SW 1: Introduction to SES

Sustainability

The energy system comprises all energy extraction, conversion, storage, transmission, and distribution processes that deliver final energy to the end-user.

Economic sustainability

- Concerns long-term economic performance.
- Objectives: ensure financial viability without exhausting resources.
- Focuses on economic stability and business continuity. Recent debates also consider degrowth and zero growth.

Environmental sustainability

- Addresses ecological issues such as reducing GHG emissions.
- Objective: protect the planet and preserve natural resources.
- Focuses on environmental quality and resource conservation.

Social sustainability

- Promotes a stable, fair, and inclusive society.
- Objectives: safeguard human dignity and human rights across generations.
- Focuses on poverty, work, and the fair distribution of social burdens.

Current and future energy sources

Primary and secondary energy sources

Primary
- Non-renewable (crude oil, coal, natural gas, nuclear)
- Waste
- Renewable (solar, biomass, wind, hydro, geoth.)

→ TRANSFORMATION →

Secondary
- Petroleum products, manufactured solid fuel and gases
- Electricity and heat
- Bio fuels

→ TO CONSUMPTION

Primary energy is the energy extracted or captured directly from the environment.

The primary energy is transformed into secondary in the form of electricity or fuel to make it transportable.

Future energy sys.

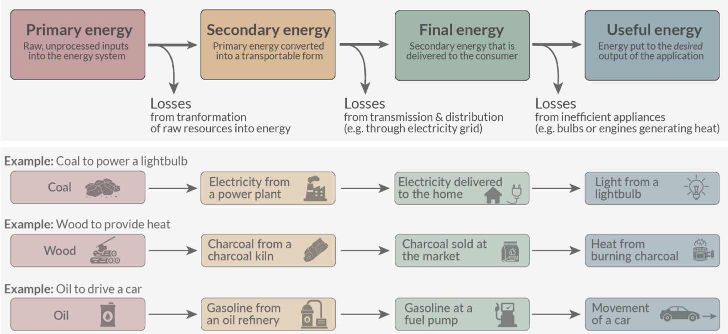
- 2016: 24% renewables, 76% non-renewables
- 2016–2050: transition phase
- 2050 "REmap Case": 86% renewables, 14% non-renewables
  → 35% wind; 25% PV; 14% hydro; 7% bioenergy; …

Others (incl. Marine) · Geothermal · Wind · Concentrates Solar Power · Solar PV · Bioenergy · Hydropower · Nuclear · Natural gas · Oil · Coal

Gross power generation would almost double, with an 86% renewables and 60% from PV + wind.

Energy efficiency

$$\eta = \frac{E_{OUT}}{E_{IN}} \cdot 100\ [\%]$$



Finite energy consumption by end-use purposes in CH

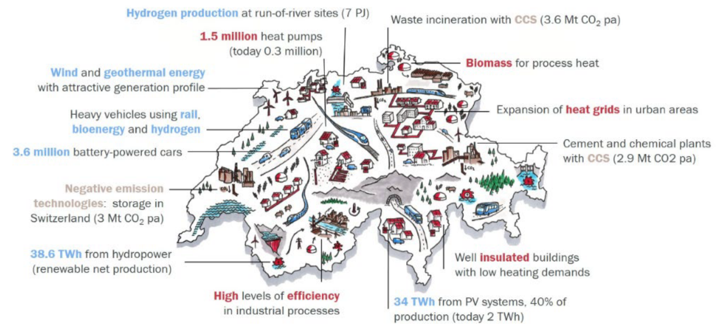
- Almost 70% of our energy consumption goes into mobility and heating systems.
  ↳ Easy to decarbonize

- 74,3%: non-renewable final energy consumption
- 25,7%: renewables "
  ↳ 15% electricity, 3% geothermal, 5% wood, 1% district heating, ⋮

Net zero challenge

1) Reduction of GHG emissions
2) Reduction of the dependence on foreign countries
3) Increase in energy efficiency

Energy perspective 2050+ : objectives for a climate-neutral Switzerland by 2050



CO_2 reduction path of different sectors } by 2050

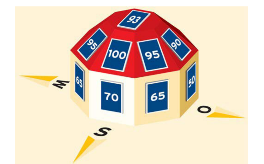
- Buildings: no GHG emissions from buildings.
- Industry: at least 90% reduction in GHG emissions from 1990.
- Transport: international flights from CH aim for net-zero climate impact.
- Agriculture: GHG footprint of food systems aligns with net-zero goals; domestic emissions reduced by at least 40% from 1990.
- Finance: Swiss financial flows align with low-emission, climate-resilient development.

