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Advancing Energy Transition through Thermal Energy Storage

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Summary

- Energy transition and energy demand
  - Context
  - Special features in France and Brazil
- Energy storage systems
  - Energy demand and energy storage
  - Energy Storage Methods
- Benefits of thermal energy storage
  - Relevance
  - Principles
    - Sensible heat storage
    - Latent energy storage
    - Thermochemical heat storage
- Latent energy storage

Energy transition

"**Energy transition**" is based on the notion that an energy resource, or a group of energy resources, dominates the market for a period or era, until it is challenged and eventually replaced by other(s) resource(s). [1](Melosi, 2010)

- **Period I (pre-1820):** dominated by human/animal power, wind-, wood-, and waterpower.
- **Period II (1820-1914):** Industrial era dependent on wood, waterpower, and ultimately coal.
- **Period III (1914-1945):** Oil emerges as a leading fuel; electrical power production dramatically increases.
- **Period IV (1945-1970s):** A 'postindustrial' economy dependent on oil, punctuated by the 1970s 'energy crisis.'
- **Period V:** Since the 1970s, when the world watched major oil crises,
    - Alternatives that could replace oil as the basis of the global energy mix.

[1] Melosi Martin, Energy transitions in historical perspective, in: Laura Nader(Ed.), The Energy Reader, Wiley Blackwell, London, 2010, pp. 45–60.

Energy transition

- **In recent years**
  - The use of clean energy sources (hydro, nuclear, wind, solar, tidal, geothermal, biofuels) emerge as possible replacements for fossil fuels
- **Not an easy transition**
  - Many questions about the ability of these new sources to meet world energy demand
- **Energy challenge**
  - How to perform the transition to a post-oil era
    - without affecting energy supply
    - maintaining equitable distribution of electricity
    - without destroying the environment and achieving carbon neutrality

Energy transition

The concept of energy basically refers to three aspects:

- natural energy resources,
- the infrastructure logistics of energy,
- the set of techniques, knowledge and energy development.

- **How can countries find the right balance between the sustainability, security of supply and affordability objectives?**

- **Which are the best available policy options to achieve them?**

- **There is no single correct answer**

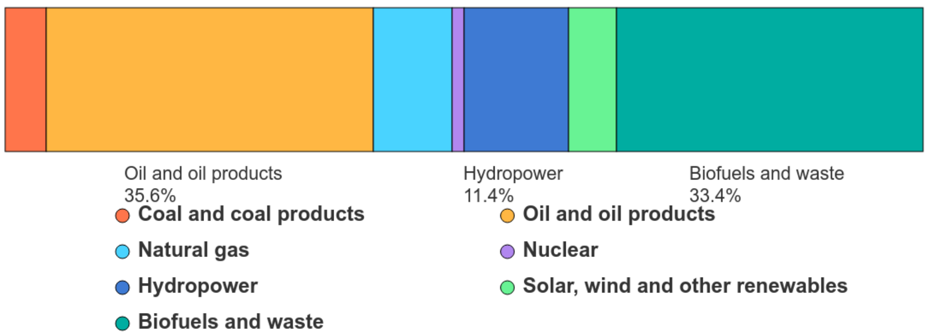
Countries differ:

- Energy mixes,
- Availability of natural resources, public acceptance and political support for the various policy options,
- Different stages of the energy transition process.

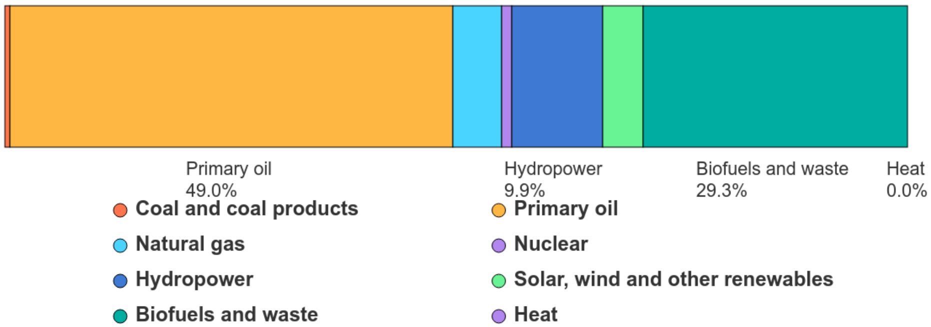
But common lessons

Example

Total energy supply, Brazil, 2024



Domestic energy production, Brazil, 2024



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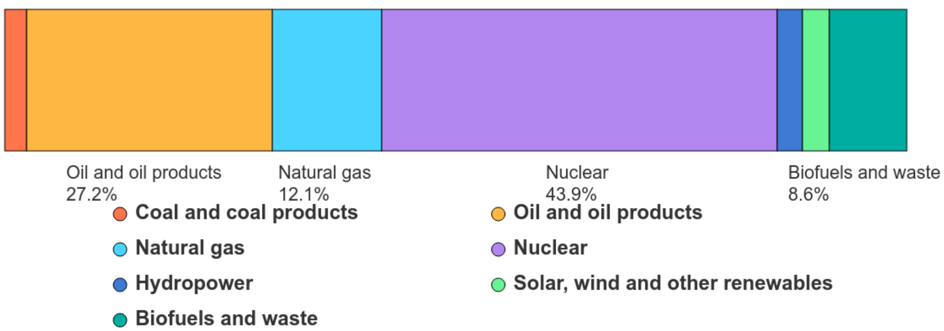
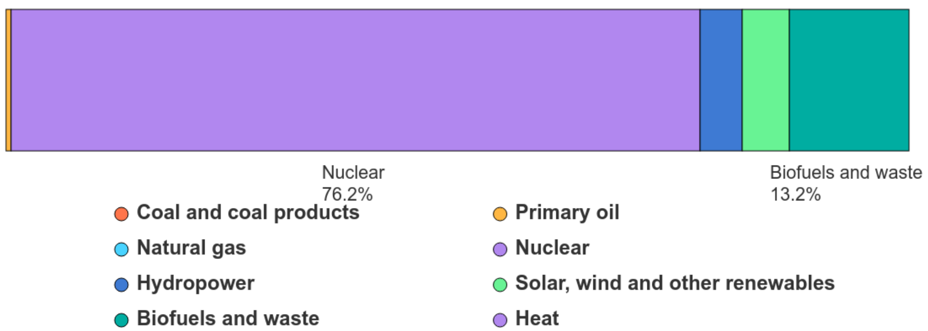


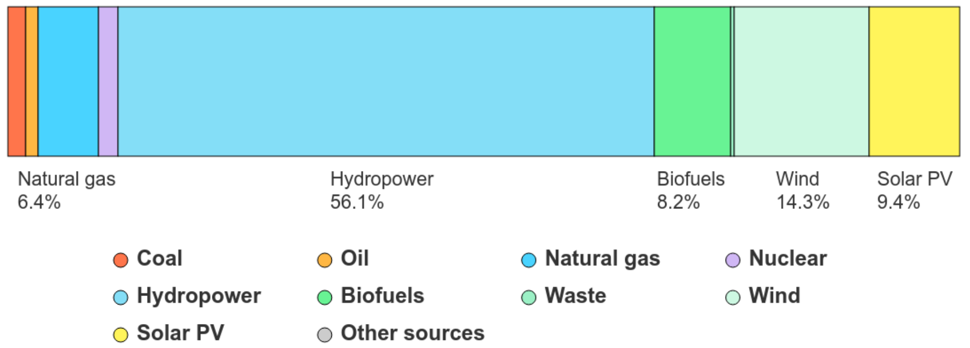
Domestic energy production, France, 2024



