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SAREF4TESS Ontology Requirements Specification

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EUROPEAN COMMITTEE FOR STANDARDIZATION
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Contents

Foreword

This CEN/CENELEC Workshop Agreement (CWA 18385:2026) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid way to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by the Workshop CEN and/or CENELEC Workshop on Thermal Energy Storage (TES) Systems”, the secretariat of which is held by UNE-Spanish Association for Standardization, consisting of representatives of interested parties on 2025-06-06, the constitution of which was supported by CEN and CENELEC following the public call for participation made on 2025-03-31. However, this CEN/CENELEC Workshop Agreement does not necessarily include all relevant stakeholders.

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1 Scope

This CWA defines a semantic framework for modelling, integrating, and optimizing Thermal Energy Storage (TES) systems within modern energy ecosystems. It supports data harmonization and semantic interoperability between TES components and energy management systems.

This CWA addresses small to medium-scale TES systems, as applied in building and district-level energy systems. Larger TES installations are outside the main scope, although the semantic framework may be extended in the future. Industrial process heat applications are excluded from the current scope and identified as future work.

NOTE The document provides a state-of-the-art description aligned with the scope of the HYSTORE Horizon Europe project, focusing on the "All-in-One Solution" for latent TES and zeolite-water sorption for TCM TES. This represents a specific initial use case and may not fully cover other PCM and TCM based TES systems. Therefore, the ontology is designed to be extensible, providing future expansion of its abstraction level and domain of application.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/obp/

— IEC Electropedia: available at http://www.electropedia.org/

3.1
Building Energy Management System (BEMS)
control system that collects, monitors, and analyzes a building's energy use in real time to optimize performance and reduce waste and operating costs

3.2
Capital Expenditure (CAPEX)
Expenditure on acquisitions of, or improvements to, assets

Note 1 to entry: Based upon accounting standards and organizational policy, CapEx usually relates to relatively large (material) expenditure, which has benefits that are expected to last for more than 12 months.

[SOURCE: ISO/TS 55010:2024, 3.8]

3.3
Demand Response (DR)
changes in electricity use by end-use customers (including automatic responses) from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized

[SOURCE: ISO/IEC TR 15067-3-8:2020, 3.9]

3.4
Distributed Energy Resources (DER)

distributed set of one or more energy service resources, including generators, energy storage and controllable load, that can be used to deliver ancillary services

[SOURCE: ISO 15118-1:2019, 3.1.20]

3.5
Energy Efficiency Ratio (EER)

ratio of the net cooling capacity to the effective power input at any given set of rating conditions

Note 1 to entry: Expressed in units of watt per watt.

[SOURCE: ISO 13256-2:2021, 3.11]

3.6
Evaporative Condenser (EVC)

high-efficiency heat exchange device used in industrial refrigeration and HVAC systems to convert hot, high-pressure refrigerant vapor into a liquid by combining air cooling and water evaporation

3.7
Heat Exchanger (HEX)

device specifically designed to transfer heat between two physically separated fluids. Heat exchangers can have either single or double walls

[SOURCE: ISO 9459-2:1995, 3.21]

3.8
Internet of Things (IoT)

infrastructure of interconnected entities, people, systems and information resources together with services which processes and reacts to information from the physical world and virtual world

[SOURCE: ISO/IEC 20924:2024, 3.2.8]

3.9
interoperability

property permitting diverse systems or components to work together for a specified purpose

[SOURCE: IEC 80001-1:2010, 2.11]

3.10
Machine Learning (ML)

process using computational techniques to enable systems to learn from data or experience

[SOURCE: ISO/IEC TR 29119-11:2020, 3.1.43]

3.11
Micro/Multi-Port Extrusion (MPE)

high-precision, thin-walled, flat aluminium tube containing multiple internal channels produced via extrusion, used primarily for enhanced heat transfer in HVAC, radiators, and condensers

3.12
Operating Expenses (OPEX)

recurrent or specific non-capital expenditures required to provide a service or product

[SOURCE: ISO/TS 55010:2024, 3.9]

3.13
Phase Change Material (PCM)

material with a high heat of fusion that allows it to store or release thermal energy as a form of melting and solidifying at a certain temperature

[SOURCE: ISO 22982-2:2021, 3.2, modified]

3.14
Resource Description Framework (RDF)

framework for representing information in the Web

Note 1 to entry: The core structure of the abstract syntax is a set of triples, each consisting of a subject, a predicate and an object. A set of such triples is called an RDF graph.

[SOURCE: OWL 2 Web Ontology Language Quick Reference Guide (Second Edition), 2012; ISO/IEC TS 24462:2024, 3.13]

3.15
Smart Applications Reference (SAREF)

suite of individually versioned ontologies that contains a core ontology, a set of reference ontology patterns that provide guidelines on how to use and extend SAREF, and different extensions for vertical domains

3.16
Smart Grid

electric power system that utilizes information exchange and control technologies, distributed computing and associated sensors and actuators

Note 1 to entry: Smart grid technologies are used for purposes such as:

- integrating the behaviour and actions of the network users and other stakeholders;
- efficiently delivering sustainable, economic and secure electricity supplies.

[SOURCE: ISO/IEC 27019:2024, 3.1.17]

3.17
Thermal Energy Storage (TES)

storage of thermal energy for later reuse

3.18
Thermochemical Material (TCM)

substance that store and release thermal energy through reversible chemical reactions or sorption processes (such as hydration/dehydration or adsorption), rather than relying on temperature changes alone

3.19
Web Ontology Language (OWL)

web-based language designed for use in applications that processes the content of information

[SOURCE: ISO 14199:2024, 3.6]

4 Background and State of the Art

4.1 Existing Standards and Ontologies

Semantic interoperability in smart buildings and grids relies on standardised ontologies and data models to ensure seamless communication across heterogeneous systems. Traditionally, building energy management systems (BEMS) operated in silos, with incompatible protocols and proprietary data formats limiting integration with IoT devices, distributed energy resources (DERs), and demand-response programs. To address these challenges, several ontology frameworks and standards have emerged, including **SAREF**, **SAREF4ENER**, **SAREF4BLDG**, **SAREF4SYST, BRICK**, **IEC 61850**, and **FIWARE NGSI-LD**, each targeting specific layers of the energy and building ecosystem.

- **SAREF**: A modular ontology from ETSI SmartM2M, providing a shared vocabulary for IoT devices, sensors, services, and commands across multiple domains.

- **SAREF4ENER**: An extension of SAREF for energy use cases, covering demand response, DER management, and smart grid integration.

- **SAREF4BLDG**: An extension of SAREF that defines semantic models for buildings, including spatial structures and building systems, to support interoperability, data exchange, and system integration in smart building and energy management applications.

- **SAREF4SYST:** An extension of SAREF that provides a generic, domain-agnostic pattern for modelling systems, their subsystems, and the connections between them, enabling consistent representation of topology and interoperability across any IoT or cyber-physical domain.

- **BRICK Schema**: An open ontology for standardising metadata schemas for building assets, especially HVAC, meters, and control equipment.

- **IEC 61850**: A standard for communication protocols and data models in power systems, now extended to DERs and microgrids.

- **FIWARE NGSI-LD**: An open standard for context information management in smart cities, supporting dynamic entities and digital twins.

These frameworks provide complementary approaches, though none yet deliver comprehensive coverage for Thermal Energy Storage (TES). Recent studies highlight the need for ontology alignments between FIWARE, SAREF, and BRICK to ensure semantic consistency, especially when integrating legacy BMS and urban IoT platforms (Booshehri et al., 2021). Nevertheless, FIWARE has gained traction in EU smart city projects due to its open-source nature and cross-sector capabilities (Leoni et al., 2020). Table 1 provides a comparative overview of the six major frameworks —SAREF, SAREF4ENER, SAREF4BLDG, SAREF4SYST, BRICK, IEC 61850, and FIWARE NGSI-LD— highlighting their focus areas, underlying data standards, key applications, and levels of integration within smart building and smart grid ecosystems.

Table 1 — Comparative Overview of Ontologies and Standards for Smart Buildings and Smart Grids

Framework	Focus Area	Data Standard	Key Applications	Integration Level
SAREFw	IoT semantics, appliances	RDF, OWL	Device & service interoperability	IoT, smart homes
SAREF4ENER	Energy systems, DR, DERs	RDF, OWL	Demand response, grid interaction	Buildings ↔ Smart Grids
SAREF4BLDG	Building semantics, building systems	RDF, OWL	Buildings, spaces, HVAC, building services	Building automation, energy management, monitoring & control
SAREF4SYST	Represents systems, their subsystems, and the connections between them to model topology and interaction	RDF, OWL	Connectivity in domains like smart energy, smart buildings, transportation, and IoT systems.	Cross-domain system to system integration
BRICK	Building assets, HVAC	RDF, OWL	BMS metadata, fault detection	Buildings & Digital Twins
IEC 61850	Power systems, substations	MMS, GOOSE	Grid automation, DER coordination	Utility ↔ Buildings ↔ Microgrids
FIWARE NGSI-LD	Context data management	JSON-LD, Linked Data	Smart cities, cross-domain services	Urban IoT platforms

4.2 Limitations in current semantic models related to TES

TES remains underrepresented in existing semantic frameworks. Limitations include:

- Sparse coverage of TES components, states, and behaviours compared with HVAC or electrical batteries.
- Lack of formal behavioural semantics for charge/discharge processes and performance profiles.
- Weak alignment between building-centric ontologies and thermal grid semantics.
- Absence of harmonised KPIs and taxonomies for quantifying flexibility.
- Limited time/space modelling capabilities for TES operations.
- Interoperability challenges when mapping TES ontologies into city-scale APIs (e.g., JSON-LD).
- Incomplete modelling of multi-energy and multi-scale coupling (building ↔ district ↔ grid).
- Barriers to adoption due to tooling, accessibility, and fragmented standards alignment.

- Insufficient representation of TES within higher-level energy system ontologies, preventing collective treatment of distributed TES assets as coordinated "swarm storage" required for renewable-rich grids.
- Lack of an internationally accepted, standardized definition of Hybrid Energy Storage Systems (HESS), hindering the semantic and operational integration of multiple storage types (e.g., electrical + thermal) and limiting EMS/ontology interoperability across heterogeneous storage assets (Stefan et al., 2025).

These issues highlight the need for a dedicated semantic framework for TES.

4.3 Research and Market Context

4.3.1 Summary of TES technologies

Thermal Energy Storage technologies are broadly classified into **sensible heat storage**, **latent heat storage with Phase Change Materials (PCM)**, and **Thermochemical Materials (TCM)**.

- **Sensible heat storage** utilises the increase or decrease in the temperature of a material without phase change to store or release thermal energy. They are simple, cost-effective, and suitable for applications in space heating, cooling, and domestic hot water (DHW) systems.
- **Latent heat storage with PCM systems** exploit phase change (solid–liquid) to store and release large amounts of thermal energy at nearly constant temperature. They are compact, efficient, and suitable for heating, cooling, and domestic hot water (DHW) applications (Mehling, 2022).
- **Hybrid thermal energy storage systems** are generally (sensible) storage systems through which a fluid flows and which exchange heat with PCM objects (PCM-O / RAL-GZ 896) within the storage system. The phase change of the PCM only takes place within the PCM-O. The achievable charging and discharging capacities depend on the shape and size of the PCM-O. Existing sensitive thermal storage systems can thus also be retrofitted to increase their thermal storage capacity.
- **TCM systems** store energy through reversible sorption or chemical reactions, enabling long-duration storage with high energy density. They are promising for seasonal storage and flexible coupling of heating and cooling services.
- Both PCM and TCM can be integrated with heat pumps, solar thermal, or district heating/cooling networks, supporting demand-side management and renewable energy integration.

4.3.2 Key findings

TES technologies directly address pressing societal challenges in the energy transition:

- **Energy security and grid flexibility**: TES enables peak-shaving, load-shifting, and resilience against supply interruptions.
- **Renewable integration**: By matching variable renewable generation with heating/cooling demand, TES reduces curtailment and improves system efficiency.
- **Affordability and equity:** Modular, scalable TES systems—designed to adapt to different demand levels and use-case requirements—enable more efficient and optimised energy use. This improved efficiency can translate into long-term cost savings for users, thereby reducing household energy bills and broadening access to clean energy solutions, **provided that initial investment costs remain affordable.**

- **Environmental sustainability**: TES reduces fossil fuel dependency, supports decarbonisation of heating/cooling, enables waste heat recovery, and contributes to circular economy principles through material reuse.
- **Economic impact**: Deployment of TES systems fosters job creation in manufacturing, installation, and maintenance while stimulating innovation in new business models.

4.3.3 Societal needs/benefits

Despite technical progress, TES deployments still face challenges in interoperability and integration:

- Fragmented communication between TES, BEMS, and district energy networks.
- Lack of standardised data models for TES performance, flexibility services, and user interaction.
- Limited integration with multi-energy systems (electricity, heat, gas, and mobility).
- Insufficient semantic alignment with city-scale digital platforms, hindering cross-domain services.

