Comparative Analysis of Heat Storage Systems

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Abstract: - An energy consumption system is always made up of three basic subsystems, starting from the primary energy source, the energy conversion system and the final energy consumption. In addition to these, there are also subsystems for the transport and distribution of energy forms and energy agents, which connect the three basic elements. Certainly, there are always quantitative, qualitative and temporal discrepancies between energy production and consumption. Their elimination is the purpose of energy accumulation. The discrepancies mentioned above are determined mainly by the non-simultaneity between the variations in energy demand, compared to the real possibilities of adaptation to them of the other subsystems, the most important of which is the one that ensures the conversion of primary energy into the form(s) of energy imposed by consumption. In other words, in certain situations, the following question arises regarding the momentary energy demand: what is the share of energy that can be provided by the energy source, compared to the demand and how can the difference be covered? The answer means solving the problem of ensuring peak load, which in very often cases can be solved by using energy storage.

Key-Words: - heat, storage, energy, efficiency, system, accumulation**,** losses.

Received: April 8, 2026. Revised: May 23, 2026. Accepted: June 26, 2026. Published: November 23, 2026.

1 Introduction

From an economic point of view, the use of energy storage facilities can lead to lower investment efforts than the introduction of a classic peaking facility. Also, the costs of the fuel used to produce the accumulated energy can be lower than those related to peaking facilities.

In cases where there are well-defined quantitative and temporal gaps between the energy produced (offered) and the energy consumed (demanded), then storage can also be used to fill load gaps, not only to eliminate peaks. This means applying the "load curve flattening" method, which is a solution currently adopted in energy systems. Also, in the case of facilities that produce several forms of energy simultaneously, such as cogeneration or trigeneration plants, energy storage facilities can harmonize production with the demand for the respective forms of energy, both quantitatively and temporally.

In addition to the rules outlined above, energy storage can also constitute a buffer reserve of energy in case of sudden interruptions in its supply [1].

Taking all this into account, Figure 1 (Appendix) presents the typical case of supply and consumption in the form of electricity and heat. In such a system, storage can be in the form of heat and/or electricity or/and primary energy. Also, in the case of heat, depending on the structure and scope of its transport and distribution system and the nature, size and structure of heat demand, storage can take place at the consumer (AQ1) or at the thermal point (AQ2), in the transport network – through natural storage (AQ3) –, or at the heat source (AQ4). Depending on the nature of the fuel used at the energy source and the set of its preparation facilities, it may be appropriate to store it in appropriate facilities (ACb). On the electricity side, accumulation can be achieved at the level of the transmission system (AE) and/or the consumption system (less often).

Regarding the form of accumulated energy, it can be entirely in the form of heat and/or mechanical. In the case of a thermal agent transport network, the accumulation can be in the form of heat (thermal flywheel effect), pneumatic (in the case of compressed air) or hydraulic. For consumption in the form of electrical energy, the accumulation is direct, electrochemical, electromagnetic or through electrical capacitors (AE – according to Figure 1, Appendix). The accumulation of energy at the level of final consumers can be thermal, electrochemical or mechanical [1].

2 Heat Storage, Principle and Implementation Solutions

Heat storage (HS) is a physical or chemical process that takes place in a battery. From a time perspective, the storage process is characterized by two distinct periods: charging and discharging.

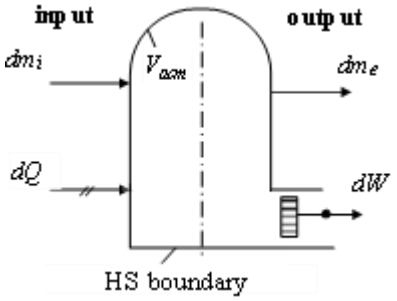


Fig. 2: HS energy balance
Source: [1]

As a device, the heat accumulator consists of a container, the storage medium, the charging and discharging mechanisms and other auxiliary elements, [2].

The storage system is defined – from case to case – by the way in which the energy required to charge the accumulator is taken from the energy source and the way in which the energy available by discharging the accumulator is finally transferred into the required energy form.

2.1 The Principle of Thermal Energy Accumulation

For the considered contour of heat storage, shown in Figure. 2, the basic equation of energy conservation is given by:

$$W_i - W_e = W_a \qquad \text{[kW]} \qquad (1)$$

where W_i, W_e are energy input and energy output from HS, Wa – storage energy

Applying the First Law of Thermodynamics to the considered control volume, the "general equation of energy accumulation" for an open system leads to the general expression [2]:

$$(u + p\cdot v + g\cdot H + c^2/2)_i \cdot dm_i + dQ -$$

$$-(u + p\cdot v + g\cdot H + c^2/2)_e \cdot dm_e - dW = d[(h + g\cdot H + c^2/2)_a \cdot m_a] \qquad (2)$$

where: u is the specific internal energy (referred to an arbitrarily chosen reference level);
p – pressure; v – specific volume; m – the specific flow energy of the mass entering or leaving the system ("flow work"); g – gravitational acceleration; H– height (relative to a reference level); c – velocity; dQ– heat flux transferred through mass transfer (+ meaning heat entering the system); dW – mechanical work produced by the system, independent of mass transfer; m_a – mass of the "medium" used for energy storage in the accumulator, h - *e*nthalp*y*.

