of the report. To complete the purpose of the report requires an in-depth and detailed study of the regulations at all levels of Law and the different sectoral areas and their intersections.

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8.1.3 Methodology used in the Research

The methodology followed in drafting this report is based on traditional legal research, understood as a thorough investigation of legal concepts, values, principles, existing legal texts and jurisprudence as applied to the specific case, in this case, the ECHO project.

The term "methodology" encompasses methods and also includes other theoretical connotations and is linked to deeper concepts and approaches, including the way in which law is conceptualized. As per "method", is referred to the way the research is conducted in relation to the choice of data and the way it is examined: e.g., literature review, document analysis, observation and study of cases similar or analogous to the project.

This section of the report aims to answer the questions posed by the ECHO project with an appropriate methodology and methods. In this sense, the sources used to carry out this research can be grouped as documentary sources. This group contains international, European and Spanish documents such as Treaties, Conventions, UN documents, international documents and reports, EU primary and secondary legislation, Spanish legislation, case law, other documents and/or press releases. All sources and references described in this report will be included in the list of bibliographic and documentary references.

In addition, the cooperation of all project members involved in the implementation of the ECHO EU policy scenario and the state of the art in the research task has been sought in the drafting of this report. Thus, the policy data collection questionnaires sent by the consortium members are incorporated as Appendix 2.

The objective of these questionnaires is to determine with a greater degree of certainty the multilevel regulations under which the project is affected. Among the main findings of the legal questionnaire, the following results can be found:

a) The questionnaire has been answered by seven members of the consortium. Four of them are EU Member States, namely: Italy, Romania, Spain, and Belgium; the remaining three members are based in third countries, namely: United Kingdom, Serbia and Turkey.

b) There are divergences between the different EU Member States as regards the transposition of European legislation, mainly concerning the Internal Energy Market Directives.

c) Within the EU countries, there is even an attribution of national and local competences in energy issues, as in the case of countries such as Belgium or Spain, where certain issues do not fall under national competence.

d) In the case of non-EU third countries, non-EU members of the consortium, specialized legal support is needed to find the necessary lines to enable the deployment of the ECHO project in all its phases.

8.1.4 Technical Description of the ECHO Project

According to the official technical information of the ECHO project funded under the Horizon Europe program, Grant ID: 1010966368, the main objective of the project is to provide new modular, compact, high performance, Plug&Play TES solutions for heating, cooling, and domestic hot water production. The new TES concept proposed in the project will provide electrical load shifting with a significant reduction of peak thermal and electrical load demand.

The ECHO project will provide a TES system capable of storing energy for heating and cooling in building applications for a period of at least four weeks. It will also provide a key tool for thermal energy storage in the context of sector coupling and demand flexibility. The TES solution will be adapted to all possible European scenarios, in terms of energy policy and end-user requirements. It will be designed so that it can

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be used either integrated in the building heating system or in the smart grid, or in buildings not connected to the district heating and cooling network.

8.1.5 Legislation under Consideration

According to the above and the characteristics of the ECHO project, the texts listed in Table 8-1 and Table 8-2 have been taken into consideration:

Table 8-1: Current legislation (source: UPV elaboration).

Area of knowledge	Current legislation
International law	United Nations Framework Convention on Climate Change 1994 (UNFCCC).
International law	2015 Paris Agreement.
European law	Treaty on the Functioning of the European Union (TFEU).
European law	Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 on batteries and batteries and their waste, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC.
European law	Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (Regulation 2021/1119).
European law	Regulation (EU) 2018/1999 on the Governance of the Energy Union.
European law	Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable energy sources.
European law	Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity and amending Directive 2012/27/EU.
European law	Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources and repealing Council Directive 2015/652/EC.
European law	Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955.
European law	European Green Deal of 11 December 2019.

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European law	EU Action Plan for the Circular Economy.
European law	European Green Deal Industrial Plan of 1 February 2023.
Spanish law	Law 7/2021, of 20 May, on climate change and energy transition (LCCTE).
Spanish law	Law 24/2013, of 26 December, on the Electricity Sector (LSE).
Spanish law	Royal Decree 1955/2000 of 1 December 2000, which regulates the transmission, distribution, commercialisation, supply and authorisation procedures for electrical energy installations.
Spanish law	Royal Decree 178/2021, of 23 March, amending Royal Decree 1027/2007, of 20 July, approving the Regulation on Thermal Installations in Buildings.
Spanish law	Law 7/1985, of 2 April 1985, Regulating the Bases of Local Government (LBRL).
Spanish law	National Integrated Energy and Climate Plan (NIECP).
Spanish law	Long-term strategy for the decarbonisation of the Spanish economy (ELP).
Spanish law	Energy Storage Strategy.
Autonomous law	Law 6/2022, of 5 December, on Climate Change and Ecological Transition of the Valencian Region.

Table 8-2: Regulations pending entry into force (source: UPV elaboration).

Area of knowledge	**Regulations pending entry into force**
Spanish law	Draft Royal Decree developing the figures of renewable energy communities and citizen energy communities.

A) International Law

As stated in the previous section of this report, the international community in general has expressed its growing concern about the climate crisis and has reached consensus on the adoption of legal instruments to decarbonise the economies of States. Among these instruments is the United Nations Framework Convention on Climate Change, adopted in 1992 and in force since 21 March 1994. The objective of the Convention is to achieve stabilisation of GHG concentrations within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure food production and to enable sustainable development.

The limitations of the UNFCCC, in terms of GHG mitigation and climate change adaptation commitments, have led to the adoption of two other instruments at the international level: (i) the 1997 Kyoto Protocol, whose compliance periods have not established obligations beyond 2020; and (ii) the 2015 Paris Agreement, whose article 2 establishes, among other objectives, the decarbonisation of the economies of its Party States. The Paris Agreement is seen as a global response to curb the effects of climate change and is currently the only solution that includes commitments to mitigate GHG emissions, thanks to the so-called Nationally Determined Contributions (NDCs).

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At the international level, as we can see, there are legal instruments agreed by the States that establish commitments to mitigate GHGs and adapt to climate change. In this sense, Project ECHO appears as a technological solution that contributes not only to the GHG mitigation pillar and increases energy efficiency, but also as a technological response to the pillar of adaptation to climate variability, making a comprehensive contribution to compliance with the provisions of the Paris Agreement in the States that implement it and develop its deployment and commercialization.

B) European Law

When we talk about European law, we must be clear about two types of rules: the provisions of original European law that come from the treaties, such as the TFEU, which contains the legal basis of the EU, and the rules of secondary law, such as Regulations, Directives and Decisions. In the latter case, it should be noted that Regulations are directly and immediately applicable to the Member States. However, European Directives have a period - determined by the Directive itself - in which they can be transposed into the legal systems of the EU Member States. Decisions, on the other hand, are measures adopted by the Heads of State and Government of the EU Member States. They can be legislative or non-legislative acts.

As Table 8-1 shows, the ECHO project has emerged in a particularly favorable situation, both within the EU and from a legal point of view. Firstly, because the EU Member States are Parties to international instruments aiming at decarbonization by mid-century, and secondly, because the EU aims to become the world’s first climate-neutral territory, aspiring to lead the energy transition, so that the technological solutions presented on the market to achieve its ambitious decarbonization targets will be indispensable. To this end, it has set binding targets to achieve climate neutrality, in accordance with Regulation 2021/1119. The EU’s climate policy ambition is being driven by the EGD, which in turn is shaping the climate legislation of the EU Member States.

Of the seven key areas of the EGD, ECHO is directly affected by three of them: (i) the energy sector; (ii) the industrial sector and; (iii) energy efficiency of buildings, as mentioned at the beginning of this report. Within the EU, energy production and use account for more than 75% of EU GHG emissions. The EGD focuses on three key axes for the clean energy transition, which will contribute to the mitigation targets under the Paris Agreement. Thus, in the energy sector, the EU aims to:

1. Ensuring secure and affordable energy supply for the EU;
2. Develop a fully integrated, interconnected and digitized EU energy market;
3. Prioritizing energy efficiency, improving the energy performance of our buildings and developing an energy sector based largely on renewable sources. The development of the ECHO project is precisely in this last area.

In addition, it should be noted that the situation of energy price volatility as a consequence of Russia’s invasion of Ukraine has also determined the adoption of measures in the energy sector within the EU, with the gradual elimination of Europe’s dependence on Russian energy imports being adopted in March 2022. Following the European Council in May 2022, the REPowerEU was adopted, consisting of a package of urgent measures to address the volatility of gas and electricity prices.

In this context, the Agency for the Cooperation of Energy Regulators (ACER), concludes that the fundamentals of the European electricity market configuration deliver significant benefits to European consumers and calls on Member States to swiftly implement any outstanding regulation or market rules. ACER identifies a few challenges ahead, in particular the need to accelerate investment in renewable generation, ensure low-carbon supply and demand response where variable renewable generation is not available, address

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increasing price volatility and increase the flexibility of the electricity system. It also points out that other tools can help to secure the necessary investments, such as support schemes for renewables or other flexible resources, in particular demand response and storage. Increasing Europe's energy security and combating climate change are compatible objectives but achieving them requires urgent changes to adapt the energy system. Hence the adoption of Regulation 2019/943 of the European Parliament and of the Council of 5 June 2019 concerning the internal market in electricity, which, right from the preamble, provides coverage for the ECHO project, stating that:

"In the future, customers must be able to participate fully in the market on an equal footing with other participants and need to be empowered to manage their energy consumption. To integrate the growing share of renewables, the future electricity system must make use of all available sources of flexibility, in particular demand-side solutions and energy storage, as well as digitalization through the integration of innovative technologies into the electricity system. The future electricity system must also promote energy efficiency in order to achieve effective decarbonization at the lowest cost. The completion of the internal energy market through the effective integration of renewable energy can boost long-term investments and contribute to the achievement of the objectives of the Energy Union and the climate and energy policy framework up to 2030, as set out in the Commission Communication of 22 January 2014 entitled "A strategic climate and energy framework for the period 2020- 2030", and endorsed in the conclusions adopted by the European Council at its meeting on 23-24 October 2014".

Given this legal landscape, the fact is that the increase in renewable energies and the need for energy self-sufficiency are "de facto" favoring the emergence of "energy communities". Note that Directive 2019/944 of 5 June on common rules for the internal market in electricity regulates "citizen energy communities" and defines them as legal entities with the capacity to participate in generation (including from renewable sources), distribution, supply, consumption and aggregation, storage, provision of energy efficiency services or charging of electric vehicles (article 2.11). These entities must be based on open and voluntary participation and be controlled by their partners or members, who must be natural persons, small enterprises, or local authorities (Article 16). Their purpose is to provide environmental, economic or social benefits to their members, rather than to generate a financial return for them. It is important to mention that this Directive is pending transposition into Spanish law, but it is not the only one. The recent Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 is also pending transposition.

Regarding the industrial sector, the Commission has tabled a Proposal for a Regulation on net zero emission industry to underpin industrial manufacturing of key technologies in the EU. If adopted, this Regulation would provide a simplified regulatory framework for production capacity for products that are key to achieving our climate neutrality goals, such as batteries, wind turbines, heat pumps and solar technology, electrolyzer technology and carbon capture and storage technology. In this respect, the ECHO project would, once again, follow the line proposed by the European Commission.

According to the European Green Deal's Industrial Plan, the transformation of industry is imminent. Those who invest first and fastest in tune with the ecological and energy transition will secure their place in this new economy and, consequently, will be able to create jobs for a newly skilled workforce, rejuvenating the industrial manufacturing base, while reducing costs for people and businesses. This puts energy efficiency projects in a unique position to help other parts of the world decarbonize their own economies.

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C) Spanish Law

Spanish legislation draws directly from international and European normative sources. The implementation of these supranational norms in the Spanish legal system finds its legal basis in Article 96.1 of the Spanish Constitution (SC), which states that:

"Validly concluded international treaties, once officially published in Spain, shall form part of the domestic legal order. Their provisions may only be repealed, modified or suspended in the manner provided for in the treaties themselves or in accordance with the general rules of international law".

On the path towards climate neutrality, in order to comply with international and European commitments, the LCCTE establishes four minimum national -intermediate- targets for the year 2030, previously contemplated in the NIECP 2021-2030, the first update of which is in the public hearing phase as of 2 July 2023. However, the targets included in the NIECP 2021-2023 are:

- To reduce GHG emissions of the Spanish economy as a whole by at least 23% by 2030 compared to 1990. The update envisages an increase to 32%.
- To achieve a penetration of renewable energy in final energy consumption of at least 42% by 2030.
- To achieve an electricity system with at least 74% of generation from renewable energy sources by 2030.
- To improve energy efficiency by reducing primary energy consumption by at least 39.5% compared to the baseline according to European standards.