Source: International Energy Agency

Example

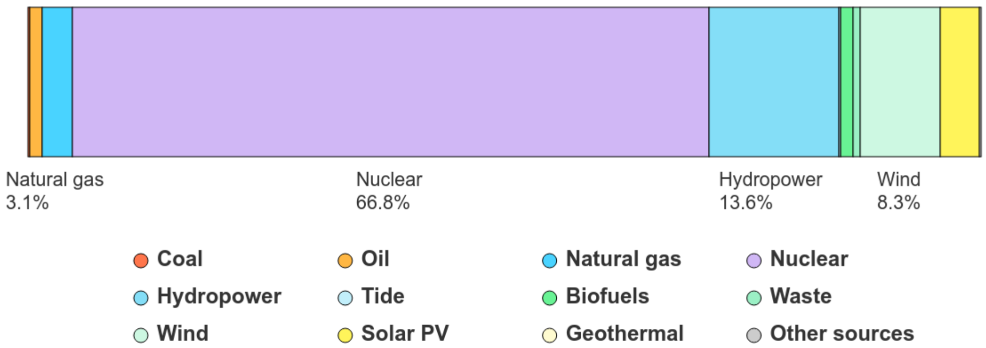
Electricity generation sources, Brazil, 2024



Source: International Energy Agency. Licence: CC BY 4.0

Share of power in emissions
11% of total energy-related CO_2 emissions, 2023

Electricity generation sources, France, 2024



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Share of power in emissions
11% of total energy-related CO_2 emissions, 2023

The Energy Transition in France and Brazil

Renewable energy deployment perspectives

France's Renewable Energy Outlook

Strong nuclear base: Nuclear provides stable low-carbon generation; renewables steadily growing
Rapid growth: Solar PV and wind expanding quickly toward 2030
Future scenarios: Carbon neutrality by 2050 requires large renewable expansion, demand reduction, and system flexibility
Planning vs. market: National plans set targets, but actual deployment may vary depending on technology costs, policy, and market dynamics

Brazil's Renewable Energy Outlook

Strong renewable base: Hydro & biomass historically dominant
Rapid growth: Wind & solar reached record shares by 2024–2025
Future scenarios:

- Continued fast renewables growth to 2030 likely
- 2050 energy mix varies with policy (electrification, bioenergy, hydrogen, new grids)

Planning vs. market: EPE's PDE (Ten-Year Energy Expansion Plan) guides expansion to 2034/35, but private investment could accelerate wind/solar deployment above PDE baselines by 2030

Lessons in common

1. The Energy Transition is a long process that requires strong political support.
2. The Energy Transition has put extra pressure on electricity bills.
3. Renewable energies have played a prominent role in the Energy Transition.

Renewable energy ⇒ Intermittent sources of energies

Energy storage

Energy Storage is critically important to the success of any intermittent energy source in meeting demand.

Separates the production from the use of energy in time and space.

Key Contributions:

- Support efficient energy use
- Applicable across a wide range of sectors

Major Benefits:

- Increased operational flexibility
- Lower energy costs and global consumption

Additional Advantages:

- More efficient equipment utilization
- Reduction of the use of fossil fuels
- Lower pollutant emissions (CO_2, CFCs)

Energy storage

Energy storage is complex and cannot be evaluated properly without a detailed understanding of **energy supplies** and **end-use considerations**.

Variable Energy demand

Sectors

Commercial
Industrial
Public
Residential
Utility

daily
weekly
seasonally

Various energy-conversion systems

Peak Hour Challenges

Energy demand

Energy storage provides an alternative method of supplying peak energy demands.

For example:

- Utility. Store inexpensive off-peak electricity for use during peak periods, reducing reliance on gas/oil peaking plants.

- Industry. Capture high-temperature waste heat for preheating and other heating operations.

- Cogeneration. Store excess heat or electricity when production doesn't match demand.

- Wind and run-of-river hydro. Charge storage during low-demand hours and use for peak periods, increasing capacity factor and economic value.

- Solar energy systems. Store excess energy from sunny periods for use at night or on cloudy days, boosting capacity factor.

Energy storage

Many different energy storage technologies are available for use in storage for renewable integration applications

- Each technology has advantages and disadvantages
- Not all these technologies are appropriate for all applications

Energy storage methods

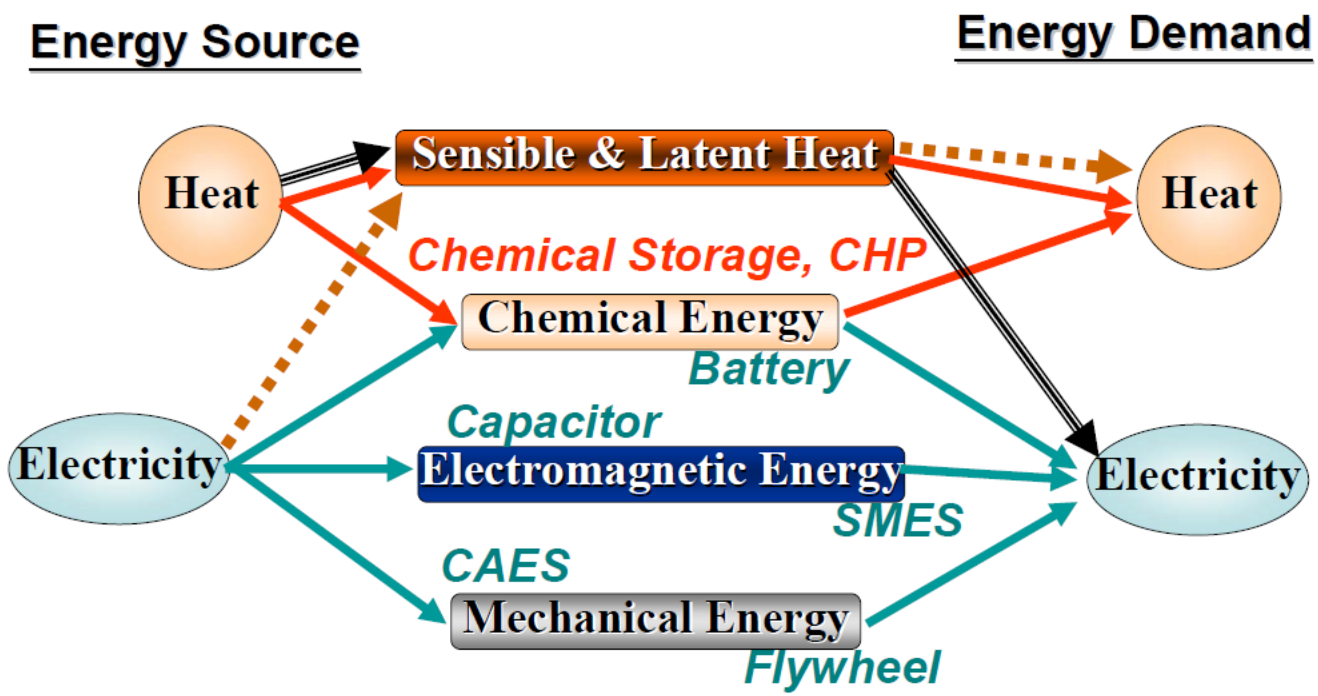
Mechanical energy storage
→ Hydrostorage (pumped storage)
→ Compressed air storage
→ Flywheels