Analyzing the general equation (2), it follows that stored energy can be exchanged with the surroundings in the form of internal, potential, kinetic, or mass-related energy, [3].

In general, the use of internal energy is specific to thermal energy storage, as is the case for mass-related energy, characterized by the fact that the internal energy is higher than that of the ambient environment.

In what follows, the definition of stored thermal energy will also include mass energy, even if the internal energy level is low, provided that the exergy content (usable energy) is high due to the state of the storage medium. These applications are used, for example, in compressed gas (air) storage systems, which have a high exergy level even if their temperature indicates a negligible internal energy content. It is evident that such an energy storage system is used only for storing mechanical work, whereas heat storage is used both for producing mechanical work and for supplying heat.

If the two accumulated forms of energy — kinetic and potential — are neglected, and if, in addition, the kinetic and potential energy terms of the entering/exiting mass are also neglected, while the mechanical work exchanged at the boundary is considered, then:

$$dW == p_a \cdot dV_a \qquad (3)$$

where V_a is the volume change of the accumulator and is the storage pressure.

Under these conditions, relation (2) takes the useful form for thermal energy storage:

$$(u + p\cdot v)_i \cdot dm_i + dQ - (u + p\cdot v)_e \cdot dm_e = d(u\cdot m)_a + p_a \cdot V_a \qquad (4)$$

Using the definition of enthalpy, the thermal balance equation becomes:

$$h_i \cdot dm_i + dQ - h_e \cdot dm_e = d(u\cdot m)_a + p_a \cdot V_a \qquad (5)$$

and the mass balance for the considered control volume is:

$$dm_i - dm_e = dm_a \qquad (6)$$

The charging and discharging processes and energy

and mass balances are generally described by previous equations, [4].

2.2 Types of Thermal Energy Storage (TES)

Taking into account the definitions and equations presented, the following types of thermal energy storage (TES) can be distinguished:

a) According to the type of storage medium and the mode of heat transfer, heat accumulation can occur in four variants:

a.1) Direct storage:

The accumulation of the working medium and the heat transferred from it occur simultaneously.

The storage medium may be solid, liquid in two phases (liquid plus vapor), or gaseous [5].

a.2) Indirect storage:

Thermal energy is transferred either solely through heat transfer (e.g., conduction through the vessel wall) or through an intermediate heat-transfer medium (liquid, two‑phase, or gaseous).

The storage medium may be solid, liquid, or gas, without phase change, or with any phase change: solid/solid, solid/liquid, or liquid/vapor.

a.3) Semi-direct storage:

Similar to case (a.2), except that the heat-transfer medium itself has a significant storage capacity (e.g., storage of hot oil).

a.4) Adsorption storage:

Based on the ability of certain working media to absorb gases and thereby release heat.

Heat transfer may be direct or through a gaseous medium.

b) According to the variation of the stored medium's mass during the storage process:

b.1) Constant mass content ($dm_a = 0$)

Typical for indirect storage.

However, it may also occur in direct storage if the mass released during cooling (discharging) or heating (charging) is completely returned to the accumulator (characteristic of systems with storage capacity).

b.2) Variable mass content ($dm_a \neq 0$)

Generally the case for direct storage.

c) According to the variation of storage volume:

c.1) Constant volume ($dV_a = 0$)

Applies to closed storage vessels (at least approximately).

c.2) Variable volume ($dV_a = \neq 0$)

Occurs in storage at ambient pressure or when special equipment is used to maintain pressure.

d) According to the variation of storage pressure:

d.1) Constant pressure ($dp_a = 0$)

d.2) Variable (sliding) pressure ($dp_a \neq 0$)

3 Types of Heat Storage

Analyzing the general equation (2), it follows that the stored energy can be exchanged with the surroundings in the form of internal, potential, kinetic, or mass-related energy.

3.1 Sensible Heat Storage of Saturated Fluid

The storage medium is almost exclusively water/steam.

In this case, the lower part of the accumulator contains the liquid phase, while the upper part contains vapor; the liquid and vapor are in thermodynamic equilibrium at the saturation temperature.

The accumulator vessel may contain a small amount of liquid or may be completely filled with liquid.

Figure 3 shows all possible charging/discharging configurations for such a system.

During discharge, the system can supply either saturated steam (through pipe 4) or superheated steam (5), via the pressure‑reducing valve (RP).

It can also supply hot water (7), or only heat, via the heat exchanger (6).

