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# Heating and Cooling Systems
# EEN-E4002 (5 cr)

## Supply and conversion systems

# Learning objectives

Student will learn to know...

- the key thermal energy sources and their significance in the energy balance of the built environment
- the key terminology, technologies and systems related to thermal energy supply and conversion

# Lesson outline

1. Thermal energy sources
2. Subsystems and terminology related to thermal energy supply
3. Thermal energy supply and conversion systems
    - centralized energy generation (separate and co-generation)
    - district heating and cooling systems
    - hydronic central heating systems (oil/gas/wooden fuel/electricity)
    - micro-cogeneration systems
    - electric heating systems (direct/storage)
    - heat pump systems (GSHP, ASHP, EAHP)
    - solar heating systems (passive/active)
    - hybrid systems

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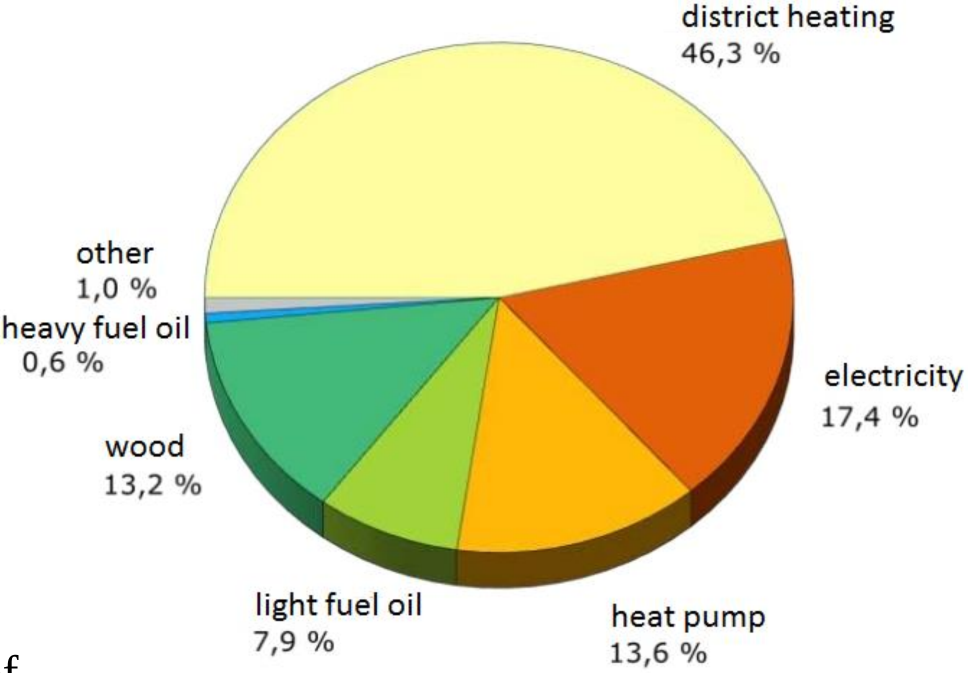
# Thermal energy sources

- Sources:
    - District heat
    - Oil or gas
    - Wood or pellet
    - Electricity
    - Heat pump
- The share of district heating covers 46.3% of the heated volume:
    - > 90 % of apartment buildings
    - 50 % of office buildings and 70 % of other public buildings
- The majority of new detached houses is electrically heated
    - calculated on the basis of the number of houses
    - in 2009 there were 540 000 electrically heated homes in Finland

Market share of heat sources in Finland (2014)



Source: Energiateollisuus Energiavuosi 2010 (tilasto vuodelta 2009)

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# Subsystems of thermal energy supply

## Energy supply systems

- Heat and power generation and distribution systems outside of the building site

## Conversion and storage systems

- Boilers and furnaces
- Heat exchangers for district heating
- Heat pumps and refrigerators
- Electric heaters
- Micro-cogeneration systems
- Solar thermal systems

## Heat distribution systems

- Pipes
- Radiators and convectors
- Floor heating
- Evaporators
- Condensers
- Hydronic cooling
- Heat sinks

## Auxiliary systems

- Pumps
- Fans
- Measurement
- Control

# Energy supply systems – terminology – I

*Primary energy*:

- Fossil fuels (oil, coal, natural gas)
- Renewable fuels (peat, biofuels)
- Solar thermal energy

*Secondary energy*:

- Electricity
- Converted heat
- Carriers (e.g. hydrogen)

*Centralized energy generation*:

- Energy is generated **in large units far from consumption** (buildings)

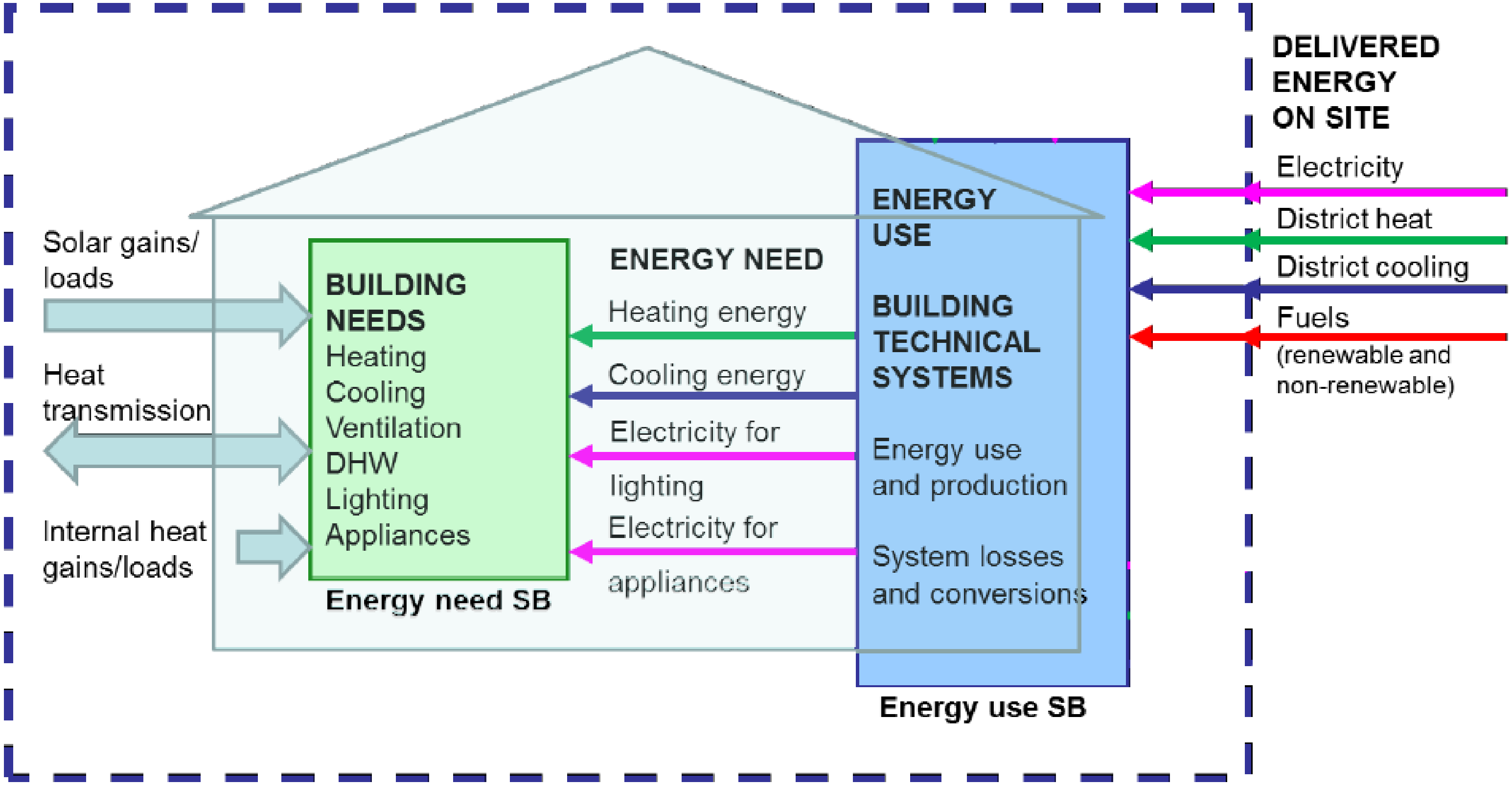
*Distributed energy generation:*

- Energy is generated **in small units close to consumption**
- AKA nearby or on-site energy generation

*Cogeneration*: simultaneous generation of electricity and useful heating and cooling from the combustion of a fuel or a solar heat collector

*Separate generation*: generation of energy form (e.g. electricity or heat) without recovering another energy form simultaneously

# Energy supply systems – terminology – II



Building site boundary = system boundary of delivered energy on site

*Delivered energy* (aka *net energy*) is energy (expressed per energy carrier) supplied to the technical building systems through the system boundary to satisfy the uses taken into account (heating, cooling, ventilation, domestic hot water, lighting, appliances, etc.) or to produce electricity (EN13790).

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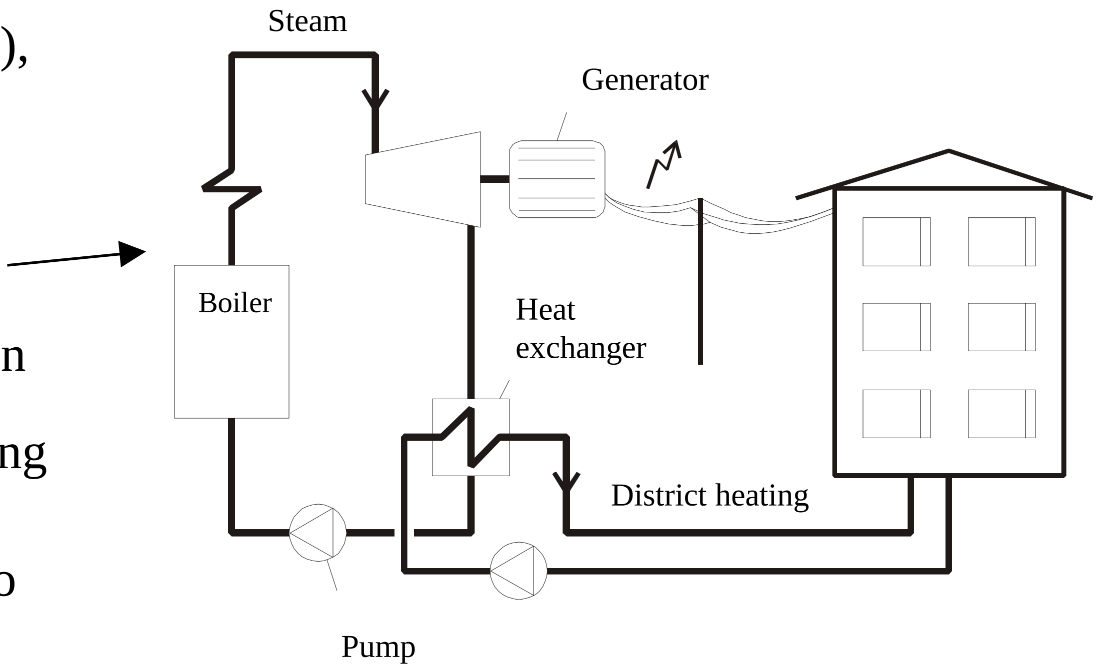
# Energy supply systems – centralized energy generation

