SESSION 3:

ENERGY STORAGE SYSTEM – APPLICATIONS AND SYSTEMS

Renewable Energy Systems

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Wroclaw, 19.04.2023

Organisation

Lecture: Energy Storage Systems: WUST Wroclaw

Master: Renewable Energy Systems

Lecturer:

Prof. Dr.-Ing. Przemyslaw Komarnicki,
M. Sc. Marcel Hallmann

Place: Building D20, Room 314

Time: Friday from 09:15 am to 2:00 pm.

Modules: I 9.15-10.45; II 10.50-12.20; III 12.30-14.00; (5*45 Minutes)

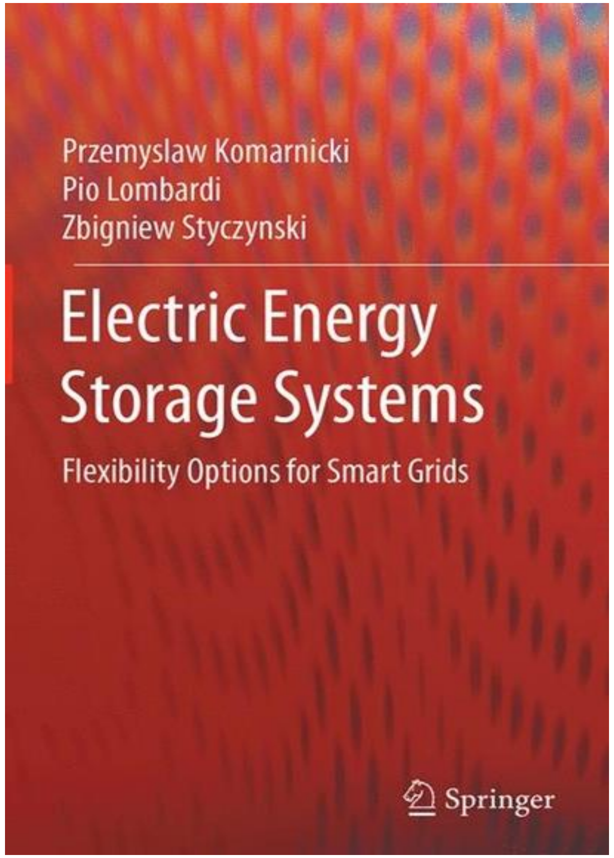
Contact: Justyna Herlender - Building D20, Room 212 - e-mail: justyna.herlender@pwr.edu.pl

Organisation

Date	Topic	Lecturer
Session 1: 08.03.24	Energy Storage System – introductions and trends	M. Hallmann
Session 2: 22.03.24	Physical properties, models and technologies	Dr. S. Balischewski
Session 3; 19.04.24	Applications and systems	M. Hallmann
Session 4: 17.05.24 (11.00 – 12.00)	EXAM Preparation (optional)	Prof. P. Komarnicki
Session 5: 07.06.24	FINAL EXAM	Prof. P. Komarnicki/ M. Hallmann

Overview and sources

Source # 1



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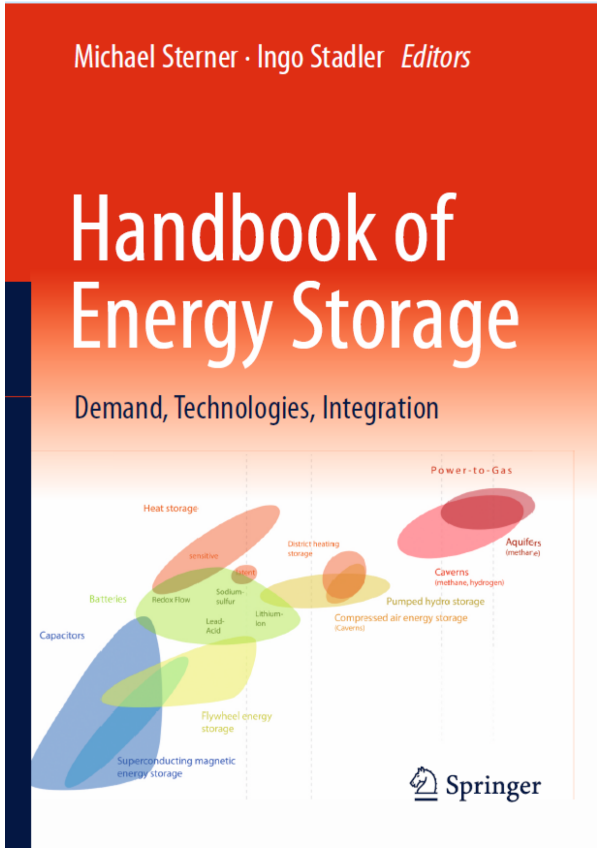

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Electrochemical Energy Storages

Exercise Batteries #1

There are different kinds of batteries, depending on the use case, the current state-of-the-art technologies or the budget for a certain project. Every battery type has special advantages and disadvantages to consider when you are planning an electrical storage system for an application.

Let's take a look at the cell technologies Lithium-Ion (Li-Ion), Lithium-Iron-Phosphate (LiFePo4) and Lead-Acid (Pb). The parameters of interest are for the given cells are:

a) How much energy does a cell with these technologies contain, if is has a capacity of 60 Ah?
b) How much will it weigh ?

Parameter	**Li-Ion**	**LiFePo4**	**Pb**
Nominal voltage	3,6V	3,2V	2V
end-of-charge voltage	4,2V	3,6V	2,4V
final discharge voltage	2,75V	2,8V	1,75V
gravimetric energy density	0,65 MJ/kg	100 Wh/kg	0,11 MJ/kg

Exercise Batteries #1

giv. 1) $U_{LiIon} = 3{,}6\,V$

$U_{LiFePO} = 3{,}2\,V$

$U_{Pb} = 2\,V$

$C = 60\,Ah$

2) $\rho_{LiIon} = 0{,}65\,MJ/kg = 180{,}6\,Wh/kg$

$\rho_{LiFePO} = 100\,Wh/kg$

$\rho_{Pb} = 0{,}11\,MJ/kg = 30{,}6\,Wh/kg$

sol. 1) $E_{LiIon}, E_{LiFePO}, E_{Pb}$

2) $m_{LiIon}, m_{LiFePO}, m_{Pb}$

Electrochemical Energy Storages

Exercise Batteries #1

Sol: 1) $E = U \cdot C$

$E_{LiIon} = 3{,}6\,V \cdot 60\,Ah = 216\,Wh = 0{,}22\,kWh$

$E_{LiFePO} = 3{,}2\,V \cdot 60\,Ah = 192\,Wh = 0{,}19\,kWh$

$E_{Pb} = 2\,V \cdot 60\,Ah = 120\,Wh = 0{,}12\,kWh$

Electrochemical Energy Storages

Exercise Batteries #1

2) $E = m \cdot \rho$

$$m = \frac{E}{\rho}$$

$$m_{Li\text{-}Ion} = \frac{E_{Li\text{-}Ion}}{\rho_{Li\text{-}Ion}} = \frac{216\ Wh}{180{,}6\ \frac{Wh}{kg}} = 1{,}2\ kg$$

$$m_{LiFePO} = \frac{E_{LiFePO}}{\rho_{LiFePO}} = \frac{192\ Wh}{100\ \frac{Wh}{kg}} = 1{,}92\ kg$$

$$m_{LiFePO} = \frac{E_{LiFePO}}{\rho_{LiFePO}} = \frac{120\ Wh}{30{,}6\ \frac{Wh}{kg}} = 3{,}96\ kg$$

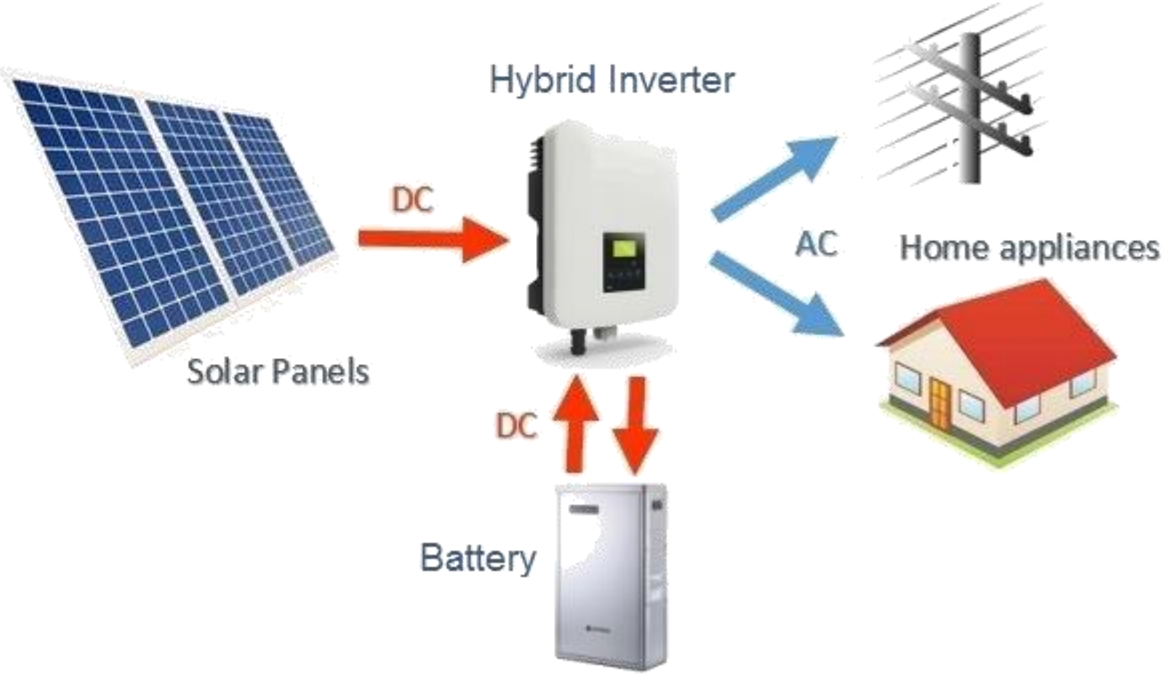
Electrochemical Energy Storages

Exercise Batteries #2 a)

Grid connection and battery storage - design of a battery storage system

A vacation home is located remotely about 100m from the nearest grid connection. The power supply shall be ensured during the summer season by a solar plant with battery storage. The system consists of PV generator, charge controller, battery storage and inverter. It shall supply electrical consumers with a total daily energy demand of 2 kWh. A bad weather period of 5 days should be able to be bridged by the storage.

a) Determine the required size (energy content and capacity), mass and the volume of the battery storage for the island operation of the vacation home!
Consider the following boundary conditions:
- Battery system voltage: **UB = 24 V DC**
- Self-discharge rate of the battery storage: **Cs = 0.4%/d**
- Permissible lower discharge limit: **SOC = 50%**
- Efficiency of the inverter: $\boldsymbol{\eta_{inv} = 90\%}$
- Lead acid battery efficiency: $\boldsymbol{\eta_{Batt} = 80\%}$
- Gravimetric energy density: $\boldsymbol{\rho_{grav} = 30\ Wh / kg}$
- Volumetric energy density: $\boldsymbol{\rho_{Vol} = 50\ Wh / l}$



Electrochemical Energy Storages

Exercise Batteries #2 A)

$U_B = 24\ V$

$C_s = 0{,}4\ \frac{\%}{d}$

$SOC_{min} = 50\ \%$ → $C_{use} = 50\eta$

$\eta_{inv} = 90\ \%$

$\eta_{bat} = 80\ \%$

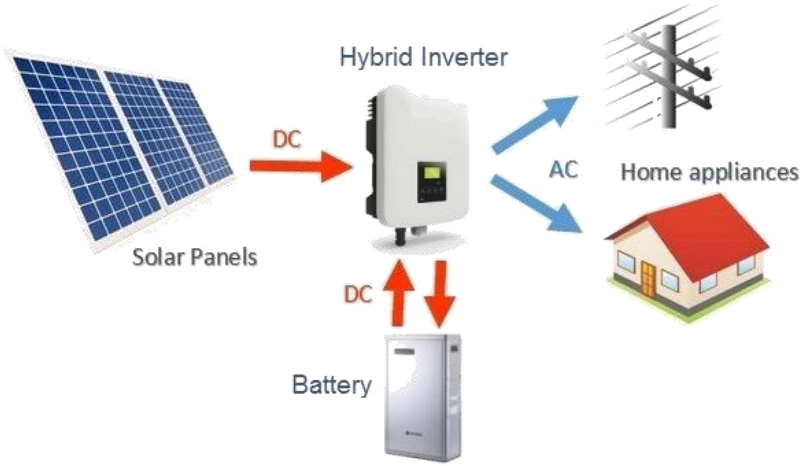
$C_{use} = SOC_{max} - SOC_{min} = 100\% - 50\% = 0{,}5$ → usable battery capacity

$C_{real} = C_{use} \cdot \eta_{total} = C_{use} \cdot \eta_{bat} \cdot \eta_{inv} = 0{,}5 \cdot 0{,}8 \cdot 0{,}9 = 0{,}36$ → real usable capacity

$$C_{bat} = \frac{E_{bat}}{U_{bat}} = \frac{28{,}33\ kWh}{24\ V} = 1181\ Ah$$

$$m_{bat} = \frac{E_{bat}}{\rho_{grav}} = \frac{28{,}33\ kWh}{30\ Wh/kg} = 943\ kg$$

$$V_{bat} = \frac{E_{bat}}{\rho_{vol}} = \frac{28{,}33\ kWh}{50\ Wh/l} = 0{,}567\ m^3$$

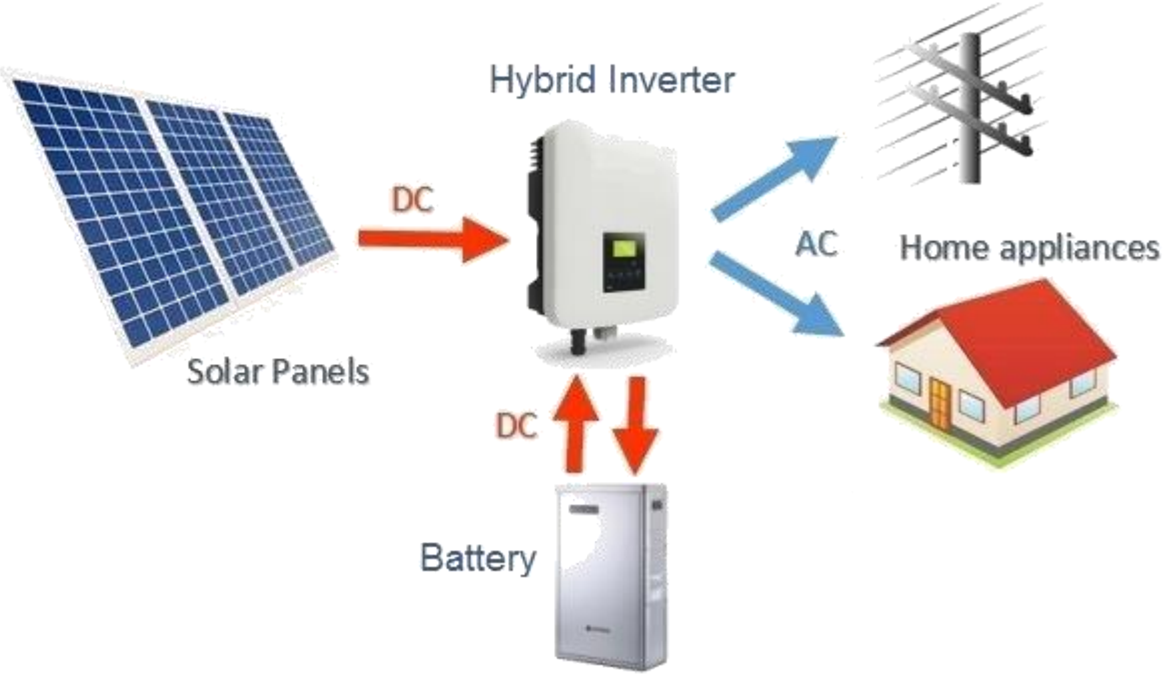


Exercise Batteries #2 b)

Grid connection and battery storage - design of a battery storage system

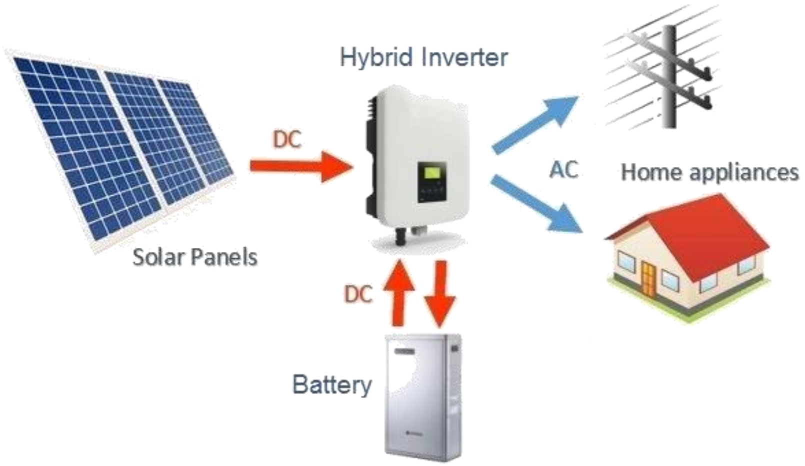
A vacation home is located remotely about 100m from the nearest grid connection. The power supply shall be ensured during the summer season by a solar plant with battery storage. The system consists of PV generator, charge controller, battery storage and inverter. It shall supply electrical consumers with a total daily energy demand of 2 kWh. A bad weather period of 5 days should be able to be bridged by the storage.

b) Determine the energy yield that can be obtained with an installed PV module power of **1.5 kWp** and seasonal application in the period from April to October can be achieved.
Consider the following boundary conditions:
- In the winter **half year 1/6** of the total yield is generated
- With south orientation about $\mathbf{E_{Irradiation}}$**= 850 kWh/(kWpeak*a)** can be generated



Electrochemical Energy Storages

Exercise Batteries #2 b)



$P_{mod} = 1{,}5\ kW_{peak}$

ges.: E_{su}

$E_{wi} = \frac{1}{6} \cdot E_{irr}$

$E_{irr} = 850\ \frac{kWh}{kW_{peak} \cdot a}$

$$E_{su} = P_{mod} \cdot \left(1 - \frac{1}{6}\right) \cdot E_{irr} = 1{,}5\ kW_p \cdot \frac{5}{6} \cdot 850\ \frac{kWh}{kW_p \cdot a} = 1062{,}5\ kWh$$

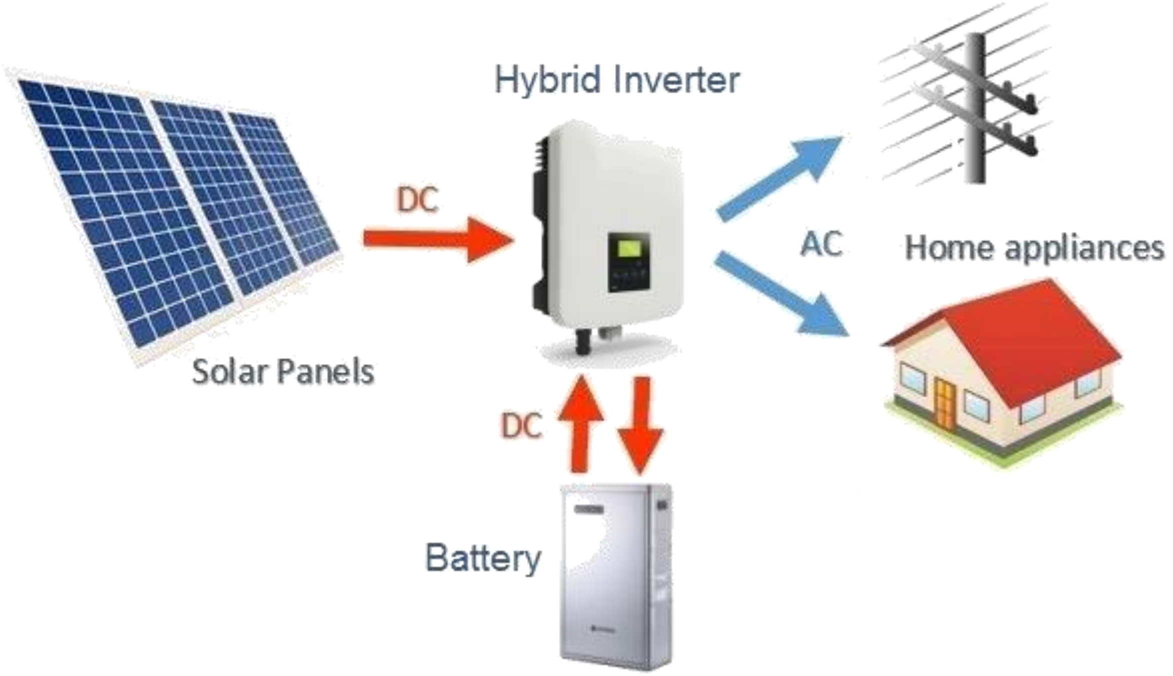
Electrochemical Energy Storages

Exercise Batteries #2 b)

Grid connection and battery storage - design of a battery storage system

A vacation home is located remotely about 100m from the nearest grid connection. The power supply shall be ensured during the summer season by a solar plant with battery storage. The system consists of PV generator, charge controller, battery storage and inverter. It shall supply electrical consumers with a total daily energy demand of 2 kWh. A bad weather period of 5 days should be able to be bridged by the storage.

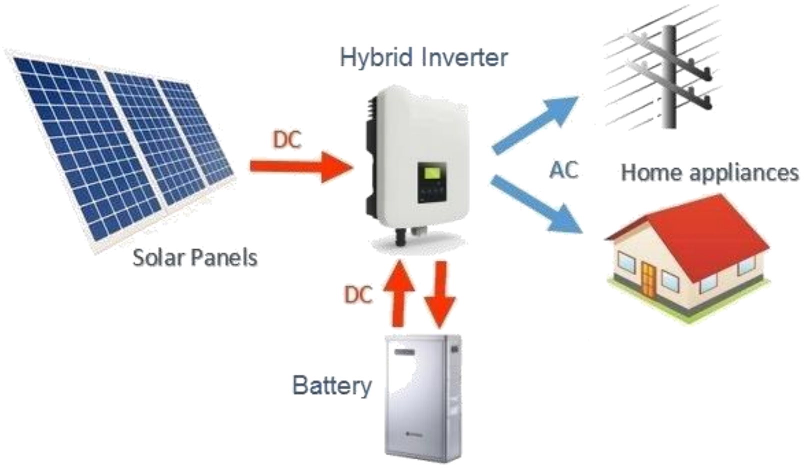
c) What would be the cost per kilowatt-hour of the system if a ten-year period of
use (determined by battery wear) of the plant takes place?
Boundary conditions:
- Cost PV modules per kWpeak: 1.000 €
- Cost charge controller up to 2 kW: 200 €
- Installation costs: 300 €
- Cost of sine wave inverter 2 kW: 1.500 €
- Cost of lead accumulators per kWh or part thereof: 100 €.