However, regarding the long-term objective, article 3.2 of the LCCTE states that: “before 2050 and in any case, in the shortest possible time, Spain must achieve climate neutrality (...) and the electricity system must be based exclusively on renewable generation sources”. However, in order to completely decarbonize the electricity sector, in addition to the deployment of renewables, it is necessary to “place citizens at the middle of energy policy”, which means that the self-sufficiency of the population in energy will be favored, as well as promoting their empowerment so that, in these cases, they become energy producers and can sell it using the electricity grid. Although the regulation is still in the approval phase, this legal line of action is being contemplated, although the Spanish regulation implementing it has not yet come into force.

There are other legal elements converging with the ECHO project that need to be mentioned, such as, for example, the actors in the Spanish electricity sector. The LSE describes in detail the different actors in the electricity production and consumption chain. Thus, and in accordance with Article 6, it is possible to identify:

- Electricity producers, which are those natural or legal persons whose function is to generate electricity, as well as to build, operate and maintain production facilities.
- The market operator, which is the trading company that will manage the system for the purchase and sale of electricity in the daily market and which has a series of functions attributed to it in article 29 LSE.
- The system operator, which is the trading company whose main function is to guarantee the continuity and security of the electricity supply and the correct coordination of the production and transmission system. It also has the functions attributed to it by article 30 of the LSE.
- The transmission company, which is the commercial company responsible for the development and extension of the transmission grid and which has the function of transporting electricity, as well as constructing, maintaining, and operating the transmission facilities and all those functions set out in article 36 LSE.

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- Distributors, which are those trading companies or consumer and user cooperative societies whose function is to distribute electricity, as well as to build, maintain and operate the distribution facilities designed to place the energy at the points of consumption and all those functions set out in article 40 LSE.
- Marketers, which are those trading companies or consumer and user cooperative societies which, by accessing the transmission or distribution networks, acquire energy for sale to consumers, to other parties in the system or to carry out international exchange operations under the terms established in this law.
- Consumers, which are natural or legal persons who purchase energy for their own consumption and for the provision of energy recharging services for vehicles. Note that those consumers who purchase energy directly on the production market are called Direct Market Consumers.
- Operators of storage installations, which are natural or legal persons owning installations in which the final use of electricity is deferred to a time later than when it was generated, or which carry out the conversion of electrical energy into a form of energy that can be stored for the subsequent reconversion of such energy into electrical energy.

In a context of climate emergency and structural changes in the energy sector motivated by: (i) the need for independence from fossil fuels; and (ii) developing ways to increase energy efficiency and, above all, ways to store the energy obtained and not consumed, there is a possibility that barriers or possible obstacles may arise in the flexibilization of demand, especially if one of the intervening parties sees its position in the market threatened, without being duly “compensated” by the public authorities.

However, as it has been reiterated on several occasions, there is a need to transform the way in which energy is consumed, albeit through regulatory compliance at supranational levels. An example of this could well be the case of Article 25 of Law 7/1985, of 2 April, regulating the Bases of Local Regime (LBRL), which recognizes the local capacity to manage their own interests, promote activities and provide services for their neighbors, indicating a series of competences of these entities, but which does not include any reference to the energy sector. For this reason, actions aimed at the creation of energy communities find support in various local competences, such as urban planning, which includes actions related to the planning, conservation or rehabilitation of buildings, or the urban environment, which includes atmospheric, light and noise pollution in urban areas.

These competences are complemented by the capacities recognized by some sectoral regulations for local entities. On this point, it should be remembered that Law 2/2011 of 4 March on Sustainable Economy envisaged the approval of a law on energy efficiency and renewable energies, which was never approved, and which could specify local competences in the sector.

Faced with this lost opportunity, the regulation on energy efficiency and renewable energies was fragmented in sectoral legislation, which recognizes local capacities that could enable the creation of energy communities. This is the case of Royal Legislative Decree 7/2015, of 30 October, which approves the Consolidated Text of the Law on Land and Urban Rehabilitation. This regulation, which enshrines the principle of sustainable territorial and urban development, provides that, within the scope of their respective competences, public authorities “shall prioritize renewable energies over the use of fossil energy sources and shall combat energy poverty, promoting energy saving and the efficient use of resources and energy, preferably self-generated” (article 3.3.i).

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It should be noted that, at the current stage of project development, the eighth additional provision on research, development, and innovation in renewable energies, of Law 7/2021 on climate change and energy transition, indicates that:

“In order to promote research and innovation in the field of renewable energies, the use of the different test facilities available at national level shall be promoted to enable the implementation of technological research and innovation projects that contribute to the development of terrestrial and marine renewable energies, as well as to the fulfilment of the objectives set out in this law. (...)”.

This implies an authorization and a use which must necessarily be followed from the development of the project. Furthermore, paragraph 4 of this additional provision provides a sort of legal cover for the ECHO project, since it is clear from its wording that:

“Pilot projects and the tests proposed within them shall not be subject to the specific regulations applicable to commercial or industrial activities related to the generation, storage, and distribution of renewable energies, and must comply, in all cases, with the provisions of this law, the regulations issued in development thereof and other applicable regulations, without prejudice to the respect for the competences corresponding to the Autonomous Communities”.

However, in view of the future implementation of the project, it could be affected by the provisions contained in the Regulation on Thermal Installations in Buildings, hereinafter RITE, whose main purpose is to establish the energy efficiency and safety requirements to be met by thermal installations in buildings. In this sense, the literal wording of Article 12, entitled “energy efficiency”, indicates that:

“Thermal installations must be designed and calculated, implemented, maintained, and operated in such a way that overall energy efficiency is improved and, as a consequence, emissions of greenhouse gases and other air pollutants are reduced, through the use of energy efficient systems, systems allowing energy recovery and the use of renewable energies and waste energies, in compliance with the following requirements:

1. Equipment: equipment for heating and cooling, ventilation, as well as for the movement and transport of fluids, shall be selected in order to ensure that their performance, under all operating conditions, meets the minimum energy efficiency requirements established by the ecodesign regulations as set out in Royal Decree 187/2011, of 18 February, on the establishment of ecodesign requirements for energy-related products.

2. Distribution of fluids: the equipment and piping of the thermal installations must be thermally insulated in order to achieve adequate levels of ventilation and to ensure that the carrier fluids reach the terminal units at temperatures close to those at the outlet of the generation equipment.

3. Regulation and control: the installations shall be equipped with the necessary regulation and control systems so that the design conditions foreseen in the air-conditioned premises can be maintained, while at the same time adjusting energy consumption to variations in thermal demand, as well as interrupting the service.

4. Metering of consumption: thermal installations must be equipped with metering systems so that the user is aware of his energy consumption, and to allow the distribution of operating costs according to consumption, among different users, when the installation satisfies the demand of multiple consumers.

5. Emitters: the emitters of the thermal installations must be selected to achieve the appropriate levels of comfort, energy efficiency requirements, use of renewable energies and use of residual energies as set out in the Technical Instructions.

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6. Energy recovery: thermal installations and ventilation installations shall incorporate subsystems that enable energy savings, energy recovery and the use of waste energy.

7. Use of renewable energies and utilization of waste energies: the thermal installations shall use renewable energies and utilize waste energies, with the aim of covering part of the building's needs with these energies".

Furthermore, in view of the foreseeability of creating an energy storage market, it should be taken into account that, with regard to the collective distribution of energy, Royal Decree 244/2019, of 5 April, which regulates the administrative, technical and economic conditions for the self-consumption of electrical energy, stands out as a regulation applicable to self-consumption, providing for the existence of coefficients to enable the collective distribution of energy. The value of these distribution coefficients depends on the agreement between the participants and may be:

- Consistent throughout the year (constant distribution)
- Different for each hour of the billing period (variable time allocation)

These criteria and coefficients must be included in the agreement between the parties, which each consumer must send to the distributor directly or through its marketing company. Annex I of Royal Decree 244/2019, of 5 April, establishes that:

"The value of these coefficients may be determined according to the power to be billed by each of the participating associated consumers, the economic contribution of each of the consumers to the generation facility, or any other criterion, provided that there is an agreement signed by all the participants and provided that the sum of these coefficients βh, of all the consumers participating in collective self-consumption is the unit for each hour of the billing period. The coefficient will take the value of 1 for each hour of the billing period in cases where there is only one consumer associated to a nearby installation via the grid. The value of these distribution coefficients may be different for each hour of the billing period, provided that there is an agreement signed by all participants and provided that the sum of these coefficients βi of all consumers participating in collective self-consumption is unity for each hour of the billing period".

Finally, it is necessary to indicate that, at the regional level, the Valencian Community, where the ECHO project emerges and will be located, ab initio, geographically, will have to consider the application of the Valencian Law on Climate Change and Ecological Transition, article 45 of which states that:

"The production of electricity using renewable energies may be complemented by the hybridization of different technologies, as well as by the installation of energy storage equipment in order to provide management capacity, ensure the quality of supply and optimize both the use of the existing grid and the development of new grids for their integration.

The competent Regional Ministry shall coordinate with the electricity system operator and the distribution grid managers the integration of energy storage equipment associated with renewable generation facilities, as well as other needs of the electricity system of the Valencian Community. This equipment may be declared public utility and will in any case be considered electrical installations for the purposes of articles 54 and following of Law 24/2013, of 26 December, on the electricity sector".

8.1.6 Legal Feasibility Analysis of the ECHO Project

Throughout this report, the legal support at all levels - international, European, national, and regional - for the ECHO project has been noted. The need to achieve climate neutrality objectives in key sectors such as energy and industry make it an ideal project in the face of the climate crisis, although it is important to adopt

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a cautious stance, especially in view of the imminent development of key regulations pending approval and subsequent entry into force.

8.1.7 Final Considerations

The following conclusions can be drawn from this report:

- The ECHO project is legally viable according to the analysis of international, European, Spanish and regional regulations. It enjoys a legal and factual justification and, above all, a favorable European regulatory scenario.
- The ECHO project may be affected by the emergence of situations of pressure on regulatory procedures that may be introduced by any actor in the electricity sector whose market position is threatened. These measures could act as barriers to commercial deployment of the project. A priori, at the time of drafting this report, the political-legal scenario provides coverage for the project.
- Article 32 of Directive (EU) 2019/944 calls on Member States to provide the necessary legal framework to incentivize the use of flexibility in distribution networks. Specifically, Article 32(3) and (4) of the Directive contains elements aimed at increasing the transparency of the need for flexibility services by distribution companies. ECHO relies on this particular legal situation.
- Periodic evaluations of the development and evolution of the standards that underpin and support the implementation of the project are highly desirable.

8.2 SWOT Analysis

Concerning categorizing the need for TES in different contexts through the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, UPV grouped partners belonging to specific countries, prepared an Excel file which is a legal analysis on the state of the art on TES in EU, and sent to the partners to be completed (Please see Appendix 2 for more information). This survey is structured in two strategic areas affecting both energy sector and energy storage policies. We have considered the integration of key questions, which should be answered in full to the highest degree of transparency. The expected answers are “yes”, “no”, “pending adoption or transposition”. The last one will depend on the adoption of domestic rules or European regulations or directives. Figure 8-1 shows the SWOT analysis of the legal feasibility of the project.