In the latter case, the amount of stored "mass" remains constant (indirect storage at variable pressure).

Charging can be performed by introducing hot water (10) at saturation, which condenses the charging steam (11), or by supplying additional heat through heat exchanger (9), or by expanding steam introduced through (8) into the water section (12).

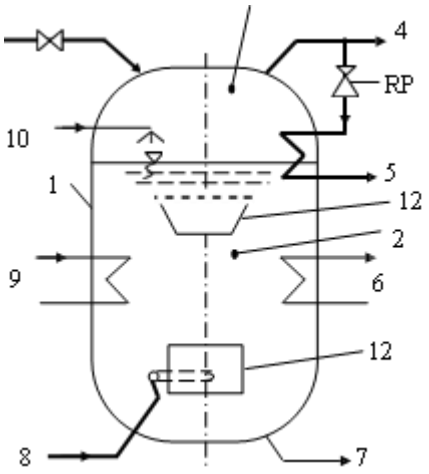


Fig. 3: Variable-pressure accumulator
1 – pressure vessel; 2 – water content; 3 – steam cushion; 4 – saturated steam discharge; 5 – superheated steam discharge; 6 – heat‑exchange surface for discharge; 7 – hot‑water discharge; 8 – steam charging; 9 – heat‑exchange surface for charging; 10 – hot‑water charging; 11 – steam charging for heating; 12 – internal elements; RP – pressure‑reducing valve
Source: [1]

The defining characteristic of this storage system is the variation of internal pressure during charging and discharging.

The accumulator may operate with:
a) Direct heating at variable pressure
In this case, approximately 75–95% of the vessel volume is occupied by saturated water, and the remaining 5–25% by the steam cushion.
This type of accumulator is known as a Ruths accumulator, named after its inventor, who introduced it in 1920 for both industrial applications and steam power plants.

Advantages include:
• technical simplicity
• relatively low cost
• direct production of steam
• steam-based charging

Charging can also be performed through the heat-exchange surface (9), using steam at a higher temperature than the liquid in the vessel.

This occurs through condensation of high-pressure saturated steam or cooling of superheated steam to the required temperature.

Discharging always involves a significant pressure drop, while charging corresponds to a pressure increase.

b) Indirect heating at variable pressure

Here, the storage medium is inside a closed accumulator vessel.

Storage is indirect, at constant volume and mass.

Charging and discharging occur through heat transfer to and from the heat‑exchange surfaces (6) and (9) — as shown in Figure 3 — heating and cooling the storage medium.

3.2 Sensible Heat Storage of Pressurized (Subcooled) Liquids

This process takes place by maintaining the pressure above the saturation value, or by keeping the temperature below the saturation temperature, thereby preventing the boiling of the liquid used as the heat-storage medium (Figure 4).

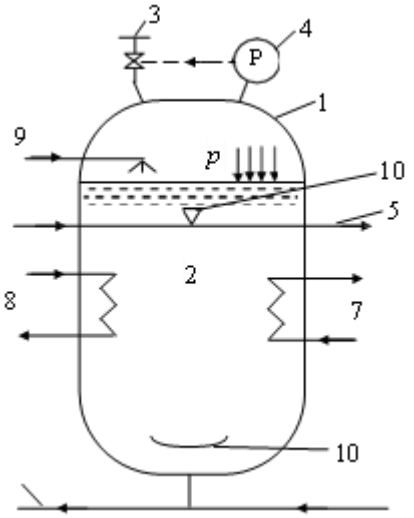


Fig. 4: Constant-pressure heat storage
1 – accumulator vessel; 2 – storage medium in liquid state; 3 – overpressure-maintaining system (p); 4 – manometer; 5 – upper charging level / beginning of discharge; 6 – lower discharge level / beginning of charging; 7 – heat-exchange surface for discharge; 8 – heat-exchange surface for charging; 9 – pipe for charging with hot water; 10 – internal level-control elements.
Source: [1]

Overpressure may be ensured externally (for storing hot water below 100 °C or for superheated fluids), using inert gases, or by implementing two-phase pressurization: maintaining pressure in the steam cushion by evacuating part of the liquid, or by condensing part of the steam.

The storage capacity is based solely on the fraction of sensible heat content that can be absorbed. Consequently, this type of storage relies

exclusively on the liquid phase of the working medium.

From the perspective of the storage medium, most of these accumulators use subcooled liquids, and less frequently liquids at saturation. Table 1 (Appendix) presents the thermal characteristics of the liquid media most used in such accumulators. The operating temperature of liquid media generally lies between their melting and boiling points [6].

In the case of liquids that exhibit high viscosity at low temperatures (such as oils), the minimum operating temperature is close to the melting point; its value may also be constrained by the power limits of the pump responsible for maintaining the required pressure of the respective liquid [7].