Electrochemical Energy Storages

Exercise Batteries #2 c)

c) geg: $t_{use} = 10\,a$ ges: $C_{total,bat}$



conditions:

→ $C_{PV} = 1000\,€/kW$

→ $C_{cc} = 200\,€$

→ $C_{inst} = 300\,€$

→ $C_{inv} = 1500\,€$

→ $C_{bat} = 100\,€/kWh$

Sol: $C_{total,bat} = P \cdot C_{PV} + C_{cc} + C_{inst} + C_{inv} + C \cdot C_{bat}$

$= 1{,}5\,kW \cdot 1000\,€/kW + 200\,€ + 300\,€ + 1500\,€ + 29\,kWh \cdot 100\,€/kWh$

$= 6400\,€$

↳ rounded value from ex. a)

energy consumption for the vacation home

$E_{Home} = 0{,}5 \cdot 10\,a \cdot 365\,d \cdot \frac{2\,kWh}{d} = 3650\,kWh$

↳ seasonal usage, half a year

$C_{kWh} = \frac{C_{total}}{E_{Home}} = \frac{6400\,€}{3650\,kWh} = 1{,}75\,€/kWh$

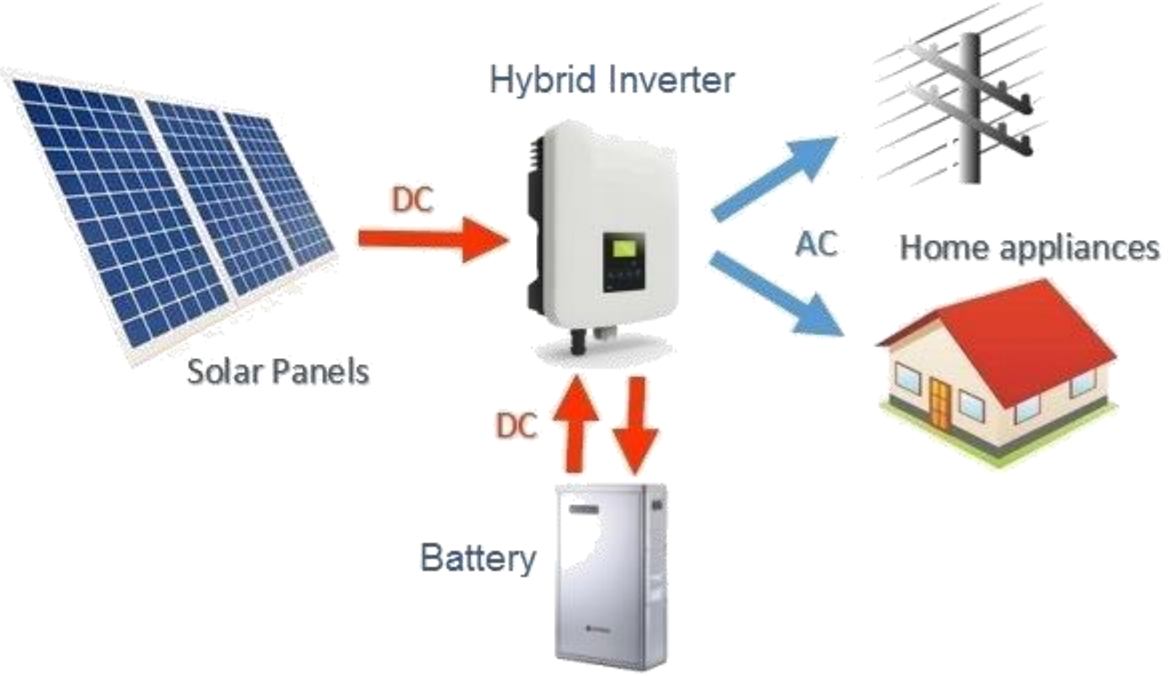
Electrochemical Energy Storages

Exercise Batteries #2 d)

Grid connection and battery storage - design of a battery storage system

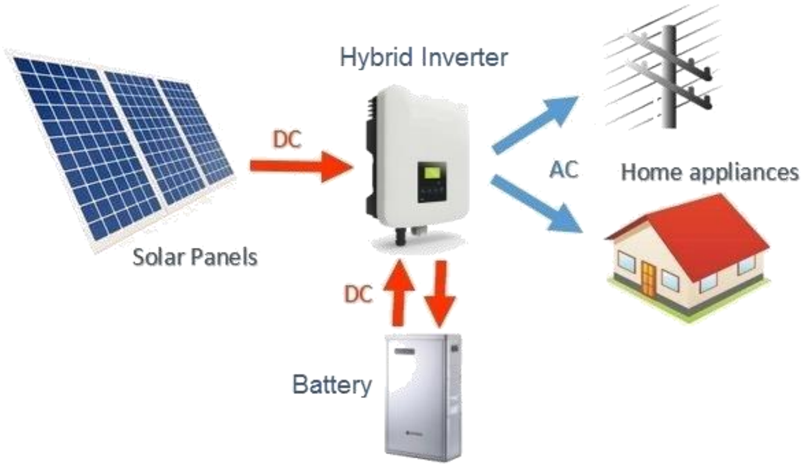
A vacation home is located remotely about 100m from the nearest grid connection. The power supply shall be ensured during the summer season by a solar plant with battery storage. The system consists of PV generator, charge controller, battery storage and inverter. It shall supply electrical consumers with a total daily energy demand of 2 kWh. A bad weather period of 5 days should be able to be bridged by the storage.

d) What would be the cost of the possible alternative of the public grid connection under the given conditions?
the given boundary conditions in the same period of time?
- Costs kWh from the public grid Ce= 0,33 €
- Lump sum. Connection costs (up to 20m all incl.) Cc= 2.500 €
- from 20m costs cable (4x 35mm²) Ccc= 20 €/m
- from 20m manhole costs/cable laying Ccl= 25 €/m



Electrochemical Energy Storages

Exercise Batteries #2 d)



d) geg.: $s = 100\ m$ ges.: C_{total}

$C_E = 0{,}33\ €$

$C_C = 2500\ €$

$C_{cc} = 20\ \frac{€}{m}$

$C_{ce} = 25\ \frac{€}{m}$

Sol: $C_{total} = C_C + (s - 20m) \cdot (C_{cc} + C_{ce}) + E_{Home} \cdot C_{kWh}$

$= 2500\ € + (100m - 20m) \cdot (20\ €/m + 25\ €/m) + 3650\ kWh \cdot 0{,}33\ €/kWh$

$= 7304{,}5\ €$

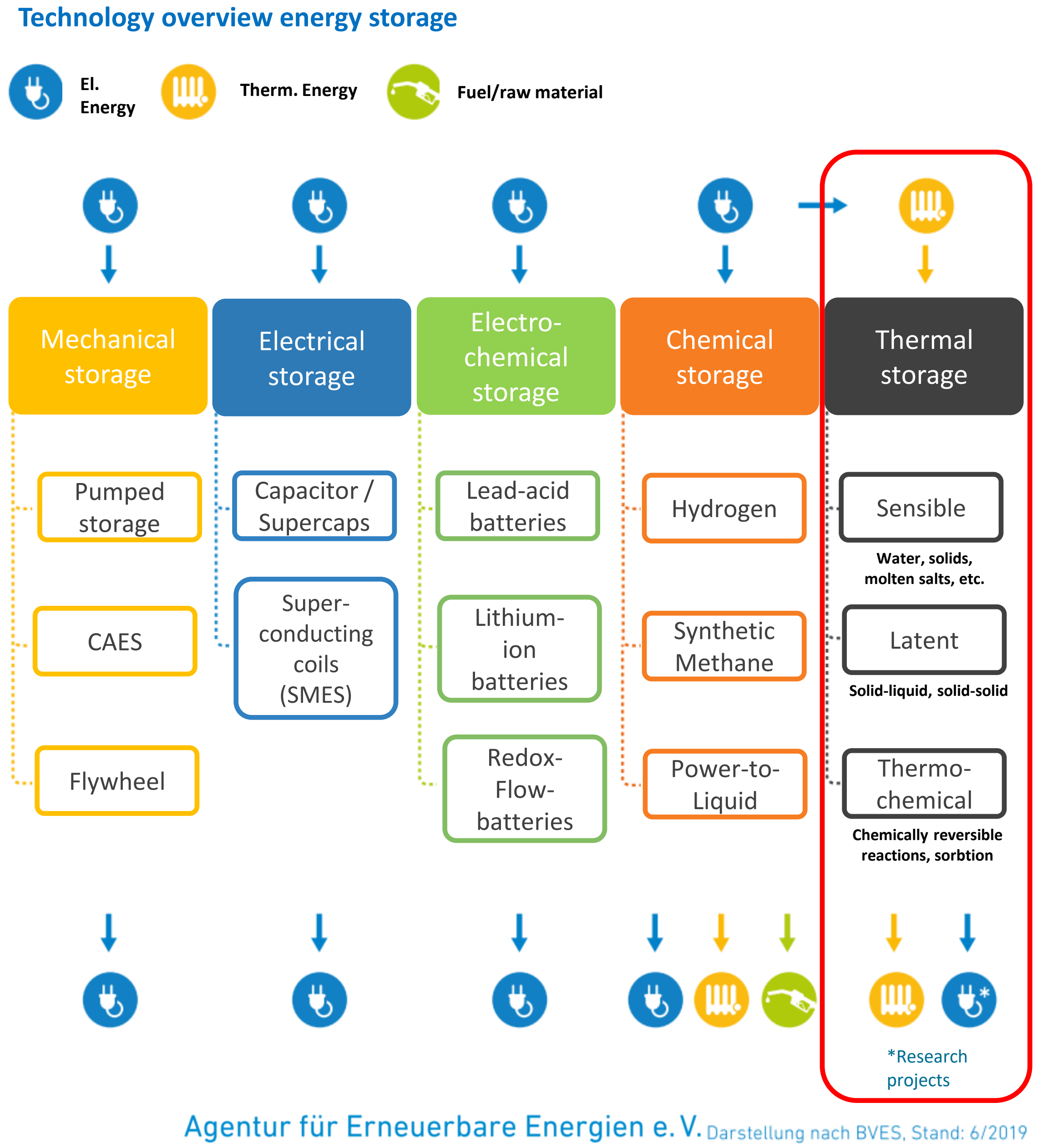
$C_{total\ bat} < C_{total} \rightarrow 6400 < 7304{,}5\ €$

↳ for 10 years self-sufficiency is more profitable

Overview thermal energy storages

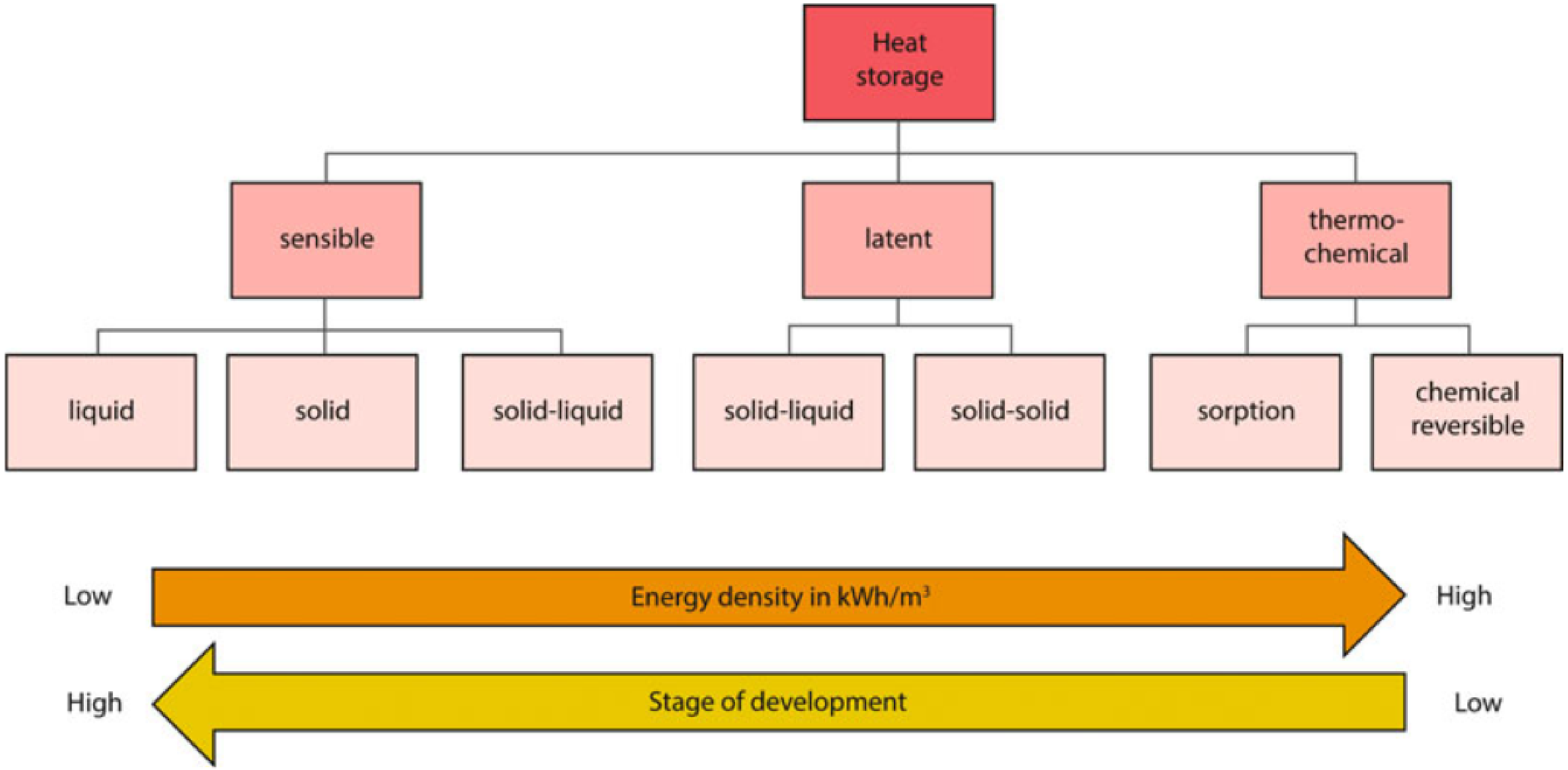
System overview

- Sensible thermal storage
- Latent thermal storage
- Thermochemical storage



Thermal energy storage

System overview



Source #2

Thermal energy storages

Physical basics: capacity and storage density

Sensitive heat storage

- Capacity is the amount of energy in J or kWh that can be stored as a maximum
- Storage density or energy density relates the capacity to the volume used (kWh / m³) or the mass (kWh / kg).

$$Q \approx 50\,\mathrm{kWh}$$

$$w = 50\,\frac{\mathrm{kWh}}{\mathrm{m}^3} \qquad w = 0.05\,\frac{\mathrm{kWh}}{\mathrm{kg}}$$

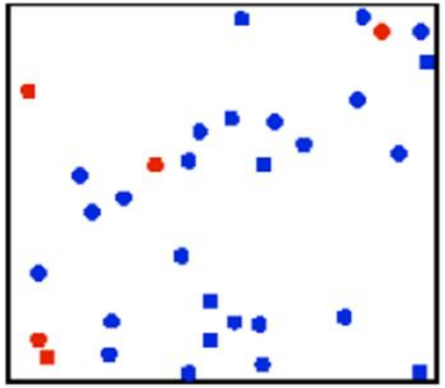
Source: Hochschule Düsseldorf; Energiespeicher – 02 Wärme

Thermal energy storages

Physical basics: internal energy

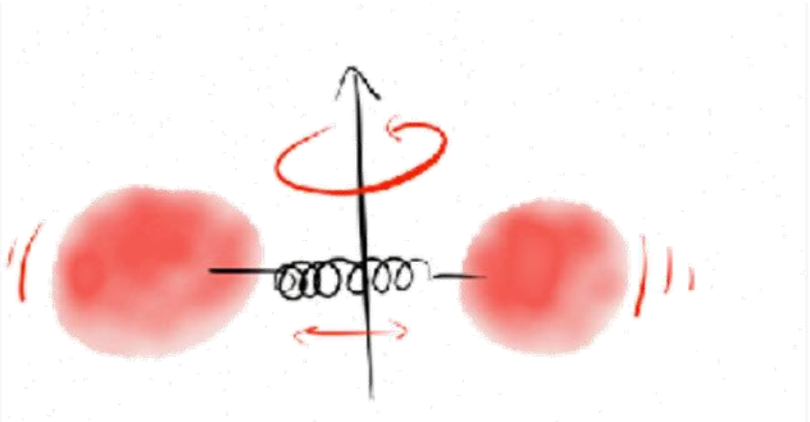
- The **internal energy *U*** describes the kinetic and potential energy of all molecules in the system
- It is divided into translational rotational and vibratory contributions
- This also includes binding energies, such as
  - Chemical
  - Nuclear

Translation



Real gas

Rotation and vibration



Quelle: Hochschule Düsseldorf; Energiespeicher – 02 Wärme

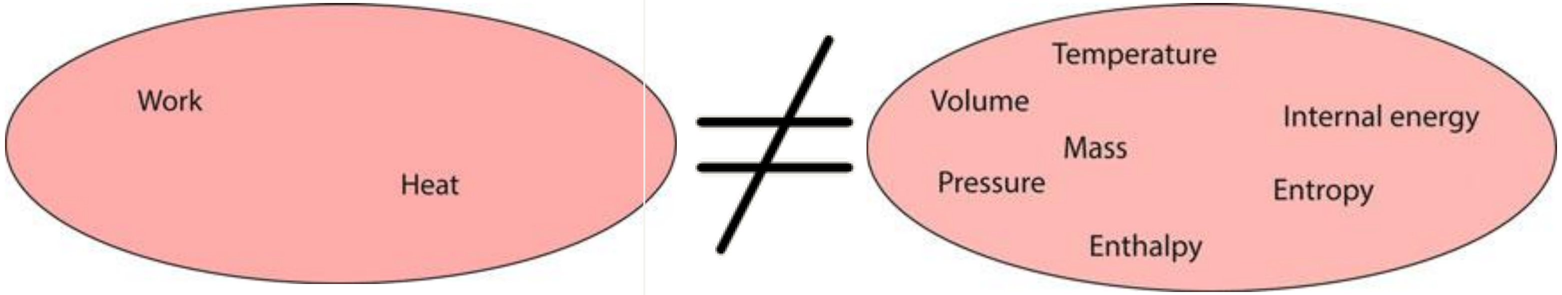
Thermal energy storages

Physical basics: heat

- **Heat is energy, not temperature**
- Heat [Q] is given in and J
- The term **heat quantity** can be better used for clarification

$$Q \neq T$$

- This means that a storage facility does not contain a certain quantity of heat or cold, but rather that it contains the thermodynamic potential to transfer a quantity of heat or cold to another medium



Process variables ≠ State variables

Quelle: Hochschule Düsseldorf; Energiespeicher – 02 Wärme

Thermal energy storages

Physical basics: heat capacity

$$Q = C \cdot \Delta T$$

- The **heat capacity** indicates how much heat a substance (gas, liquid or solid) can store.
- Symbol: ***C***
- Unit: ***J/K***
- The heat capacity of gases and liquids is typically measured at constant volume.
- At constant pressure, the volume increases and mechanical work must be applied against the cylinder pressure.
- Because of this, the heat capacity is higher at constant pressure.

$$C_V = \left.\frac{\partial U}{\partial T}\right|_{\mathrm{V}}$$

$$C_p = \left.\frac{\partial H}{\partial T}\right|_{\mathrm{p}}$$

Quelle: Hochschule Düsseldorf; Energiespeicher – 02 Wärme

Thermal energy storages

Physical basics: specific heat capacity

$$C = \frac{\Delta Q}{\Delta T}$$

- The specific heat capacity relates the amount of heat Q to the mass m of the substance (in kg)
- Symbol: ***c***
- Unit: ***J / (kg K)***
- Alternative: per Mole
- The specific heat capacity c indicates how much heat is necessary to heat a body with a mass of 1kg by 1K.
- **Accordingly, the capacity of the storage is:**

$$c = \frac{C}{m} = \frac{\Delta Q}{m \cdot \Delta T}$$

$$\Delta Q = m \cdot c \cdot \Delta T$$

Examples for spec. heat capacities

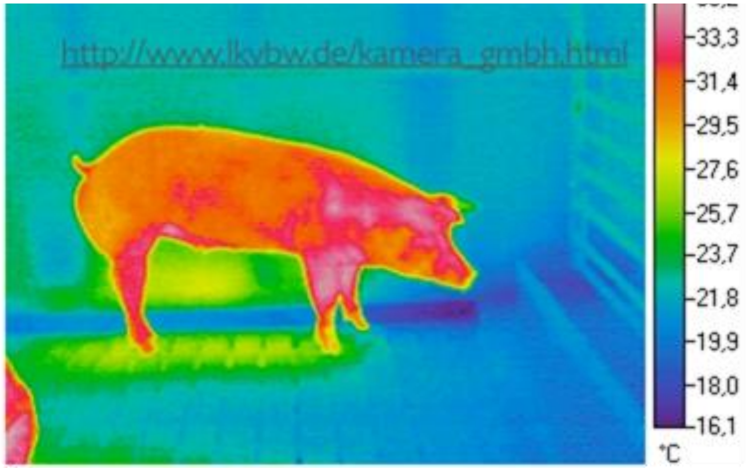
Material	Specific heat capacity c $[\frac{kJ}{kg \cdot K}]$
Air (gaseous)	1
Water (liquid)	4,2
Copper (solid)	0,385

Quelle: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Thermal energy storages

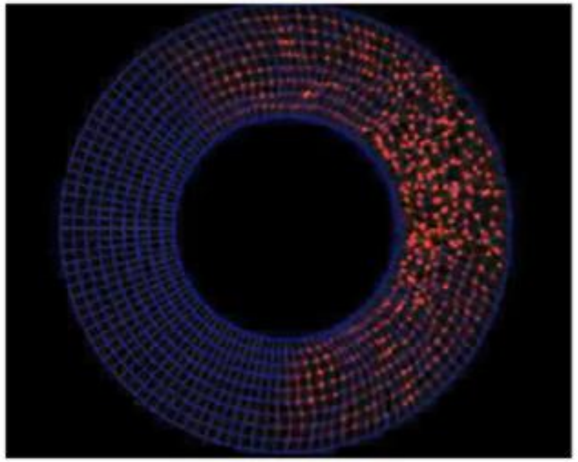
Physical basics: heat transport

Radiation



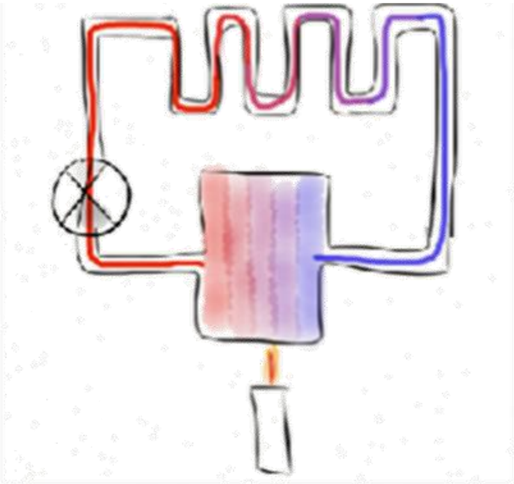
Thermal radiation is a type of heat transfer in which heat is transferred by electromagnetic waves (infrared radiation, infrared light). In contrast to heat conduction and heat flow, heat radiation can also spread in a vacuum.

Conduction



The conduction of heat through direct body contact (e.g. heat dissipation via the bare soles of the feet on cold floor tiles)

Convection

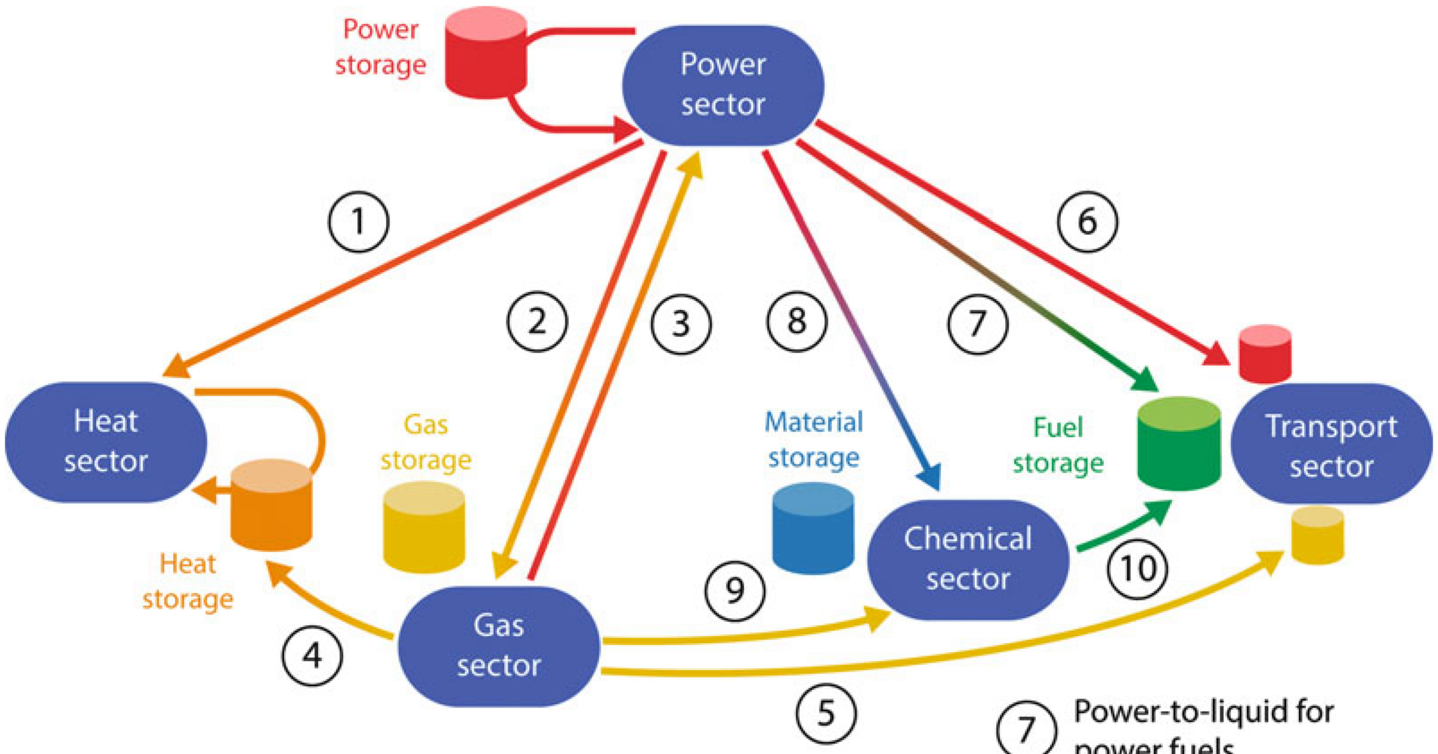


Describes the heat transport through flowing gases or liquids.