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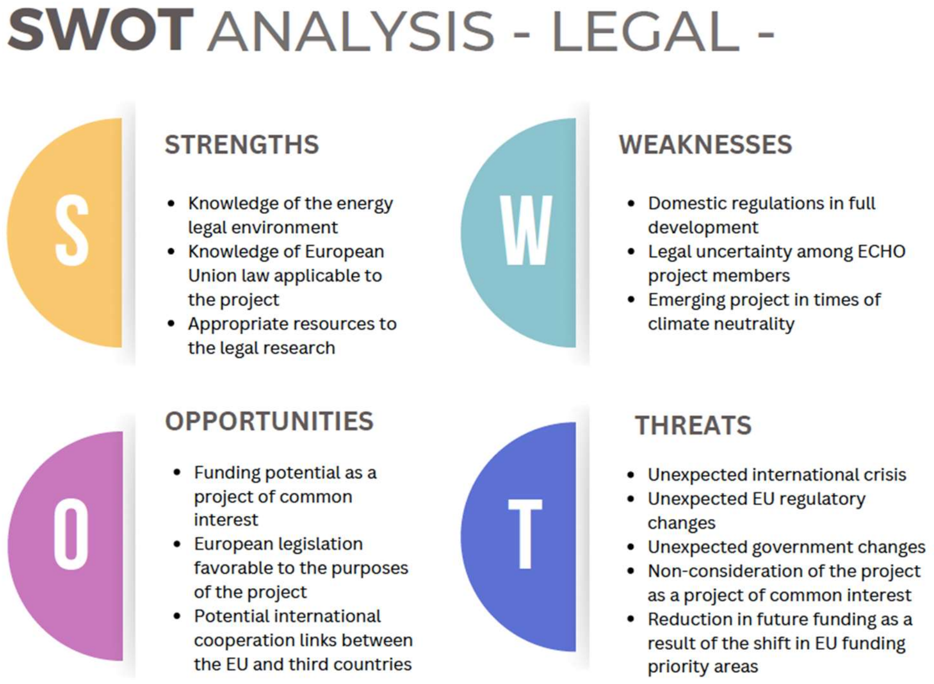

SWOT ANALYSIS - LEGAL -

STRENGTHS

- Knowledge of the energy legal environment
- Knowledge of European Union law applicable to the project
- Appropriate resources to the legal research

WEAKNESSES

- Domestic regulations in full development
- Legal uncertainty among ECHO project members
- Emerging project in times of climate neutrality

OPPORTUNITIES

- Funding potential as a project of common interest
- European legislation favorable to the purposes of the project
- Potential international cooperation links between the EU and third countries

THREATS

- Unexpected international crisis
- Unexpected EU regulatory changes
- Unexpected government changes
- Non-consideration of the project as a project of common interest
- Reduction in future funding as a result of the shift in EU funding priority areas

Figure 8-1: SWOT analysis of the legal feasibility of the project.

8.2.1 United Kingdom (UK)

According to the questionnaire received from the UK, it meticulously examines the UK's alignment with EU legislation, particularly focusing on energy efficiency and the internal market for electricity, where it clarifies that the UK has not transposed Directive 2012/27/EU on energy efficiency and Directive 2019/944 on internal electricity market rules.

The analysis also delves into the UK's commitment to climate change initiatives, noting the national legislation implementing the Paris Agreement. It highlights the UK's proactive measures in setting decarbonization targets within the energy sector and addressing energy demand flexibility, crucial for integrating renewable energy sources and enhancing grid stability.

Financial compensation mechanisms for energy producers, managed by the Office of Gas and Electricity Markets (OFGEM), are outlined, underscoring the UK's efforts to incentivize energy production and support the adoption of renewable energy technologies. The survey further explores the legislative framework surrounding energy communities and the specific regulations governing the storage of energy through various devices, emphasizing the comprehensive approach to ensuring safety, efficiency, and environmental sustainability in energy storage.

Additionally, the analysis touches upon the mandatory requirements for architectural and building construction in relation to energy efficiency, showcasing the integration of energy considerations into building standards. This aspect is particularly relevant to TES as it pertains to energy storage and efficiency in building designs.

Future regulatory requirements are also mentioned, such as the obligation for a carbon footprint declaration for battery and energy storage device models from 2026, reflecting a forward-looking stance on

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environmental sustainability. It concludes by addressing waste management measures for batteries and energy storage devices, highlighting the importance of environmentally responsible end-of-life management practices.

8.2.2 Turkey

The survey from Turkey provides a detailed legal analysis of their approach to TES and related energy regulations, demonstrating the country's efforts in aligning with international environmental standards and advancing its energy sector.

Turkey has ratified the Paris Agreement, showcasing its commitment to international climate change initiatives. This ratification is backed by the development of a comprehensive national climate action plan, including targets for emission reductions across various sectors and a goal to achieve net-zero carbon emissions by 2053. The country's efforts are supported by strategic plans focusing on sustainable development, green economy, and investments in climate-friendly technologies.

Unlike EU member states, Turkey is pending approval/transposition to EU directives, such as 2012/27/EU on energy efficiency and 2019/944 on internal electricity market rules, into its national law. However, Turkey has its own regulatory framework aimed at enhancing energy efficiency and promoting renewable energy sources, reflecting a national commitment to sustainable energy practices.

Turkey's energy policies include measures to encourage energy production from renewable sources, with the Ministry of Energy and Natural Resources managing financial compensations for consumers who produce energy. This approach is part of a broader strategy to foster a sustainable energy future, supported by various incentives and projects like the Green Industry Project, which assists industries in adopting sustainable practices and investing in renewable energy.

The country has introduced regulations to support the development and integration of energy storage systems, particularly in combination with renewable energy sources. These regulations facilitate the operation of energy storage facilities with unlicensed power plants, allowing for increased renewable energy capacity and supporting the transition to a more sustainable energy infrastructure.

In terms of building and construction, Turkey's legislation emphasizes energy efficiency, with specific regulations aiming to reduce energy consumption in public buildings and promote sustainable building practices. While these regulations focus on energy efficiency and renewable energy use in buildings, they do not explicitly detail the integration of energy storage devices within the construction sector.

Overall, Turkey's legal framework and policy initiatives in the energy sector illustrate a strong commitment to environmental sustainability, renewable energy, and the advancement of energy storage solutions, positioning the country as a proactive player in addressing global energy and climate challenges.

8.2.3 Serbia

Legal analysis regarding Serbia's stance on TES and its alignment with relevant energy sector regulations offers insights into Serbia's legal framework, highlighting its commitment to international climate agreements and energy efficiency, though with some areas still in development or lacking specific directives.

Serbia has enacted national legislation implementing the Paris Agreement on climate change, indicating its dedication to global environmental standards. While the country has fully transposed the EU directive related to energy efficiency (Directive 2012/27/EU), the EU directive related to the internal market for electricity (Directive 2019/944) has yet to be transposed. Nevertheless, Serbia has made strides in integrating aspects of Directive 2019/944, focusing on storage aggregation, active customers, smart metering systems, and addressing energy poverty. Decarbonization targets within the energy sector are not explicitly mentioned,

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suggesting an area where Serbia might further refine its energy strategies. The concept of energy demand flexibility is recognized, aligning with emerging market practices and Serbia's move towards an integrated European electricity market.

Serbian legislation acknowledges the role of prosumers (producer-consumers) in the energy market, offering a modern approach to energy production and consumption. However, financial compensation mechanisms for energy producers are not detailed, indicating a potential area for further legislative development to incentivize renewable energy generation.

The country has specific legislation on energy communities, aligning with broader European trends towards decentralized and community-driven energy solutions. Legal constraints or barriers to TES development are noted, suggesting room for legislative enhancements to support TES integration into Serbia's energy infrastructure. Local and municipal regulations in Serbia, particularly in Belgrade, align with the Covenant of Mayors for Climate and Energy, demonstrating a commitment to sustainable energy and climate action plans at the local level. Regulations governing energy storage, particularly for batteries and other storage devices, are in place, focusing on sustainability and safety. Serbia has established rules for architectural and building construction to promote energy efficiency, though the direct link to energy storage within these regulations is not explicitly detailed.

In summary, Serbia's legal framework reflects a commitment to aligning with international standards and adapting to new energy paradigms, with a focus on integrating renewable energy sources and enhancing energy efficiency. However, areas such as the full transposition of EU directives, detailed financial incentives for energy producers, and specific regulations connecting building construction with energy storage present opportunities for further legislative development.

8.2.4 Romania

Romania has ratified the Paris Agreement and is actively implementing its commitments through national legislation, demonstrating a strong commitment to global climate initiatives. The country has transposed EU Directive 2019/944, related to the internal electricity market, and Directive 2012/27/EU, concerning the energy efficiency, through Emergency Ordinance no. 130 of 2022, showing its alignment with EU energy market regulations.

Romania is preparing to transpose the new Directive 2023/1791 on energy efficiency by October 2025, indicating ongoing efforts to enhance its energy efficiency framework. The country has set decarbonization targets in the energy sector through various legislative acts, reflecting a clear commitment to reducing carbon emissions and transitioning to a sustainable energy future. The concept of energy demand flexibility is addressed in Romanian legislation, aligning with the need for a more adaptable and efficient energy system. Financial compensation mechanisms for energy producers are in place, managed by the National Energy Regulatory Authority (ANRE), promoting renewable energy production and supporting energy prosumers. Specific legislation on energy communities exists, encouraging collaborative and sustainable energy production and consumption models. Legal constraints and barriers to TES development are acknowledged, which could guide future legislative improvements to facilitate TES integration. Local and municipal regulations, particularly regarding energy-efficient buildings, align with the Covenant of Mayors, showcasing Romania's commitment to energy efficiency at the local level. Romania's regulations cover a broad spectrum of energy storage technologies, not exclusive to batteries, indicating a comprehensive approach to energy storage within its legal framework. Specific requirements on sustainability, safety, labeling, marking, and information dissemination are considered for batteries and energy storage devices, ensuring a responsible and transparent energy storage sector.

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Overall, Romania’s legal and regulatory framework reflects a proactive approach to addressing energy efficiency, renewable energy, and energy storage, aligning with European standards, and demonstrating a commitment to a sustainable and efficient energy future.

8.2.5 Italy

The legal survey from Italy illustrates the country’s adherence to international and European directives and its initiatives in energy efficiency and renewable energy. Italy has ratified the Paris Agreement through Law No. 204 of November 4, 2016, demonstrating its commitment to international climate change efforts. The country has also transposed EU Directive 2019/944 concerning common rules for the internal electricity market through Legislative Decree No. 210 of November 8, 2021, showcasing alignment with EU energy market standards. Italy’s active engagement in setting decarbonization targets and energy policies suggests a comprehensive approach to energy sector reform, aiming for increased sustainability and reduced carbon emissions. Italy recognizes the importance of energy demand flexibility, particularly in the context of electricity supply contracts, and is fostering the development of energy communities. These initiatives indicate a shift towards a more decentralized, consumer-involved energy system, with industries playing a significant role as both consumers and suppliers. Based on the legal survey, financial compensation mechanisms are applied for energy producers, managed by GSE, supporting the promotion of renewable energy and the involvement of consumers in energy production.

Specific legislation in Italy addresses energy communities, aligning with European directives and fostering collaborative energy generation and consumption models. The country’s efforts in this area are aimed at promoting renewable energy sources and enhancing energy system efficiency at the community level. Regarding energy storage, Italy has regulations governing the use of batteries and other energy storage devices, emphasizing sustainability and integration into the broader energy framework. These regulations are part of Italy’s commitment to ensuring a reliable, efficient, and environmentally friendly energy storage sector.

In summary, Italy’s legal and regulatory framework reflects a proactive approach to energy efficiency, renewable energy, and energy storage. The country’s alignment with EU directives and international agreements, coupled with national initiatives in energy communities and demand flexibility, underscores its commitment to a sustainable and innovative energy future.

8.2.6 Belgium

Belgium’s legal framework regarding TES and broader energy sector regulations shows the country’s adherence to international and European directives and its initiatives in energy efficiency and renewable energy. Belgium has national legislation implementing the Paris Agreement, demonstrating its commitment to global climate initiatives. The country has transposed the essential EU directives related to energy efficiency and the internal electricity market, illustrating alignment with EU energy policies. Belgium is also actively working on integrating the new Directive 2023/1791 on energy efficiency into its national law, indicating ongoing efforts to enhance energy efficiency standards.

A decarbonization target in the energy sector is set, reflecting Belgium’s commitment to reducing carbon emissions and transitioning to a sustainable energy future. The concept of energy demand flexibility is recognized, signifying a shift towards more adaptive and efficient energy systems. Financial compensation mechanisms for energy producers exist. Belgium’s legislation supports energy communities, aligning with European initiatives to promote collaborative and sustainable energy production and consumption models.

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Regarding energy storage, Belgium has regulations governing the use of batteries and other storage devices, focusing on sustainability and integration within the broader energy framework. The country's regulations encompass various energy storage technologies, ensuring a comprehensive approach to energy storage within its legal framework. Specific requirements related to human health, safety, security, labeling, marking, and information dissemination for batteries and energy storage devices are considered, ensuring a responsible and transparent energy storage sector in Belgium.

In summary, Belgium's legal and regulatory framework reflects a proactive approach to energy efficiency, renewable energy, and energy storage. The country's commitment to international and European directives, coupled with national initiatives in energy communities and demand flexibility, underscores its dedication to a sustainable and innovative energy future.

8.2.7 Spain

Spain has ratified the Paris Agreement, illustrating its commitment to global climate change initiatives. The country has successfully transposed the EU directive pertinent to energy efficiency (Directive 2012/27/EU) but EU directive related to the internal market for electricity (Directive 2019/944) is still pending approval/transposition. Additionally, Spain is addressing the recent Directive 2023/1791 on energy efficiency, reflecting ongoing efforts to enhance its energy efficiency framework. Spain has established decarbonization targets within its energy sector, signaling a firm commitment to reducing carbon emissions and transitioning towards a sustainable energy future. The legislation recognizes the concept of energy demand flexibility, which is crucial for adapting to and efficiently managing varying energy demands and integrating renewable energy sources.