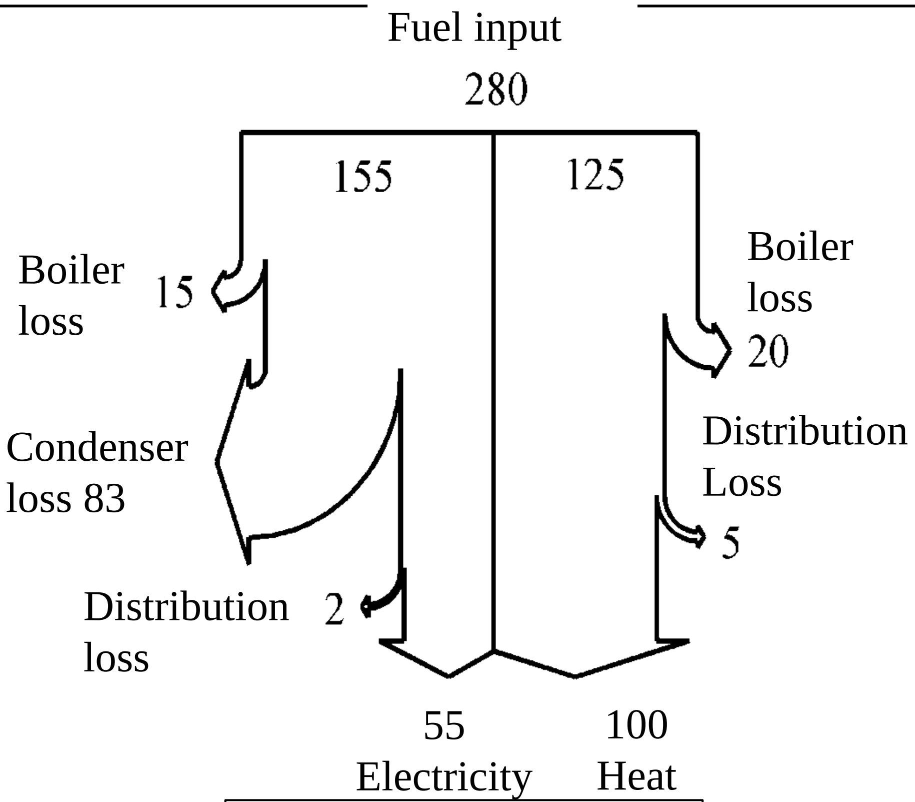
- In a power plant (power station), the energy content of primary energy (fuel) is converted into electricity by turbine and generator.
- In Finland, ca 30% of power generation and 80% of district heating is based on cogeneration (figure on the right).
- Since heat is recovered to heating of buildings via district heating network, the total efficiency (electricity + heat) is high, up to 80-90%.
- *District heating plant* is a power plant (figure on the right) *without* turbine and generator.
- *Condensing power plant* is a power plant (figure on the right) *without* district heating network. The heat exchanger is replaced by condenser.



*District heating* is a heat supply system based on heat generated in a centralized location for residential and commercial heating requirements such as space heating and water heating.

*Block heating* is small-scale district heating: e.g. a shared heating station for several buildings (semi-distributed energy generation).

# Energy supply systems – separate vs. cogeneration



Fuel input

280

155

125

Boiler loss 15

Boiler loss 20

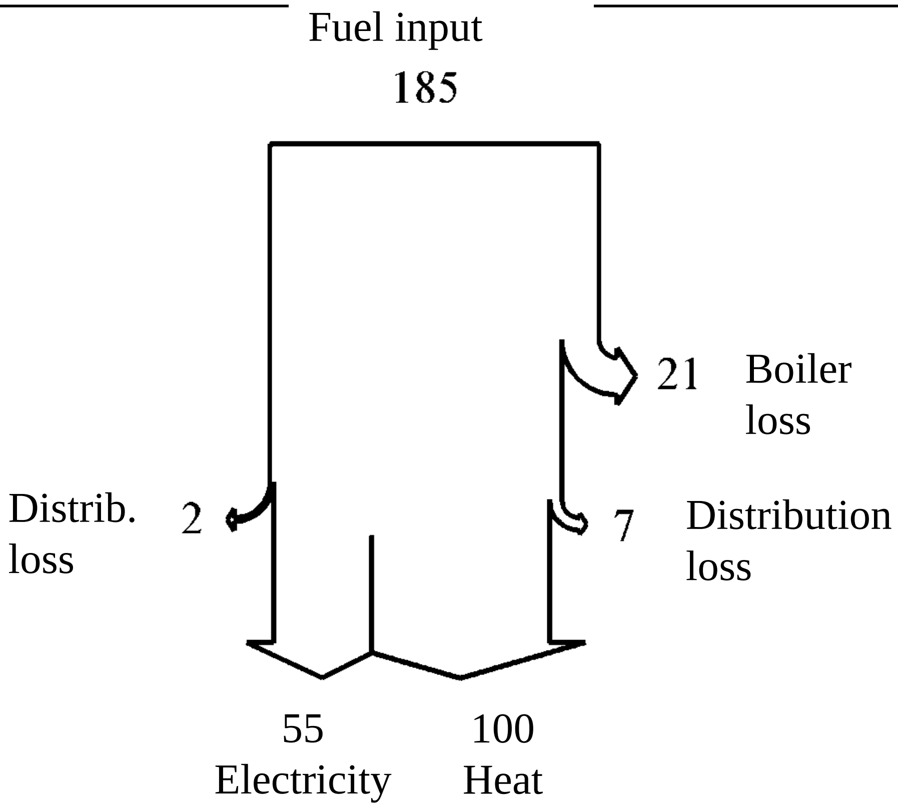
Condenser loss 83

Distribution Loss 5

Distribution loss 2

55 Electricity

100 Heat



Fuel input

185

21 Boiler loss

Distrib. loss 2

7 Distribution loss

55 Electricity

100 Heat

Separate generation:

$$\eta_e = \frac{P_e}{\Phi_{fuel}} = \frac{55}{155} = 36\%$$

$$\eta_{th} = \frac{\Phi_{th}}{\Phi_{fuel}} = \frac{100}{125} = 80\%$$

$$\eta_{tot} = \frac{P_e + \Phi_{th}}{\Phi_{fuel}} = \frac{55+100}{280} = 55\%$$

Cogeneration:

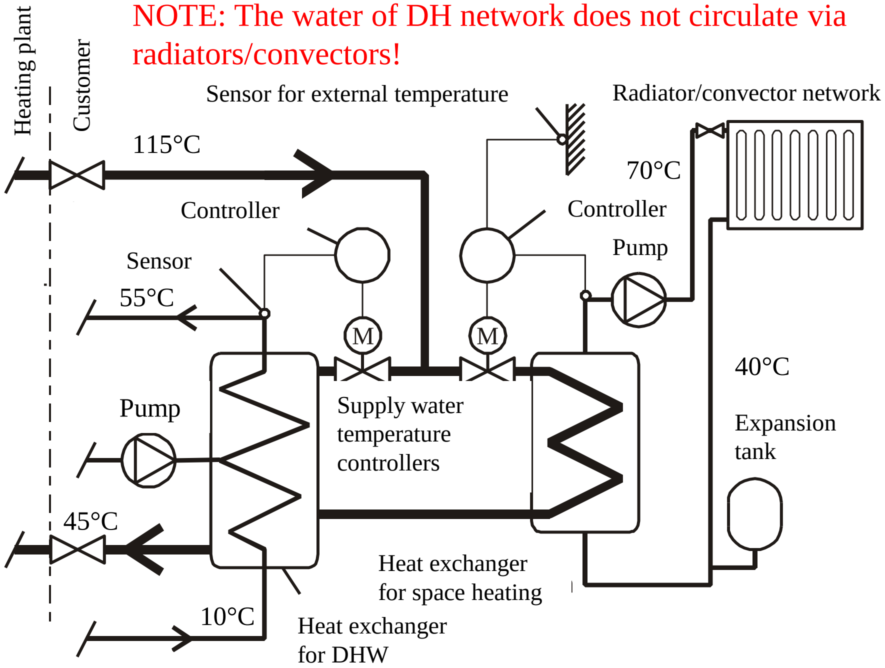
$$\eta_e = \frac{P_e}{\Phi_{fuel}} = \frac{55}{185} = 30\%$$

$$\eta_{th} = \frac{\Phi_{th}}{\Phi_{fuel}} = \frac{100}{185} = 54\%$$

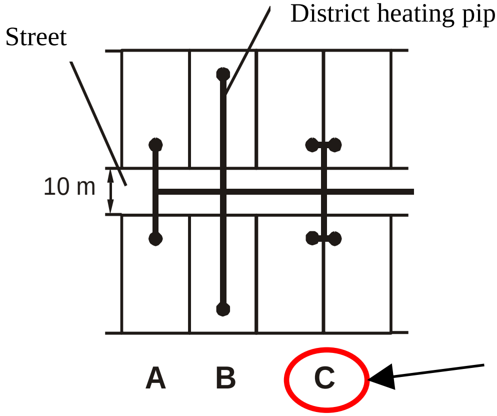
$$\eta_{tot} = \frac{P_e + \Phi_{th}}{\Phi_{fuel}} = \frac{55+100}{185} = 84\% \left(= \eta_e + \eta_{th}\right)$$

# Conversion systems – district heating system

- District heating presumes a *hydronic central heating system*.
- *Central heating* is heat generation/conversion and distribution system to deliver heat from a heating plant (usually located in on-site or nearby) via fluid to rooms through radiators or convectors. The fluid is commonly water, wherefore the expression hydronic central heating system is used.
- The *heat distribution centre* includes:
  1. separate heat exchangers at least for both space heating and DHW (plus sometimes for ventilation/air-conditioning)
  2. thermal energy measurement
  3. auxiliary system (measurement, control and pumps)



NOTE: The water of DH network does not circulate via radiators/convectors!



Space requirement of heat distribution centre:

- detached houses: 2–3 $m^2$
- rowhouses: 3–8 $m^2$
- apartment buildings: ~10 $m^2$
- offices: 14–20 $m^2$

Preferred location: C

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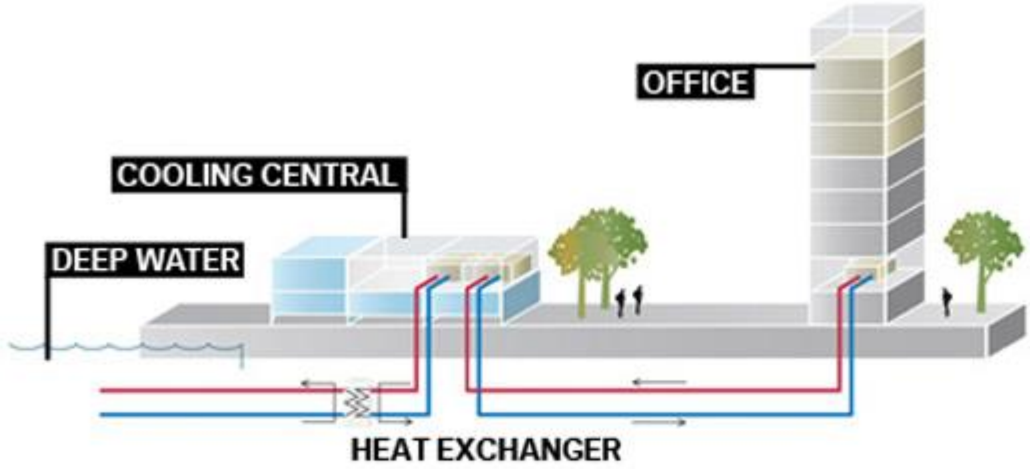
# Heat distribution centre

# District cooling systems

- Buildings are cooled down by cold water ($T \approx 5$°C).
- Buildings have on-site heat exchangers (as with district heating).
- District cooling network is used to circulate the cooling water from a district heating plant to the building.
- Cold bottom and deep waters and specific cold water storages are harnessed as cooling resources.