Quelle: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Thermal energy storages

Power-to-heat



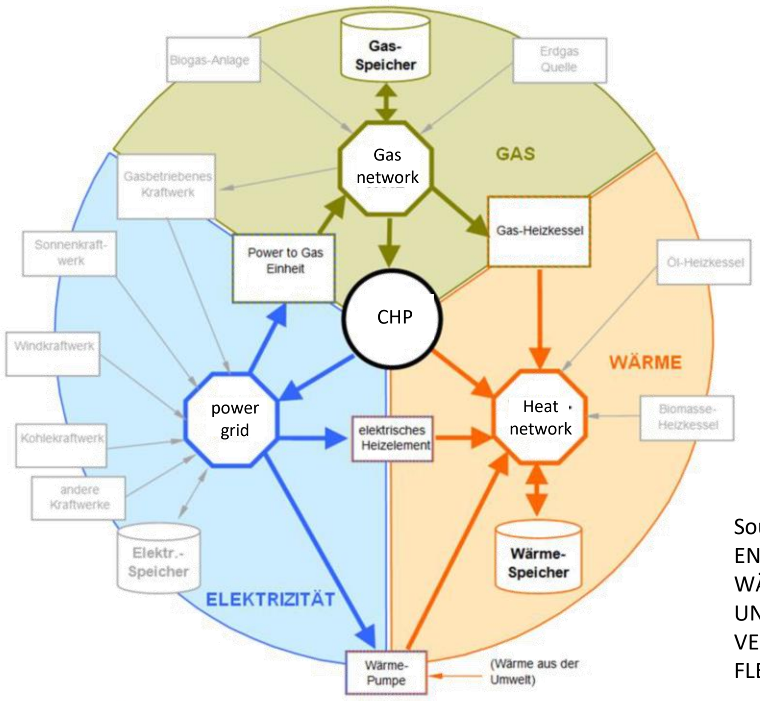
1. Power-to-heat, heat pump, flexible CHP
2. Charge technology power-to-gas
3. Power-to-gas for power storage
4. Power-to-gas for heat storage
5. power-to-Gas for power fuels
6. Electromobility
7. Power-to-liquid for power fuels
8. Charge technology power-to-Chemicals
9. Power-to-Gas for material storage
10. Power-to-chemicals for fuel storage

Source #2

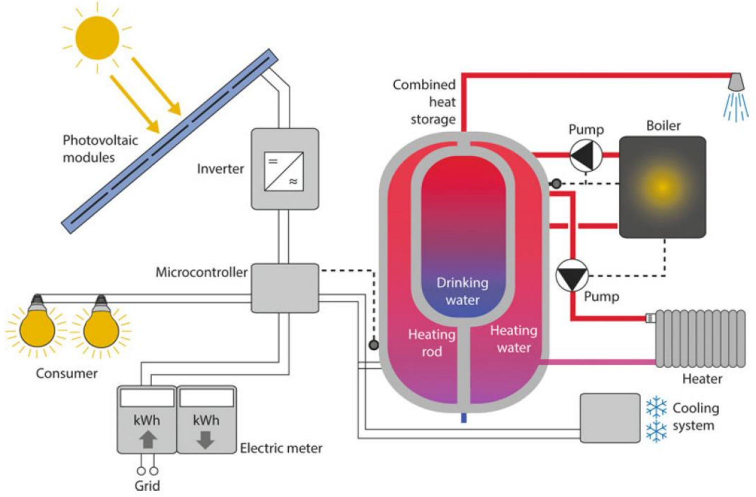
Thermal energy storages

Power-to-Heat (PtH)

- Power-to-heat is the generation of heat using electrical energy (optimally excess energy from renewable energies). This can be done using both electric boilers and heat pumps, which can save fossil fuels and emissions in the heating sector. To increase flexibility, power-to-heat systems are often coupled with heat storage systems.
- The feed mostly takes place in local or district heating networks, but power-to-heat systems can also supply individual buildings or large industrial plants with heat.
- In addition to electrical energy, the heat can also be obtained as a waste product from biogas plants (via CHP).
- Big advantage: Low investment costs (if CHP system and heat storage are available)



Source: Fraunhofer IFAM: ENERGIESPEICHERUNG MITTELS WÄRMESPEICHERN; POWER-TO-HEAT UND POWER-TO-GAS – VERGLEICH VERSCHIEDENER FLEXIBILISIERUNGSOPTIONEN

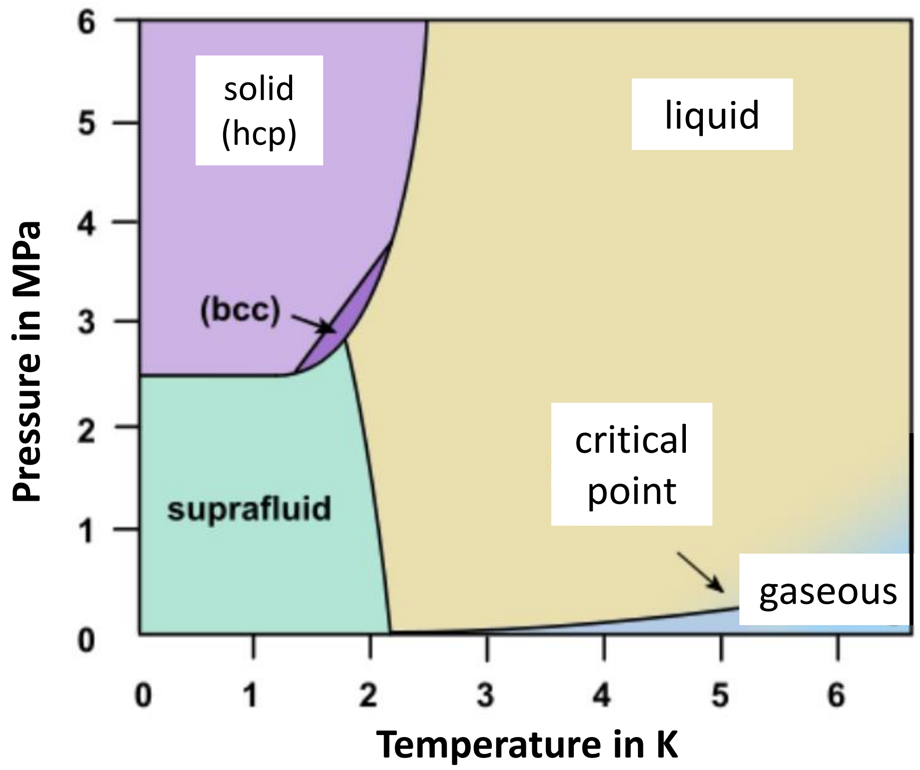


Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

Sensible thermal storages

Physical basics

$$Q = m \cdot c_p \cdot (T_2 - T_1)$$

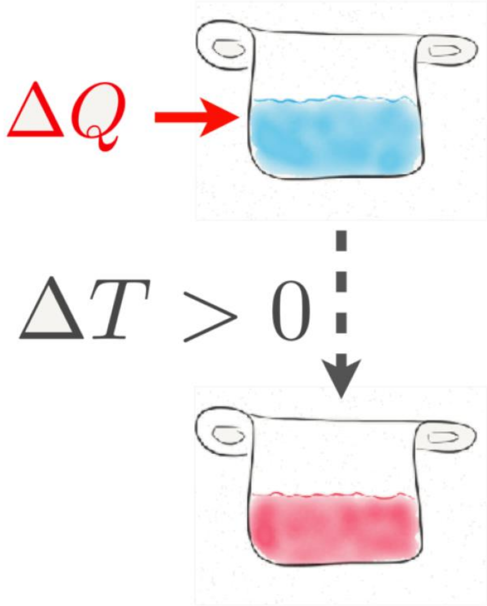


- perceptible change of temperature
- the storage medium is heated or cooled
- Amount of stored energy is dependent of the specific heat capacity (c_p value) of the substance
- typical for sensible storages is that they have no phase change
- The volumetric heat capacity is often also used to assess sensible storages

Sensible thermal storages

Examples heat capacity

Material	spec. heat capacity c / kJ / (kg K)
Air (gaseous)	1
Water (liquid)	4,2
Copper (solid)	0,385



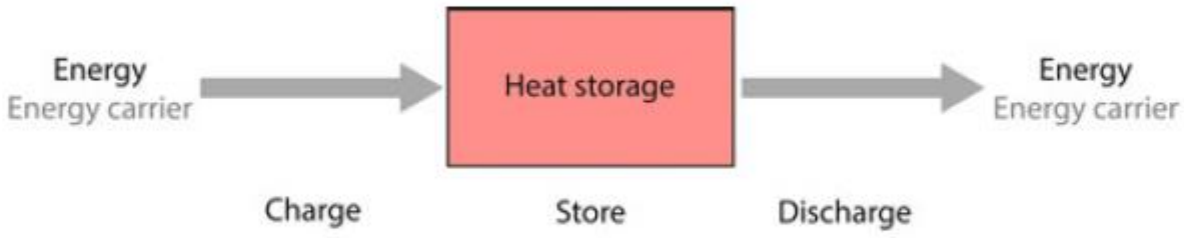
- No other liquid has a higher specific heat capacity than water
- No other liquid has a higher storage density than water
- No other liquid is cheaper than water
- Water has the lowest working temperature

Source: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Sensible thermal storages

Storage types

- Liquid storage
  - Two-tank direct storage
  - Two-tank indirect storage
  - One-tank thermocline
- Solid-state storage

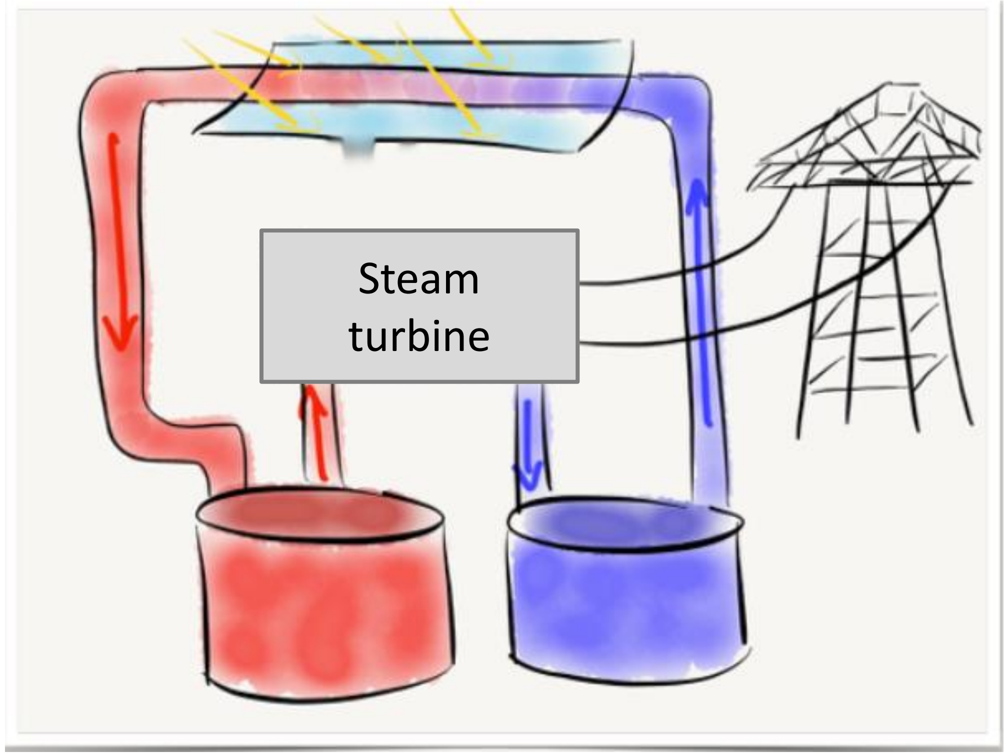


Source #2

Sensible thermal storages

Liquid storage - Two-tank direct storage

- The storage medium is at the same time that Operating medium
- Solar thermal energy in this system is stored in the same fluid
- The fluid is stored in two tanks
  - one at high temperature
  - and the other at low temperature
- Fluid from the low-temperature tank flows through the solar collector or receiver, where solar energy heats it to a high temperature and it then flows to the high-temperature tank for storage.
- Fluid from the high-temperature tank flows through a heat exchanger, where it generates steam for electricity production.
- The fluid exits the heat exchanger at a low temperature and returns to the low-temperature tank.

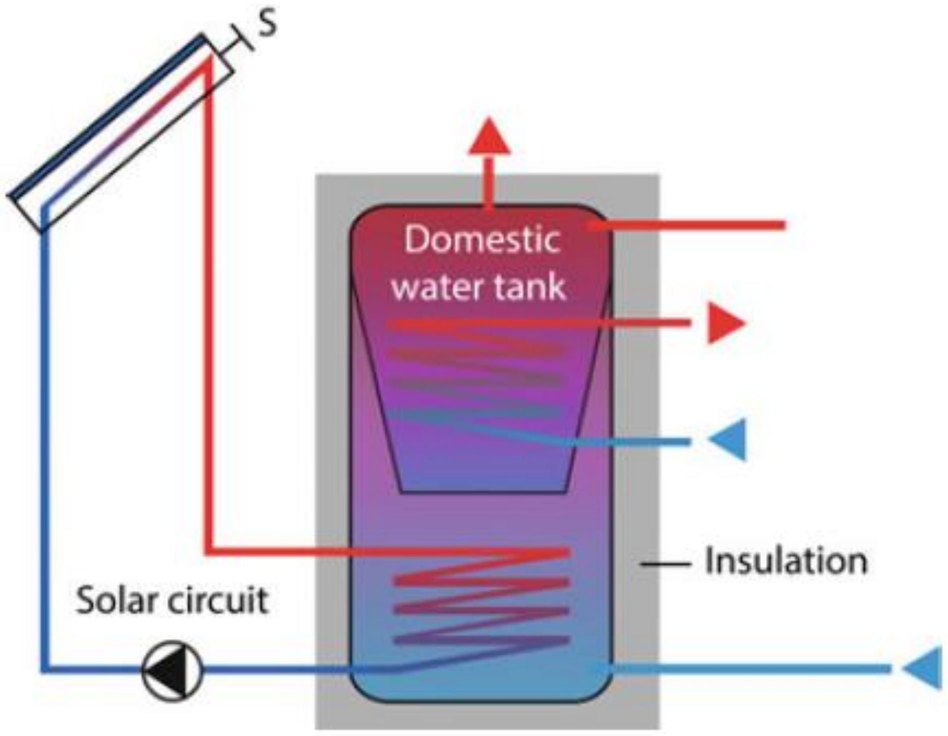


Source: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Sensible thermal storages

Liquid storage - Two-tank indirect storage

- Two-tank indirect systems function in the same way as two-tank direct systems
- Storage and Operating medium are separated.
- Transfer heat exchanger the energy gained both when charging and discharging.
- This system is used in plants in which the heat-transfer fluid is too expensive or not suited for use as the storage fluid.
- This system will be used in many of the parabolic power plants in Spain and has also been proposed for several U.S. parabolic plants. The plants will use organic oil as the heat-transfer fluid and molten salt as the storage fluid.

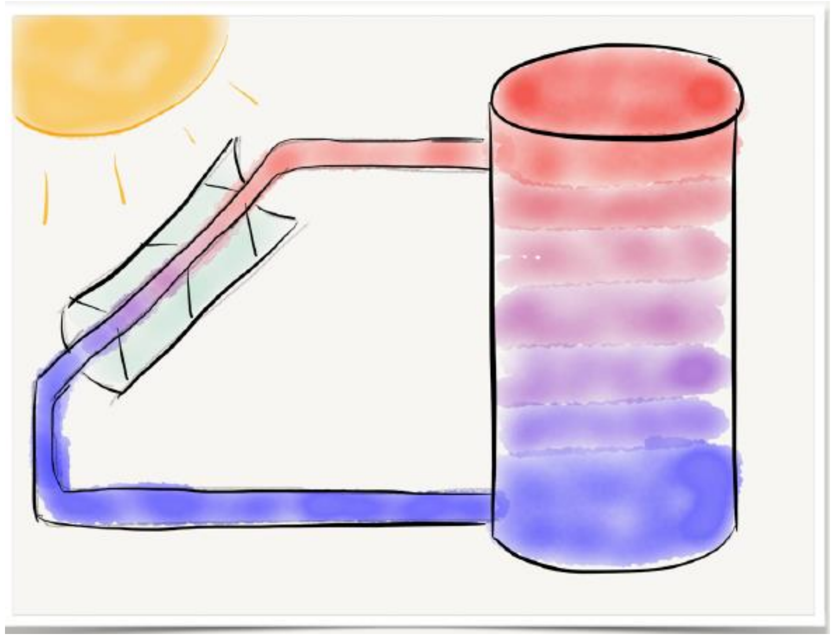


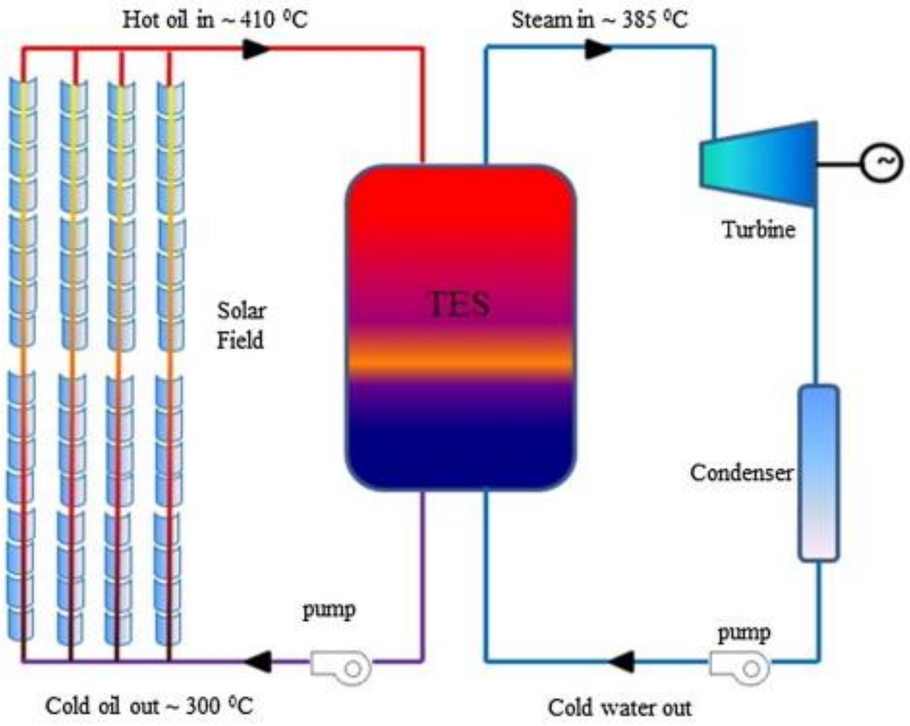
Source #2

Sensible thermal storages

Liquid storage - One-tank thermocline

- A single tank is at the same time heat and cold storage.
- Can be direct and indirect operate.
- The system is dependent on the Temperature gradient and thus the maximum Temperature limited.





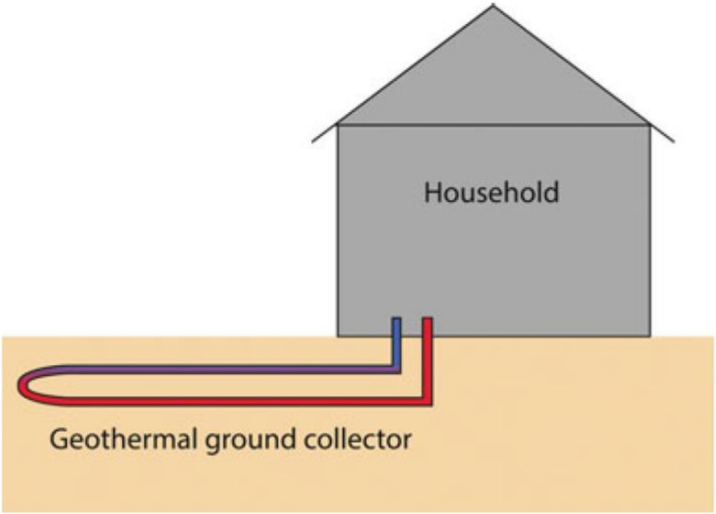
Source: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Source: Performance investigation of single-tank thermocline storage systems for CSP plants

Sensible thermal storages

Liquid storage - Solid-state storage

- Stones, rocks or concrete.
- Thermal expansion of the Storage and pipes must be adapted.
- Without natural resources (Bed of rock) also high Costs.
- Natural resource: Desert sand.

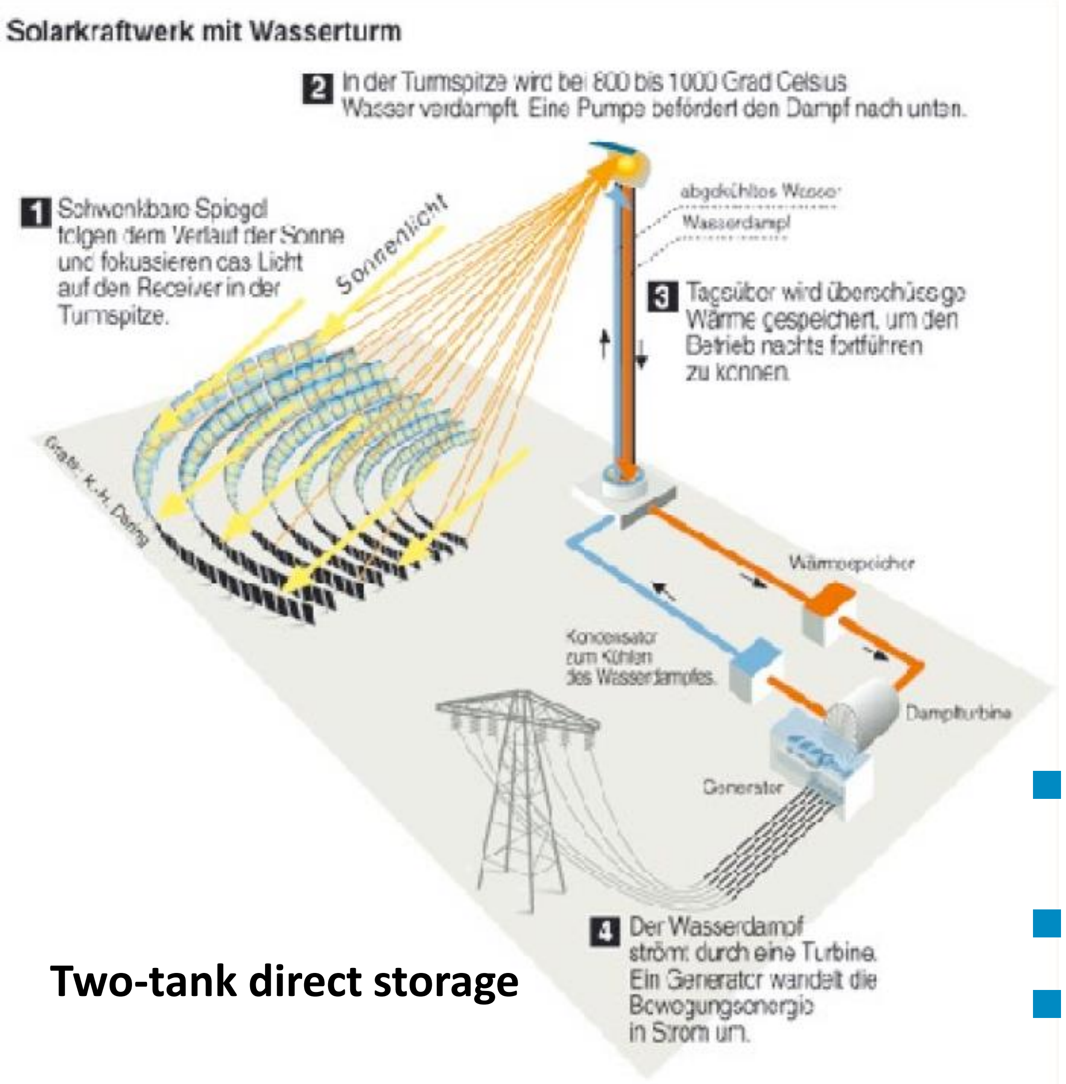


Ground properties	Thermal extraction capacity in W/m^2
Dry, sandy	10–15
Moist, sandy	15–20
Dry, loamy	20–25
Moist, loamy	25–30
Groundwater-bearing	30–35

