

SW 1: Introduction to SES

Sustainability

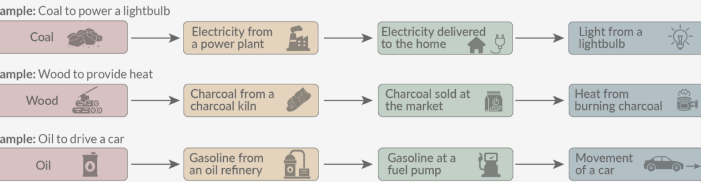
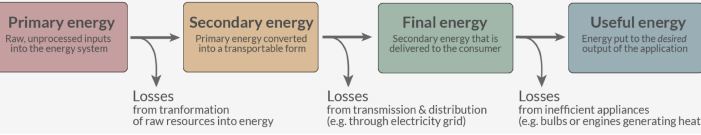
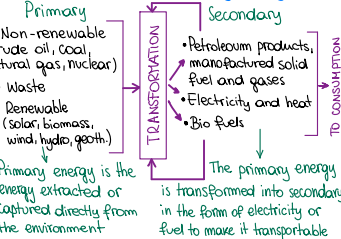
The energy system comprises all energy extraction, conversion, storage, transmission, and distribution processes that deliver final energy to the end-user.

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.

Current and future energy sources

Primary and secondary energy sources



Finite energy consumption by end-use purposes in CH

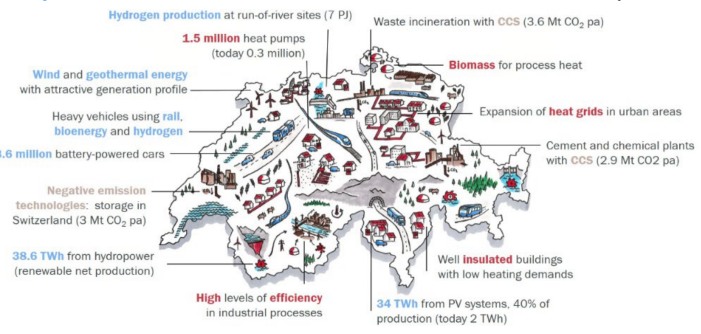
- Almost 70% of our energy consumption goes into mobility and heating systems.
- Easy to decarbonize

- 74.3%: non-renewable final energy consumption
- 25.7%: renewables
 - 15% electricity
 - 3% geothermal
 - 5% wood
 - 1% district heating

Net zero challenge

- Reduction of GHG emissions
- Reduction of the dependence on foreign countries
- Increase in energy efficiency

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



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.

Future energy sys.

- 2016: 24% renewables, 76% non-renewables
- 2016-2050: transition phase
- 2050 "REmap Case":
 - 86% renewables
 - 4% non-renewables
 - 35% wind; 25% PV; 4% hydro; 7% bioenergy; ...
- Gross power generation would almost double, with an 86% renewables and 60% from PV + wind.

Energy efficiency

$\eta = \frac{E_{out}}{E_{in}} \cdot 100 [\%]$

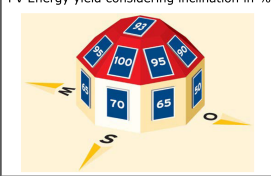
CO2 reduction path of different sectors } by 2050

- 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.

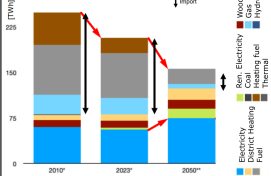
PV surface calculation

$A_{PV} = \frac{E_{TARGET}}{Y_{PV} \cdot \rho_{inc}} \cdot \alpha_{KW} = \frac{E_{TARGET}}{\rho_{area}}$

- where:
- A_{PV} = required PV surface [m²]
 - E_{TARGET} = annual energy to cover [kWh/y]
 - Y_{PV} = annual yield per installed kW at optimal inclination [kWh/kW.y]
 - ρ_{inc} = inclination factor relative to optimum
 - α_{KW} = area needed per installed kW [m²/kW]
- PV Energy yield considering inclination in %



Energy demand -> 2050

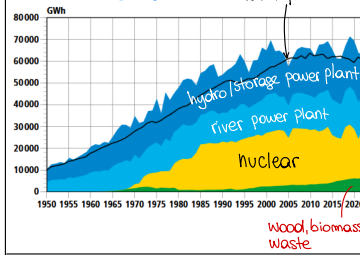


- Energy demand decreases due to better house insulation
- Future: higher efficiency, electrification
- Fossil sources must be replaced:
 - electrification, sector coupling, synthetic fuels, more efficient heating
- Electricity demand will increase

Sun

- The annual solar irradiance on CH surface is 200 times higher than the annual energy consumption
- Sun (primary energy source)
 - PV (electricity)
 - Concentrated (high-T heat converted Solar Power to electricity)
 - Solar thermal (low/medium-T heat)
 - Solar fuel (fuels)

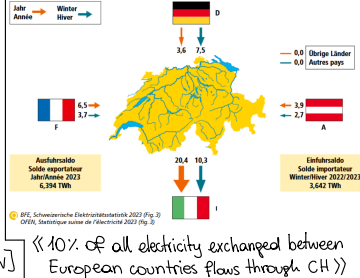
Evolution of today's (CH) electricity system



Energy Strategy 2050

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

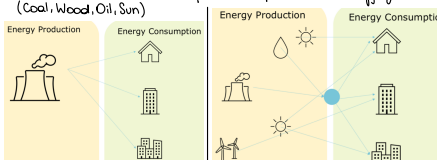
Swiss electricity statistics



SW2: Renewable Energy Sources 1

Energy production mix

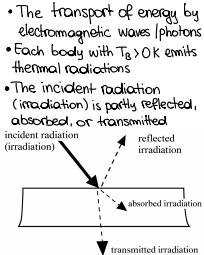
- Energy use per person [kWh/pp]
- Substitution method: raw unprocessed inputs into the energy system (Coal, Wood, Oil, Sun)



Solar horizontal irradiance

$E_{sol} = \frac{I}{A_{tot}} \cdot h_g \cdot A_s \cdot \eta$
 $[\%] = \frac{A_s}{A_{tot}}$

Radiation



Black body

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

Stefan-Boltzmann Law

Emission power: $P = A \cdot \epsilon \cdot \sigma \cdot T^4$
Emissivity: $0 \leq \epsilon \leq 1$
Black-body: $\epsilon_{BB} = 1$
Stefan-Boltzmann constant: $\sigma = 5.670 \cdot 10^{-8} [W/m^2K^4]$

Net Radiation Loss

Object radiating to its cooler surrounding:
 $P_{net} = A \cdot \epsilon \cdot \sigma \cdot (T_{body}^4 - T_{surrounding}^4)$

Specific radiation power & distance

$r_x = \frac{r_{sol}}{d_{star-planet}} \Rightarrow \epsilon_{sol} = \frac{P}{A} \cdot r_x \cdot \frac{1}{r_x} [W/m^2]$

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.

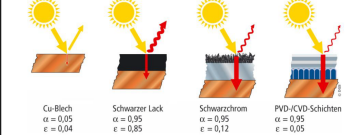
Solar thermal

3 types of heat transfer

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

Goal of S.Th.

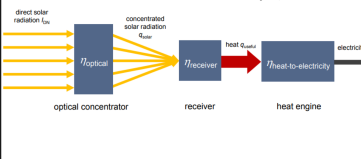
- Absorber with:
 - High absorption coefficient α in the frequency of the Sun-ray (low reflectivity, low transmittivity → $\alpha + \rho + \tau = 1$)
 - Low emission coefficient ϵ in the infrared region



Concentrated solar power (CSP)

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

$\eta_{receiver} \sim \eta_{absorption}$; $\eta_{heat-to-el} < \eta_{carnot} = 1 - \frac{T_c}{T_h}$



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 access 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. Agriculture 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.

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.

