Carl von Ossietzky Universität Oldenburg

Heat pumps I – Thermodynamic processes

Dr. Herena Torio

Carl von Ossietzky Universität Oldenburg

Agenda

- Heat pump overview
- Re-visiting thermodynamics
- Components and cycles

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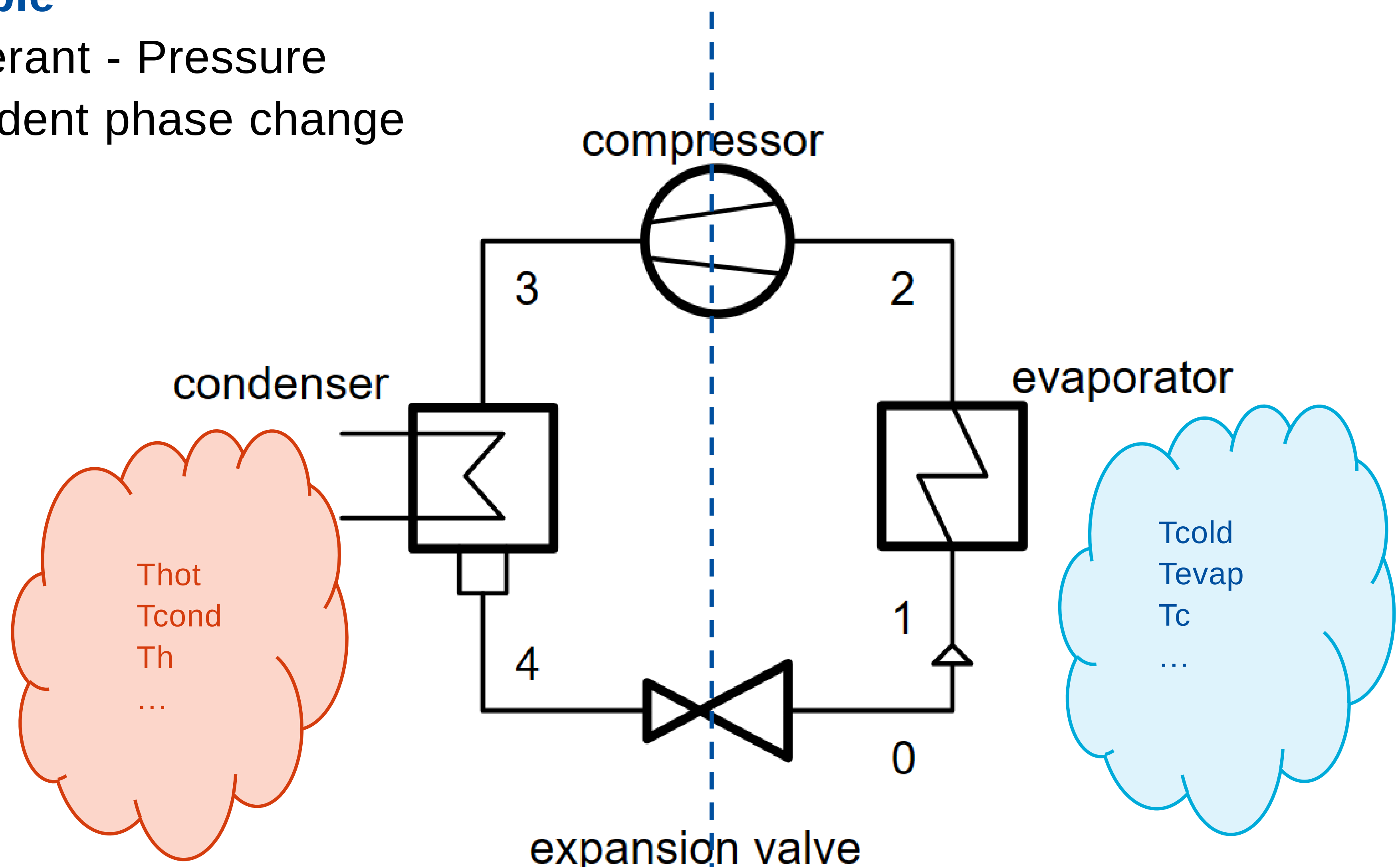
Heat pump overview

The heat pump cycle

Principle

Refrigerant - Pressure dependent phase change points



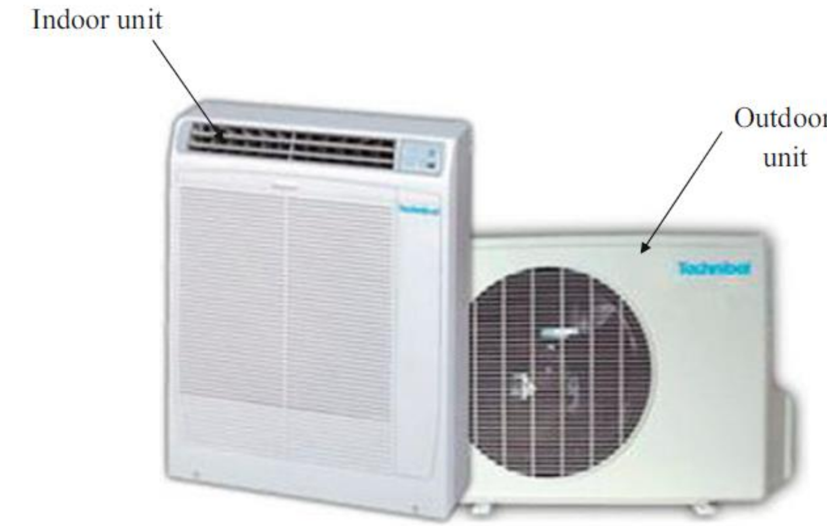
High pressure
ca.10 bar
Function of temperature!

Low pressure
ca. 2 bar
Function of temperature!

Source: Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

Heat pump overview

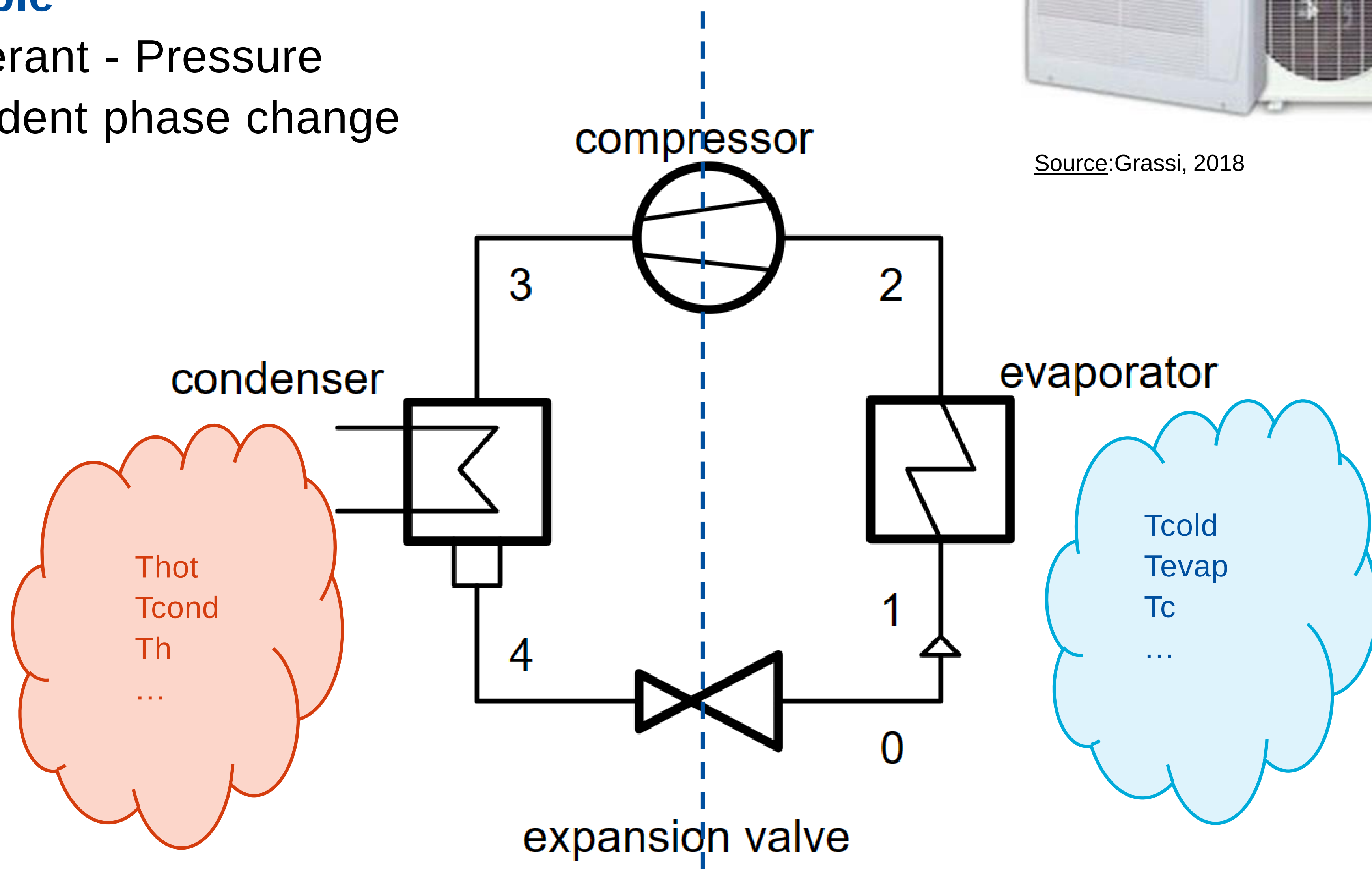
The heat pump cycle



Source:Grassi, 2018

Principle

Refrigerant - Pressure dependent phase change points



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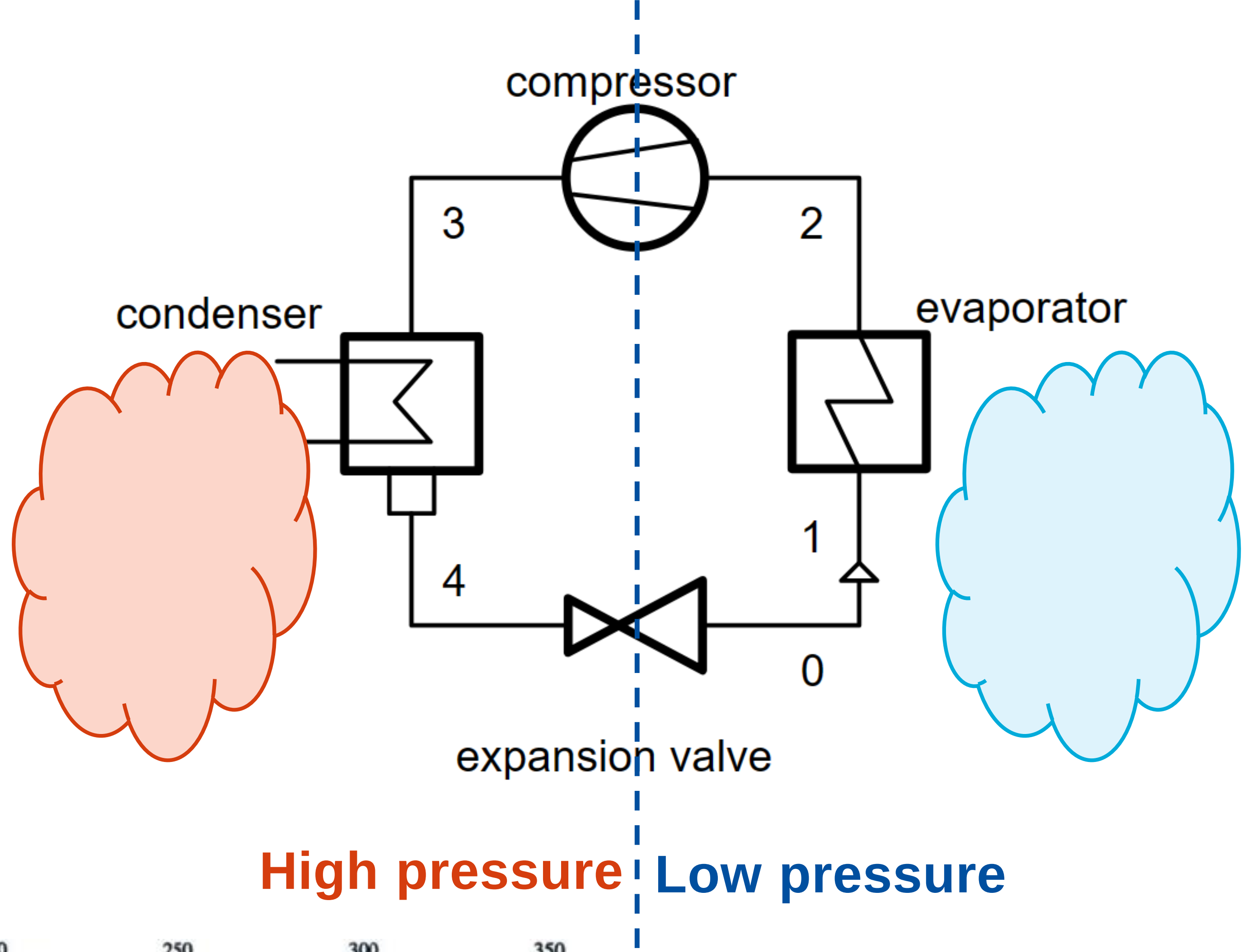
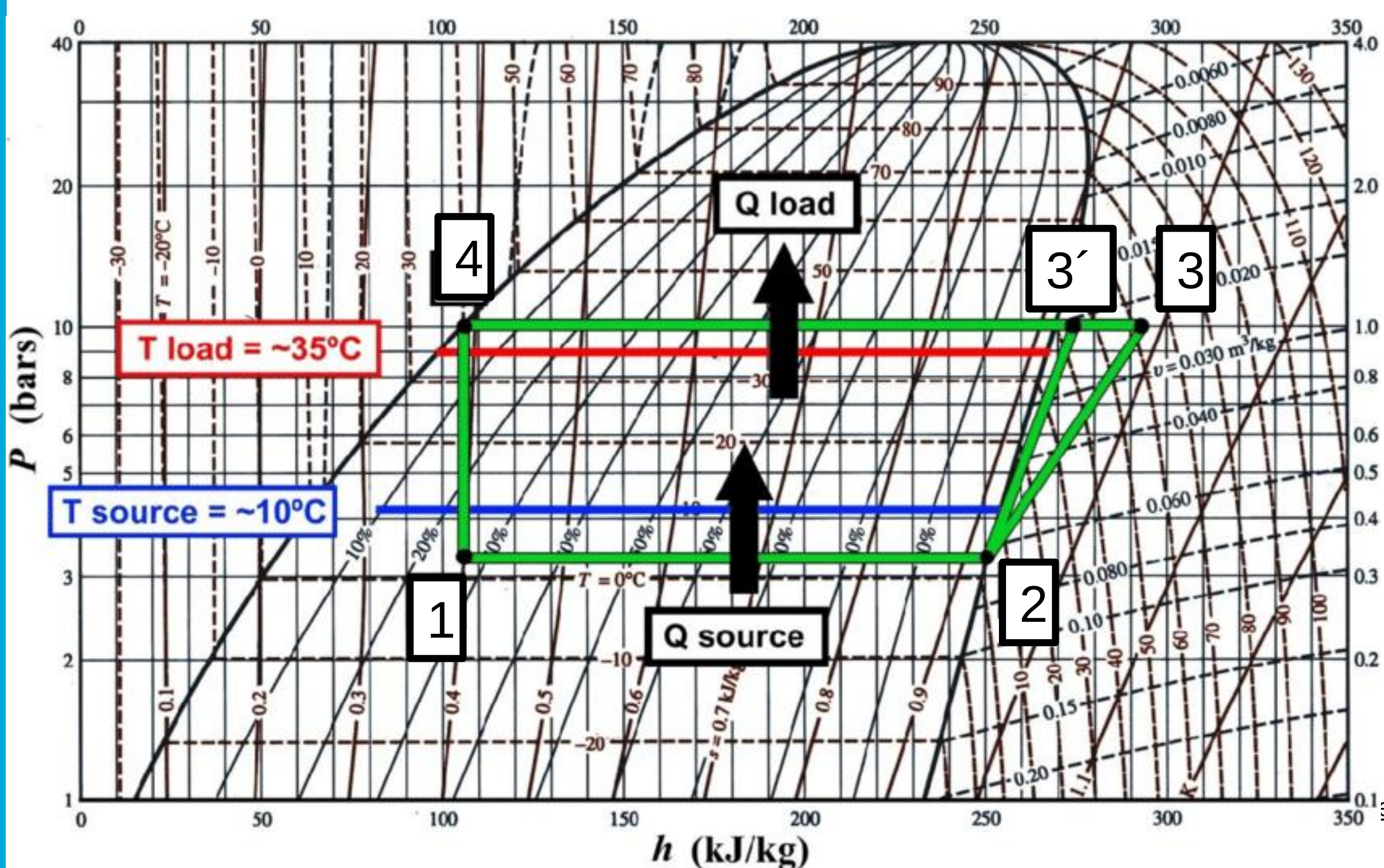
Heat pump overview