Reference: Vattenfall

Supply water: 5°C
Return water: >10°C

**Self-studying: Familiarize yourself with the Katri Vala (Helsinki) district cooling plant.**

https://www.helen.fi/en/helen-oy/about-us/energy-production/power-plants/katri-vala-heating-and-cooling-plant/

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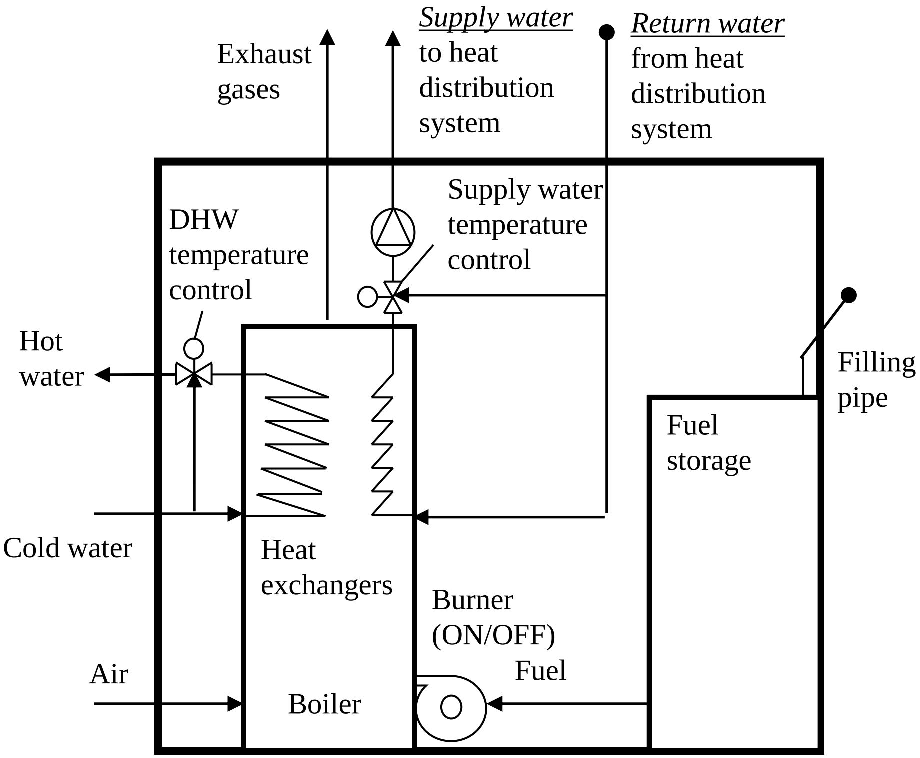
# Conversion systems – oil-/gas fuelled hydronic central heating system

- Oil/gas- fuelled heating presumes a hydronic central heating system.
- The *heating plant* consists of:
  1. boiler
  2. fuel storage
  3. auxiliary system
- For a gas fuelled heating system the fuel storage is replaced by a gas valve and a flow meter.
- The boiler includes a water tank (150–200 L), which shaves the peak thermal demands.



Space requirement of heating plant:
- detached houses: 4 m²
- rowhouses: 10–15 m²
- apartment buildings: ~10 m²
- offices (< 5000 m²): 30–40 m²
- oil tank: ~3 $m^3$

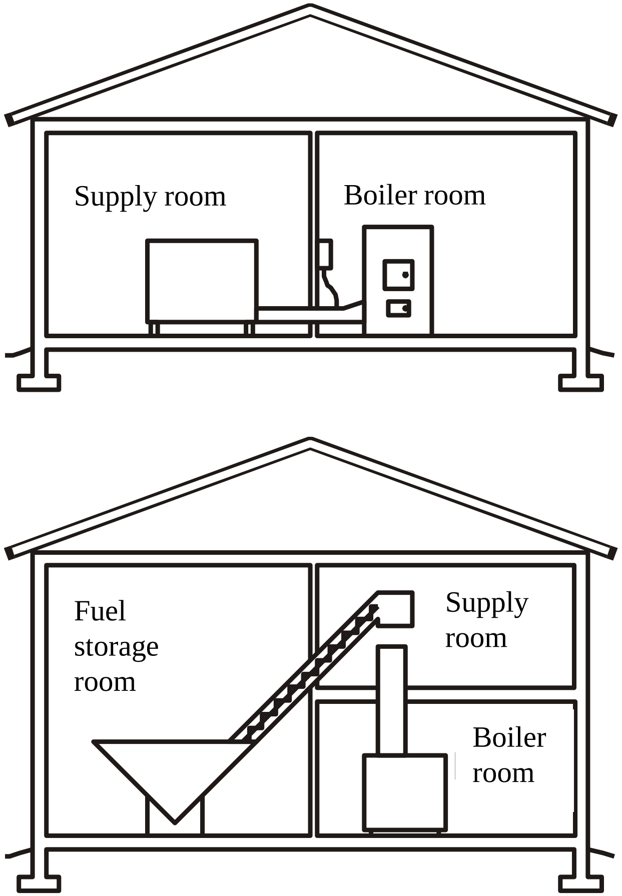
# Conversion systems – wooden fuel-based hydronic central heating system

- Fuels: firewood, wood chip, pellets
- The integration (with heat distribution) as in oil- and gas-fueled systems
- LHV is 1/10 of that of oil

→ significant space requirement of the fuel storage (min 5 m$^3$)

- Difficult to control (firewood-fueled boilers)

→ A large thermal storage tank (> 1 m$^3$) required



# Energy use of boilers

- *__Boiler efficiency__* is calculated from:

$$\eta_{th} = \frac{\Phi_{th}}{\Phi_{fuel}} = \frac{\Phi_{fuel} - \Phi_{exh} - \Phi_{skin}}{\Phi_{fuel}} = 1 - \frac{\Phi_{exh}}{\Phi_{fuel}} - \frac{\Phi_{skin}}{\Phi_{fuel}}$$

*__Idling loss__* refers to the fuel consumption for maintaining the temperature of DHW when there is no DHW demand (summer).

- Boiler efficiency is:
  - modern boilers: ≥ 95 % (LHV)
  - old boilers: 75–80 % (LHV)

- exhaust loss $Q_{exh}$
- skin loss $Q_{skin}$
- *__idling loss__* $Q_{idle}$

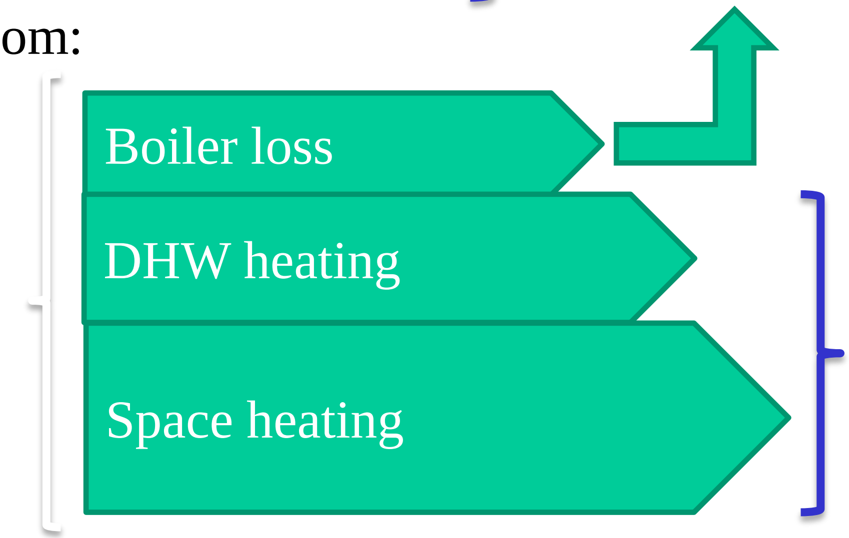
$$\left.\begin{array}{l}\text{exhaust loss } Q_{exh}\\ \text{skin loss } Q_{skin}\\ \text{idling loss } Q_{idle}\end{array}\right\} Q_{loss} = Q_{exh} + Q_{skin} + Q_{idle}$$

- *__Annual efficiency__* is calculated from:

$$\eta_a = \frac{Q_{th}}{Q_{fuel}} = \frac{Q_{fuel} - Q_{loss}}{Q_{fuel}}$$

$$= 1 - \frac{Q_{loss}}{Q_{fuel}} \left( < \eta_{th} \right)$$

where [Q] = kWh/a

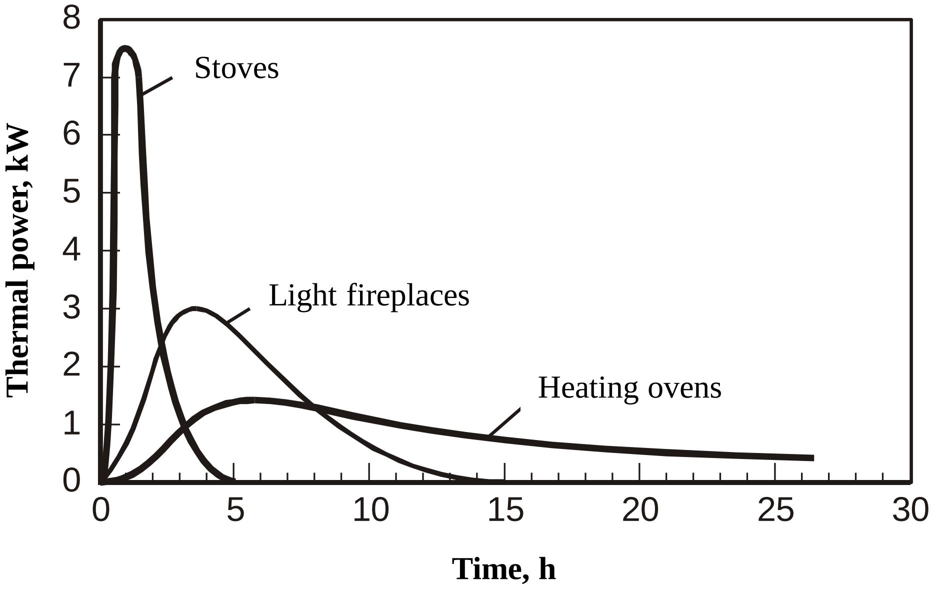


__Fuel input__ $Q_{fuel}$ ($\Phi_{fuel}$)

__Useful output__ $Q_{th} = Q_{fuel} - Q_{loss}$ ($\Phi_{th} = \Phi_{fuel} - \Phi_{exh} - \Phi_{skin}$ )

# Conversion systems – Furnaces

- Classification on the basis of thermal power and heat capacity (capacitance)
- Fireplaces
  - *continuous combustion* (fuel is added continuously)
  - low thermal power, low capacitance
- Stoves and light fireplaces
  - continuous combustion
  - high momentary thermal power, low capacitance
- Heating ovens and heavy (storage) fireplaces
  - *batch combustion* (fuel is added at intervals)
  - low thermal power, high capacitance