C	Receiver	Concentration Ratio
C = 10-60	Fixed receiver	Point focus / 2D concentrator
C = 30-80	Moving receiver	Line focus / 1D concentrator
C = 1000-13'000	Dish	Point focus / 3D concentrator
C = 200-10'000	Tower / central receiver	Point focus / 3D concentrator

where: C = concentration ratio
C = $\eta_{optical} \cdot \eta_{collector}$

SW5: Renewable Energy Sources 2

Geothermal Natural Earth heat

- > 15m : ground T stays nearly constant year-round
 - T increases $\approx 30^\circ\text{C/km}$
 - At 5 km $\rightarrow 160^\circ\text{C}$
- Why is it renewable**
- Natural, sustainable energy source
 - Independent of time of day and weather

- Close to surface
- Borehole
 - Ground water
 - Geostuctures
 - Borehole field
 - Deep Borehole
 - Thermalbath
- Medium depth
- Heat for Agriculture
 - Heat for residential heating and hot water
 - Deep Hydrothermal system: heat and electricity
- Deep
- 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

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

Energy heat/Water head/hydraulic head

- Energy head: theoretical energy per unit weight of water
 - ρ : specific weight $[\text{N/m}^3]$
- $H = z + \frac{p}{\rho g} + \frac{v^2}{2g}$ **elevation head** **pressure head** **velocity head**
- Power**
- $P = \rho g Q H_{\eta}$ Q = flow rate; $\eta \sim 0,85 - 0,9$

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

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

Capacitor

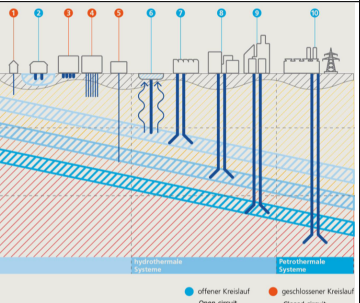
$V_{\text{vacuum}}: \epsilon_r = 1$

$E = \frac{1}{2} C U^2$; $C = \epsilon \frac{A}{d}$; $t = E/\rho$

$E = \epsilon_r \epsilon_0$; $\epsilon_0 = 8,854 \cdot 10^{-12} \frac{[As]}{Vm}$

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 $\rightarrow$ Soil regeneration
 - To store heat
 - To produce electricity (T high enough)



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 $\rightarrow$ el. generation possible
- Challenges**
- High investment costs, deep drilling
 - Uncertainty of subsurface conditions before drilling
 - Risk of induced seismicity due to hydraulic stimulation

Waste hierarchy

Disposal $\rightarrow$ Energy recover $\rightarrow$ Recycle $\rightarrow$ Reuse

Reduce (waste at source) $\leftarrow$

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}

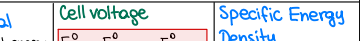
Power

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

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

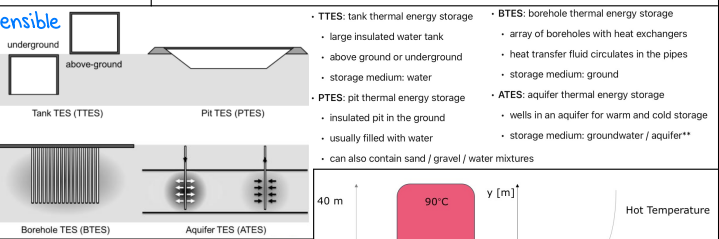


Electrochemical

- electricity $\leftrightarrow$ chemical energy
- Electrochemistry**
- Redox: electron transfer coupled with chemical change
 - Electrodes: conduct electrons
 - Electrolyte: conduct ions
 - Reactions: occur at the electrode-electrolyte interface
 - Anode: oxidation, loss of e^-
 - Cathode: reduction, gain of e^-

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	2000-5000 cycles
Hazard	Acid accelerates aging, such as corrosion of the positive electrode Lead is an environmental hazard	Electrodes are mechanical stable, which supports high cycle lifetime 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



Stratification

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

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

Solved example:

1) Tank mass: $m = \rho V = \rho \pi R^2 H$

2) Energy: $Q = mc_p(T_{\text{mix}} - T_{\text{amb}})$

3) Exergy: $f(T) = (T - T_{\text{amb}}) - T_{\text{amb}} \ln \frac{T}{T_{\text{amb}}}$

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

where $\int_{T_c}^{T_h} f(T) dT = \int_{T_c}^{T_h} (T - T_{\text{amb}}) - T_{\text{amb}} \ln \frac{T}{T_{\text{amb}}} dT$

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

Latent

- Heat stored during phase change
 - Storage medium: PCM (Phase-Change Mat)
 - Passive: indirect heat transfer through a surface, no contact between the heat transfer fluid and PCM
 - Active indirect: enhanced transfer eg. with mixing/agitation $\rightarrow$ 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.

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
 - FTES: flywheel ES
 - PTES: pumped thermal ES
 - GES: gravity ES
- Pumped hydro**
- Water stored in an upper reservoir
 - High demand: water is released through turbine $\rightarrow$ electricity generation
 - Low demand: water is pumped back to the upper reservoir
 - Pros: reliable, low lifetime cost, grid stabilization
 - Cons: env. impact, ecosystem disruption
- 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
- $E_{\text{kin}} = \frac{1}{2} I \omega^2$; $\frac{E}{m} = k \left(\frac{\sigma}{\rho} \right)$
- $K = 1$ for constant-stress disc
- $= 0,606$ for constant thickness
-

SW5: Residential Building Energy System

Energy bill

$C_{\text{heating}} [\text{CHF}] = E_{\text{heating}} [\text{kWh}_{\text{heat}}] \cdot \eta_{\text{heating}} \cdot C_{\text{heating}} [\text{CHF/kWh}]$

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

Return on investment

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

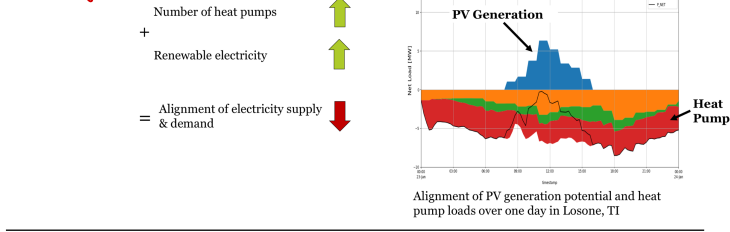
$\text{Payback Time} = \frac{\text{Investment}}{\text{Net profit annually}} = \frac{\text{Investment Cost}}{\text{Cost business as usual} - \text{cost with new investment}} = \frac{1}{ROI}$

For a heat pump

$ROI = \frac{\text{yearly expense} - \frac{\text{thermal energy}}{COP} \cdot \text{cost of electricity}}{\text{investment}}$

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

Buildings inertia



SW 6: PtX and Syn Fuels

Power to X (PtX)

PtX: conversion of excess electricity into other useful products.

Main PtX types

- Power-to-Gas:** H_2 , CH_4
- Power-to-Heat:** heat from electricity
- Power-to-Fuel:** liquid fuels (eg. methanol)
- Power-to-Chemicals:** feedstock (eg. ammonia, syngas)

Purpose of PtX

- Convert excess renewable electricity for long-term storage
- Stabilize the grid and reduce seasonal energy gaps
- Increase energy system resilience

Advantages

Long-term storage, high energy density, scalable to MW range

PtX concept

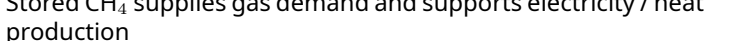
Electrolysis



Hydrogen path

Stored H_2 feeds fuel cells to produce electricity and heat

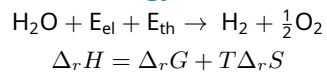
Methane path + use



Stored CH_4 supplies gas demand and supports electricity / heat production

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

Electrolysis (hydrogen production)**Chemical reaction and energy relation****Enthalpy**

- $\Delta_r H$ (25°C, atm) = 285.83 kJ/mol_{H₂O}: total energy demand
- Endothermic: $\Delta_r H > 0$

Gibbs free energy

- $\Delta_r G$ (25°C, atm) = 237.13 kJ/mol_{H₂O}: min. electrical energy
- Non-spontaneous: $\Delta_r G > 0$

Reversible cell voltage

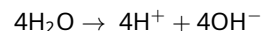
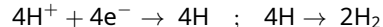
$$U_{\text{rev}} = -\frac{\Delta_r G}{zF} = -1.23\text{V}$$

Hydrogen properties

- Highly flammable, much lighter than air
- Highest gravimetric energy density: 33.3 kWh/kg
- Low volumetric energy density: 3 kWh/m³

Water electrolysis

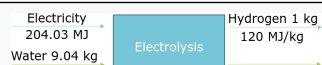
Water is split using electricity. Hydrogen is produced at the cathode, Oxygen is produced at the anode.

Ion formation**Cathode = reduction****Anode = oxidation****Exercise: Waste heat reuse of PEM electrolysis**

Input: Electricity: 204.03 MJ/kg H₂
Water: 9.04 kg

Output: Hydrogen: 1 kg
Oxygen: 7.94 kg

- Draw a schematic of the situation
- What is the cell efficiency? (LHV_{H₂} = 120 MJ/kg)
- Assuming 80% of the waste heat can be used for another purpose. What is the exergetic efficiency of the electrolysis? Assuming a reaction temperature of 80°C, ambient temperature of 25 °C



-
- $\eta_{\text{cell}} = \frac{120 \text{ MJ}}{204.03 \text{ MJ}} = 0.588 = 58.8\%$
- $Q_{\text{waste}} = (204.03 - 120) \text{ MJ} = 84.03 \text{ MJ}$
 $Q_{\text{waste,use}} = 84.03 \text{ MJ} \cdot 0.8 = 67.22 \text{ MJ}$
 $EX_{\text{waste,use}} = 67.22 \text{ MJ} \left(1 - \frac{T_0}{T}\right) = 67.22 \left(1 - \frac{298}{353}\right) = 10.49 \text{ MJ}$
 $\eta_{\text{cell,EX}} = \frac{120 \text{ MJ} + 10.49 \text{ MJ}}{204.03 \text{ MJ}} = 0.6395 = 64\%$

Types of electrolysis**AEL – Alkaline Electrolysis**

- Mature, industrial scale: > 100 MW_{el}
- Electrolyte: 20–40 wt% KOH, not consumed
- Ni electrodes; diaphragm transports OH[−] and split gases

PEM – Proton Exchange Membrane

- Less mature, up to several MW_{el}; 5–10 times smaller than AEL
- Solid polymer membrane conducts H⁺ and blocks electrons
- Acidic, anode-fed system; needs costly durable materials, eg. Nafion

SOEC – Solid Oxide Electrolysis Cell

- High-temperature steam electrolysis: 700 - 1000 °C
- Heat replaces part of the electrical demand
- Solid oxide membrane conducts O^{2−}

Methane**Pros and Cons**

Pros: good fuel and storage gas, higher volumetric energy density than H₂, uses existing gas infrastructure, can form longer hydrocarbons.