The heat pump cycle



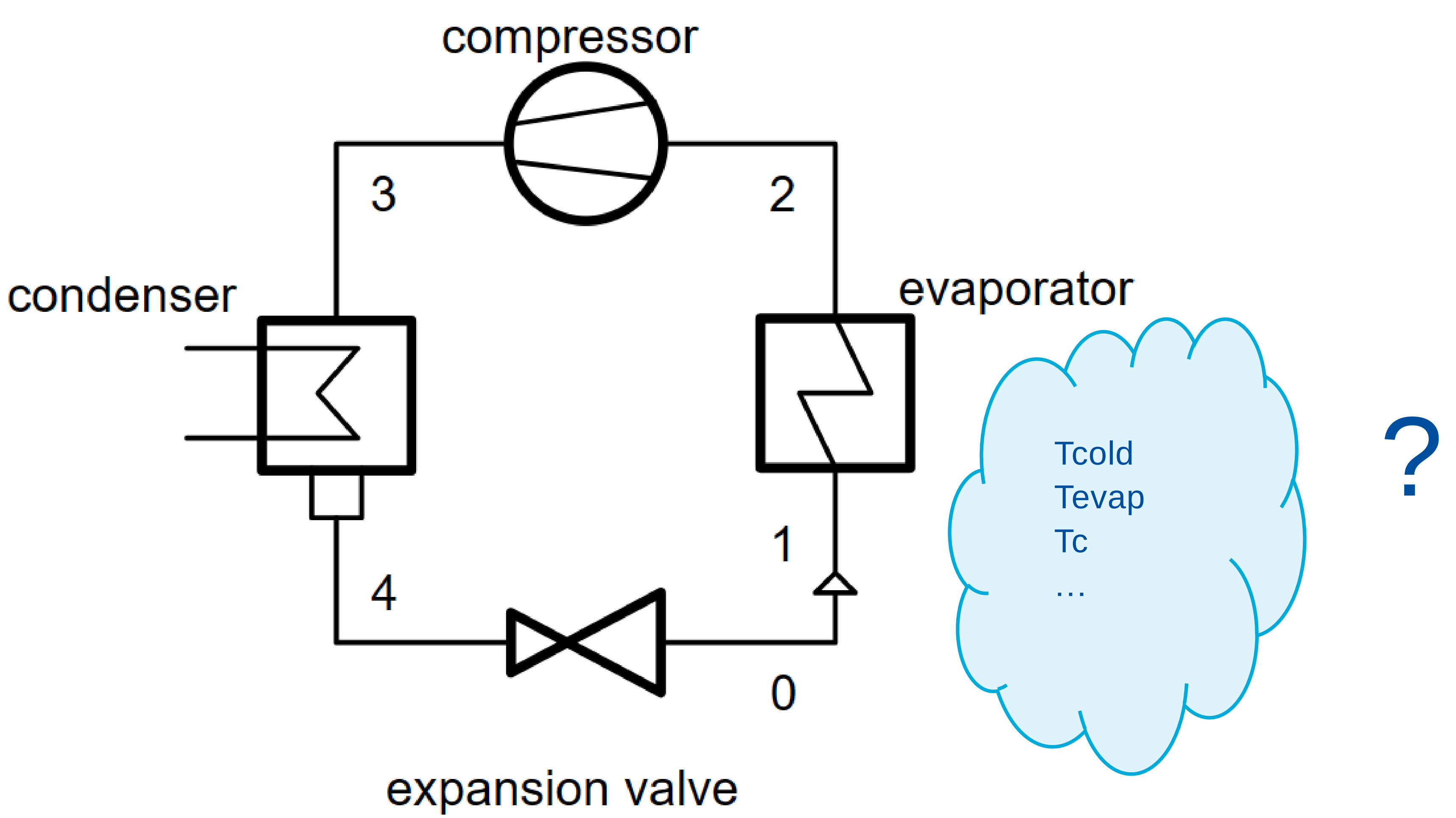


eat pump model — oemof Workshop on Modeling of

Heat pump overview

The heat pump cycle

Typical sources and sinks



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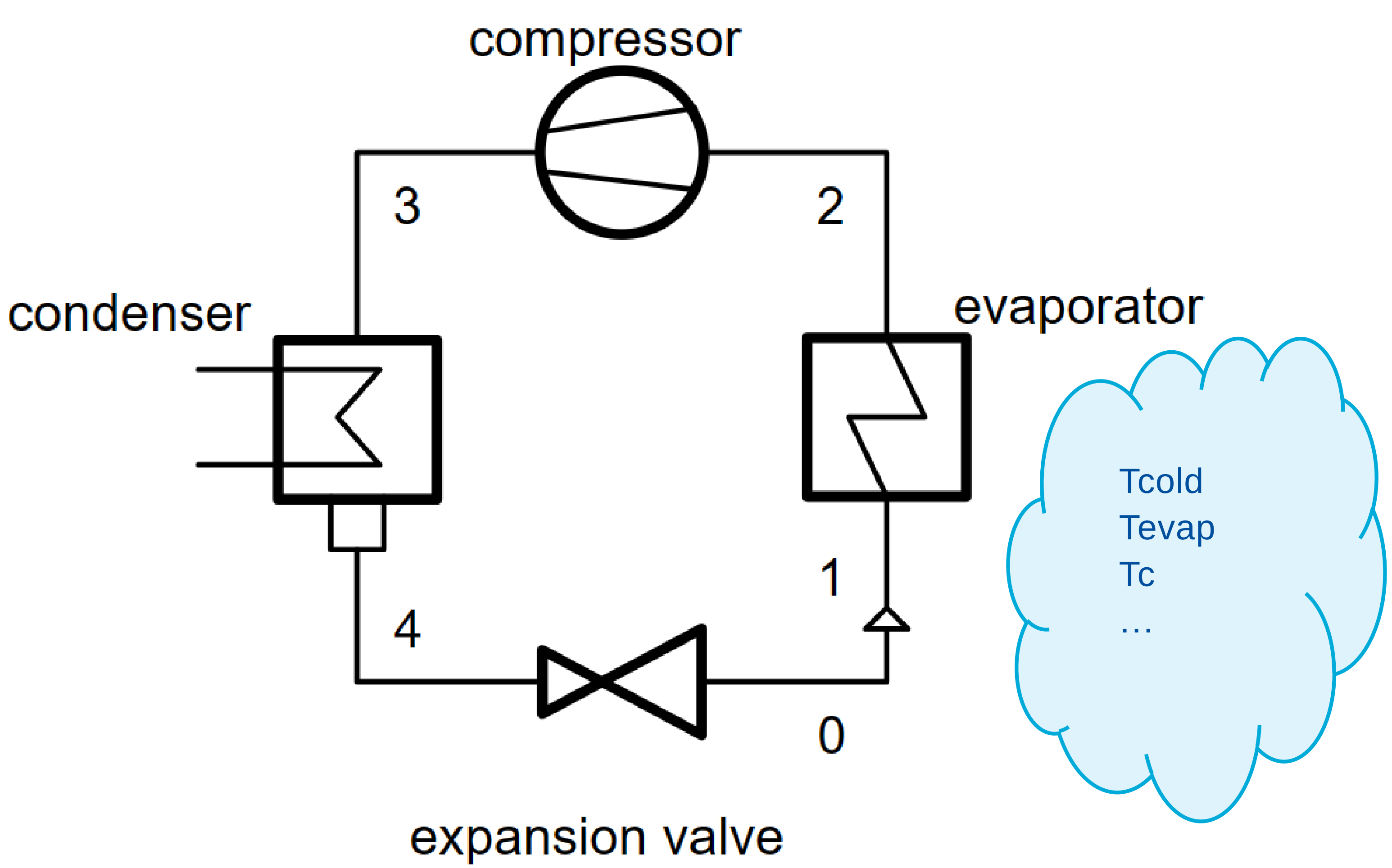

Ambient air

Groundwater (or any other water source)

Waste heat

Solar thermal! ☺

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Function of temperature!

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Heat pump overview

The heat pump cycle

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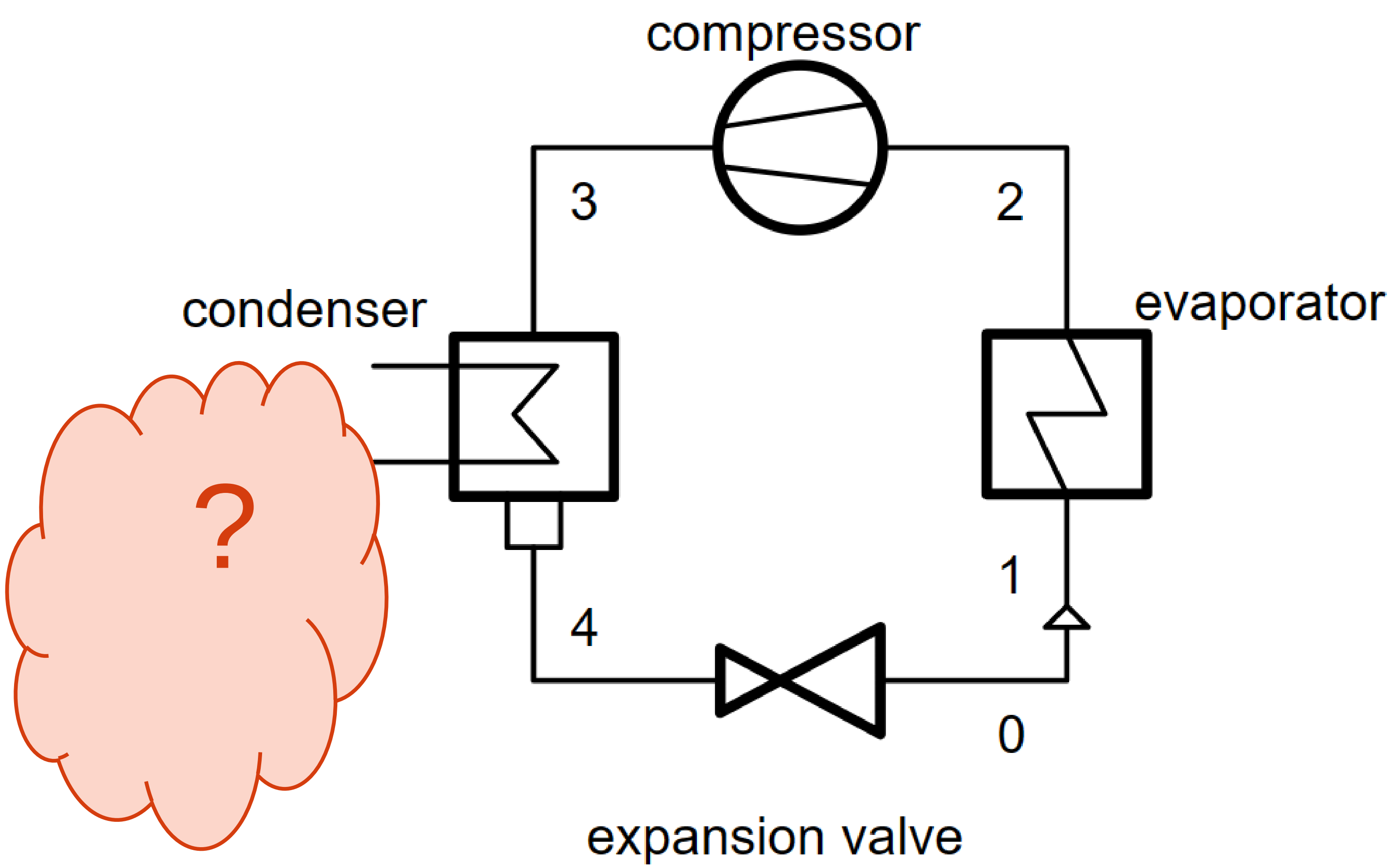

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Heat pump overview

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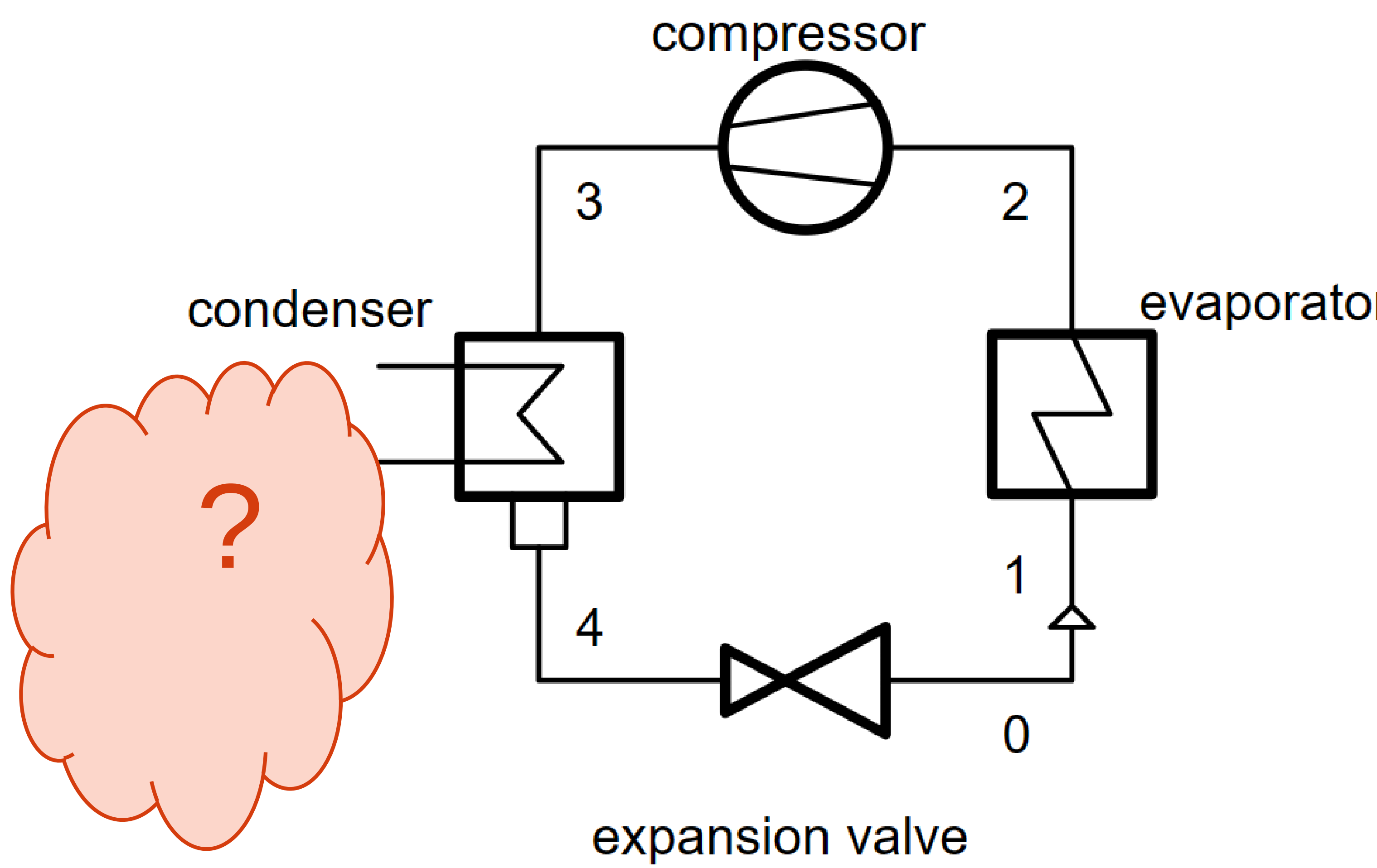
Typical sources and sinks