PV surface calculation

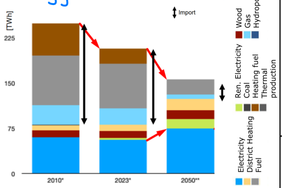
$$A_{PV} = \frac{E_{TARGET}}{Y_{PV} \cdot f_{inc}} \cdot a_{kW} = \frac{E_{TARGET}}{e_{area}}$$

where:
- A_{PV} = required PV surface $[m^2]$
- E_{target} = annual energy to cover $[kWh/y]$
- Y_{PV} = annual yield per installed kW at optimal inclination $[kWh/kW \cdot y]$
- f_{inc} = inclination factor relative to optimum
- a_{kW} = area needed per installed kW $[m^2/kW]$

PV Energy yield considering inclination in %



Energy demand → 2050



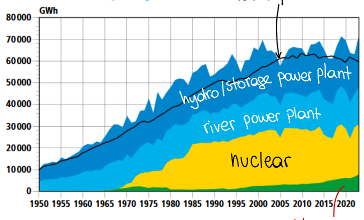
- Energy demand decreases due to better house insulation
- Future: higer efficiency, electrification
- Fossil sources must be replaced:
  → electrification, sector coupling, synthetic fuels, more efficient heating
- Electricity demand will increase

Sun

- The annual solar irradiance on CH surface is 200 times higer than the annual energy consumption

Sun (primary energy source)
- PV (electricity)
- Concentrated Solar Power (high-T heat converted to electricity)
- Solar thermal (low/medium-T heat)
- Solar fuel (fuels)

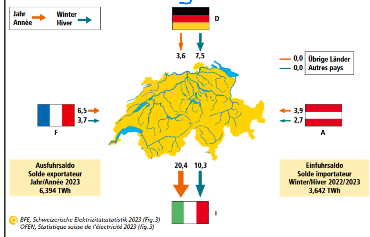
Evolution of today's (CH) electricity system



Energy Strategy 2050

1) Phasing out nuclear energy
2) Expansion of new renewables (mostly PV)
3) ↑ efficiency, ↓ consumption

Swiss electricity statistics

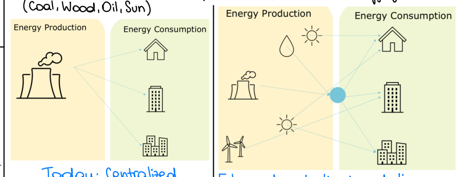


《10% of all electricity exchanged between European countries flows through CH》

SW2: Renewable Energy Sources 1

Energy production mix

- Energy use per person $[kWh/pp]$
- Substitution method: raw unprocessed inputs into the energy system (Coal, Wood, Oil, Sun)



Today: Centralized production

Future: decentralized production
- ↑ complexity
- ↑ numbers of players to coordinate
- ↑ fluctuation in energy production (need for storages)
- ↑ number of uncertainties (like weather)

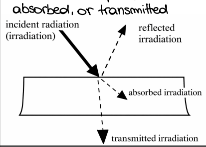
Solar horizontal irradiance

$$E_{solar} = \bar{I} \cdot h/y \cdot A_s \cdot \eta$$

$$[\%] = \frac{A_S}{A_{TOT}}$$

Radiation $E = h\nu$

- The transport of energy by electromagnetic waves / photons
- Each body with $T_B > 0K$ emits thermal radiations
- The incident radiation (irradiation) is partly reflected, absorbed, or transmitted



Black body

- Absorbs all irradiation ($\alpha = 1$)
- No surface can emit more energy for a given T and λ ($\varepsilon = 1$)
- Not existing in nature

Stefan-Boltzmann Law

Emission power: $P = A \cdot \varepsilon \cdot \sigma \cdot T^4$

- Emissivity: $0 \leq \varepsilon \leq 1$
  Black-body: $\varepsilon_B = 1$
- Stefan-Boltzmann constant: $\sigma = 5{,}670 \cdot 10^{-8}\ [W/m^2K^4]$