Cons: Lower gravimetric energy density than H₂

Methanation

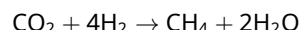
Conversion of H₂ and CO₂ into methane CH₄

Chemical

- Sabatier reaction
- Converts CO₂ + H₂ → CH₄

Biological

- Uses H₂
- Bacteria/enzymes act as catalyst

Thermochemical methanation

$$\Delta_r H = \Delta_r G + T\Delta_r S$$

- Exothermic: $\Delta_r H < 0$; 300–500°C
- Ni-based catalyst, needs CO₂
- Waste heat improves efficiency

Fuels**Fischer-Tropsch reaction**

Aims to produce sustainable liquid hydrocarbons C_nH_{2n+2} from CO₂ and H₂

Process

- Electrolysis → H₂
- RWGS → syngas CO + H₂
- FT synthesis → liquid fuels

Main products

Kerosene, diesel, naphtha, lubricating oil

Synhelion

- Concentrated solar heat drives fuel production

- TES stores heat for continuous operation
- CO₂ + H₂O → CO + H₂
- Syngas → GTL/FT → gasoline, diesel, kerosene

Storage

- Tank: limited volume
- Porous caverns: existing tanks; scarcity, contamination risk
- Aquifer: abundant; needs exploration, low leak rate
- Rock salt caverns: large volumes, high gas purity
- Underground pipes: independent from geology, expensive

X-t-P**Fuel cell**

- Reverse electrolysis: H₂ + $\frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$ + electricity
- Continuous input: H₂ + air/O₂
- Output: water, electricity, heat
- Anode + cathode + electrolyte
- Porous electrodes for gas flow
- Cell voltage < 1 V → stack needed

Fuel cell types

Type	Temp.	Carrier	Electrolyte	Eff.
AFC	60–120°C	OH [−]	KOH	35–55%
PEMFC	50–100°C	H ⁺	polymer membr.	35–45%
SOFC	800–1000°C	O ^{2−}	zirconia	>50%

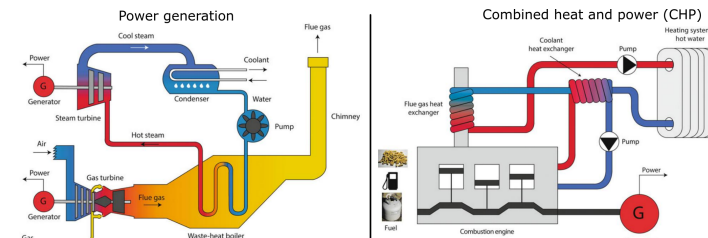
Proton Exchange Membrane (PEM) fuel cell

Polymer membrane conducts only H⁺, not electrons:

- Anode: H₂ → H⁺ + e[−]
- H⁺ passes through membrane
- e[−] goes through external circuit → current
- Cathode: H⁺ + e[−] + O₂ → H₂O

Combustion

- Power generation:** fuel → turbine → generator
- CHP:** produces electricity + useful heat
- CHP improves total efficiency by reusing waste heat

**PtXtP**

PtX has low electricity-to-electricity efficiency: CH₄ gives only 30–38%, while batteries reach 80–90%.

PtX is mainly useful for long-term storage or when gas / heat / fuels are needed, not for short-term electricity storage.

SW 8: Electrical Grids

Grid integration of renewables

- Main issues: fluctuating production, winter/day supply gaps, congestion, voltage limits
- More RES requires storage, smart control, grid reinforcement/expansion
- Switzerland: voltage issues at connection points are often more critical than transformer overloads
- PV curtailment: limiting peak power can lose little energy; 50% power limit $\approx$ 10% energy loss

Synchronous grids

- All generators/loads operate at common frequency: Europe 50 Hz, North America 60 Hz
- Interconnected AC network enables power flow and trading over large areas
- Stability needs supply-demand balance, frequency control, voltage control, overload mitigation
- Large rotating machines provide inertia and slow frequency changes
- Alternatives: isolated grids, microgrids, DC grids, HVDC links

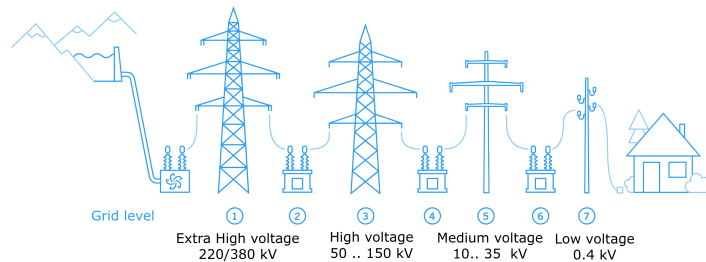
DC transmission

- Connects asynchronous areas/islands; different frequencies possible
- Efficient for long distance > 500 km: no reactive power losses, no skin effect
- Drawbacks: costly converters, harder monitoring/balancing, meshed DC grids complex

Grid structure and components

Swiss grid levels

Swiss transmission grid: 1 TSO, 380/220 kV, ~ 6700 km, substations, cross-border links, 2.5m CHF planned investment.



Components

- Generation: hydro, nuclear, thermal, renewables
- Delivery: overhead lines, underground cables, substations
- Conversion/control: transformers, converters, tap changers, capacitor banks
- Storage/loads: pumped hydro, BESS, industrial and local loads
- Protection/monitoring: circuit breakers, fuses, SCADA, sensors, automation

sors, automation

Operation requirements

- Frequency stable and in range
- Voltage stable and in range
- Operation within nominal current, voltage, thermal limits
- Resilience against faults/short circuits
- Transient stability after disturbances
- $n - 1$ criterion: supply remains guaranteed after any single component failure

Renewable Energy Sources (RES) integration measures

Voltage issues

- Reactive power regulation: absorb/inject Q to control local voltage
- Active power limitation: curtail feed-in peaks
- Voltage regulating transformer: static or adjustable
- Grid reinforcement: lower line/transformer impedance $\rightarrow$ lower voltage rise

Overloading

- Increase self-consumption; synchronize local loads with local production
- Active power limitation: fixed feed-in limit or dynamic limit
- Grid reinforcement increases transport capacity and reduces impedance

Power in AC lines

Complex power

$$S = VI^* = P + jQ$$

where:

S : apparent/complex power [VA], I^* : current conjugate

- Active power: $P = \operatorname{Re}(S) = VI \cos \theta$ [W]
- Reactive power: $Q = \operatorname{Im}(S) = VI \sin \theta$ [var]
- Power factor: $\cos \theta = P/S$

Line impedance, Power in a transmission line, Power losses

$$Z = R + jX \quad ; \quad S = P + jQ \frac{|V|^2}{Z} \quad ; \quad P_{\text{loss}} = I^2 R$$

- Higher voltage levels usually have higher reactance X
- Reactive power flow is inefficient in transmission grids

Voltage drop/rise at a connection point

$$\Delta U_2[\%] \approx \frac{R \Delta P + X \Delta Q}{U_n^2} \cdot 100$$

where U_n : rated voltage = 400 V

- $\Delta P > 0$ MW (more load) $\rightarrow \Delta U$ positive $\rightarrow U_2$ decreases
- $\Delta P < 0$ MW (more feed-in) $\rightarrow \Delta U$ negative $\rightarrow U_2$ increases
- $\Delta Q > 0$ Mvar (inductive) $\rightarrow \Delta U$ positive $\rightarrow U_2$ decreases
- $\Delta Q < 0$ Mvar (capacitive) $\rightarrow \Delta U$ negative $\rightarrow U_2$ increases
- Local feed-in/load changes voltage; high RES feed-in can cause overvoltage.

Exercise: Loss in a transmission line

An existing 10 kV transmission line carries 2 MVA (single phase line).