Source #2

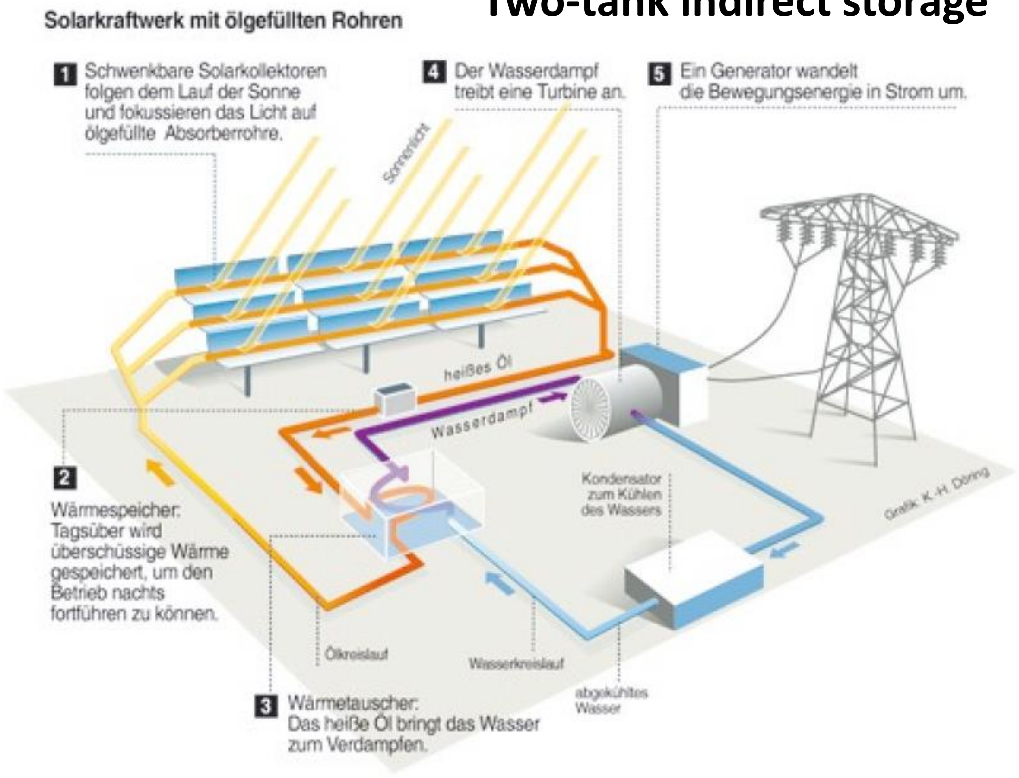
Sensible thermal storages

Power plant operation - solar power plants



Two-tank direct storage

Two-tank indirect storage



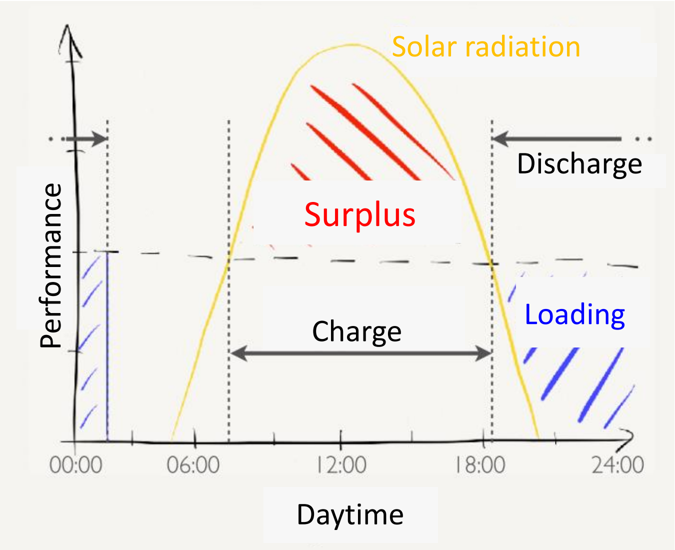
Goal of the storage use

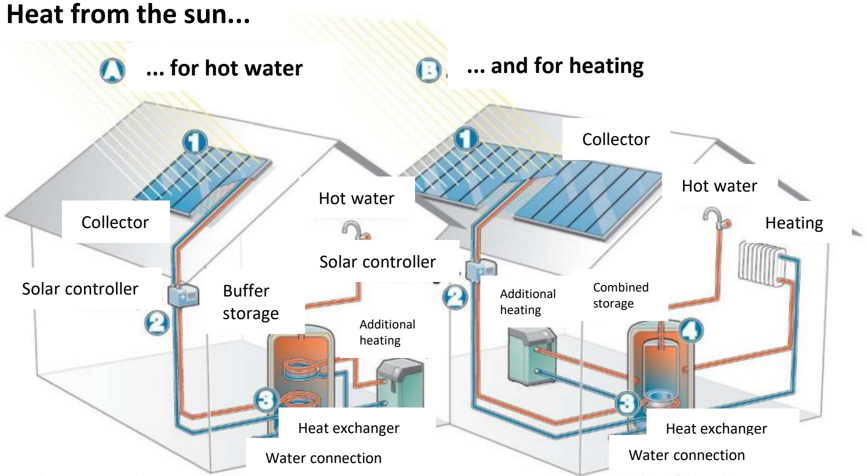
- When operating a power plant, it is primarily solar power plants that use large heat accumulators.
- The storage compensates for short-term fluctuations.
- The storage system extends the availability of the power plant into the sun-free hours (cloud cover, night).

Quelle: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Sensible thermal storages

Short term storage – hot water heat storage



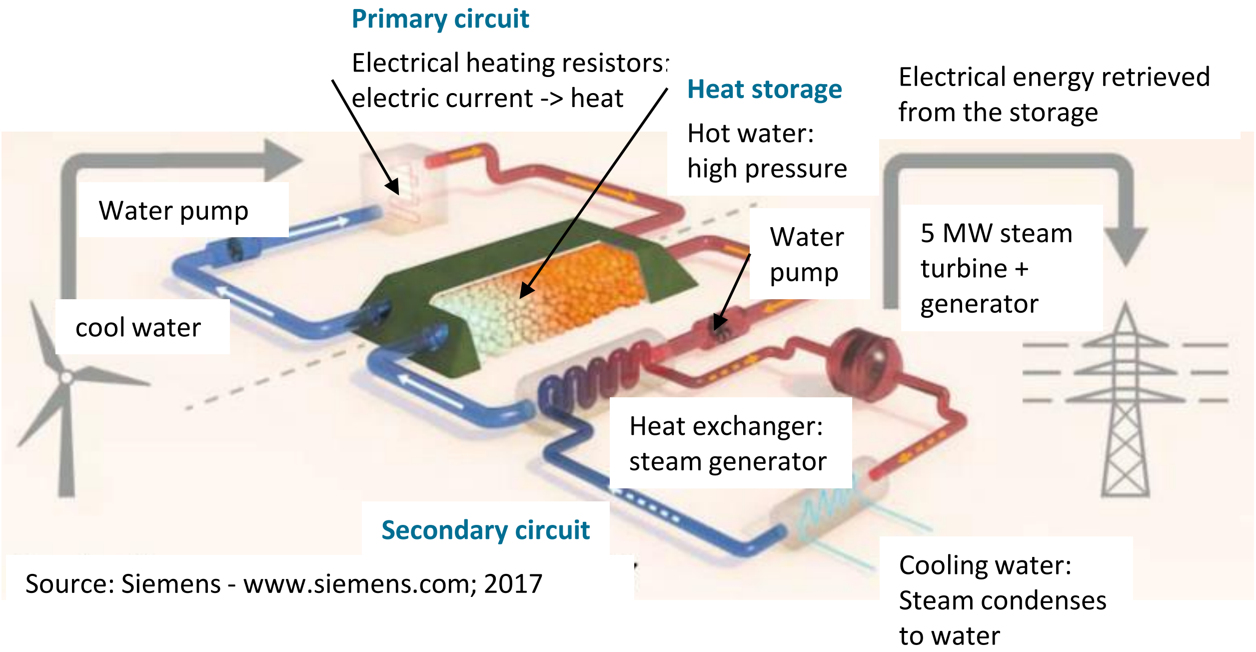


- Often in combination with solar energy
- electrical energy is converted into thermal energy (mostly liquid storage medium)
- The storage compensates for short-term fluctuations
- Burner must be less often be switched on
- Small storage for use water support

Source: FhG: Energiespeicher: Technische Grundlagen und energiewirtschaftliches Potenziale

Sensible thermal storages

Long term storage – gravel water heat storage



Source: Siemens - www.siemens.com; 2017

- Power-to-Heat procedure: Waste heat from industry or surpluses from power generation are stored in thermal energy
- Example: sensible large heat storage with a storage capacity of 36 MWh
- Electricity is converted into heat (hot air) and heats up stone rubble to 600°C
  - Charge-discharge-efficiency is 25%
- Recovery via the inflow of cold air, which is led through a turbine

Source: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Sensible thermal storages

Advantages and disadvantages

Advantages	Disadvantages
Already established as a classic heat storage.	The main disadvantages of all sensible heat storages are the necessity for thermal insulation and the relatively short maximum storage period.
High availability and low material costs.	Heat losses are proportional to the surface-to-volume ratio, therefore small systems can only be used as short-term storage.

Thermal Energy Storage – Exercise I

A brick masonry has the thermal conductivity λ_1, the specific heat capacity c_1 and the density ρ_1.

a) Calculate the heat flow $\dot{Q}$ through the brick wall of thickness d_1 at the inside temperature w_i and the outside temperature w_{A_1} for $A = 1.00\ m^2$ wall area! (The heat transfer is to be left out of consideration).

b) Overnight, a temperature drop from w_{A_1} to w_{A_2} occurs.
What heat Q_W does the wall piece give off due to its heat capacity until the new steady-state temperature curve, if the internal temperature is kept constant? For what time t_1 could this heat be used to cover the increase in heat flow?

c) What are the times t_2 and t_3 for a wall made of gas silicate concrete (ρ_2, λ_2, c_2) and a wall insulated with expanded polystyrene (ρ_3, λ_3, c_3), each with the same heat transfer coefficient?

Parameters:

Brick wall:	$\rho_1 = 1800\ {kg}/{m^3}$	$\lambda_1 = 0{,}81\ {W}/{(m \cdot K)}$		$d_1 = 36\ cm$
		$c_1 = 0{,}26\ {Wh}/{(kg \cdot K)}$		$\vartheta_{inside} = 20\ °C$
Gas concrete wall:	$\rho_2 = 500\ {kg}/{m^3}$	$\lambda_2 = 0{,}22\ {W}/{(m \cdot K)}$		$\vartheta_{outside_1} = +5\ °C$
		$c_2 = 0{,}29\ {Wh}/{(kg \cdot K)}$		$\vartheta_{o_2} = -10\ °C$
Plystyrene foam:	$\rho_3 = 15\ {kg}/{m^3}$	$\lambda_3 = 0{,}025\ {W}/{(m \cdot K)}$		
		$c_3 = 0{,}41\ {Wh}/{(kg \cdot K)}$		

Thermal Energy Storage – Exercise I

a) $\dot{Q} = \Lambda \cdot A \cdot (\vartheta_i - \vartheta_o)$

$\dot{Q} = \Lambda \cdot A \cdot (\vartheta_i - \vartheta_{o_1})$

$\Lambda = \frac{\lambda}{d}$ $\rightarrow$ heat transfer coefficient

$\dot{Q} = \frac{\lambda_1}{d_1} \cdot A \cdot (\vartheta_i - \vartheta_{o_1})$

$\dot{Q} = \frac{0{,}81 \frac{W}{m \cdot K}}{0{,}36\ m} \cdot 1\ m^2 \cdot (20°C - 5°C)$

$\underline{\underline{\dot{Q} = 33{,}75\ W}}$

Thermal Energy Storage – Exercise I

b) 1) $Q = m \cdot c \cdot \Delta T$

$Q_W = m \cdot c_1 \cdot (\overline{\vartheta_1} - \overline{\vartheta_2})$ | $\overline{\vartheta_1} = \frac{\vartheta_{a_1} + \vartheta_i}{2}$; $\overline{\vartheta_2} = \frac{\vartheta_{a_2} + \vartheta_i}{2}$

$Q_W = m \cdot c_1 \cdot \left(\frac{\vartheta_{a_1} + \vartheta_i - (\vartheta_i + \vartheta_{a_2})}{2}\right)$

$Q_W = m \cdot c_1 \cdot \left(\frac{\vartheta_{a_1} + \vartheta_i - \vartheta_i - \vartheta_{a_2}}{2}\right)$

$Q_W = m \cdot c_1 \cdot \frac{\vartheta_{a_1} - \vartheta_{a_2}}{2}$

$m = \rho_1 \cdot d_1 \cdot A$

$m = 1800 \, \frac{kg}{m^3} \cdot 0{,}36 \, m \cdot 1 m^2$

$\underline{m = 648 \, kg}$

$Q_W = 648 \, kg \cdot 0{,}26 \, \frac{Wh}{kg \cdot K} \cdot \frac{(5°C - (-10°C))}{2}$

$\underline{\underline{Q_W = 1263{,}6 \, Wh}}$

2) $Q = \Delta \dot{Q} \cdot t$

$Q_W = \Delta \dot{Q} \cdot t_1$

$\Delta \dot{Q} = \dot{Q}_2 - \dot{Q}_1 = \frac{\lambda_1}{d_1} \cdot A \cdot (\vartheta_i - \vartheta_{a_2}) - \frac{\lambda_1}{d_1} \cdot A \cdot (\vartheta_i - \vartheta_{a_1})$

$= \frac{\lambda_1}{d_1} \cdot A \left[(\vartheta_i - \vartheta_{a_2}) - (\vartheta_i - \vartheta_{a_1})\right]$

$= \frac{\lambda_1}{d_1} \cdot A \cdot (\vartheta_{a_2} - \vartheta_{a_1})$

$\Delta \dot{Q} = \frac{0{,}81 \, \frac{W}{m \cdot K}}{0{,}36 \, m} \cdot 1 m^2 \cdot \left|-10°C - 5°C\right|$

$\underline{\Delta \dot{Q} = (-) \, 33{,}75 \, W}$

↳ positive, since Kelvin is always an absolute value

$t = \frac{Q}{\Delta \dot{Q}}$

$t_1 = \frac{Q_W}{\Delta \dot{Q}}$

$t_1 = \frac{1263{,}6 \, Wh}{33{,}75 \, W}$

$\underline{\underline{t_1 = 37{,}44 \, h}}$

Thermal Energy Storage – Exercise I

c) heat transfer coefficient = const.

$$\Lambda = \frac{\lambda}{d} = \text{const.}$$

$$\frac{\lambda_1}{d_1} = \frac{\lambda_2}{d_2} = \frac{\lambda_3}{d_3}$$

$$\Lambda = \frac{0{,}81 \frac{W}{m \cdot K}}{0{,}36\ m}$$

$$\underline{\Lambda = 2{,}25 \frac{W}{K}}$$

$$d = \frac{\lambda}{\Lambda}$$

$$d_2 = \frac{0{,}22 \frac{W}{m \cdot K}}{2{,}25 \frac{W}{K}}$$

$$\underline{d_2 = 0{,}088\ m}$$

$$\underline{d_3 = 0{,}01\ m}$$

$$t_2 = \frac{Q_{W_2}}{\Delta \dot{Q}_2} = \frac{106{,}57}{33{,}67} = 3{,}16\ h$$

$$t_3 = \frac{Q_{W_3}}{\Delta \dot{Q}_3} =$$

$$t_2 = \frac{Q_{W_2}}{\Delta \dot{Q}_2} = \frac{106{,}57\ Wh}{33{,}67\ W}$$

$$\underline{\underline{t_2 = 3{,}16\ h}}$$

$$t_3 = \frac{Q_{W_3}}{\Delta \dot{Q}_3} = \frac{0{,}46\ Wh}{37{,}5\ W}$$

$$\underline{\underline{t_3 = 0{,}012\ h \mathrel{\hat{=}} 44\ s}}$$

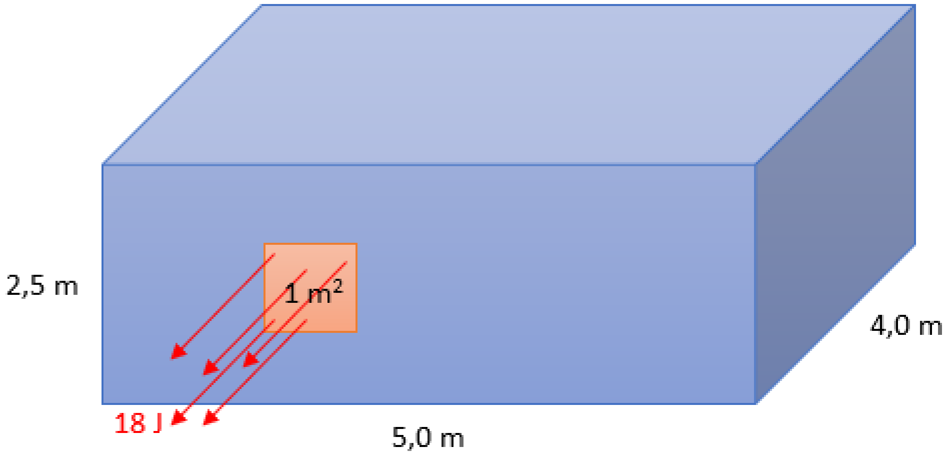
Thermal Energy Storage – Exercise II

In an ideally insulated hot water tank there is 1.0 m^3 water with $c_{Water} = 4.2\ \frac{kJ}{kg \cdot K}$

a) Calculate the increase in the internal energy of water when it is heated by $\Delta\vartheta = 80\ °C$.

b) The hot water tank should cover the energy losses of one room. The temperature in the room should be 18 °C, the temperature of the outside air 12 °C. For simplicity, assume that each square meter of wall, floor, ceiling, and window gives off 18 Joule to the outside every second at this temperature difference.

Estimate how long the water heater can maintain the temperature of 18 °C in a room 5.0 m long, 4.0 m wide, and 2.50 m high.



Thermal Energy Storage – Exercise II

a) $\Delta E_i = c_W \cdot m \cdot \Delta\vartheta$

$m = V \cdot \rho$

$\Delta E_i = c_W \cdot V \cdot \rho \cdot \Delta\vartheta$

$\Delta E_i = 4{,}2 \frac{kJ}{kg \cdot K} \cdot 1\,m^3 \cdot 1000 \frac{kg}{m^3} \cdot 80\,K$

$\underline{\underline{\Delta E_i = 336.000\,kJ}}$

b) $A_{Room} = 2 \cdot l \cdot w + 2 \cdot l \cdot h + 2 \cdot w \cdot h$

$= 2 \cdot 5m \cdot 4m + 2 \cdot 5m \cdot 2{,}5m + 2 \cdot 4m \cdot 2{,}5m$

$\underline{\underline{= 85\,m^2}}$

P_{Loss} per second

$P_L = 18 \frac{J}{m^2 \cdot s} \cdot 85\,m^2$

$\underline{P_L = 1{,}5 \frac{kJ}{s}}$

$E = P \cdot t$

$\Delta E_i = P_L \cdot \Delta t$

$\Delta t = \frac{\Delta E_i}{P_L} = \frac{336.000\,kJ}{1{,}5 \frac{kJ}{s}}$

$\Delta t = 224.000\,s$

$\underline{\underline{\Delta t \approx 62\,h\ 10\,min}}$

Latent thermal storages

Energy and Enthalpy

Energy *U*

- The inner energy is the kinetic and potential energy of all particles in the System
- Also binding energies (chemical, nuclear)
- the internal energy is the amount of heat exchanged at constant volume
- Is usually a closed system

$$dU = dQ + dW$$
$$= dQ - pdV$$

Enthalpy *H*

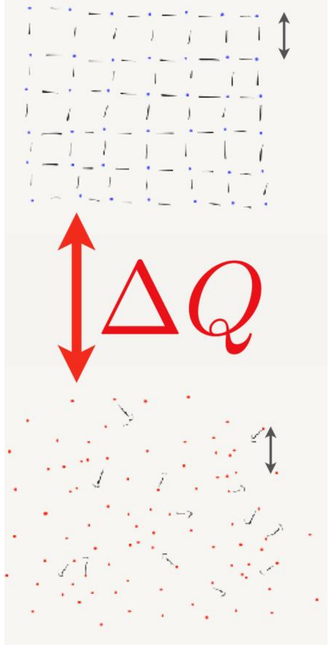
- The enthalpy contains additionally the energy the was needed to be able to pressure p the system into the volume V (from to the "nothing" there expand)
- the enthalpy is the amount of heat exchanged at constant pressure
- Is usually a opened system

$$H = U + pV$$

$$dH = dU + d(pV)$$
$$= dU + pdV + Vdp$$
$$= dQ - pdV + pdV + Vdp$$

Latent thermal storages

Enthalpy



Phase	Density kg/m³
Ice	917
Water	1000
Steam	0,6

Water has a melting enthalpy of Δh = 333 kJ/kg, i.e. to melt 1kg ice to water 333kJ heat is needed.

- During **melting / crystallization** the distance between the molecules remains comparable.
- Therefore the volume hardly changes (typically around 10%) during this phase change, i.e. the density remains comparable.
- For technical applications this is a big Simplification

- When **boiling/ condensing**, it increases the distance between the Molecules huge.
- That's why the Volume or the density clearly.
- In the technical Application must therefore high pressures considered will be.

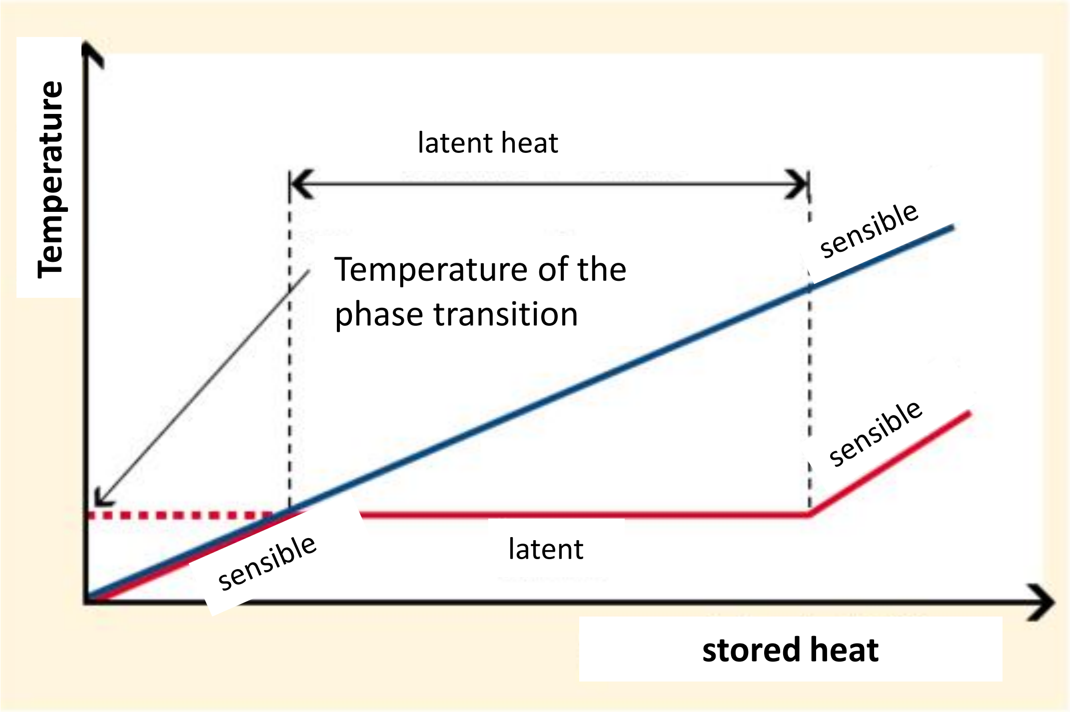
Latent thermal storages

Physical basics

- The thermal energy is used to change the aggregate state (solid, liquid or gaseous) of the storage medium
- Material melts and evaporates by the heat input without increasing the temperature of the storage medium
- Simplest example of a phase change material is an ice cube in a glass -> ice cube extracts heat from the glass in order to melt
- Example for inverse principle -> hand heater
- During the charging process, heat absorption by the storage medium is fixed by changing the state of aggregation
- Also called PCM-Storage (Phase Change Material Storage)

Latent thermal storages

Comparing latent and sensible



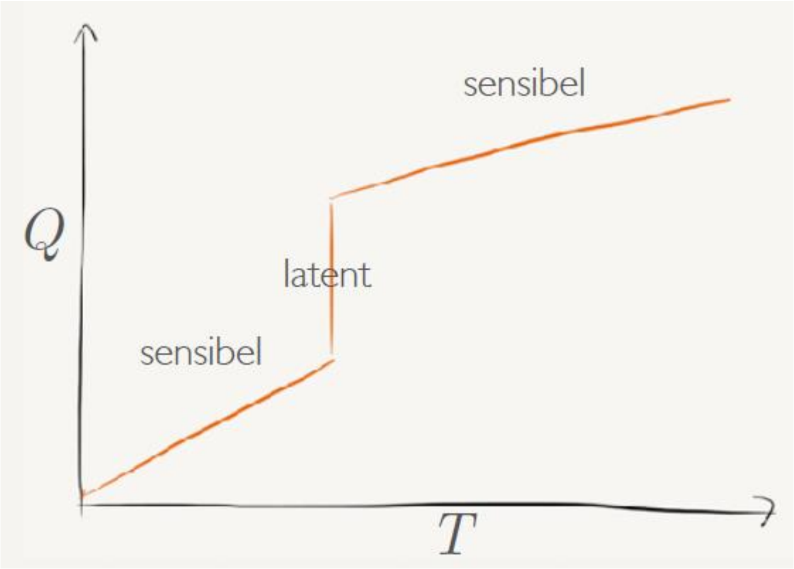
Source: FhG: Energiespeicher: Technische Grundlagen und energiewirtschaftliches Potenziale