The Spanish legislation provides for financial compensation mechanisms for energy producers, fostering the participation of consumers in energy production and supporting the growth of renewable energy. Specific legislation on energy communities is in place, promoting collaborative energy generation and consumption models, in line with European trends towards decentralized energy systems.

Spain has authorized regulations governing the use of batteries and other energy storage devices, focusing on sustainability and integration within the broader energy framework. These regulations encompass various energy storage technologies, ensuring a comprehensive approach to energy storage within the national legal framework. Regarding energy storage policies, Spain has considered specific requirements related to human health, safety, security, labeling, marking, and information dissemination for batteries and energy storage devices. This ensures that energy storage systems are integrated responsibly and transparently into the national energy infrastructure.

In summary, Spain's legal and regulatory environment demonstrates a proactive approach to energy efficiency, renewable energy, and energy storage. The country's commitment to international and European directives, coupled with national initiatives in energy communities and demand flexibility, indicates a supportive legislative landscape for the development and integration of TES and related energy technologies.

8.2.8 Comparative SWOT Analysis

A comparative SWOT analysis based on the received individual legal questionnaire of each country is given below, giving us the results to the evaluation of the Internal Key indicator (see ECHO deliverable D2.2) QLI4.1: LEGISLATIVE PENETRABILITY FOR TES TECHNOLOGY:

Strengths:

- **United Kingdom (UK):** Proactive measures in setting decarbonization targets, comprehensive legislative framework, financial compensation mechanisms managed by OFGEM.

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- **Turkey:** Commitment to sustainable energy practices, efforts to incentivize renewable energy production, regulations facilitating energy storage system development.
- **Serbia:** Dedication to aligning with international climate agreements, recognition of energy demand flexibility, establishment of rules for energy storage safety.
- **Romania:** Adherence to international climate agreements, financial compensation mechanisms supporting renewable energy production, comprehensive regulations covering various energy storage technologies.
- **Italy:** Adherence to international and EU directives, financial compensation mechanisms supporting renewable energy production, emphasis on energy communities.
- **Belgium:** Adherence to international and EU directives, financial compensation mechanisms supporting renewable energy production, comprehensive regulations governing energy storage technologies.
- **Spain:** Ratification of the Paris Agreement, financial compensation mechanisms supporting renewable energy production, comprehensive regulations governing energy storage technologies.

Weaknesses:

- **United Kingdom (UK):** Lack of transposition of certain EU directives into national law, limited integration of energy storage regulations into building construction standards.
- **Turkey:** Pending transposition of certain EU directives into national law, limited detail on the integration of energy storage devices into building construction regulations.
- **Serbia:** Incomplete transposition of certain EU directives into national law, limited financial incentives for energy producers.
- **Romania:** Need for continued efforts to enhance energy efficiency standards, challenges in fully transposing new EU directives into national law.
- **Italy:** Need for ongoing efforts to enhance energy demand flexibility, challenges in fully integrating new EU directives into national law.
- **Belgium:** Need for ongoing efforts to enhance energy efficiency standards, challenges in fully integrating new EU directives into national law.
- **Spain:** Pending transposition of certain EU directives into national law, challenges in fully integrating new EU directives into national law.

Opportunities:

- **United Kingdom (UK):** Future regulatory requirements present opportunities for environmental sustainability, potential for legislative developments to incentivize renewable energy generation.
- **Turkey:** Scope for further enhancements in energy efficiency frameworks, potential for legislative enhancements to support energy storage integration.
- **Serbia:** Opportunities for legislative enhancements to support sustainable energy practices, potential for further refinements in energy sector strategies.
- **Romania:** Scope for further enhancements in energy efficiency frameworks, potential for refining legislative support for energy storage integration.
- **Italy:** Scope for further enhancements in energy efficiency frameworks, potential for refining legislative support for energy storage integration.
- **Belgium:** Scope for further enhancements in energy efficiency frameworks, potential for refining legislative support for energy storage integration.
- **Spain:** Future regulatory requirements present opportunities for environmental sustainability, potential for legislative developments to incentivize renewable energy generation.

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Threats:

- **United Kingdom (UK):** Incomplete alignment with certain EU directives might hinder harmonization with European energy standards, lack of detailed financial compensation mechanisms might hinder renewable energy investment.
- **Turkey:** Insufficient financial compensation mechanisms for energy producers might slow renewable energy growth, incomplete integration of energy storage considerations into building standards could limit efficiency gains.
- **Serbia:** Lack of detailed financial compensation mechanisms might hinder renewable energy investment, challenges in fully transposing new EU directives into national law.
- **Romania:** Challenges in meeting evolving energy demands and sustainability goals, lack of detailed financial compensation mechanisms might hinder renewable energy investment.
- **Italy:** Challenges in meeting evolving energy demands and sustainability goals, lack of detailed financial compensation mechanisms might hinder renewable energy investment.
- **Belgium:** Challenges in meeting evolving energy demands and sustainability goals, lack of detailed financial compensation mechanisms might hinder renewable energy investment.
- **Spain:** Incomplete alignment with certain EU directives might affect international cooperation and standards compliance, challenges in meeting evolving energy demands and sustainability goals.

In addition, a graphical representation of the SWOT analysis conducted on the countries participated in Task 2.1 of ECHO project is displayed in Figure 8-2. Overall, while each country demonstrates strengths in various aspects of energy policy and regulation, there are opportunities for further improvement and collaboration to address common challenges and capitalize on emerging trends in renewable energy and energy storage technologies.

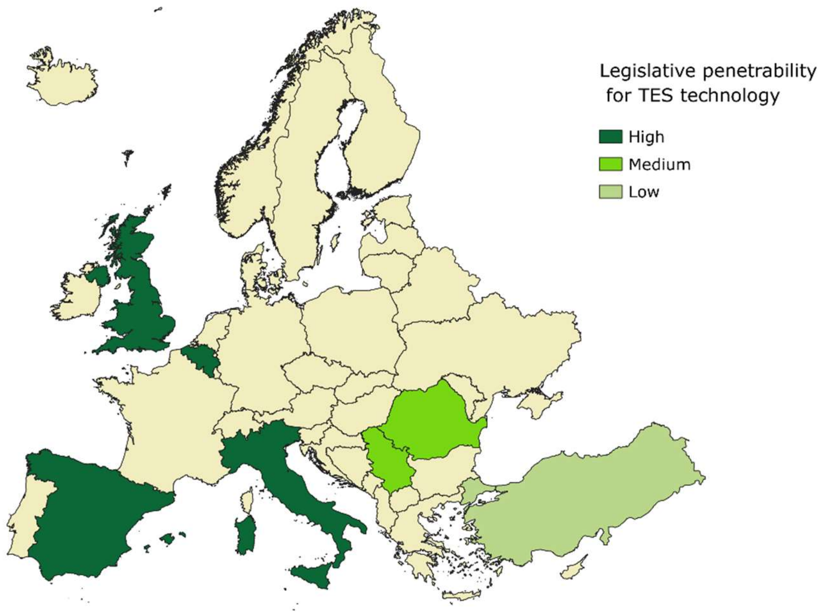

Figure 8-2: Graphical representation of the SWOT analysis conducted on the countries participated in Task 2.1 of ECHO project.

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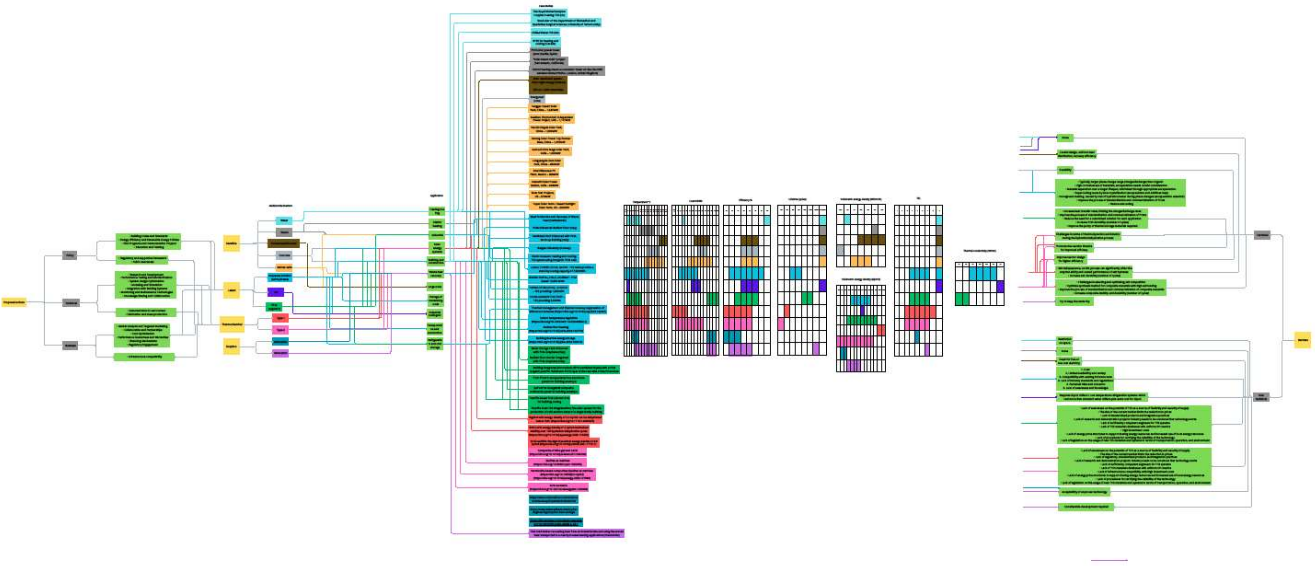
10 Appendix

Appendix 1

Taxonomy:

Online link with high resolution:
https://www.canva.com/design/DAF1k5REGxA/MtW8y4j79bHDFjKYtaZNbw/edit?utm_content=DAF1k5REGxA&utm_campaign=designshare&utm_medium=link2&utm_source=sharebutton



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Appendix 2

Legal Survey received from the partners for the SWOT analysis:

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DRAFT V. 1.0

Legal Analysis on the State of the Art on Thermal Storage Energy (TES) in the European Union

Aspects and criteria to be assessed for the final report

PARTNER	EU COUNTRY	KEY QUESTIONS		LEVEL OF KNOWLEDGE				SELECTION OF LEVEL
				YES	NO	PENDING APPROVAL OR TRANSPOSITION	If the answer has been marked as YES, please, include references/websites/information	Level
UNIVERSITAT POLITÈCNICA DE VALÈNCIA –SPAIN–	X	**Energy sector**	Does your country have national legislation implementing the Paris Agreement on climate change?	x			https://www.boe.es/diario_boe/txt.php?id=BOE-A-2021-8447	
			Has your country's legislation transposed the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency?	x			https://www.boe.es/buscar/doc.php?id=BOE-A-2016-1460	
			Has your country's legislation transposed the Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity?			x		
			Has your country's legislation transposed the new Directive 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency?			x		
			Does your country's legislation provide for a decarbonisation target in the energy sector?	x			https://www.miteco.gob.es/content/dam/miteco/images/es/pnieccompleto_tcm30-508410.pdf	
			Is the concept of energy demand flexibility specifically covered by your country's legislation?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2019-81028	
			In electricity supply contracts concluded between industries and the energy trader, are industries treated as consumers?		x			
			Does your country's legislation provide for financial compensation to consumers who produce energy?	x			https://www.boe.es/buscar/doc.php?id=BOE-A-2019-5089	
			If yes to the above question, who manages these financial compensations?				The consumer and producer througout an arrangement. Article 4.1. Real Decreto 244/2019, de 5 de abril	
			Does your country have specific legislation on energy communities?			x		
			Has your country's legislation specified legal constraints or barriers limiting TES development?		x			
			In local or municipality regulation, does your national legislation include specific measures Covenant of Mayors related to energy efficiency?	x				
		Energy storage policies	Does your country have specific regulations in force governing the storage of energy through the use of batteries or energy storage devices?	x			https://www.miteco.gob.es/content/dam/miteco/es/prensa/estrategiaalmacenamiento_tcm30-522655.pdf	
			Does your national legislation apply to all categories of energy storage devices?	x			https://www.miteco.gob.es/content/dam/miteco/es/prensa/estrategiaalmacenamiento_tcm30-522655.pdf	
			Has your domestic legislation considered specific requirements on sustainability to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	
			Has your current legislation a set of rules about architectural and building construction mandatory requirements in energy efficency?	x			https://www.boe.es/buscar/doc.php?id=BOE-A-2007-15820	
			If yes to the above question, which of them are related to energy storage devices				https://www.boe.es/buscar/doc.php?id=BOE-A-2007-15820	
			Depending the TRL project's target and its market expected milestones, the following questions are important.					
			Has your domestic legislation considered specific requirements on human health to allow the placing on the market or putting into service of batteries or energy storage devices?		x			
			Has your domestic legislation considered specific requirements on safety and security to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	
			Has your domestic legislation considered specific requirements on labelling to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	
			Has your domestic legislation considered specific requirements on marking to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	
			Has your domestic legislation considered requirements on information to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific weight requirements for batteries or energy storage devices in private environments?	x			https://www.miteco.gob.es/content/dam/miteco/es/prensa/estrategiaalmacenamiento_tcm30-522655.pdf	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific durability parameters of batteries or energy storage devices?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific waste management measures for batteries or energy storage devices?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific obligations to issue a carbon footprint declaration for each battery or energy storage device model from 2026 onwards?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	
			According to your current legislation and depending on whether or not your country belongs to the EU, does your national legislation have considered specific obligations related to the return of waste for the distributors of the batteries or energy storage devices?	x			https://www.boe.es/buscar/doc.php?id=DOUE-L-2023-81096	