A harmonised semantic framework addressing these gaps would facilitate wider deployment of TES, enabling consistent modelling, monitoring, and control across applications and scales.

4.3.4 Economic and environmental benefits of TES

Thermal Energy Storage (TES), encompassing both Phase Change Materials (PCM) and Thermochemical Materials (TCM), delivers a range of economic and environmental benefits that support Europe's energy transition and climate objectives. By complementing renewable energy technologies and enabling demand-side flexibility, TES solutions can reduce energy costs, strengthen grid resilience, and advance sustainability.

a) Economic Benefits

One of the most direct economic advantages of TES is cost savings for consumers. By storing thermal energy during periods of low-cost electricity and discharging it during peak demand, both households and businesses can reduce their energy bills while simultaneously supporting grid stability. TES also enables participation in time-of-use tariffs and demand response programs, allowing users to benefit from dynamic pricing structures and helping utilities balance supply and demand more effectively.

The deployment of PCM- and TCM-based storage systems will also stimulate job creation and skills development across the energy sector. Manufacturing, installation, and maintenance of these systems will require new roles, while training programs will help address the existing shortage of technical expertise. This not only supports local economies but also builds capacity for long-term market growth.

In terms of market competitiveness, latent (i.e., PCM) and thermochemical material-based TES technologies are positioned to become attractive alternatives to conventional sensible based storage solutions. While hot water tanks remain inexpensive, they are limited by low energy density and bulky design. In contrast, PCM and TCM systems provide more compact and efficient storage, particularly when integrated with renewable energy incentives. Benchmarking against existing solutions ensures that these technologies can achieve economic viability while creating opportunities for innovative business models and value chains.

b) Environmental Benefits

TES also generates substantial environmental benefits by accelerating the decarbonization of heating and cooling, which represent some of Europe's largest sources of energy demand. Carbon emission reductions are achieved through widespread adoption of TCM and PCM systems, as they reduce reliance on fossil fuels and enable greater integration of clean electricity for thermal needs.

Furthermore, TES supports the circular economy through the reuse and recycling of advanced materials, such as zeolite in TCM systems. This not only minimizes resource waste but also aligns with EU strategies on sustainability and resource efficiency. By embedding circular design principles, TES technologies contribute to reducing environmental footprints over their life cycle.

Finally, both PCM and TCM offer opportunities for efficient waste heat recovery. Their high energy density and storage efficiency make it possible to capture and reuse energy that would otherwise be lost, improving overall system efficiency and further contributing to environmental targets. This capacity to reduce energy waste strengthens the role of TES as a key enabler of sustainable energy systems.

4.3.5 Interoperability and integration gaps in current TES deployments

Despite progress in the development of Phase Change Material (PCM) and Thermochemical Material (TCM) systems, the integration of Thermal Energy Storage (TES) into buildings, districts, and wider energy systems remains limited by interoperability challenges. Current gaps can be summarised as follows:

- **Fragmented data models**: Existing building ontologies and grid standards rarely capture TES processes in detail (e.g., charging/discharging dynamics, stratification, round-trip efficiency). This hinders seamless integration with Building Energy Management Systems (BEMS), District Heating and Cooling (DHC) networks, and smart grid platforms.

- **Limited cross-domain alignment**: TES connects multiple energy domains—thermal, electrical, and sometimes gas—but is often represented as an isolated asset. Lack of harmonised semantics across domains prevents TES from fully participating in multi-energy optimisation and demand-side management strategies.

- **Inconsistent KPI definitions**: Metrics for energy flexibility, storage capacity, and efficiency vary across projects and vendors. Without standardised indicators, comparison of TES performance and value propositions is difficult, reducing confidence for policymakers, utilities, and end-users.

- **Challenges in city-scale integration**: Mapping TES ontologies (often RDF/OWL-based) to urban IoT and smart-city APIs (e.g., NGSI-LD/JSON-LD) remains complex and error-prone. This complicates data exchange between TES systems and broader city platforms.

- **Heterogeneous protocols and legacy systems**: Many TES units are installed in combination with legacy heating or cooling systems using proprietary protocols. This creates barriers to plug-and-play integration and slows adoption of interoperable semantic frameworks.

- **Lack of alignment with control and automation standards**: Standards such as IEC 61850 or CIM provide communication frameworks for power systems, but their extension to thermal assets is incomplete. TES is therefore not yet consistently represented in automated demand-response mechanisms.

Addressing these gaps requires a harmonised semantic framework that captures TES functions at multiple levels (device, building, district, grid) and ensures compatibility with existing and emerging standards.

5 Semantic Framework Specification

5.1 TES Ontology Overview

5.1.1 High-level architecture of SAREF4TESS

Thermal energy storage refers to the process of storing thermal energy for a period of time and utilizing it at a later stage to meet energy demand. By decoupling the timing of energy supply and demand, thermal energy storage enhances system efficiency, flexibility, and reliability across a wide range of energy applications. By storing thermal energy when it is abundantly available and releasing it when required, TES supports higher utilization of renewable energy sources, reduces peak energy demand, and improves overall system performance (Dincer & Rosen, Thermal Energy Storage: Systems and Applications). Among the various TES technologies, phase change material (PCM) and thermochemical material (TCM)–based storage systems have emerged as particularly promising solutions due to their high energy storage density and their ability to operate effectively within well-defined temperature ranges.

Thermal energy storage systems based on PCM and TCM can be charged using a variety of renewable and low-carbon sources, such as solar thermal collectors, heat pumps, photovoltaic (PV)-powered electric heaters, and geothermal energy systems (Dincer & Rosen, 2011; Cabeza et al.,2021). Solar thermal energy can be stored directly when the collector outlet temperature exceeds the storage system's minimum charging temperature. Furthermore, heat pumps and PV-powered electric heaters enable efficient power-to-heat integration by converting electrical energy into thermal energy that can be stored in PCM or TCM units (IEA, 2020). Geothermal energy is a continuous, low-emission heat source that can be effectively combined with both PCM and TCM storage technologies, especially for low- and medium-temperature heating applications (Zhou et al., 2022). The integration of these various heat sources increases renewable energy utilisation while decreasing reliance on traditional fossil-based heat supply.

Depending on the system design and temperature requirements, the stored thermal energy can be discharged to meet space heating and domestic hot water (DHW) demands, either directly or via heat exchangers (Cabeza et al., 2021). PCM-based storage systems are ideal for short- to medium-duration thermal buffering due to their ability to deliver heat at nearly constant temperatures. TCM-based storage systems, on the other hand, are better suited for long-term or seasonal storage because they allow surplus heat collected during low demand periods to be preserved with minimal losses and used during peak demand periods (Zondag et al., 2022; Scapino et al., 2023). As a result, PCM and TCM thermal energy storage systems have significant potential for increasing system flexibility, improving renewable energy integration, and lowering greenhouse gas emissions in building and district-scale heating applications.

Based on the data available, the present ontology for thermal energy storage finds alignment with SAREF4ENER and grid/building ecosystems.

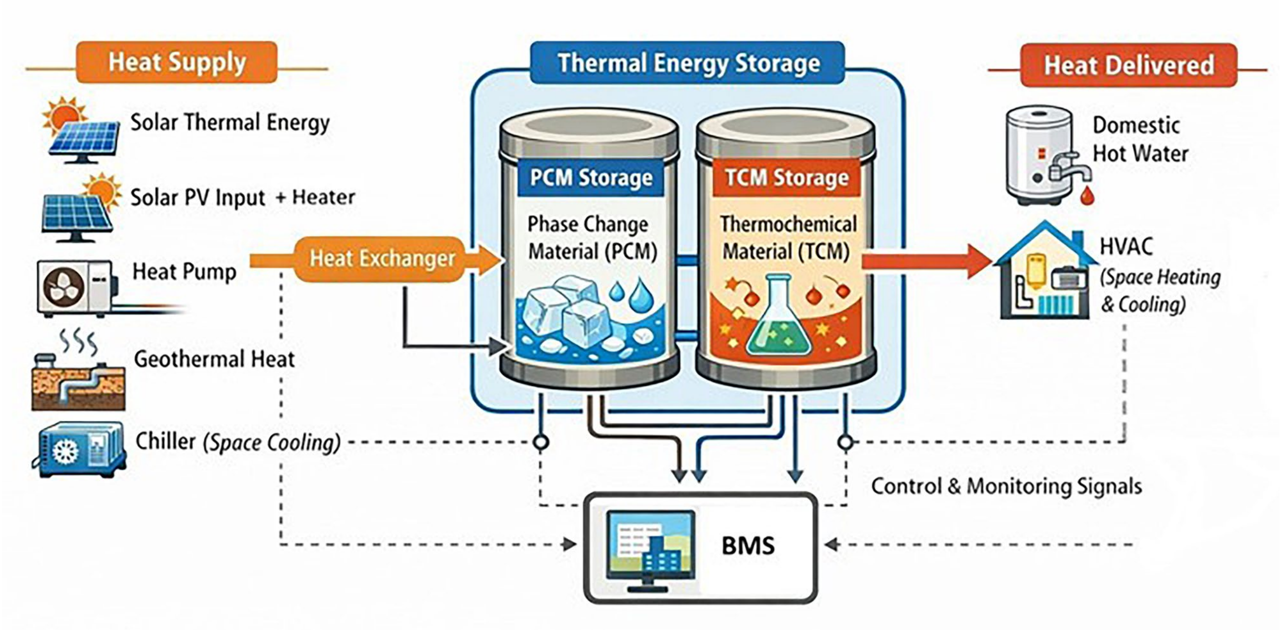

Figure 1 — Heat supply–heat delivery system with PCM/TCM thermal energy storage

5.1.2 PCM System

Phase change material (PCM) thermal energy storage systems are a type of latent heat thermal energy storage that stores and releases thermal energy via a reversible phase transition, typically between solid and liquid states. During the phase transition process, PCMs may absorb or release significant amounts of heat at nearly uniform temperatures, allowing for greater energy storage density and temperature control than conventional sensible heat storage systems (Cabeza et al., 2021; Zhou et al., 2022).

By choosing PCMs with phase change temperatures matched to specific operating conditions, PCM thermal storage systems can be effectively integrated into applications that demand stable and well-defined temperatures. It has potential use in building heating and cooling systems, solar thermal energy storage, waste heat recovery, district heating networks, and cold energy storage, where it helps in load shifting, peak demand reduction, and better integration of renewable energy sources (Agyenim et al., 2022; Li et al., 2023).

PCM All-in-one system is one such system which utilises heat pump for charging PCM and delivering domestic hot water demand as explained in the next section.

5.1.3 PCM “All-in-one Solution”

PCM All-in-one Solution is a modular heat pump with integrated latent heat storage, and a fresh-water station to deliver domestic hot water. Figure 2 shows the general hierarchical structure of the PCM system.

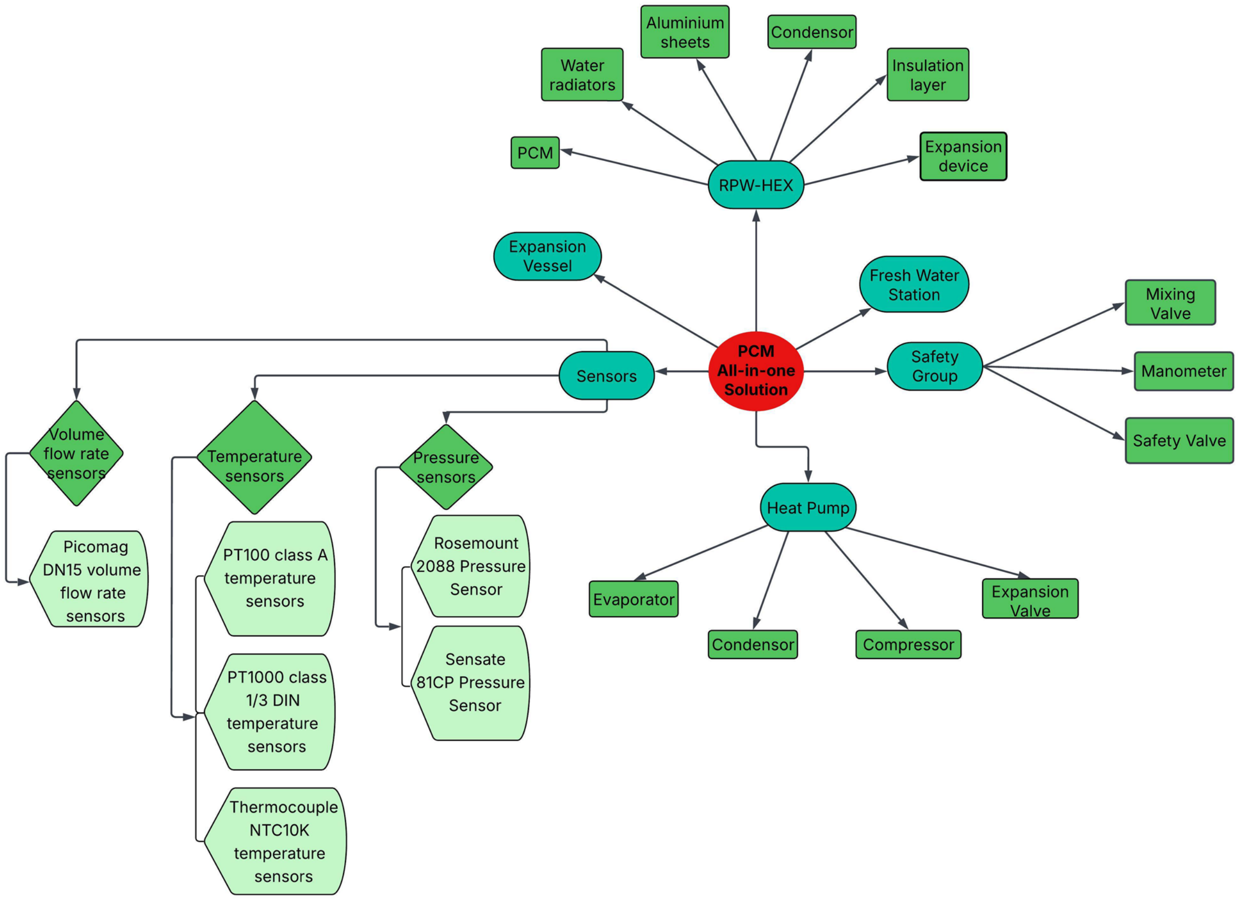

Figure 2 — General hierarchical structure of the PCM System

Figure 3 shows the hierarchical structure based on the device application. The components are brought under two main classifications namely Thermal energy conversion device and Thermal energy flow controller.