Electrochemical energy storage
→ Batteries

Magnetic storage
→ superconducting materials

Thermal energy storage
→ Sensible heat storage
→ Latent heat storage
→ Thermochemical heat storage

Comparison of Energy Storage Technologies



CHP: Chemical Heat Pump
SMES: Superconductors Magnetic Energy Storage
CAES: Compressed Air Energy Storage

Heat to Heat

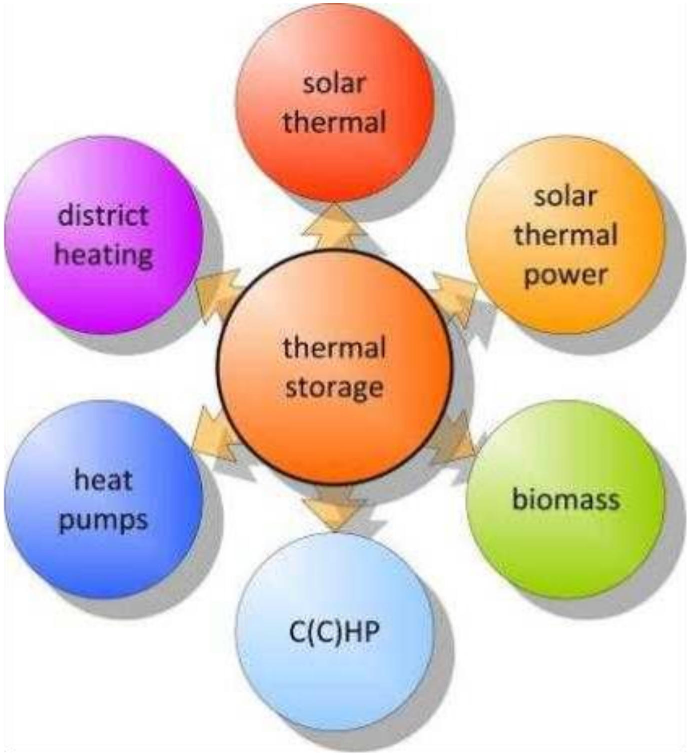
Power to Heat

Power to Heat to Power

Relevance of Thermal Energy Storage

- **Position of Thermal Energy Storage**

  - solar thermal
  - concentrated solar power
  - biomass
  - cogeneration
  - heat pumps
  - district heating
  - …



Principles for Thermal Energy Storage

- **Sensible energy**

- principle: heat capacity and temperature difference

- Example: DHW tanks, reservoirs, aquifers, ground/soil,…

- **Latent energy**

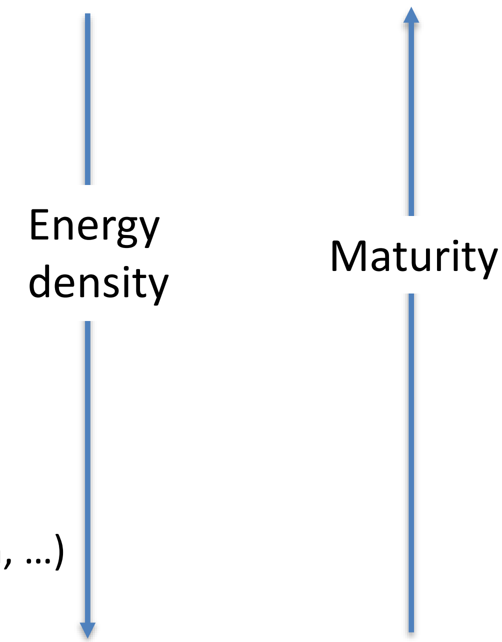
- Principle: phase change (melting, crystallization, evaporation, …)

- Example: water, organic and inorganic PCMs (Phase Change Material)

- **Thermochemical energy**

- Principle: endothermic/exothermic reaction (adsorption and absorption, …)

- Example: zeolite, silica gel, hydrated salts,…



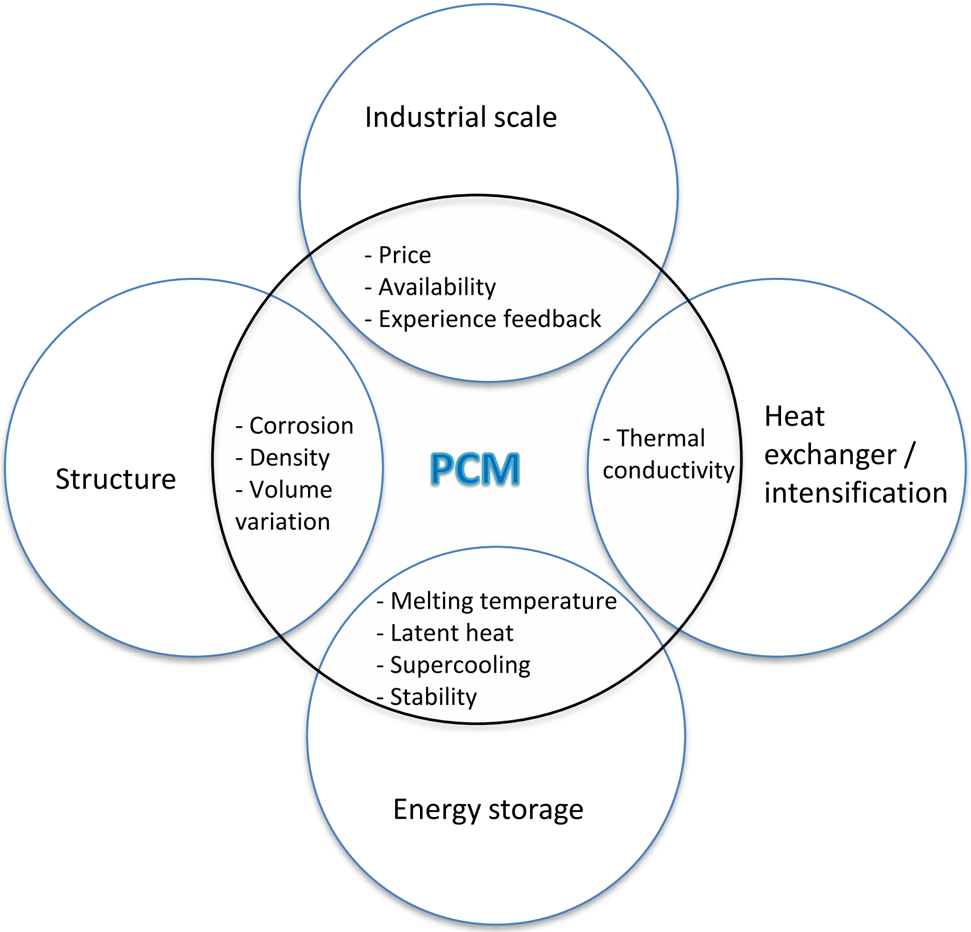
➢ Storage of thermal energy by liquid solid phase change

Using Phase Change Materials (PCM)