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DRAFT V. 1.0

Legal Analysis on the State of the Art on Thermal Storage Energy (TES) in the European Union

Aspects and criteria to be assessed for the final report

PARTNER	EU COUNTRY	KEY QUESTIONS		LEVEL OF KNOWLEDGE YES	NO	PENDING APPROVAL OR TRANSPOSITION	If the answer has been marked as YES, please, include references/websites/information	SELECTION OF LEVEL Level
CNR - ITALY -	X	**Energy sector**	Does your country have national legislation implementing the Paris Agreement on climate change?	x			LEGGE 4 novembre 2016, n. 204 Ratifica ed esecuzione dell'Accordo di Parigi collegato alla Convenzione quadro delle Nazioni Unite sui cambiamenti climatici, adottato a Parigi il 12 dicembre 2015. (16G00214) (GU Serie Generale n.263 del 10-11-2016) - https://www.gazzettaufficiale.it/eli/id/2016/11/10/16G00214/sg	
			Has your country's legislation transposed the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency?	x			DECRETO LEGISLATIVO 8 novembre 2021, n. 210 Attuazione della direttiva UE 2019/944, del Parlamento europeo e del Consiglio, del 5 giugno 2019, relativa a norme comuni per il mercato interno dell'energia elettrica e che modifica la direttiva 2012/27/UE, nonché recante disposizioni per l'adeguamento della normativa nazionale alle disposizioni del regolamento UE 943/2019 sul mercato interno dell'energia elettrica e del regolamento UE 941/2019 sulla preparazione ai rischi nel settore dell'energia elettrica e che abroga la direttiva 2005/89/CE. (21G00233) (GU Serie Generale n.294 del 11-12-2021) - https://www.gazzettaufficiale.it/eli/id/2021/12/11/21G00233/sg	
			Has your country's legislation transposed the Directive Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity?	x				
			Has your country's legislation transposed the new Directive 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency?		x			
			Does your country's legislation provide for a decarbonisation target in the energy sector?	x			Piano nazionale integrato per l'energia e il clima per gli anni 2021-2030 - https://www.mimit.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf	
			Is the concept of energy demand flexibility specifically covered by your country's legislation?				Piano nazionale integrato per l'energia e il clima per gli anni 2021-2030 - https://www.mimit.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf	
			In electricity supply contracts concluded between industries and the energy trader, are industries treated as consumers?	X			Generally, industries are treated as usual consumers. Lately, the energy policies are pushing to develop Energy Communities. In this context, the industries are meant to play a crucial role as both consumer and suppliers. https://www.gse.it/servizi-per-te/autoconsumo	
			Does your country's legislation provide for financial compensation to consumers who produce energy?	Scambio sul posto?			https://www.gse.it/servizi-per-te/fotovoltaico/scambio-sul-posto	
			If yes to the above question, who manages these financial compensations?				GSE	
			Does your country have specific legislation on energy communities?	x			Per quanto riguarda la normativa sulle comunità energetiche a livello italiano, la regolamentazione nazionale ha recepito quella europea (Direttiva Red II) in una prima fase, attraverso l'emanazione e conversione in legge del DL 162/19 ("Decreto Milleproroghe") e successivamente con il DLgs 199/2021 e il i DLgs 210/2021. In particolare, l'art. 42-bis del Decreto Milleproroghe aveva introdotto una disciplina di carattere transitorio con l'obiettivo di regolare una prima fase sperimentale di configurazione delle CER che comprendeva impianti alimentati a fonti rinnovabili di potenza non superiore a 200 kW ciascuno ed un perimetro di aggregazione degli impianti limitato a quelli facenti capo alla stessa cabina di trasformazione secondaria. Il 4 gennaio 2023 è stata adottata la delibera ARERA, conosciuta come Tiad (Testo Integrato per l'Autoconsumo Diffuso), che si aggiunge alle precedenti delibere sui Sistemi semplici di produzione e consumo e sui Sistemi di distribuzione chiusi, promulgate in ottemperanza ai Decreti 199/21 e 210/21. https://www.arera.it/allegati/docs/22/727-22alla.pdf	
			Has your country's legislation specified legal constraints or barriers limiting TES development?		x			
			In local or municipality regulation, does your national legislation include specific measures Covenant of Mayors related to energy efficiency?	x			https://www.eai.enea.it/archivio/efficienza-energetica-avanti-tutta/efficienza-energetica-e-lotta-al-cambiamento-climatico-il-ruolo-del-patto-dei-sindaci.html	
		Energy storage policies	Does your country have specific regulations in force governing the storage of energy through the use of batteries or energy storage devices?	x			CEI 0-16 "Regola tecnica di riferimento per la connessione di Utenti attivi e passivi alle reti AT ed MT delle imprese distributrici di energia elettrica" e CEI 0-21 "Regola tecnica di riferimento per la connessione di Utenti attivi e passivi alle reti BT delle imprese distributrici di energia elettrica"	
			Does your national legislation apply to all categories of energy storage devices?		x			
			Has your domestic legislation considered specific requirements on sustainability to allow the placing on the market or putting into service of batteries or energy storage devices?		x			
			Has your current legislation a set of rules about architectural and building construction mandatory requirements in energy efficency?	x			Attuazione della direttiva (UE) 2018/2002 che modifica la direttiva 2012/27/UE sull'efficienza energetica. (20G00093) - https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2020-07-14&atto.codiceRedazionale=20G00093 DECRETO LEGISLATIVO 10 giugno 2020, n. 48 Attuazione della direttiva (UE) 2018/844 del Parlamento europeo e del Consiglio, del 30 maggio 2018, che modifica la direttiva 2010/31/UE sulla prestazione energetica nell'edilizia e la direttiva 2012/27/UE sull'efficienza energetica. (20G00066) (GU Serie Generale n.146 del 10-06-2020) - https://www.gazzettaufficiale.it/eli/id/2020/06/10/20G00066/sg	
			If yes to the above question, which of them are related to energy storage devices	None				
			Depending the TRL project's target and its market expected milestones, the following questions are important.					
			Has your domestic legislation considered specific requirements on human health to allow the placing on the market or putting into service of batteries or energy storage devices?		x			
			Has your domestic legislation considered specific requirements on safety and security to allow the placing on the market or putting into service of batteries or energy storage devices?	x			**AT EUROPEAN LEVEL** - REGOLAMENTO (UE) 2023/1542 DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 12 luglio 2023 relativo alle batterie e ai rifiuti di batterie, che modifica la direttiva 2008/98/CE e il regolamento (UE) 2019/1020 e abroga la direttiva 2006/66/CE (Testo rilevante ai fini del SEE)	
			Has your domestic legislation considered specific requirements on labelling to allow the placing on the market or putting into service of batteries or energy storage devices?	x			**AT EUROPEAN LEVEL** - REGOLAMENTO (UE) 2023/1542 DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 12 luglio 2023 relativo alle batterie e ai rifiuti di batterie, che modifica la direttiva 2008/98/CE e il regolamento (UE) 2019/1020 e abroga la direttiva 2006/66/CE (Testo rilevante ai fini del SEE)	
			Has your domestic legislation considered specific requirements on marking to allow the placing on the market or putting into service of batteries or energy storage devices?	x			**AT EUROPEAN LEVEL** - REGOLAMENTO (UE) 2023/1542 DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 12 luglio 2023 relativo alle batterie e ai rifiuti di batterie, che modifica la direttiva 2008/98/CE e il regolamento (UE) 2019/1020 e abroga la direttiva 2006/66/CE (Testo rilevante ai fini del SEE)	
			Has your domestic legislation considered requirements on information to allow the placing on the market or putting into service of batteries or energy storage devices?		x			
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific weight requirements for batteries or energy storage devices in private environments?		x			
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific durability parameters of batteries or energy storage devices?		x			
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific waste management measures for batteries or energy storage devices?	x			DECRETO LEGISLATIVO 14 marzo 2014, n. 49 Attuazione della direttiva 2012/19/UE sui rifiuti di apparecchiature elettriche ed elettroniche (RAEE). - https://www.governo.it/sites/governo.it/files/75158-9343.pdf	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific obligations to issue a carbon footprint declaration for each battery or energy storage device model from 2026 onwards?	x			**AT EUROPEAN LEVEL** - Batteries and waste batteries European Parliament legislative resolution of 14 June 2023 on the proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) 2019/1020 (COM(2020)0798 – C9-0400/2020 – 2020/0353(COD)) - https://www.europarl.europa.eu/doceo/document/TA-9-2023-0237_EN.pdf	
			According to your current legislation and depending on whether or not your country belongs to the EU, does your national legislation have considered specific obligations related to the return of waste for the distributors of the batteries or energy storage devices?	x			**AT EUROPEAN LEVEL** - REGOLAMENTO (UE) 2023/1542 DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 12 luglio 2023 relativo alle batterie e ai rifiuti di batterie, che modifica la direttiva 2008/98/CE e il regolamento (UE) 2019/1020 e abroga la direttiva 2006/66/CE (Testo rilevante ai fini del SEE)	

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PARTNER	EU COUNTRY	KEY QUESTIONS		LEVEL OF KNOWLEDGE				SELECTION OF LEVEL
				YES	NO	PENDING APPROVAL OR TRANSPOSITION	If the answer has been marked as YES, please, include references/websites/information	Level
BELGIUM - EHPA	X	**Energy sector**	Does your country have national legislation implementing the Paris Agreement on climate change?	x			https://climat.be/doc/NAP_EN.pdf - https://climat.be/politique-climatique/belge/federale/adaptation	
			Has your country's legislation transposed the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency?	x			https://energy.ec.europa.eu/system/files/2020-09/be_final_necp_parta_en_0.pdf - https://energy.ec.europa.eu/system/files/2023-05/Belgium%20NEEAP.pdf	
			Has your country's legislation transposed the Directive Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity?	x			https://eur-lex.europa.eu/legal-content/EN/NIM/?uri=CELEX:32019L0944&qid=1704796438720	
			Has your country's legislation transposed the new Directive 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency?			x		
			Does your country's legislation provide for a decarbonisation target in the energy sector?	x			https://iea.blob.core.windows.net/assets/638cb377-ca57-4c16-847d-ea4d96218d35/Belgium2022_EnergyPolicyReview.pdf	
			Is the concept of energy demand flexibility specifically covered by your country's legislation?	x			https://commission.europa.eu/system/files/2023-12/Belgium%20-%20Draft%20updated%20NECP%202021-2030%20EN.pdf	
			In electricity supply contracts concluded between industries and the energy trader, are industries treated as consumers?					
			Does your country's legislation provide for financial compensation to consumers who produce energy?	x			https://cms.law/en/int/expert-guides/cms-expert-guide-to-electricity/belgium	
			If yes to the above question, who manages these financial compensations?					
			Does your country have specific legislation on energy communities?	x			https://energy-communities-repository.ec.europa.eu/system/files/2023-12/ECR_MSfiche_Flanders_final_public.pdf	
			Has your country's legislation specified legal constraints or barriers limiting TES development?		x		https://energy.ec.europa.eu/system/files/2023-03/SWD_2023_57_1_EN_document_travail_service_part1_v6.pdf	
			In local or municipality regulation, does your national legislation include specific measures Covenant of Mayors related to energy efficiency?					
		Energy storage policies	Does your country have specific regulations in force governing the storage of energy through the use of batteries or energy storage devices?	x			https://navigator.emis.vito.be/detail?woId=70098	
			Does your national legislation apply to all categories of energy storage devices?					
			Has your domestic legislation considered specific requirements on sustainability to allow the placing on the market or putting into service of batteries or energy storage devices?					
			Has your current legislation a set of rules about architectural and building construction mandatory requirements in energy efficincy?	x			https://epbd-ca.eu/ca-outcomes/outcomes-2015-2018/book-2018/countries/belgium-flanders	
			If yes to the above question, which of them are related to energy storage devices					
		Depending the TRL project's target and its market expected milestones, the following questions are important.						
			Has your domestic legislation considered specific requirements on human health to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022D0639	
			Has your domestic legislation considered specific requirements on safety and security to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://www.ejustice.just.fgov.be/cgi_loi/change_lg.pl?language=nl&la=N&cn=2009032738&table_name=wet	
			Has your domestic legislation considered specific requirements on labelling to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://navigator.emis.vito.be/light?woId=43991&woLang=en&woVersion=2023-12-25	
			Has your domestic legislation considered specific requirements on marking to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022D0639	
			Has your domestic legislation considered requirements on information to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022D0639	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific weight requirements for batteries or energy storage devices in private environments?		x			
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific durability parameters of batteries or energy storage devices?	x			https://www.ejustice.just.fgov.be/cgi_loi/change_lg.pl?language=nl&la=N&cn=2009032738&table_name=wet	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific waste management measures for batteries or energy storage devices?	x			https://navigator.emis.vito.be/light?woId=43991&woLang=en&woVersion=2023-12-25	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific obligations to issue a carbon footprint declaration for each battery or energy storage device model from 2026 onwards?	x			https://navigator.emis.vito.be/light?woId=43991&woLang=en&woVersion=2023-12-25	
			According to your current legislation and depending on whether or not your country belongs to the EU, does your national legislation have considered specific obligations related to the return of waste for the distributors of the batteries or energy storage devices?	x			https://navigator.emis.vito.be/light?woId=43991&woLang=en&woVersion=2023-12-25	