Net Radiation Loss

Object radiating to its cooler surrounding:

$$P_{net} = A \cdot \varepsilon \cdot \sigma \cdot (T^4_{body} - T^4_{surrounding})$$

Specific radiation power + distance

$$r_{\%} = \frac{r^2_{star}}{d^2_{star-planet}} \Rightarrow e_{sol} = \frac{P}{A} \cdot r_{\%}\ [W/m^2]$$

Average radiation power on a planet surface

$$\langle P_{sol} \rangle = \frac{e_{sol}}{4}\ [W/m^2]$$

Radiation incoming

- Earth receives energy from the Sun (340 W/m² at the top of the atm)
- About 30% is reflected (Albedo)
- ~161 W/m² are absorbed by Earth's surface and warm it
- All bodies emit radiation:
  Sun → short-wave
  Earth → long-wave (infrared)
- GHGs absorb outgoing infrared radiation and re-emit it (greenhouse effect)
- Earth currently absorbs slightly more energy than it emits
  ↳ energy imbalance

Alpine PV

- Over the year, the amount of import and export equals out in Switzerland
- During winter, Switzerland imports a lot of electricity and exports in summer
  ↳ This imbalance is expected to increase due to increase of PV installation
- It's important to give subsidies for winter electricity production and to not subsidize overproduction.

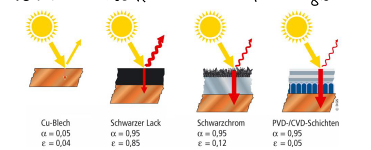
Solar thermal

3 types of heat transfer

1) Conduction $\propto \lambda \Delta T^4$
   - Energy transfer through vibration and moveable charge carriers – free electon movement
   - In a solid or stationary fluid
2) Convection
   - From a surface to moving fluid
   - Heat transfer through free or forced flow
3) Radiation $\propto T^4$
   - Heat transfer without a material medium (photontransfer)

Goal of S.Th.

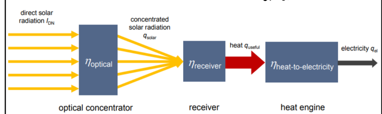
Absorber with:
- High absorpion coefficient α in the frequency of the Sun-ray (low reflectivity, low trasmittivity → $\alpha + \rho + \tau = 1$)
- Low emission coefficient ε in the infrared region

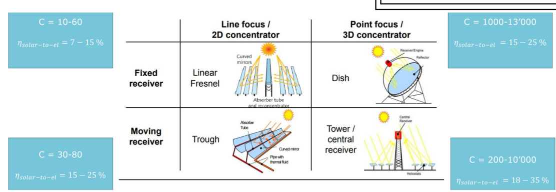


Concentrated solar power (CSP)

$$\eta_{system} = \eta_{optical} \cdot \eta_{receiver} \cdot \eta_{heat\text{-}to\text{-}el} (\cdot \eta_{storage} \cdot \eta_{transp})$$

$$\eta_{receiver} \sim \eta_{absorption};\ \eta_{heat\text{-}to\text{-}el} < \eta_{carnot} = 1 - \frac{T_L}{T}$$





where:
C = concentration ratio

$$C = \eta_{optical} \cdot \frac{A_{collector}}{A_{receiver}}$$

Photovoltaic Types of PV

Type of Plant	Technical Potential
Roofs	Most important and cost-effective PV category. Future market will focus on rooftops. Potential: Over 100 TWh/a if fully utilized. Realistic estimate: **~50 TWh/a, 25% in winter.**
Facades	More challenging due to aesthetics and permits. Potential limited by suitability, not area. Study estimates potential at **17 TWh/a**. Winter share: **~40-50%.**
Infrastructure	Previously not a focus for PV. Includes noise barriers, parking lots, etc. Estimated potential: **9-11 TWh/a**. Hard to exploit due to shading and winter limitations.
Alpine	Controversial due to **nature and acceptance issues**. Theoretical benefit for winter power. Estimated potential: **41 TWh/a**. Considered with caution due to landscape impact. High cost.
Open Land	Considered only if not competing with agriculture. Hard to estimate compared to alpine PV. Swiss agricultural land area potential is **~2000 TWh/a**, ~1% would replace a nuclear power plant.
Agri-PV	Synergy between agriculture and PV (weather protection). Estimated potential: **10-18 TWh/a**. Assumptions still theoretical, requiring practical testing.
Floating PV	Mainly built on artificial reservoirs internationally. Potential in Switzerland limited. Very low current utilization (~1422 km² available). Uncertain feasibility due to social acceptance.

