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Option : Renewable Energy and Environment

Chapter 4: Solar energy storage

IV.1 Introduction:

Solar energy, although abundant and free, is intermittent and varies with the time of day, the season, and weather conditions. To ensure the continuous operation of solar thermal systems (heating, drying, electricity generation, etc.), it is necessary to store the energy captured during sunny periods so it can be delivered later. Solar energy storage therefore aims to:

- Improve system reliability,
- Reduce production discontinuity,
- Optimize energy use,
- Increase the overall efficiency of the solar device.

IV.2 Energy Storage System (Heat Accumulator)

An energy storage system (or heat accumulator) is a system that can be charged (1) to store energy (2) for a certain period, and later discharged (3) to release this energy (Figure 1). It plays an essential role in:

- solar thermal systems,
- domestic heating,
- industrial processes,
- concentrated solar power plants,
- solar dryers or thermal furnaces.

The selection of a heat accumulator depends on its thermal, physical, chemical, and economic character:

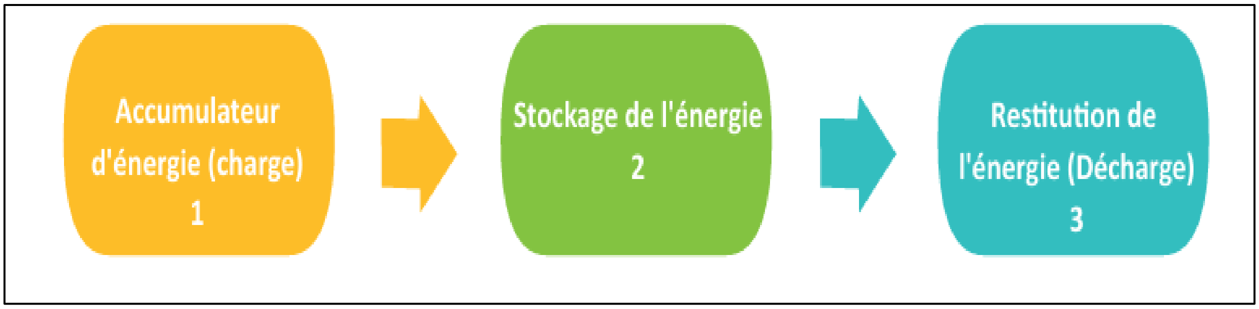

Figure 1 : Block Diagram of Charging/Discharging in an Energy Storage System

IV.3 Classification of Storage Systems

Solar energy can be stored in different forms, as shown in Table 1:

Type of Storage	Principle	Example
Thermal – energy stored as heat/cold	Storage of heat in a material	Water heating, molten salts
Chemical	Reversible chemical reactions	Hydrogen, endothermic reactions
Electrical	Conversion and storage in the form of electricity	Batteries, supercapacitors
Mechanical	Storage of mechanical energy	Flywheel, compressed air

In the case of solar thermal energy, heat storage is the most widely used.

IV.3.1 Thermal Storage

Once thermal energy is collected by solar collectors (flat-plate, parabolic, hyperbolic, or mirror-based), it must be efficiently stored for later use. This is why it is important to design an efficient energy storage system. Several parameters influence the effectiveness of heat storage systems. The main aspects that must be considered when designing such a system are the technical properties of the storage system and its cost-effectiveness.

Thermal Energy Storage (TES) is defined as the temporary storage of energy through heating or cooling, so that the stored energy can later be used for electricity generation or for heating or cooling applications.

Thermal storage applications differ according to their useful temperature level (high-, medium-, or low-temperature storage), their storage duration (short-term or seasonal storage), and the thermodynamic principle governing the storage process (sensible heat storage, latent heat storage, and thermochemical storage).

Figure 2 provides an overview of these storage modes as well as the main storage materials used in thermal energy storage.