Latent energy storage

Latent heat

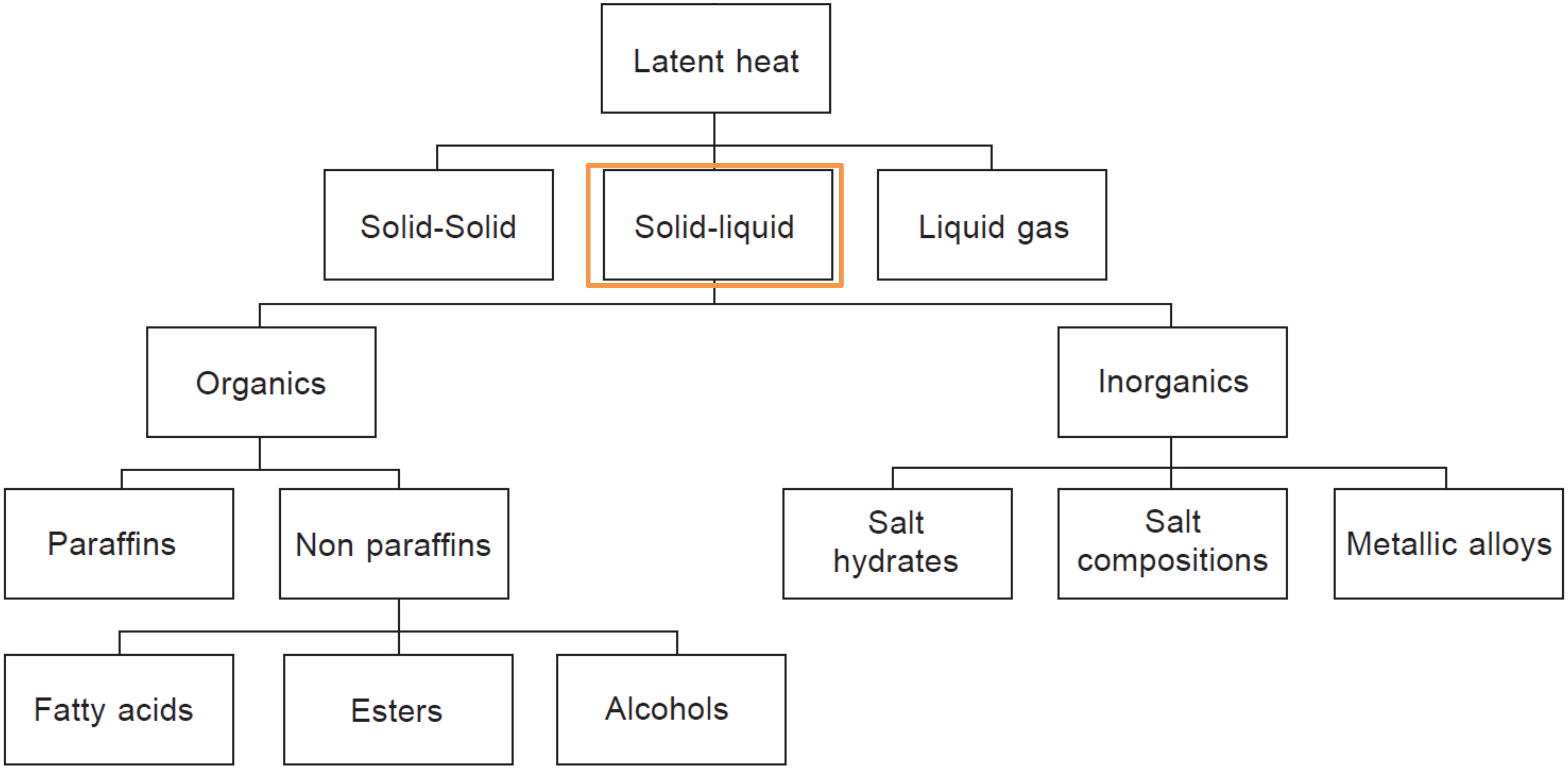
$$H_2 - H_1 = M\,c_S\left(T_F - T_1\right) + \boxed{M\,L_F(T_F)} + M\,c_L\left(T_2 - T_F\right)$$



Methodology

Coupling experimentation-modeling

- Selection of the PCM
  - **- Adapted melting temperature - high latent heat**
  - - high density
  - - low cost
  - - low danger and toxicity
  - - stability over time
  - - reliability of containment materials
  - - low supercooling (delay at liquid –solid transition)
- Thermophysical characterization
- Study of the phase change kinetics (melting - crystallization)
- Experiments on an industrial scale



Classifications of phase change materials (Cárdenas and León, 2013)

Organic PCMs - Paraffin (C_nH_{2n+2}) and Fatty acids ($CH_3(CH_2)_{2n}COOH$)

Advantages

- Availability in a large temperature range
- Low or no supercooling
- Compatibility with conventional material of construction
- No segregation
- Chemically stable
- Good melting heat
- Safe and non-reactive

Disadvantages

- Low thermal conductivity in their solid state (High heat transfer rates are required during the freezing cycle).
- Flammable.
- Due to cost consideration only technical grade paraffins may be used which are essentially paraffin mixture.

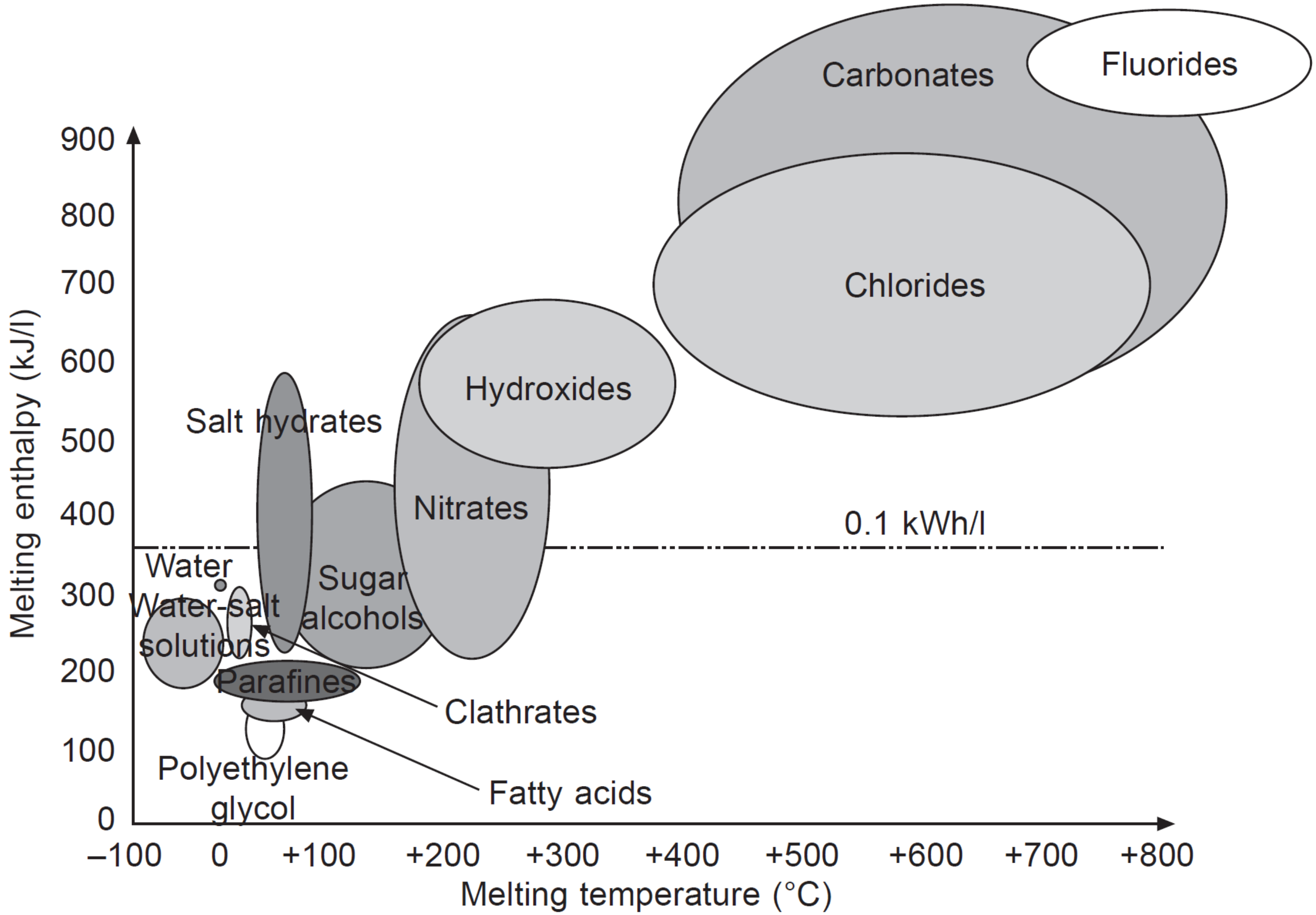
Inorganic PCMs - Salt hydrates, Salts, metals