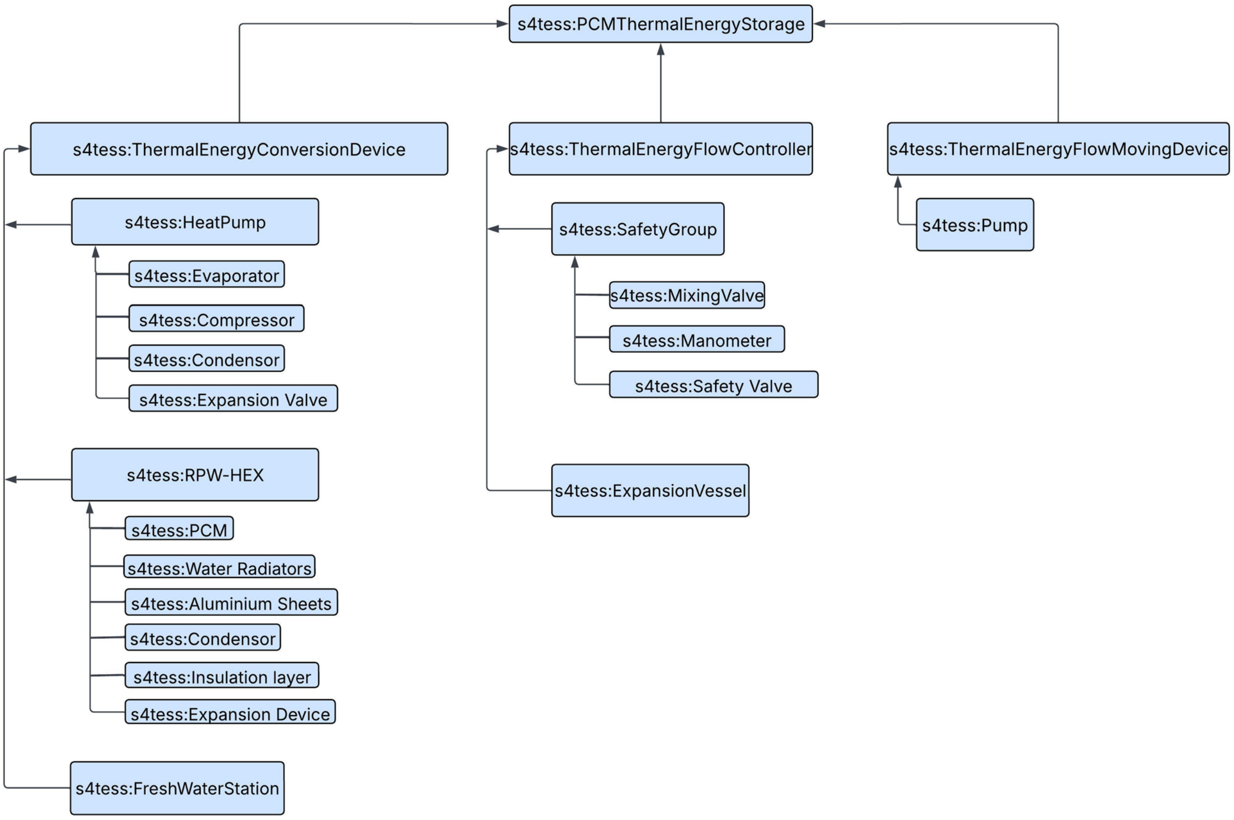

Figure 3 — PCM system hierarchical structure based on devices application

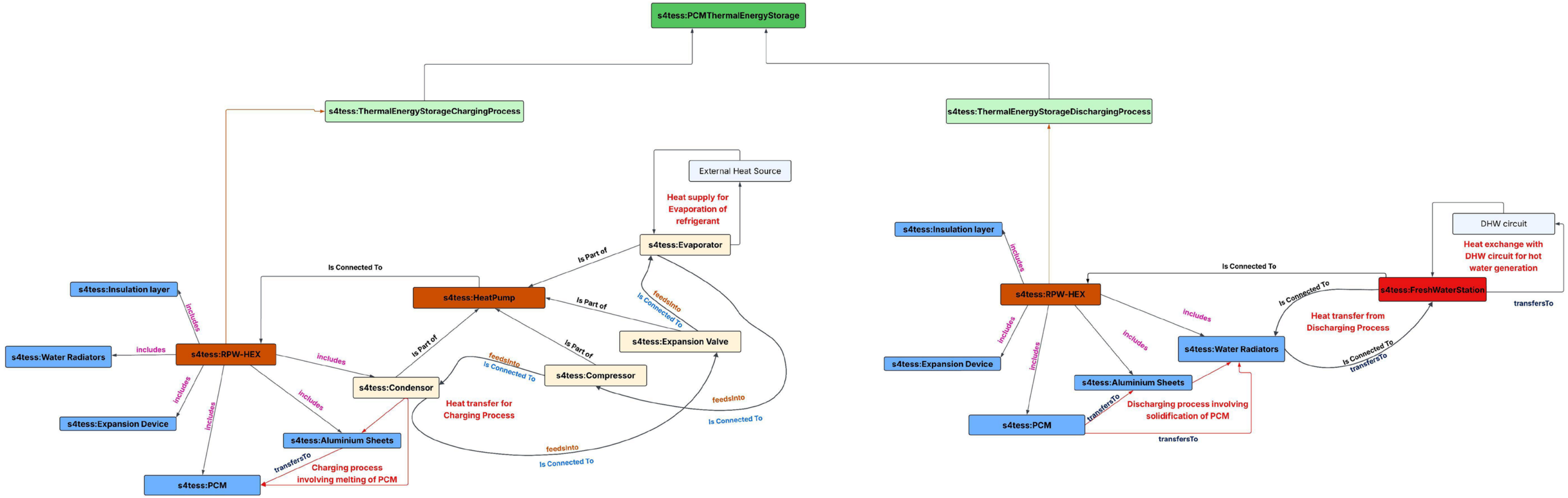

Figure 4 — Component relationship for PCM based storage system during charging and discharging

5.1.4 TCM System

Thermal energy storage systems based on thermochemical materials (TCMs) store and release heat via reversible chemical reactions or sorption processes, rather than temperature or phase transitions. Thermal energy is stored by driving an endothermic reaction (charging), and heat is released via a reverse exothermic reaction (discharging). TCM systems have a significant advantage in terms of energy storage density and the ability to store energy for long periods of time with minimum thermal losses, as energy is stored in chemical potential rather than sensible or latent heat (Cabeza et al., 2022; Michel et al., 2021).

Because of these qualities, TCM thermal storage systems are thought to be especially ideal for long-term and seasonal heat storage, particularly in applications such as solar thermal energy storage, building heating, industrial waste heat recovery, and district heating networks. Recent research has focused on improving material stability, reaction kinetics, and system integration, with a particular emphasis on the potential of salt hydrates, metal oxides, and sorption materials to enable efficient and compact thermal energy storage solutions that support renewable energy integration and heating system decarbonisation (Zondag et al., 2022; Scapino et al., 2023). Many such sorption materials are zeolite, silica-gel, etc.

One of the TCM system specific to domestic hot water application is explained in the next section.

5.1.5 TCM System (Specific to domestic hot water case)

The TCM heating and cooling solution developed consists of a sorption storage that is suitable for storing energy and then allowing for heating or cooling provision according to a flexible operating mode. General hierarchical structure for the TCM system based thermal storage system is shown in Figure 5. Figure 6 shows the hierarchy based on device applications.