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PARTNER	EU COUNTRY	KEY QUESTIONS		LEVEL OF KNOWLEDGE				SELECTION OF LEVEL	
				YES	NO	PENDING APPROVAL OR TRANSPOSITION	If the answer has been marked as YES, please, include references/websites/information	Level	
MIHAJLO PUPIN INSTITUTE	NO	**Energy sector**	Does your country have national legislation implementing the Paris Agreement on climate change?	x			https://en.wikipedia.org/wiki/List_of_parties_to_the_Paris_Agreement		
			Has your country's legislation transposed the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency?	x			https://unece.org/fileadmin/DAM/energy/se/pp/geee/geee2_nov2015/ai3/5_Solujic.pdf		
			Has your country's legislation transposed the Directive Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity?		x		Figure 3.1 and "The Energy Law (Official Gazette of the Republic of Serbia, no. 40/2021), amended in 2021, partially transposes the new elements of the Directive (EU) 2019/944 related to storage, aggregation, active customers, smart metering systems and energy poverty. " TRINITY D8.5 Figure 3.1 and	**Only partly**	
			Has your country's legislation transposed the new Directive 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency?		x				Not enough time has passed for this diective to be considered
			Does your country's legislation provide for a decarbonisation target in the energy sector?		x				There are targets embodided in the legislative, but it appears none of them directly target decarbonisaton of the energy sector
			Is the concept of energy demand flexibility specifically covered by your country's legislation?			x	Serch for "fleksiblnost potrošnje" on https://balkangreenenergynews.com/rs/srbija-u-junu-dobija-unutardnevno-trziste-struje-sledeci-korak-je-spajanje-sa-jedinstvenim-evropskim-trzistem/		
			In electricity supply contracts concluded between industries and the energy trader, are industries treated as consumers?	x					Except in cases where the industries register as a prosumer under new(er) regulation.
			Does your country's legislation provide for financial compensation to consumers who produce energy?		x		"Kupac-proizvođač iz stava 1. ovog člana ne može koristiti podsticajne mere u vidu tržišne premije i fid-in tarife, niti može imati pravo na garancije porekla." from ZAKON O KORIŠĆENJU OBNOVLJIVIH IZVORA ENERGIJE ("Sl. glasnik RS", br. 40/2021 i 35/2023)		
			If yes to the above question, who manages these financial compensations?	-	-				
			Does your country have specific legislation on energy communities?	x			Section "X ZAJEDNICE OBNOVLJIVIH IZVORA ENERGIJE" of ZAKON O KORIŠĆENJU OBNOVLJIVIH IZVORA ENERGIJE ("Sl. glasnik RS", br. 40/2021 i 35/2023)		
			Has your country's legislation specified legal constraints or barriers limiting TES development?		x				There is no mention of any particular "thermal" or "storage" kind of chemical in the corresponding law governing chemicals ZAKON O HEMIKALIJAMA ("Sl. glasnik RS", br. 36/2009, 88/2010, 92/2011, 93/2012 i 25/2015). Typical regulations do apply.
			In local or municipality regulation, does your national legislation include specific measures Covenant of Mayors related to energy efficiency?	x			"The City of Belgrade signed the Covenant of Mayors for Climate and Energy (CoM) in October 2018, thereby making a commitment to: submitting a Sustainable Energy and Climate Action Plan (SECAP) within two years;" https://serbia.un.org/sites/default/files/2021-09/UN%20Serbia%20Thematic%20Update%20%232%20_%20Climate%20Change%20Energy%20Environment%20Aug%202021.pdf#:~:text=The%20City%20of%20Belgrade%20signed,to%20the%20impacts%20of%20climate		
		Energy storage policies	Does your country have specific regulations in force governing the storage of energy through the use of batteries or energy storage devices?		x				
			Does your national legislation apply to all categories of energy storage devices?		x				
			Has your domestic legislation considered specific requirements on sustainability to allow the placing on the market or putting into service of batteries or energy storage devices?		x				
			Has your current legislation a set of rules about architectural and building construction mandatory requirements in energy efficency?	x			PRAVILNIK O ENERGETSKOJ EFIKASNOSTI ZGRADA ("Sl. glasnik RS", br. 61/2011)		
			If yes to the above question, which of them are related to energy storage devices	-	-				Question is unclear, how are architectural and building construction connected to energy storage?
			Depending the TRL project's target and its market expected milestones, the following questions are important.						
			Has your domestic legislation considered specific requirements on human health to allow the placing on the market or putting into service of batteries or energy storage devices?	x			PRAVILNIK O NAČINU I POSTUPKU UPRAVLJANJA ISTROŠENIM BATERIJAMA I AKUMULATORIMA ("Sl. glasnik RS", br. 86/2010)		
			Has your domestic legislation considered specific requirements on safety and security to allow the placing on the market or putting into service of batteries or energy storage devices?	x			PRAVILNIK O NAČINU I POSTUPKU UPRAVLJANJA ISTROŠENIM BATERIJAMA I AKUMULATORIMA ("Sl. glasnik RS", br. 86/2010)		
			Has your domestic legislation considered specific requirements on labelling to allow the placing on the market or putting into service of batteries or energy storage devices?	x			PRAVILNIK O NAČINU I POSTUPKU UPRAVLJANJA ISTROŠENIM BATERIJAMA I AKUMULATORIMA ("Sl. glasnik RS", br. 86/2010)		
			Has your domestic legislation considered specific requirements on marking to allow the placing on the market or putting into service of batteries or energy storage devices?	x			PRAVILNIK O NAČINU I POSTUPKU UPRAVLJANJA ISTROŠENIM BATERIJAMA I AKUMULATORIMA ("Sl. glasnik RS", br. 86/2010)		Difference between previous question is unclear.
			Has your domestic legislation considered requirements on information to allow the placing on the market or putting into service of batteries or energy storage devices?	x			PRAVILNIK O NAČINU I POSTUPKU UPRAVLJANJA ISTROŠENIM BATERIJAMA I AKUMULATORIMA ("Sl. glasnik RS", br. 86/2010)		
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific weight requirements for batteries or energy storage devices in private environments?		x				
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific durability parameters of batteries or energy storage devices?		x				
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific waste management measures for batteries or energy storage devices?	x			PRAVILNIK O NAČINU I POSTUPKU UPRAVLJANJA ISTROŠENIM BATERIJAMA I AKUMULATORIMA ("Sl. glasnik RS", br. 86/2010)		
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific obligations to issue a carbon footprint declaration for each battery or energy storage device model from 2026 onwards?		x				
			According to your current legislation and depending on whether or not your country belongs to the EU, does your national legislation have considered specific obligations related to the return of waste for the distributors of the batteries or energy storage devices?	x			PRAVILNIK O NAČINU I POSTUPKU UPRAVLJANJA ISTROŠENIM BATERIJAMA I AKUMULATORIMA ("Sl. glasnik RS", br. 86/2010)		