Space heating

DHW

Industrial heat



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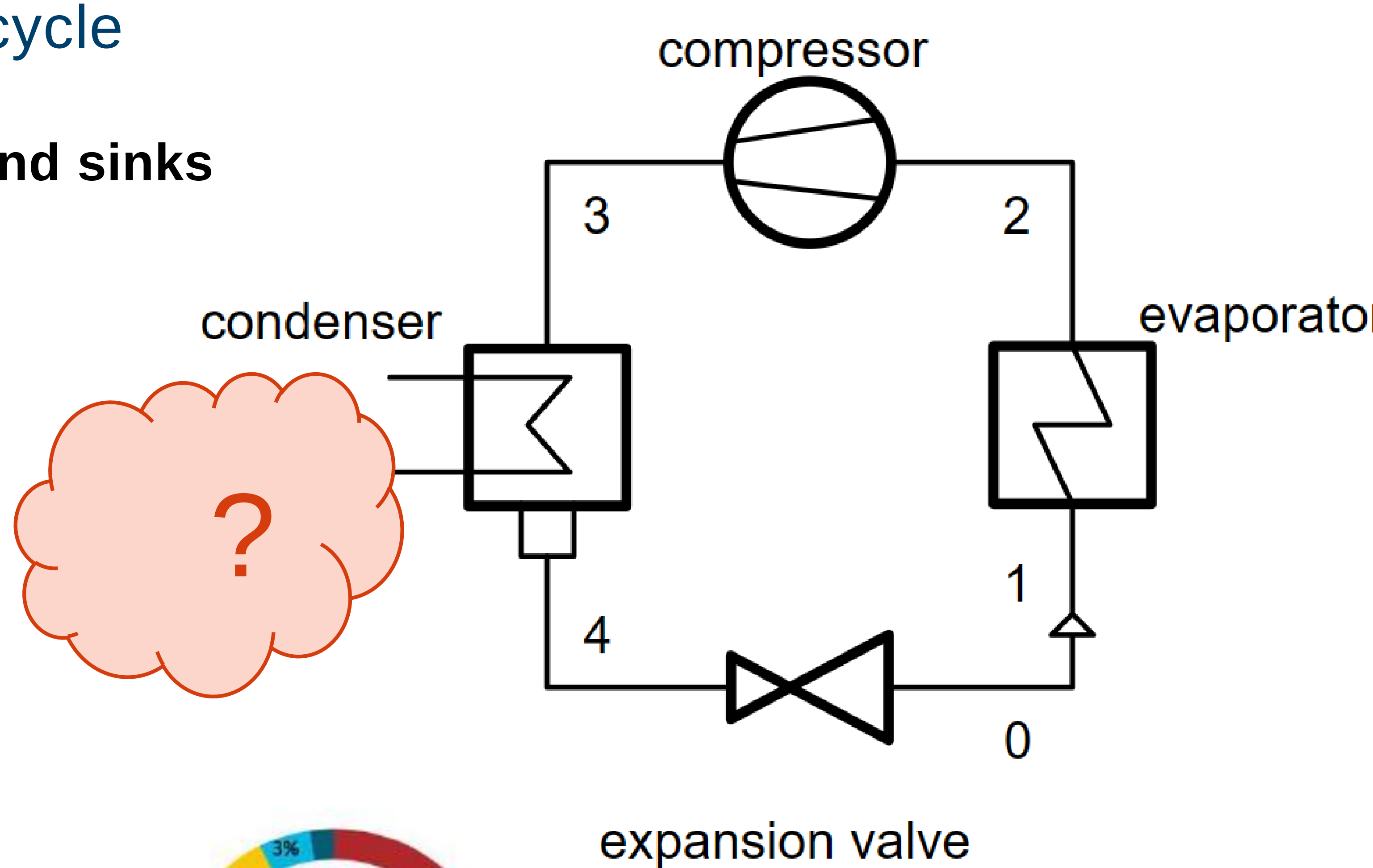
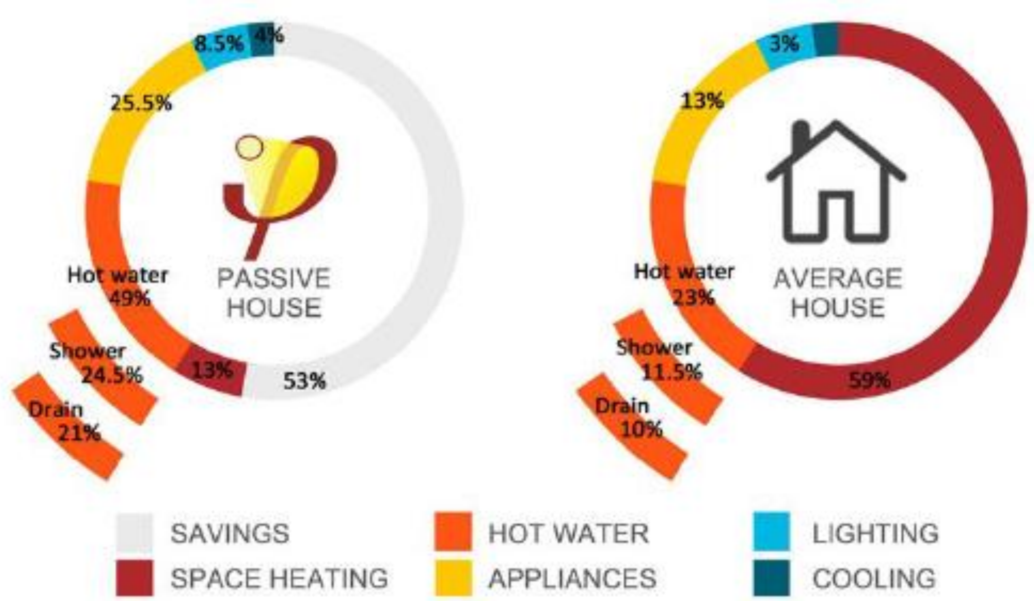




Source:Hervas, 2020

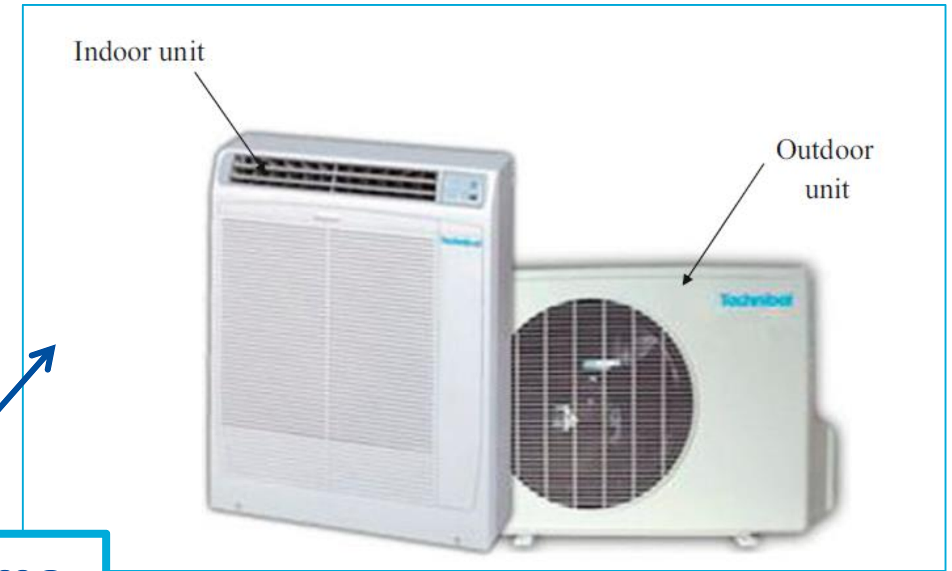
Small Excurs:
DHW demands on the rise, in share and importance

Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

Heat pump overview

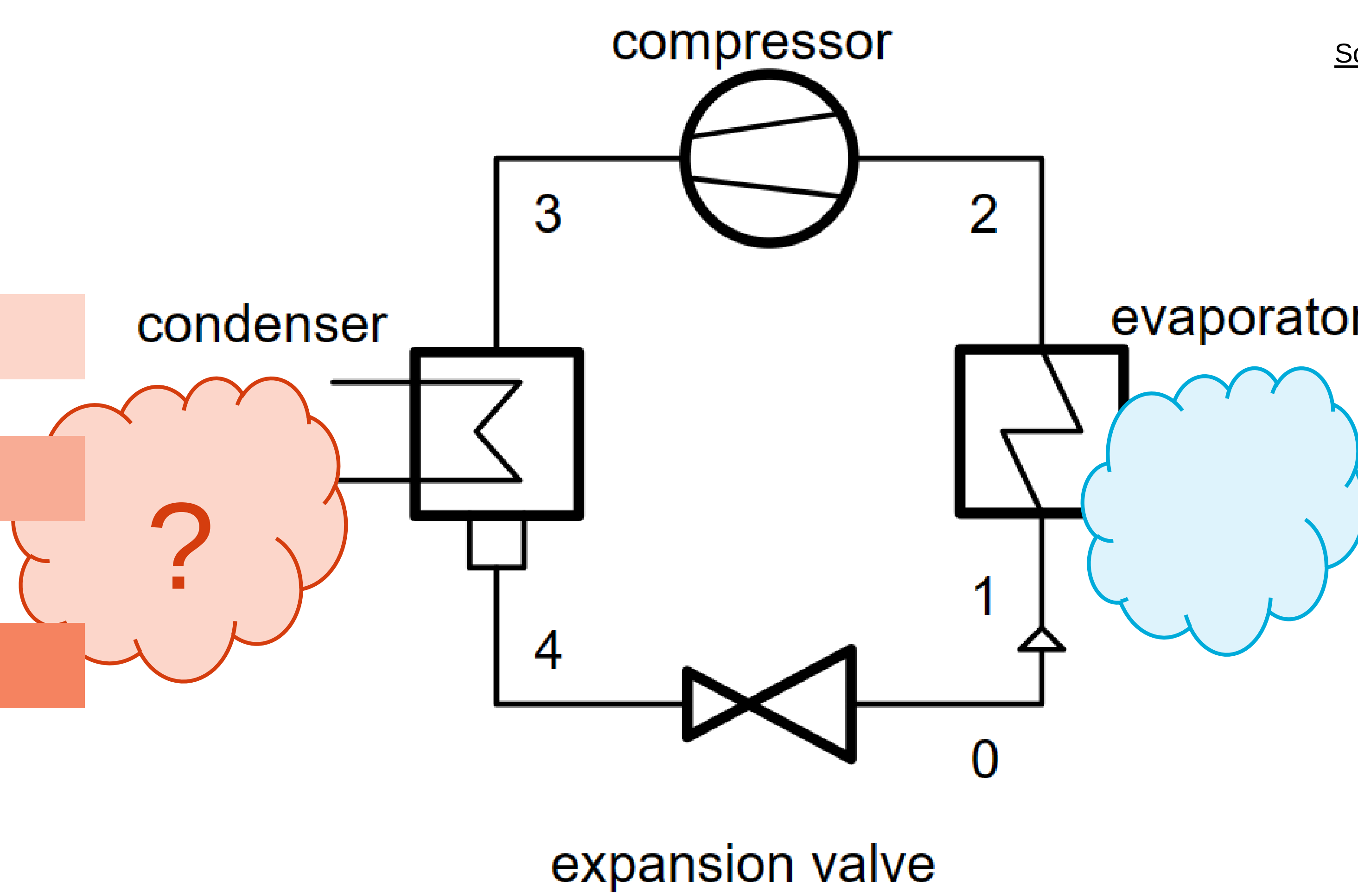
The heat pump cycle

Typical sources and sinks



Source:Grassi, 2018

Air- based systems (secondary sideS)!!



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Space heating

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Industrial heat

Ambient air

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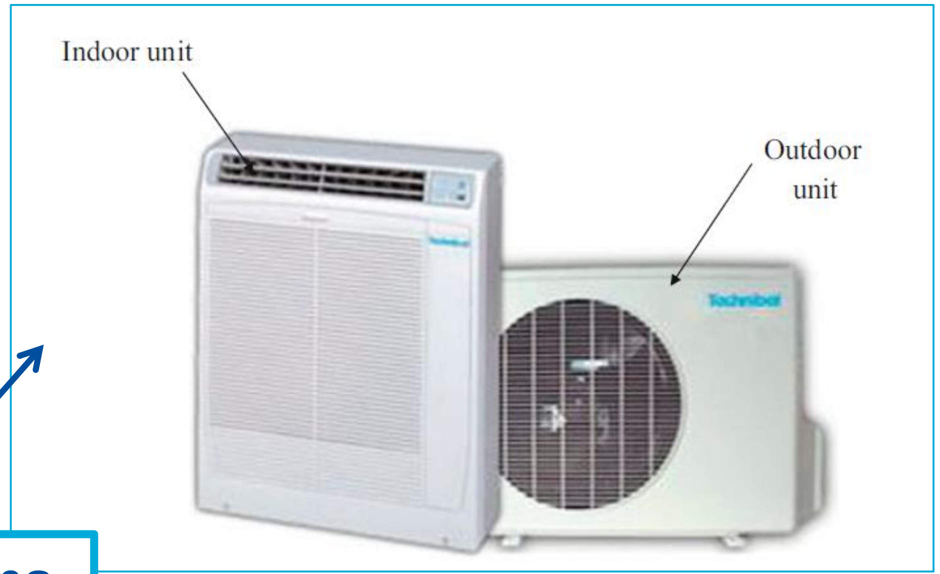
Heat pump overview

The heat pump cycle

Typical sources and sinks



Air- based systems (secondary sideS)!!