From Table 1 (Appendix) it follows that water and aqueous solutions have the highest volumetric specific heat capacities, making them recommended media because they reduce the required volume of the storage vessel. However, the use of water as a liquid working medium requires the presence of a minimum pressure in the heat‑storage tank corresponding to temperatures of approximately 100 °C.

From this perspective, using aqueous solutions such as sodium hydroxide (NaOH) allows operation at higher temperatures, around 130–150 °C, without the need for pressurized storage vessels, as is necessary when using water at temperatures around 100 °C. Another working medium is the eutectic mixture of molten salts, which, in addition to having a relatively high volumetric heat capacity, is recommended because it prevents solidification (freezing).

3.3 Sensible Heat Storage in Solid Media

From Table 1 (Appendix) it follows that water and aqueous solutions have the highest volumetric specific heat capacities, making them recommended media because they reduce the required volume of the storage vessel. However, the use of water as a liquid working medium requires the presence of a minimum pressure in the heat-storage tank corresponding to temperatures of approximately 100 °C.

This type of storage is based on the absorption of heat by solid bodies that are heated or cooled without undergoing a change in their state of aggregation. The portion of sensible enthalpy contained in these media determines their storage capacity.

In terms of configuration, these accumulators are similar to those using liquids. Heat transfer from the solid working medium can occur either outside the accumulator—using a "packed bed" of stones—or inside the accumulator, through an auxiliary fluid (liquid or gas). In the latter case, the pressure at which heat transfer occurs determines the design and sizing of the accumulator.

If the heat-storage medium is in solid form, the thermocline effect can be achieved relatively easily. The storage vessel is cylindrical, with upward axial flow of the heat-transfer agent, as shown in Figure 5a.

Heat transfer from the solid medium to the liquid or gaseous heat-transfer agent is based on the presence of short channels that allow conductive heat transfer, a sufficiently large heat‑exchange surface, and a low thermal conductivity in the axial direction.

The temperature distribution along the accumulator during charging and discharging is shown in Figure 5b and Figure 5c.

In Figure 5b, the heat-exchange surface and the overall heat-transfer coefficient have relatively low values compared to the flow rate, whereas in Figure 5c the opposite is true (typical of a stone bed). In both cases, heat transfer occurs axially, which flattens the temperature curves.

In case (c), a transition zone is formed, which moves upward during charging and downward during discharging, following the movement of the mixing zone of the working fluid along the vessel. The outlet temperature remains practically constant until nearly the end of the discharge process.

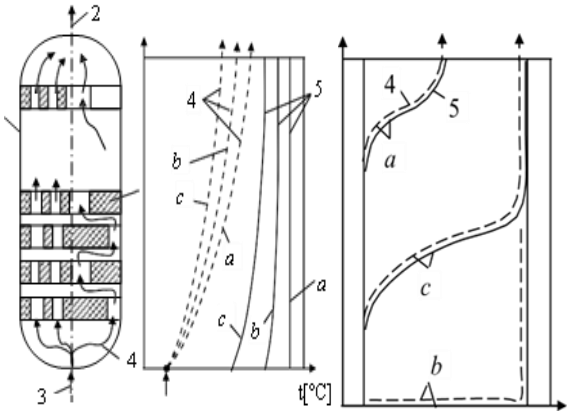


Fig. 5: Sensible heat storage using a solid medium
a – position of the solid heat-storage medium;
b – temperature variation during discharge – low heat-transfer rate and high flow velocity;
c – temperature variation during discharge – good heat transfer and low flow velocity;
1 – storage vessel; 2 – discharge; 3 – charging; 4 – heat-transfer agent (medium); 5 – solid heat-storage medium; a – fully charged; b – 50% charged; c – empty.
Source: [1]

Naturally, the thermal capacity of the heat-transfer agent inside the heat-storage system adds to the thermal capacity of the solid medium, thereby increasing the total thermal-storage capacity.

However, it must be noted that due to the flow of the working fluid through the entire system, additional pressure losses occur, and heat transfer takes place only in the immediate vicinity of the transition zone—an aspect that may be considered a disadvantage of this system.

3.4 Solid Media for Heat Storage

Table 2 (Appendix) presents the main properties of solid media used for heat storage. In general, these materials are characterized by a high volumetric specific heat over the temperature range in which they operate. It can be observed that among metals, cast iron has the highest heat-storage capacity. Among non‑metals, fireclay (chamotte) also exhibits good heat capacity, although it has relatively low thermal conductivity.

Aluminum oxide (Al_2O_3) and magnesium oxide (MgO) also have high heat capacities. Considering the ratio between heat-storage capacity and cost, magnesium oxide can be regarded as the most advantageous solid medium for heat storage. Sintered iron oxide, shaped into bricks, is likewise an effective storage material.

3.5 Latent Heat Storage

This type of storage is based on the ability to store heat during a phase change of the storage medium at constant temperature. From this perspective, the transition from liquid to vapor allows the use of the highest latent heat. However, because the volumetric storage capacity of the gaseous phase is low, latent heat storage in practice refers mainly to the storage of heat of fusion.