# Conversion systems – Micro-cogeneration (micro-CHP)

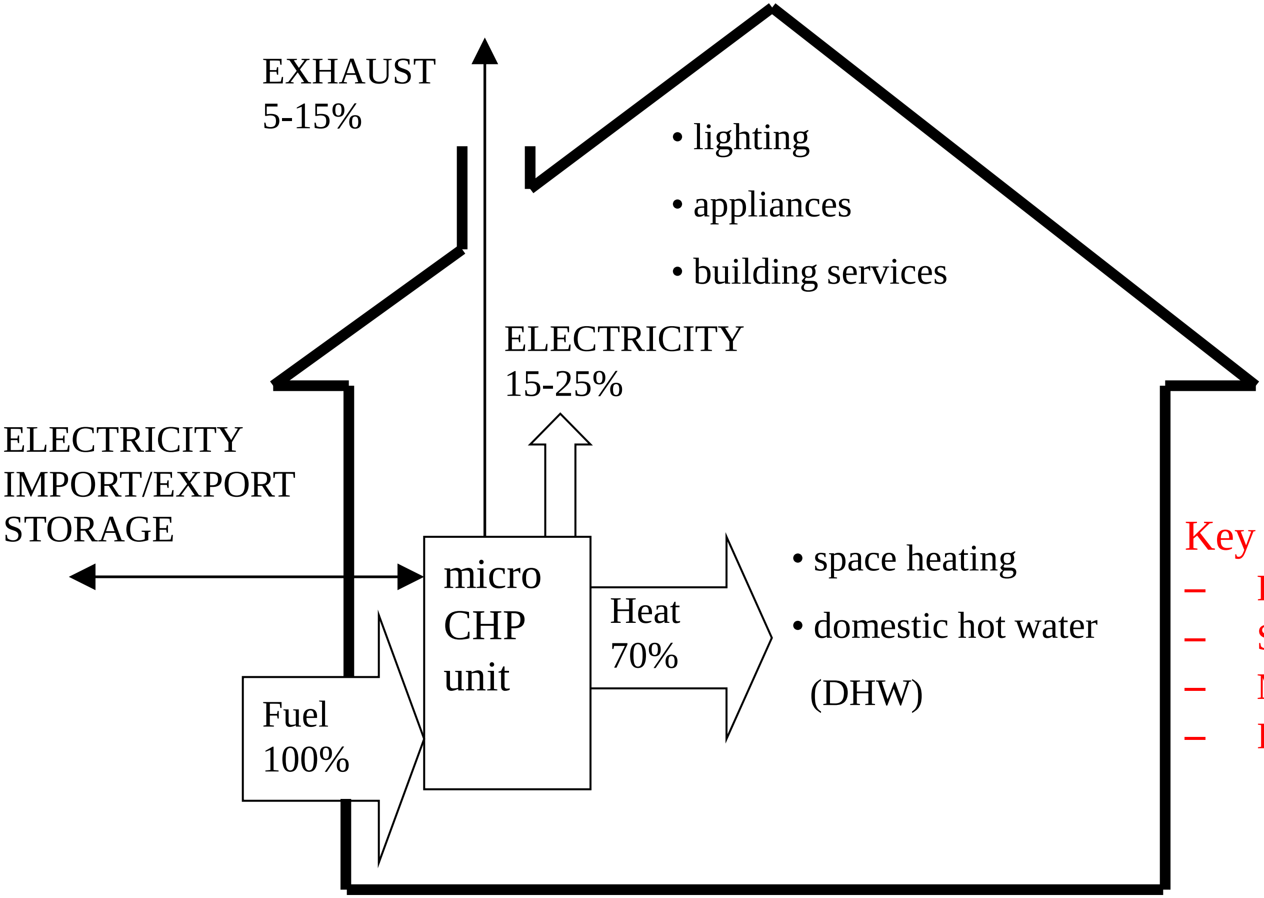
## General definition:

- *CHP*: ***C**ombined **H**eat and **P**ower*
- ”Simultaneous production of electricity and thermal energy in small units close to consumers”
- ”A direct replacement for a boiler in a hydronic heating system, which simultaneously produces heat & electrical power”

## Technical definition:

- EU Directive on micro-cogeneration:
  - electrical power less than 50 kWe
  - ”Mini-CHP”: electrical power > 50 $kW_e$
- European Committee for Standardization (EN50438):
  - 16 A per phase in three phase (25 A single phase)
- Domestic scale micro-cogeneration (DCHP):
  - “one unit per home”
  - practically: less than 5 kWe

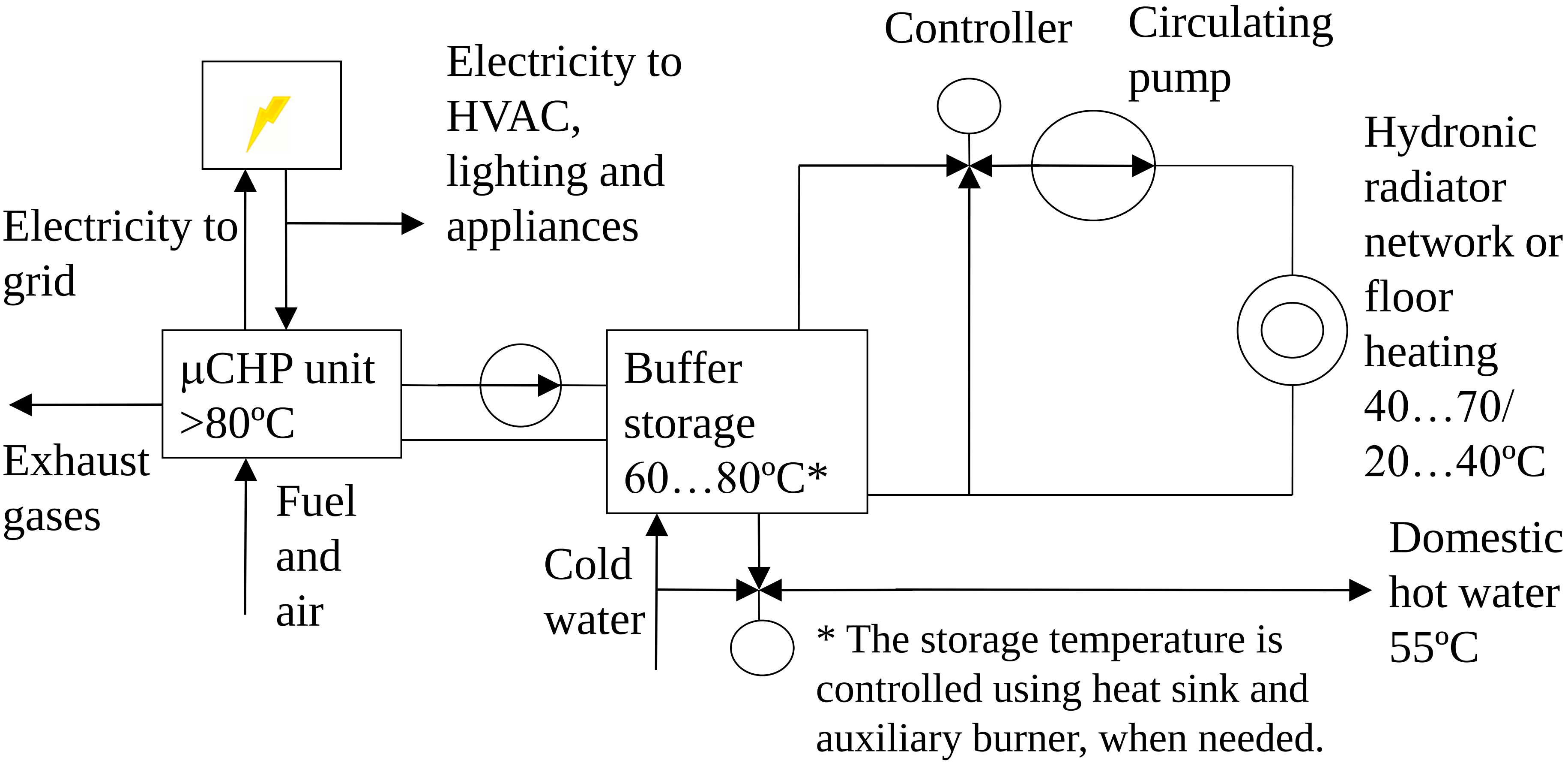
# Domestic micro-CHP (DCHP)



Key DCHP technologies

- Fuel Cells (FC)
- Stirling Engines (SE)
- Micro Turbines (MT)
- Internal Combustion Engines (ICE)

# Integration of micro-CHP plant into building



* The storage temperature is controlled using heat sink and auxiliary burner, when needed.

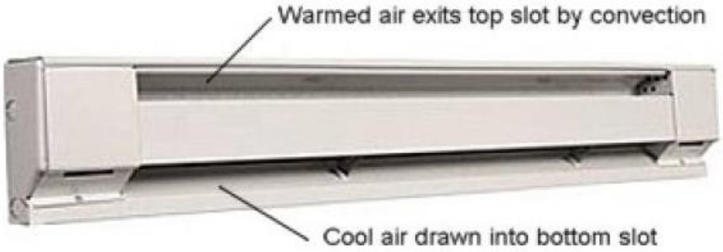
# Conversion systems - Electric heating systems

Also known (particularly in the Anglo-Saxon world) as *electric baseboard heating system:* Electricity is converted into heat using electric heating resistors.

*Direct electric heating (DEH)*: Electricity is converted in a room. Electric demand follows directly the heating demand.

*Storage heating*: Heating resistor warms up water or a solid body. The stored heat is used later, according to the heating demand. The storage heating allows the utilization of low electricity prices (e.g. night time).

There is a variety of electric heaters available.



Electric Baseboard Convection Heater

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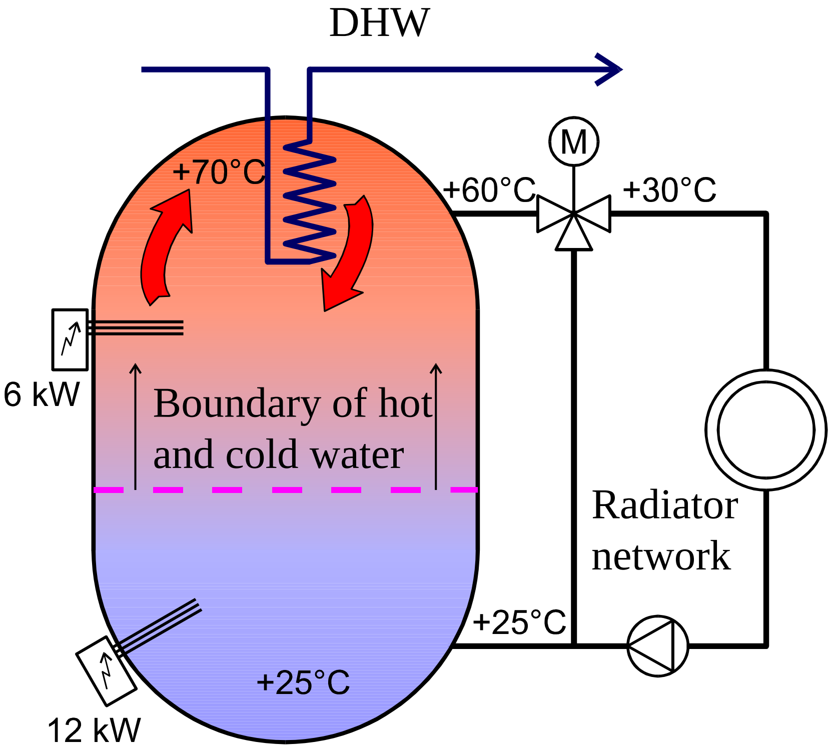
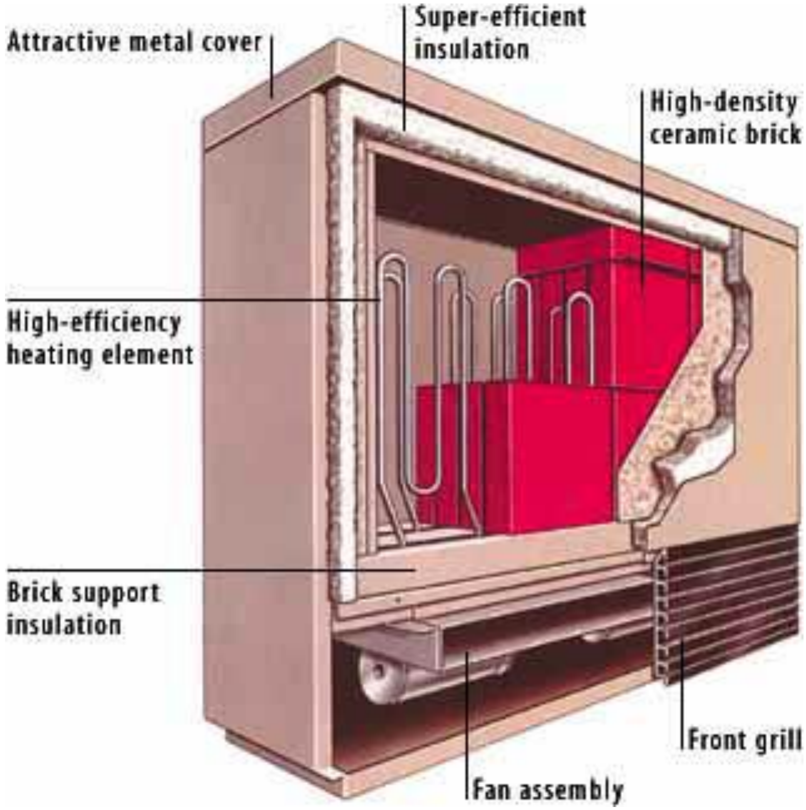
# Conversion systems – Electric central heating

- *Electric central heating* refers to a hydronic central heating system where electricity is converted into heat and distributed via water.
- The boiler is replaced by a large storage tank (e.g. 2–3 m³ for detached houses).
- There are heating resistors at both the bottom and on the top of the tank.
- The resistors on the top of the tank are for auxiliary heating and they are enabled during the coldest periods to ensure the availability of hot water.