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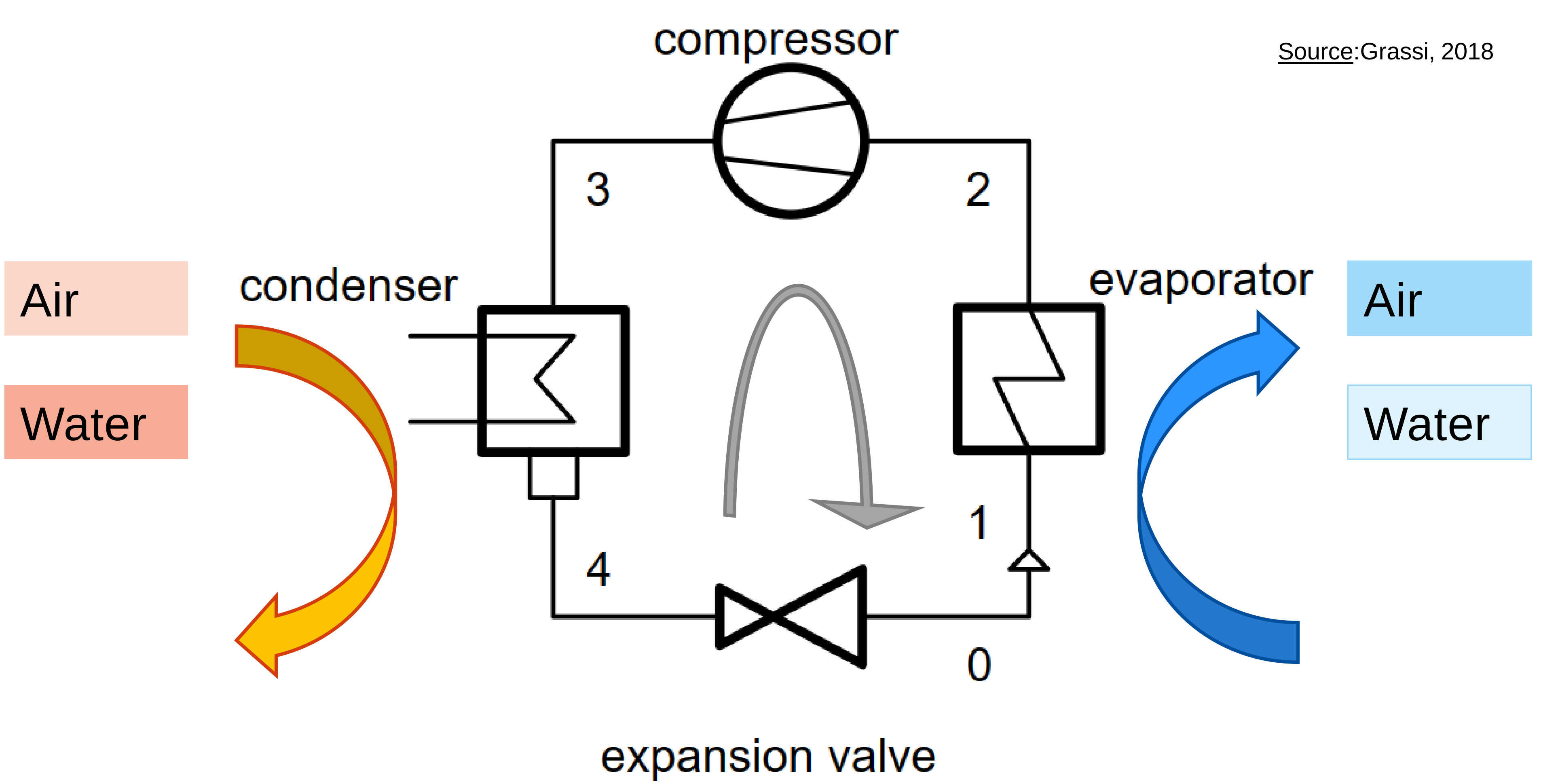
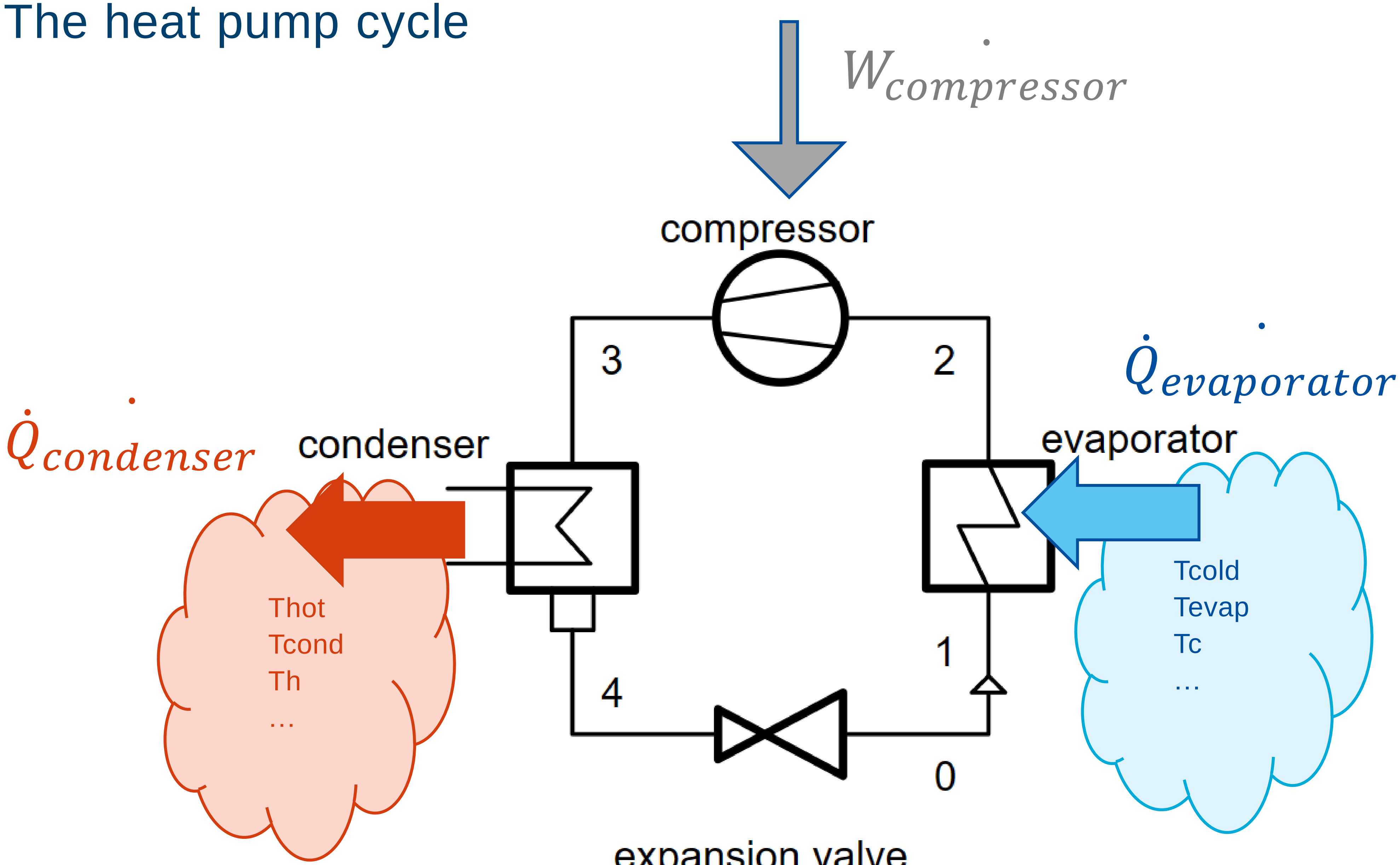


Source:Grassi, 2018

Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

Heat pump overview

The heat pump cycle



$$\mathrm{COP} = \frac{\dot{Q}_{condenser}}{W_{compressor}}$$

Source: Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

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Agenda

- Heat pump overview
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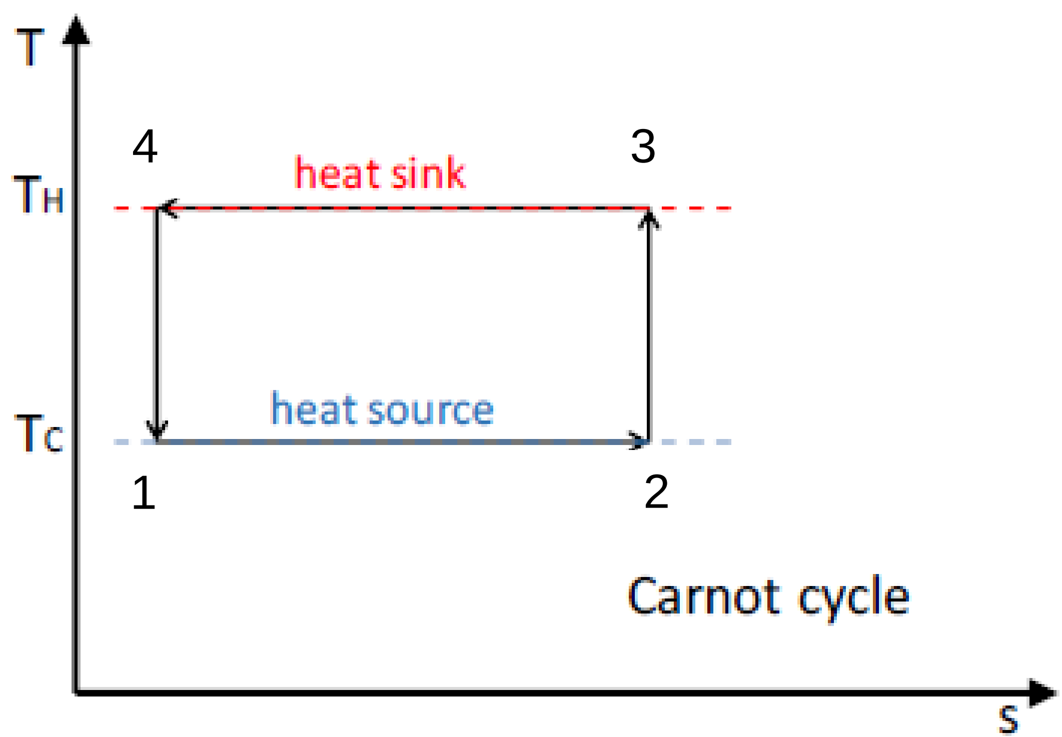
- Components and cycles

Heat pump overview

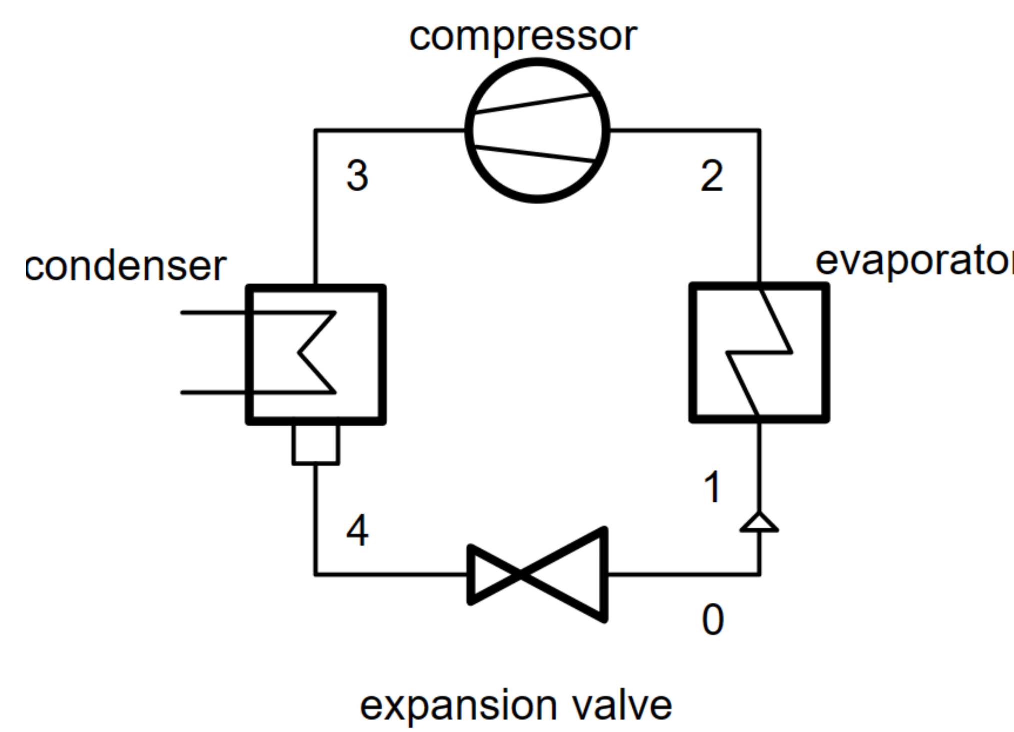
The heat pump cycle

Carnot approximation

Assumptions: → isothermal heat transfer at both source and sink
→ infinite sink and reservoir (source)



Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps



$$\mathrm{COP} = \frac{\dot{Q}_{condenser}}{W_{compressor}}$$

Heat pump overview

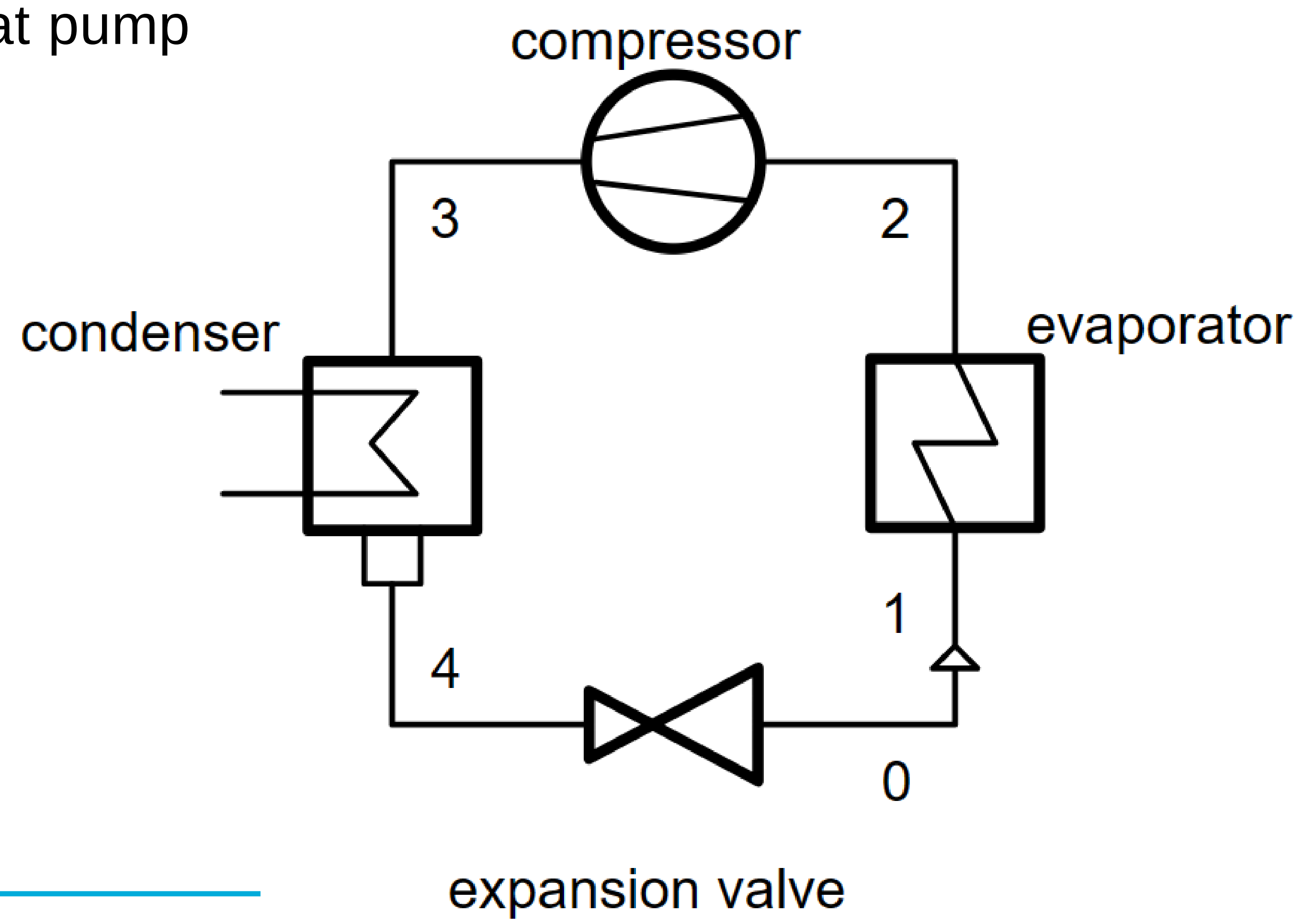
The heat pump cycle

Source: Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

Carnot (ideal) COP

The ideal performance of a heat pump

$$\mathrm{COP} = \frac{\dot{Q}_{condenser}}{W_{compressor}}$$



Energy balance

$$\dot{Q}_{cond.} = W_{compr.} + \dot{Q}_{evap.}$$

$$\mathrm{COP} = \frac{\dot{Q}_{cond.}}{\dot{Q}_{cond.} - \dot{Q}_{evap.}}$$

Assumption: ideal heat transfer (isothermal),

Temperatures are considered at the „secondary side" of the cond/evap

$$\mathrm{COP}_{Carnot} = \frac{T_{cond}}{T_{cond} - T_{evap}} = \frac{T_h}{T_h - T_c} = \frac{T_4}{T_4 - T_2}$$