- Latent heat can store large amounts of energy in a small temperature range
- The difference in density from the solid to the liquid state in many materials is negligibly small
- Exergy loss during storage is lower than with sensible storage concepts, since the energy supply does not simultaneously reduce the temperature difference elevated to the surrounding

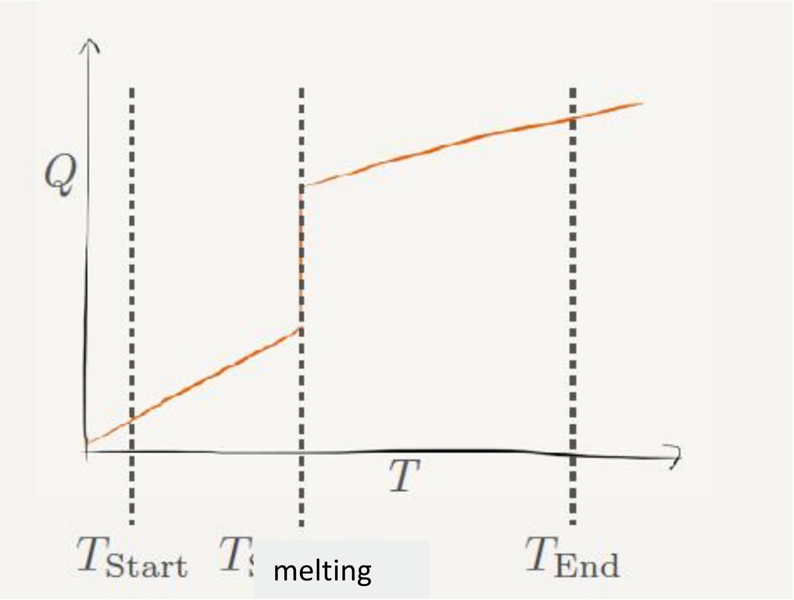
Latent thermal storages

Capacity

- The total capacity is the Sum of
  - sensible heat (solid)
  - latent heat
  - sensible heat (liquid)



$$\Delta Q = m \cdot c_{solid} \cdot (T_{melting} - T_{start}) + m \cdot \Delta h + m \cdot c_{liquid} \cdot (T_{melting} - T_{start})$$



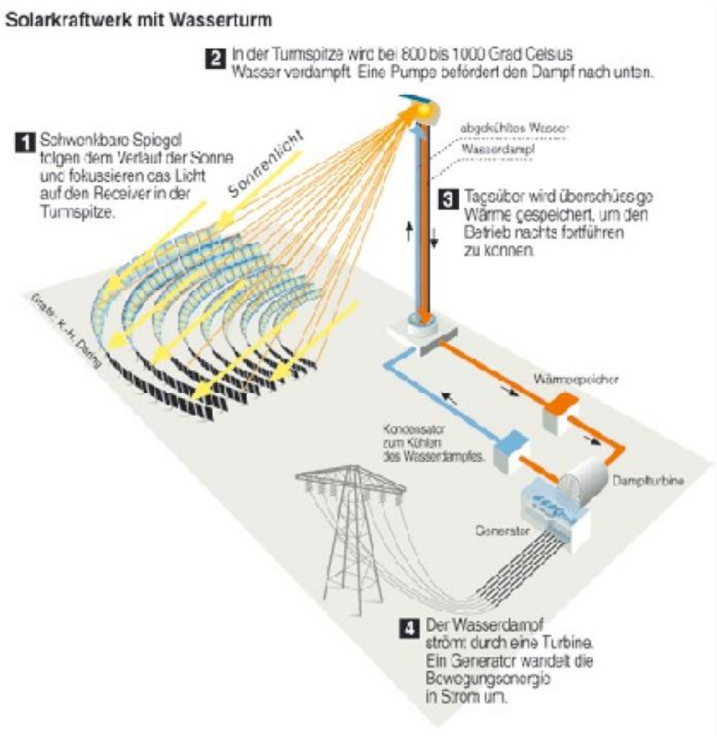
Source: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Latent thermal storages

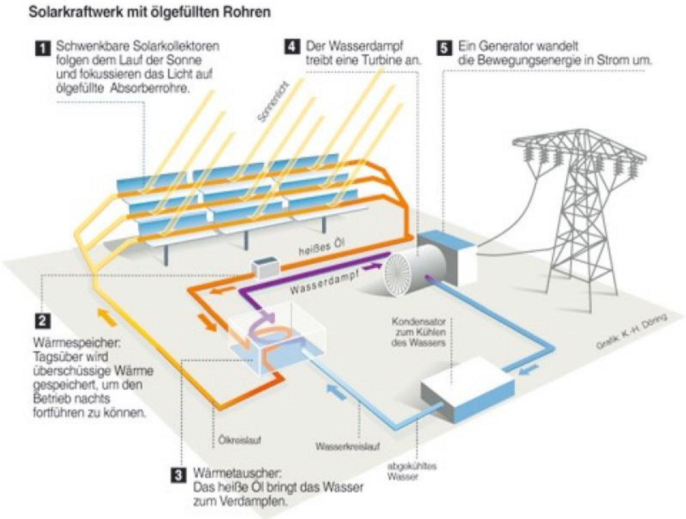
Applications

- Potassium and sodium nitrate is used in solar power plants as Melted salt needed, it melts at just over 300 ° C.
- The stores presented in the case of sensible heat are therefore actually also latent heat storage.

Two-tank direct storage



Two-tank indirect storage



Source: Hochschule Düsseldorf; Energiespeicher – 05 Sensible Wärmespeicher

Latent thermal storages

Application

- Idea: heat storage is included industrial waste heat.
- The heat becomes one Consumer driven
- Latent heat storage based on sodium acetate.
- Storage weight: 27 t
- 17m^3 sodium acetate.
- Storage capacity > 2MWh.

Same functional principle as with heat pillows

- For quick charge and discharge, the material itself has to be good thermal conductivity.
- Otherwise, the energy transfer in heat exchanger too long.

Source:https://www.deutschlandfunk.de/tolle-idee-was-wurde-draus-hitze-auf-raedern.676.de.html?dram:article_id=410599

Latent thermal storages

Materials

Class of material	Material	Molecular formula	Melting temperature in °C	Melting enthalpy in kJ/kg	Thermal conductivity in W/m²K	Density in kg/m³
Eutectic salt water mixture	Water/sodium chloride	$H_2O/NaCl$	–21	222	–	1,165 (liquid 20 °C)
Water	Water	H_2O	0	334	0.597 (liquid 20 °C)	998 (liquid 20 °C) 917 (solid)
Salt hydrate	Calcium chloride hexahydrate	$CaCl_2 \cdot 6H_2O$	29	171	0.54 (liquid 39 °C)	1,562 (liquid 32 °C)
	Disodium hydrogen phosphate Dodecahydrate	$Na_2HPO_4 \cdot 12H_2O$	35–40	280	0.476 (liquid)	1,442 (liquid)
	Sodium sulfate penthahydrate	$Na_2S_2O_3 \cdot 5H_2O$	48	187	–	1,670 (liquid)
	Sodium acetate trihydrate	$Na(CH_3COO) \cdot 3H_2O$	58	226	–	1,280 (liquid)
	Magnesium nitrate hexahydrate	$Mg(NO_3)_2 \cdot 6H_2O$	89	149	0.49 (liquid 95 °C)	(liquid)
	Magnesium chloride hexahydrate	$MgCl_2 \cdot 6H_2O$	117	165	0.57 (liquid 120 °C)	(liquid)
Salts						

Class of material	Material	Molecular formula	Melting temperature in °C	Melting enthalpy in kJ/kg	Thermal conductivity in W/m²K	Density in kg/m³
Salt mixture	Sodium nitrate + potassium nitrate	$KNO_3/NaNO_3$	222	100	0.5 (liquid)	1,900 (liquid)
	Lithium nitrate + sodium nitrate	$LiNO_3–NaNO_3$	194	265	0.5 (liquid)	1,900 (liquid)
Paraffin	Octadecane	$C_{18}H_{38}$	28	245	0.15 (solid)	777 (liquid)
Fatty acid	Lauric acid	$CH_3(CH_2)_{10}COOH$	43	178	0.15 (liquid 50 °C)	870 (liquid 50 °C)
	Myristic acid	$CH_3(CH_2)_{12}COOH$	58	186	–	861 (liquid 55 °C)
Sugar alcohol	Erythritol	$C_4H_5(OH)_6$	120	340	0.32 (liquid 140 °C)	1,300 (liquid 140 °C)
PEG	PEG 6000	$HO\text{-}[CH_2\text{-}CH_2\text{-}O]_n\text{-}H$	60	190		1,085 (liquid 70 °C)

Source #2

Latent thermal storages

Advantages and Disadvantages

Advantages	Disadvantages
Users can save energy and thus costs with a latent heat storage device.	The acquisition costs of a latent heat storage unit are relatively high.
The heat required to melt the PCM can be generated by a solar thermal system.	The function depends on outside temperatures and solar radiation.
Latent heat accumulators can store and release heat over a long period of time.	
Temperature peaks can be compensated.	

Thermal Energy Storages – Exercise III

Can you cool a beer (200ml) from room temperature (20°C) to 10°C with a single ice cube (20g, -18°C)?

Given:

$$c_{Water_{solid}} = 1{,}9\ \frac{kJ}{kg\ \cdot K}$$

$$c_{Water_{liquid}} = 4{,}2\ \frac{kJ}{kg\ \cdot K}$$

$$Melting\ enthalpy\ \Delta h = 333\ \frac{kJ}{kg}$$

Thermal Energy Storages – Exercise III

1) What Energy is needed to cool the beer as intended?

$$E = c \cdot m \cdot \Delta\vartheta$$

$$E = 4{,}2 \frac{kJ}{kg \cdot K} \cdot 0{,}2\,kg \cdot 10\,K$$

$$\underline{E = 8{,}4\,kJ}$$

Thermal Energy Storages – Exercise III

2) What heat capacity does the ice cube have?

The total capacity is the sum of

- sensible heat (solid)
- latent heat
- sensible heat (liquid)

$\downarrow$

$$\Delta Q = m \cdot c_{w_{solid}} \cdot (T_{melting} - T_{start}) + m \cdot \Delta h + m \cdot c_{w_{liquid}} \cdot (T_{end} - T_{melt})$$

$$\Delta Q = m \cdot c_{w_s} \cdot (0°C - (-18°C)) + m \cdot \Delta h + m \cdot c_{w_l} \cdot (10°C - 0°C)$$

10°C, because this is the maximum temperature that the water of the ice cube may take to cool down the beer to the 10°C.

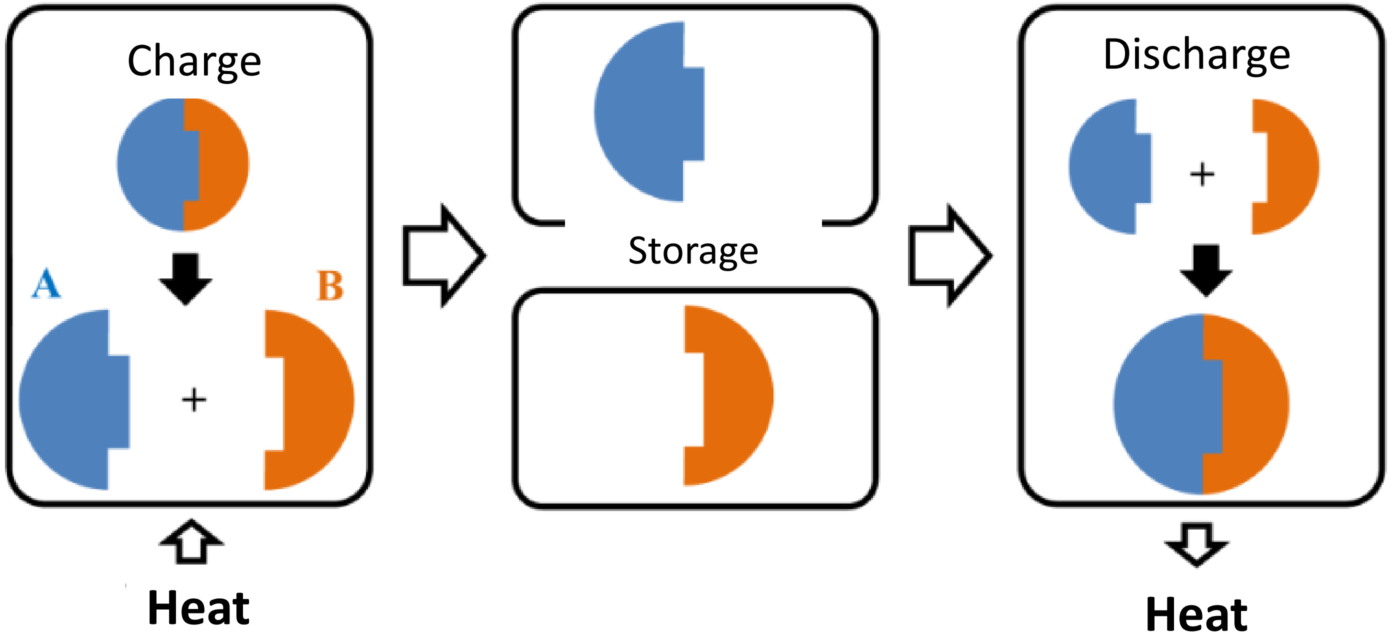
$$\Delta Q = 0{,}02\ kg \cdot 1{,}9\ \frac{kJ}{kg \cdot K} \cdot 18\ K + 0{,}02\ kg \cdot 333\ \frac{kJ}{kg} + 0{,}02\ kg \cdot 4{,}2\ \frac{kJ}{kg \cdot K} \cdot 10\ K$$

$$\underline{\underline{\Delta Q = 8{,}184\ kJ}}$$

$\downarrow$ internal heat energy of the ice cube is not enough to cool the beer to 10°C

Thermochemical storages

Physical basics



$$AB + \Delta H_R \underset{\text{exotherm}}{\overset{\text{endotherm}}{\rightleftharpoons}} A + B$$

- **Charging**: Thermal energy is supplied to storage materials, which dissociates into two materials in an endothermic reaction.
- **Storage**: The substances A and B are stored separately from each other (excluding possible reaction partners)
- **Discharge**: The materials are brought together and react exothermically to the initial compound AB, releasing the introduced energy

Thermochemical storages

Materials

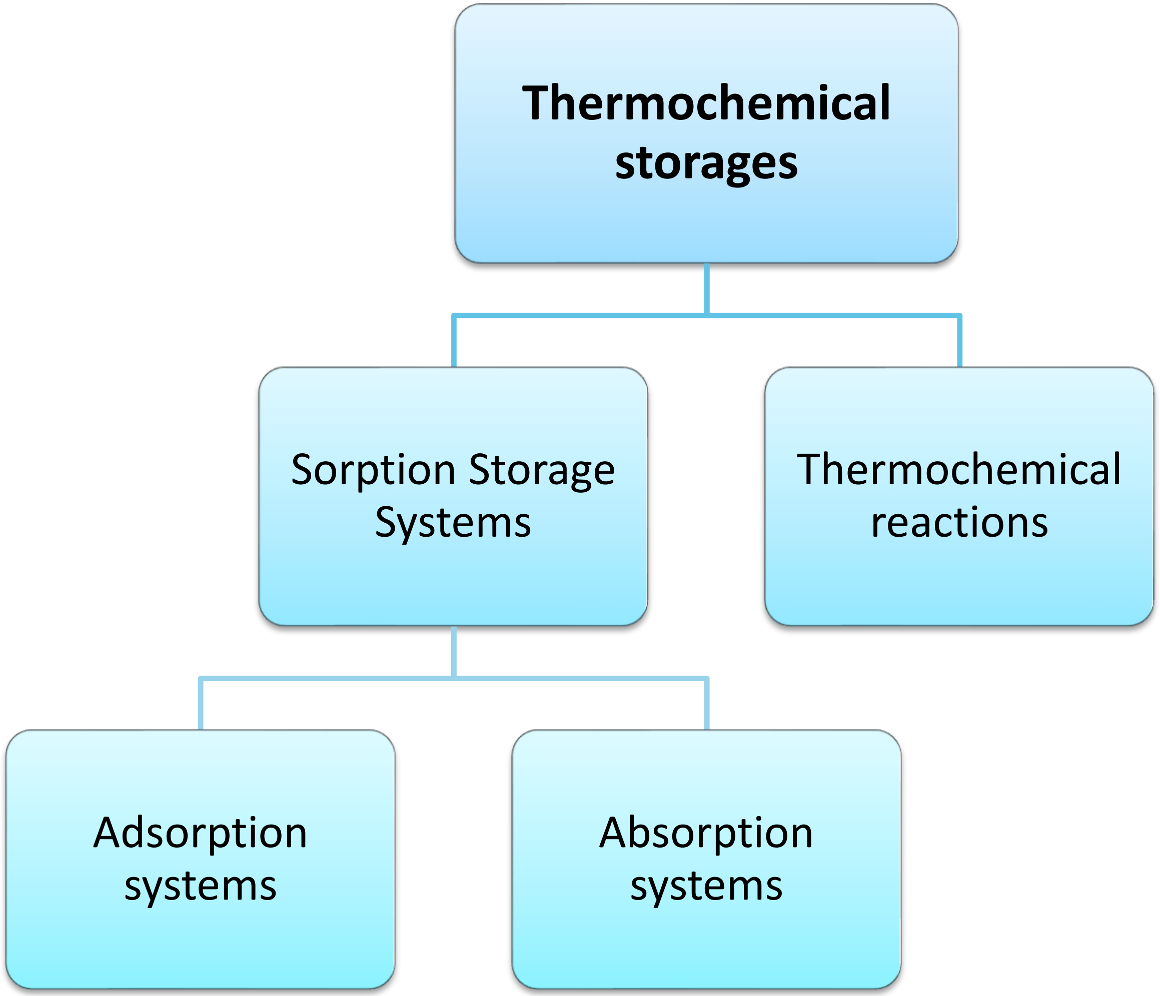
Reaction type	Equation	Equilibrium temperature (1 bar) in °C	Energy storage density in kW h/kg
Salt-hydrate	$MgSO_4 \cdot 7H_2O \Leftrightarrow MgSO_4 + 7H_2O$ $CaCl_2 \cdot 2H_2O \Leftrightarrow CaCl_2 \cdot H_2O + H_2O$	122 174	0.463 0.091
Hydroxide	$Mg(OH)_2 \Leftrightarrow MgO + H_2O$ $Ca(OH)_2 \Leftrightarrow CaO + H_2O$	268 521	0.372 0.373
Carbonate	$CaCO_3 \Leftrightarrow CaO + CO_2$ $BaCO_3 \Leftrightarrow BaO + CO_2$	896 1,497	0.463 0.298
Metal hydride	$MgH_2 \Leftrightarrow Mg + H_2$	293	0.834
Catalytic reactions	$SO_3 \Leftrightarrow SO_2 + 0.5O_2$	767	0.340
Steam reformation	$CH_4 + H_2O \Leftrightarrow CO + 3H_2$	687	1.672

- Store heat through endothermic reactions and release it through exothermic reactions
- Releases or absorbs at least two substances/components of thermal energy

Source 2

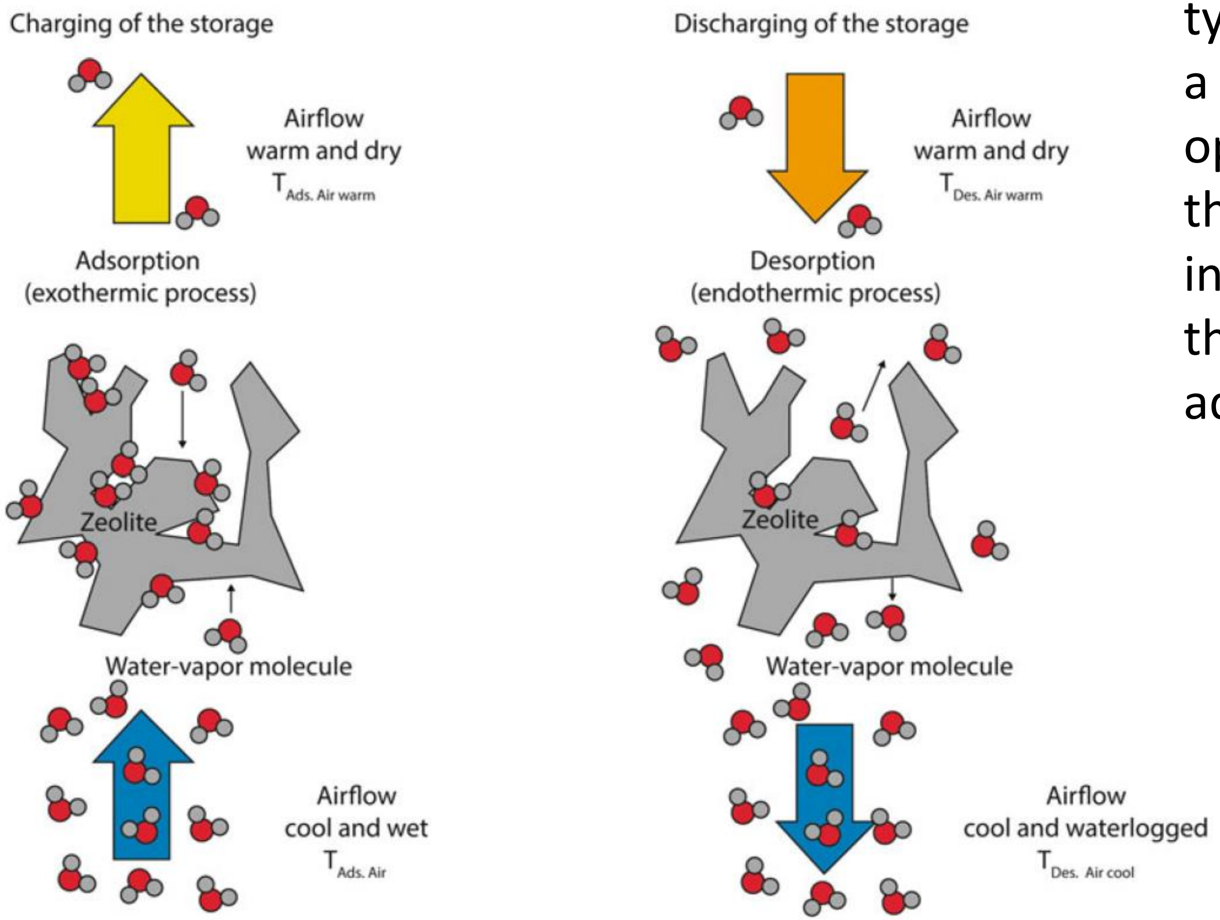
Thermochemical storages

Types of thermochemical storages



Thermochemical storages

Adsorption storage systems



The zeolite/water system is the most commonly used type of open, adsorption storage design. This is more a physical process than a chemical reaction. The operating principle of this storage system is based on the adsorption of water vapor by electrostatic forces in the micro-porous zeolite. This process functions as the discharging process in the storage system. Here, adsorption enthalpy is released in the form of heat.