In some cases, combinations of solid–liquid and solid–solid phase changes occur at temperatures close to the melting point.

Despite their theoretical advantages, latent heat storage systems have seen limited development. Although they offer high heat-storage capacity and constant temperatures at low pressures, several challenges remain:

- achieving efficient heat transfer between the storage medium and the working fluid;
- the temperature levels that can be reached and the need for a controlled atmosphere;
- the cost of heat exchangers.

When selecting a medium for latent heat storage, the following important characteristics must be considered:

- low cost;
- high latent heat and high density;
- reasonable melting temperature;
- high thermal conductivity in both solid and liquid phases (for intensive heat transfer);
- high specific heat in both phases;
- no tendency toward segregation; good thermal stability
- absence of super cooling during freezing and of supersaturation during melting;
- low thermal expansion (minimal volume change during melting);
- low corrosiveness (to allow the use of inexpensive vessel materials);
- low risk (no harmful vapors, no dangerous reactions). the working fluid or heat-transfer medium)

Table 3 (Appendix) presents the basic thermal characteristics of latent heat-storage media. These are mainly of two types: pure substances and binary systems.

For pure substances, the main properties are the melting capacity in the liquid phase and the storage capacity in the solid phase, which characterize the sensible heat storage; the thermal conductivity, which determines the heat-transfer performance—especially during discharge; as well as corrosion behavior and density changes, which influence the design and material selection of the storage vessel.

Regarding binary systems used for latent heat storage, their main advantages include favorable melting points, high energy densities at low melting temperatures, and the possibility of combining substances with high but expensive storage capacities with cheaper ones, without significantly reducing the overall storage capacity of the mixture. Their use requires that the mixture freeze and melt homogeneously, [8].

The main difficulty in latent heat storage lies in transferring heat into the storage unit during charging and then extracting it during discharge. This is due to the low thermal conductivity and convection, as well as volume changes.

The storage capacity in latent heat systems is determined considering that the process occurs at constant pressure and constant mass of the system. Consequently, the enthalpy increase of the solid/liquid system from temperature T1 < Tt (where Tt is the melting temperature) to T2 > Tt is given by:

$$\Delta h = [c_{p\cdot s} \cdot (T_t - T_1)] + \Delta h_t + [c_{p\cdot l} \cdot (T_2 - T_t)] \text{ [kJ/kg]} \quad (7)$$

where:

- $c_{p\cdot s,}\ c_{p\cdot l}$ – specific heat of the solid and liquid

phases (at constant pressure), in kJ/kg·K;
• Δh_t – enthalpy exchanged during the phase change, in kJ/kg.

In equation (7), the first term corresponds to the sensible heat absorbed in the solid phase, the second term represents the latent heat, and the third term corresponds to the sensible heat in the liquid phase.

For pure substances, it can be approximated that for organic substances $\Delta h_t \cong 0{,}7 \cdot T_t$ or $\rho \cdot \Delta h_t \cong \rho \cdot 0{,}7 \cdot T_t$ and for pure substances, it is observed that water/ice, salts, and metals (such as LiF) have the highest latent heats of fusion. Lithium hydroxide (LiOH) is also very effective. Salts have low thermal conductivity and relatively low volumetric heat capacities. In contrast, metals have high thermal conductivity, and some also have high specific heats, resulting in high energy density.

Binary systems are characterized mainly by the following advantages: suitable melting temperatures, high energy densities even at low melting temperatures, and the possibility of combining expensive but high‑capacity substances with cheaper ones without significantly altering the storage capacity.

A fundamental requirement for binary systems is that they freeze and melt homogeneously, which occurs for two special compositions: eutectic and disectic.

Note:
– Eutectic composition corresponds to the minimum point on the melting diagram.
– Disectic composition is a stoichiometric mixture that forms a mixed phase and behaves almost like a pure substance.

3.6 Storage of Gases under Pressure

Unlike steam-cushion storage systems, compressed-gas storage uses the gas itself as the storage medium, belonging to the category of storage methods without phase change. There is no separation phase, since the gas remains in the same state during discharge and storage. The system consists of a standard pressure vessel, with or without thermal insulation (most commonly without). If air or moist gas is used, the water removed during drying is discharged to the drain.

Industrial applications of this type of storage—often involving many cubic meters of compressed air—are typical for gas-turbine power plants, where it is used to smooth pressure fluctuations or to handle peak loads.

In practice, discharge is neither perfectly adiabatic nor perfectly isothermal. Some heat is always added—for example, from the thermal capacity of the pressure vessel—but not enough to prevent temperature drop entirely. In such cases, storage capacity can be evaluated similarly to sliding-pressure storage, using relation.