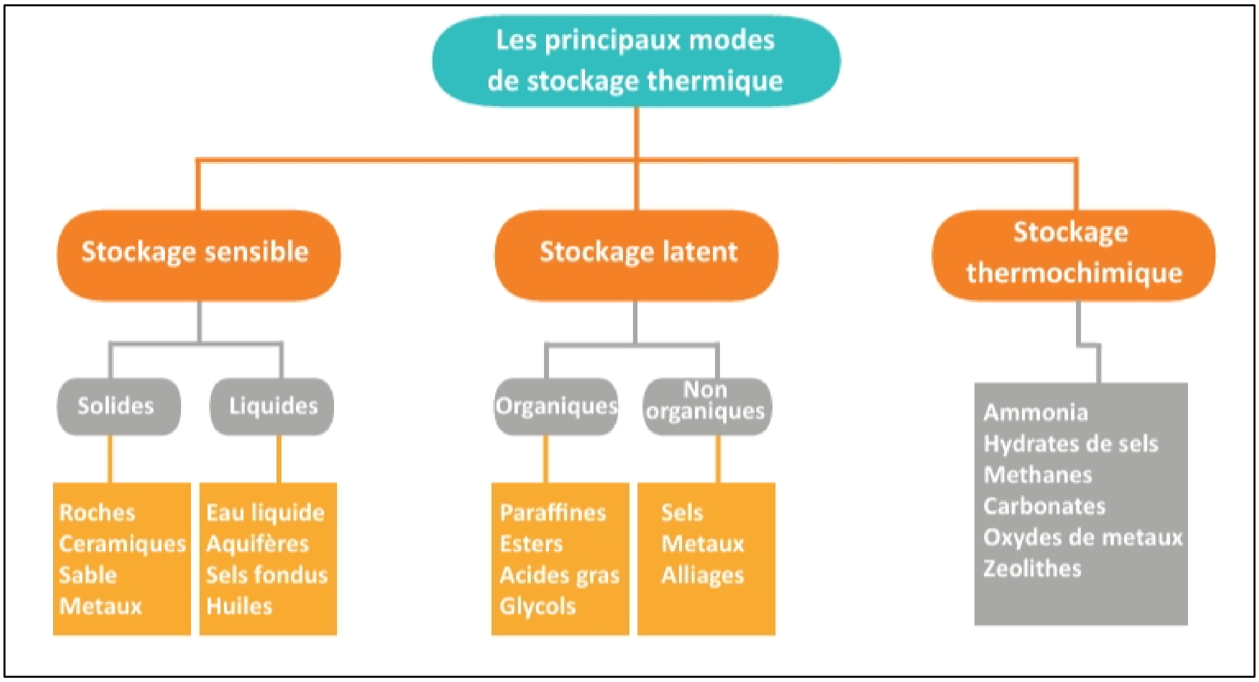

Figure 2. Classification of the Different Types of Thermal Storage

IV.4 The Three Main Modes of Thermal Storage

IV.4.1 Sensible Heat Storage

Sensible heat storage is the simplest method. It simply involves increasing or decreasing the temperature of a certain medium. This type of storage is the most commercially available of the three, as the others are still under research and development. Sensible storage is used both for short-term storage (domestic water heating, space heating, and solar drying) and for seasonal storage (greenhouse heating, hot water tanks in buildings).

IV.4.2 Latent Heat Storage (Phase Change Materials, PCM)

This storage mode is based on the energy involved when a material changes its state (e.g., solid-liquid). The reverse transformation releases the accumulated energy as heat or cold, with an efficiency of about 60%. This technique can be applied in buildings using Phase Change Materials

(PCM). Incorporated into walls, they act as thermal regulators according to the heat supplied by the sun.

IV.4.3 Thermochemical Storage

Chemical heat storage, or thermochemical storage, involves a reversible exothermic/endothermic chemical reaction using thermochemical materials. Depending on the reactants, this method can allow a higher storage capacity than latent heat storage.

Reaction example:

A + B ↔ C + heat

- **Charging phase:** endothermic reaction (heat absorption).
- **Discharging phase:** exothermic reaction (heat release).