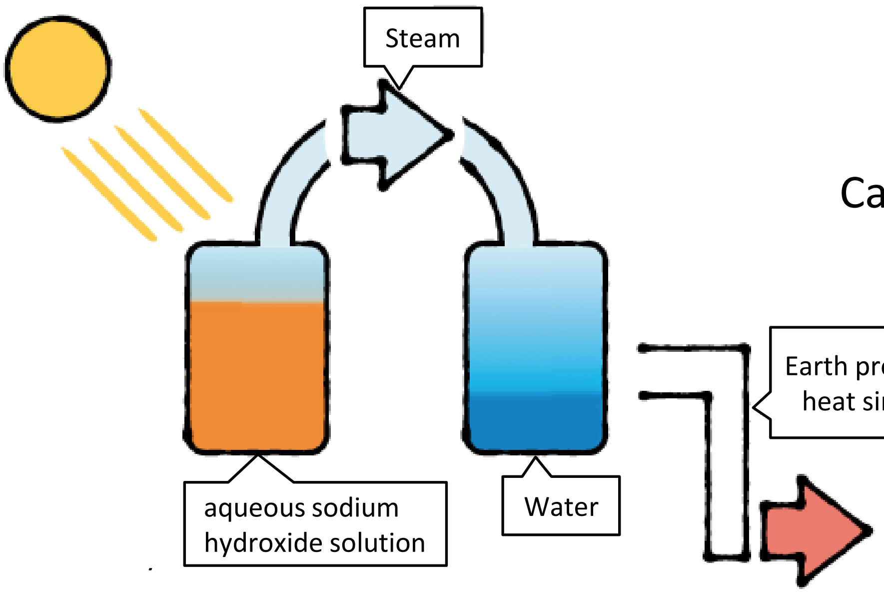
Source #2

Thermochemical storages

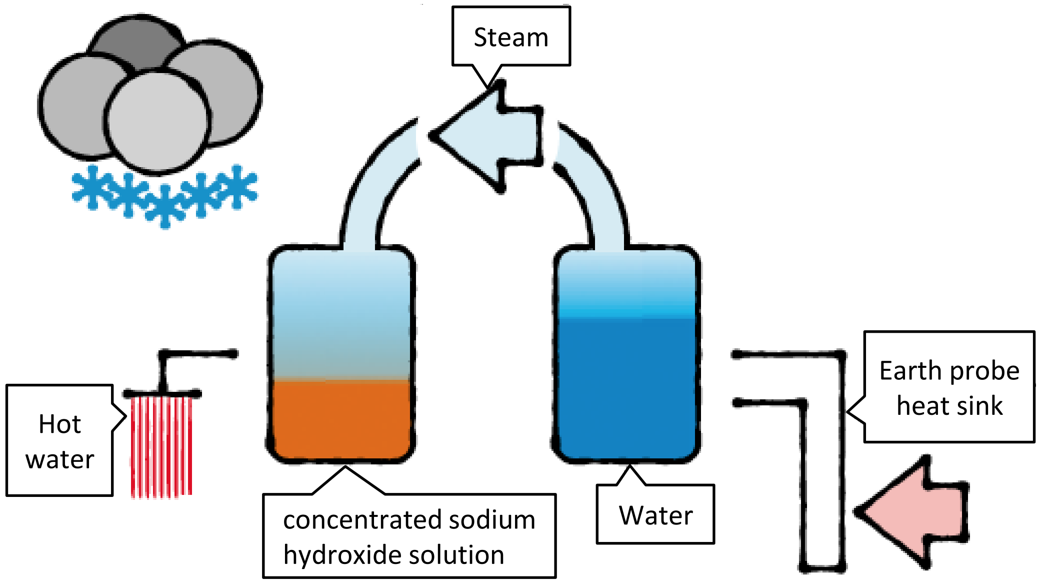
Absorption storage systems

Absorbent	Absorbate	Absorption enthalpy in $kJ/mol_{absorbate}$	Molar mass in $g/mol_{absorbate}$	Energy storage density in $kW\,h/kg_{absorbate}$
$H_2O(l)$	$LiBr(s)$	49.04	86.85	0.157
$H_2O(l)$	$NH_3(g)$	34.18	17.03	0.558
$H_2O(l)$	$H_2SO_4(l)$	95.28	98.08	0.270

Absorption heat storage, energy is stored in the liquid absorption medium by thermal separation of absorbent and absorbate. The energy is not stored as sensible heat, but as a potential with which heat is recovered.



NaOH
Caustic soda

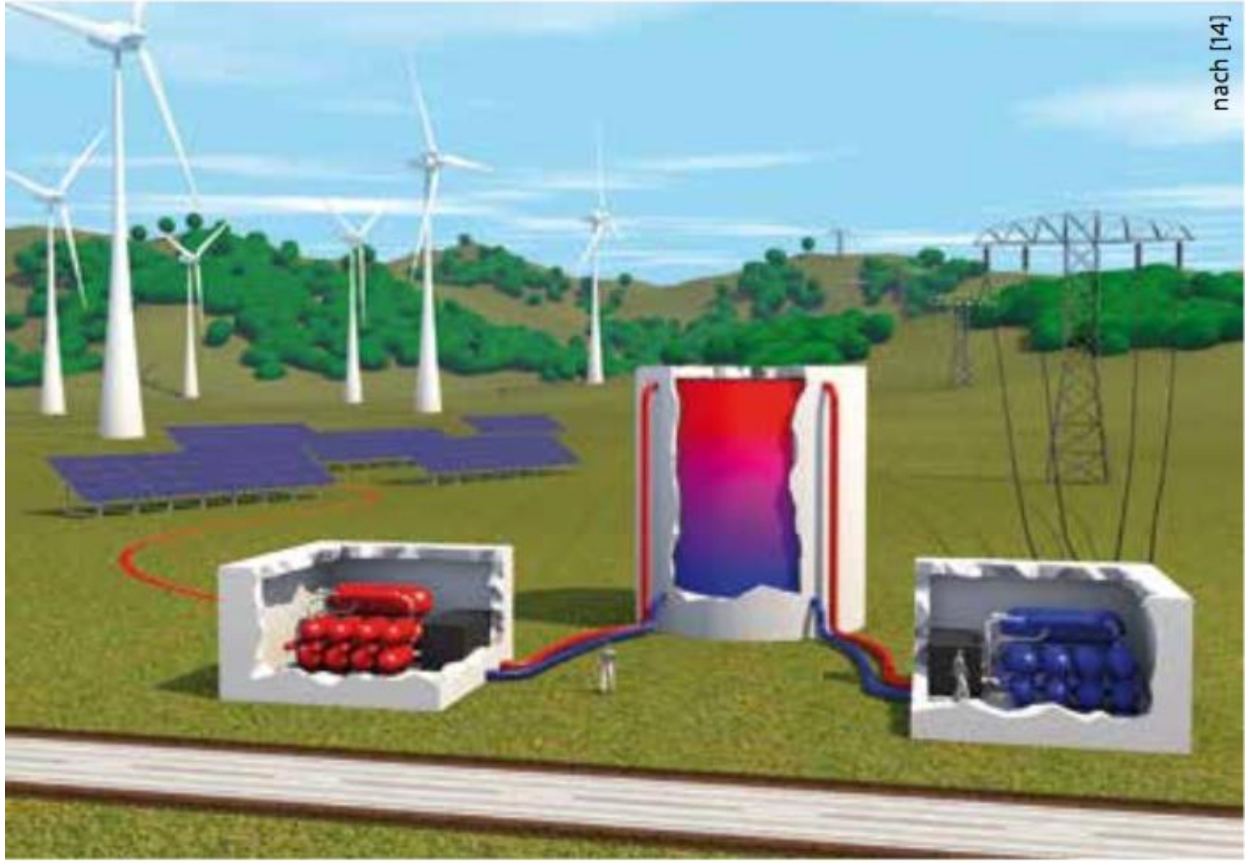


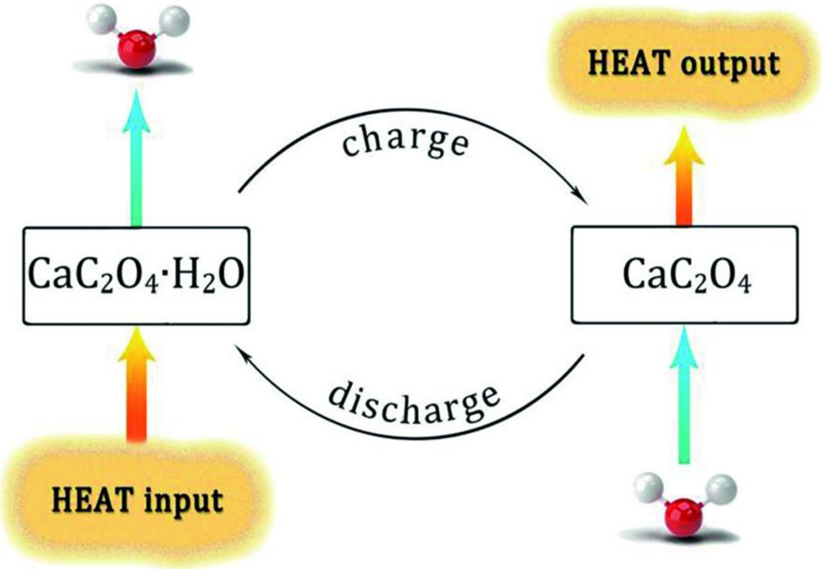
Source: https://www.espazium.ch/de/aktuelles/langzeitloesung

Thermochemical storages

Thermochemical reaction systems

If slaked lime (Ca(OH)2) is heated to temperatures of about 550 °C, it is transformed into steam and burnt lime (CaO). Conversely, heat is generated when quicklime is mixed with steam.





Source: https://www.dlr.de/tt/Portaldata/41/Resources/dokumente/veroeffentlichung_alle/Waermespeicher_Physik_Journal_2015.pdf

Thermochemical storages

Advantages and disadvantages

Advantages	Disadvantages
Can overcome the disadvantages of latent and sensible heat storage	Very high investment costs
Thermochemical energy storage systems allow very high energy storage densities	Relatively new technology -> not yet fully developed

Design of storage systems using the example of

Application example storage in the PV park

Use in combination with renewable energies

- Development of business models for the optimal operation of battery storage systems in connection with large-scale renewable power plants

- Technical-economic consideration
  - Development of necessary algorithms
  - System models and
  - Control software

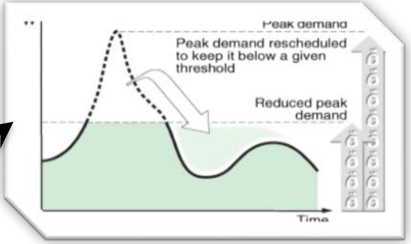
ENERPARC

Operating strategies & software applications

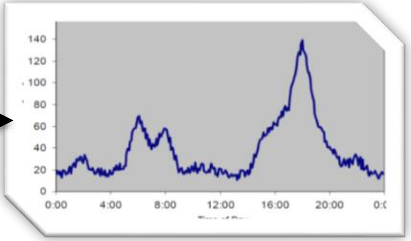
Operating experience with large storage facilities in real applications

Design of storage systems using the example of

Application example storage in the PV park



PV and SP standby supply(night)



Use of DSP regulation

Intraday Trading

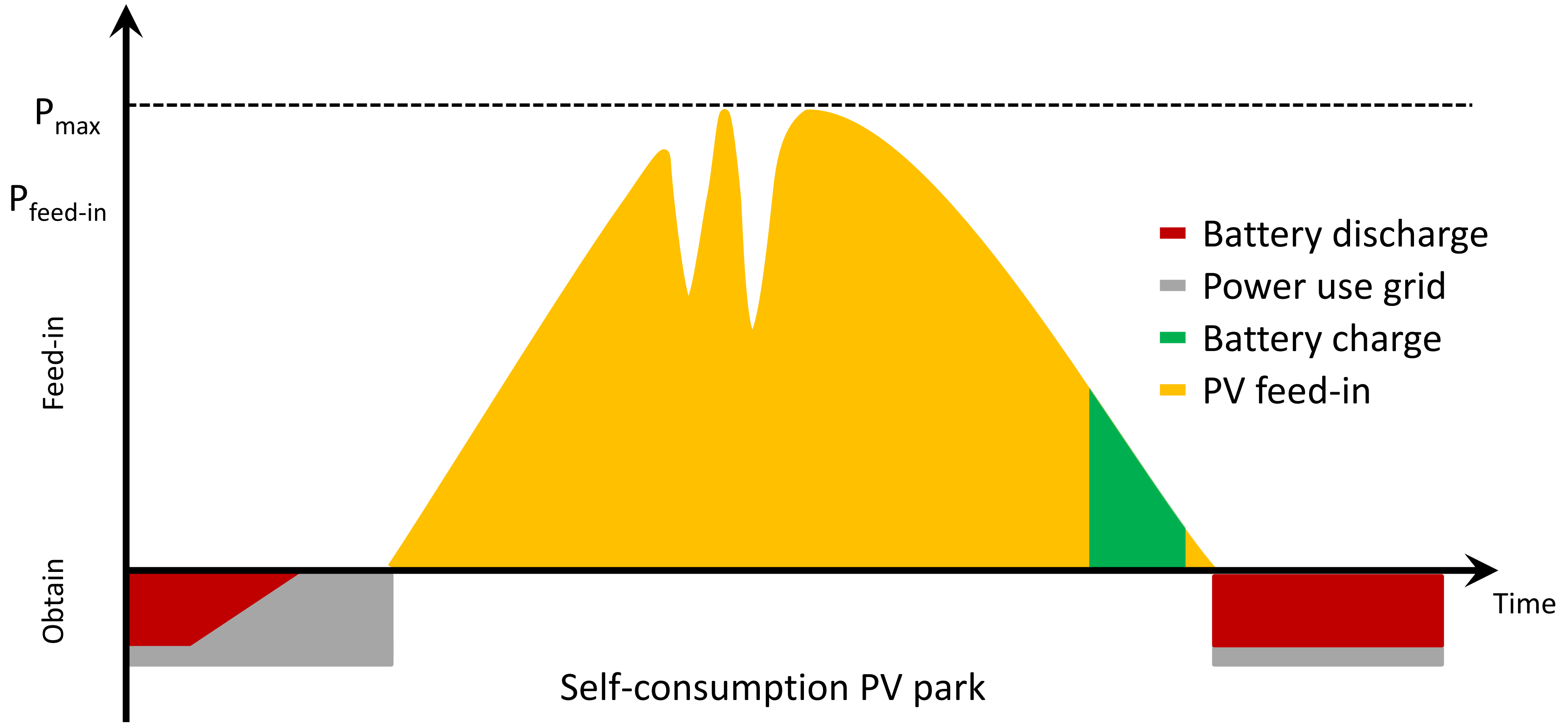
OPTIMAL COMBINATION

- ✓ Lifetime
- ✓ Profit
- ✓ Grid/ market efficiency

Design of storage systems using the example of

Application example storage in the PV park

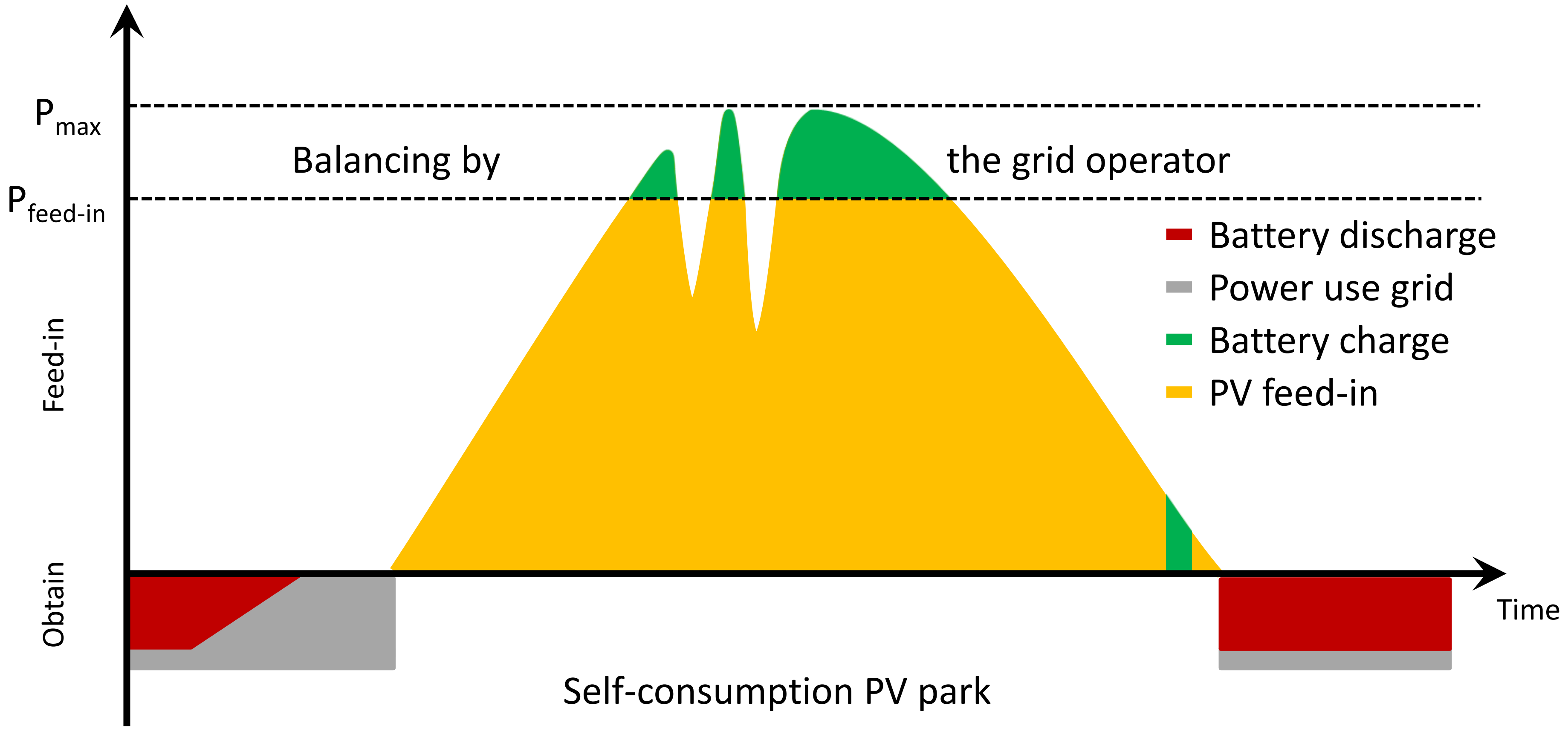
- A - Back-up power supply



Design of storage systems using the example of

Application example storage in the PV park

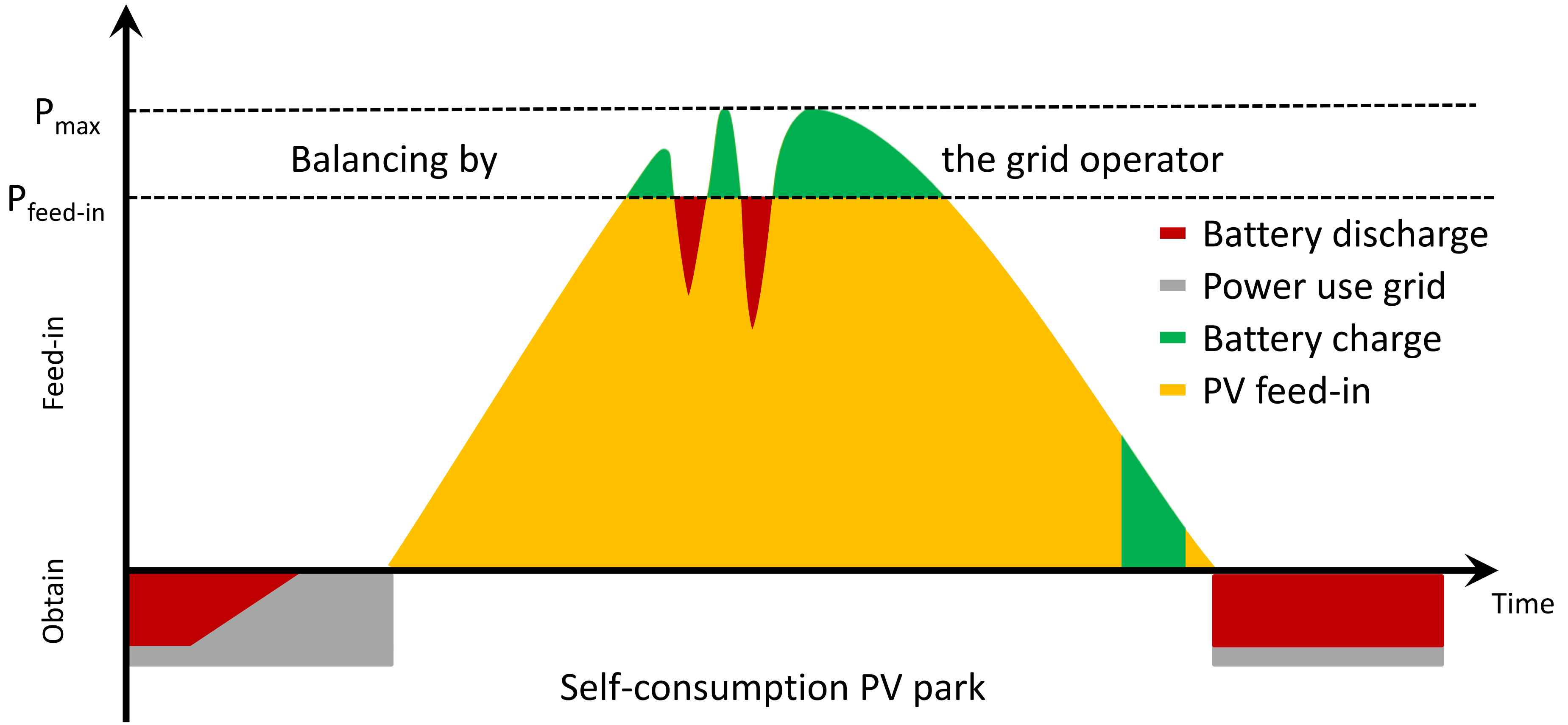
- B – + Compensation PV feed-in control



Design of storage systems using the example of

Application example storage in the PV park

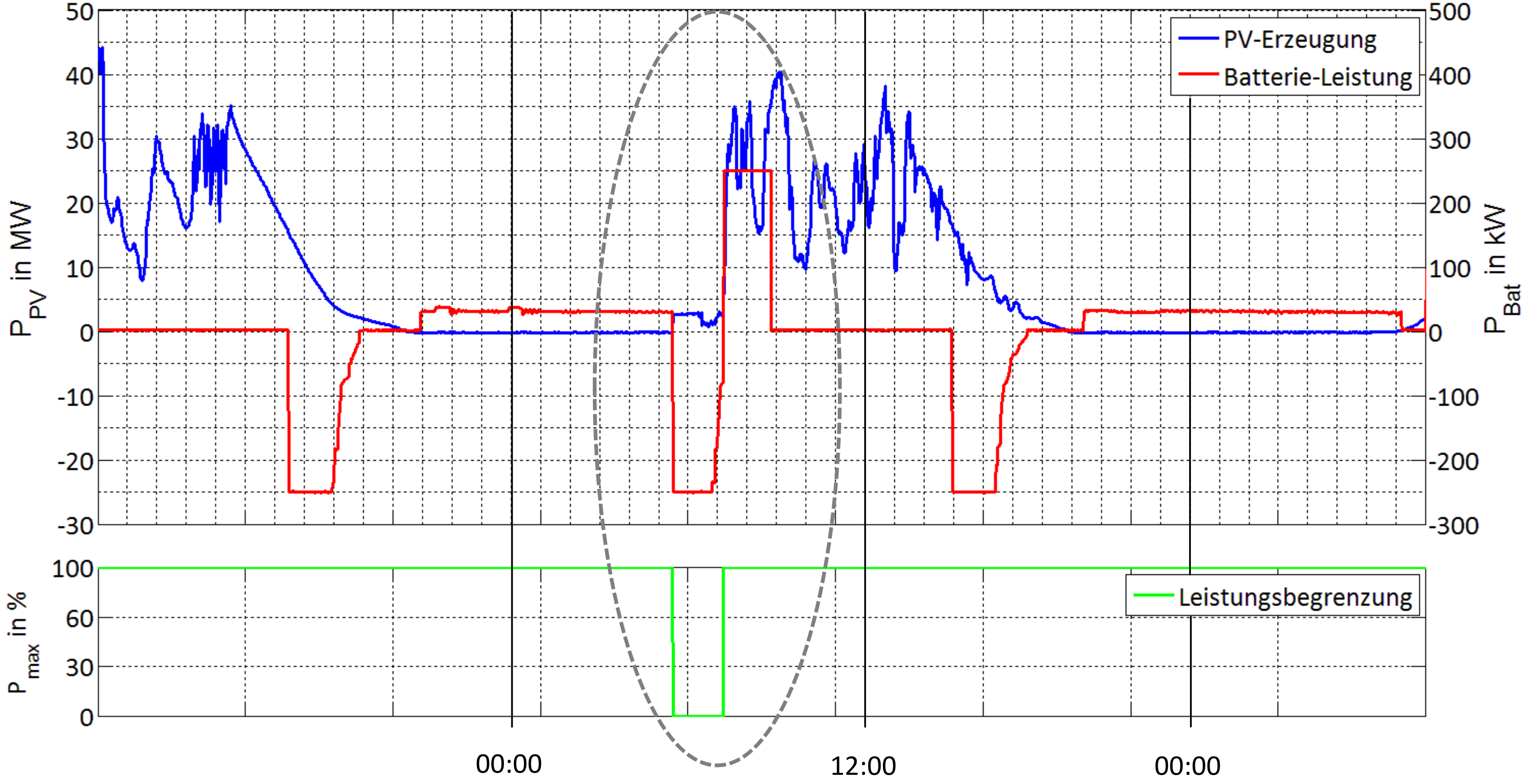
- C – + Feed-in maximisation



Design of storage systems using the example of

Application example storage in the PV park

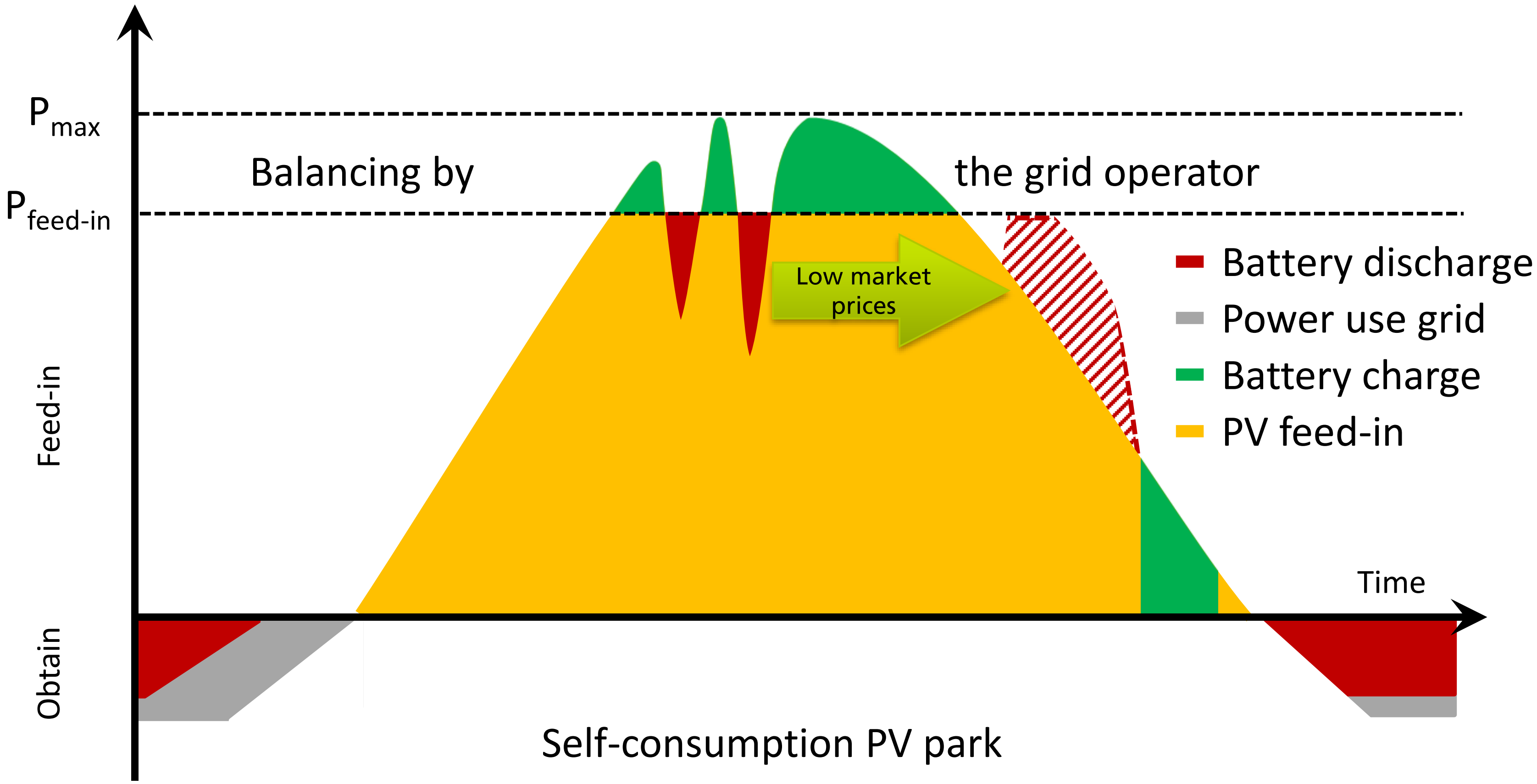
- C – + Feed-in maximisation
  - Real characteristic