# Conversion systems – Electric storage heating

- Insulated mass storage made of ceramic bricks and tiles is heated during night up to 600–700°C and released during day time by circulating air through the storage.
- Old tiled stoves can be converted to mass storages by installing electric resistors.
- In Finland: common in 1960-70s.



**Direct electric heating and electric floor heating will be treated in the context of heat distribution and auxiliary systems.**

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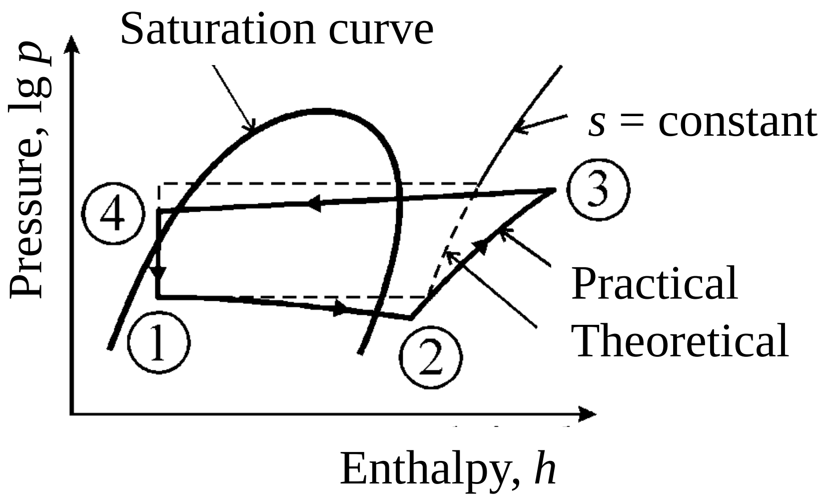
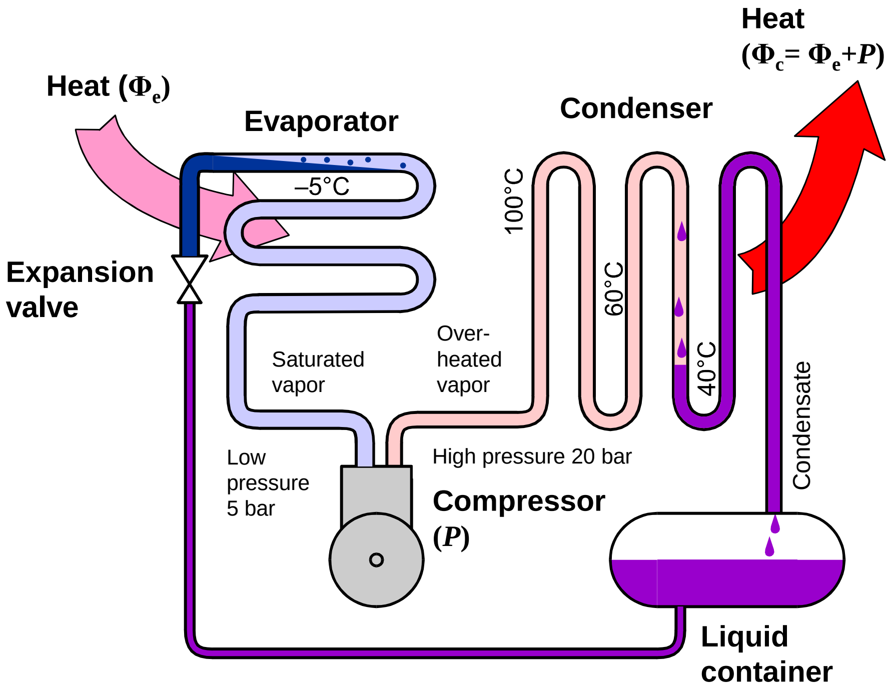
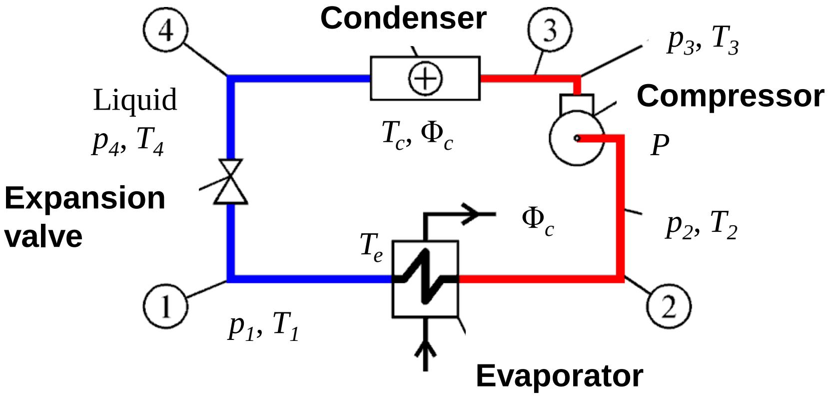
# Conversion systems – Heat pump/refrigerator

The operation of heat pump is based on the utilization of the latent heat of *refrigerant*: Evaporation absorbs heat at low pressure and temperature and condensation releases it into the environment presuming that there is a temperature difference between the refrigerant and the environment.



Entropy ($s$) increases due to losses in compressor and pressure drops in evaporator and condenser.





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# Coefficient Of Performance (COP)

NOTE: Since the compressors are mostly electric-powered, heat pump systems are often interpreted as electric heating systems. Presuming that the electricity is generated from renewable sources, heat pump can be also interpreted as a renewable energy supply system.

- Theoretical upper bound (Carnot efficiency):

$$\varphi_c = \frac{T_c}{T_c - T_e}$$

- *COP of equipment*: the ratio of the utilizable thermal power and the power demand of the compressor (*P*)

$$\text{For heat pump}: COP = \frac{\Phi_c}{P} = \frac{\Phi_e + P}{P} \qquad \text{For refrigerator}: COP = \frac{\Phi_e}{P} = \frac{\Phi_e}{\Phi_c - \Phi_e}$$

- *COP of system*: the electrical demand (*P*) includes the power demand of the auxiliaries (pumps etc.).
- *Seasonal COP (SCOP)* (for time period Δ*t*):

$$SCOP = \frac{Q_c}{W} = \frac{Q_e + W}{W} \text{ where } \begin{cases} W = \int_{\Delta t} P dt = \text{seasonal electrical demand of system} \left[\frac{\text{kWh}}{\text{a}}\right] \\ Q_c = \int_{\Delta t} \Phi_c dt = \text{seasonal thermal energy processed by condenser} \left[\frac{\text{kWh}}{\text{a}}\right] \\ Q_e = \int_{\Delta t} \Phi_e dt = \text{seasonal thermal energy processed by evaporator} \left[\frac{\text{kWh}}{\text{a}}\right] \end{cases}$$

# Temperature requirements for heat pumps

The most useful heat sources for heat pumps:

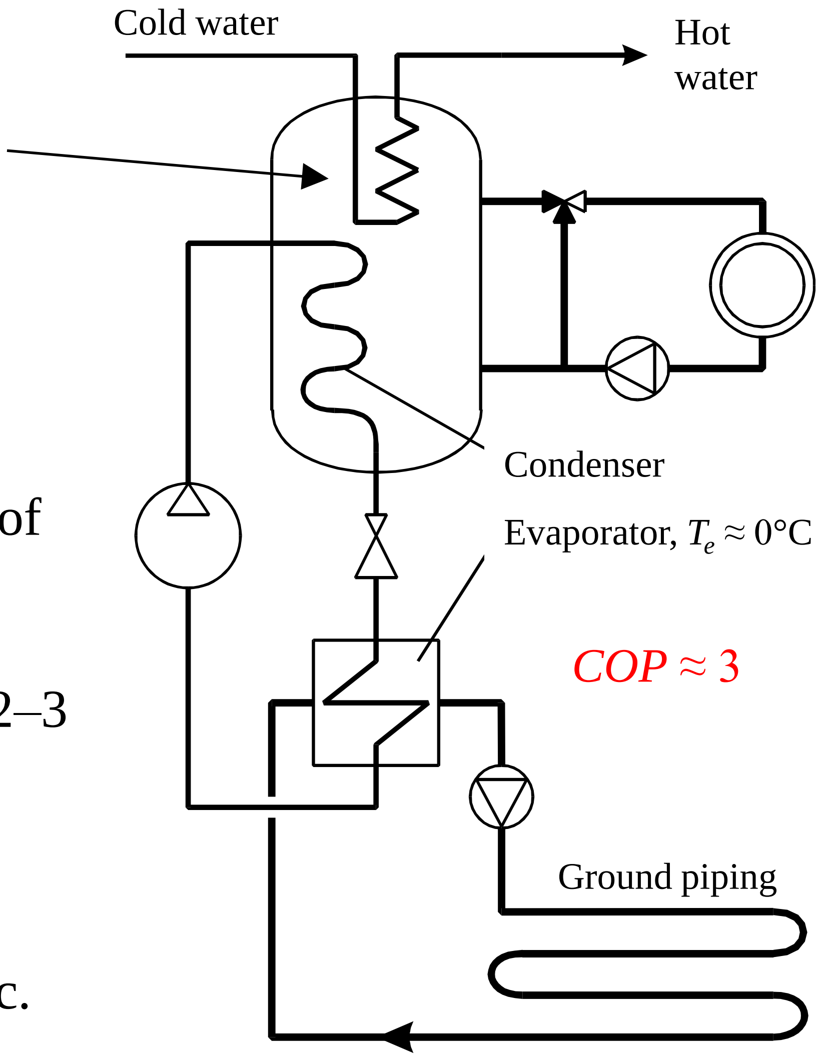
- Exhaust air (~20°C)
- Ground, water (~0°C)
- Waste heat from industrial processes and cooling water
- Outdoor air (+15…–15°C)

The useful heat distribution temperatures for heat pumps:

- Air heating: 20–40°C
- Floor heating 20–30°C
- Radiator heating 40–60°C

A ground-source heat pump plant

# Integration of a ground-source heat pump (GSHP) plant

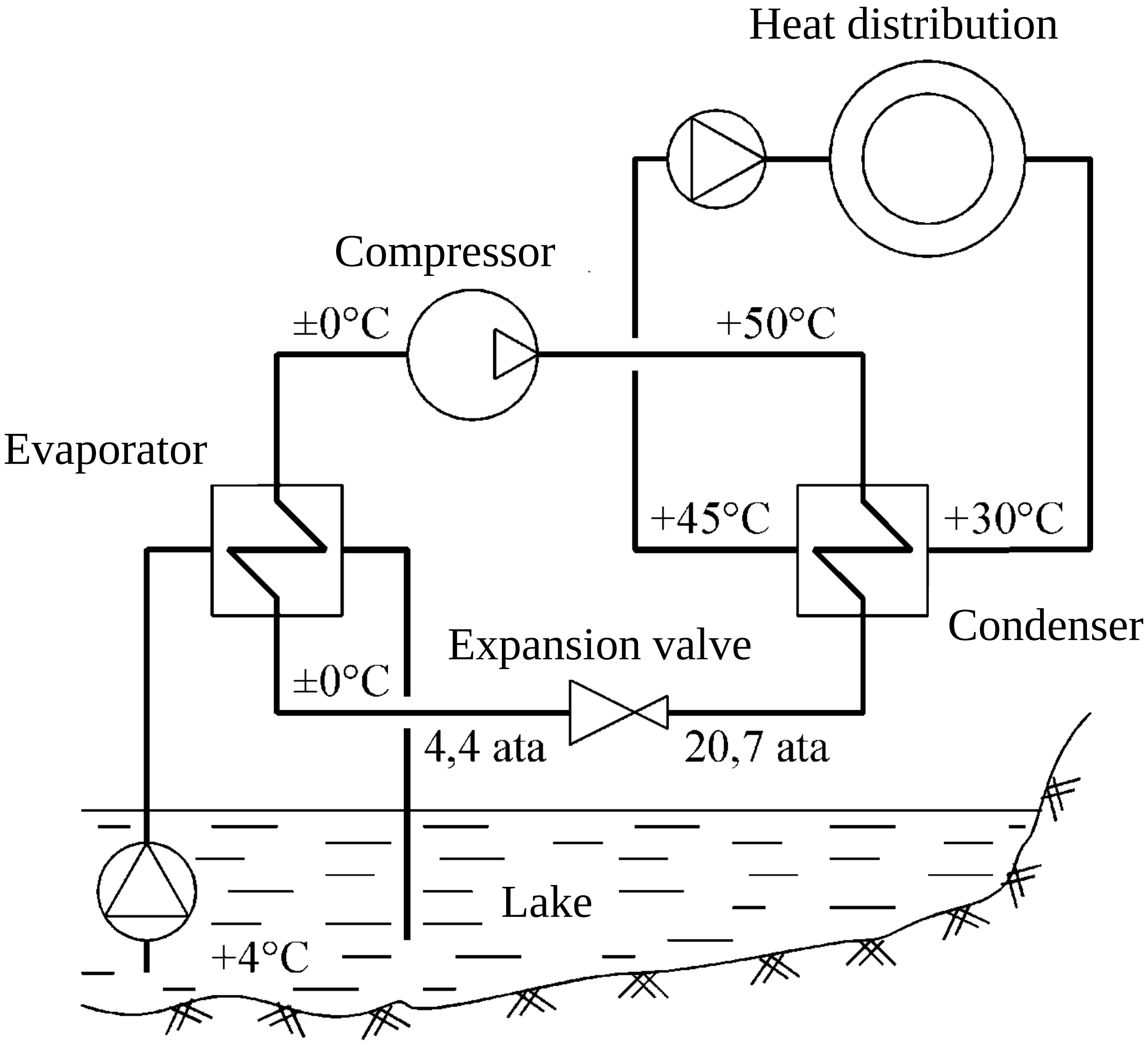


Resistance heaters are used as an auxiliary heat source for ensuring the DHW supply.

$COP \approx 3$

- A ground-source heat pump requires ground piping to be located:
  1. horizontally into the depth of 1 m, the distance between pipes being 1.2–1.5 m, the ground requirement being 2–3 m²/building-m$^3$
  2. into a borehole (depth ~150 m)
  3. into the bottom of a lake etc.

# Integration of a water-source heat pump (WSHP) plant



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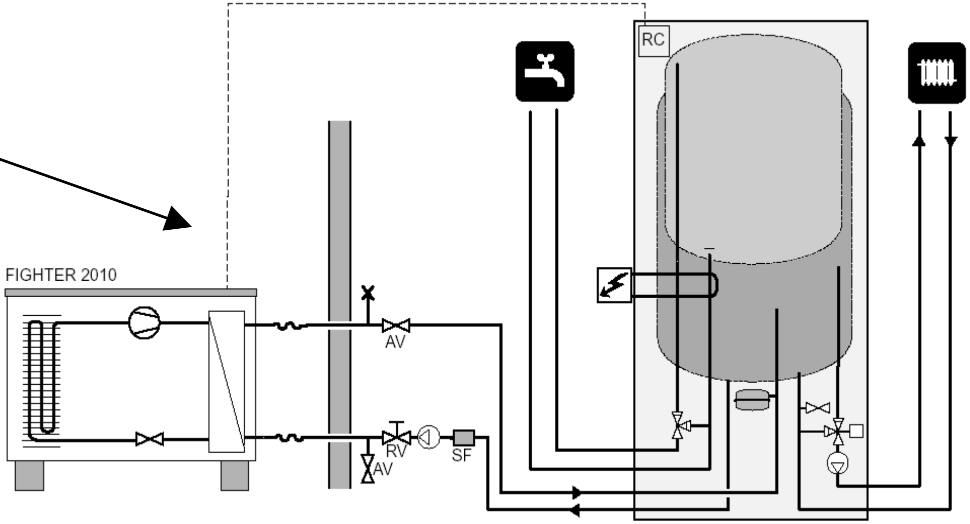
# Air-source heat pump (ASHP)

- Less complicated than GSHP
- Used as an auxiliary heat source
- Air-to-air and air-to-water installations possible
  - External unit: evaporator, fan and compressor
  - Internal unit for air-to-air installation: condenser and recirculation fan
  - Internal unit for air-to-water installation: condenser integrated with thermal storage
  - Pipework: Ø < 100 mm



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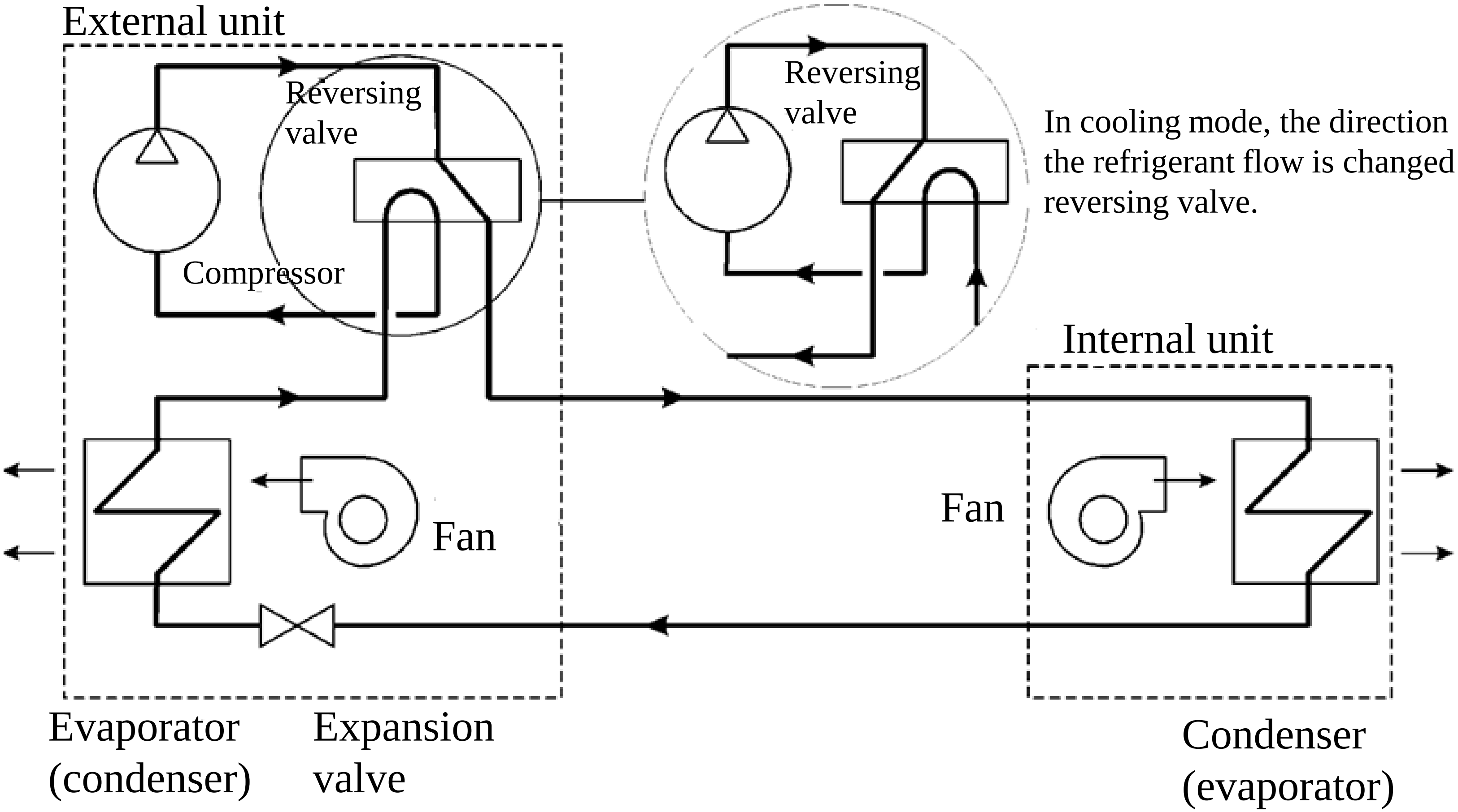
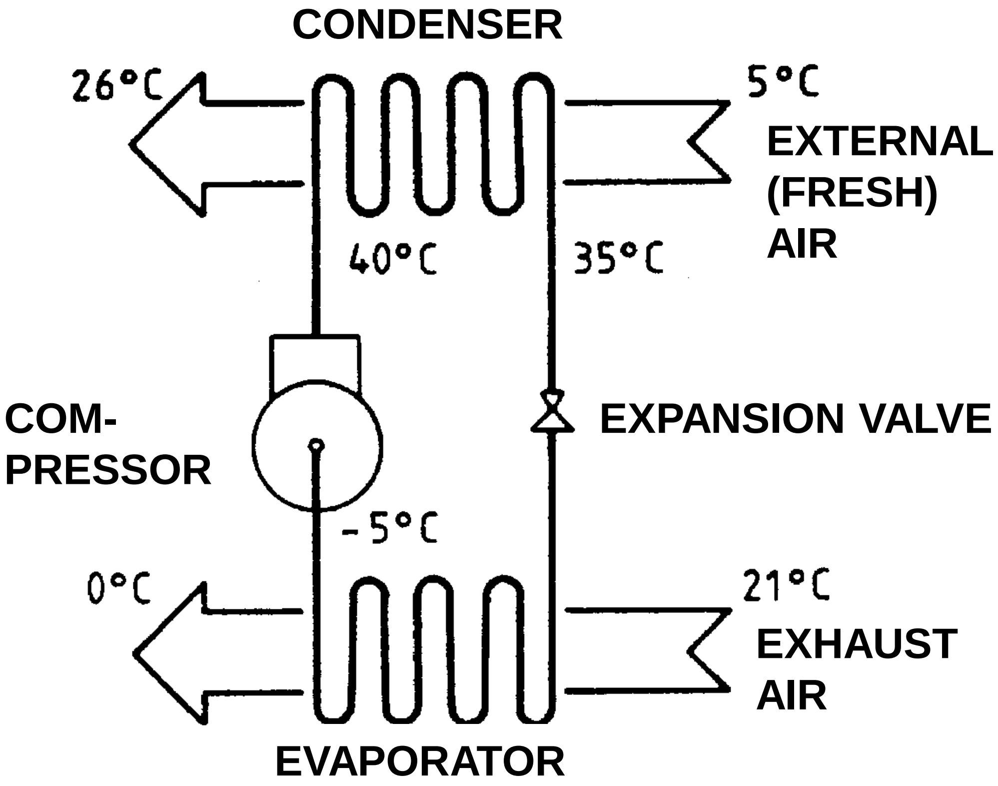
# Using an ASHP for cooling

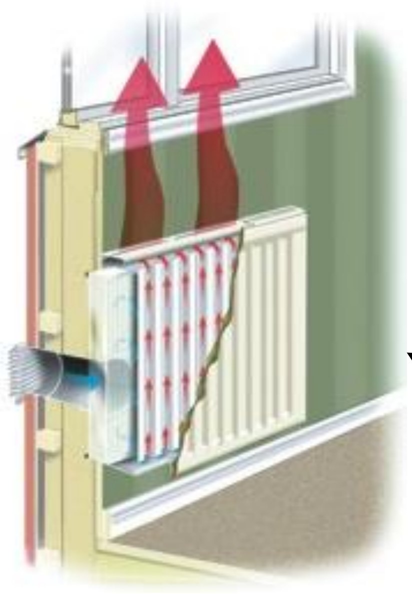


In cooling mode, the direction of the refrigerant flow is changed by reversing valve.