Components

Component	Description	Key Characteristics
Solar Cells	Convert sunlight into electrical energy through the photovoltaic effect.	Typically made of monocrystalline or polycrystalline silicon; efficiency ranges from 15% to 23%.
Solar Modules	Multiple solar cells connected and encapsulated in protective glass and plastic.	Standard modules have a power output of 300–450 W; available in different sizes and efficiencies.
Inverter	Converts the direct current (DC) from solar panels into alternating current (AC) for household use or grid feed-in.	Can be string inverters, microinverters, or hybrid inverters; efficiency typically >95%.
Battery Storage	Stores excess solar energy for later use, increasing self-consumption.	Lithium-ion batteries are the most common; capacity ranges from a few kWh to several hundred kWh.
Mounting System	Secures solar modules to roofs, facades, or ground installations.	Made of aluminum or stainless steel; designed for wind and weather resistance.
Cabling & Wiring	Transfers electricity from the solar modules to the inverter and grid.	Must be UV-resistant, weatherproof, and low-loss to minimize energy losses.

Solar collector efficiency

- $\eta_K = \frac{\text{heat output transfered to the solar fluid}}{\text{radiation incident to the collector}}$
- Short-wave radiation E_e
  → a portion is reflected on the glass → loss
  → the rest falls on the absorber as transmitted portion $E_e \times \tau$
  → portion α is absorbed, the rest reflected

Optical efficiency η_0

$$\eta_0 = \frac{E_e \cdot \tau \cdot \alpha}{E_e} = \tau \cdot \alpha = \frac{Q_N(\Delta T = 0)}{E_e}$$

where: Q_N = useful collector power $[W/m^2]$
E_e = incident irradiation $[W/m^2]$

Thermal losses

- If $\Delta T > 0$, a part of absorbed energy is released back to the environment through losses due to heat conduction, convection, and radiation

$$Q_V = K_{eff} \cdot \Delta T$$

where: Q_V = specific thermal losses $[W/m^2]$
K_{eff} = heat transfer coeff. $[W/m^2K]$

Useful collector power

$$Q_N = Q_N(\Delta T = 0) - Q_V = E_e \cdot \alpha \cdot \tau - K_{eff} \cdot \Delta T$$

Solar collector efficiency η_K

$$\eta_K = \frac{Q_N}{E_e} = \eta_0 - \frac{K_{eff} \cdot \Delta T}{E_0} = \frac{E_e \cdot \alpha \cdot \tau - K_{eff} \cdot \Delta T}{E_e}$$

$$\eta_K = \frac{E_e \cdot \alpha \cdot \tau - a_1 \Delta T - a_2 \Delta T^2}{E_e} = \eta_0 - \frac{a_1 \Delta T}{E_e} - \frac{a_2 \Delta T^2}{E_e}$$

where: a_1 = 1st order loss coeff. $[W/m^2K]$
a_2 = 2st order loss coeff. $[W/m^2K^2]$

SW3: Renewable Energy Sources 2

Geothermal Natural Earth heat

- >15 m: ground T stays nearly constant year-round
- T increases $\approx 30°C/km$
- At 5 km → 160°C

Sources of geothermal heat
- Radioactive decay (U–Th–K): 50–70%
- Residual heat from Earth's formation: 30–50%

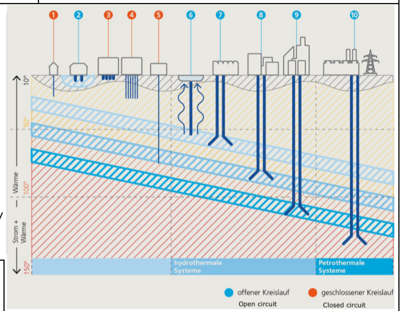
Use
- Heating (buildings, warm water, industry)
- Cooling → Soil regeneration
- To store heat
- To produce electricity (T high enough)

Why is it renewable
- Natural, sustainable energy source
- Independent of time of day and weather

Close to surface
1. Borehole
2. Ground water
3. Geostructures
4. Borehole field
5. Deep Borehole

Medium depth
6. Thermalbath
7. Heat for Agricutture
8. Heat for residential heating and hot water
9. Deep Hydrothermal system: heat and electricity

Deep
10. Petro thermal system: Heat and electricity



Boreholes
- Single: used to improve residential heating efficiency
- Field: heating & cooling larger residential, industrial buildings
- Low T source: usually combined with one or more HP.