1. How much active power can it carry at $\cos(\theta) = 0.95$?
2. What are the active power losses for $Z = 1 + j2 \Omega$?
3. For the same active power, what are the losses at $\cos(\theta) = 0.8$?

$$\begin{aligned} 1. \quad P &= S \cos \theta = 2 \text{ MVA} \cdot 0.95 = 1.9 \text{ MW} \\ 2. \quad I &= \frac{S}{U} = \frac{2 \text{ MVA}}{10 \text{ kV}} = 200 \text{ A} \\ P_{\text{loss}} &= I^2 R = (200 \text{ A})^2 \cdot 1 \Omega = 40 \text{ kW} \\ 3. \quad S &= \frac{P}{\cos \theta} = \frac{1.9 \text{ MW}}{0.8} = 2.375 \text{ MVA} \\ I &= \frac{S}{U} = \frac{2.375 \text{ MVA}}{10 \text{ kV}} = 237.5 \text{ A} \\ P_{\text{loss}} &= (237.5 \text{ A})^2 \cdot 1 \Omega \approx 56.4 \text{ kW} \end{aligned}$$

Exercise: Voltage drop in a low-voltage grid

A 400 V LV feeder supplies a household.

$R = 0.15 \Omega$, $X_L = 0.1 \Omega$, $U_n = 400$ V, initial $P = 5$ MW, $Q = 2$ MVar. A PV plant changes $\Delta P = -100$ kW and voltage control sets $\Delta Q = 100$ kVar inductive.

1. Calculate $\Delta U_2[\%] \approx \frac{\Delta P R + \Delta Q X_L}{U_n^2} \cdot 100$
2. Does the household voltage increase or decrease?
3. How can voltage fluctuations be mitigated?

$$\begin{aligned} 1. \quad \Delta U_2 &= \frac{(-100000) \cdot 0.15 + 100000 \cdot 0.1}{400^2} \cdot 100 = -3.125\% \\ 2. \quad \text{Negative voltage drop} &\rightarrow \text{voltage rises by } \approx 3.13\%: \Delta U \approx 12.5 \text{ V, so } U_2 \approx 412.5 \text{ V} \\ 3. \quad \text{Reactive power control, active power curtailment, tap changer, local load shifting/self-consumption, grid reinforcement} \end{aligned}$$

SW 9+10: Mobility and Smart Grid Trends

E-mobility status quo

- Mobility uses $\approx 1/3$ of Swiss final energy; transport is still mostly fossil
- Electrification of transport/heating increases electricity demand; transport electricity still $< 10\%$
- EVs: ~ 50 – 80% life-cycle CO_2 savings vs. combustion vehicles
- Switzerland: BEV/PHEV $\sim 1/3$ of new car registrations; total EV stock still low
- 2050: ~ 4 – 5 million EVs; storage potential ~ 200 GWh, comparable to pumped storage
- Policy: Climate and Innovation Act, new Electricity Act incentives for electric mobility/storage

Role in Energy Strategy 2050

- High PV/wind share $\rightarrow$ more fluctuating production
- Almost fully electrified car fleet can become flexible load and distributed storage
- Bidirectional charging potential depends on charger power and availability for grid services

Powertrains and storage

Powertrain comparison

- BEV: highest well-to-wheel efficiency; best suited if electricity is low-carbon
- FCEV/H₂: lower chain efficiency due to electrolysis, compression/storage, fuel cell losses
- ICE/H₂ combustion: low drivetrain efficiency; fuel handling easier than batteries
- BEV mid-size car life-cycle emissions much lower than ICE; lecture example $\approx 55\text{--}58\%$ reduction

Battery storage

- E-mobility needs high specific energy [kWh/kg] and energy density [kWh/L]
- Li-ion batteries store much less energy per kg than liquid fuels, but EV drivetrain efficiency is high
- Typical drivetrain efficiency: EV $\sim 80\%$ vs. combustion $\sim 20\%$
- Li-ion battery costs fell strongly; lecture: about $-80\%/10\text{ yr}$

Battery ageing

- Ageing types: calendar ageing and cycling ageing
- Drivers: temperature, C-rate, depth of discharge, energy throughput, deep discharge at high temperature
- V2X ageing likely low/minimal for slow grid services; warranty conditions vary by manufacturer
- Typical warranty: 5–8 years, 160'000–240'000 km, often $\geq 70\%$ remaining capacity

Charging infrastructure

AC vs. DC charging

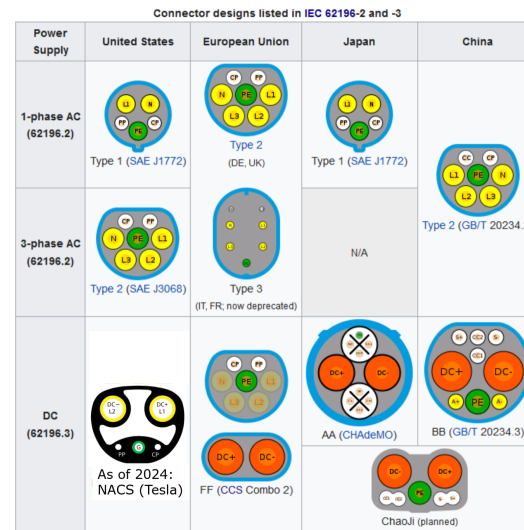
	Converter	Characteristics
AC	On-board	• Lower rated power $\leq 22\text{kW}$ • Installed in most vehicles • Bidirectionality commercially unavailable • Cheaper chargers (CHF 800–2000) • Grid compliance at vehicle level
DC	Off-board	• Less space/weight restrictions • Higher rated power $\leq 350\text{kW}$ • Supported by most vehicles (at least unidirectionally) • Bidirectionality commercially available • More expensive chargers (CHF >10k)

- DC bidirectional charging is commercially more available
- AC bidirectional still limited
- Requirements:
 - AC/DC conversion, DC voltage regulation, galvanic isolation
- MCS for heavy vehicles: MW scale, up to $\sim 3.75\text{ MW}$ target

Connector types

DC connector types

- CCS: PLC communication, de facto standard in Europe/North America, bidirectional specified but limited
- CHAdeMO: CAN bus, bidirectional commercially available, standard in Japan, phased out in Europe
- Inductive charging (wireless)



IEC 61851 charging modes

Charging mode	Mode 1	Mode 2	Mode 3	Mode 4
AC/DC	AC	AC	AC	DC
Communication	none	PWM-Module in plug	PWM-Modul in charging station	PLC
Max. Current/Power	1-phase 3-phase	16 A / 3.7 kW 32 A / 22 kW	16 A / 3.7 kW 63 A / 44 kW	400 A / 350 kW
Comments	Slow charging at household sockets with protective contact (Schuko)	Charging in one to three phases via permanently coded signal on the plug side	Charging with specific charging plug systems for electric vehicles with pilot and control contact	Fast charging with control by an external DC charger

Management and interoperability

Charge management (local parameters)

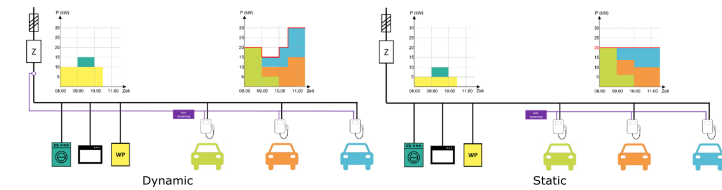
Charging is regulated based on several parameters:

- State of charge and temperature of the high-voltage battery
- Charger's power and load of the charging station (wallbox)
- Permissible charging power of the cable

Load management (upstream limitations)

- Regulates the charging process within a building or area
- Prevents the maximum reference power at the connection point from being exceeded
- Other input variables are considered (eg. PV system optimisation and special tariffs)
- Applies to both local and higher-level load management

Dynamic and static load management



Interoperability

- Required across backend systems, charging infrastructure, vehicles, users
- Challenges: cybersecurity, privacy, protocols, response times, plug types, warranties, regulation
- No one-size-fits-all solution today; V1G/V2G compatibility depends on car, charger, backend

Grid integration and Flexibility of EVs, V2X

Impacts of EVs on electrical power systems

- EV uptake increases energy demand and peak power consumption
- Superchargers create high ramp rates and local 100+ kW power steps
- Risks: transformer/line overloads, congestion, higher losses, network reinforcement needs

Impacts on distribution grids

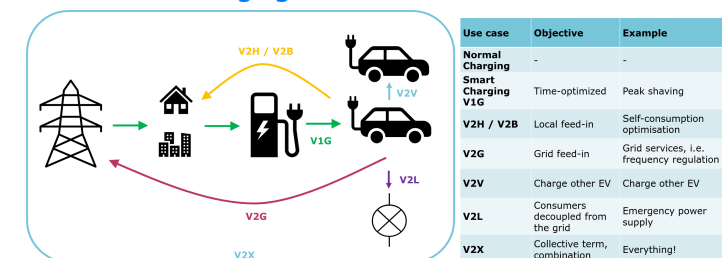
- Directly affects voltage level
- Affects power flows in lines and transformers
- Reverse power flows can be challenging for sys. protection
- Might increase network losses
- Causes high ramp rates after dark (Duck curve)

Challenges for distribution system operation

1. Increasing demand from EV charging
2. Uncertainty in renewable generation

Mitigation: uni- and bidirectional charging; smart charging; Vehicle-to-grid (V2G) integration.