Design of storage systems using the example of

Application example storage in the PV park

- D – + Power Exchange

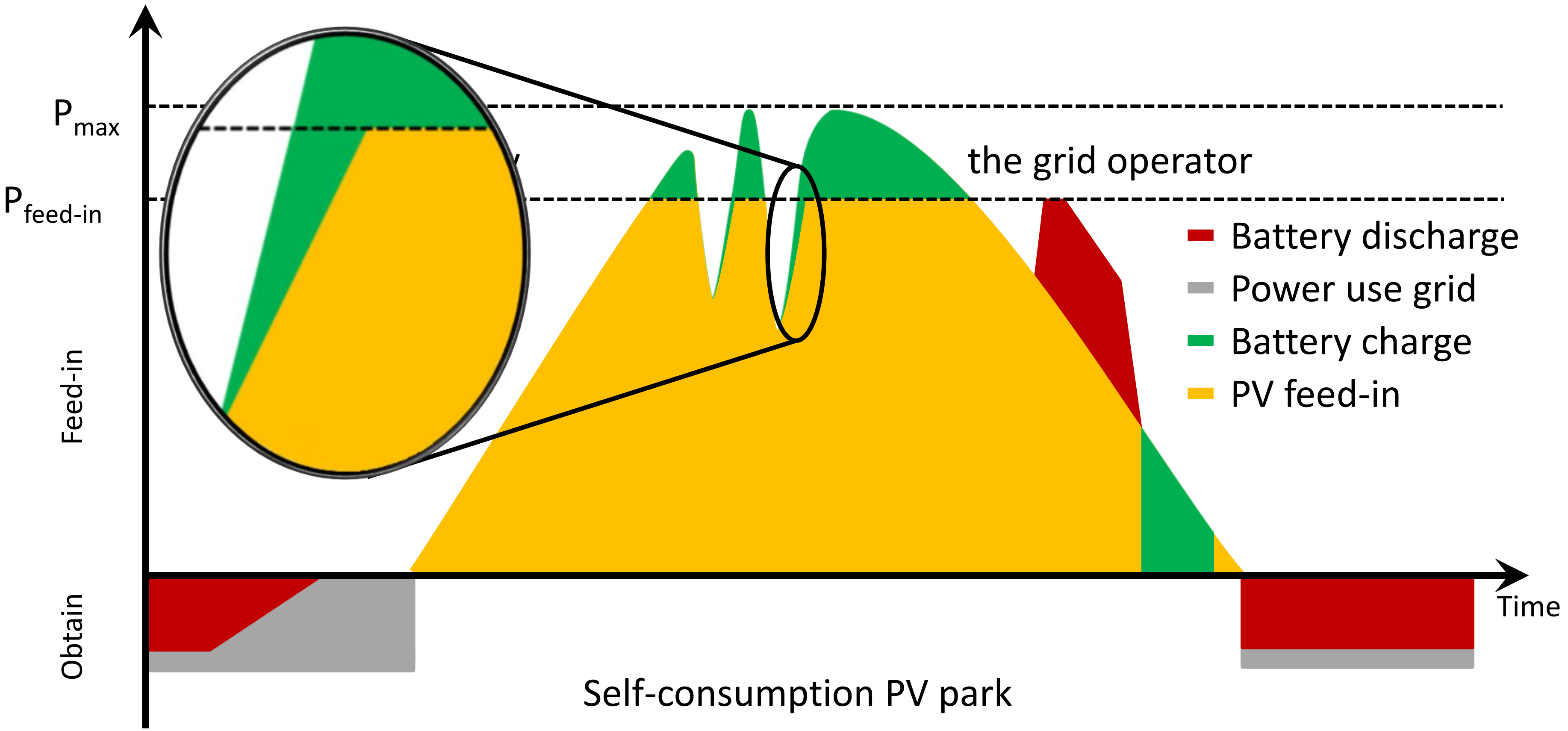


- Scenario combination:
  - Covering own demand at night
  - Absorption of depleted energy (safety measures)
  - Arbitrage trading
- **Technical feasibility** ✓
- **Business Case** ✗

Design of storage systems using the example of

Application example storage in the PV park

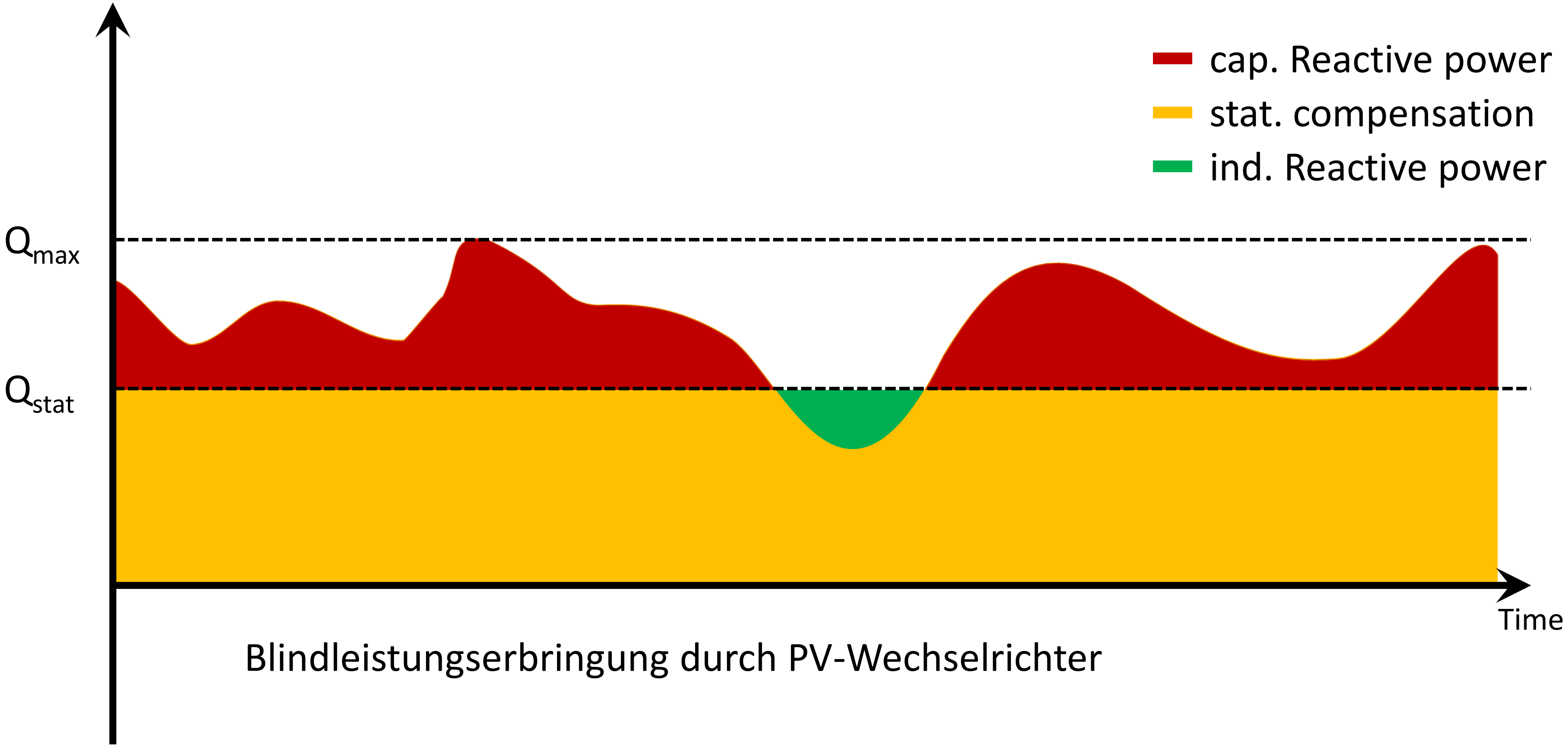
- E – + Ramp compensation



Design of storage systems using the example of

Application example storage in the PV park

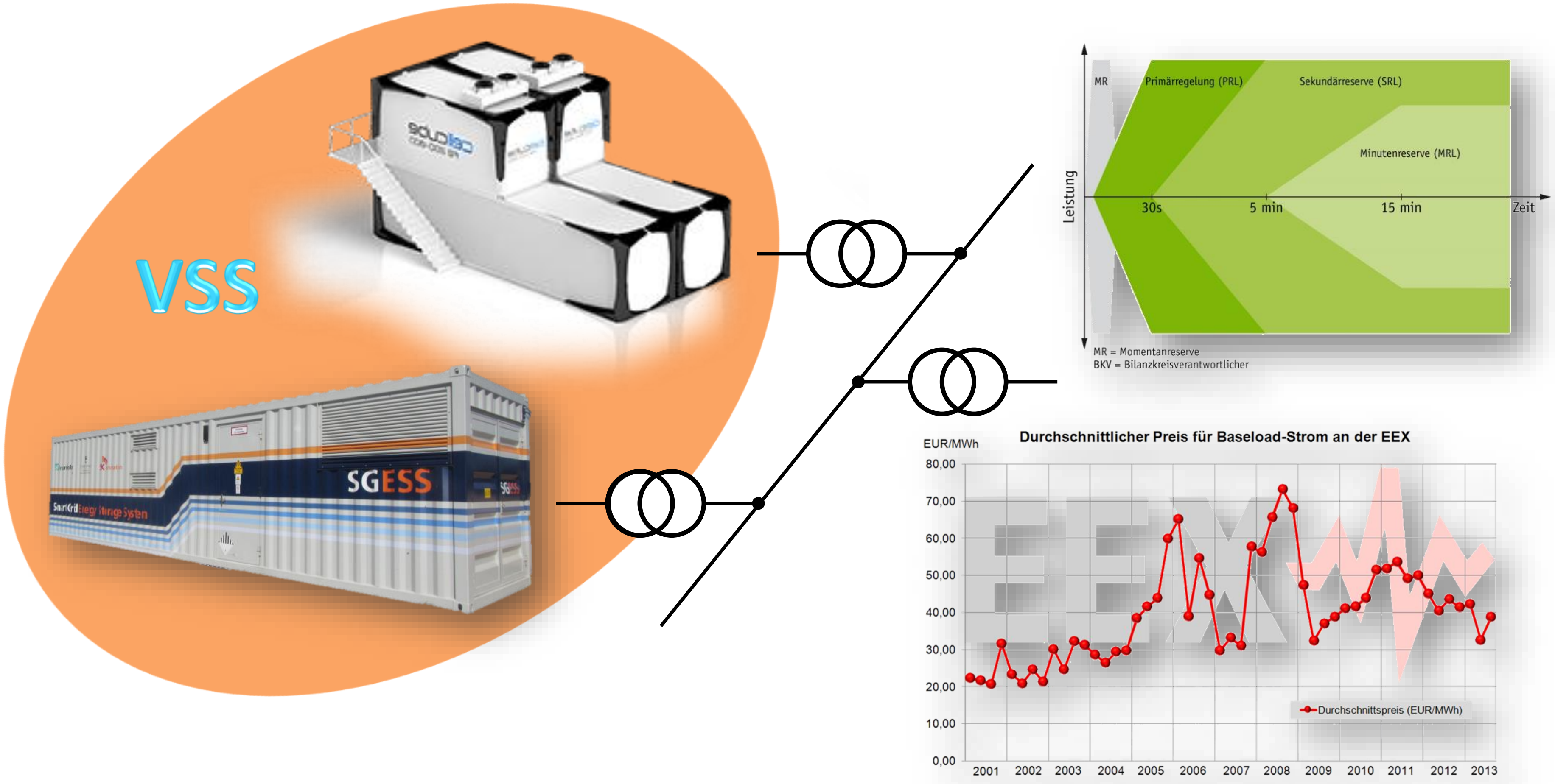
- F – + Power factor correction



Blindleistungserbringung durch PV-Wechselrichter

Application example storage in the PV park

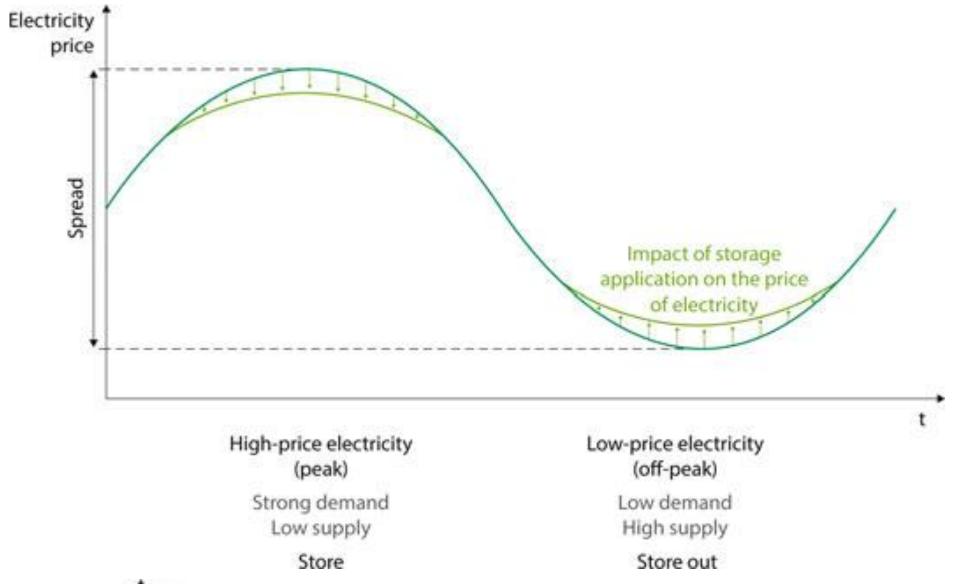
- F – Storage-Pooling

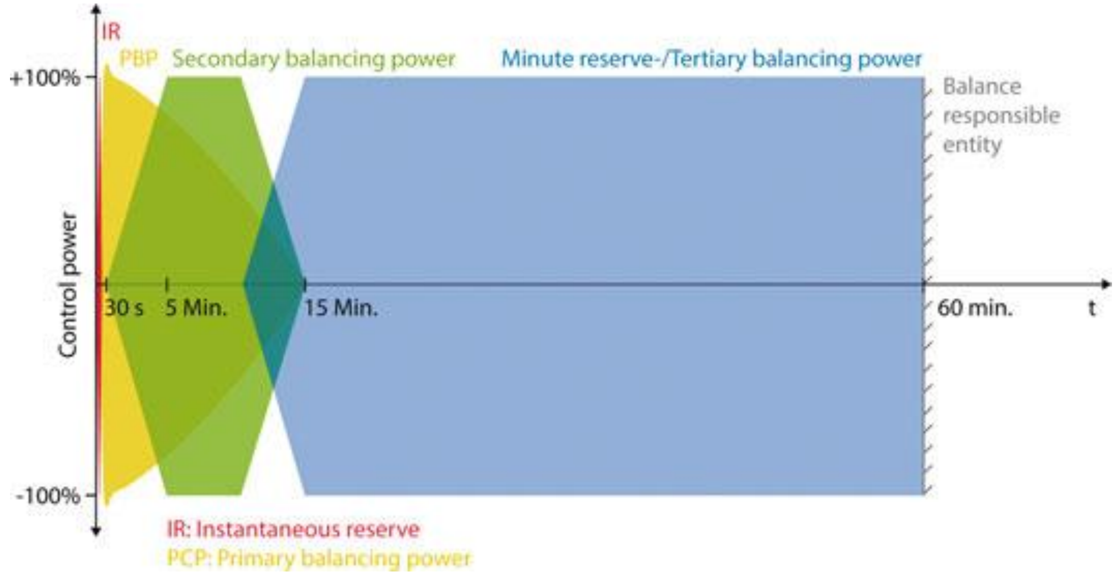


Integration into the power sector

Function and benefits of Storage in the power sector

- Generation balancing and Arbitrage
  - Spot market
  - Derivative Market
- Providing System Services
  - Frequency Control Using Balancing and Reserve Power
  - Using Reactive Power to Maintain Voltage Levels and Voltage Quality
  - Grid Congestion Management and Grid Load Relief—Redispatch
  - Generation Recovery and Black-Start Capability
- Uninterruptible Power Supply (UPS)

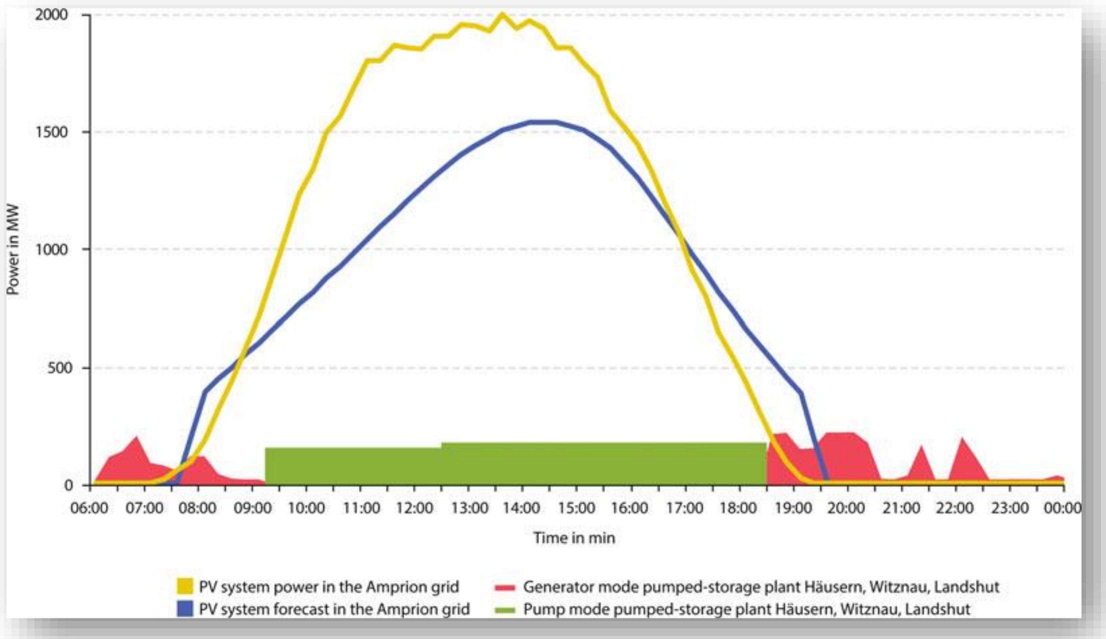


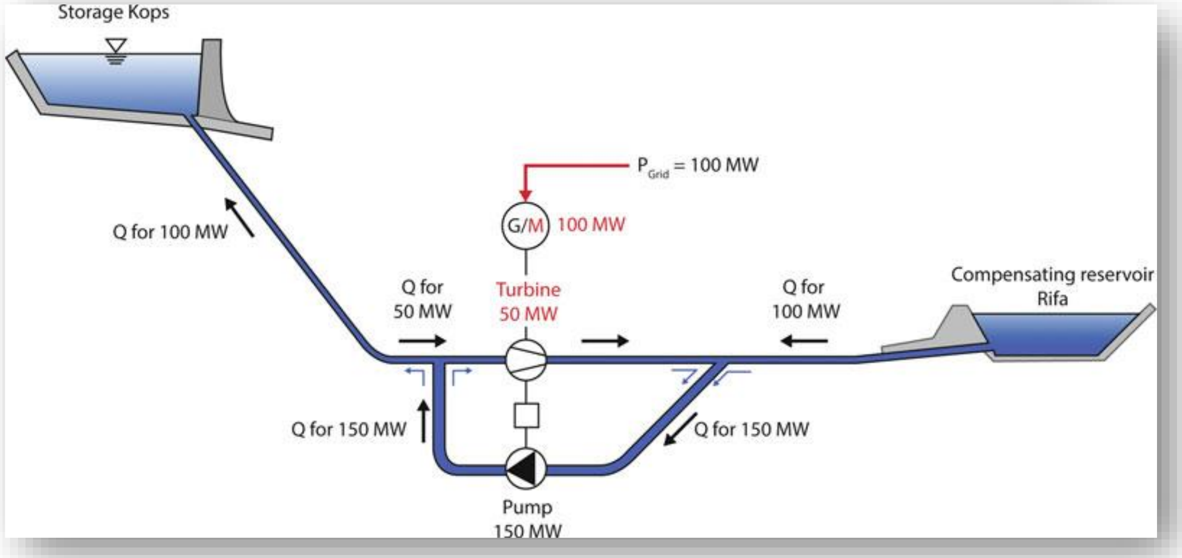


Integration into the power sector

Pumped storage plants and Storage power plants

- Pumped and storage power plants have the ability to start up and shut down quickly (1 to 3 min.)
- Goldisthal pumped storage plant requires only to turbine operation takes only 75 s
  - Compensation of forecast errors and for shifting the feed-in peaks
- Arbitrage business
- System Services Provided by Pumped-Storage
  - **PBP Provided by Hydraulic Short-Circuit**
  - reactive power control
  - frequency maintenance
  - black-start capable