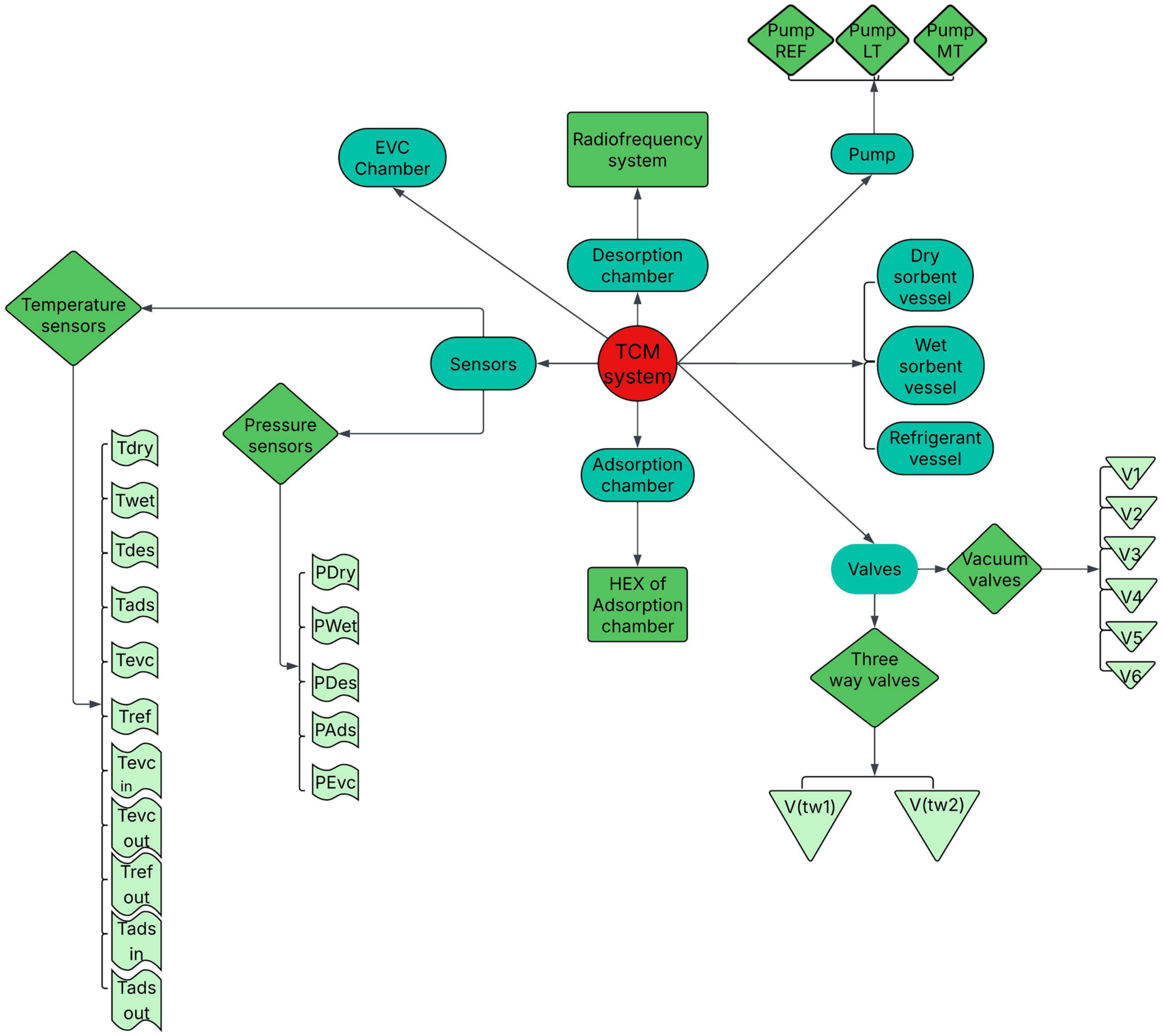

Figure 5 — General hierarchical structure of the TCM System

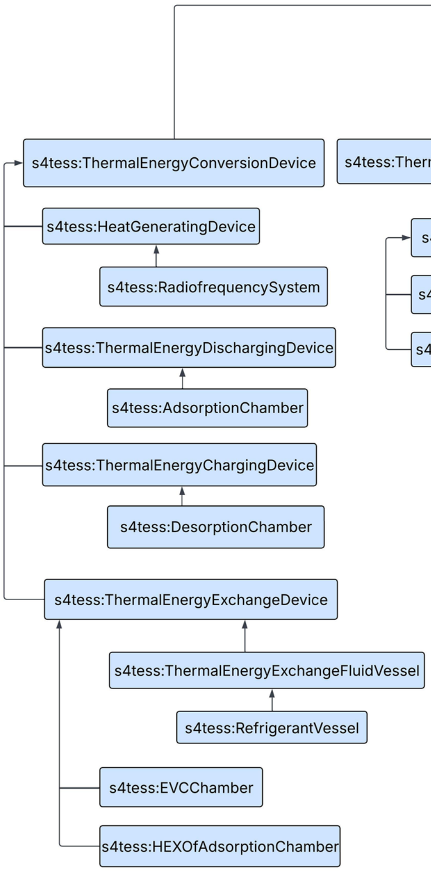

Figure 6 — TCM system hierarchical structure based on devices application

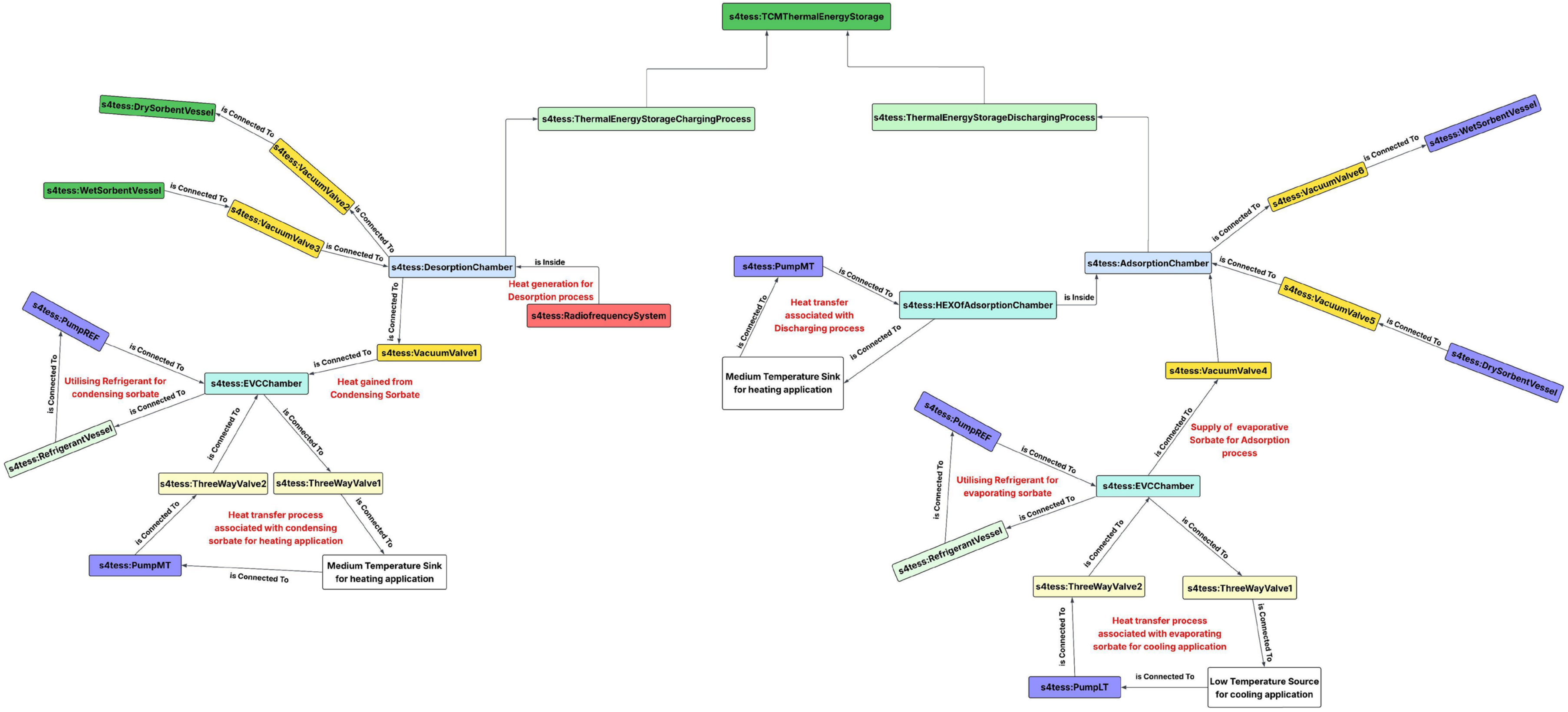

Figure 7 — Component relationship for TCM based storage system during charging and discharging

5.2 Classes and Hierarchies

5.2.1 Definition of core PCM System TES components:

5.2.1.1 General

The following are the main components of a PCM based thermal storage system (Cabeza et al., 2011):

1) **Phase change material (PCM)**: A material that stores and releases thermal energy through a reversible phase transition.

2) **PCM Containment/Encapsulation:** Material used to contain/encapsulate PCM and prevent leakage during phase transition. Example: Polymer or Metal shell, etc.

3) **PCM Storage tank/module:** The external structure or a physical unit that integrates PCM, encapsulation, and heat transfer structures. Example: Cylindrical or rectangular tank, Plate-based module.

4) **Heat or Cold Source:** A hot source transfers heat to a PCM during charging to store heat and releases this stored thermal energy to the connected heating application. Conversely, the cold source removes heat during charging to store cooling in the PCM and releases this stored cooling to the connected cooling application. Example: Heat pump, soar thermal energy, chiller, etc.

5) **Heat transfer fluid:** A working fluid that transports thermal energy between the PCM system and external sources/sinks.

6) **Heat Exchanger:** Device enabling thermal interaction between PCM and heat transfer fluid (HTF).

7) **Insulation:** Thermal barrier minimizing PCM energy losses to surroundings.

8) **Fluid circulation component:** Mechanical elements enabling HTF flow (i.e., pump, valves, pipes, etc.).

5.2.1.2 PCM based "ALL-IN-ONE" Solution

1) **PCM "ALL-IN-ONE" Solution:** It is a modular heat pump with integrated latent heat storage, and a fresh-water station to deliver domestic hot water.

2) **Heat Pump:** A heat pump is a device that can provide heating, cooling (in this case is known as chiller) and hot water for residential, commercial and industrial use. It pumps thermal energy from the air, ground or water (low-temperature energy source) to a final destination environment (high-temperature energy sink, e.g., a building) thanks to the use of a refrigeration cycle. The refrigerant fluid is responsible to transport heat by passing through four different components: evaporator, compressor, condenser and expansion valve.

3) **Evaporator:** An evaporator is a device in which a liquid refrigerant is vaporized and absorbs heat from the surrounding fluid.

4) **Compressor:** A Compressor is a device that compresses a fluid typically used in a refrigeration circuit.

5) **Condenser:** A condenser is a device that is used to dissipate heat, typically by condensing a substance such as a refrigerant from its gaseous to its liquid state.

6) **Expansion Valve:** An expansion valve is a passive orifice responsible for the expansion of the liquid refrigerant to reach evaporating conditions.

7) **Refrigerant-PCM-Water Heat Exchanger (RPW-HEX):** Refrigerant-PCM-Water heat exchanger (RPW-HEX) is a type of heat exchanger with three heat transfer fluids: Refrigerant, PCM and water.

8) **Water Radiators:** A water coil is a coil through which water flows as a heat exchanger fluid.

9) **Aluminium Sheets:** Aluminium sheets are inserted between the water-PCM HEXs and refrigerant-PCM HEXs to increase the heat transfer between them.

10) **Insulation Layer:** An insulation layer is an additional layer of material with low thermal conductivity which serves to prevent the thermal losses of a storage device.

11) **Expansion device:** An expansion unit is an expansion tank, which is used as safety measure to compensate changes in pressure in pressurized heating systems.

12) **Fresh-Water Station:** A fresh-water station is a device for quick and hygienic domestic hot water supply. It constitutes an additional separate circuit to prevent water contamination due to corrosion from the main heat exchanger circuit.

13) **Expansion Vessel:** An expansion vessel is an expansion tank, which is used as safety measure to compensate changes in pressure in pressurized heating systems.

14) **Safety Group:** A safety group is a combination of a safety valve, limiting the maximum pressure in a hydraulic system, an automatic air vent and a manometer.

15) **Temperature sensors:** A temperature sensor is a measurement device used to measure and monitor the temperature in a system.

16) **Pressure Sensors:** A pressure sensor is a measurement device used to measure and monitor the pressure .in a system.

17) **Volume flow rate sensors:** A volume flow rate sensor is a measurement device used to measure and monitor the volume flow rate of a fluid flowing in a channel.

18) **Mixing valve:** A mixing valve is a mechanical or thermostatically controlled device designed to blend hot and cold fluid to achieve a precise, safe, and consistent output temperature. Its primary purpose is to regulate fluid temperature.

19) **Safety valve:** A safety valve (or pressure relief valve) is a critical safety device designed to automatically release excess pressure from a system.

20) **Manometer:** A manometer is a device used to measure the pressure of a fluid in a system.

5.2.2 Hierarchical structure of TES types and subcomponents (PCM “ALL-IN-ONE” Solution)

Table 2 — Hierarchical structure of All-In-One Solution components

Category	Sub-Category	Sub-sub-category
“PCM ALL-IN-ONE” Solution	(A) Heat Pump	1 Evaporator, 2 Compressor, 3 Condenser, 4 Expansion Valve
	(B) Refrigerant-PCM-Water Heat Exchanger (RPW-HEX)	1 PCM 2 Water Radiators 3 Condenser 4 Aluminium sheets 5 Insulation Layer 6 Expansion device
	(C) Fresh-Water Station	
	(D) Expansion Vessel	
	(E) Safety Group	1 Mixing valve 2 Safety valve 3 Manometer

Table 3 — SAREF terminology and sub-class for PCM All-In-One-Solution

Category	SAREF Terminology	Sub class
“PCM ALL-IN-ONE” Solution	(A) Heat Pump No specific term s4syst:System	1 Evaporator, s4bldg:Evaporator 2 Compressor, s4bldg:Compressor 3 Condenser, s4bldg:Condenser 4 Expansion Valve (subClassOf s4bldg:Valve)
	(B) Refrigerant-PCM-Water Heat Exchanger (RPW-HEX) Subclass of s4bldg:HeatExchanger	1 PCM (energy commodity: :PCMMaterial, subClassOf saref:Commodity (thermal storage material) 2 Water Radiators (:WaterRadiator a subClassOf s4bldg:SpaceHeater) 3 Condenser (s4bldg:Condenser) 4 Aluminium sheets 5 Insulation Layer 6 Expansion device (:ExpansionValve (subclass of s4bldg:Valve)
	(C) Fresh-Water Station	FreshWaterStation a subClassOf s4bldg:HeatExchanger
	(D) Expansion Vessel	ExpansionVessel a :subClassOf s4bldg:Tank

Category	SAREF Terminology	Sub class
	(E) Safety Group s4syst:System s4syst:hasSubSystem the three devices	1 Mixing valve (subClassOf s4bldg:Valve) 2 Safety valve (subClassOf s4bldg:Valve) 3 Manometer (PressureSensor a subclass of saref:Sensor)

5.2.3 Definition of core TCM System TES components:

5.2.3.1 General

Following are the main components of a TCM based thermal storage system (Jong et al., 2014):

1) **Thermochemical Material (TCM / Sorbent):** A thermochemical material is a solid or liquid sorbent that stores thermal energy using a reversible sorption reaction (adsorption) with a working fluid, converting it into chemical potential during charge and releasing it during discharge. Example: Zeolites, Silica gel, Salt hydrates, Metal oxides.

2) **Working Fluid (Sorbate)**: The working fluid, also known as the sorbate, interacts reversibly with the thermochemical working material during the sorption and desorption processes, allowing mass and energy transfer within the TCM system. Example: Water vapor, Ammonia, Methanol.

3) **Containment Structure:** Containment structure physically encloses the thermochemical material and allows for controlled contact between the sorbent and the working fluid while ensuring mechanical stability and reaction integrity.

4) **Heat Exchange Interface:** The heat exchange interface is the structural surface through which thermal energy is supplied to the sorbent material during charging and extracted during discharging.

5) **Evaporator:** An evaporator is a component in which the working fluid absorbs heat and changes phase (usually from liquid to vapour), supplying vapour to the thermochemical reactor during the discharging or charging process, depending on the system configuration.

6) **Condenser:** A condenser is a heat rejection component in which the working fluid releases heat and condenses from vapour to liquid, allowing the thermochemical cycle to be closed and the working fluid to be regenerated.

7) **Mass transport component:** Mass transport components are mechanical devices that govern and direct the movement of working fluid vapour between the reactor, evaporator, and condenser, ensuring proper sorption and desorption processes. Example: Valves, Ducts, etc.