Bidirectional charging



Use cases

- Standard charging: uncontrolled, cheap, but causes load spikes
- V1G / smart charging: unidirectional controlled charging; peak shaving, tariff/PV optimization

- V2H/V2B: vehicle supplies home/building; self-consumption, peak shaving, backup power
- V2G: vehicle feeds grid; frequency control, congestion management, voltage regulation
- V2L: loads supplied directly from vehicle; V2V: charge another vehicle; V2X: umbrella term

Technology readiness

Unidirectional	Bidirectional
Standard + Available and affordable - Uncontrolled, uncoordinated charging - Causes load spikes - Battery aging negatively impacted - Does not necessarily increase self-consumption	Smart charging (V1G) + Preventing peak loads through electromobility + Self-consumption can be increased + Charging at low tariff times + Available and affordable - No storage/no recovery - Limited use of flexibility - ICT Technology required
Vehicle to Home (V2H) + Reduce load peaks + Self-consumption can be increased even more + Load shifting low-high tariff + Local storage/recovery + Optimal local use of flexibility - Expensive, availability limited - Self-use, not for the power grid	Vehicle to Grid (V2G) + Added value for the power grid + Additional Revenue Streams + Widespread use of storage - Regulatory hurdles - Added value for flexibility - Vendor uncertain - Difficult market access
Availability/Low Cost	Added value for power grid/complexity

Battery ageing and warranty

Ageing

- Complex, even without bidirectional charging
- Calendar Ageing & Cycling Ageing
- Operating temperature, charge/discharge rates, depth of discharge, energy throughput → individual use
- Deep discharge combined with elevated temp. → main driver
- Limited experience for bidirectional charging
- Low discharge rates due to V2X use cases
- Extra V2X ageing is expected to be low; not enough to make V2X technically infeasible

Warranty

- Battery warranties usually limited by both age and mileage
- Typical range: 5–8 years and 160'000–240'000 km
- End-of-warranty guarantee often requires at least 70% remaining capacity
- V2X warranty treatment differs strongly by manufacturer
- Market is still early; warranty impact cannot yet be judged

Flexibility and business cases

Bidirectional charging / Vehicle-to-grid (V2G)

Transmission system grid services (TSO)

- Frequency control: primary, secondary, tertiary reserves
- Other services: voltage support, active power loss compensation, black start/island operation
- Small assets need aggregation into virtual power plants (VPPs) after prequalification

Distribution system grid services (DSO)

- DSO needs: congestion management, voltage regulation, grid-capacity management
- Local optimization: TOU tariff shifting, kW_{max} peak shaving, PV self-consumption, emergency supply
- Barriers: limited distribution-grid visibility, no unified DSO market, uncertain local market design

Aggregation and tariffs

- Aggregators pool EV fleets for ancillary/grid services and market participation
- Benefits depend on availability, user behavior, charger power, tariffs, battery limits
- Lecture pilot order: low daily savings per vehicle, but scalable with many vehicles

V2X SWOT

- Strengths:** distributed storage/flexibility, owner/grid revenues, supports decarbonization
- Weaknesses:** no seasonal storage, charging time constraints, comfort impact, limited bidi-ready EVs
- Opportunities:** new business models, local energy markets, dual-use vehicles, CO₂ savings
- Threats:** uncertain adoption/customer behavior, uncertain grid impact, flexibility not always available

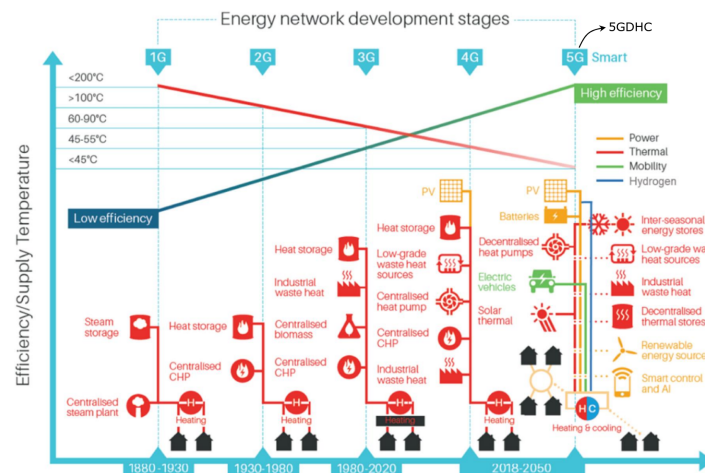
SW 11 + 12: Thermal grids

Thermal grids

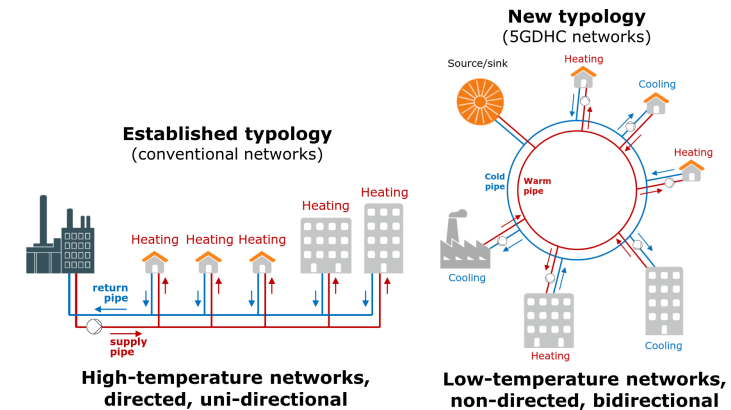
- Purpose: economies of scale, RES/waste heat integration, flexibility, lower peak load by diversity
- Heating/cooling can be centralized, decentralized, or bidirectional in 5GDHC
- 5GDHC/anergy: low-temperature warm/cold pipes, decentralized heat pumps/chillers, bidirectional use

Generations and temperatures

- HT district heating: directed supply/return, $T_{\text{supply}} \geq 60^\circ\text{C}$ (70–130°C in CH)
- LT heating: 30–60°C; preheating: 20–30°C; cooling/anergy: < 20°C
- Lower temperature = lower heat losses, easier RES/waste heat integration, larger pipes/mass flow if ΔT is small
- 5GDHC $\Delta T = 4\text{--}5\text{ K}$; large ΔT increase transport capacity

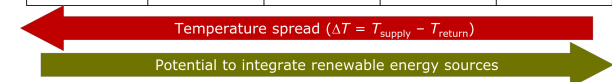


Conventional network vs 5GDHC



Pipe size

Network typology	HT-Network $\geq 60^\circ\text{C}$	LT-Network (Heating) 30–60°C	LT-Network (Preheating) 20–30°C	LT-Network (Cooling) <20°C
Relative pipe cross-sectional area	100	130	200	330
In [%], without thermal insulation				
Heat losses In [%] of the transported heat	10	6	4	0
Pumping energy In [%] of the transported heat	1	2	4	8



Potential of district heating in CH

- CH: ~ 1400 thermal networks, > 9 TWh/a heat; mostly HT
- Main sources today: waste incineration (W2E), biomass, gas, environmental/waste heat + HP

Outlook 2050 (CH)

- Swiss building stock = 50% of primary energy consumption
- More lakes, rivers, groundwater, geothermal, wastewater, environmental heat
- Increase of share of renewables, security of energy supply, and domestic value creation
- Decrease of CO₂ emissions
- DH potential: ~ 17 TWh/a; likely where heat density is high

Climate and cooling

- Climate change: HDD decrease, CDD increase strongly
- Swiss service sector cooling demand forecast: 5–7 times today's demand by 2050. Cooling demand rises
- DHC with lakes/rivers/groundwater can provide efficient cooling and heat-source regeneration

Temperatures and pipes

Pipe types in district heating

- Plastic jacket pipes: steel process pipe, PUR insulation $\lambda \sim 0.03 \text{ W/(mK)}$, PE jacket, up to 140°C , single or dual pipes
- KMR/Premant: steel pipe, up to 140°C
- Calpex: plastic pipe, up to 90°C
- Coolmant: plastic pipe, up to 40°C
- 5GDHC: uninsulated plastic pipes at very low temperature
- Heat losses decrease with lower network temperature and better insulation

District heating characteristics

Heat sources

Heat sources	Typical temperature / medium
Waste incineration heat	$>120^\circ\text{C}$
Wood firing	Hot water, supply $>110^\circ\text{C}$, steam
CHP unit	Supply $<120^\circ\text{C}$, typical 90°C
Lake water, rivers, groundwater, shallow geothermal	Supply $<60^\circ\text{C}$
Waste heat, sewage water	Supply $<60^\circ\text{C}$

Choice of supply temperature

Criterion	Implication
Heat demand characteristics	Buildings old/new, industry, hospitals
Heat source	Available temperature
Steam from steam turbine (CHP)	Supply temp. as low as possible for high electrical efficiency
Size of network	Influence of heat losses