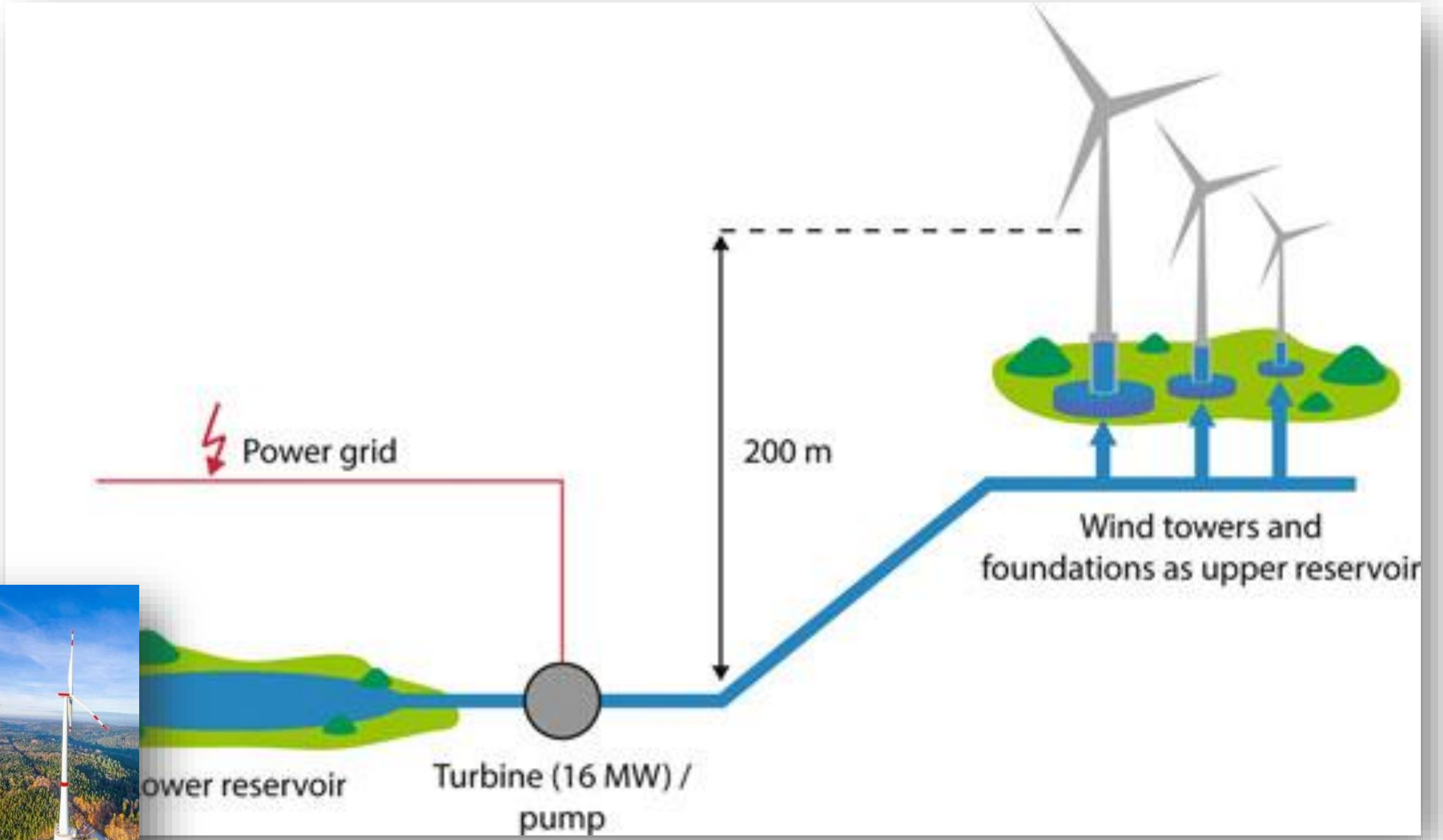


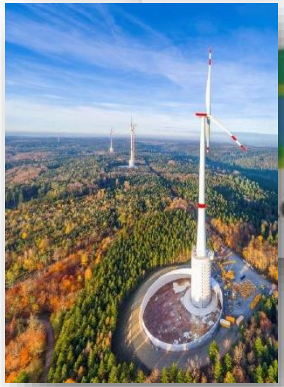


Integration into the power sector

Special form of wind pumped storage - the natural power storage Gaildorf

- Gaildorf in Baden-Württemberg four wind turbines with a capacity of 5.0 MW each
- The tower foundations of the wind turbines are used as water reservoirs
- 160,000 m³ capacity in the tower foundations
- Electrical storage capacity is 70 MWh
- Several variable-speed pump turbines -> in addition to energy storage, simultaneously for the provision of controlling power range

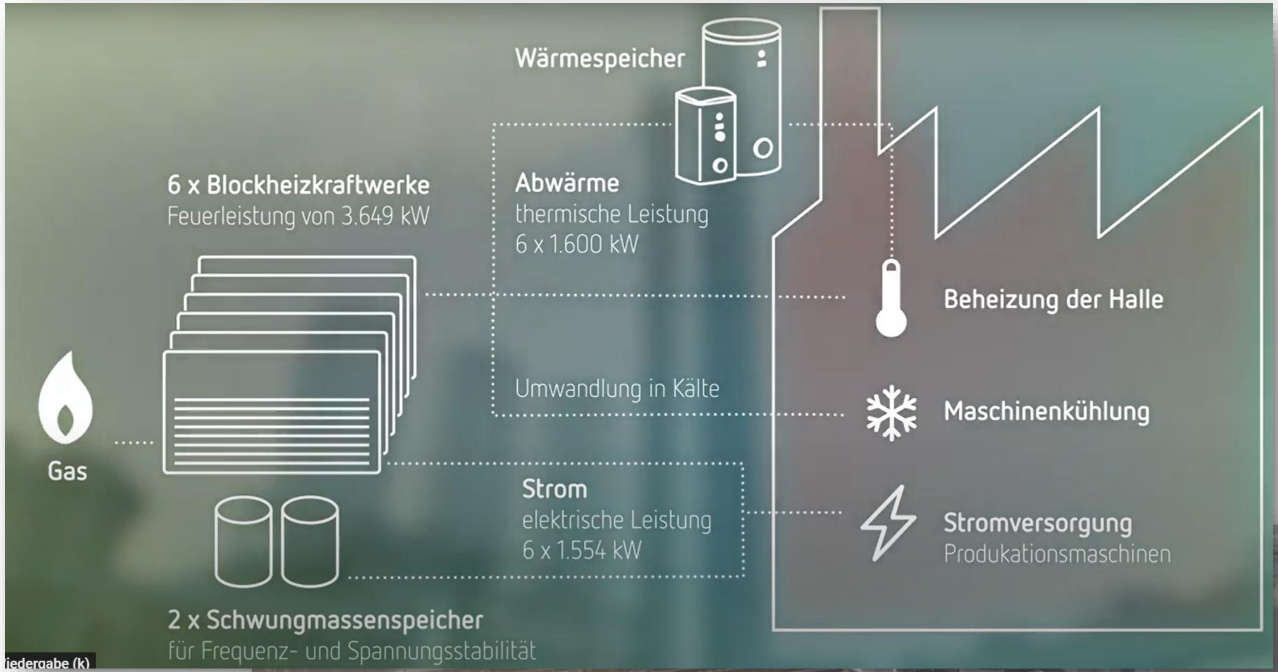




Integration into the power sector

Flywheel storage

- Compensation of Grid fluctuations
  - commercial size of 20 MW buffer capacity
  - between 3000 and 5000 full cycles on the grid each year
- Uninterruptible Power supply systems
  - fast energy supply and their low maintenance costs
  - Power range of up to 2.4 MW and storage capacities from 6-21 MWs (1.7-5.8 kWh)
- Short-term High power energy
  - Up to 300 MW
  - The same technology is also used at Cern, the European Organisation for Nuclear Research, Switzerland, in the particle research facility



Integration into the power sector

Battery power plants

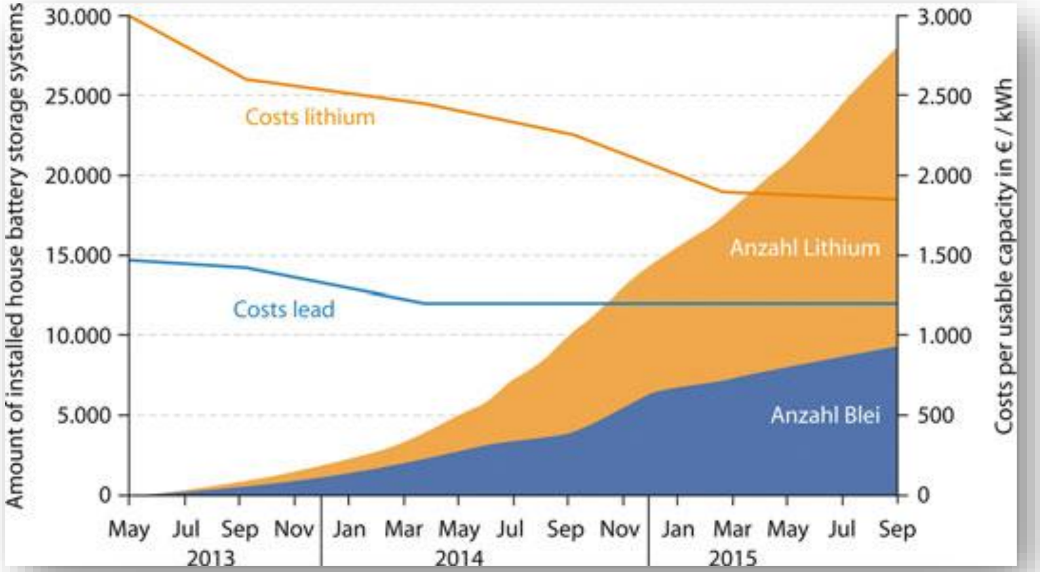
- Largest commercial battery power plant in Europe in Germany (Schwerin, Mecklenburg Western Pomerania)
- Using for controlling power range (negative and positive)
  - mpensates for short-term grid fluctuations and is remunerated for this with a capacity price
- Transient requirements (short-circuit power/fault ride-through/torque reserve) due to power electronics
- The power plant is controlled via the grid frequency

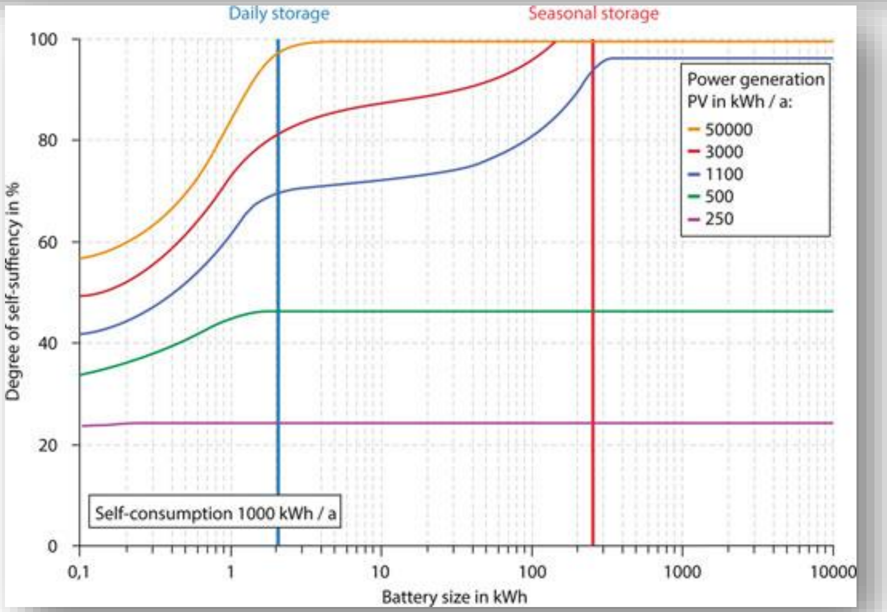
Capacity	5 MW h
Power	5 MW
Cell manufacturer	Samsung SDI
Cells installed	25,600 cells
Guaranteed service life	20 years
System service	Primary balancing energy
Co-operating partners	WEMAG, Younicos AG
Funding	1.3 million € grant from the German Federal Ministry for the Environment

Integration into the power sector

Decentralized battery storage in houses and quarters

- Increasing Number of Installed Household-Battery Storage Systems
  - Many state support programs
  - Price for lithium systems significantly reduced -> out for lead batteries
- Home battery storage as a virtual Swarm power plant in the primary controlling power range
- Increasing Self-Sufficiency

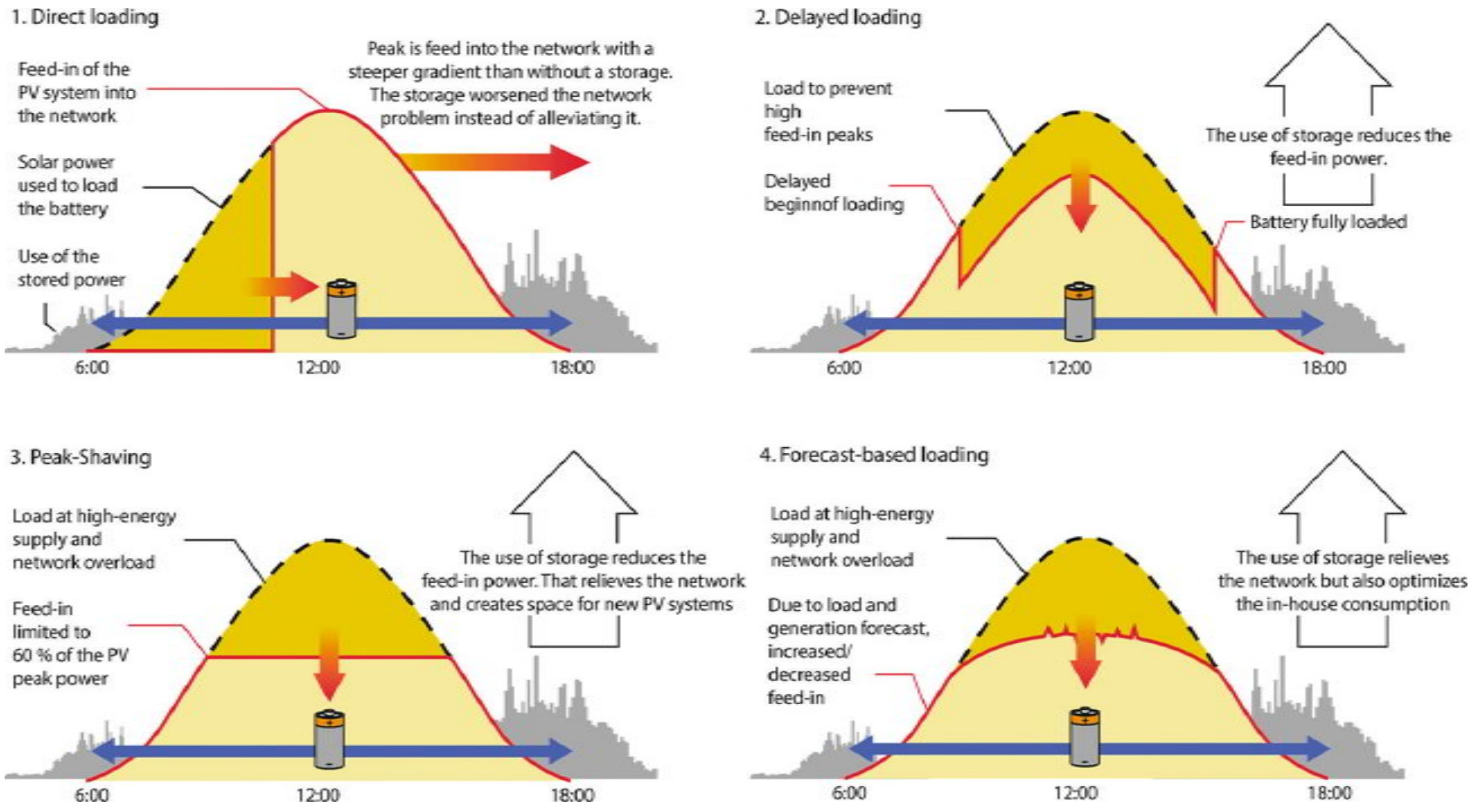




Integration into the power sector

Decentralized battery storage in houses and quarters

- Stabilizing the Electricity Grid
- Maximizing Self-Consumption of Solar Electricity
  - Direct charging
  - Delayed charging
  - Peak shaving
  - Forecast-based charging

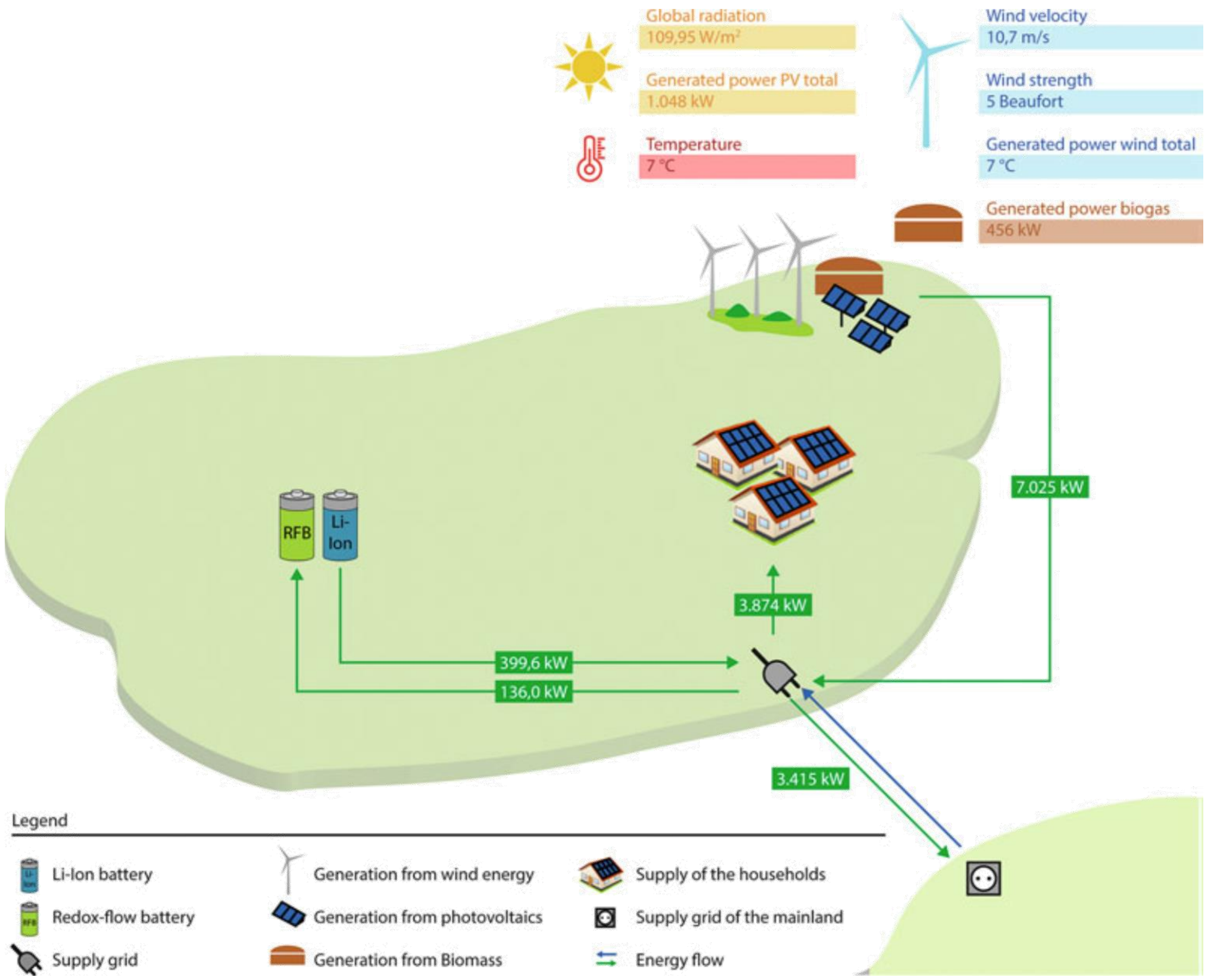


Integration into the power sector

Island grids with renewable energies and storage

- SmartRegion Pellworm on the North Sea island of Pellworm in Schleswig-Holstein's Wattenmeer National Park

Generation unit	Installed power in kW	Quantity of energy feed-in in 2011, in MW h/a	Number of full load hours in hours per year
Hybrid power plant Wind	330	946	2,868
Hybrid power plant PV	772	745	965
Wind Grüner Deich 1+2	400	1,082	2,705
Wind Schütting	225	693	3,080
Pellworm wind park	4,800	13,866	2,889
Biogas facility	530	4,463	8,422
Private PV facilities	3,404	3,740	1,099
Total	**10,461**	**25,535**	**2,441**
Consumption unit	**Number of meters**	**Annual energy consumption in MW h per year**	
Households	731	3,275	
Businesses	185	1,179	
Special agreements	57	815	
Heat storage stoves	148	1,498	
Electric heat-pumps	20	179	
Farming	15	123	
Total	**1,156**	**7,069**	

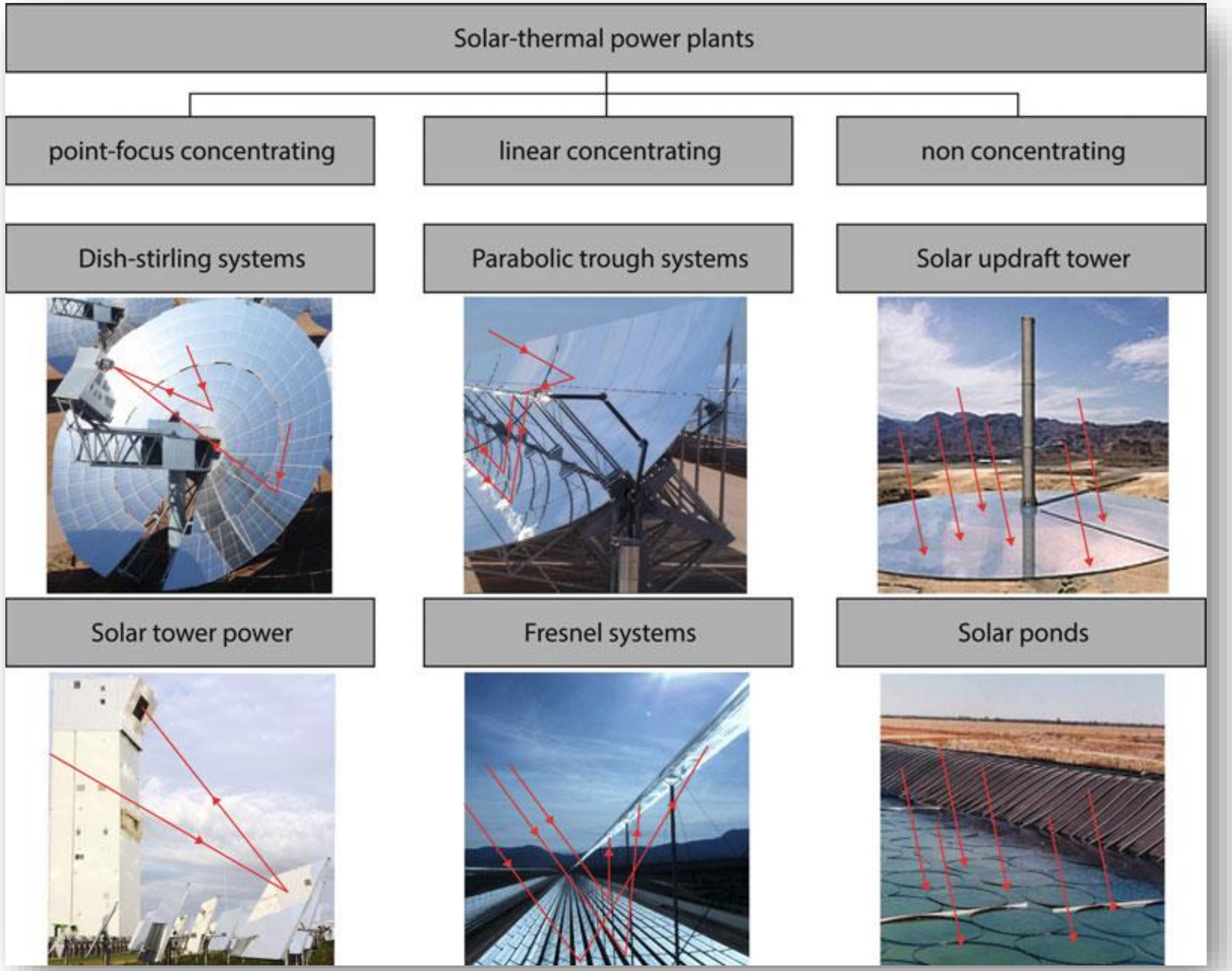


Current feed-in, consumption, and weather data for the SmartRegion Pellworm

Integration into the power sector

Heat storage in solar thermal power plants

- convert solar radiation into electrical energy via a thermal circuit and
- use thermal storage to buffer the solar energy.
- Solar radiation is absorbed by collectors and converted into heat
- In temperate latitudes, solar thermal energy is mainly used to generate hot water and to support heating systems.
- In countries with high direct solar radiation, this can be concentrated and reach very high temperatures.
- temperatures, whereby a steam power process can be operated to generate electricity.
- Advantage over photovoltaics lies in the storage possibility
- Heat is easier to store than electricity, making energy storage in solar thermal power plants energy storage in solar thermal power plants to be realized in solar thermal power plants.



Overview of solar-thermal power plants used for electricity generation

Thank you very much for your attention