# Exhaust air heat pump (EAHP)

- Heat source: exhaust air
- Suitable for buildings with mechanical ventilation
- Heat from the condenser can be released to
  - hydronic heating
  - DHW heating
  - ventilation





Example: Fresh air is filtered and heated using a heat recovery fresh air radiator.

Note: Due to the risk of icing, the minimum exhaust air temperature is 0°C → not useful in extremely cold weather.

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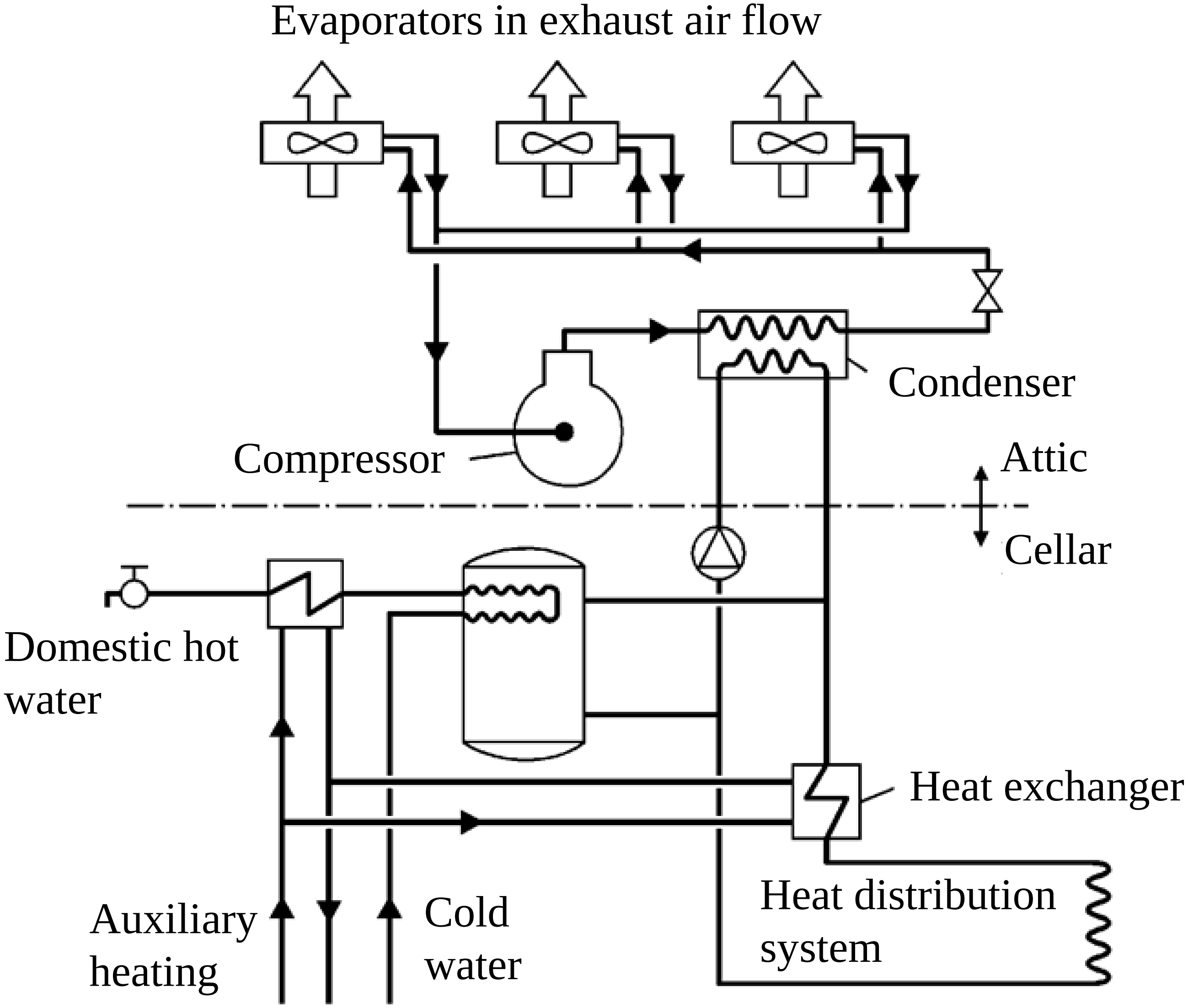
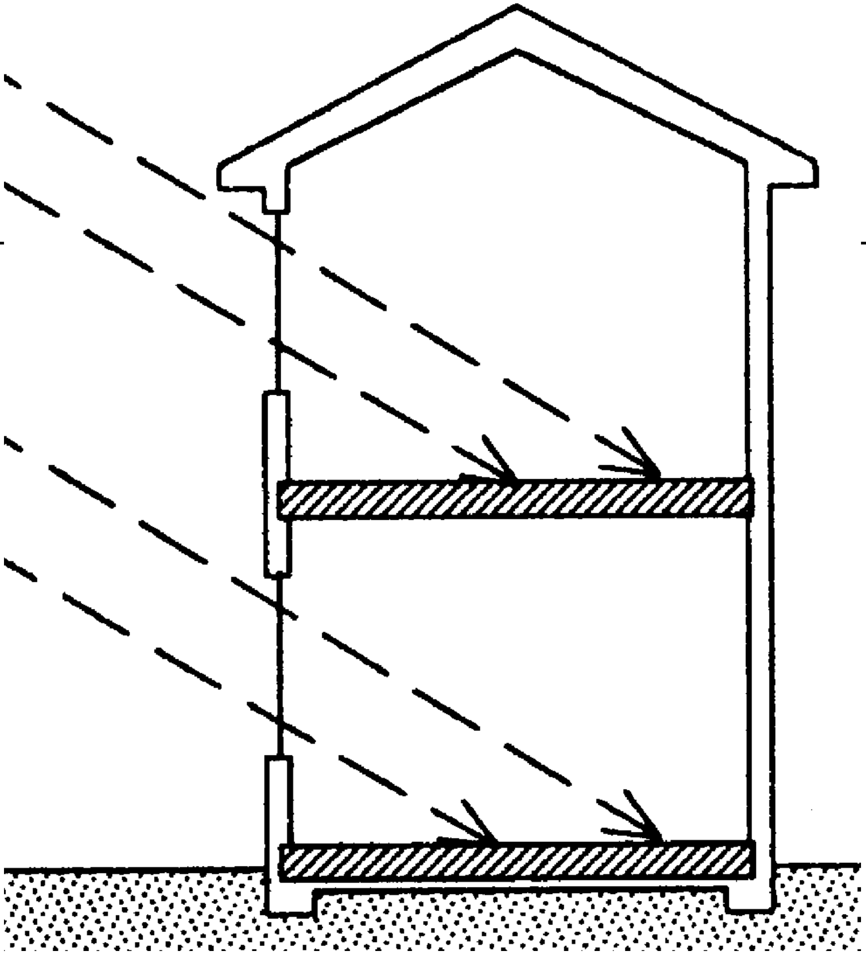
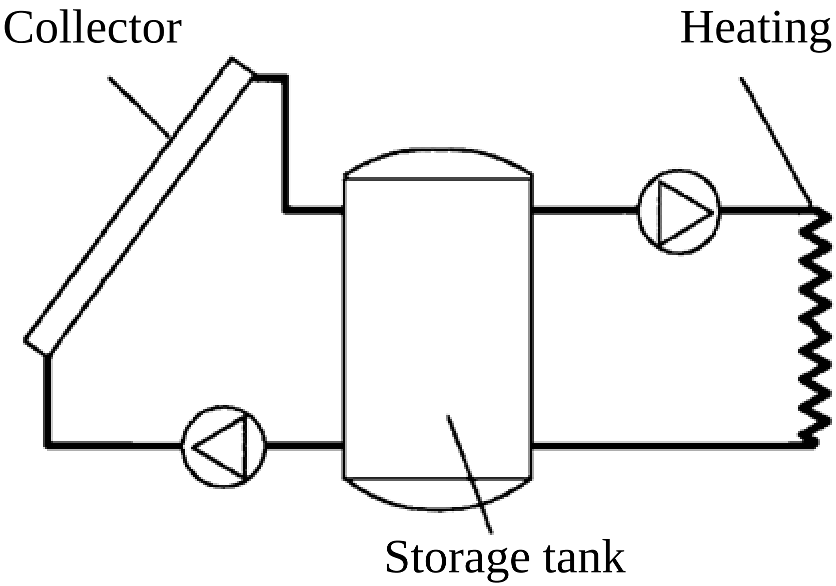
# Integration of exhaust air heat pump (EAHP) plant



# Solar heating

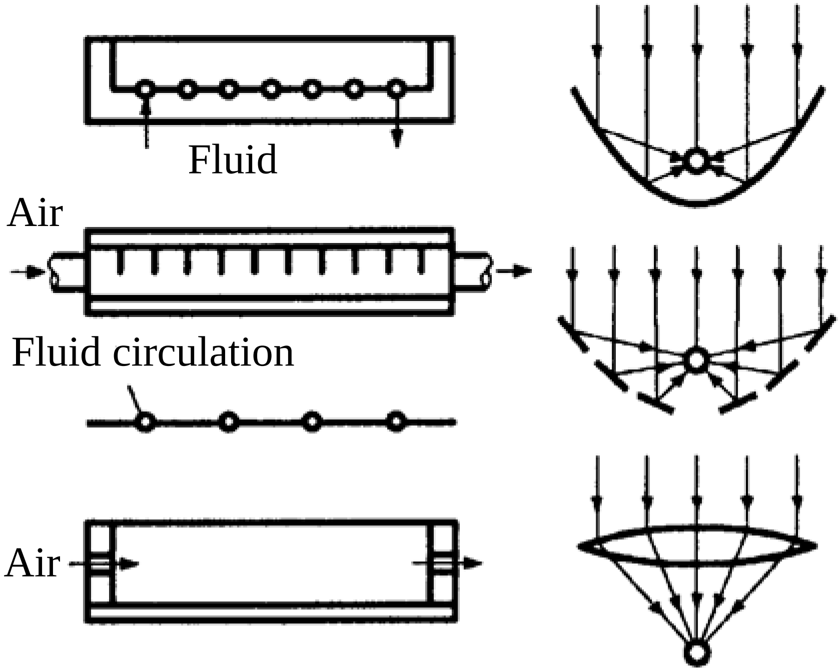




*Passive solar heating*: Solar heat is utilized by way of space planning and construction, incl. orientation of building and massive structures.

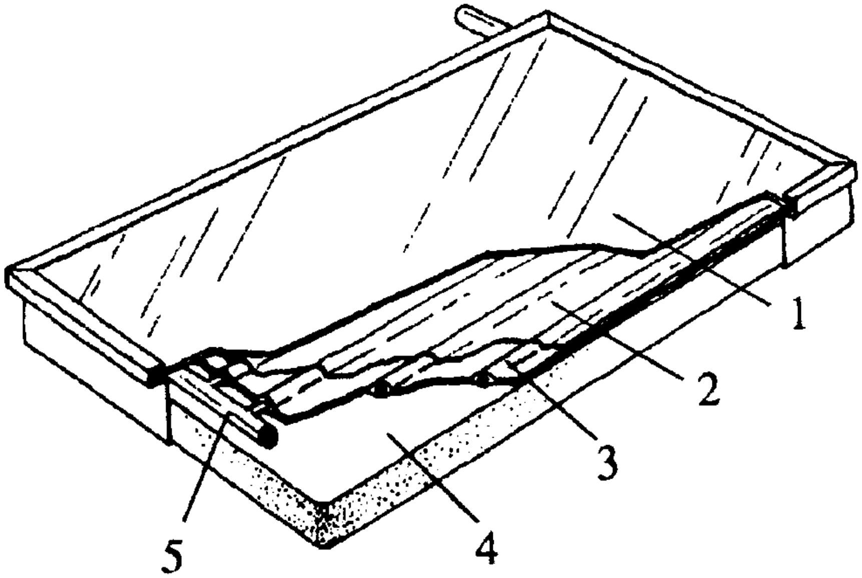
*Active solar heating*: Solar irradiation is converted into heat in solar collectors, stored in a heat storage tank and  utilized according the demand.