Temperature spread

$$\Delta T = T_{\text{supply}} - T_{\text{return}}$$

Criterion	Effect
Large ΔT	Lower mass flow, smaller pipes, lower pumping energy
Small ΔT	Higher COP for HP/chillers in 5GDHC, but higher mass flow
Half ΔT	Double mass flow for same heat power
High supply temp.	Higher heat losses, but larger ΔT possible
Low supply temp.	65°C : limit for conventional heating/DHW 35°C : low-T heating, eg. underfloor
Low return temp.	Efficient CHP/cogeneration, larger ΔT , low-T waste heat usable
5GDHC/anergy	Small ΔT helps high HP/chiller COP; large ΔT helps high thermal load

Heat demand and economics

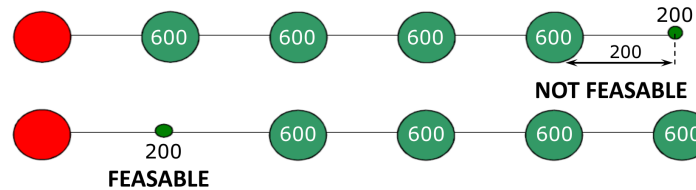
Economic feasibility of thermal networks

Linear heat density

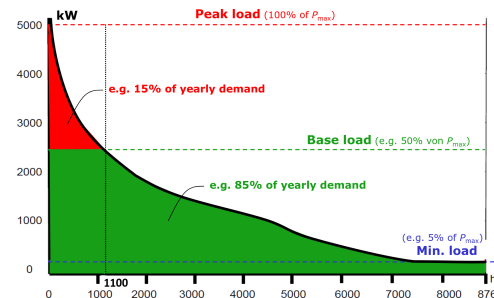
$$q_L = \frac{Q_{\text{year}}}{L} \text{ [MWh/(km} \cdot \text{a)]}$$

- Linear heat density: annual heat demand per pipe length
- Rough profitability criterion:** $q_L > 2000 \text{ MWh/(km} \cdot \text{a)}$
- Heat/power density: max. heating power per area; rough criterion $\sim 50 \text{ MW/km}^2$
- Connection rate: share of units connected in an area
- Annual full-load hours: $h_{\text{FL}} = Q_{\text{year}}/P_{\text{sub}}$; typical residential $\sim 2000 \text{ h}$

Reduced linear heat density



Load duration curve



- Load sorted by frequency/duration over the year
- Area under curve = annual heat demand
- Base load covers many hours and much energy; peak load covers few hours
- Heat storage can shift short peak loads and reduce peak generator capacity

Thermal power and sizing

Power and mass flow

$$\dot{Q} = \dot{m} c_p (T_{\text{supply}} - T_{\text{return}}) = \dot{m} c_p \Delta T$$

$$\dot{m} = \frac{\dot{Q}}{c_p \Delta T}$$

Required network (nominal) power

$$\dot{Q}_{\text{req}} = \dot{Q}_{\text{sub}} \cdot f_{\text{div}} + \dot{Q}_l$$

- $\dot{Q}_{\text{sub}}$: subscribed/connected customer power
- $\dot{Q}_l$: network heat losses
- In classic DH (90°C): $\dot{Q}_l \approx 2\% \cdot \dot{Q}_{\text{req}}$

Diversity factor (or simultaneity factor)

$$f_{\text{div}} = \frac{\text{power drawn}}{\text{subscribed power}} = \frac{\sum_i \dot{Q}_i(t_{\text{max}})}{\sum_i \dot{Q}_{\text{sub},i}}$$

- Consumers do not peak simultaneously; network power lower than sum of subscribed powers
- Diversity reduces required generation and pipe dimensions

$$f_{\text{div}} = a + \frac{b}{1 + \left(\frac{n}{c}\right)^d}$$

where:

$$a = 0.4497, b = 0.5512, c = 53.8438, d = 1.7627, n = \text{customers}$$

Peak load and reserves

$$P_P = P_{\text{sub}} \cdot f_{\text{div}} + P_L - P_S$$

- P_P : peak load coverage; P_S : base source power; P_L : losses
- Maintain supply if largest generator fails ($n - 1$)
- Typical reserve agreement: 100% network power for critical/larger grids; lower possible if accepted

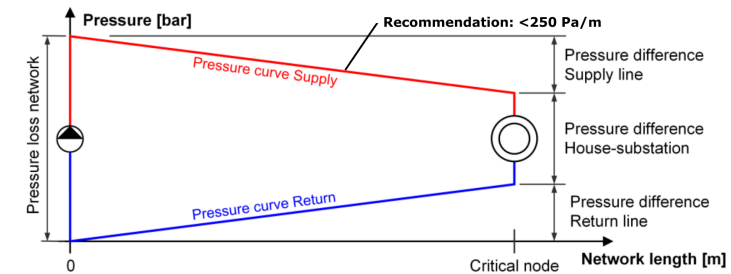
Hydraulics

Pressure loss

$$\Delta p = \lambda \frac{L}{D} \frac{\rho v^2}{2} \quad ; \quad Re = \frac{\rho v d}{\mu} = \frac{v d}{\nu}$$

- $\lambda = f(Re, k/D)$ depends on flow regime and pipe roughness
- For same pipe and similar flow regime: $\Delta p \propto v^2$
- Scaling: $\Delta p_2 = \Delta p_1 \left(\frac{v_2}{v_1}\right)^2$

Graphical visualization



Pumps and pressure

- Transfer stations need differential pressure, typically $\sim 0.7\text{--}1 \text{ bar}$
- Network pressure must stay above vapor pressure plus safety margin at highest point
- Pump redundancy examples: $2 \times 100\%$, $3 \times 50\%$, $4 \times 33\%$
- Booster pumps can reduce maximum network pressure and central pump power

District heating exercise

Available information	Power	Energy	Number of customers	Time per year
V1 (consumer 1)	400 kW	800 MWh/a	1	2000 E/P
V2	400 kW	800 MWh/a	1	2000 E/P
V3	300 kW	800 MWh/a	10	2667 E/P
V4	500 kW	1100 MWh/a	10	2200 E/P
V5	600 kW	1200 MWh/a	20	2000 E/P
Number of consumers	42			
Supply temperature	80 °C			
Return temperature	50 °C			
Line lengths (L)				
L21	200 m			
L12	50 m			
L25	200 m			
L34	500 m			
L23	2000 m			

Q1		
Heat sales	4700 MWh/a	sum of all energies

Q2		
Hours in a year	8760	
Simultaneity factor	78%	using the formula f_div(n)

Q3		
Total power (without heat losses)	1726 kW	sum of all powers * f_div(n)
Heat losses	4%	given
Total power (with heat losses)	1798 kW	Total power (without heat losses) – (100% - Heat losses)
Heat losses	72 kW	Total power (without heat losses) – Total power (with heat losses)
	24 W/m	(Heat losses / (sum of L))*1000

Q4 + Q5		
Temperature spread	30 K	Supply T – Return T
cp water	4,18 kJ/kg·K	
rho water	1000 kg/m3	
Tamb	10 °C	
ΔT_supply	70 K	Supply T – Tamb
ΔT_return	40 K	Return T – Tamb
lambda	0,03 W/m·K	

pipe section -->	T21	T12	T25	T24	T23	
Number of customers	42	41	20	10	10	sum of n in the line
Simultaneity factor	0,78	0,79	0,92	0,97	0,97	f_div(n)
Subscribed power	2200	1800	600	500	300 kW	sum of P in the line
Power	1798	1482	574	507	304 kW	(Subscriber P * f_div(n))
m_dot	14,34	11,82	4,58	4,05	2,43 kg/s	/(100% - Heat losses)
v_dot	52	43	16,5	14,6	8,7 m3/h	Power / (cp * Temp. Spread)
DN	100	100	65	65	50	m_dot / (rho * 3600)
do_r	114,3	114,3	76,1	76,1	60,3 mm	
Insulation thickness	52	52	20	20	10 mm	
U-value	0,2193	0,2193	0,2009	0,2009	0,1793 W/mk	
Length	200	50	200	500	2.000 m	
Ql_supply	3,07	0,77	2,81	7,03	25,10 kW	U-value * dT_supply * L / 1000
Ql_return	1,75	0,44	1,61	4,02	14,34 kW	U-value * dT_return * L / 1000
Ql_total	4,82	1,21	4,42	11,05	39,45 kW	Ql_supply + Ql_return
Ql_total (fraction)	0,3	0,1	0,8	2,2	13,0 %	Ql_total / Power * 1000
E_loss (annual)	42,3	10,6	38,7	96,8	345,5 MWh	Ql_total * 8760 / 1000
Q_loss_tot	61 kW		Sum of all Ql_total			
Q_loss_tot	3,4%		initial assumption: 4%	Q_loss_tot / Total power (with heat losses)		
Q_loss_year_tot	534 MWh		Sum of all E_loss (annual)			
Q_loss_year_tot	11%		Q_loss_year_tot / Heat sales			