The heat-storage capacity in this case is negligible. Therefore, compressed-air storage is not suitable for heat storage, but rather for storing electrical energy produced by power plants equipped with gas turbines. In such applications, the accumulator is placed upstream of the combustion chamber or the hot-air boiler. For capacity reasons, the storage process is intentionally carried out mainly at low temperatures.

3.7 Other Heat-Storage Systems

Aside from temperature variations and/or phase changes, the mandatory transfer of energy between two or more storage media also makes it possible to use reversible physico-chemical reactions for heat storage. If the reaction heat can be stored in the liquid phase, this method allows the achievement of very high energy densities. Such systems eliminate the additional heat losses caused by imperfect thermal insulation, which occur in sensible or latent heat storage. For this reason, these storage systems are recommended for long-term heat storage.

Considering both the possibilities and the limitations involved, two variants emerge for this type of heat storage: sorption processes and thermochemical processes, [9].

• Heat Storage by Sorption Processes
Some of these systems are based on the following reaction model:
AB (solid or liquid) + $\Delta Q \rightleftarrows$ *A* (solid or liquid) + *B* (vapour); substance A may be an element, a component, or a mixture.

The reaction heat (at atmospheric pressure) is approximately:

$$\Delta h_s = (125 \div 150) \cdot T_s / M_B$$

Δh_s – sorption enthalpy, T_s – sorption temperature (K), M_B – molecular mass of component B (kmol/kg).

In general, is higher than the heat of fusion or vaporization. In any case, the mass of component A also plays an important role.

Figure 6 (Appendix) shows four basic schemes for reaction-based heat-storage systems.

In Figure 6a (Appendix), heat is introduced into the absorbent medium (e.g., $CaCl_2$), while the adsorbate (NH_3) is sent to the gas-storage reservoir,

which operates at constant or sliding pressure. Cooling the gas increases the storage capacity. The energy density is low.

If the gas can be condensed at a temperature close to ambient, the scheme in Figure 6b (Appendix) can be applied. In this case, the condensation heat is absorbed by the working medium. During discharge, the liquid working medium vaporizes, absorbing heat at ambient temperature. This scheme is similar to a refrigeration system, in which the absorbent (working fluid) is alternately heated and cooled: during heating, heat is absorbed in the condenser; during cooling, the pressure drops and the condensate in the evaporator begins to boil.

In the scheme shown in Figure 6c (Appendix), storage of the working medium in liquid form is replaced by storage through adsorption, including an additional absorber that performs absorption and desorption at ambient temperature.

The scheme in Figure 6d (Appendix) combines adsorption-based storage with a steam turbine: when valve (5) is opened, steam from the boiler enters the turbine and then reaches the accumulator. Charging is performed with a steam compressor, following the principle of a heat-pump compressor or an absorption heat-pump cycle.

The energy density refers to the storage of the medium used for desorption in the gaseous state, corresponding to Figure 6a (Appendix), and in the liquid state, corresponding to Figure 6.b (Appendix).

• Thermochemical Storage

Thermochemical storage consists of storing heat produced by reversible chemical reactions, which may occur with or without the presence of a catalyst. After the reaction, the reactants are separated and stored individually—according to the scheme in Figure 6.c (Appendix). Charging reactions proceed from right to left (from vessel (12) toward (1)). The reaction products are gaseous. If one of the reaction products is stored in the liquid phase, a high energy density can be achieved.

4 Conclusion

A comparative analysis of various heat-storage methods considers the following aspects:

• energy density of the storage media, in MJ/m³
• exergy density of the storage media, in MJ/m³
• energy efficiency of heat storage — the energy losses associated with the storage process and the storage installation

The energy density decreases significantly as the temperature of the storage medium decreases. It can be observed that oils can be used above approximately 350 °C, while molten salts are suitable up to around the same temperature, [10].

It also follows that latent-heat storage leads to a higher energy density than sensible-heat storage. Some media exhibit very high energy densities (e.g., lithium salts and eutectic mixtures of fluorinated compounds).

Among solid storage media, cast iron has the highest energy density.

Exergy leads to the same qualitative conclusions as in the case of energy density of the storage media. In addition, when air is used as the storage medium, it is evident that the exergy density is much lower than in the case of hot water.

• Pressurized storage systems

In this case, the energy density depends strongly on the saturation pressure of the working medium compared to atmospheric pressure. A clear difference appears between the energy-density values for hot water and those for sliding-pressure steam.

The slopes of the curves are strongly regressive in the case of steam and much smaller for hot water, especially at high pressures.

In practice, however, energy losses occur due to heat dissipation during the standby period and due to heat-transfer processes during charging and discharging. These losses ultimately determine the efficiency factor of the storage system, defined as the ratio between the exergy available at discharge and the exergy supplied during charging to restore the initial conditions, [11].

In special cases (for example, when heat is stored outside the reference installation used for power generation), the efficiency factor may be defined as the ratio of enthalpies (energies), known as the thermal efficiency factor of the storage system.