Thermochemical storage can be achieved through several pathways. It is mainly divided into two processes: sorption processes (absorption and adsorption) and thermochemical reactions. A solar thermochemical storage cycle uses the heat produced in the solar collector during sunlight hours to trigger a fully reversible endothermic chemical reaction, which allows the total thermal energy to be restored via the reverse exothermic reaction during non-sunlight hours.

IV.5 Fundamental Characteristics of a Heat Accumulator

IV.5.1 Thermal Storage Capacity

The thermal storage capacity indicates the amount of heat that the accumulator can store.

a) **For sensible heat storage:**

The stored heat is given by the following formula:

$$Q = \dot{m}\, C_p \Delta T \qquad (1)$$

Where:

- Q = stored energy (J)
- m = mass of the material (kg)
- Cp = specific heat capacity (J/kg·K)
- ΔT = temperature change (K)

👉 The higher the Cp, the better the material as a heat accumulator.

👉 Water is one of the best materials for this type of storage.

b) **For latent heat storage (PCM):**

The stored heat is given by:

$$Q = \dot{m}\, L \qquad (2)$$

Where L is the latent heat of fusion (J/kg).

👉 A very large amount of heat can be stored without a significant change in temperature.

c) **For thermochemical storage:**

The stored heat in this case is given by:

$$Q = \dot{m}\, \Delta H \qquad (3)$$

Where ΔH is the enthalpy of the reaction (J/kg).

👉 Very high energy density.

IV.5.2 Energy Density

Energy density indicates the amount of energy stored per unit volume or per unit mass.

a) **Mass-specific energy density:**

$$\rho E = C_p\, \Delta T \qquad (4)$$

b) **Volumetric energy density:**

$$\rho V = \rho C_p\, \Delta T \qquad (5)$$

Where ρ is the material density (kg/m^3).

👉 Dense materials (rocks, molten salts) have high volumetric energy density.

IV.5.3 Operating Temperature

The operating temperature is the thermal range in which the accumulator can function.

- **Low temperature:** 20–100 °C (domestic heating, hot water)
- **Medium temperature:** 100–400 °C (industrial drying, thermal oils)
- **High temperature:** >400 °C (CSP plants, molten salts)

👉 The chosen material must be thermally stable within this range.

IV.5.4 Thermal Conductivity

Thermal conductivity (λ\lambdaλ) expresses how easily heat propagates through the material, in W/m·K. It is high for metals and molten salts, medium for rocks and concrete, and low for paraffin and insulators.

👉 Higher conductivity allows faster charging and discharging of the storage.

IV.5.5 Thermal Inertia

This is the ability of a material to store a large amount of energy without a rapid change in temperature. Materials with high inertia include water, stones, and concrete; low-inertia materials include insulators and wood.

IV.5.6 Storage Efficiency

Storage efficiency is expressed as:

$$\eta_s = \frac{Q_{\ restitué}}{Q_{stocké}} \quad (6)$$

This efficiency depends on the quality of insulation, thermal conductivity, losses by convection and radiation, and storage duration.

👉 Latent heat and thermochemical accumulators often achieve higher long-term efficiency.

IV.5.7 Thermal and Cyclic Stability

A good accumulator must withstand thousands of thermal cycles, not degrade at high temperatures, and retain its physical and chemical properties. Potential issues include chemical degradation (hydrated salts), phase segregation, and container corrosion.

IV.5.8 Compatibility with Heat Transfer Fluids

The material must be compatible with water, thermal oil, molten salts, hot air, and steam. This includes absence of chemical reaction, corrosion, and good thermal interface.

IV.5.9 Safety and Non-toxicity

Important characteristics include:

- Flammability (paraffins)
- Toxicity (some hydrated salts)
- Internal pressure (tanks)
- Risk of leakage or explosion

IV.5.10 Cost and Availability

Economic criteria include material cost (€/kg or €/m^3), insulation cost, and installation and maintenance costs.

👉 The choice often involves a compromise between performance and cost.