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				YES	NO	PENDING APPROVAL OR TRANSPOSITION	If the answer has been marked as YES, please, include references/websites/information	Level
GREENCO - ROMANIA	X	**Energy sector**	Does your country have national legislation implementing the Paris Agreement on climate change?	X			Yes, Romania has national legislation implementing the Paris Agreement on climate change. The Paris Agreement of December 12, 2015, was signed by Romania on April 22, 2016. This law was adopted by the Romanian Parliament, in accordance with the provisions of Article 75 and Article 76 paragraph (2) of the republished Constitution of Romania. Romania, as part of the Paris Agreement is required to develop and communicate nationally determined contributions (NDCs) outlining their climate action plans and goals. These commitments are reflected in domestic legislation and policies. Romania, like other signatories, is expected to align its national laws and regulations with the objectives of the Paris Agreement. https://legislatie.just.ro/Public/DetaliiDocumentAfis/188443	
			Has your country's legislation transposed the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency?	x			The law for transposing into national legislation Directive (EU) 2019/944 of the European Parliament and of the Council on common rules for the internal market in electricity and amending Directive 2012/27/EU has been transposed through EMERGENCY ORDINANCE no. 130 of September 29, 2022, amending and supplementing Law no. 121/2014 on energy efficiency and concearning common rules for the internal market in electricity. https://legislatie.just.ro/Public/DetaliiDocumentAfis/259797 https://legislatie.just.ro/Public/DetaliiDocumentAfis/249500	
			Has your country's legislation transposed the Directive Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity?	x				
			Has your country's legislation transposed the new Directive 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency?	x			Romania as the other Member States will bring into force the laws, regulations and administrative provisions necessary to comply with the specific Articles and Annexes of the Directive by 11 October 2025. Regulation (EU) 2023/955 of the European Parliament and of the Council of 10 May 2023 establishing the Social Climate Fund and amending Regulation (EU) 2021/1060 was adopted in Romania and will be implemented until the foreseen date. https://energie.gov.ro/wp-content/uploads/2023/12/NECP_Romania_first-draft-version-21.12.2023_RO.pdf	
			Does your country's legislation provide for a decarbonisation target in the energy sector?	x			Yes, Romania provided legislation for a decarbonisation target in the energy sector in the regulatory act provided for by the Government Emergency Ordinance no. 108/2022, approved with amendments and supplements to Law no. 344/2022. Also Law no. 334/2022 for the approval of Government Emergency Ordinance no. 108/2022 on the decarbonisation of the energy sector is relevant. https://www.cdep.ro/proiecte/2023/000/50/7/oug44.pdf	
			Is the concept of energy demand flexibility specifically covered by your country's legislation?	x			Integrated National Plan for Energy and Climate Change 2021-2030 April 2020 https://energy.ec.europa.eu/system/files/2020-04/ro_final_necp_main_ro_0.pdf	
			In electricity supply contracts concluded between industries and the energy trader, are industries treated as consumers?	x			Integrated National Plan for Energy and Climate Change 2021-2030 April 2020 https://energy.ec.europa.eu/system/files/2020-04/ro_final_necp_main_ro_0.pdf	
			Does your country's legislation provide for financial compensation to consumers who produce energy?	x			EMERGENCY ORDINANCE no. 143 of December 28, 2021, amending and supplementing the Electricity and Natural Gas Law no. 123/2012, as well as amending certain normative acts. https://legislatie.just.ro/Public/DetaliiDocumentAfis/250107 LEGE (A) 123 10/07/2012 - Portal Legislativ (just.ro)	
			If yes to the above question, who manages these financial compensations?				ANRE (National Energy Regulatory Authority https://anre.ro/	
			Does your country have specific legislation on energy communities?	x			Specific legislation related to energy communities in Romania includes: 1.Law no. 220/2008 on the establishment of a promotion system for energy generation from renewable sources: This law provides the legal framework for promoting renewable energy and could be relevant to energy communities involved in renewable energy projects. 2.Law no. 123/2012 on electricity and natural gas: This law regulates the electricity and natural gas sectors and may contain provisions related to energy communities. 3.Emergency Ordinance no. 88/2018 on the establishment of fiscal measures: While not specific to energy communities, this ordinance may contain fiscal measures that impact the renewable energy sector, including community projects.	
			Has your country's legislation specified legal constraints or barriers limiting TES development?	x			Yes, there are mentioned some legal onstrains and barriers limiting TES development https://www.cdep.ro/comisii/industrii/pdf/2023/rm038.pdf	
			In local or municipality regulation, does your national legislation include specific measures Covenant of Mayors related to energy efficiency?	x			Mayors of localities with more than 5,000 inhabitants initiate multiannual local plans for increasing the number of new and existing buildings whose energy consumption is nearly zero, in which differentiated objectives can be included based on climatic zones and building functions specified in Article 7 paragraph (1) from the below law, approved through decisions of the local councils. (https://legislatie.just.ro/Public/DetaliiDocument/66970	
		Energy storage policies	Does your country have specific regulations in force governing the storage of energy through the use of batteries or energy storage devices?		x		Romania did not have specific regulations exclusively dedicated to energy storage through batteries or other energy storage devices. However, various aspects of energy storage, including batteries, were covered by broader energy and electricity regulations Energy storage regulations, especially those related to batteries, are addressed in laws and regulations governing the electricity sector, renewable energy, and grid connection under the authority of The National Energy Regulatory Authority (ANRE) and the Ministry of Energy. https://www.cdep.ro/comisii/industrii/pdf/2023/rp266_22.pdf	
			Does your national legislation apply to all categories of energy storage devices?	x			In Romania, legislation related to energy storage cover various technologies, including batteries, pumped hydro storage, compressed air energy storage, and others. National legislation aims to provide a regulatory framework for the energy sector as a whole, and specific regulations related to energy storage may be embedded within broader energy laws or regulations governing electricity generation, transmission, and distribution. Romanian legislation (through ANRE) considered some specific requirements on sustainability to allow the placing on the market or putting into service of batteries or energy storage devices.	
			Has your domestic legislation considered specific requirements on sustainability to allow the placing on the market or putting into service of batteries or energy storage devices?	x				
			Has your current legislation a set of rules about architectural and building construction mandatory requirements in energy efficency?	x			Yes, the current legislation in Romania includes provisions regarding mandatory requirements for energy efficiency in architectural and building construction.	
			If yes to the above question, which of them are related to energy storage devices	x			The relevant law in this context is Law No. 121/2014 on energy efficiency. https://www.engie.ro/wp-content/uploads/2021/07/Legea-nr-121-din-2014-actualizata.pdf	
				Depending the TRL project's target and its market expected milestones, the following questions are important.				
			Has your domestic legislation considered specific requirements on human health to allow the placing on the market or putting into service of batteries or energy storage devices?				Romanian doesn't have specific legislation related to human health requirements for placing on the market or putting into service batteries or energy storage devices. However, regulations addressing health and safety concerns may be embedded in broader environmental, health, and safety laws (Environmental Protection Legislation, Occupational Health and Safety Legislation and Product Safety Legislation)	
			Has your domestic legislation considered specific requirements on safety and security to allow the placing on the market or putting into service of batteries or energy storage devices?	x			Law 211/2011 on Waste Management, establishes the necessary measures for environmental protection and public health, by preventing or reducing the adverse effects caused by the generation and management of waste, by reducing the overall effects of resource use, increasing their efficiency and considering specific requirements on safety and security to allow the placing on the market of batteries or other energy storage devices. Other relevant legislation: GD (Government decision) 1061/2008 on the transport of hazardous and non-hazardous waste in Romania; GD (Government decision) 856/2002 on waste management records; Law 132/2010 on compulsory selective collection in public institutions	
			Has your domestic legislation considered specific requirements on labelling to allow the placing on the market or putting into service of batteries or energy storage devices?	x			Yes, the domestic legislation in Romania has considered specific labeling requirements to enable the placing on the market or putting into service of batteries or energy storage devices. Government Decision (Hotărârea de Guvern) HG 540/2016 addresses specific aspects related to the management of waste electrical and electronic equipment (WEEE), including labeling requirements; **Regulation 1103/2012 on battery labelling and GD (Government Decision) 856/2002 on waste management records**	
			Has your domestic legislation considered specific requirements on marking to allow the placing on the market or putting into service of batteries or energy storage devices?	x			Yes there are specificications regarding specific requirements on marking to allow the placing on the market or putting into service of batteries or energy storage devices in the Law 211/2011 and the Government Decision (Hotărârea de Guvern) HG 540/2016 together with HG 540/2016 addressesing specific aspects related to the management of waste electrical and electronic equipment (WEEE), including labeling requirements; Regulation 1103/2012 on battery labelling and GD (Government Decision) 856/2002 on waste management records	
			Has your domestic legislation considered requirements on information to allow the placing on the market or putting into service of batteries or energy storage devices?	x			Yes, the domestic legislation in Romania has considered requirements on information to allow the placing on the market or putting into service of batteries or energy storage devices. The Technical Norm (NORMĂ TEHNICĂ) from January 18, 2023 includes specific provisions related to information requirements for these products. We can also consider HG 540/2016 that addresses specific aspects related to the management of waste electrical and electronic equipment (WEEE), including labeling requirements; Regulation 1103/2012 on battery labelling and GD (Government Decision) 856/2002 on waste management records https://legislatie.just.ro/Public/DetaliiDocument/264042; https://www.snrb.org/acte-normative	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific weight requirements for batteries or energy storage devices in private environments?	x			Yes, Romania's legislation, has considered specific weight requirements for batteries or energy storage devices in private environments, according to current provisions. (Government Decision no. 1132/2008) Bans: (1) Without prejudice to harmonised national legislation transposing Directive 2000/53/EC, the introduction of the placing on the market of: (a) all batteries or accumulators containing more than 0,0005% of mercury by weight, whether or not integrated in appliances; (b) portable batteries and accumulators, including those integrated in appliances, containing more than 0.002% by weight.	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific durability parameters of batteries or energy storage devices?	x			Yes, according to the current legislation, specific durability parameters for batteries or energy storage devices have been considered in Romania. DIRECTIVE (EU) 2018/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2008/98/EC on wasteDirective 2008/98/EC and Regulation (EU) 2019/1020 https://eur-lex.europa.eu/legal-content/RO/TXT/?uri=celex%3A32018L0851	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific waste management measures for batteries or energy storage devices?	x			Yes, according to the current legislation, specific waste management measures for batteries or energy storage devices have been considered in Law 211/2011 in Romania and GD 856/2002 on waste management records, https://legislatie.just.ro/Public/DetaliiDocumentAfis/133184	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific obligations to issue a carbon footprint declaration for each battery or energy storage device model from 2026 onwards?	x			Yes, Romania considered specific obligations to issue a carbon footprint declaration for each battery or energy storage device model from 2026 onwards. Batteries will have to have a label reflecting their carbon footprint so that their environmental impact is more transparent. This will be mandatory for electric vehicle (EV) batteries, light duty vehicle (LMT) batteries and industrial rechargeable batteries with a capacity of more than 2 kWh. In addition, the label will cover the entire life of the battery and ensure that new batteries contain a minimum percentage of certain raw materials. 1542 UE rule from 2023, implemented in Romania - https://eur-lex.europa.eu/legal-content/RO/TXT/HTML/?uri=OJ:L:2023:191:FULL	
			According to your current legislation and depending on whether or not your country belongs to the EU, does your national legislation have considered specific obligations related to the return of waste for the distributors of the batteries or energy storage devices?	x			Yes Romania considered and implemented specific obligations related to the return of waste for the distributors of the batteries and energy storage devices in the Law 211/2011 and the Government Decision (Hotărârea de Guvern) HG 540/2016 together with HG 540/2016 addressesing specific aspects related to the management of waste electrical and electronic equipment (WEEE), including labeling requirements; Regulation 1103/2012 on battery labelling and GD (Government Decision) 856/2002 on waste management records. GD 856/2002 on waste management records; Law 132/2010 on compulsory selective collection in public institutions; Regulation 493/2012 laying down the calculation rules on recycling efficiency in the recycling processes of waste batteries and accumulators	
					In the recycling industry the following legislation regarding batteries and energy storage equipment, should be considered :			
							Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators Government Decision no. 1132/2008 transposing Directive 2006/66/EC into Romanian law Ministerial Order no. 669/1304/2009 approving the procedure for the registration of producers of batteries and accumulators Ministerial Order no. 1399/2032/2009 approving the Procedure on how to record and report data on batteries and accumulators and on waste batteries and accumulators Ministerial Order No 2743/3189 of 21 November 2011 approving the Procedure and criteria for the assessment and authorisation of collective organisations Regulation 493/2012 laying down the calculation rules on recycling efficiency in the recycling processes of waste batteries and accumulators Regulation 1103/2012 on battery labelling Directive 2013/56/EU amending Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators Directive 2008/103/EC amending Directive 2006/66/EC Ministerial Order No 2145/2014 on the establishment of the Commission for the assessment and authorisation of collective organisations Law 211/2011 on the waste regime republished in 2014 GD 856/2002 on waste management records Law 132/2010 on compulsory selective collection in public institutions GD 1061/2008 on the transport of hazardous and non-hazardous waste in Romania Emergency Ordinance no. 39/2016 amending and supplementing Government Emergency Ordinance no. 196/2005 on the Environment Fund Order no. 2413/2016 on the modification of the Order of the Minister of Environment and Water Management no. 578/2006 for the approval of the Methodology for the calculation of contributions and taxes due to the Environment Fund Order no. 594/9.06.2006 for the approval of the Certificate of Attestation on the obligations to the Environment Fund Order no. 149/2019 amending and supplementing the Annex to the Order of the Minister for the Environment and Water Management no. 578/2006 approving the Methodology for the calculation of contributions and taxes due to the Environment Fund Order No 591/2017 approving the model and content of the form "Declaration on obligations to the Environmental Fund" and the instructions for its completion and submission	

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Institution or company
Date of completion

DRAFT V. 1.0

Legal Analysis on the State of the Art on Thermal Storage Energy (TES) in the European Union