8) **External Heat Source:** An external heat source supplies thermal energy needed for the TCM desorption process (charging) without taking part in energy storage.

9) **Insulation:** Thermal barrier surrounding the reactor and auxiliary components that minimizes heat losses to the environment.

5.2.3.2 Specific for the TCM HYSTORE Solution

1) **Desorption Chamber:** The function of this component is to allow the desorption process of the cycle. According to this mechanism, energy storage is obtained for a specific time. For this charge phase of the cycle, part of the wet sorbent (hydrated zeolite) from the wet sorbent vessel is sent inside the

desorption chamber. The desorption process is an endothermic chemical reaction and involves the sorbent material (zeolite 13X) and sorbate (water). For this reason, the RF system generates the heat necessary for the desorption process. Once the desorption process has begun, the sorbent releases the sorbate, which evaporates from the sorbent.

2) **Radiofrequency system (RF):** RF system generates heat necessary for the desorption process, during the charge phase of the cycle.

3) **Adsorption chamber:** The function of this component is to allow the adsorption process of the cycle. For the discharge phase of the cycle, part of the dry sorbent (dry zeolite) from the dry sorbent vessel is sent inside the adsorption chamber. Heat is released in this process (i.e., discharging process).

4) **Dry sorbent vessel:** The function of the dry sorbent vessel is to store the dry sorbent material and to allow the functioning of the TCM system by exchanging the dry sorbent (dry zeolite) with the desorption chamber, after the desorption process and the adsorption chamber, before the adsorption process.

5) **Wet sorbent vessel:** The function of the wet sorbent vessel is to store the wet sorbent material and to allow the functioning of the TCM system by exchanging the wet sorbent (hydrated zeolite) with the desorption chamber, before the desorption process; and the adsorption chamber, after the adsorption process.

6) **Falling-film Evaporator/Condenser (EVC) chamber:** EVC plays a crucial role in thermochemical energy storage systems by facilitating the efficient evaporation and condensation of the sorbate material. It enables the storage and release of thermal energy through controlled phase change processes, enhances system efficiency, ensures temperature regulation, and supports overall system stability and sustainability.

7) **Refrigerant vessel:** Refrigeration vessel is the container for storing the refrigerant required for efficient heat transfer. The refrigerant in the vessel acts as a medium for transferring heat between different stages of the thermochemical process. It facilitates the absorption and release of thermal energy during the charging (storage) and discharging (release) phases.

8) **Moving platform:** Moving platform moves some components vertically up and down.

9) **Pump of the refrigerant loop (PUMP REF):** The pump is responsible for circulating the refrigerant through the entire refrigerant loop. This ensures continuous movement of the refrigerant between the storage vessel, heat exchangers, and other components of the system.

10) **Pump of the LT source (PUMP LT):** Pump LT is a device which increases the pressure of fluid and makes the flow possible. Here the pump is involved in the flow of heat transfer fluid from the LT tank. LT receives as an input the heat transfer fluid from the Low temperature source tank and pumps it, by increasing its pressure.

11) **Pump of the MT sink (PUMP MT):** Pump is a device which increases the pressure of fluid and makes the flow possible. Here the pump is involved in the flow of heat transfer fluid from the MT tank. MT receives as an input the heat transfer fluid from the Medium temperature source tank and pumps it, by increasing its pressure.

12) **Temperature sensors:** A temperature sensor is used for continuous monitoring of temperature inside the system.

13) **Pressure sensors:** A pressure sensor is used for continuous monitoring of pressure inside any system.

14) **Vacuum valves:** Allow the passage of sorbent and sorbate into or out of the chambers under vacuum conditions.

15) **Three-way valves:** For mixing two flow rates of fluid coming from two components and sending a single flow rate to the input/output. The function of the three-way valves is to allow the correct connections between the components involved in the charging and discharging phases of the TCM system.

16) **Heat Exchanger (HEX) of the adsorption chamber:** The function of this component is to allow the heat exchange between the TCM and the heat transfer fluid.

5.2.4 Hierarchical structure of TES types and subcomponents (TCM System)

Table 4 — The hierarchical structure of TCM components (Water-zeolite based sorption thermal storage system)

Category	Sub-Category	Sub-sub-category (if needed)
Desorption chamber		
Radiofrequency system (RF)		
Adsorption chamber		
Dry sorbent vessel		
Wet Sorbent Vessel		
EVC Chamber		
Refrigerant Vessel		
Moving platform		
Pump	PUMP REF PUMP LT PUMP MT	
Sensors	Temperature sensors	Sensor T_{DRY} Sensor T_{WET} Sensor T_{DES} Sensor T_{ADS} Sensor for temperature monitoring T_{EVC} Sensor T_{REF} Sensor $T_{EVC,IN}$ Sensor $T_{EVC,OUT}$ Sensor $T_{REF,OUT}$ Sensor $T_{ADS,IN}$ Sensor $T_{ADS,OUT}$
	Pressure Sensors	Sensor P_{DRY} Sensor P_{WET} Sensor P_{DES}

Category	Sub-Category	Sub-sub-category (if needed)
		Sensor P_{ADS} Sensor for pressure monitoring P_{EVC}
Valves	Vacuum valves	Vacuum valve 1 Vacuum valve 2 Vacuum valve 3 Vacuum valve 4 Vacuum valve 5 Vacuum valve 6
	Three-way valves	Three-way valve 1 Three-way valve 2
Heat Exchanger (HEX) of the adsorption chamber		

Table 5 — SAREF terminology and sub-class for TCM system

Category	SAREF terminology	Subclass
Desorption chamber	No exact SAREF term	(DesorptionChamberSystem as a subclass of s4syst:System)
Radiofrequency system (RF)	No specific RF class	saref:Device (generic device class)
Adsorption chamber	No exact SAREF term	AdsorptionChamberSystem⟶sub Class Of s4syst:System
Dry sorbent vessel	s4bldg:Tank (Vessel could be treated as tank)	New subclass :DrySorbentTank
Wet Sorbent Vessel	s4bldg:Tank (Vessel could be treated as tank)	New subclass :DrySorbentTank
EVC Chamber	No exact SAREF term	EVCChamberSystem⟶subclass of s4syst:System
Refrigerant Vessel	s4bldg:Tank (Vessel could be treated as tank)	New subclass :RefrigerantTank
Pump	PUMP REF PUMP LT PUMP MT s4bldg:Pump	New Subclass under s4bldg:Pump: RefrigerantPump, LowTemperaturePump and MediumTemperaturePump
Sensors SAREF core defines saref:Sensor; SAREF4BLDG refines it as s4bldg:Sensor	Temperature sensors saref:temperaturesensor	Sensor T_{DRY} Sensor T_{WET} Sensor T_{DES} Sensor T_{ADS} Sensor for temperature monitoring T_{EVC}

Category	SAREF terminology	Subclass
		Sensor T_{REF} Sensor $T_{EVC,IN}$ Sensor $T_{EVC,OUT}$ Sensor $T_{REF,OUT}$ Sensor $T_{ADS,IN}$ Sensor $T_{ADS,OUT}$ **subclass** of saref:temperaturesensor (Example :Sensor_T_{DRY} a saref:TemperatureSensor)
	Pressure Sensors Can be used as subclass of sensor with saref:measures pressure	Sensor P_{DRY} Sensor P_{WET} Sensor P_{DES} Sensor P_{ADS} Sensor for pressure monitoring P_{EVC}
Valves s4bldg:Valve	Vacuum valves New subClassOf s4bldg:Valve	Vacuum valve 1 Vacuum valve 2 Vacuum valve 3 Vacuum valve 4 Vacuum valve 5 Vacuum valve 6 (Example: VacuumValve_1 a :VacuumValve)
	Three-way valves subClassOf s4bldg:Valve	Three-way valve 1 Three-way valve 2 (Example: Three-way Valve_1 a :Three-way Valve)
Heat Exchanger (HEX) of the adsorption chamber s4bldg:HeatExchanger		

6 Properties and Relationships

6.1 Capacity, thermal characteristics, operational state, material types (PCM System)

Thermal Energy Storage (TES) utilizing Phase Change Materials (PCM) is characterised by a complex interrelationship among material, thermal, and operational aspects that all affect energy storage capacity, heat transfer efficiency, and long-term reliability of TES systems. Considerations of the Thermophysical properties of PCMs (latent heat, phase change temperatures, thermal conductivity, density, specific heat), the material composition, and encapsulation method; as well as the operating conditions of the TES systems (charging/discharging rates, cycling stability, heat transfer configuration) must all undergo thorough evaluation to adequately assess the performance, applicability, and scalability of PCM storage systems within practical applications of energy storage (Mao et al., 2025).

Table 6 — Properties associated with the PCM thermal storage are tabulated below:

Properties		Definition
Capacity	Sensible capacity	Total sensible capacity of PCM
	Latent capacity	Total latent capacity of PCM
	Nominal capacity	Total capacity of TES, including sensible and latent capacity
Thermal characteristics	Phase Change (Phase transition temperature range)	Lower temperature (at which the melting process begins); Upper temperature (at which the melting process is complete); Upper temperature (at which the solidification process begins); Lower temperature (at which the solidification process is complete). E.g.: Tmelt_low, Tmelt_high, Tsolid_low, Tsolid_high.
	Latent Heat of Fusion	Thermal energy required to change the phase of the phase change material
	Thermal Conductivity	Ability of a PCM to propagate heat energy via conduction
	Specific Heat Capacity	Amount of heat energy required to raise the temperature of one unit mass of a substance by one degree Celsius (°C) or one Kelvin (K).
	Nucleation temperature	The temperature at which the liquid phase of the PCM, when cooled, begins to solidify or nucleate
Operational Characteristics	Max. charging power	Maximum power which can be used to charge the unit
	Max. discharging power	Maximum power which can be used to discharge the unit
	Max. number of cycles	Lifetime of PCM in number of cycles
Material Types	PCM material	Name of PCM utilised
	PCM material class	Organic, Inorganic and Eutectic & mixtures

6.2 Ontological Relationships – PCM System

Table 7 — Ontological Relationships for All-In-One-Solution System

No.	Related Concepts	Relationship	Cardinality
1	Generates	ALL-IN-ONE Solution Generates DHW	one-to-one
2	Includes	ALL-IN-ONE Solution includes Heat Pump	one-to-many
		ALL-IN-ONE Solution includes RPW-HEX	one-to-one
		ALL-IN-ONE Solution includes Fresh-Water Station	one-to-one
		ALL-IN-ONE Solution includes Expansion Vessel	one-to-one
		ALL-IN-ONE Solution includes Safety Group	one-to-one
		Heat Pump includes Evaporator	one-to-one
		Heat Pump includes Compressor	one-to-one
		Heat Pump includes Condenser	one-to-one
		Heat Pump includes Expansion Valve	one-to-one
		RPW-HEX Includes Water radiators	one-to-one
		RPW-HEX Includes Condensers	one-to-one
		RPW-HEX Includes Aluminum sheets	one-to-one
		RPW-HEX Includes Insulation layer	one-to-one
		RPW-HEX Includes Expansion device	one-to-one
		Safety Group Includes Mixing valve	one-to-one
		Safety Group Includes safety valve	one-to-one
		Safety Group Includes manometer	one-to-one
3	isPartOf	Heat Pump isPartOf ALL-IN-ONE Solution	many-to-one
		Evaporator isPartOf Heat Pump	one-to-one
		Compressor isPartOf Heat Pump	one-to-one
		Condenser isPartOf Heat Pump	one-to-one
		Expansion Valve isPartOf Heat Pump	one-to-one
		RPW-HEX isPartOf ALL-IN-ONE Solution	one-to-one
		PCM isPartOf RPW-HEX	one-to-one
		Water radiators isPartOf RPW-HEX	one-to-one
		Aluminium Sheets isPartOf RPW-HEX	one-to-one
		Insulation Layer isPartOf RPW-HEX	one-to-one
		Expansion Device isPartOf RPW-HEX	one-to-one
		Fresh-Water Station isPartOf ALL-IN-ONE Solution	one-to-one
		Expansion Vessel isPartOf ALL-IN-ONE Solution	one-to-one
		Safety Group isPartOf ALL-IN-ONE Solution	one-to-one
		Mixing valve isPartOf Safety Group	one-to-one
		Safety valve isPartOf Safety Group	one-to-one
		Manometer isPartOf Safety Group	one-to-one