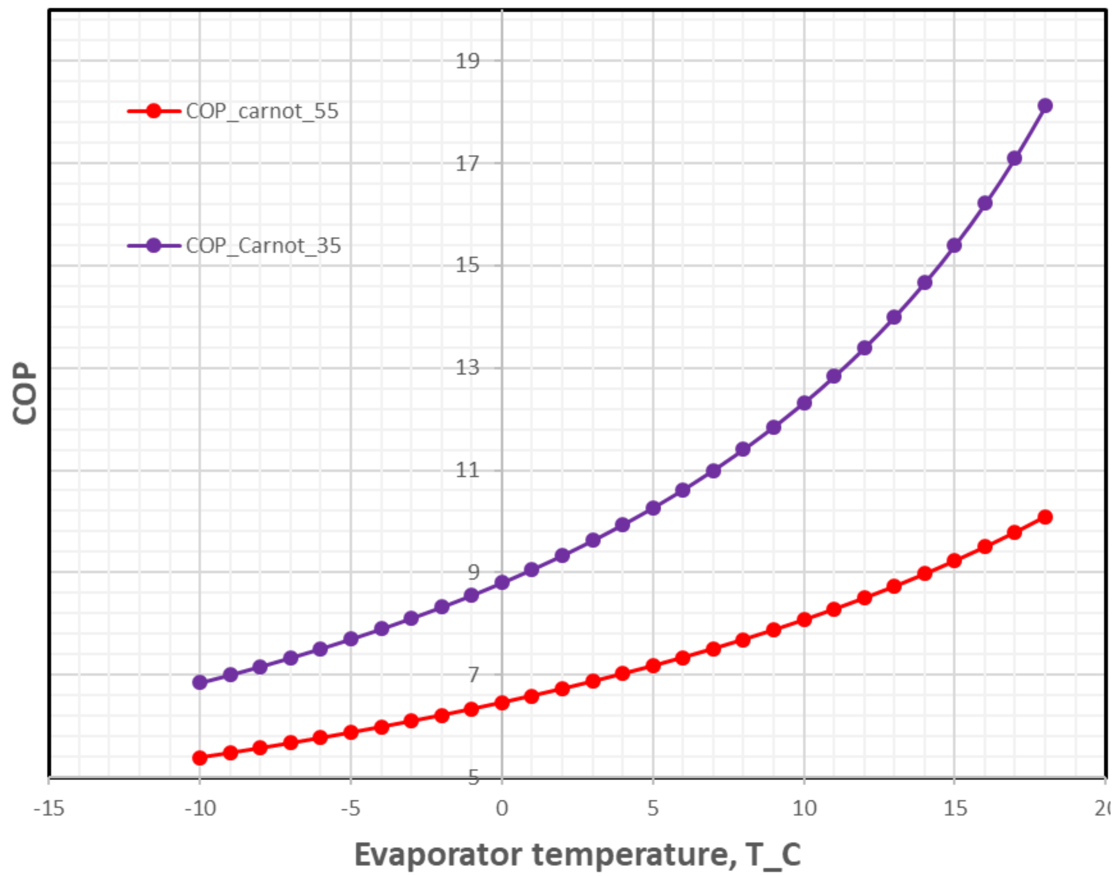
Heat pump overview

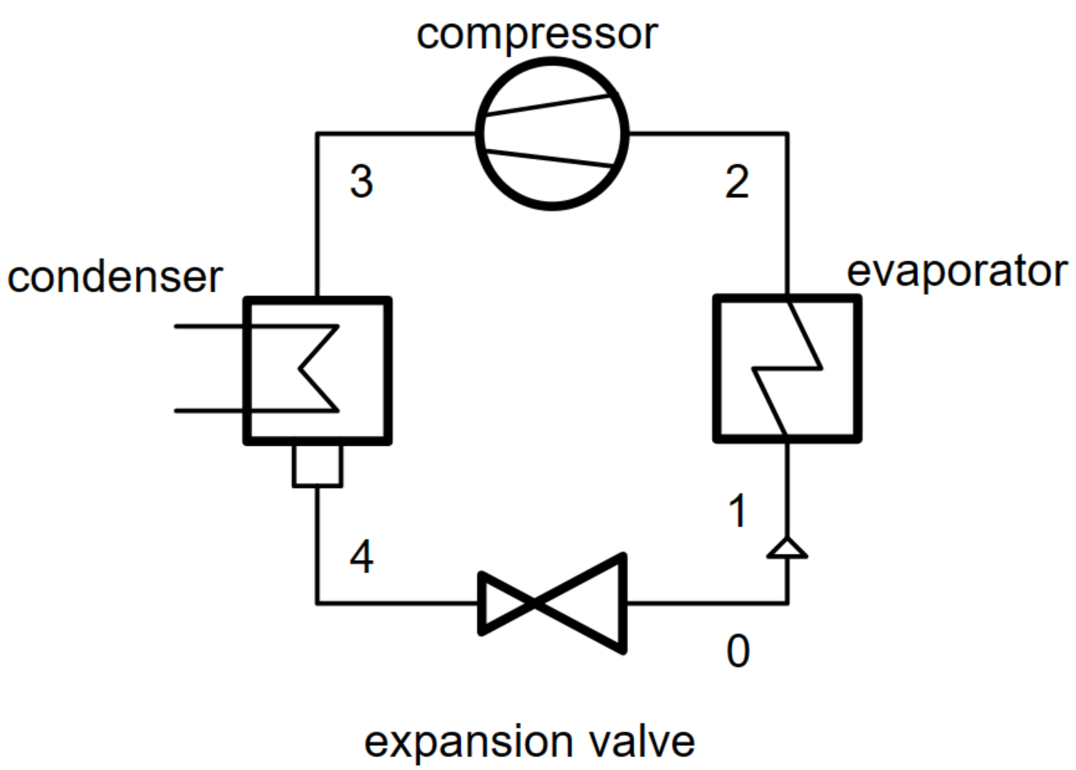
The heat pump cycle

Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

Carnot (ideal) COP

The ideal performance of a heat pump





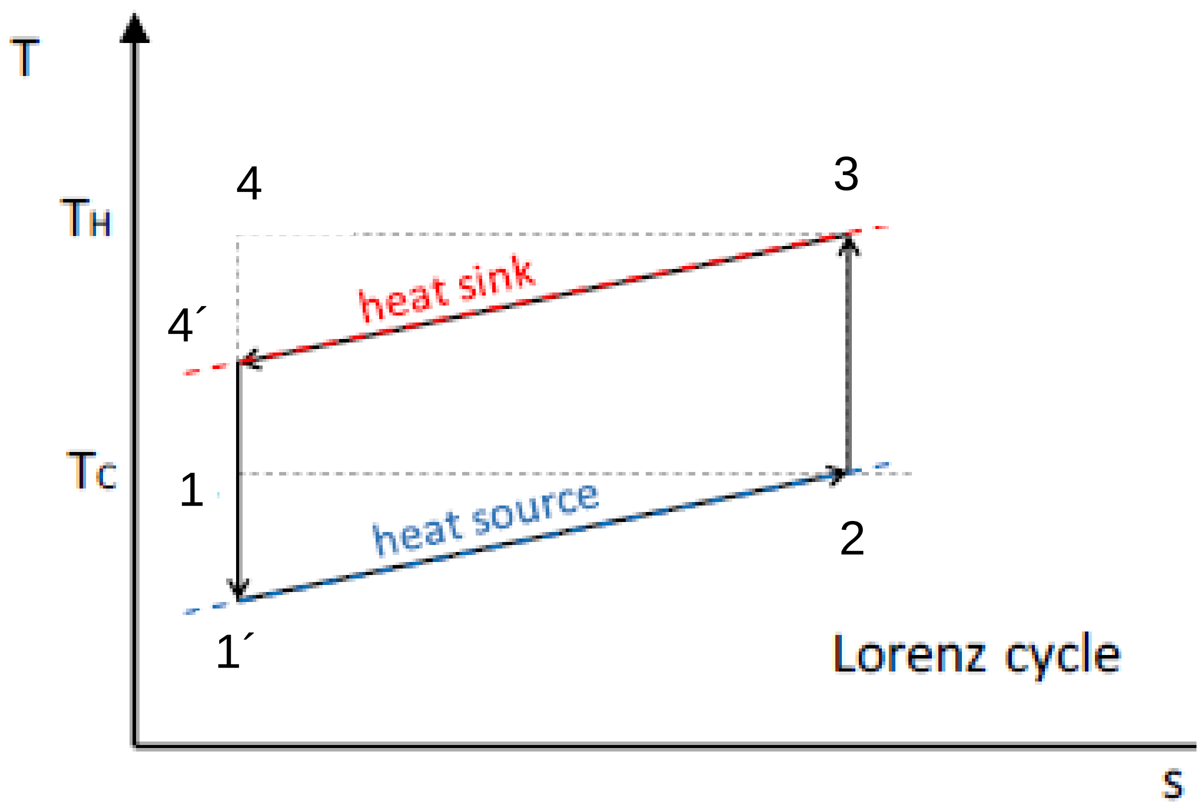
$$COP_{Carnot} = \frac{T_{cond}}{T_{cond} - T_{evap}} = \frac{T_h}{T_h - T_c} = \frac{T_4}{T_4 - T_2}$$

Heat pump overview

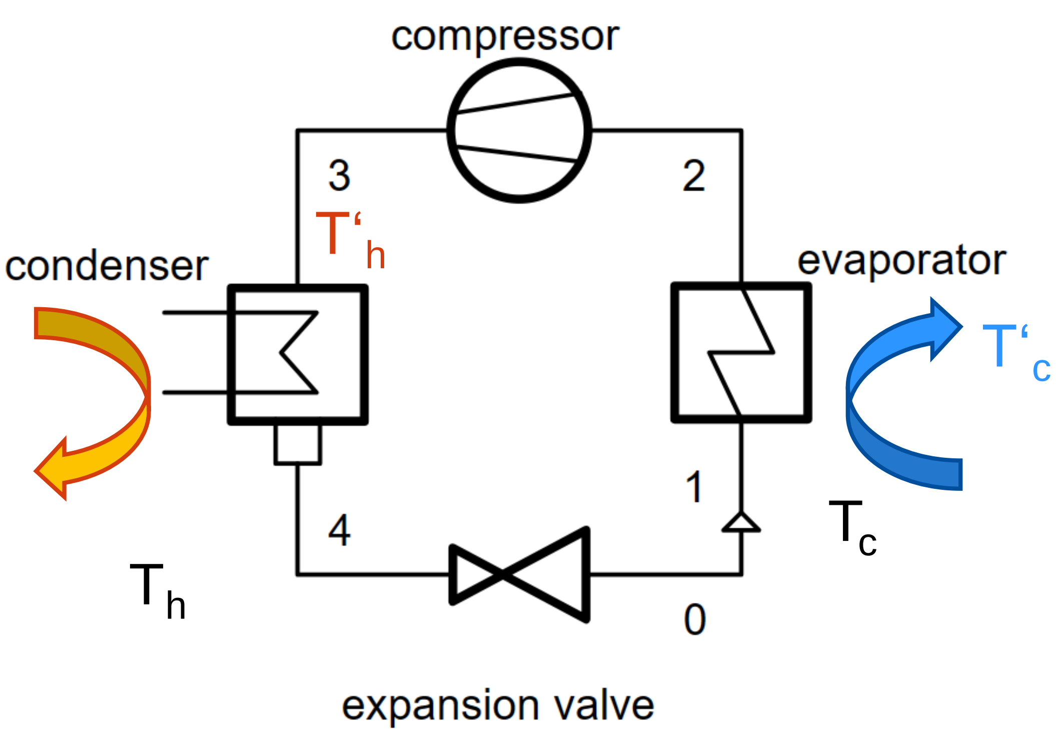
The heat pump cycle

Lorenz approximation

Assumptions: → non-isothermal heat transfer at both source and sink
→ temperature gradients at sink and reservoir (source)



Source:Linear oemof-solph heat pump model —



$$COP = \frac{\dot{Q}_{cond}}{W_{compr}} = \frac{\dot{Q}_{3-4'}}{W_{3-2}}$$

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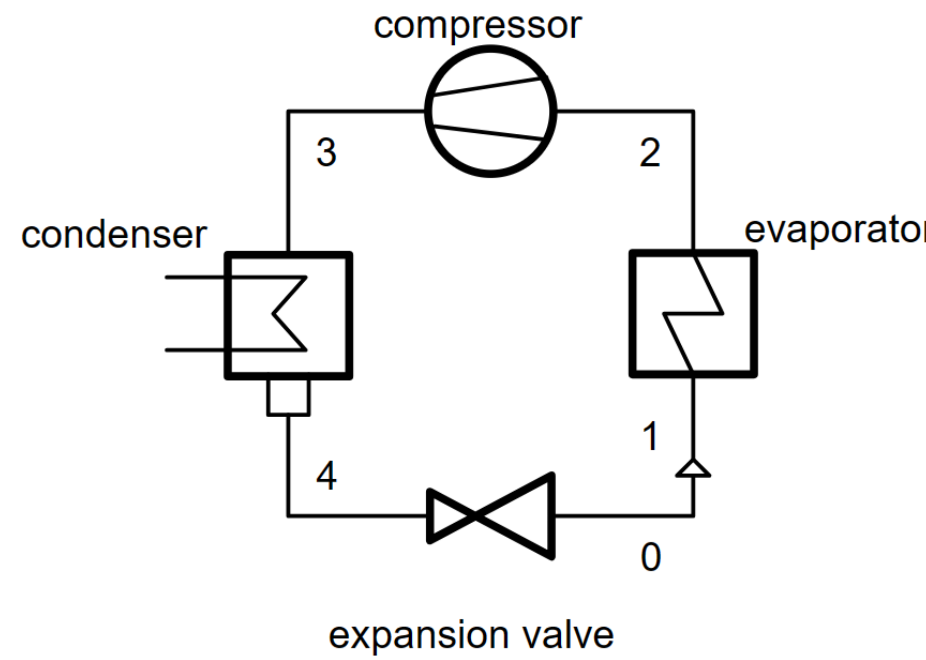
Source: Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps



Heat pump overview

The heat pump cycle

Lorenz COP

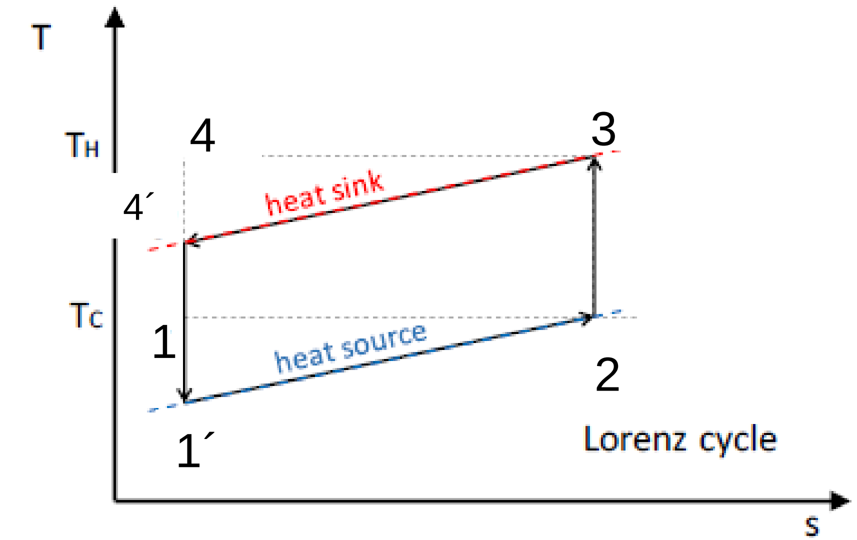
The ideal performance of a heat pump

$$COP = \frac{\dot{Q}_{cond}}{W_{compr}} = \frac{\dot{Q}_{3-4'}}{W_{3-2}} = \frac{\overline{T}_H\,(s_2 - s_1)}{(\overline{T}_H - \overline{T}_C)\,(s_2 - s_1)}$$

$\overline{T}_H, \overline{T}_C$ Entropy-averaged temperatures = avg. Temperature in T-S diagramm representing avg. Temperature difference

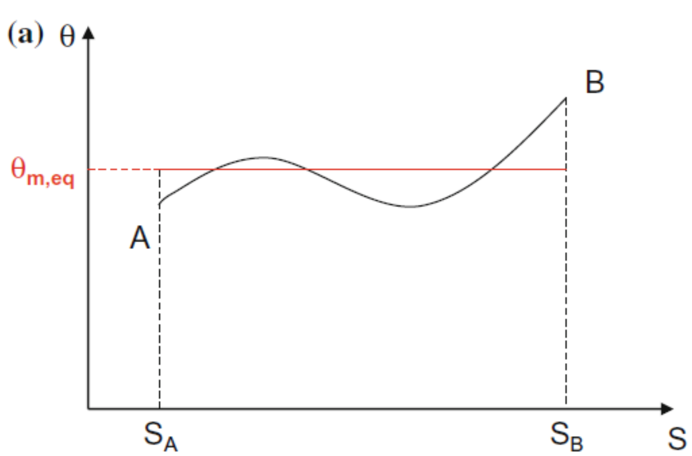
Assumptions: $\dot{m}c_p$ =*constant*

pressure, p_H, p_C = constant



$$\overline{T}_H = \frac{h_3 - h_{4'}}{s_3 - s_{4'}} = \frac{T_3 - T_{4'}}{\ln(\frac{T_3}{T_{4'}})}$$

$$\overline{T}_C = \frac{h_2 - h_{1'}}{s_2 - s_{1'}} = \frac{T_2 - T_{1'}}{\ln(\frac{T_2}{T_{1'}})}$$



$$COP_{Lorenz} = \frac{\dot{Q}_{cond}}{W_{compr}} = \frac{\overline{T}_H\,(s_2 - s_1)}{(\overline{T}_H - \overline{T}_C)\,(s_2 - s_1)} = \frac{1}{1 - \frac{\overline{T}_C}{\overline{T}_H}}$$