IV.6 Specific Characteristics According to Accumulator Types

IV.6.1 Sensible Heat Accumulators

There are several sensible heat accumulators using water, rock, concrete, oils, and molten salts. An example is shown in Figure 3. They are characterized by:

- Simple and inexpensive
- Moderate thermal capacity
- Operation over a wide temperature range
- Heat loss over time

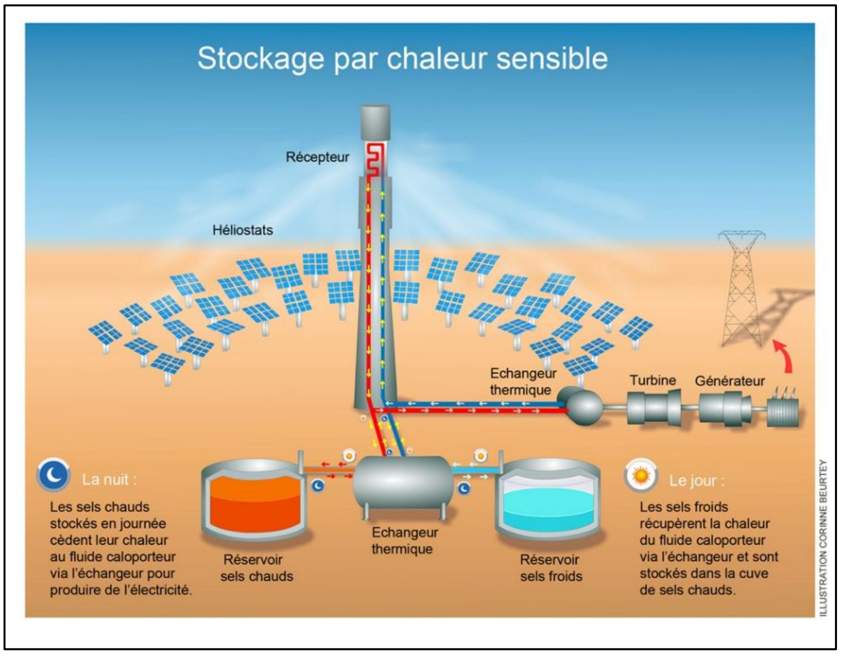

Figure 3. Sensible Heat Storage

IV.6.2 Latent Heat Accumulators (PCM)

There are several latent heat accumulators using paraffins (organic PCMs), hydrated salts (inorganic PCMs), fatty acids (organic PCMs), and molten salts (nitrates, nitrites, carbonates, chlorides). An illustrative example is shown in Figure 4 (Sodium Nitrate).

They are characterized by:

- High energy density
- Nearly constant operating temperature
- Low thermal conductivity (often compensated with additives)
- Possible cycling issues (physical, chemical, or thermal degradation)

IV.6.3 Thermochemical Accumulators

There are several thermochemical accumulators using paraffins. Examples include $CaO/Ca(OH)_2$, $MgO/Mg(OH)_2$, and metal-based cycles. An example is shown in Figure 5. They are characterized by:

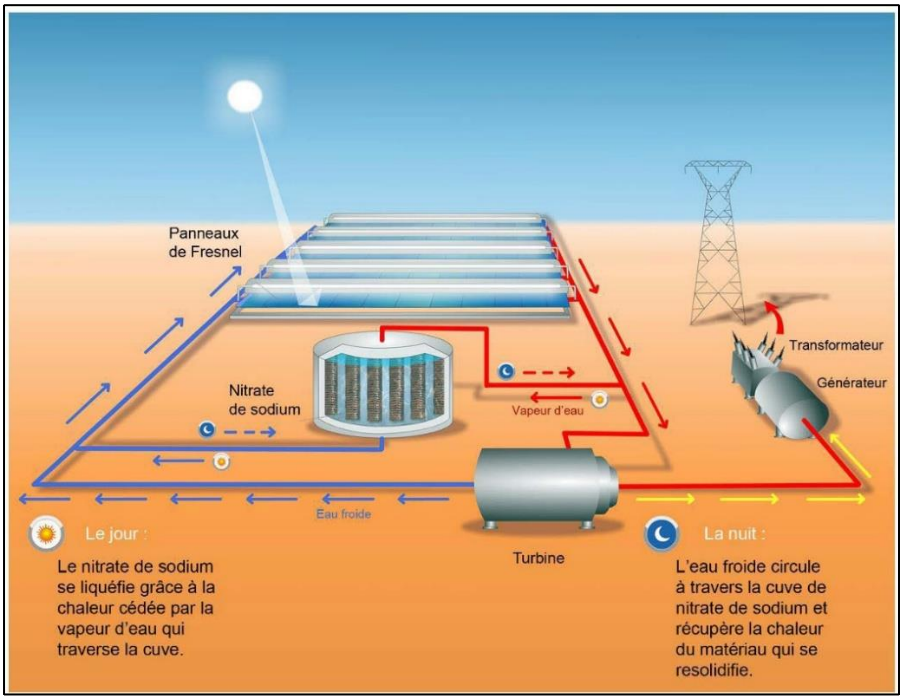

Figure 4. Latent Heat Storage.

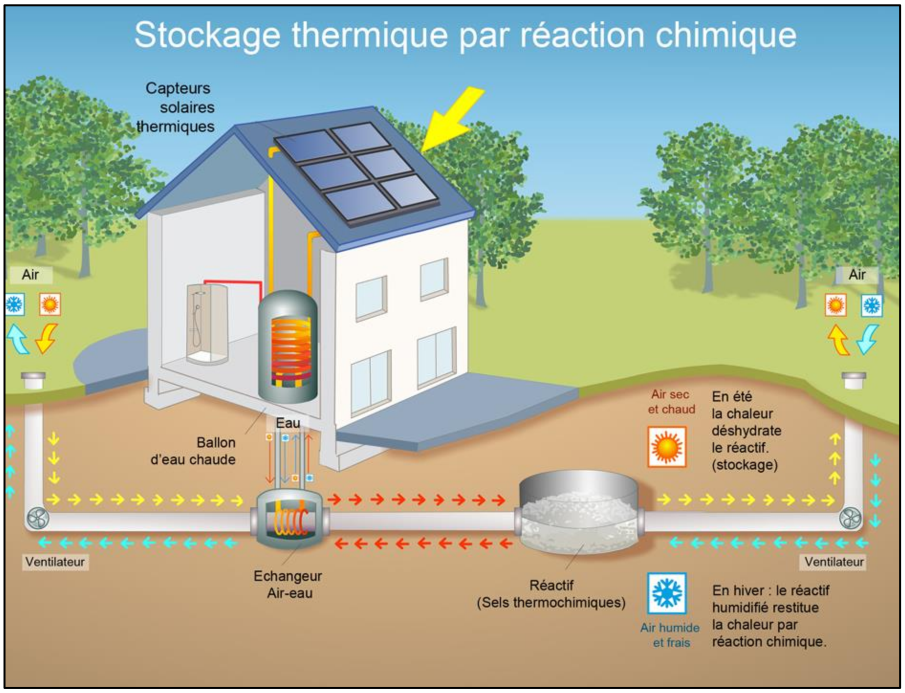

Figure 5. Chemical Reaction Storage

- Very high energy density
- Loss-free storage (in chemical form)
- Technical complexity
- Technologies still under development

Practical Example: Comparative Characteristics of Common Materials

Material	**Type**	**Temp. (°C)**	**cp (kJ/kg·K)**	**Advantages**	**Limitations**
Water	Sensible	0–100	4.18	Excellent heat capacity, inexpensive	High pressure at high T
Rocks	Sensible	20–400	0.80–0.95	Very cheap, stable	High volumetric mass
Thermal oils	Sensible	0–400	1.5–2	Good stability	High cost
Paraffins	Latent	20–80	Latent 150–200 kJ/kg	Stable temperature	Low conductivity
Molten salts (nitrates)	Sensible/Latent	200–600	1.5	High temperature, good conductivity	Corrosion, cost
$CaO/Ca(OH)_2$	Thermochemical	>450	Very endothermic reaction	Very high energy density	High technical complexity