Regenerated bhs
- Winter: heat is extracted from the ground for heating
- Summer: excess building heat injected back into the ground
→ Result: underground thermal storage

Deep hydrothermal system
- Source: hot water from natural deep aquifers
- Production: extracts hot water for heating, hot water supply, industrial, and agricultural use
- Injection: reinjects cooled water underground
- System: doublet = production well + injection well
- T > 100°C and sufficient flow rate → el. generation possible

Challenges
- High investment costs, deep drilling
- Uncertainty of subsurface conditions before drilling
- Risk of induced seismicity due to hydraulic stimulation

Hydropower in Switzerland
- Run-of-river plant: no own reservoir, uses continuous river inflow
- Pure circulation plant: uses previously pumped and stored water
- Storage plant: part of the water is used immediately, the rest is stored for later; at least 25% of the expected average winter production
- Pumped-storage plant: combination of a storage plant and a pure circulation plant

Waste hierarchy
Disposal → Energy recover → Recycle → Reuse
Reduce (waste at source) ←

Energy head/Water head/hydraulic head
- Energy head: theoretical energy per unit weight of water
- γ: specific weight [N/m^3]

$$H = z + \frac{p}{\gamma} + \frac{v^2}{2g}$$

elevation head, pressure head, velocity head

Power
$$P = \rho g Q H \eta$$

Q = flow rate ; $\eta \sim 0{,}85–0{,}9$

Wind turbine components
- Blades + hub: convert wind energy into rotational motion
- Low-speed shaft: rotates with the hub. 7–12 rpm.
- Gearbox: increases rotational speed
- High-speed shaft: drives the generator, 1500 rpm
- Generator: converts E_{mech} into E_{el}

Power
In the wind: $P_0 = \frac{1}{2}\rho A v^3$

Usable power: $P = \frac{1}{2}\rho A v^3 c_p(v)$

where: $c_p(v)$: max. 0,593 (Betz factor). 0,4–0,5.

Bioenergy
- Bioenergy: useful energy driven from biomass
- Use: cascading use
- Biofuels: liquid/gaseous fuel from biomass. For transportation
- Biomass: material from recently living organisms by photosynthesis

Examples:
wood, rice straw, sugar cane, sewage sludge, manure, algae
Switzerland: wood = 80% biomass

Advantages	Disadvantage
Inexpensive source of energy	Low energy density – hard to transport over a long distance
Byproduct can be used as nutrients for the soil	High moisture content – making the processing difficult
CO2 neutral energy source	Some biomass products are only available seasonally (crop residues…)
Energy Storage is feasible (storage of Biomass)	Scarcity of land (competition with food production)
	Very low conversion efficiency due to Photosynthesis

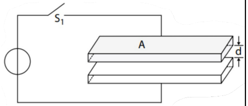
Carbon cycle
$$CO_2 + H_2O + light \rightarrow (CH_2O) + O_2$$

SW4: Energy Storage Electrical: En. stored in either electrostatic or magnetic field

Capacitor
Vaacum: $\varepsilon_r = 1$

$$E = \frac{1}{2}CU^2 \; ; \; C = \varepsilon\frac{A}{d} \; ; \; t = E/P$$

$$\varepsilon = \varepsilon_r\varepsilon_0 \; ; \; \varepsilon_0 = 8{,}854\cdot10^{-12}\left[\frac{As}{Vm}\right]$$



Electrochemical
electricity ⇄ chemical energy

Electrochemistry
- RedOx: electron transfer coupled with chemical change
- Electrodes: conduct electrons
- Electrolyte: conducts ions
- Reactions: occur at the electrode–electrolyte interface
- Anode: oxidation, loss of e^-
- Cathode: reduction, gain of e^-