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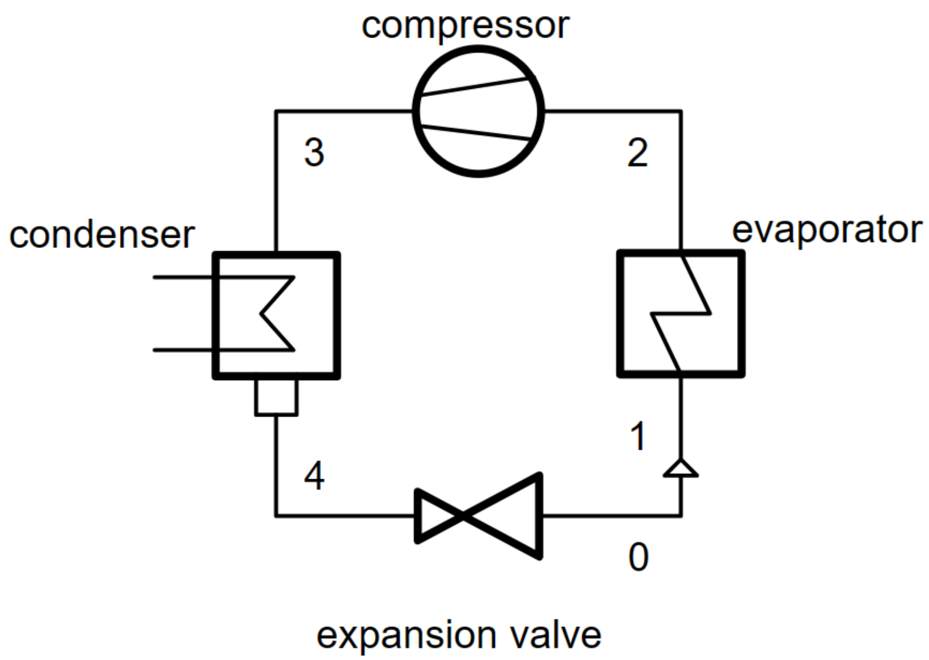
Heat pump overview

The heat pump cycle



Lorenz + Carnot COP

The ideal performance of a heat pump

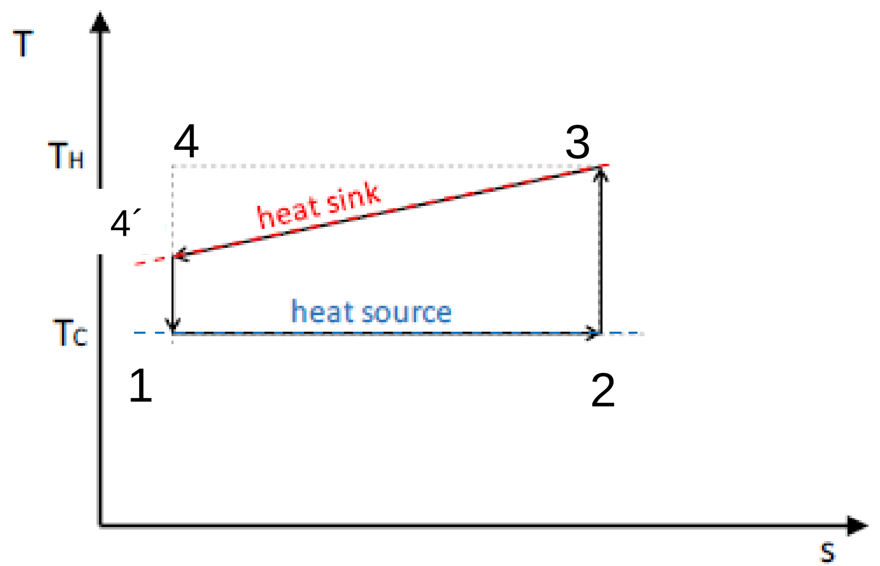
$$COP = \frac{\dot{Q}_{cond}}{W_{compr}} = \frac{\dot{Q}_{3-4'}}{W_{1-2}} = \frac{\bar{T}_H\,(s_2-s_1)}{(\bar{T}_H-\bar{T}_C)\,(s_2-s_1)}$$

$\bar{T}_H, \bar{T}_C$ Entropy-averaged temperatures = avg. Temperature in T-S diagramm representing avg. Temperature difference

Assumptions: $\dot{m}c_p$ =*constant*

pressure, p_H, p_C = *constant*

$$\bar{T}_H = \frac{h_3 - h_{4'}}{s_3 - s_{4'}} = \frac{T_3 - T_{4'}}{\ln(\frac{T_3}{T_{4'}})}$$

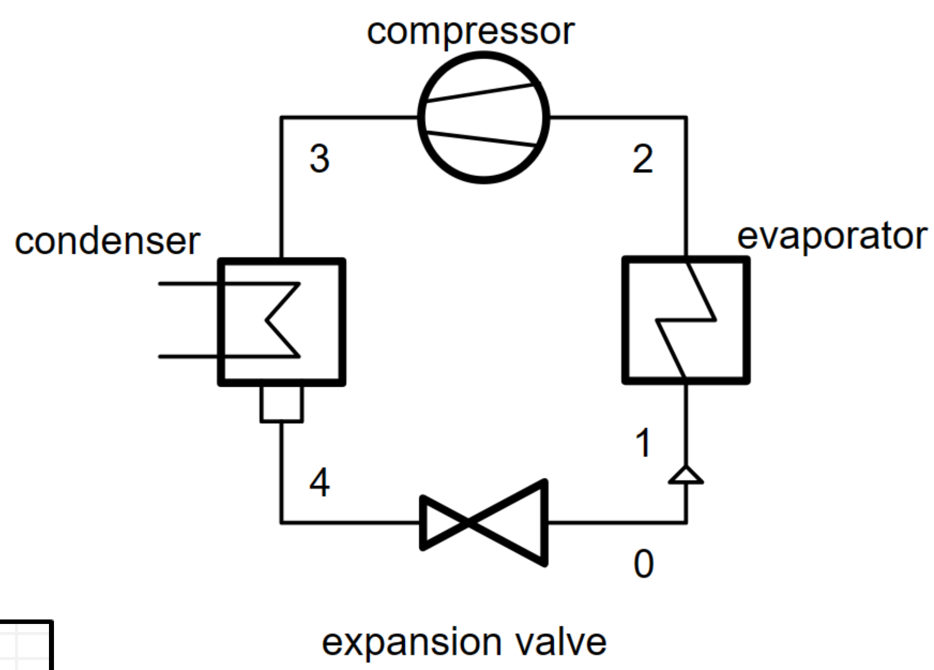


$\bar{T}_C = T_C$, infinite sink/source, constant temperature

$$COP_{mixed} = \frac{\dot{Q}_{cond}}{W_{compr}} = \frac{\bar{T}_H\,(s_2-s_1)}{(\bar{T}_H-\bar{T}_C)\,(s_2-s_1)} = \frac{1}{1-\frac{T_C}{\bar{T}_H}}$$

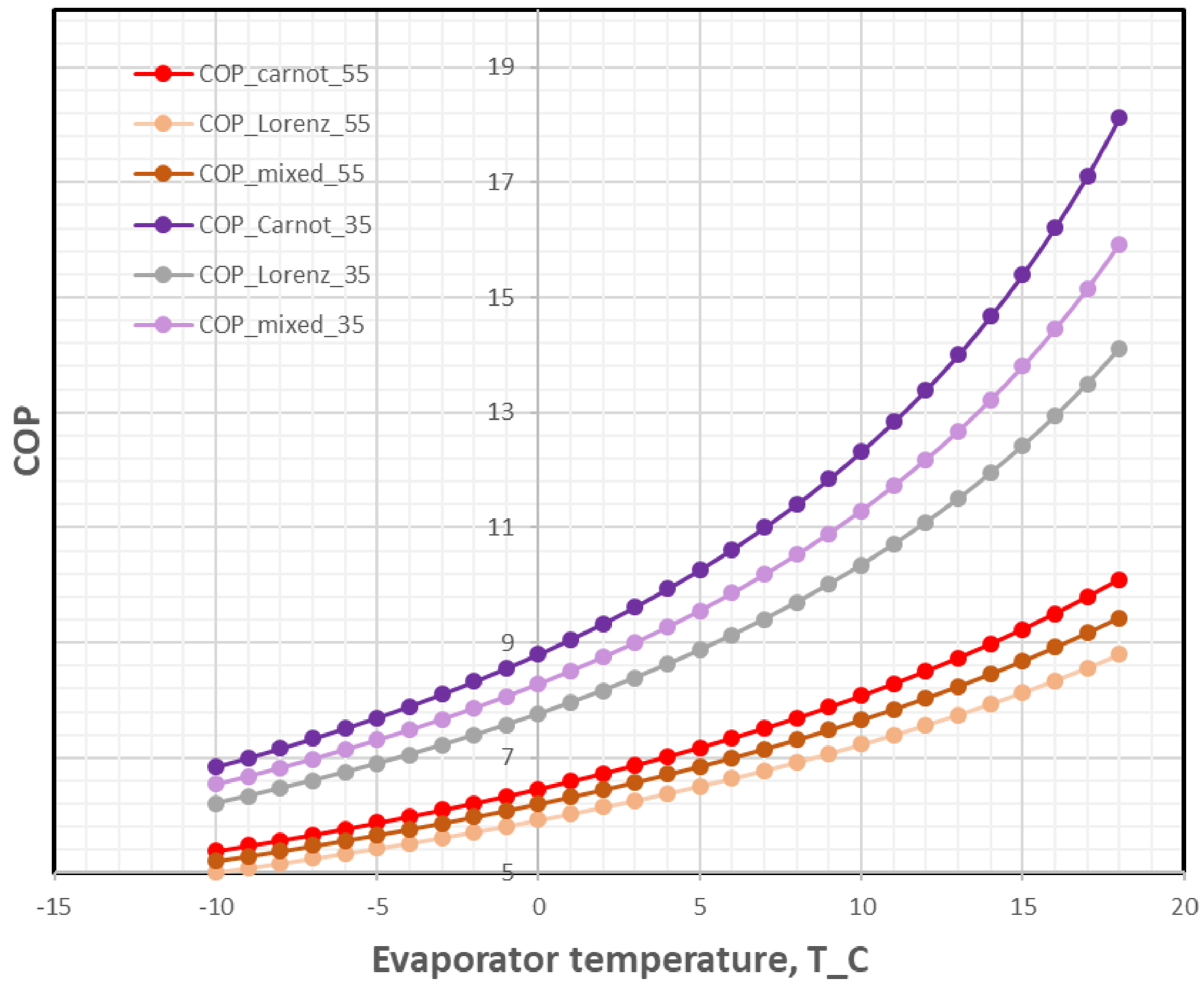
Heat pump overview

The heat pump cycle



Lorenz + Carnot COP

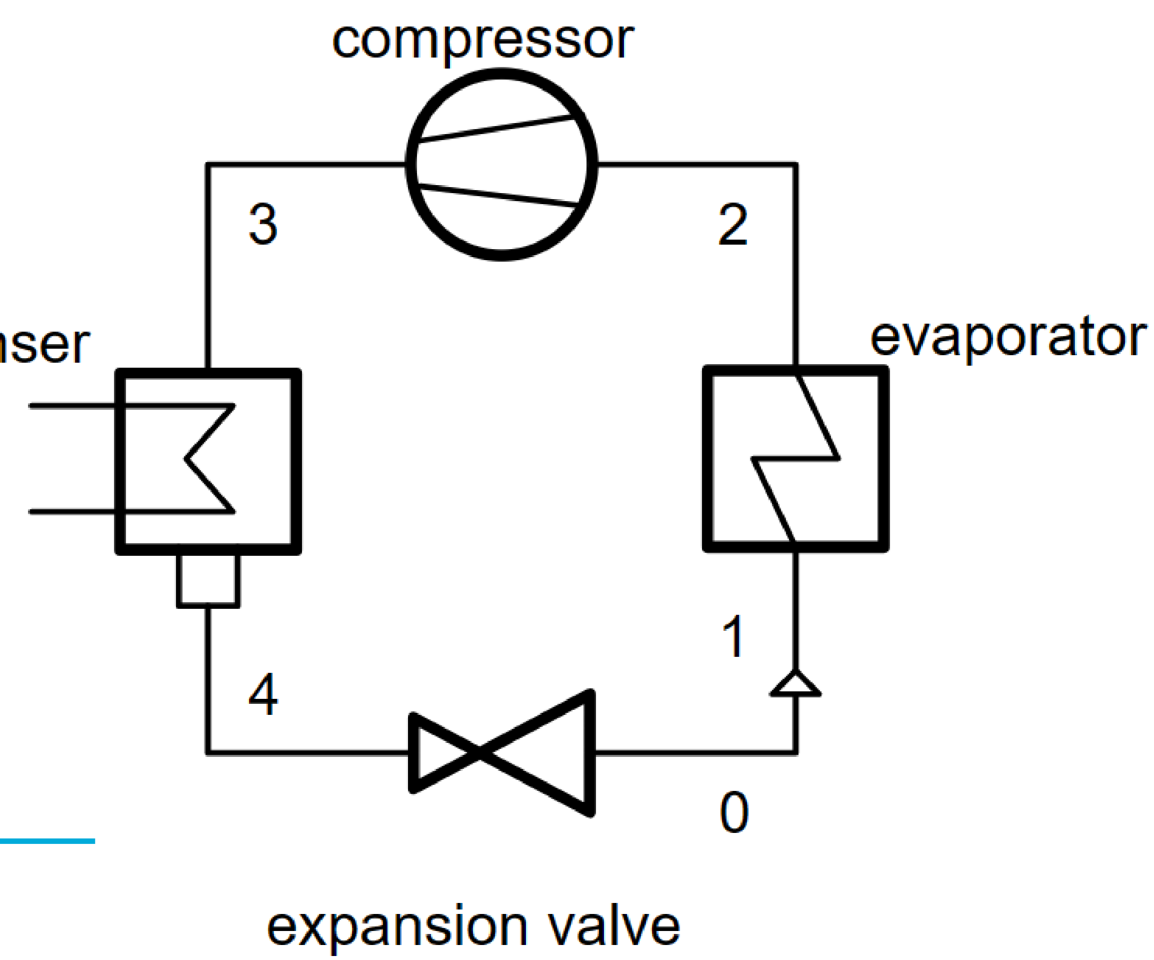
The ideal performance of a heat pump



Heat pump overview

The heat pump cycle

Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps



Real (and ideal) COP

The ideal performance of a heat pump

$$\mathrm{COP} = \frac{\dot{Q}_{condenser}}{W_{compressor}}$$

$$\mathrm{COP}_{Carnot} = \frac{T_h}{T_h - T_c} = \frac{T_4}{T_4 - T_2}$$

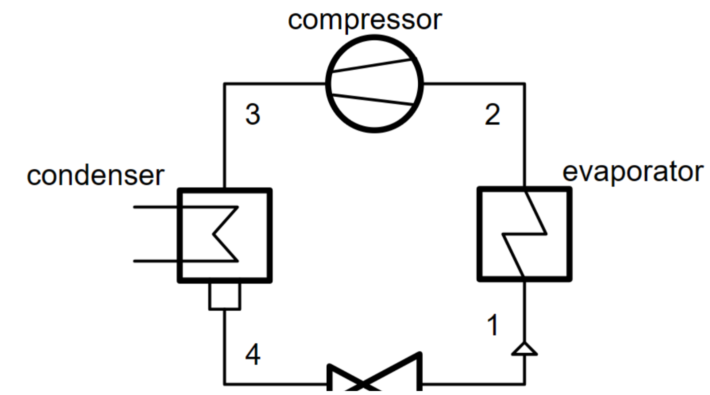
$$\eta_{hp} = \frac{COP}{COP_{Carnot}}$$

Characterizes how far the **real performance** deviates from an ideal one.