Advantages

- Low cost and easy availability
- Good melting heat
- Non-flammable

Disadvantages

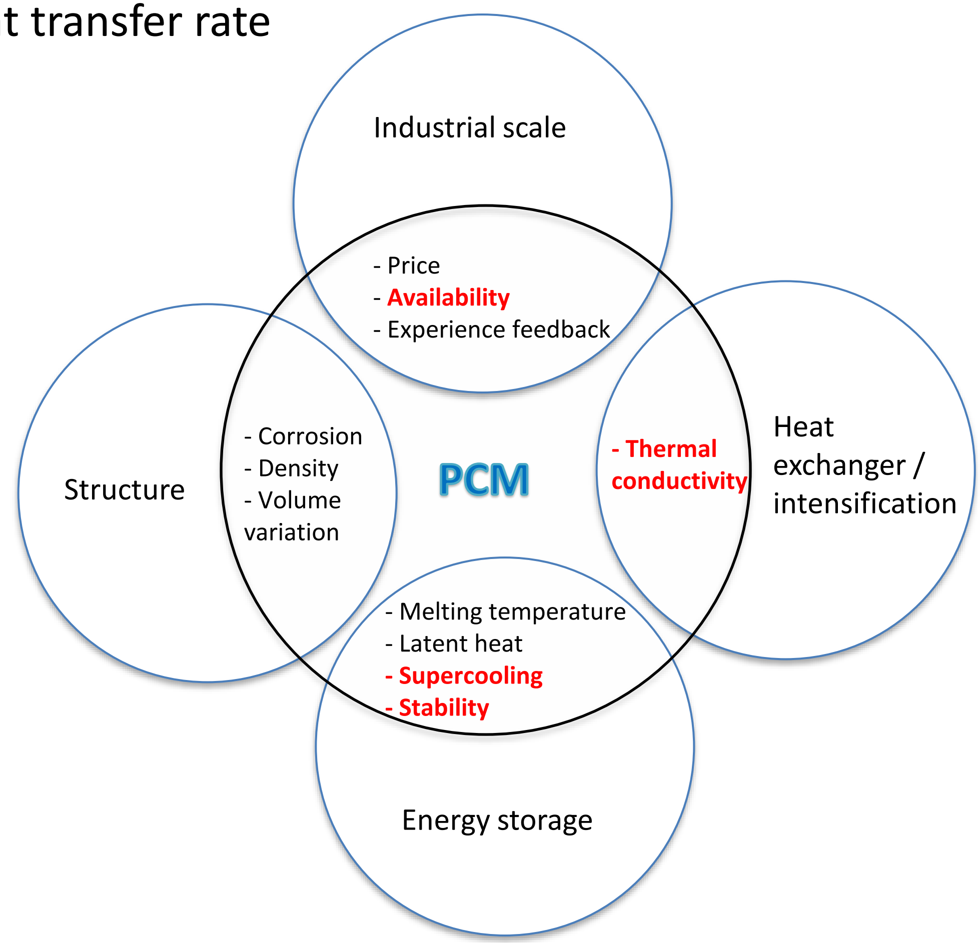
- Change of volume is very high
- Supercooling



Melting temperature and melting enthalpy of common PCM candidates (ZAE Bayern)

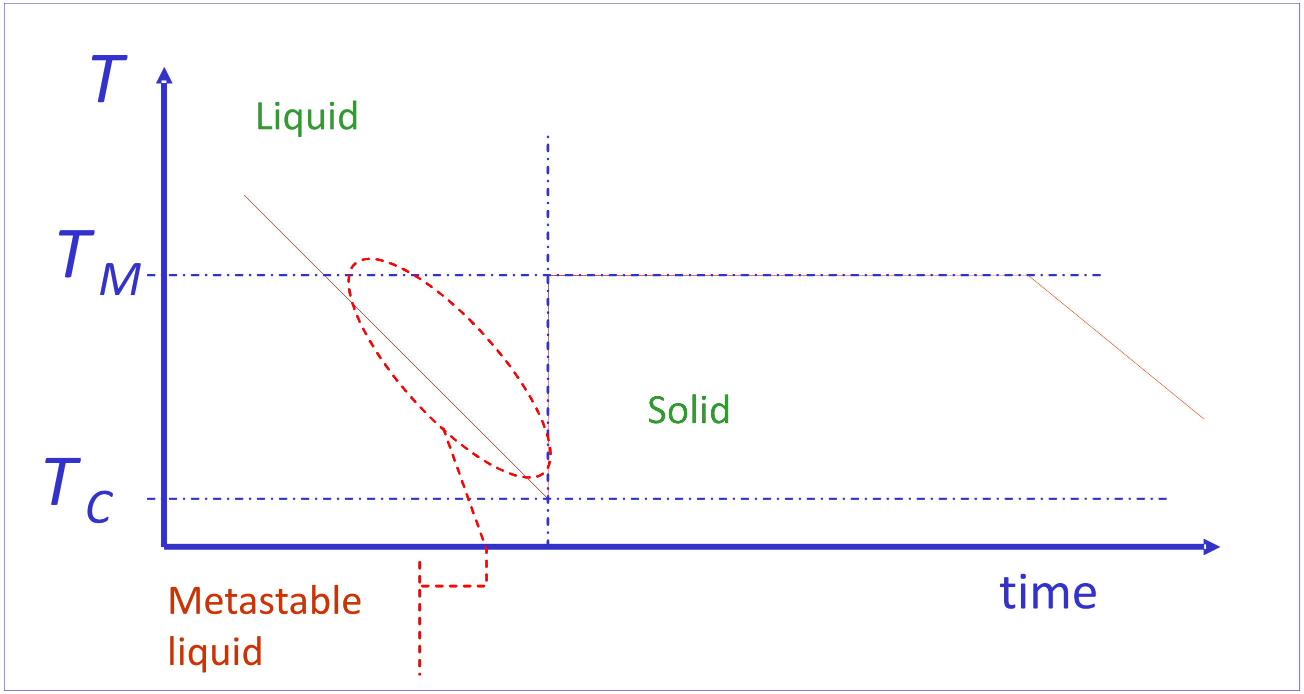
Shortcomings of PCMs in thermal energy storage systems