Cell voltage
$$E^0_{cell} = E^0_{cathode} - E^0_{anode}$$

example:
$Zn \rightarrow Zn^{2+} + 2e^-$
$Cu^{2+} + 2e^- \rightarrow Cu$
$E^0_{cell} = 0{,}342 + 0{,}763 = 1{,}103\,[V]$

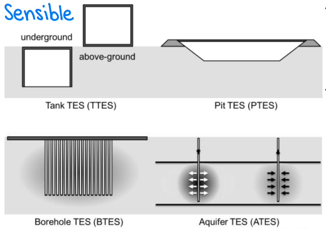
Thermodynamic relation
$$E^0_{cell} = -\frac{\Delta G^0}{zF}$$

Specific Energy Density
$$W_{theo} = \Delta E^0_{theo} \cdot C^{cell}_{theo} = \Delta E^0_{theo} \cdot \frac{zF}{\sum M_{reactant}}$$

Batteries / Pile

	Lead-Acid	Lithium-Ion
Energy Density	Low energy density (30-50 Wh/kg)	High Energy density (150-250 Wh/kg)
Lifespan	300-1000 cycles Acid accelerates aging, such as corrosion of the positive electrode	2000-5000 cycles Electrodes are mechanical stable, which supports high cycle lifetime
Hazard	Lead is an environmental hazard	Safety is critical especially under high temperatures
Cost	Lower initial cost (however maintenance cost due to water refill)	Expensive
Material		Rare earth materials are used (cobalt)
Additional Challenges	The electrolyte includes water, leading to: I. Loss of water through gassing, which results in a cycle that causes future overheating. II. Water can freeze and mechanically damage the battery through expansion	Solidification of active material reduces capacity

Thermal (TES) Energy Storage
- Sensible
  - Solid
  - Liquid
- Latent
  - Solid-Solid
  - Solid-Liquid
  - Liquid-Gas
- Thermo Chemical
  - Sorption
  - Chemical reversible

Sensible


- TTES: tank thermal energy storage
  - large insulated water tank
  - above ground or underground
  - storage medium: water
- PTES: pit thermal energy storage
  - insulated pit in the ground
  - usually filled with water
  - can also contain sand / gravel / water mixtures
- BTES: borehole thermal energy storage
  - array of boreholes with heat exchangers
  - heat transfer fluid circulates in the pipes
  - storage medium: ground
- ATES: aquifer thermal energy storage
  - wells in an aquifer for warm and cold storage
  - storage medium: groundwater / aquifer**

Stratification
Energy: $E(T) = mc_p(T - T_{amb})$

Exergy:
$$E_x(T) = mc_p\left[(T - T_{amb}) - T_{amb}\ln\frac{T}{T_{amb}}\right]$$

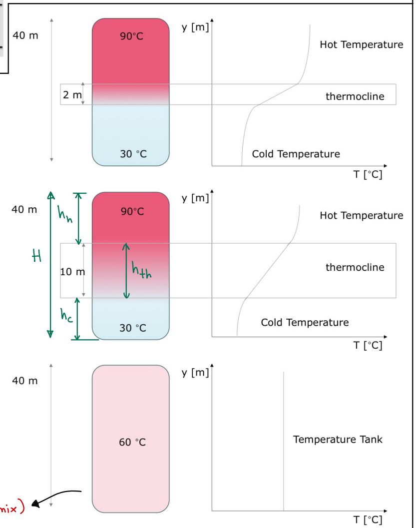
Solved example:
1) Tank mass: $m = \rho V = \rho\pi R^2 H$
2) Energy: $Q = mc_p(T_{mix} - T_{amb})$
3) Exergy:

$f(T) = (T - T_{amb}) - T_{amb}\ln\frac{T}{T_{amb}}$

$$E_x = \frac{mc_p}{H}\left[h_c f(T_c) + h_h f(T_h) + \frac{h_{th}}{T_h - T_c}\int_{T_c}^{T_h} f(T)\,dT\right]$$

where $\int_{T_c}^{T_h} f(T)\,dT = \left[\frac{T^2}{2} - T_{amb}\cdot T\ln\frac{T}{T_{amb}}\right]_{T_c}^{T_h}$

Perfectly mixed: $E_x = mc_p f(T_{mix})$



Latent
- Heat stored during phase change
- Storage medium: PCM (Phase-Changing Mat)
- Passive: indirect heat transfer through a surface, no contact between the heat transfer fluid and PCM
- Active indirect: enhanced transfer
  e.g. with mixing/agitation
  → still no direct contact
- Active direct: heat transfer fluid (HTF) directly over the PCM

Thermochemical
- Energy stored in a reversible chemical reaction
- Exothermic: heat released
- Endothermic: heat required
- Mechanism: often surface reaction/adsorption–desorption
- Energy stored in reaction energy, not sensible heat
- Pros: ideally no th. losses.