Calibration parameter

Heat pump overview

The heat pump cycle



Real (and ideal) COP

The real performance of a heat pump

$$COP = \frac{\dot{Q}_{condenser}}{W_{compressor}}$$

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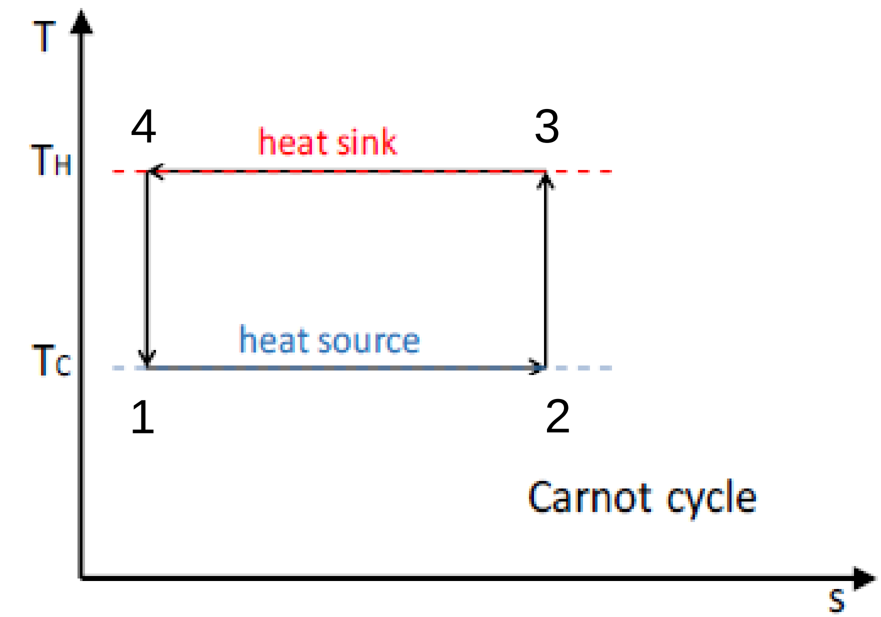

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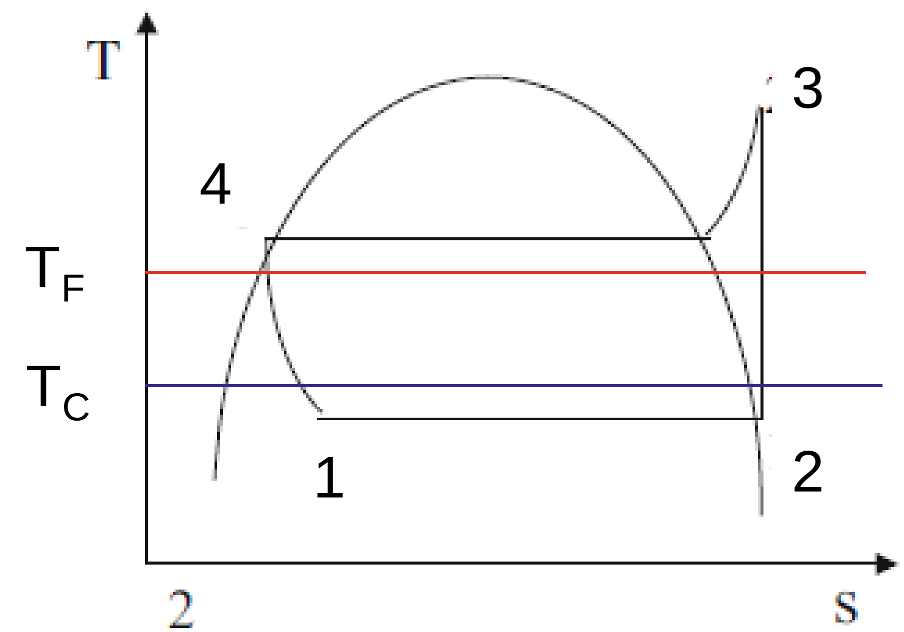


Characterizes how far the **real performance** deviates from an ideal one.

Calibration parameter

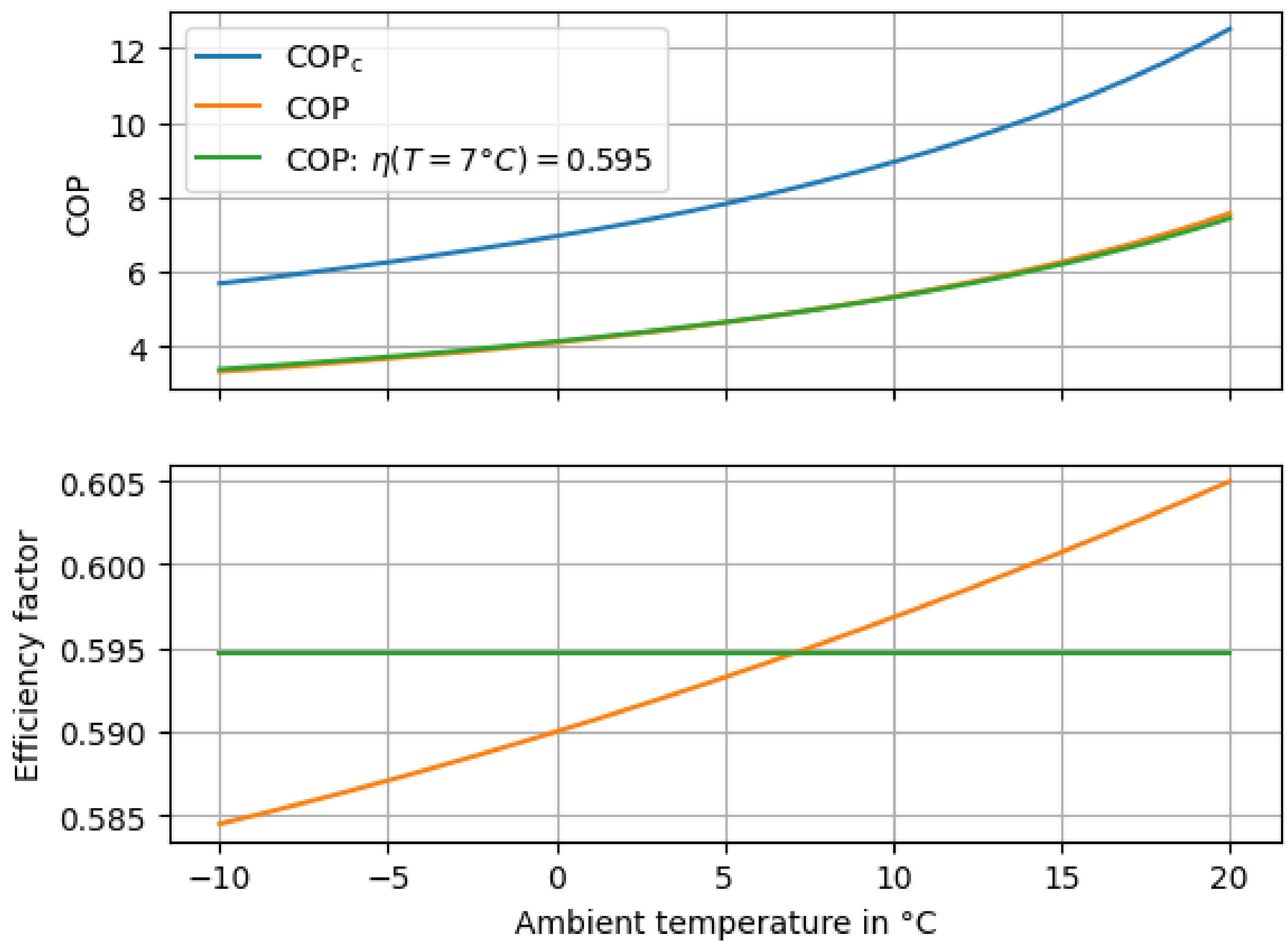
Heat pump overview

The heat pump cycle

Real (and ideal) COP

The real performance of a heat pump

$$\eta_{hp} = \frac{COP}{COP_{Carnot}}$$



- Characterizes how far the real performance deviates from an ideal one.
- Calibration parameter; assumed to be **constant** often!
- Assuming constant compressor efficiency

Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

Heat pump overview

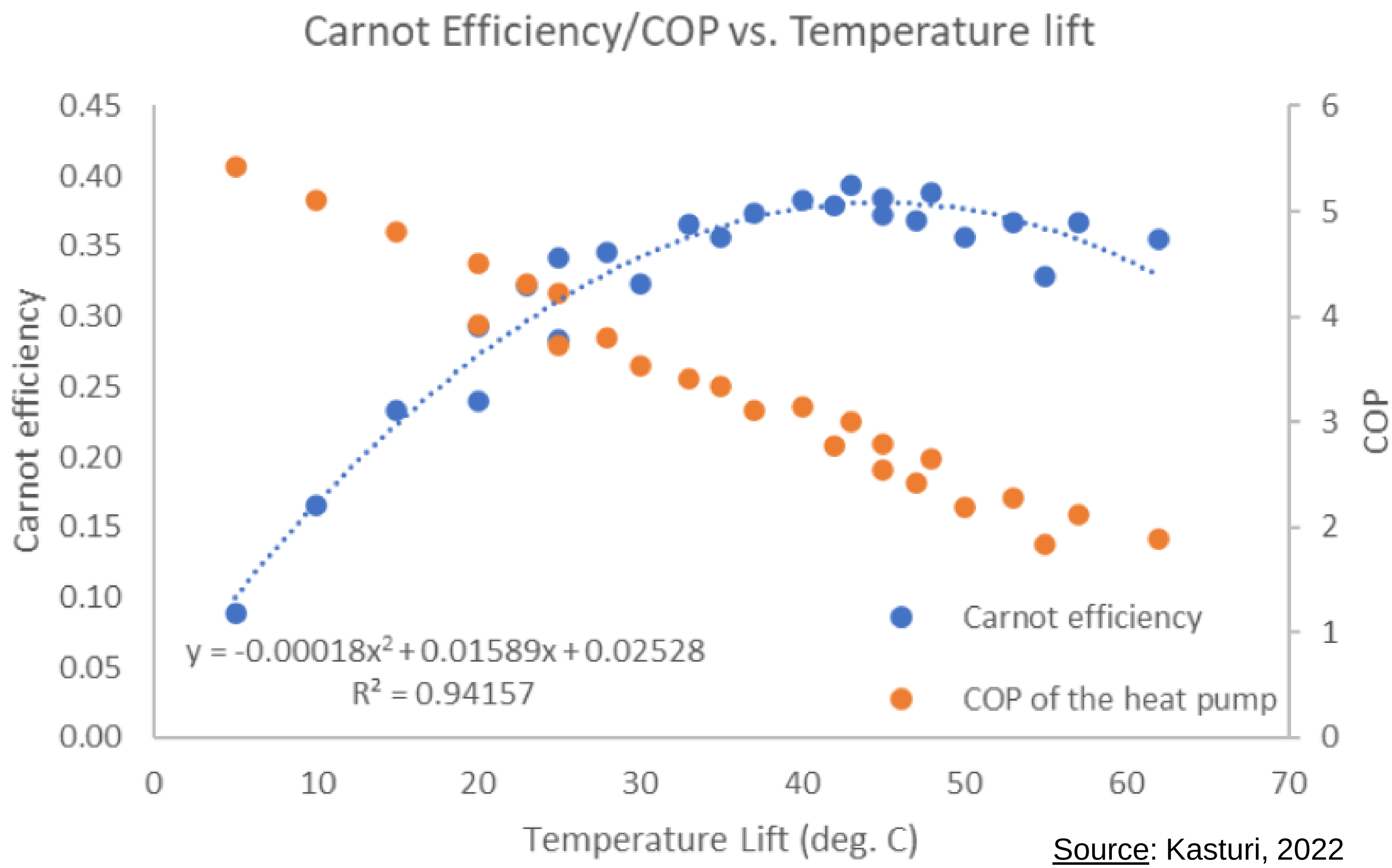
The heat pump cycle

Real (and ideal) COP

The real performance of a heat pump

$$\eta_{hp} = \frac{COP}{COP_{Carnot}}$$

- Carnot efficiencies are rather low
- Lower carnot efficiencies at lower temperature lifts, T_H-T_C



Source: Kasturi, 2022

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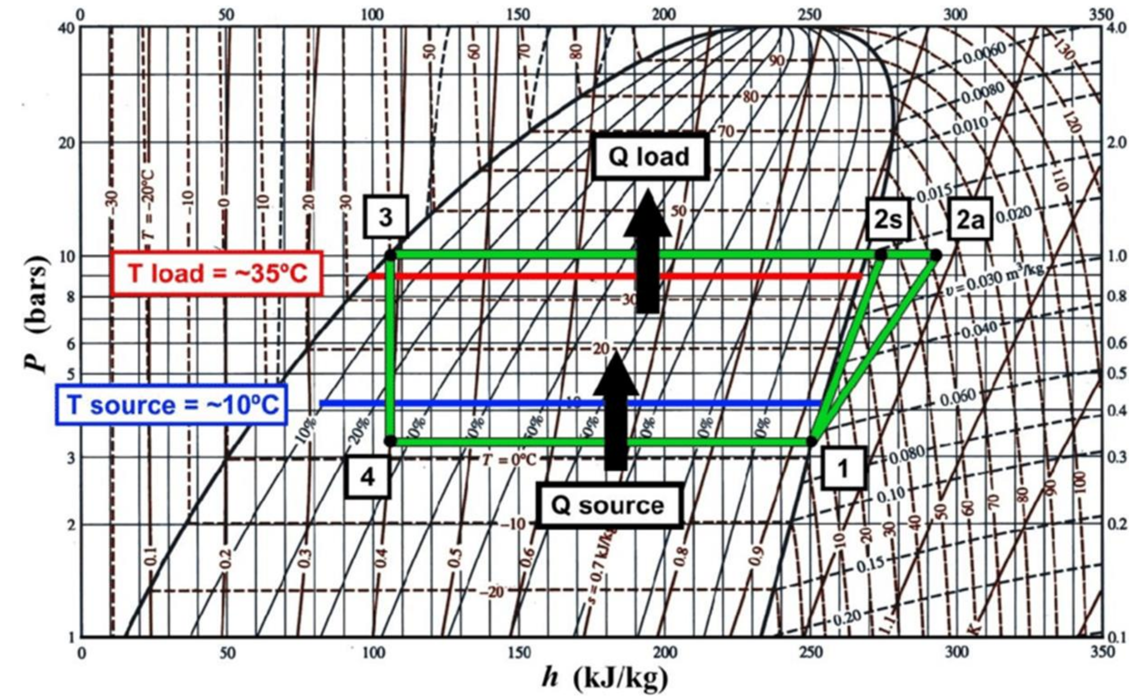
Heat pump overview