No.	Related Concepts	Relationship	Cardinality
4	isConnectedTo	Heat Pump isConnectedTo RPW-HEX	many-to-one
		Heat Pump isConnectedT floor heating system	many-to-one
		Evaporator isConnectedTo Compressor	one-to-one
		Evaporator isConnectedTo Expansion Valve	one-to-one
		Compressor isConnectedTo Evaporator	one-to-one
		Compressor isConnectedTo Condenser	one-to-one
		Condenser isConnectedTo Compressor	one-to-one
		Condenser isConnectedTo Expansion Valve	one-to-one
		Expansion Valve isConnectedTo Evaporator	one-to-one
		Expansion Valve isConnectedTo Condenser	one-to-one
		Water radiators isConnectedTo Fresh-Water Station	one-to-one
		Fresh-Water Station isConnectedTo RPW-HEX	one-to-one
		Expansion Vessel isConnectedTo RPW-HEX	one-to-one
		Expansion Vessel isConnectedTo Fresh-Water Station	one-to-one
		Safety Group isConnectedTo RPW-HEX	one-to-one
		Safety Group isConnectedTo Fresh Water Station	one-to-one
5	feedsInto	Evaporator feedsInto Compressor	one-to-one
		Compressor feedsInto Condenser	one-to-one
		Condenser feedsInto Expansion Valve	one-to-one
		Expansion Valve feedsInto Evaporator	one-to-one
6	transfersTo	Heat Pump transfersTo RPW-HEX	many-to-one
		RPW-HEX transfersTo Fresh-Water Station	one-to-one
		Water radiators transfersTo Fresh-Water Station	one-to-one
		Aluminium Sheets transfersTo PCM	one-to-one
		Fresh-Water Station transfersTo RPW-HEX	one-to-one
		Fresh-Water Station transfersTo DHW	one-to-one
		Water radiators transfersTo PCM	one-to-one
7	monitoredBy	ALL-IN-ONE Solution Monitored By sensors	one-to-many
		Heat Pump monitoredBy Sensate 81CP (x1 sensor)	one-to-one
		Heat Pump monitoredBy Sensate 82CP (x1 sensor)	one-to-one
		Heat Pump monitoredBy PT1000 class 1/3 DIN (x2 sensors)	one-to-many
		Heat Pump monitoredBy NTC10k (x3 sensors)	one-to-many
		Heat Pump monitoredBy Picomag DN15(x1 sensor)	one-to-one
		RPW-HEX monitoredBy PT100 class A (x 10 sensors)	one-to-many
		RPW-HEX monitoredBy Picomag DN15 (x1 sensor)	one-to-one
		RPW-HEX monitoredBy Rosemount 2088 (x1 sensor)	one-to-one
		Fresh-Water Station monitoredBy PT100 Class A (x2 sensors)	one-to-many
		Fresh-Water Station monitoredBy Picomag DN15 (x1 sensor)	one-to-one

No.	Related Concepts	Relationship	Cardinality
8	operatesIn	Evaporator operatesIn Heat Pump	one-to-one
9	controlsFlow	Fresh-Water Station controlsFlow Water radiators	one-to-one
10	Measures	Safety Group Measures Pressure	one-to-one

6.3 Capacity, thermal characteristics, operational state, material types – TCM System

For a TCM using a sorption heat storage system, performance and suitability depend on various thermodynamic, kinetic, and system-level parameters which govern the adsorption and desorption of the sorbate from the porous sorbent material. These include the adsorption capacity of the material, the isotherms of the materials that determine how much energy the system can store, the heats of adsorption and equilibrium conditions that determine the highest temperature this system can provide for domestic hot water supply, the kinetics of mass and heat transfer which will determine how quickly these systems can charge and discharge, and the reactor's configuration, water vapour movement through the reactor, and the integration of the heat exchangers will all be critical factors in determining the overall efficiency, power density, and long-term operational stability of these systems (Scapino et al., 2017).

Table 8 — Properties associated with the TCM thermal storage are tabulated below:

	Properties	Definition
Capacity	Sorption capacity	Sorption capacity refers to the amount of sorbate that sorbent can adsorb per unit mass, and it determines how much thermal energy can be stored and released in the adsorption/desorption cycle.
	Volume of TCM	Volume of Sorbent
	Heat of adsorption	The amount of heat released when a unit mass of sorbate vapor is adsorbed onto the sorbent surface.
	Volumetric energy density	The amount of thermal energy that can be stored per unit volume of the sorbent bed or storage container.
	Usable storage capacity	The portion of the theoretical storage capacity that can actually be accessed within the practical operating temperature and humidity range of the system.
	Degree of regeneration	The extent to which the sorbent has been dried during charging, expressed as the fraction of adsorbed sorbate removed.
Thermal characteristics	Charging Heat input	Heat input supplied by the heating system used for desorption
	Thermal charging power	Rate at which thermal energy is supplied to the sorbent during regeneration (kW).
	Thermal discharging power	Rate at which useful heat is released during adsorption (kW).
	Adsorption temperature range	The temperature range at which water vapor is adsorbed by the sorbent and useful heat is released for applications such as domestic hot water.

	Properties	Definition
	Desorption temperature	The temperature required to remove adsorbed sorbate from the sorbent during charging of the storage system.
	Heat transfer coefficient	A measure of how effectively heat is transferred between the sorbent and the heat exchanger surfaces.
	Thermal losses	The amount of heat lost from the system to the surroundings during charging, storage, or discharging.
Operational Characterstics	Operating Temperature	RF system operating temperature
	Reaction kinetics (adsorption/desorption rate)	The rate at which sorbate vapor is adsorbed or desorbed by the sorbent under given temperature and pressure conditions.
	Desorption rate	
	Thermal power output	The rate at which useful heat is delivered during the discharging phase.
	Desorption rate	The rate at which water is released from the zeolite during regeneration.
	Cycle time	The duration required to complete a full charge or discharge cycle.
	System efficiency	The ratio of useful heat delivered to the amount of heat originally supplied during charging.
	Cycling stability	The ability of the sorbent to maintain its adsorption capacity and structural integrity over repeated cycles.
Material Types	TCM material	Sorbent material
		Sorbate material
	Pore size distribution	The range and proportion of pore diameters in the sorbent, which controls how easily sorbate molecules enter and leave.
	Surface area	The total internal surface of the sorbent available for sorbate adsorption.

6.4 Ontological Relationships — TCM System

Table 9 — Ontological Relationships for TCM System

No.	Related Concepts	Relationship	Cardinality
1	Is-inside	Radiofrequency system is-inside DesorptionChamber HEX of Adsorption chamber is-inside Adsorption chamber	one-to-one one-to-one
2	isConnectedTo	Desorption Chamber isConnectedTo Vacuum Valve 1 Desorption Chamber isConnectedTo Vacuum Valve 2 Desorption Chamber isConnectedTo Vacuum Valve 3 Adsorption Chamber isConnectedTo Vacuum Valve 4 Adsorption Chamber isConnectedTo Vacuum Valve 5 Adsorption Chamber isConnectedTo Vacuum Valve 6 HEX of Adsorption chamber isConnectedTo PUMP MT Vacuum Valve 1 isConnectedTo EVC Chamber Vacuum Valve 2 isConnectedTo Dry sorbent vessel Vacuum Valve 3 isConnectedTo Wet sorbent vessel Vacuum Valve 4 isConnectedTo EVC Chamber Vacuum Valve 5 isConnectedTo Dry sorbent vessel Vacuum Valve 6 isConnectedTo Wet sorbent vessel PUMP MT isConnectedTo Three-way valve 2 PUMP MT isConnectedTo Three HEX of Adsorption chamber EVC Chamber isConnectedTo PUMP REF EVC Chamber isConnectedTo Three-way valve 1 EVC Chamber isConnectedTo Vacuum Valve 1 EVC Chamber isConnectedTo Vacuum Valve 4 EVC Chamber isConnectedTo Three-way valve 2 PUMP REF isConnectedTo Refrigerant vessel PUMP REF isConnectedTo EVC Chamber Three-way valve 1 isConnectedTo EVC Chamber Three-way valve 2 isConnectedTo EVC Chamber Three-way valve 2 isConnectedTo PUMP LT Three-way valve 2 isConnectedTo PUMP MT Refrigerant vessel isConnectedTo EVC Chamber Refrigerant vessel isConnectedTo PUMP REF PUMP LT isConnectedTo Three-way valve 2 Dry sorbent vessel isConnectedTo Vacuum Valve 2 Dry sorbent vessel isConnectedTo Vacuum Valve 5 Wet sorbent vessel isConnectedTo Vacuum Valve 3 Wet sorbent vessel isConnectedTo Vacuum Valve 6	one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one ne-to-one one-to-one

No.	Related Concepts	Relationship	Cardinality
3	monitoredBy	Desorption Chamber monitoredBy T_{Des} Desorption Chamber monitoredBy P_{Des} Adsorption chamber monitoredBy T_{Ads} Adsorption chamber inletmonitoredBy $T_{\text{Evc in}}$ Adsorption chamber outletmonitoredBy $T_{\text{EVC out}}$ Adsorption chamber monitoredBy P_{ads} EVC Chamber monitoredBy T_{EVC} EVC Chamber inletmonitoredBy $T_{\text{EVC in}}$ EVC Chamber outletmonitoredBy $T_{\text{EVC out}}$ EVC Chamber outletmonitoredBy $T_{\text{REF out}}$ EVC Chamber monitoredBy P_{Evc} Refrigerant vessel monitoredBy T_{Ref} Dry sorbent vessel monitoredBy T_{Dry} Dry sorbent vessel monitoredBy P_{Dry} Wet sorbent vessel monitoredBy T_{Wet} Wet sorbent vessel monitoredBy P_{Wet}	one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one one-to-one

7 Use Case Integration

7.1 Pilot Use Cases

7.1.1 Residential buildings (non-DHC)

Ontology applications in residential buildings focus on energy flexibility, occupant comfort, and demand-side management rather than district-scale interactions. Several studies highlight the use of ontologies to model occupant behaviour, appliance flexibility, and local energy resources for home energy management systems. For instance, ontologies have been employed to integrate real-time sensor data, occupant preferences, and device control models into unified building energy management systems to optimize heating and cooling while maintaining comfort (Belafi et al., 2019). The Energy Flexibility Ontology (EFOnt) has been proposed to formalize flexible loads, KPIs, and building services, supporting smart homes in reacting to dynamic electricity prices and demand response signals (Li and Hong, 2022). Moreover, multi-agent systems based on shared semantic vocabularies enable automated decision-making across appliances, local PV, and battery systems, ensuring interoperability between heterogeneous devices and platforms (Moghaddam et al., 2017). Some studies integrate weather forecasts, building thermal dynamics, and control setpoints into semantic layers for predictive optimization in residential energy systems (Wu et al., 2022).

At the community level, the PARMENIDES Energy Community Ontology (PECO) provides the foundational semantic layer for representing renewable energy communities, including members, multi-vector assets, hybrid energy storage systems (HESS), tariffs, incentives, flexibility signals, and system topology, allowing for real-time interoperability between EMS, smart meters, and grid capacity management systems (Interoperability framework and semantic interoperability, The PARMENIDES Consortium, 2023 – 2025). Building on this basis, subsequent research has used semantic structures to maximise renewable energy communities using ontology-driven EMS designs that coordinate energy flows, asset behaviours, and community adaptability (Stefan et al., 2025). Further enhancements show how PECO's semantic architecture facilitates automated flexibility provision and operational decision-making by organising community assets, user objectives, and grid-support requirements within common Renewable Energy Community contexts Stefan et al., 2024).

7.1.2 District Heating & Cooling (DHC)

District heating and cooling systems have attracted growing interest in ontology research due to their multi-building, multi-energy, and real-time optimization requirements. One major use case involves real-time DR for thermal grids, where ontologies model heat demand forecasts, price or carbon intensity signals, and comfort constraints to orchestrate loads across multiple buildings (Li et al., 2020). Dynamic knowledge graphs have been used to integrate building energy data, district network topologies, and emission models for city-scale optimization and digital twin applications (Hofmeister et al., 2024). Urban energy planning tools increasingly rely on semantic data integration to merge geospatial information, building stock data, and energy infrastructure into consistent urban energy models (Corrado et al., 2020). Multi-agent control architectures based on shared ontologies allow distributed energy producers, storage systems, and consumer buildings to coordinate thermal energy flows and react to external signals (Moghaddam et al., 2017).

7.1.3 University campuses

Some studies explicitly focus on university campuses as intermediate-scale testbeds for multi-energy microgrids and semantic energy management. For example, a multi-agent decision support system based on ontologies has been developed to enable interoperability among PV systems, battery storage, demand response programs, and external markets within campus microgrids (Teixeira et al., 2018). These ontologies provide a shared knowledge base for scheduling, optimization, and coordination across heterogeneous energy subsystems. Other works extend campus ontologies for predictive maintenance and fault detection in HVAC and energy subsystems, combining rule-based reasoning with real-time monitoring to reduce energy waste and improve reliability (Pruvost et al., 2023).