Thermal Energy Storage

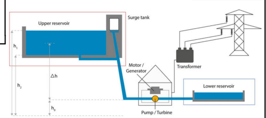
Sensible	Latent	Thermochemical
Advantages: • No chemical decomposition • Non-corrosive • Non-flammable • Commercially available • Low cost	**Advantages:** • High energy density • Temperature stability	**Advantages:** • Very high energy density • No thermal losses
Challenges: • Low energy density → large volume • Heat losses → self-discharge	**Challenges:** • Supercooling • Phase segregation • Corrosiveness • Poor heat transfer • High cost	**Challenges:** • Low chemical stability • Poor heat and mass transfer • Effective energy density still low • Very high cost

Mechanical
- electricity stored as mechanical work
- Kinetic, Potential, pressure

Examples (–ES = en. storage)
- PHES: pumped hydro ES
- CAES: compressed air ES
- LAES: liquid air ES
- FES: flywheel ES
- PTES: pumped thermal ES
- GES: gravity ES

Pumped hydro
- Water stored in an upper reservoir
- High demand: water is released through turbine
  ↳ electricity generation
- Low demand: water is pumped back to the upper reservoir
- Pros: reliable, low lifetime cost, grid stabilization
- Cons: env. impact, ecosystem disruption

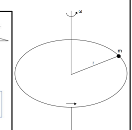
$$\Delta h = \frac{h_1 + h_2}{2} - h_0$$



Flywheel
- ES as rotational kinetic energy
- E_{el} accelerates a rotating mass
- Max rotation speed
- Pros: high energy density, low maintenance, lifespan
- Cons: high specific strength required

$$E_{kin} = \frac{1}{2}J\omega^2 \; ; \; \frac{E}{m} = K\left(\frac{\sigma}{\rho}\right)$$

K = 1 for constant-stress disc
= 0,606 for constant thickness



SW5: Residential Building Energy System

Energy bill
$$C_{heating}\,[CHF] = E_{heating}\,[kWh_{heat}] \cdot \eta_{heating} \cdot C_{heating}\,[CHF/kWh]$$

$$C_{el} = P_{utility}\,[kW] \cdot t_{usage}\,[h] \cdot C_{el}\,[CHF/kWh] \quad C_{el} \sim 0{,}30\,CHF/kWh$$

Rebound effect
- Definition: efficiency improvement of a technology can lead to higher use of that technology
- Result: actual energy savings are smaller than expected
- Reason: lower effective cost of the service increases demand
- Difference:
  - anticipated conservation > actual conservation
  - the gap is the rebound consumption

Key idea
- better efficiency does not automatically mean proportional reduction in total energy consumption

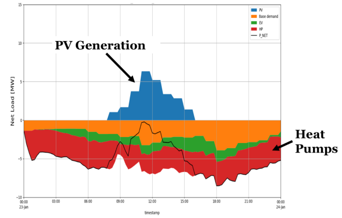
Return on investment
$$ROI = \frac{Net\ profit}{Investment} = \frac{Cost\ business\ as\ usual - cost\ with\ new\ investment}{Investment}$$

$$Payback\ Time = \frac{Investment}{Net\ profit\ annualy} = \frac{Investment\ Cost}{Cost\ business\ as\ usual - cost\ with\ new\ investment} = \frac{1}{ROI}$$

For a heat pump
$$ROI = \frac{yearly\ expense - \frac{thermal\ energy}{COP}\cdot cost\ of\ electricity}{investment}$$

$$Payback\ time = \frac{1}{ROI}$$

Buildings inertia
Number of heat pumps ↑
+
Renewable electricity ↑
=
Alignment of electricity supply & demand ↓



Alignment of PV generation potential and heat pump loads over one day in Losone, TI