- Availability at the industrial scale
- Supercooling
- Low thermal conductivity and heat transfer rate
- Insufficient long-term stability



Shortcomings of PCMs in thermal energy storage systems

Supercooling



- Supercooling degree : $\Delta T = T_M - T_C$
- Stochastic phenomenon (erratic)

The supercooling depends on several parameters :

- Sample volume : V ↘ ΔT ↗

Examples :

	0,3 l	mm^3	μm^3
Water	8 K	20 K	36 K
Paraffins	*	< 0,5 K	12-14 K
Organic substances		20 K	> 100 K
Metal		1-2 K	> 200 K

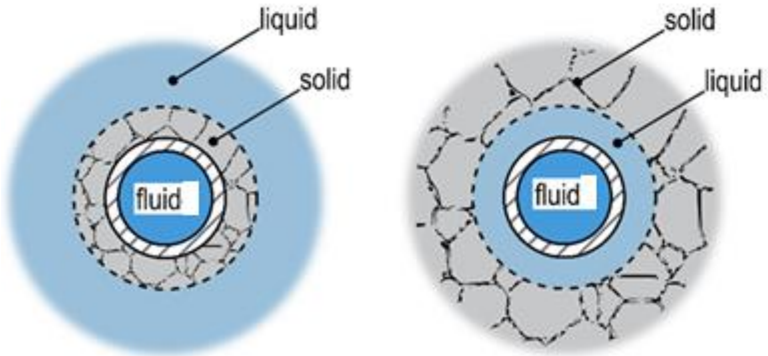
The supercooling can be decreased:

- Use of nucleating agents (crystal structure similar to that of the PCM)
- Cold finger technique : *A nucleating device is maintained cooler than the maximum supercooling temperature.*
- Application of a surface roughness : *to create a site of nucleation*

Shortcomings of PCMs in thermal energy storage systems

- Low thermal conductivity and heat transfer rate

PCMs have a low thermal conductivity (usually between 0.2 and 0.7 [W/m K])
A low thermal conductivity reduces the transfer of the energy in and out of the PCM



Melting vs. Solidification: PCM melts faster than it solidifies.

Reason: Buoyancy-driven convection during melting enhances heat transfer.

Heat transfer can be improved using various enhancement techniques

Shortcomings of PCMs in thermal energy storage systems

- Heat transfer rate improvement

➢ graphite / PCM composites

- High increase of thermal conductivity

But

- *High cost*
- *Stability*

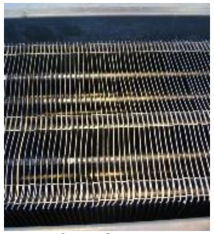
➢ metal / PCM composites

- Metal powders
- Metal matrice
- Metal foam

corrosion

➢ Larger heat exchanger surface

- Metal fins
- Graphite fins
- Different fin geometries



Finned Tube Design
effective thermal conductivity >10 W/(mK)

➢ other solutions

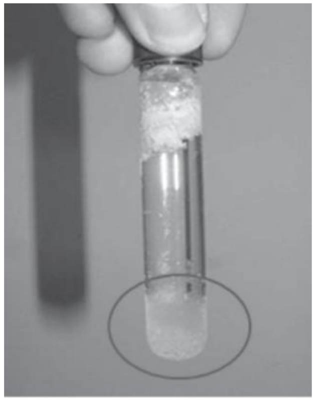
- Microencapsulation
- direct contact between the heat transfer fluid and the PCM.
- Scraped heat exchanger

Shortcomings of PCMs in thermal energy storage systems

- PCM Stability & Durability

Possible issues:

- poor stability
- corrosion with container materials



Incongruent melting in hydrated salt (Streicher, 2006).

The liquid phase is not exactly the same chemical composition as the solid phase

Must endure many melt–freeze cycles without degradation

Experimental validation is essential

Key performance indicators

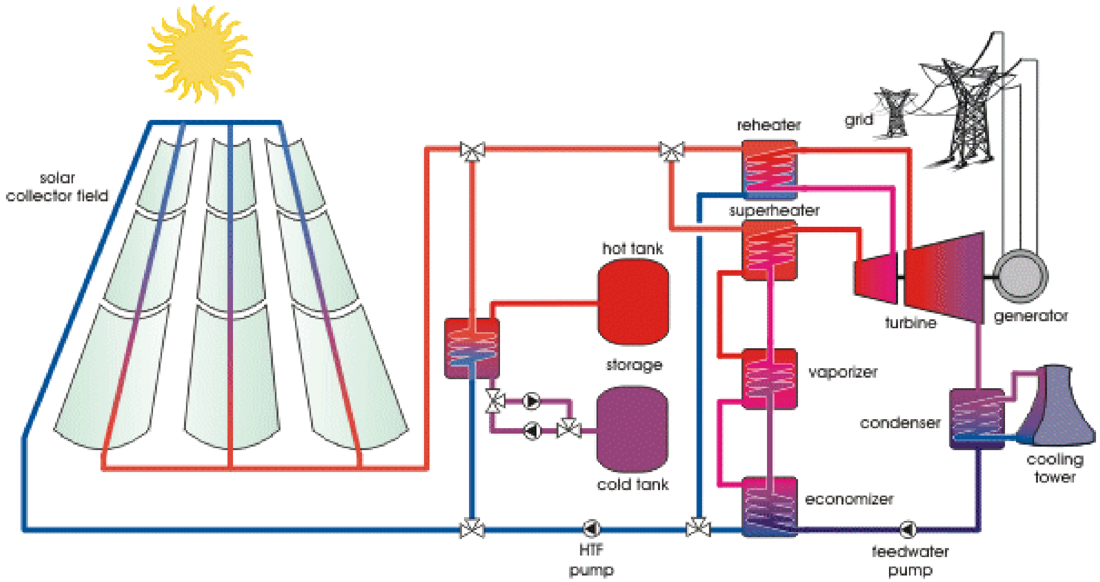
KPI	Unit	Purpose / Interpretation
Storage Capacity	kWh_{th} or MWh_{th}	Maximum energy stored (system size indicator).
Energy Density	kWh_{th}/m^3	Compactness of storage (key for space-limited systems).
Charging/Discharging Time	h	Determines operational flexibility.
Charge/Discharge Power	kW_{th} or MW_{th}	Determines responsiveness; sizing of heat exchangers/pumps.
Thermal Loss Rate	%/day	Indicates insulation quality.
Storage Duration	h, days, months	Maximum period over which heat can be stored without excessive loss Short-, mid-, or long-term application suitability.
Operational Temperature Range	°C	T_{max} - T_{min} determines compatibility with heat sources and uses.