Standby losses occur in the interval between the charging and discharging phases and differ depending on the type of heat storage: sensible, latent, or thermochemical.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and

responsibility for the accuracy, integrity, and final content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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APPENDIX

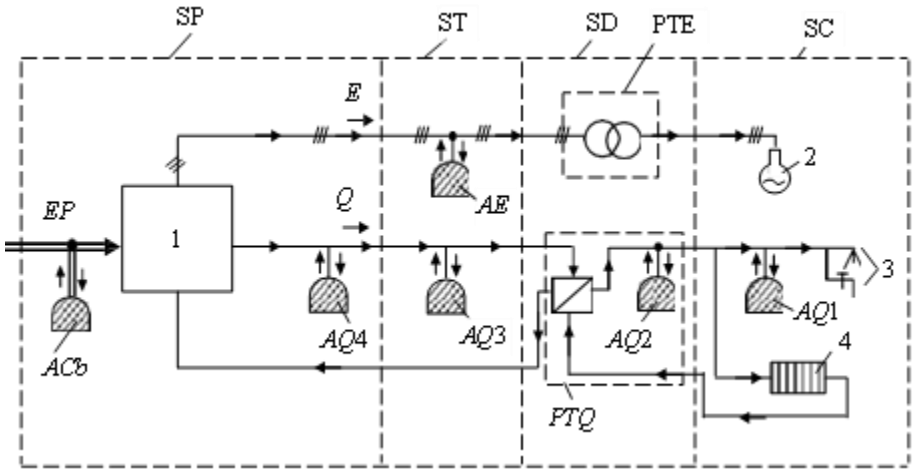


Fig. 1: Schematic diagram of the possibilities of energy accumulation in the various subassemblies of a heat and electricity supply system: SP - energy production system; ST - energy transport system; SD - energy distribution system; SC - energy consumption system; PTE - electrical energy transformation point; PTC - heat transformation point (thermal point); ACb, AQ, AE - energy accumulators, in the form of fuel, heat and electrical energy; E - electrical energy; Q - heat; EP - primary energy (fuel); 1 - energy production source (heat and/or electrical energy); 2 - electrical energy consumers; 3, 4 - heat consumers in the form of hot water for consumption and heating

Source: [1]

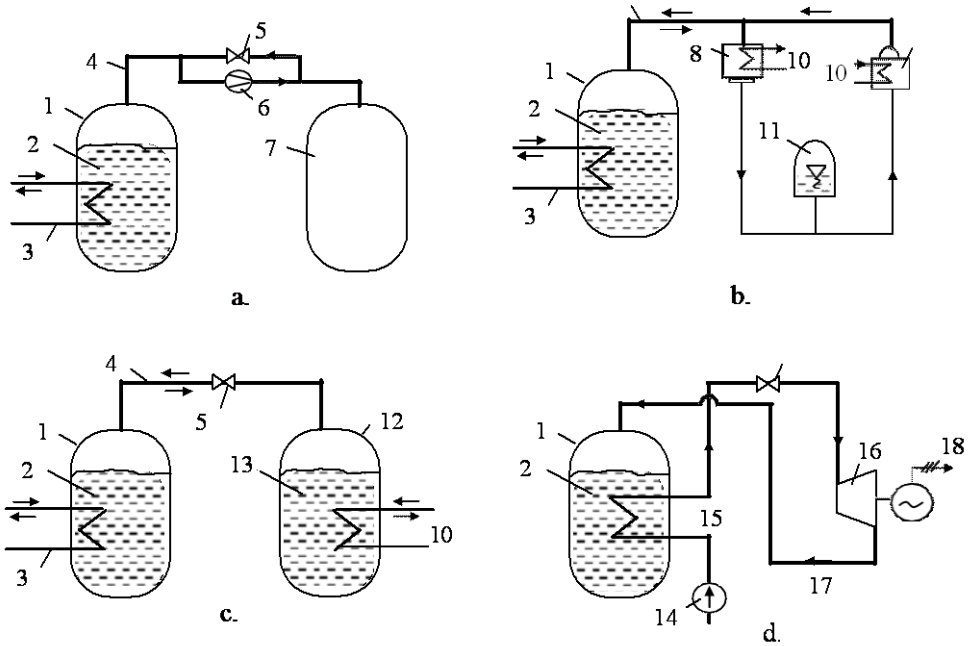


Figure 6 – Basic schemes for reaction-heat storage:
a – with gas storage; b – with condensate storage; c – resorption cycle; d – with steam boiler and steam turbine.And 1 – absorber; 2 – absorbent medium;3 – heat exchanger for "charging/discharging" heat;4 – gas pipeline;5 – pressure reducer;6 – compressor;7 – gas storage;8 – condenser;9 – evaporator;10 – low-temperature (low-exergy) heat source;11 – condensate storage;12 – resorption vessel;13 – resorbent medium;14 – feed pump;15 – steam boiler;16 – steam turbine;17 – exhaust steam;18 – electric power.