Aspects and criteria to be assessed for the final report

PARTNER	EU COUNTRY	KEY QUESTIONS		LEVEL OF KNOWLEDGE				SELECTION OF LEVEL
				YES	NO	PENDING APPROVAL OR TRANSPOSITION	If the answer has been marked as YES, please, include references/websites/information	Level
PCM Products Ltd - UK	NO	**Energy sector**	Does your country have national legislation implementing the Paris Agreement on climate change?	x			https://unfccc.int/sites/default/files/NDC/2022-09/UK%20NDC%20ICTU%202022.pdf	
			Has your country's legislation transposed the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency?		x			
			Has your country's legislation transposed the Directive Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity?		x			
			Has your country's legislation transposed the new Directive 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency?		x			
			Does your country's legislation provide for a decarbonisation target in the energy sector?	x			https://www.theccc.org.uk/what-is-climate-change/a-legal-duty-to-act/#:~:text=The%20Climate%20Change%20Act%202008,to%20deliver%20on%20these%20requirements.	
			Is the concept of energy demand flexibility specifically covered by your country's legislation?	x			https://www.gov.uk/government/publications/powering-up-britain/powering-up-britain-energy-security-plan	
			In electricity supply contracts concluded between industries and the energy trader, are industries treated as consumers?					
			Does your country's legislation provide for financial compensation to consumers who produce energy?	X			chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1126107/Feed-in_Tariff_load_factor_analysis_2021-22.pdf	
			If yes to the above question, who manages these financial compensations?	OFGEM			https://www.ofgem.gov.uk/environmental-and-social-schemes/feed-tariffs-fit#:~:text=The%20FIT%20scheme%20closed%20to%20new%20applicants%20from%201%20April%202019.&text=Introduced%20on%201%20April%202010,and%20exported%20by%20accredited%20installations.	
			Does your country have specific legislation on energy communities?		X			
			Has your country's legislation specified legal constraints or barriers limiting TES development?		X			
			In local or municipality regulation, does your national legislation include specific measures Covenant of Mayors related to energy efficiency?		X			
		Energy storage policies	Does your country have specific regulations in force governing the storage of energy through the use of batteries or energy storage devices?	X			https://www.ofgem.gov.uk/energy-policy-and-regulation/industry-licensing/licences-and-licence-conditions	
			Does your national legislation apply to all categories of energy storage devices?	X			https://www.ofgem.gov.uk/energy-policy-and-regulation/industry-licensing/licences-and-licence-conditions	
			Has your domestic legislation considered specific requirements on sustainability to allow the placing on the market or putting into service of batteries or energy storage devices?	X			https://www.ofgem.gov.uk/energy-policy-and-regulation/industry-licensing/licences-and-licence-conditions	
			Has your current legislation a set of rules about architectural and building construction mandatory requirements in energy efficency?	X			https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l	
			If yes to the above question, which of them are related to energy storage devices	6.2 Doc J			chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1133079/Approved_Document_L__Conservation_of_fuel_and_power__Volume_1_Dwellings__2021_edition_incorporating_2023_amendments.pdf	
			Depending the TRL project's target and its market expected milestones, the following questions are important.					
			Has your domestic legislation considered specific requirements on human health to allow the placing on the market or putting into service of batteries or energy storage devices?	X			https://www.legislation.gov.uk/uksi/2005/1803/contents/made https://www.gov.uk/guidance/regulations-waste-electrical-and-electronic-equipment https://www.gov.uk/guidance/regulations-batteries-and-waste-batteries	
			Has your domestic legislation considered specific requirements on safety and security to allow the placing on the market or putting into service of batteries or energy storage devices?	X			AS ABOVE	
			Has your domestic legislation considered specific requirements on labelling to allow the placing on the market or putting into service of batteries or energy storage devices?	X			https://www.gov.uk/government/publications/electrical-equipment-safety-regulations-2016/electrical-equipment-safety-regulations-2016-great-britain https://www.gov.uk/government/publications/electromagnetic-compatibility-regulations-2016/electromagnetic-compatibility-regulations-2016-great-britain	
			Has your domestic legislation considered specific requirements on marking to allow the placing on the market or putting into service of batteries or energy storage devices?	x			https://www.gov.uk/government/publications/electromagnetic-compatibility-regulations-2016/electromagnetic-compatibility-regulations-2016-great-britain	
			Has your domestic legislation considered requirements on information to allow the placing on the market or putting into service of batteries or energy storage devices?					
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific weight requirements for batteries or energy storage devices in private environments?		x			
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific durability parameters of batteries or energy storage devices?		x			
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific waste management measures for batteries or energy storage devices?	x			https://www.gov.uk/guidance/regulations-waste-electrical-and-electronic-equipment https://www.gov.uk/guidance/regulations-batteries-and-waste-batteries	
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific obligations to issue a carbon footprint declaration for each battery or energy storage device model from 2026 onwards?		X			
			According to your current legislation and depending on whether or not your country belongs to the EU, does your national legislation have considered specific obligations related to the return of waste for the distributors of the batteries or energy storage devices?	x			https://www.gov.uk/guidance/regulations-waste-electrical-and-electronic-equipment	

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Legal Analysis on the State of the Art on Thermal Storage Energy (TES) in the European Union

Aspects and criteria to be assessed for the final report

PARTNER	EU COUNTRY	KEY QUESTIONS		LEVEL OF KNOWLEDGE				SELECTION OF LEVEL	
				YES	NO	PENDING APPROVAL OR TRANSPOSITION	If the answer has been marked as YES, please, include references/websites/information	Level	Notes added by Maestrocks Consultancy Ltd. [CKS]
IDG-TURKIYE	X	Energy sector	Does your country have national legislation implementing the Paris Agreement on climate change?	X			Turkey ratified the Paris Climate Agreement as reported by the Library of Congress, indicating the country's commitment to international environmental standards and climate change policy. Information about Turkey's actions following the ratification of the Paris Agreement, including the updating of its national climate action plan and targets for emission reductions in various sectors, was detailed on Mondaq. Further details on Turkey's efforts in drafting a long-term strategy and action plan to combat climate change, and the renaming of the Environment Ministry to include climate change, were provided by Anadolu Agency, highlighting the country's comprehensive approach towards environmental sustainability.		Yes, Turkey has national legislation implementing the Paris Agreement on climate change. Turkey ratified the Paris Agreement on October 7, 2021, through the publication of Law No. 7335, which formally approved the ratification of the Agreement. This marked a significant step for Turkey in its climate change policy and commitment to international environmental standards.
			Has your country's legislation transposed the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency?			X			We searched for information regarding the transposition of the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency by Turkey but did not find specific details about Turkey's transposition of this directive. The search results from the International Energy Agency (IEA) primarily provided information about the transposition of the directive by other countries, such as Italy and Portugal.
			Has your country's legislation transposed the Directive Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity?			X			As of our latest search, there is no specific information available regarding the transposition of the Directive (EU) 2019/944 by Turkey. This directive, part of EU law, concerns common rules for the internal market in electricity, aiming to create an integrated, competitive, consumer-centered, flexible, fair, and transparent electricity market within the European Union. The directive includes provisions like smart metering, network access rights, and the separation of network owners from electricity retailers for transparency.
			Has your country's legislation transposed the new Directive 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency?			X			As of our latest search, there is no specific information available about Turkey's transposition of the new Directive 2023/1791 of the European Parliament and the Council of 13 September 2023 on energy efficiency. This directive, which is a part of the EU's legislative framework, focuses on elevating the EU's ambition on energy efficiency and establishes the principle of "energy efficiency first" as a fundamental aspect of EU energy policy. It was published in the EU Official Journal on 20 September 2023 and is set to enter into force 20 days after this publication. EU
			Does your country's legislation provide for a decarbonisation target in the energy sector?	X					Turkey's legislation and policy initiatives in the energy sector reflect a focus on reducing greenhouse gas emissions and moving towards decarbonization, although specific decarbonization targets in the energy sector are not explicitly outlined. Turkey has made significant climate change commitments, including ratifying the Paris Agreement in October 2021
			Is the concept of energy demand flexibility specifically covered by your country's legislation?	X					Turkey's legislation and energy policy focus significantly on renewable energy, energy efficiency, and sustainable practices, which indirectly support the concept of energy demand flexibility. However, there isn't explicit mention of specific legislation covering energy demand flexibility in the traditional sense of the term, which often refers to the ability to adjust or shift energy usage in response to external signals like changes in electricity price.
			In electricity supply contracts concluded between industries and the energy trader, are industries treated as consumers?	X					In Turkey's electricity market, industries engaged in contracts with energy traders are indeed treated as consumers. The regulatory framework governing electricity supply in Turkey includes provisions for various types of contracts for electricity supply to consumers. These contracts can be categorized broadly into retail sale contracts and bilateral agreements.
			Does your country's legislation provide for financial compensation to consumers who produce energy?	X					Turkey's legislation on renewable energy includes various incentives and support mechanisms for consumers who produce energy, especially through renewable sources. However, the specific provision of financial compensation for energy-producing consumers is not explicitly detailed in the sources reviewed. The Turkish government has implemented several initiatives to encourage the adoption of renewable energy and
			If yes to the above question, who manages these financial compensations?	MINISTRY OF ENERGY AND NATURAL RESOURCES					Turkey has implemented various initiatives to support renewable energy, which includes financial compensation for consumers who produce energy. One of the key mechanisms in place is the YEKDEM (Renewable Energy Resources Support Scheme). YEKDEM provides a feed-in tariff for renewable energy production, incentivizing the generation of electricity from renewable sources. The scheme has seen adjustments in recent years, reflecting changes in market conditions and currency values. For example, the average feed-in remuneration tariff for
			Does your country have specific legislation on energy communities?	X					Turkey's approach to renewable energy and sustainable practices, while comprehensive, does not explicitly mention specific legislation on energy communities. The country's initiatives mainly focus on large-scale renewable energy projects, energy efficiency, and sustainable practices, as evidenced by projects like the Green Industry Project. This project, funded by the World Bank, is designed to assist Turkish industries in adopting more sustainable approaches, including investments in renewable energy and green technologies. Additionally, the
			Has your country's legislation specified legal constraints or barriers limiting TES development?		X				Turkey has recently introduced new regulations for energy storage, including thermal energy storage (TES) development. These regulations are designed to facilitate and encourage the development of energy storage systems, particularly in combination with renewable energy sources like wind and solar power. One of the key features of these new rules is that they allow energy storage facilities to operate in conjunction with
			In local or municipality regulation, does your national legislation include specific measures Covenant of Mayors related to energy efficiency?	X					Turkey's national legislation does not explicitly mention specific measures related to the Covenant of Mayors for energy efficiency, especially in the context of local or municipal regulation. However, the country has been actively involved in several initiatives that align with the goals of the Covenant of Mayors, particularly in terms of enhancing energy efficiency and promoting sustainable energy practices.
		Energy storage policies	Does your country have specific regulations in force governing the storage of energy through the use of batteries or energy storage devices?	X					Yes, Turkey has specific regulations governing the storage of energy through the use of batteries or energy storage devices. The Turkish government has introduced new rules for energy storage, including regulations for battery storage systems. These regulations are designed to facilitate the development and integration of energy storage systems, particularly in combination with renewable energy sources such as wind and solar power.
			Does your national legislation apply to all categories of energy storage devices?	X					Turkey's national legislation on energy storage, particularly the regulations introduced for energy storage systems, generally applies to various categories of energy storage devices, including battery storage systems. However, the specific scope and applicability to all categories of energy storage devices may vary depending on the details of the regulation and its implementation.
			Has your domestic legislation considered specific requirements on sustainability to allow the placing on the market or putting into service of batteries or energy storage devices?	X					Turkey has recently updated its energy legislation to include specific rules for energy storage, including the use of batteries or energy storage devices. The new provisions aim to integrate energy storage systems more effectively with the country's growing renewable energy sector, particularly solar and wind power. Key aspects of Turkey's energy storage legislation include:
			Has your current legislation a set of rules about architectural and building construction mandatory requirements in energy efficency?	X					Yes, Turkey's current legislation includes specific rules about architectural and building construction with mandatory requirements in energy efficiency. These regulations aim to reduce energy consumption and promote sustainable building practices. Energy Efficiency in Public Buildings: Under the DKTI Programme, Energy Efficiency in Public Buildings in Turkey
			If yes to the above question, which of them are related to energy storage devices						The Turkish legislation related to energy efficiency in building construction does not specifically detail regulations regarding the use of energy storage devices within buildings. The focus of the legislation and regulations is primarily on enhancing the energy efficiency of buildings and incorporating renewable energy sources. The key regulations related to energy efficiency in buildings in Turkey are:
			Depending the TRL project's target and its market expected milestones, the following questions are important.						
			Has your domestic legislation considered specific requirements on human health to allow the placing on the market or putting into service of batteries or energy storage devices?	X					Yes, Turkey's domestic legislation has considered specific requirements on human health for the placement on the market or putting into service of batteries or energy storage devices. The Regulation on the Management of Waste
			Has your domestic legislation considered specific requirements on safety and security to allow the placing on the market or putting into service of batteries or energy storage devices?	X					Yes, Turkey's domestic legislation has included specific requirements on safety and security for the placement on th
			Has your domestic legislation considered specific requirements on labelling to allow the placing on the market or putting into service of batteries or energy storage devices?	X					Yes, Turkey's domestic legislation has considered specific requirements on labeling for the placing on the market or
			Has your domestic legislation considered specific requirements on marking to allow the placing on the market or putting into service of batteries or energy storage devices?	X					Yes, Turkey's domestic legislation includes specific requirements for marking batteries and energy storage devices t
			Has your domestic legislation considered requirements on information to allow the placing on the market or putting into service of batteries or energy storage devices?	X					Yes, Turkey's domestic legislation has considered requirements for providing information on batteries and energy st
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific weight requirements for batteries or energy storage devices in private environments?	X					No, Turkey's national legislation does not specifically consider weight requirements for batteries or energy storage d
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific durability parameters of batteries or energy storage devices?	X					Based on the available information, there is no specific mention of Turkey's current legislation including durability pa
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific waste management measures for batteries or energy storage devices?	X					Yes, Turkey's national legislation has considered specific waste management measures for batteries or energy storag
			According to your current legislation and depending on whether your country belongs to the EU or not, does your national legislation have considered specific obligations to issue a carbon footprint declaration for each battery or energy storage device model from 2026 onwards?	X					No, as of our last update, Turkey's national legislation does not specifically mandate the obligation to issue a carbon
			According to your current legislation and depending on whether or not your country belongs to the EU, does your national legislation have considered specific obligations related to the return of waste for the distributors of the batteries or energy storage devices?	X					Yes, Turkey's national legislation has considered specific obligations related to the return of waste for the distributor

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