Key performance indicators

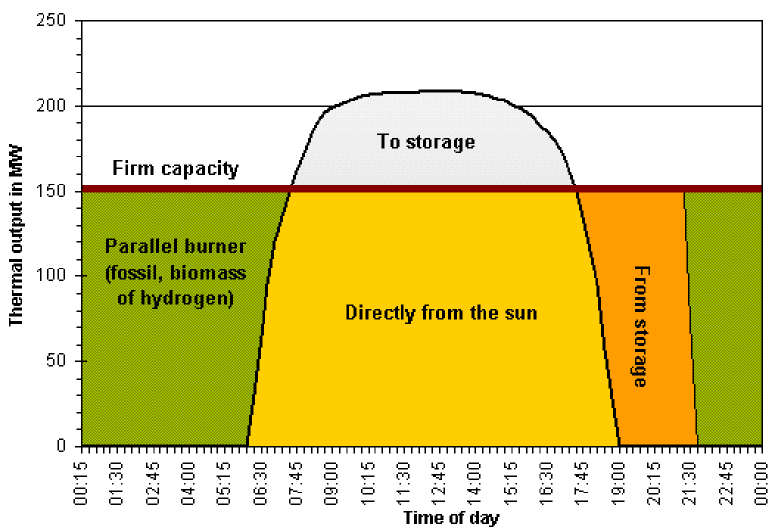
KPI	Definition / Formula	Unit	Meaning
Round-trip Efficiency (η_s)	$\eta_s = Q_{discharge} / Q_{charge}$	%	Global efficiency of storage cycle.
Exergy Efficiency (η_{ex})	$\eta_{ex} = Ex_{out} / Ex_{in}$	%	Accounts for temperature level and energy quality.
Performance Ratio (PR)	$PR = Q_{useful,delivered} / Q\_{theoretical,max}$	–	Measures real vs. ideal energy output.
Utilization Factor	$UF = Q_{used} / Q_{max}$	–	Indicates how fully the storage is cycled.
Storage Utilization Rate (SUR)	SUR =time active /total time	%	How often the storage is used.

Benefits of thermal energy storage

Solar thermal storage



Concentrating Solar thermal power Plants (CSP) with integrated energy storage

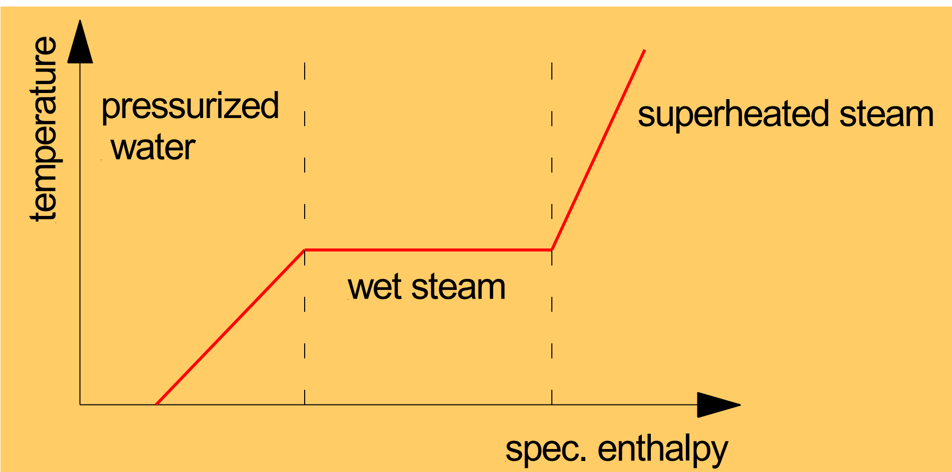


Typical output of a solar thermal power plant with two-hour thermal storage and backup heater to guarantee capacity

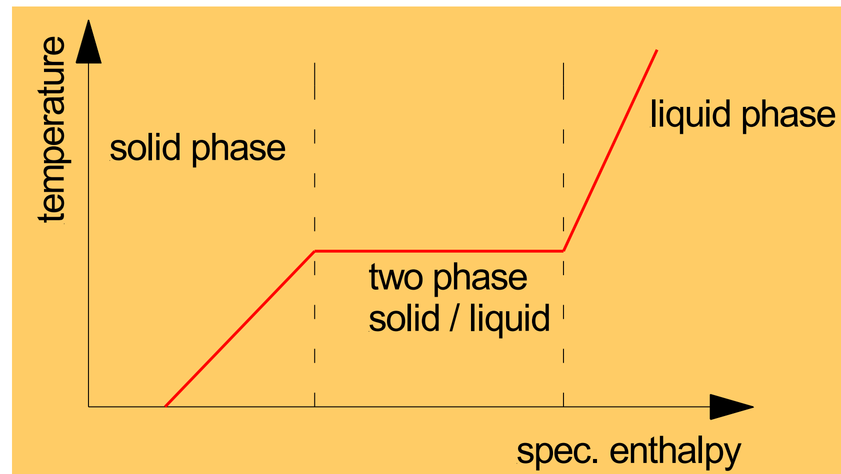
Energy storage necessary for successful market implementation of CSP technology

Why using Phase Change Material (PCM) ?

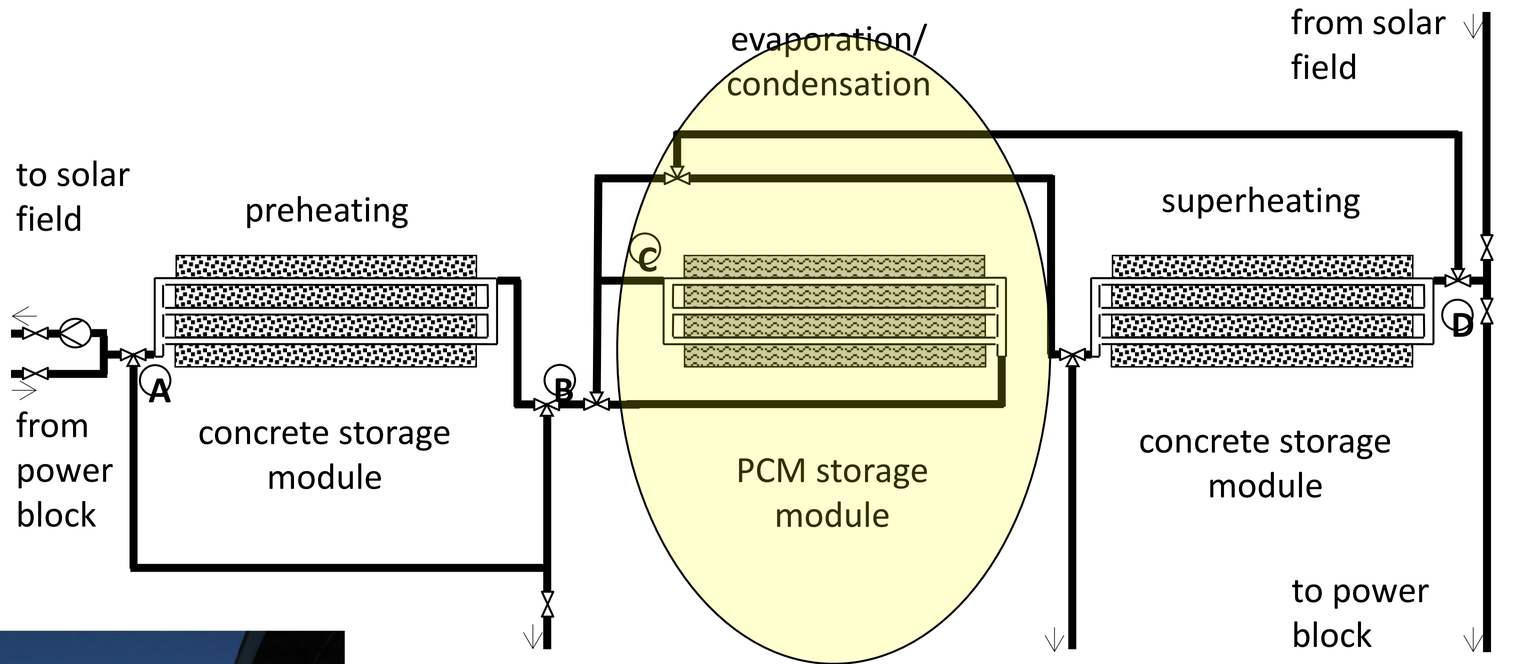
Working fluid water/steam:
=> Evaporation phase (T=const)