Source: [1]

Table 1. Thermal Characteristics of Liquid Media Used for Heat Storage

Medium/ composition	**Temperature (°C)**				**Density (kg/m³)**		**Specific heat c,(kJ/kg·K)**	**Specifiv volumetric heat (c_v)**		**Wall Material**
	melting (t_t)	**high limit (t_m)**	**low limit (t_M)**	**boiling (t_f)**	**at (t_m)**	**at (t_M)**		**kJ/m³·K**	**kWh/m³·K**	
1	2	3	4	5	6	7	8	9	10	11
a) **water** 1bar	0	0	100	100	1000	958	4,19	4010	1,12	OL
a) **water** 10bar	0	0	180	180	1000	881	4,19	3690	1,03	OL
a) **water** 100bar	0	0	311	311	1005	688	4,19	2950	0,82	OL
b) 50H_2O/50Ethylen- glicol	-36	0	100	-	1075	1015	3,48	3530	0,98	-
Ethylenglicol	-13	0	100	197	1130	-	2,50	2700	0,75	-
c) 50NaOH/50H_2O	-	20	140	140	1550	-	3,27	5060	1,4	-
d) **oil** for heat transfer: - petrochimic (mediu)	-20	-	-	300	900	750	2,4	1800	0,5	OL
- sintetic (obişnuit)	-70/ -10	-	200/350	230/410	1000	750	2,1	1600	0,44	OL
e) melted salt 53HnO3/40NaNo2/ 7NaNO3	142	-	450	-	1970	1725	1,3	2300	0,64	OL
f) liquid metals: Na	98	-	-	880	925	750	1,26	945	0,26	OLA
K	63	-	-	760	830	660	0,77	508	0,14	-

Source: created by the author

Table 2. Thermal Characteristics of Solid Heat-Storage Media

Solid state	**Melting temperature t_p (°C)**	**Density ρ (kg/m³)**	**Specific heat c (kJ/kg·K)**	**Specific volumetric heat**		**Thermal conductivity, λ (W/m·K)**
				ρ·c (kJ/m³·K)	**(kWh/m³·K)**	
a) **metals**:						
- OL	1510	7850	0,46	3615	1,00	50
- fontă turnată	1150-1300	7200	0,54 (2	3920	1,09	42
- cupru	1083	8960	0,39	3190	0,97	395
- aluminiu	660	2700	0,92	2490	0,69	200
b) **non-metals**						
- fire clay	-	2100-2600	1,0	2350	0,65	1,0-1,5
- Al_2O_3 (90%)	1700	3000	1,0	3000	0,83	2,5
- MgO (90%)	1700	3000	1,0	3000	0,83	4,5-6
- stone	-	1900-2600	0,8-0,9	1600-2300	0,44-0,64	1,5-5,0

Source: created by the author

Table 3. Thermal data characteristic of the media used for latent heat accumulation

Composition	**Melting temp. (t_t) [°C]**	**Density (kg/m^3)**		**Melting heat temperature Δh_t [kJ/kg]**	**Specific heat [kJ/kg·K]**		**Conducti-vity λs [W/m·K]**	**Storage container material**	**Degree of risk**
		ρ_s	ρ_l		c_s	c_l			
a) **Pure substances**									
- H_2O	0	917	1000	335	2,1	4,2	2,2	P	0
- $LiNO_3$	252	2310	1776	530	2,025	2,04	1,35	OL·AU	-
- NaOH	318	2130	1780	160	2,01	2,09	0,92	OL·SA	2
- LiOH	471	1425	1385	1080	3,3	3,9	1,30	OL·AU	2
- Al	660	2560	2370	400	0,92	-	200	-	-
- Li_2CO_3	726	2114	1810	607	-	-	1,45	OL·AU	-
- LiF	848	-	-	1050	-	-	-	OL·AU	-
b) **Binary mixtures**									
48NaCl/52MgCl	450	2225	1610	431	0,92	1,0	-	OL·AU	2
33NaCl/67$CaCl_2$	500	2160	1900	282	0,84	1,0	-	OL·AU	1
35Li2CO_3/65K_2CO_3	505	2265	1960	345	1,34	1,76	2,18	OL·AU	2
88Al/12Si	579	2553	2445	515	1,49	1,27	high	-	-
67LiF/33MgF_2	741	-	-	900	-	-	-	OL·AU	-
67NaF/33MgF_2	832	2690	2190	618	1,42	1,38	4-12	OL·AU	3
c) **Ternary mixtures**		-						-	-
24,5Nacl/20,5KCl/ 55MgCl2	385-	2300	1800	410			1,0	OL·AU	2
32Li_2CO_3/35K CO_3/ 33Na_2CO_3	393 397		2140	277			-		

Source: created by the author