Table 10 — Classification of Key Ontology Applications and Representative Works

Domain	Key Ontology Applications	Representative Works
Residential Buildings	Occupant behavior, DR, energy flexibility, IoT integration	(Belafi et al., 2019; Li and Hong, 2022; Moghaddam et al., 2017)
District Heating & Cooling	Real-time DR, digital twins, emission modelling, multi-agent coordination	(Li et al., 2020; Hofmeister et al., 2024; Corrado et al., 2020)
University Campuses	Microgrid energy management, DR, predictive maintenance	(Teixeira et al., 2018; Pruvost et al., 2023)

7.2 Metrics for Validation

7.2.1 General

The validation of the SAREF4TESS ontology requires a set of harmonised metrics to assess performance, interoperability, financial viability, environmental impact, and user acceptance across diverse TES use cases (residential buildings, district heating & cooling, and university campuses). In the context of this CWA, validation does not mean validating the physical performance of a TES system. Instead, validation refers to verifying that the SAREF4TESS ontology is fit for purpose in representing, exchanging, and using TES-related information across real systems. Metrics are grouped into six categories: interoperability, efficiency and performance, capacity and system, financial benefits, environmental benefits, and socio-technical validation. The validation within this specification is two-layered:

a) Ontology-level validation (semantic & technical)

This concerns whether the ontology itself is correct and usable:

- Logical consistency (OWL/RDF consistency, no contradictions)
- Structural completeness (coverage of TES components, states, processes)
- Semantic adequacy (correct meaning, alignment with domain concepts)
- Interoperability (alignment with SAREF, SAREF4ENER, BRICK, NGSI-LD)

b) Use-case validation (fitness-for-purpose)

This concerns whether the ontology can:

- Represent real TES systems (PCM/TCM)
- Support real data flows (monitoring, control, KPIs)
- Enable comparison, reasoning, and analytics across systems

For the purposes of this CEN-CENELEC Workshop Agreement, the validation metrics defined in this section are discussed and applied primarily in the context of **residential buildings and university campus buildings**, reflecting the pilot use cases addressed in this CWA. It is acknowledged that **some or all of these metrics may be directly applicable or adaptable to industrial Thermal Energy Storage (TES) applications**, which are considered outside the present scope and may be addressed in future standardisation work.

Table 11 — KPI and validation aspects

KPI Category	What is validated in the ontology
Efficiency KPIs	Ability to model charge/discharge processes, losses, cycles
Capacity KPIs	Representation of storage capacity, SoC, usable energy
Financial KPIs	Representation of economic attributes as semantic properties
Environmental KPIs	Alignment with LCA, emissions, sustainability vocabularies
Comfort KPIs	Linkage between TES operation and building-level outcomes
Grid KPIs	Interoperability with DR, flexibility, smart grid semantics

7.2.2 Interoperability

- **Ontology alignment score**: Degree of semantic consistency with related frameworks (SAREF4ENER, BRICK, FIWARE NGSI-LD).
- **Cross-domain integration**: Successfully mapping TES data into Building Energy Management Systems (BEMS), district energy networks, and smart grid platforms.
- **Plug-and-play compatibility**: Demonstration that TES systems can be seamlessly integrated into legacy and modern systems without major data conversion.

7.2.3 Financial Benefit Metrics

- **Levelized Cost of Storage (LCOS, €/kWh)**: Economic competitiveness compared to other storage technologies[1].
- **Payback period (years)**: Time required for investment in TES to be recovered through operational savings.
- **Participation in demand response markets (€/year)**: Revenue streams generated through grid flexibility services.
- **Operational cost savings (%)**: Reduction in household, campus, or district heating/cooling bills.
- **Capital expenditure (CAPEX) vs. operational expenditure (OPEX)**: Balance of upfront and ongoing costs, benchmarked against alternatives[2].

7.2.4 Environmental Benefit Metrics

- **Carbon footprint reduction (kg CO_2e/year)**: Quantified decrease in greenhouse gas emissions[3].
- **Renewable integration (%)**: Proportion of variable renewable energy (solar, wind) successfully stored and utilised.
- **Waste heat recovery potential (kWh/year)**: Energy captured that would otherwise be lost.
- **Material recyclability and embodied carbon (%)**: Share of TES components that can be reused or recycled; assessment of embodied energy.
- **Life cycle assessment (LCA)**: Holistic measure of environmental impacts from production, operation, and end-of-life phases.

7.2.5 Socio-Technical Validation

- **Energy savings (%)**: Reduction in energy consumption achieved in real-world pilot sites.

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[1] Levelized Cost of Storage (LCOS, €/kWh): Economic indicator expressing the cost per unit of thermal energy delivered over the lifetime of a TES system. For the purposes of this CWA, LCOS is evaluated relative to functionally comparable storage or heat supply solutions, such as sensible thermal storage (e.g. hot water tanks), latent thermal storage (PCM-based systems), thermochemical storage systems, or alternative power-to-heat configurations. The reference technology, system boundary, lifetime assumptions, and cost components (CAPEX and OPEX) used for comparison is explicitly documented. No fixed benchmark values are prescribed within this CWA.

[2] Capital expenditure (CAPEX) vs. operational expenditure (OPEX): Representation of the balance between upfront investment costs and ongoing operational and maintenance costs over the lifecycle of a TES system. For the purposes of this CWA, CAPEX and OPEX are analysed relative to functionally comparable heat supply or storage solutions, such as conventional heating systems, sensible thermal storage, alternative TES technologies, or power-to-heat configurations. The selected reference system, system boundaries, lifetime assumptions, and included cost components are explicitly documented. No fixed benchmark values are prescribed within this CWA.

[3] Carbon footprint reduction (kg CO_2e/year): Quantified decrease in greenhouse gas emissions associated with the operation of a TES-enabled energy system, relative to a defined baseline heat supply scenario providing equivalent thermal services. Baselines may include conventional fossil-based heating systems, electric heating without thermal storage, alternative TES configurations, or a business-as-usual system without TES integration. The selected baseline, system boundaries, emission factors, and temporal scope are explicitly documented. No fixed baseline scenario is prescribed within this CWA.

- **Grid flexibility contribution**: Ability of TES to provide peak-shaving, load-shifting, and resilience benefits.
- **User feedback and thermal comfort**: Surveys on system usability, satisfaction, and acceptance.
- **Annual number of discomfort hours** (for thermal comfort - for space heating and cooling).
- **Societal benefits**: Evidence of equity improvements (e.g., reduced energy poverty, accessibility in social housing or community-scale systems).

7.2.6 Technical Key Figures (Metrics) for Thermal Energy Storage (TES)

7.2.6.1 Efficiency and Performance Metrics

- **Round-trip efficiency (%)**: Ratio of energy retrieved to energy stored.
- **Thermal losses (%/day)**: Percentage of stored energy lost under steady-state conditions.
- **Response time (s/min)**: Time required for the system to deliver stored heat/cold on demand.
- **Partial load efficiency:** Variation in performance under non-ideal operating conditions.
- **Storage Efficiency relative to Reference Heat Content (η_{Ref}):** Ratio of discharged to charged heat (including auxiliary energy for pumps, heat losses).
- **Storage Efficiency relative to Useful Heat Content (η_{Nutz}):** Ratio of useful discharged energy to charged energy within system conditions.
- **Momentary Power ($\dot{Q}$)**: Instantaneous charging/discharging rate at a given time.
- **Power-dependent Useful Heat Content**: Usable heat depending on the applied charging/discharging power (important for dynamic applications).
- **Storage Utilization Factor (η_N)**: Ratio of useful discharged energy to supplied charging energy over a complete cycle.
- **Heat Transfer Performance:** Especially for indirect TES with heat exchangers; characterizes gradients and exchanger performance.
- **Measurement Parameters:** Standard test setup (ΔT_{Ref}, flow rates, termination criteria, sensor accuracy). Definition of standardised measurement conditions and instrumentation used to characterise TES properties, including reference temperature range (ΔTRef), flow rates, termination criteria, and sensor accuracy. For the purposes of this CWA, measurement parameters shall be associated with either static or dynamic TES properties:
    - Static measurement parameters apply to design-time or laboratory characterisation of TES systems (e.g. nominal capacity, theoretical reference heat content).
    - Dynamic measurement parameters apply to operational monitoring and control within Energy Management Systems (EMS), capturing time-dependent behaviour under real operating conditions.

7.2.6.2 Capacity and System Metrics

- **Energy storage capacity (kWh or MJ)**: Total amount of energy stored.
- **Energy density (kWh/m^3 or kWh/kg)**: Storage per unit volume or mass.
- **Charging/discharging power (kW)**: Average constant charging and discharging capacity at which TES can be charged/discharged.
- **Integration metrics**: Compatibility with solar thermal, CHP, district heating/cooling, and smart grid infrastructures. Assessment of the capability of TES systems to be integrated with solar thermal, CHP, district heating and cooling (DHC), and smart grid infrastructures across multiple integration layers. For the purposes of this CWA, integration shall be considered at Hydraulic/physical; Thermal; Operational; Control and Communication.
- **State of Charge (SoC)**: Representing the current level of stored energy as a percentage of its usable capacity.
- **Theoretical Sensible Storage Capacity**: Calculated heat capacity based on mass and specific heat of all materials within the tank.
- **Theoretical Reference Heat Content**: Heat content the storage could theoretically store over ΔTRef (includes sensible + latent if PCM).
- **Actual Reference Heat Content**: Heat effectively stored and released, measured on a test stand. Considers losses, dead volumes, inhomogeneous temperature distribution.
- **Reduction Factor**: Percentage difference between theoretical and actual reference heat content. Indicates how well the TES reaches its design potential.
- **Useful Heat Content**: Portion of stored energy that is actually usable in the integrated system.

7.2.6.3 Temperature Ranges

- **Reference Temperature Range (ΔT_{Ref}):** Standardised temperature difference used for the characterisation and comparison of TES units under defined testing conditions. ΔTRef is defined by the inlet temperatures during charging and discharging and follows established testing conventions in TES standards and guidelines.
  - Sensible thermal storage: ΔTRef typically in the range of 35–45 K (e.g. 65/25 °C → 40 K), in line with common practice in EN 12977, EN 15316, and VDI 4657 for hot water storage testing.
  - Latent thermal storage (PCM): ΔTRef typically defined as TPh ± 20 K, where TPh is the phase change temperature, reflecting established PCM characterisation practices reported in VDI 4657 extensions and IEA ECES Annex work. In order to achieve efficiency gains when operating with heat pumps, it is recommended to reduce the dT to +-10K.
  - Latent cold storage: ΔTRef typically defined as TPh ± 5 K, consistent with cold storage and cooling system testing practice in EN cooling standards and IEA ECES guidelines.

The reference temperature ranges given above represent commonly adopted testing conventions rather than fixed normative limits. Alternative ΔTRef values may be used, provided they are clearly documented and ensure functional equivalence of the tested thermal service.

- **Useful Temperature Range:** Determined by the actual energy system into which the TES is integrated (based on supply/return conditions).

Annex A
(informative)

Specific data from HYSTORE project

A.1 Properties tables

Table A.1 — Properties of PCM ALL-IN-ONE" Solution:

Properties		Definition	Values
Capacity	Sensible capacity	Total sensible capacity of PCM	0,46 kWh
	Latent capacity	Total latent capacity of PCM	6,53 kWh
	Nominal capacity	Total capacity of TES, including sensible and latent capacity	6,99 kWh
Thermal characteristics	Phase Change Temperature	Temperature at which phase change occurs	58 °C
	Latent Heat of Fusion	Thermal energy required to change the phase of the phase change material	250 kJ/kg
	Thermal Conductivity	Ability of a PCM to propagate heat energy via conduction	0,6 W/(m K)
	Specific Heat Capacity	Amount of heat energy required to raise the temperature of one unit mass of a substance by one degree Celsius (°C) or one Kelvin (K).	2 kJ/(kg K)
	Nucleation temperature	The temperature at which the liquid phase of the PCM, when cooled, begins to solidify or nucleate	56-59 °C
Operational Characteristics	Max. charging power	Maximum power which can be used to charge the unit	3 kW
	Max. discharging power	Maximum power which can be used to discharge the unit	20 kW
	Max. number of cycles	Lifetime of PCMALL-IN-ONE Solution expressed in number of cycles	7 500
Material Types	PCM material	Name of PCM utilised	SP58
	PCM material class	Organic, Inorganic and Eutectic & mixtures	Inorganic

Table A.2 — Properties of the Hystore TCM system

Properties		Definition	Values
Capacity	Volume of TCM	Volume of Sorbent	11 Liters
Thermal characteristics	Charging Heat input	Heating input supplied by thee RF system for desorption	3,5 kW
Operational Characterstics	Operating Temperature	RF system operating temperature	150 °C
Material Types	TCM material	Sorbent	Zeolite 13X
		Sorbate	Water

A.2 Formulae

1) Levelized cost of system

$$LCOS = \frac{\sum_{t=0}^{N} \frac{C_{\text{cap,t}} + C_{\text{O\&M,T}} + C_{\text{rep,t}}}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_{\text{dis,t}}}{(1+r)^t}} \quad (1)$$

where

$$E_{\text{dist,t}} = E_{\text{cap}} \cdot n_{\text{cycles,t}} \cdot \eta_{\text{rt}} \quad (2)$$

$C_{\text{cap,t}}$	is Capital investment cost;
$C_{\text{O\&M,T}}$	is Operation and maintenance cost in year;
$C_{\text{rep,t}}$	is Replacement or refurbishment cost (e.g., PCM degradation, sorbentreplacement) €;
$E_{\text{dis,t}}$	is Useful thermal energy discharged in year;
E_{cap}	is Nominal thermal storage capacity (kWh_{th});
$n_{\text{cycles,t}}$	is Number of full equivalent cycles per year;
η_{rt}	is Round-trip thermal efficiency;
r	is the discount rate.