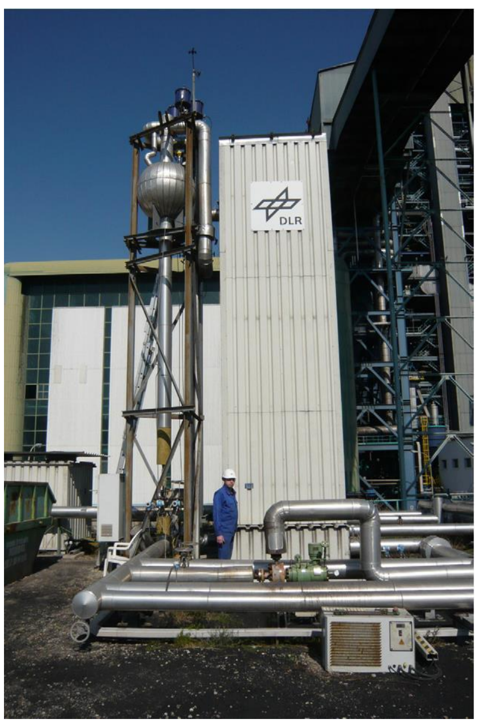


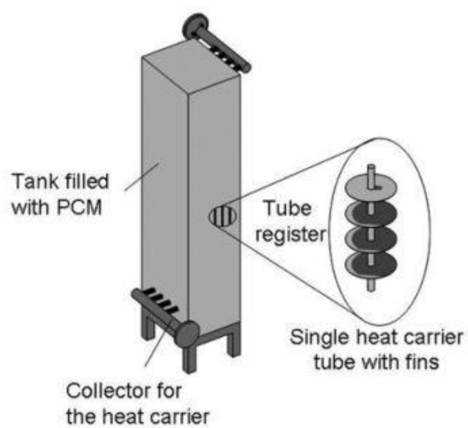
Phase change storage medium
=> Melting phase (T=const)



Significant advantage of PCM technology in steam production due to constant temperature







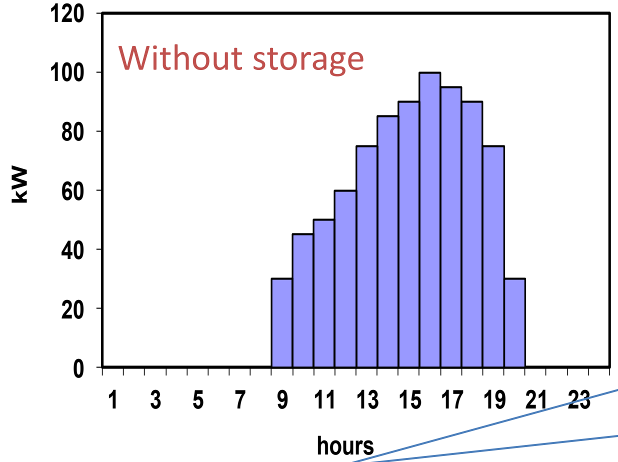
A feed water inlet / outlet
B liquid water
C saturated steam
D live steam inlet / outlet

Experimental demonstrator of latent heat storage (sodium nitrate) with a capacity of 700 kWh

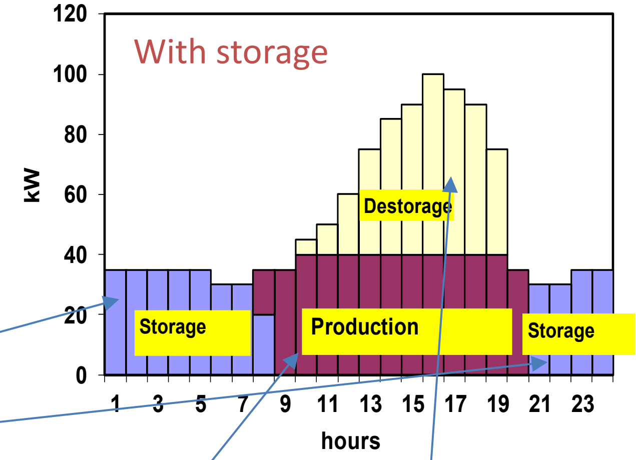
Benefits of thermal energy storage

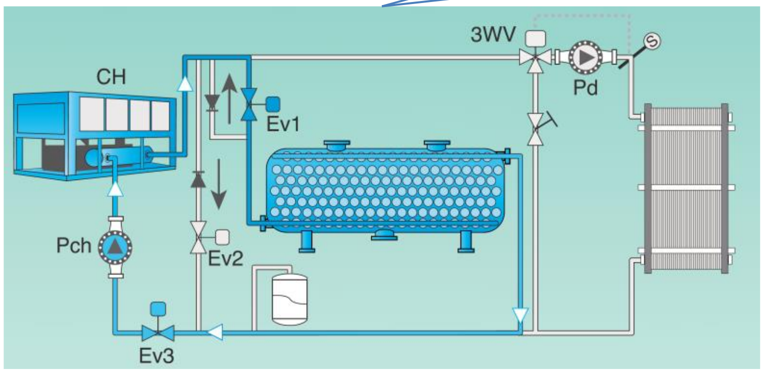
Air conditioning systems

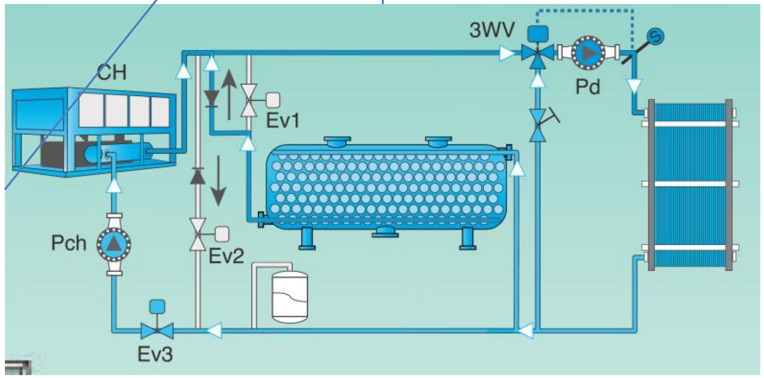
Daily consumption

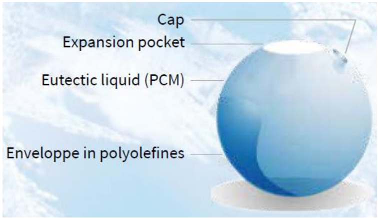


Cool thermal storage









- Reduction of chiller size
- Maximum electricity demand during lower tariff time
- Reduced running costs
- Improved security
- Environment (refrigerants, CO_2)

Conclusions

Energy transition

There is no single correct solution

But a common strategy is the improvement of **energy efficiency** and the use of **renewable energies.**

Energy storage is a key issue for energy transition

- Separates the production from the use of energy in time and space

→ **Better control of energy demand**

Thermal storage is an attractive solution

- 3 main types of thermal storage

→ **PCM storage technology is one the most promising technology**

PCM

- Methodology of selection
- Limitations

Continuous research and development effort is needed

Thank you for your attention

Advancing Energy Transition through Thermal Energy Storage

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