Q6		
Q_produced	5234 MWh	Q_loss_year_tot + Heat sales

Q7		
V1	4.000 MWh/km-a	V1 Energy / L21 * 1000
V2	16.000 MWh/km-a	V2 Energy / L12 * 1000
V3	400 MWh/km-a	Not interesting
V4	2.200 MWh/km-a	
V5	6.000 MWh/km-a	

Q8 + Q9 + Q10		
Q_wood	50%	Fraction of Q_max
Q_wood	899 kW	Total power (with heat losses) * Q_wood
Q_gas	50%	(50% of Q_max)
Q_gas	899 kW	Total power (with heat losses) * Q_gas
Fraction wood	85%	Recommendation (see script)
	4449 MWh	Q_produced * Q_wood
Fraction gas	15%	
	785 MWh	Q_produced * Q_gas

Losses and cooling

Heat loss during operation

q = U · (TB – TE) [W/m]

where:

- U = heat transfer coefficient [W/mK]
- TB = avg. T between VL/RL [°C]
- TE = avg. ground temperature [°C]

Temperature drop along pipe

ΔT = Q̇l / ṁcp or ΔT = qlL / ṁcp

- Low demand periods → low ṁ → larger cooling of supply pipe
- Summer DHW-only operation can suffer larger temperature drop along the network

Heat loss through insulation

Q̇ = 2πLΔT / ((1/λ) ln(da/di))

- da, di: outer/inner insulation diameters; L: pipe length
- Losses scale with temperature difference and length; earth cover reduces losses somewhat
- Lower network temperatures reduce distribution losses

Cooling of pipes

Ti = Tu + (Tio – Tu) exp (– 1 / ṁcpRges)

where:

- Ti = Pipe T after a distance L
- Tu = Ambient T
- Tio = Pipe T at the source
- Rges = Thermal resistance [K/W]

SW 14 + 15: Cost benefit analysis

CBA basics

- Cost-benefit analysis (CBA/BCA): accounting framework to compare project benefits and costs
- Societal CBA: aim is public welfare, not profit maximisation
- Project CBA: company/project perspective; include all relevant financial costs/benefits
- Can include market and non-market goods via shadow prices

CBA workflow

1. Define scope, assumptions, perspective, period, actors
2. Identify alternatives/baseline and quantify costs/benefits
3. Select discount rate and calculate present values
4. Compare alternatives using NPV or benefit-cost ratio
5. Discuss uncertainties, risks, and sensitivity

1. Definition of scope and assumptions

- State problem and define perspective (societal vs project)
- Proportionate analysis: depth of CBA ∝ expected effect size
- Find C/B stakeholders: municipality, company, users, society

Partial equilibrium analysis

- Analyse one market separately from the rest of the economy
- Valid when effects on other markets are negligible

- e.g. town compares buying a garbage truck vs. outsourcing collection

General equilibrium analysis

- Analyse all affected markets at the same time
- Includes effects on transport, plastics, labour, and other linked markets
- e.g. national waste strategy or nationwide oil tax

2. Alternatives / Quantification of C/B

- Identification of alternatives or baseline
- Translation of costs and benefits in monetary units
- Goods/services traded in the market vs. non-market costs and benefits

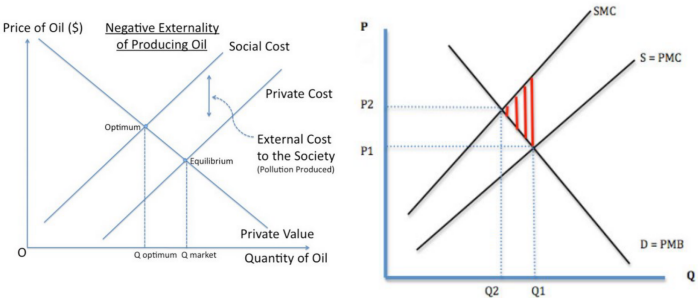
Shadow prices and externalities

Shadow price

Assigned value for a non-market good, e.g. users' time savings. Also used when market prices do not reflect true social value. If the shadow price exceeds the market price, hidden costs indicate a negative externality.

Negative externality

Third-party cost not included in transaction, e.g. noise or pollution



Positive externality

A third party gains an additional benefit without being part of the transaction. The social value is higher than the private transaction value, e.g. technology spillovers where society benefits from new knowledge beyond the company itself.

Market failure

Market price does not reflect full social cost/benefit

WTP and WTA

- Willingness-to-pay (WTP): amount someone pays to gain benefit or reduce harm
- Willingness-to-accept (WTA): compensation needed to accept a harm/loss
- WTA often higher than WTP; legal rights affect which measure is appropriate
- WTP is income constrained; WTA less directly constrained

Methods for determining WTP and WTA**Travel cost method**

- Estimates WTP for recreational sites or environmental quality changes
- Travel time, travel expenses, and entry fees act as the implicit access price
- Higher travel cost usually means fewer visits; visit frequency reveals demand/WTP
- eg. national park with \$2.50 entry fee; individual WTP = entry fee + travel cost
- Average visitor demand gives the shadow price of one visit
- Shadow price $\times$ annual visitors = annual recreational value of the site

Contingent method

- Stated-preference method: survey directly asks WTP/WTA for an environmental service
- "Contingent" because valuation depends on a hypothetical scenario
- Useful for monetising non-market goods when no market behaviour is observable
- Case: reservoir outflow decision trades hydropower generation against recreational water quality
- Survey estimates visitors' WTP for better water quality
- Optimum outflow: compare water-quality value with lost hydropower value

Conjoint analysis

- Similar to contingent valuation, but compares bundles of attributes instead of one good
- Example options combine water quality, electricity mix, and lake outflow impacts
- Respondents choose their preferred bundle
- Regression analysis estimates the value of each individual attribute

Challenges with WTP/WTA methods

- Sample bias: surveyed group may not represent the average population
- Response bias: people may overstate or understate their true WTP/WTA
- Legal rights determine whether WTP or WTA is appropriate
- Airport-noise example: WTP asks what residents pay for noise reduction; WTA asks compensation to accept noise
- WTP is income constrained, WTA is less constrained and often gives higher shadow prices

3. Discount rate and present value

- Costs/benefits occur at different times: initial investment, future gains, future O&M
- Cash flows are spread over time, not paid as one lump sum
- Time value of money: money today is worth more because it can earn interest

- Therefore, yearly cash flows must be discounted to present value

Present value

$$PV_t = \sum_{t=0}^N \frac{F_t}{(1+r)^t}$$

- F_t : cash flow at time t ; r : discount rate; t : year
- Future cash flows are worth less than immediate cash flows
- High discount rates penalise projects with near-term costs and future benefits
- Recommended rates vary widely, often 2–10%; use sensitivity analysis

Real vs. nominal

$$r_{\text{real}} \approx r_{\text{nominal}} - \pi$$

- Use comparable monetary units: nominal or constant prices
- For constant prices, subtract expected inflation π from nominal rate
- Example: nominal 8%, inflation 5% $\rightarrow$ real rate $\approx$ 3%

4. Comparing alternatives**Net present value (NPV)**

$$NPV = \sum_{t=0}^N \frac{B_t - C_t}{(1+r)^t} = PV(B) - PV(C)$$

- NPV = present value of benefits - present value of costs
- $NPV > 0$: project passes CBA test
- $NPV < 0$: reject from the chosen perspective
- Good absolute measure when alternatives differ in size

Benefit-cost ratio (B/C)

$$B/C = \frac{PV(B)}{PV(C)}$$

- $B/C > 1$: financially acceptable
- Drawback: can favour small projects with high ratio but low absolute benefit
- Use together with NPV when project scales differ
- e.g. Project A may cost \$100'000 and have lower B/C than project B costing \$100, but A can still create more total net benefit

5. Uncertainty and risk

- Sensitivity analysis: vary uncertain parameters and observe output
- Important parameters: discount rate, fuel price, demand, lifetime, investment cost
- CBA result depends strongly on scope, valuation, and assumptions

Example: garbage truck**Setup**

- Lucerne compares buying a garbage truck vs. outsourced collection
- Perspective: city treasury; no resident externalities included
- Period: 5 years; real discount rate: 3%; partial equilibrium

Item	Value
Truck purchase	60'000 EUR initial cost
Driver + maintenance + fuel	38'000 EUR/a
Scrap value	12'000 EUR in year 5
Year 5 truck cost	26'000 EUR
Contract cost	50'000 EUR/a
Undiscounted difference	12'000 EUR saved over 5 years

Results

Case	Result
3% discount rate	$NPV = 5'308 \text{ EUR} \rightarrow$ buy truck
B/C at 3%	$228'985/223'678 = 1.024 > 1$
7% discount rate	$NPV = -2'242 \text{ EUR} \rightarrow$ do not buy
Fuel cost 3'000 EUR/a	$NPV = -3'852 \text{ EUR at } 3\%$

- Same undiscounted savings can become unattractive after discounting
- Fuel-cost and discount-rate assumptions change the decision
- CBA supports decisions but does not remove uncertainty

SW 2 – 5: exercises**SW2: Renewable Energy Sources 1****Exercise: Solar area for world energy demand**

World energy demand: 183'230 TWh/a. Average solar irradiance: 1361 W/m². PV efficiency: $\eta = 25\%$. Earth area: 510'100'000 km², land share: 29%.