2) Simple Payback Period:

$$SPP = \frac{C_0}{B_{\mathrm{net,ann}}} \tag{3}$$

$$B_{\mathrm{net,ann}} = p_{\mathrm{th}} \times Q_{\mathrm{use,ann}} - C_{\mathrm{energy,ann}} - C_{\mathrm{O\&M,ann}} \tag{4}$$

where

C_0	is Upfront capital cost (CAPEX) of the thermal storage system (€);
$B_{\mathrm{net,ann}}$	is Net annual benefit (€/kWh);
p_{th}	is Value of useful delivered heat (€/kWh);
$Q_{\mathrm{use,ann}}$	is Useful thermal energy delivered per year;
$C_{\mathrm{energy,ann}}$	is Annual cost of electricity/fuel for charging, pumps, fans, vacuum, etc. (€/kWh);
$C_{\mathrm{O\&M,ann}}$	is Annual O&M cost (€/kWh).

3) Participation in Demand Response (DR) Markets (€/year)

$$R_{\mathrm{DR,ann}} = \sum_{i=1}^{N_{\mathrm{DR}}} \left[P_{\mathrm{DR},i} \cdot E_{\mathrm{shift},i} + I_{\mathrm{DR},i} \right] \tag{5}$$

where

$R_{\mathrm{DR,ann}}$	is Annual revenue or savings from DR participation (€/year);
N_{DR}	is Number of DR events or DR periods per year;
$P_{\mathrm{DR},i}$	is Electricity price difference or avoided peak price during event i (€/kWhe)
$E_{\mathrm{shift},i}$	is Electrical energy shifted or avoided due to TES (kWhe);
$I_{\mathrm{DR}i}$	is Direct incentive or capacity payment for event I (€).

4) Operational Cost Savings (%)

$$\text{Operational Cost Savings (\%)} = \frac{C_{\mathrm{ref}} - C_{\mathrm{TES}}}{C_{\mathrm{ref}}} \times 100 \tag{6}$$

where

C_{ref}	is Annual heating/cooling operating cost without TES (baseline);
$\mathrm{C}_{\mathrm{Tes}}$	is Annual heating/cooling operating cost with TES.

5) Capital Expenditure (CAPEX) vs Operational Expenditure (OPEX)

General CAPEX:

$$CAPEX = C_{\mathrm{storage}} + C_{\mathrm{HX}} + C_{\mathrm{BoP}} + C_{\mathrm{install}} \tag{7}$$

Normalised CAPEX (€/kWh$_{\text{th}}$):

$$CAPEX_{\text{norm}} = \frac{CAPEX}{E_{\text{cap}}} \tag{8}$$

where

C_{storage}	is cost of Thermal Storage medium + Container;
C_{HX}	is Heat exchangers cost;
C_{BoP}	is cost of Balance of plant (pumps, valves, sensors, vacuum system, controls);
C_{install}	is cost of Installation, commissioning, engineering;
E_{cap}	is nominal thermal storage capacity (kWhth).

Annual OPEX:

$$OPEX_{\text{ann}} = C_{\text{O\&M}} + C_{\text{aux}} + C_{\text{rep}} \tag{9}$$

where

$C_{\text{O\&M}}$	is Routine operation and maintenance;
C_{aux}	is Auxiliary energy cost (pumps, fans, vacuum, controls);
C_{rep}	is Replacement/refurbishment cost (PCM or sorbent aging, reactor maintenance).

Normalised OPEX:

$$OPEX_{\text{norm}} = \frac{OPEX_{\text{ann}}}{E_{\text{dis,ann}}} \tag{10}$$

where

$E_{\text{dis,ann}}$	is annual useful thermal energy discharged (kWh$_{\text{th}}$/year).

CAPEX–OPEX Ratio (Comparative KPI):

$$CAPEX\ /\ OPEX\ Ratio = \frac{CAPEX}{OPEX_{\text{ann}}} \tag{11}$$

6) Carbon Footprint Reduction (kg CO$_2$e/year)

$$\Delta CO_{2,\text{ann}} = CO_{2,\text{ref}} - CO_{2,\text{TES}} \tag{12}$$

where

$\Delta CO_{2,\text{ann}}$	is annual CO$_2$-equivalent emission reduction (kg CO$_2$e/year).

Baseline System (No TES):

$$CO_{2,\mathrm{ref}} = \sum_{t=1}^{T} \left(E_{\mathrm{el,t}}^{\mathrm{ref}} \cdot EF_{\mathrm{el,t}} + E_{\mathrm{fuel,t}}^{\mathrm{ref}} \cdot EF_{\mathrm{fuel}} \right) \tag{13}$$

With Thermal Energy Storage:

$$CO_{2,\mathrm{TES}} = \sum_{t=1}^{T} \left(E_{\mathrm{el,t}}^{\mathrm{TES}} \cdot EF_{\mathrm{el,t}} + E_{\mathrm{fuel,t}}^{\mathrm{TES}} \cdot EF_{\mathrm{fuel}} \right) \tag{14}$$

where

E_{el} is Electricity consumption;

E_{fuel} is Fuel consumption (gas, oil, biomass);

EF_{el} is Electricity emission factor (time-dependent or average);

EF_{fuel} is Fuel emission factor;

T is Number of operating periods per year.

7) Renewable Integration (%)

$$\text{Renewable Integration (\%)} = \frac{Q_{\mathrm{RES,use}}}{Q_{\mathrm{tot}}} \times 100 \tag{15}$$

where

$Q_{\mathrm{RES,use}}$ is Useful thermal energy delivered from renewable sources (via TES);

Q_{tot} is Total useful thermal energy demand (heating + cooling).

8) Waste Heat Recovery Potential (kWh/year)

$$Q_{\mathrm{WHR,ann}} = \sum_{t=1}^{T} Q_{\mathrm{WH,avail,t}} \cdot \eta_{\mathrm{cap}} \cdot \eta_{\mathrm{TES}} \tag{16}$$

where

$Q_{\mathrm{WHR,ann}}$ is Annual recoverable waste heat;

$Q_{\mathrm{WH,avail}}$ is Available waste heat at source;

η_{cap} is Heat capture efficiency (heat exchangers, matching losses);

η_{TES} is TES charging + discharging (round-trip) efficiency;

T is Number of operating periods per year.

9) Material Recyclability and Embodied Carbon (%):

$$Recyclability\ (\%) = \frac{\sum_{i=1}^{n} m_i \cdot \eta_{\mathrm{rec},i}}{\sum_{i=1}^{n} m_i} \times 100 \qquad (17)$$

where

m_i	is mass of material i (PCM, sorbent, steel, aluminum, polymers, etc.);
$\eta_{\mathrm{rec},i}$	is Recycling efficiency of material *i*;
n	is Number of material categories.

Total Embodied Carbon (kg. CO_2 e):

$$EC_{\mathrm{tot}} = \sum_{i=1}^{n} m_i \cdot EF_i \qquad (18)$$

where

EF_i is embodied carbon emission factor of material *i* (kg CO_2e/kg).

Normalized Embodied Carbon (kg CO_2e/kWh$_{th}$):

$$EC_{\mathrm{norm}} = \frac{EC_{\mathrm{tot}}}{E_{\mathrm{cap}}} \qquad (19)$$

where

E_{cap} is nominal thermal storage capacity (kWh$_{th}$).

Embodied Carbon Reduction Due to Recyclability (%):

$$EC\ Reduction\,(\%) = \frac{EC_{\mathrm{virgin}} - EC_{\mathrm{recycled}}}{EC_{\mathrm{virgin}}} \times 100 \qquad (20)$$

where

EC_{virgin}	is embodied carbon assuming virgin materials only;
EC_{recycled}	is embodied carbon accounting for recycled content or end-of-life credits.

10) Life Cycle Assessment (LCA):

$$LCA_{\mathrm{tot}} = LCA_{\mathrm{prod}} + LCA_{\mathrm{trans}} + LCA_{\mathrm{install}} + LCA_{\mathrm{use}} + LCA_{\mathrm{EoL}} \qquad (21)$$

where

LCA_{prod}	is Production: PCM/sorbent, reactor, heat exchangers;
LCA_{trans}	is Transport & installation;

LCA_{use} is Use phase: auxiliary electricity, efficiency losses;

LCA_{EoL} is End-of-life (EoL): recycling, disposal, credits.

General LCA Impact Formula:

$$LCA_{\text{impact}} = \sum_{j=1}^{m} \left(\sum_{i=1}^{n} A_{i,j} \cdot CF_{i,j} \right) \tag{22}$$

11) Energy Savings (%):

$$Energy\ Savings\ (\%) = \frac{E_{\text{ref}} - E_{\text{TES}}}{E_{\text{ref}}} \times 100 \tag{23}$$

where

E_{ref} is Annual final energy consumption without TES;

E_{TES} is Annual final energy consumption with TES.

12) Round-Trip Efficiency (%):

$$\eta_{\text{RT}} = \frac{Q_{\text{dis}}}{Q_{\text{chg}}} \times 100 \tag{24}$$

where

Q_{dis} is Useful thermal energy discharged from TES;

Q_{chg} is Thermal energy supplied to charge TES;

η_{RT} is Round-trip efficiency.

13) Thermal Losses (%/day):

$$Thermal\ Losses\ (\%/\text{day}) = \frac{Q_{\text{stored}}(t_0) - Q_{\text{stored}}(t_0 + 24\ \text{h})}{Q_{\text{stored}}(t_0)} \times 100 \tag{25}$$

where

$Q_{\text{stored}}(t)$ is Thermal energy stored at time t;

t_0 is Start of storage period.

14) Response Time (s / min)

$$Response\ time\ t_{\text{resp}} = t\left(Q_{\text{out}} \geq \lambda\, Q_{\text{rated}}\right) - t_{\text{cmd}} \tag{26}$$

where

t is time at which discharge command is issued;

Q_{out} is Delivered thermal power;

Q_{rated} is Rated thermal discharge power;

λ is Acceptance threshold.

15) Partial Load Efficiency (%):

$$\eta_{\text{PL}}\ (x) = \frac{Q_{\text{use}}(x)}{Q_{\text{in}}(x)} \times 100 \tag{27}$$

where

$x = \frac{\dot{Q}}{\dot{Q}_{\text{rated}}}$ = load ratio (0<x<1);

$Q_{\text{use}}\ (x)$ is useful thermal energy delivered at part load;

$Q_{\text{in}}\ (x)$ is thermal (and auxiliary) energy input at part load.

16) Storage Efficiency relative to Reference Heat Content (%):

$$\eta_{\text{Ref}} = \frac{Q_{\text{use}}}{Q_{\text{ref}}} \times 100 \tag{28}$$

where

Q_{use} is Useful thermal energy delivered after storage;

Q_{ref} is Reference heat content of the storage system.

17) Storage Efficiency relative to Useful Heat Content (%)

$$\eta_{\text{Ref}} = \frac{Q_{\text{use}}}{Q_{\text{ref}}} \times 100 \tag{29}$$

where

Q_{use} is Actual useful thermal energy delivered to the load;

Q_{ref} is Useful (deliverable) heat content under operating conditions.

18) Momentary Power ($\dot{Q}$):

$$\dot{Q}(t) = \frac{dQ(t)}{dt} \tag{30}$$

where

$\dot{Q}(t)$ is Momentary thermal power at time;

$Q(t)$ is Stored or delivered thermal energy.

19) Power-Dependent Useful Heat Content:

$$Q_{\mathrm{use}}\left(\dot{Q}\right) = \int_{t_0}^{t_{\mathrm{f}}\left(\dot{Q}\right)} \dot{Q}_{\mathrm{out}}\left(t\right) dt \quad (31)$$

where

$Q_{\mathrm{use}}\left(\dot{Q}\right)$	is Useful heat content available at power level;
$\dot{Q}_{\mathrm{out}}\left(t\right)$	is Instantaneous discharge power;
$t_{\mathrm{f}}\left(\dot{Q}\right)$	is End time of discharge at the specified power level.

20) Storage Utilization Factor:

$$\eta_{\mathrm{N}} = \frac{E_{\mathrm{use,ann}}}{E_{\mathrm{cap}} \cdot N_{\mathrm{max}}} \quad (32)$$

where

$E_{\mathrm{use,ann}}$	is Total useful thermal energy delivered in one year;
E_{cap}	is Nominal usable storage capacity;
N_{max}	is Maximum possible equivalent full cycles per year.

Annex B
(informative)

ETSI SAREF4TESS Implementation Guidelines

A new issue for the project SAREF4TESS was initiated as https://labs.etsi.org/rep/saref/saref-portal/-/issues/114. This issue requested the creation of a dedicated repository saref4tess.

A work item on the extension to SAREF for Thermal Energy Storage Systems Domain was introduced and discussed in meetings convened from 1.07.2025 to 3.07.2025.

The work item was adopted on 2.07.2025.

URL for the SAREF ETSI portal accessible at ETSI Portal ≥ Home

The sources of a SAREF extension SAREF4TESS could be assessed from the ETSI portal through ETSI Labs

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