# Solar collector

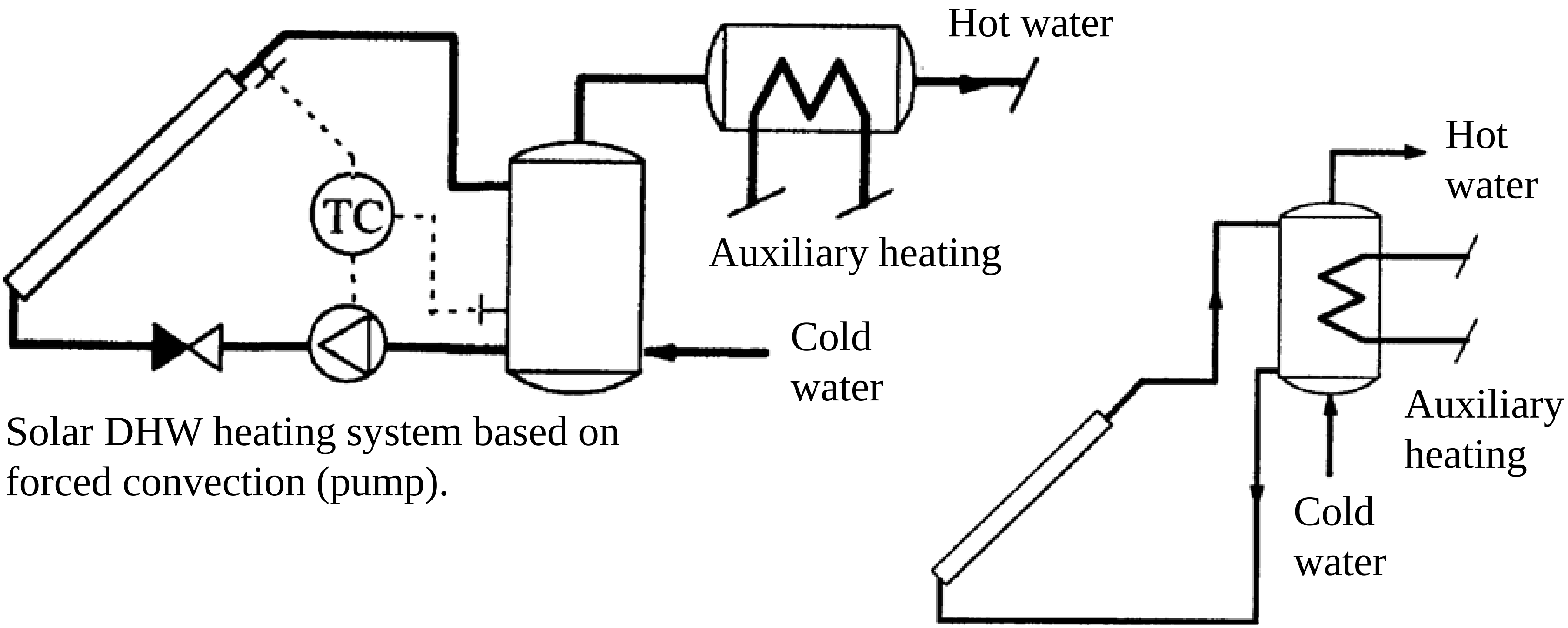


Structure of a solar collector

1. Selective cover plate
2. Selective coating
3. Absorption plate
4. Insulation
5. Collector tube



# DHW heating using solar collector

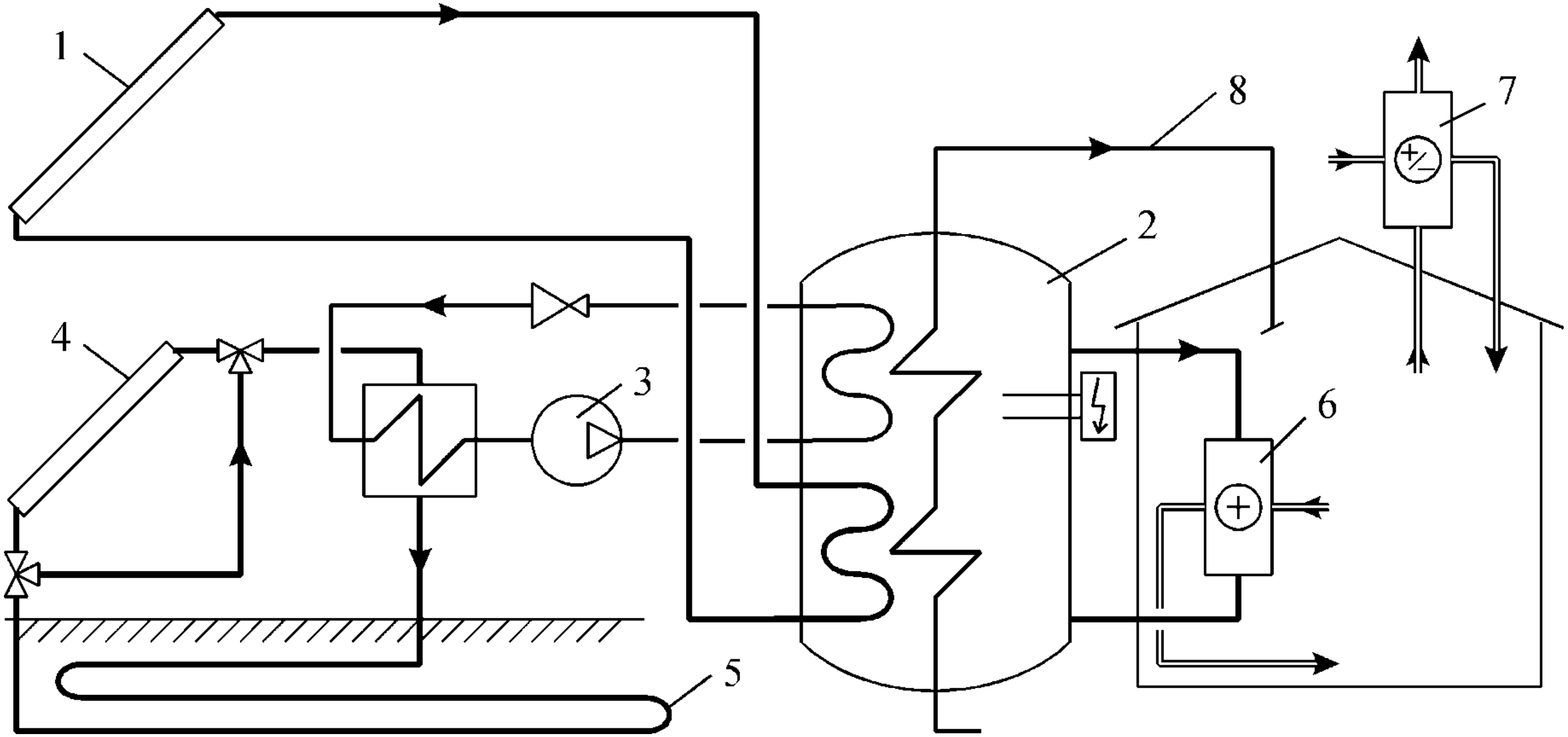


Solar DHW heating system based on forced convection (pump).

In Nordic climates (e.g. Finland) the availability of sunlight in winter is limited, wherefore solar heating is rather an option for DHW heating in summer.

Solar DHW heating system based on natural convection (thermosiphon).

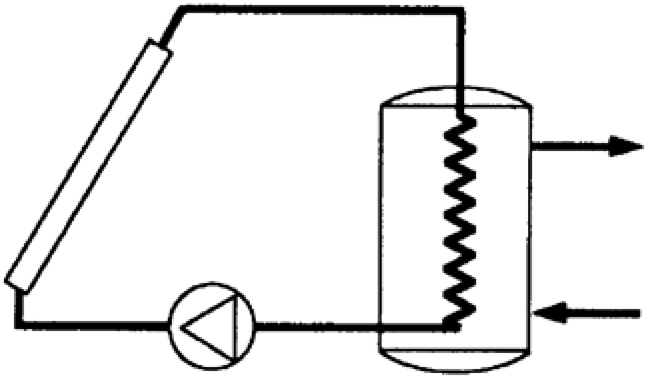
# GSHP + solar heating (hybrid)

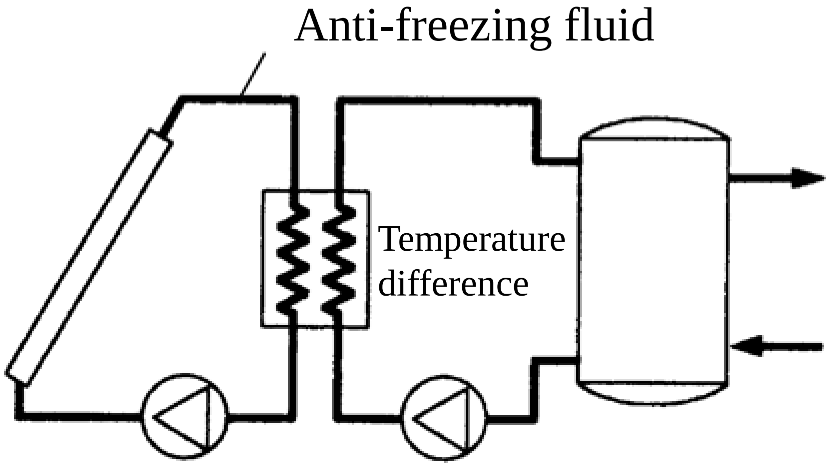


1. Collector
2. Heat storage with electric heater
3. Heat pump
4. Collector for evaporator
5. Ground piping
6. Heat exchanger for supply air
7. Heat exchanger for fresh air
8. Heat exchanger for DHW

Aalto University

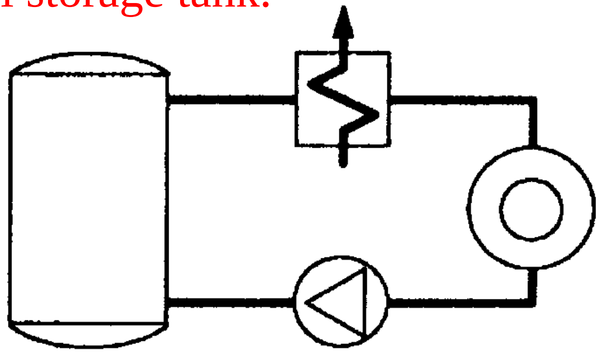
# On the integration of heat sources in hybrid systems



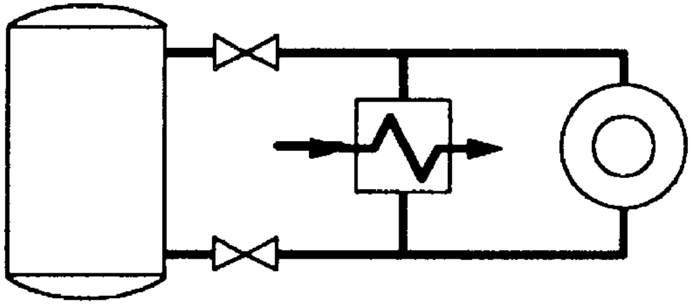


External heat source is separated from the heat storage tank using a heat exchanger. The heat exchanger may be located in the storage tank (above) or outside (below).

Auxiliary heating is connected with the heating distribution network directly rather than via a thermal storage tank.



Heat exchangers in series



Heat exchangers in parallel