- How much PV area is required to cover the world energy demand?
- What share of world land surface is this?

$$\begin{aligned} \text{a. } A &= \frac{183'230 \cdot 10^{12} \text{ Wh}}{1361 \text{ W/m}^2 \cdot 8760 \text{ h} \cdot 0.25} \approx 6.15 \cdot 10^{11} \text{ m}^2 = 615'000 \text{ km}^2 \\ \text{b. } A_{\text{land}} &= 510'100'000 \text{ km}^2 \cdot 0.29 \approx 147.9 \cdot 10^6 \text{ km}^2 \\ &\frac{615'000}{147.9 \cdot 10^6} \cdot 100 \approx 0.42\% \end{aligned}$$

Exercise: Sun radiation

Given $\sigma = 5.670 \cdot 10^{-8} \text{ W/(m}^2\text{K}^4)$, $T_{\text{sun}} \approx 5780 \text{ K}$.

- Calculate the specific radiation power at the sun surface.
- Calculate total radiation power of the sun.
- Estimate solar irradiance at Earth distance.
- Estimate average radiation power over Earth surface.

- $E_{\text{sun}} = \sigma T^4 \approx 6.33 \cdot 10^7 \text{ W/m}^2$
- $P_{\text{sun}} = E_{\text{sun}} \cdot 4\pi R_{\text{sun}}^2 \approx 3.85 \cdot 10^{26} \text{ W}$
- Inverse-square scaling gives $E_{\text{solar}} \approx 1354 \text{ W/m}^2$
- Average over sphere: $\bar{E}_{\text{Earth}} \approx E_{\text{solar}}/4 \approx 340 \text{ W/m}^2$

SW3: Renewable Energy Sources 2**Exercise: Run-of-river plant Lucerne**

Given: head $h = 2 \text{ m}$, two Kaplan turbines with $Q = 29 \text{ m}^3/\text{s}$ each, river speed $v = 2 \text{ m/s}$, actual yearly production 2400 MWh/a, $\eta_{\text{el}} = 0.9$.

- Compute hydraulic power and kinetic river-power share.
- Compute yearly electricity at full load.
- Compare with actual production and explain the gap.

- $Q_{\text{tot}} = 58 \text{ m}^3/\text{s}$
 $P_h = \rho g Q h = 1000 \cdot 9.81 \cdot 58 \cdot 2 \approx 1.14 \text{ MW}$
 $P_k = \frac{1}{2} \rho Q v^2 = \frac{1}{2} \cdot 1000 \cdot 58 \cdot 2^2 \approx 0.116 \text{ MW}$
- $E_{\text{full}} = P_h \eta \cdot 8760 \text{ h} \approx 1.14 \cdot 0.9 \cdot 8760 \approx 8970 \text{ MWh/a}$
- Actual output is lower due to variable/low head and flow, down-time, ecological constraints, and non-full-load operation.

Exercise: Storage power plant Goeschenen

Given: storage lake volume $V = 75 \cdot 10^6 \text{ m}^3$, Pelton turbines $3 \cdot 41 = 123 \text{ MW}$, $\eta = 0.9$, household demand 4500 kWh/a. Head h is not given on the extracted slide.

- Calculate potential energy and produced electricity.
- Estimate number of households supplied.
- Estimate minimum depletion time.

- $E = \rho g V h$, $E_{\text{el}} = \eta \rho g V h$; insert known/given head h if available.
- $N_{\text{HH}} = \frac{E_{\text{el}} [\text{kWh}]}{4500 \text{ kWh/a}}$
- $t_{\text{min}} = \frac{E_{\text{el}}}{123 \text{ MW}}$

SW4: Energy Storage**Exercise: Capacitor**

Given: $U = 10 \text{ V}$, $r = 20 \text{ cm}$, $d = 5 \text{ mm}$, $P_{\text{LED}} = 75 \text{ mW}$, glass $\varepsilon_r = 4.7$.

- Energy stored with air between plates?
- How long can an LED burn with this energy?
- Energy stored with glass dielectric?

$$C = \varepsilon \frac{A}{d}, \quad E = \frac{1}{2} C U^2, \quad t = \frac{E}{P}$$

- Air: $E \approx 1.1 \cdot 10^{-8} \text{ J}$
- $t = 1.1 \cdot 10^{-8} / 0.075 \approx 1.5 \cdot 10^{-7} \text{ s}$
- Glass: $E \approx 5.2 \cdot 10^{-8} \text{ J}$

Exercise: Stratified sensible tank

Compare energy and exergy for tanks with 2 m thermocline, 10 m thermocline, and fully mixed state. Also discuss replacing water by gravel. Given: $r = 8 \text{ m}$, $H = 40 \text{ m}$, hot 90°C , cold 30°C , mixed 60°C , ambient 18°C , $c_p = 4.18 \text{ kJ/(kgK)}$.

- Tank mass:

$$m = \rho V = \rho \pi R^2 H$$

- Energy:

$$Q = m c_p (T_{\text{mix}} - T_{\text{amb}})$$

- Exergy:

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

$$Ex = \frac{m \cdot c_p}{H} \left[h_c f(T_c) + h_h f(T_h) + \frac{h_{\text{th}}}{T_h - T_c} \int_{T_c}^{T_h} f(T) dT \right]$$

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

Exercise: Flywheel

Solid cylindrical flywheel: $m = 50 \text{ kg}$, $r = 0.5 \text{ m}$, 6000 RPM. Load: 2 kW.

- Calculate moment of inertia.
- Calculate stored rotational kinetic energy.
- Calculate runtime at 2 kW.

- $J = \frac{1}{2} m r^2 = \frac{1}{2} \cdot 50 \cdot 0.5^2 = 6.25 \text{ kg m}^2$
- $\omega = 2\pi \cdot 6000/60 \approx 628 \text{ rad/s}$
 $E = \frac{1}{2} J \omega^2 \approx 0.5 \cdot 6.25 \cdot 628^2 \approx 1.23 \text{ MJ}$
- $t = E/P = 1.23 \text{ MJ}/2 \text{ kW} \approx 615 \text{ s} \approx 10.3 \text{ min}$

SW5: Residential Buildings**Exercise: Residential energy bill**

Estimate yearly household energy costs for heating, TV, phone charging, and showering. Use $C_{\text{el}} = P \cdot t \cdot c_{\text{el}}$ and $E = m c_p \Delta T$. Typical orders: heating 7000 kWh/a, hot water 3000 kWh/a, electricity 4000–5000 kWh/a.

Examples from slides:

- TV: 2 h/week, 32 kWh/1000 h $\rightarrow E \approx 3.33 \text{ kWh/a} \rightarrow$ about 1 CHF/a
- Phone: 10.28 Wh/day $\rightarrow E \approx 3.75 \text{ kWh/a} \rightarrow$ about 1.13 CHF/a at 0.30 CHF/kWh
- Shower: 8 min, 9 l/min, 365 showers/a, $\Delta T = 30 \text{ K}$
 $E \approx 898 \text{ kWh/a} \rightarrow$ about 269 CHF/a electricity plus water cost

Exercise: Heat pump ROI

Oil heating cost: 3500 CHF/a. Water-water heat pump investment: 27000 CHF. Thermal demand: 20000 kWh/a, COP = 3.5, electricity price: 0.29 CHF/kWh.

- Calculate payback time and ROI.
- Would you recommend the heat pump?

- $E_{\text{el}} = 20000/3.5 = 5714 \text{ kWh/a}$
 $C_{\text{HP,el}} = 5714 \cdot 0.29 \approx 1657 \text{ CHF/a}$
Savings = 3500 – 1657 = 1843 CHF/a
 $ROI = \frac{1843}{27000} = 0.068 = 6.8\%$
Payback = $\frac{27000}{1843} \approx 14.6 \text{ a}$
- Marginal: payback is close to heat-pump lifetime. Arguments: future heat-demand reduction, possible oil-price increase, PV can lower electricity cost.

Renergia

- Waste has a high calorific value: roughly comparable with coal for the same mass
- Waste crane/loading cycles: about 3500 smartphone charges; truck unloading takes about 16 min
- Highest waste input after Christmas; observed maximum about 1700 t/day
- Typical plant output: about 50 MW
- Bottom ash/slag: about 20% of input; about 10% of slag is metal, including non-ferrous metals
- Metals are recovered from slag, e.g. at Uri/Attinghausen treatment facilities
- Combustion residues are water-cooled, limiting dust/wind dispersion and cooling material from about 110°C
- Tubular heat exchangers last roughly 10 years; ash deposits require periodic cleaning to avoid blockage
- Flue gas cleaning: baking soda neutralises acidic gases; cloth/bag filters remove particles
- NO_x reduction uses catalyst with AdBlue/ammonia; activated carbon removes remaining pollutants