The heat pump cycle

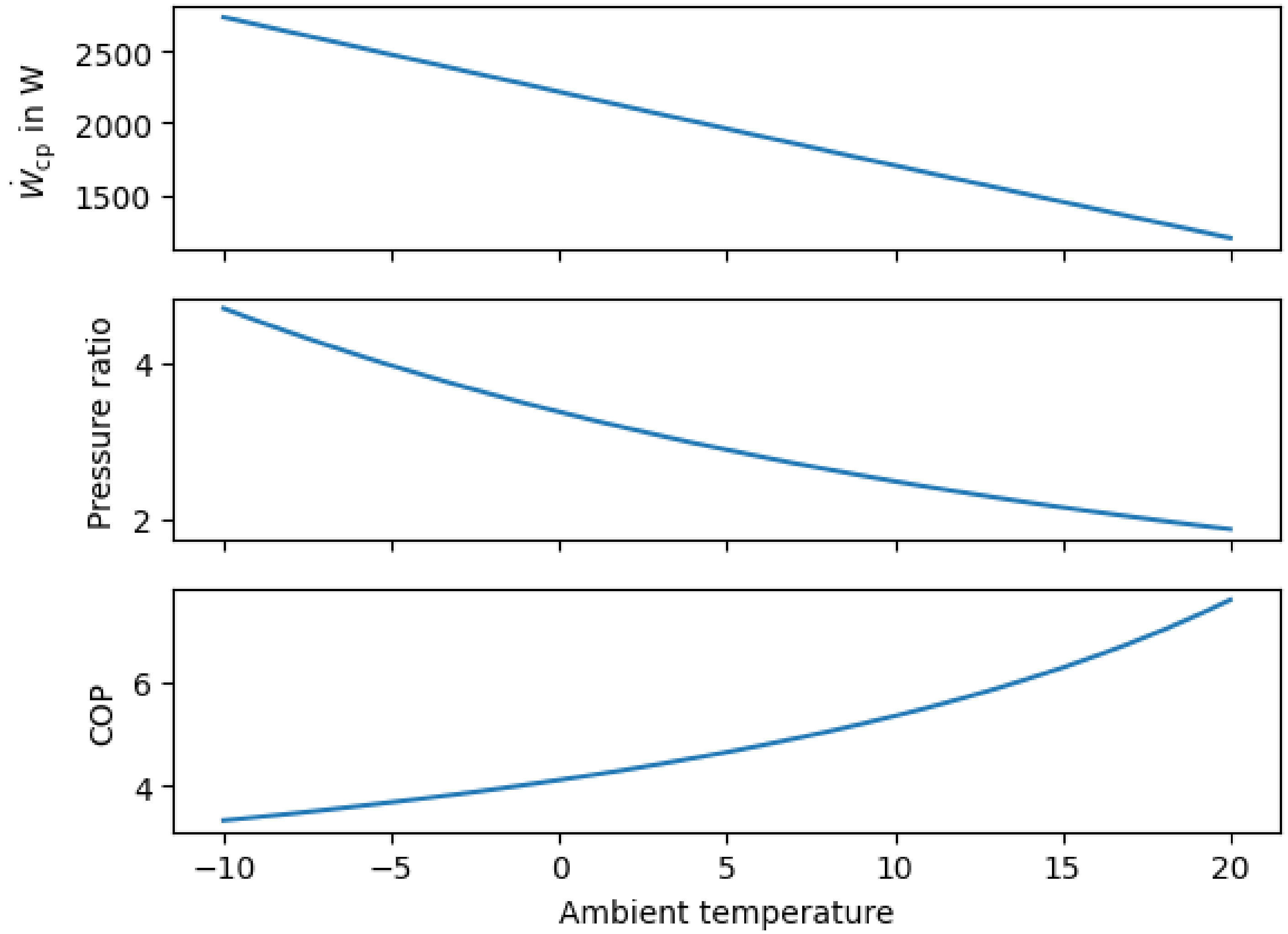
Full load

Compressor efficiency can be considered as constant (calibration point)



Pressure ratio and electrical input decline with increasing source temperature

COP dependent on Temperatures



Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

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Heat pump overview

The heat pump cycle

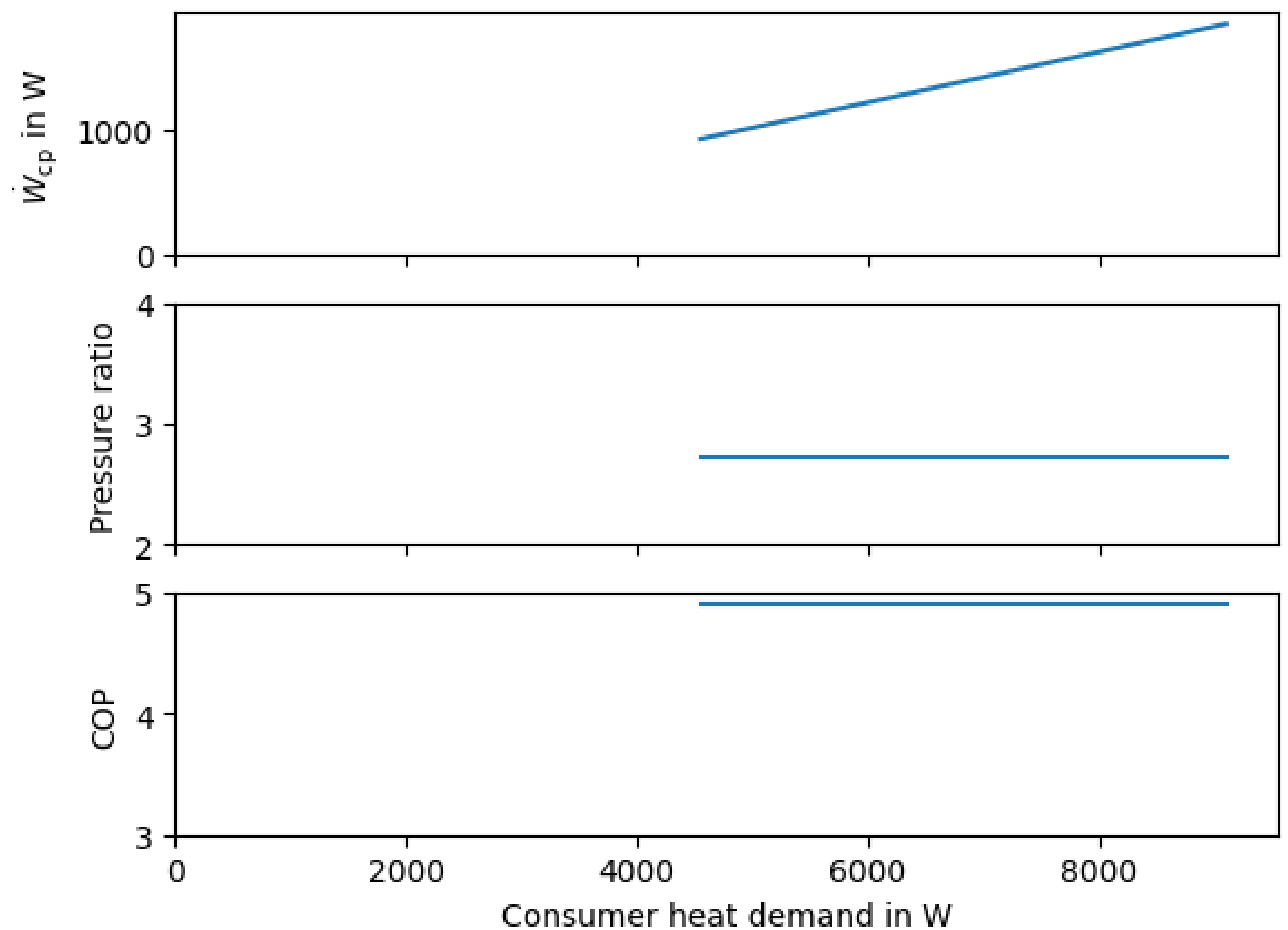
Full load

Compressor efficiency can be considered as constant (calibration point)

Electrical input is a linear function of the heat supplied (constant compr. eff.)

Pressure ratio independent of load to be supplied

COP **IN**dependent on heat supplied (Qcond)



Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

Heat pump overview

The heat pump cycle

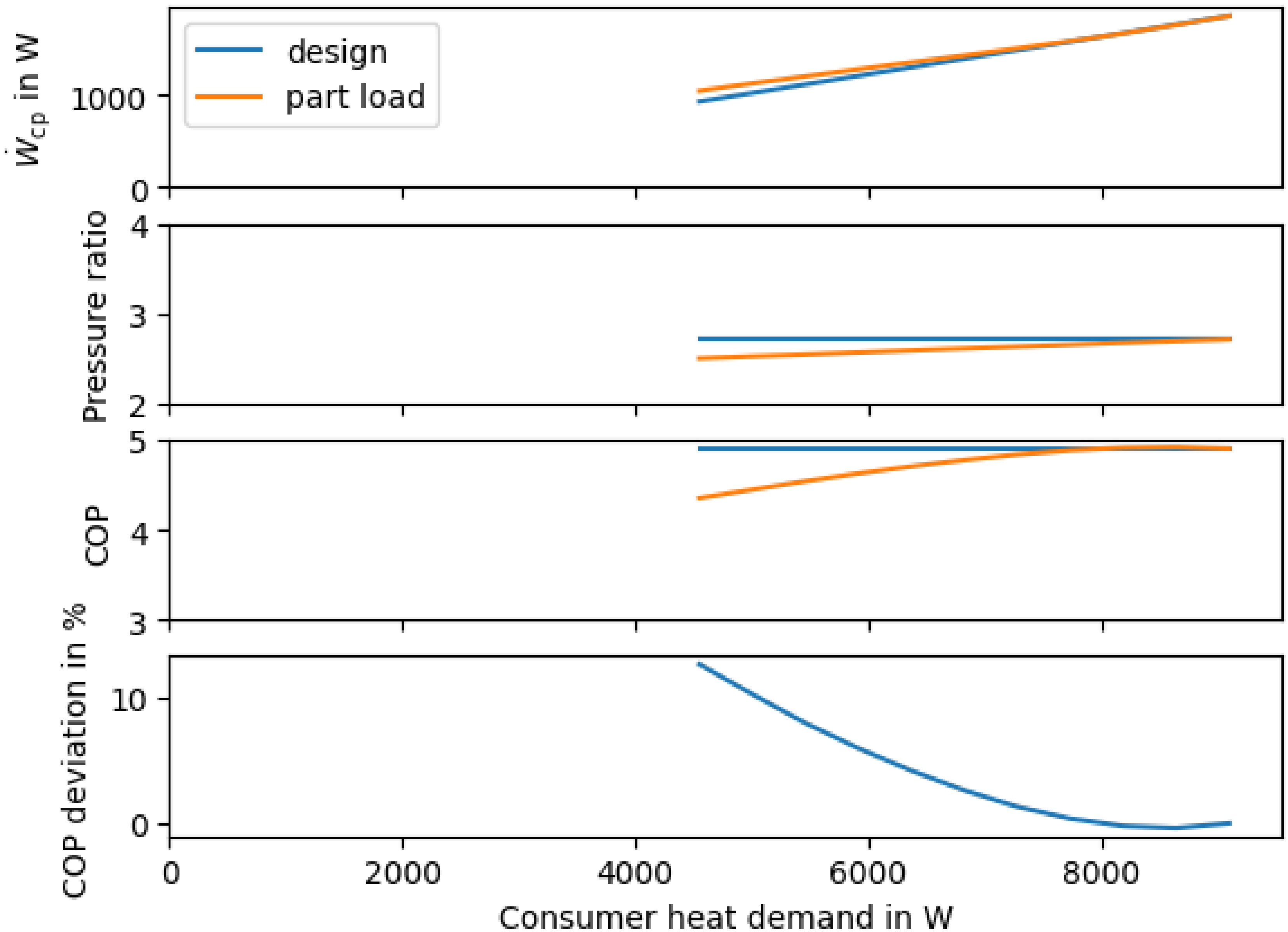
Partial load

Compressor efficiency can be considered as **state-dependent** (non constant)

For loads lower than 75-50% of max.power higher deviations of the power ratio

Leading to higher differences in the COP

COP is dependent of the partial load behaviour



Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

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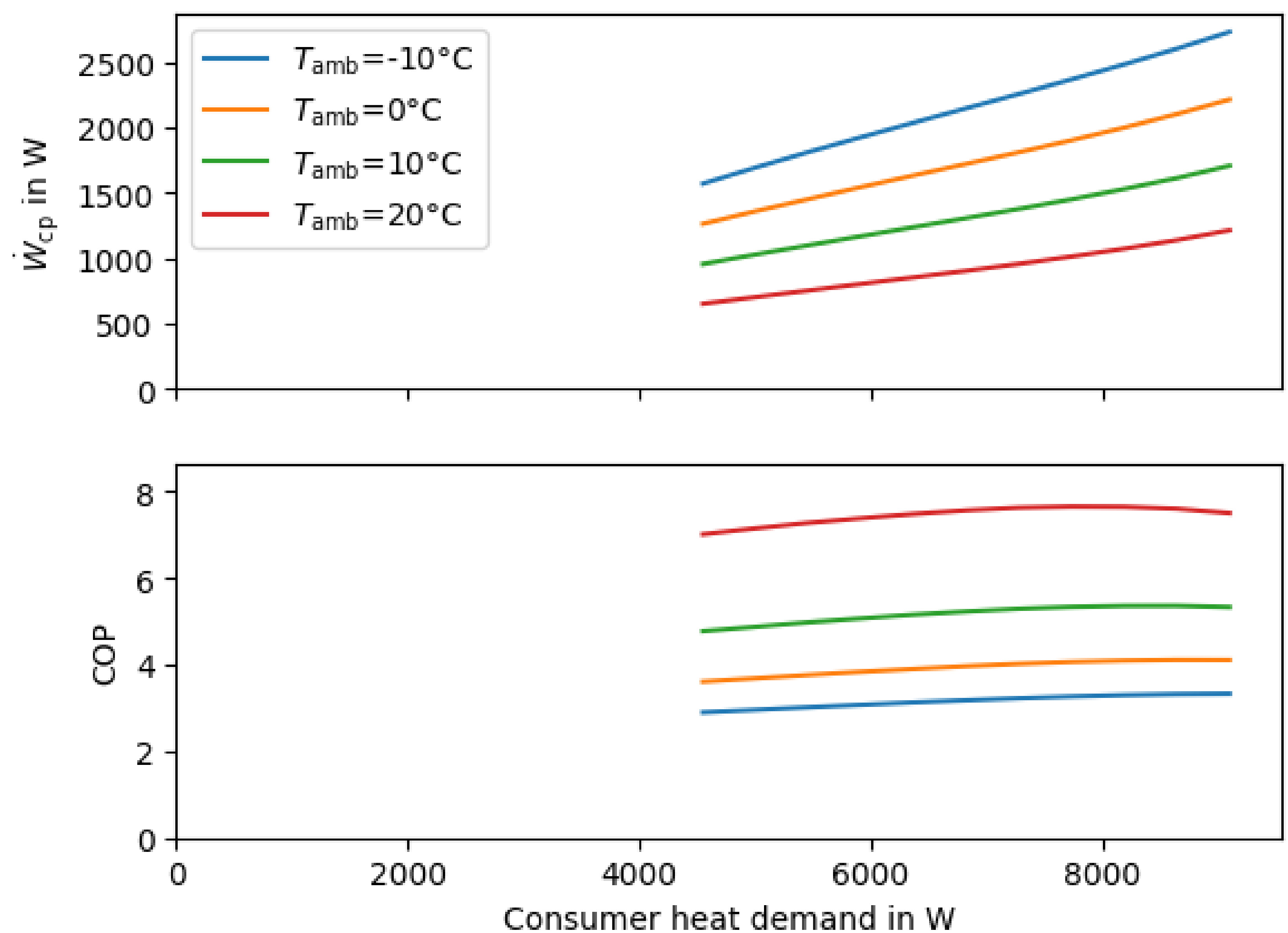
Heat pump overview

The heat pump cycle

Partial load

Compressor efficiency can be considered as **state-dependent** (non constant)

- At part load COP decreases
- For loads lower than 75-50% of max.power compressor power is not a linear function of the load anymore
- COP is not fully constant for lower loads



Source:Linear oemof-solph heat pump model — oemof Workshop on Modeling of Heat Pumps

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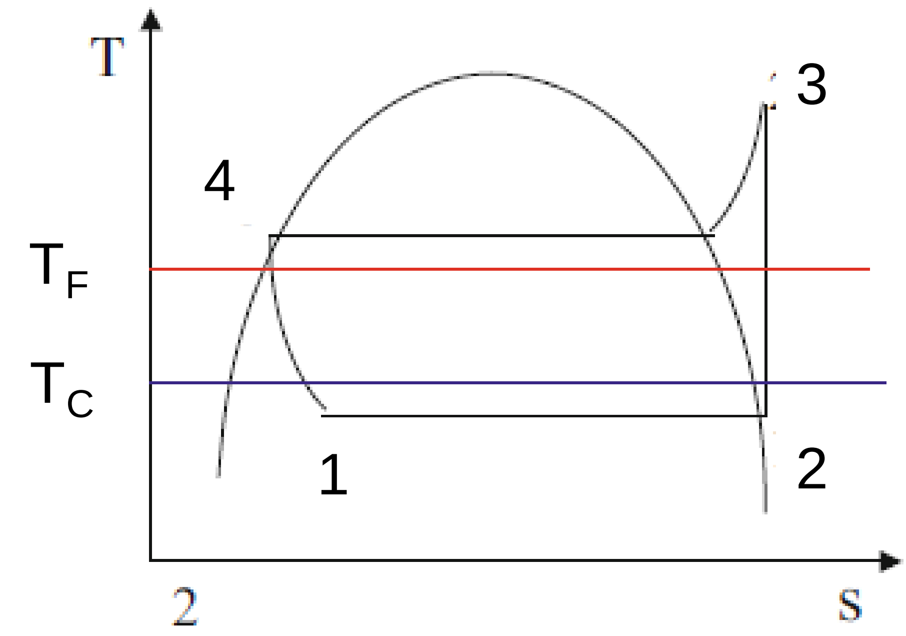
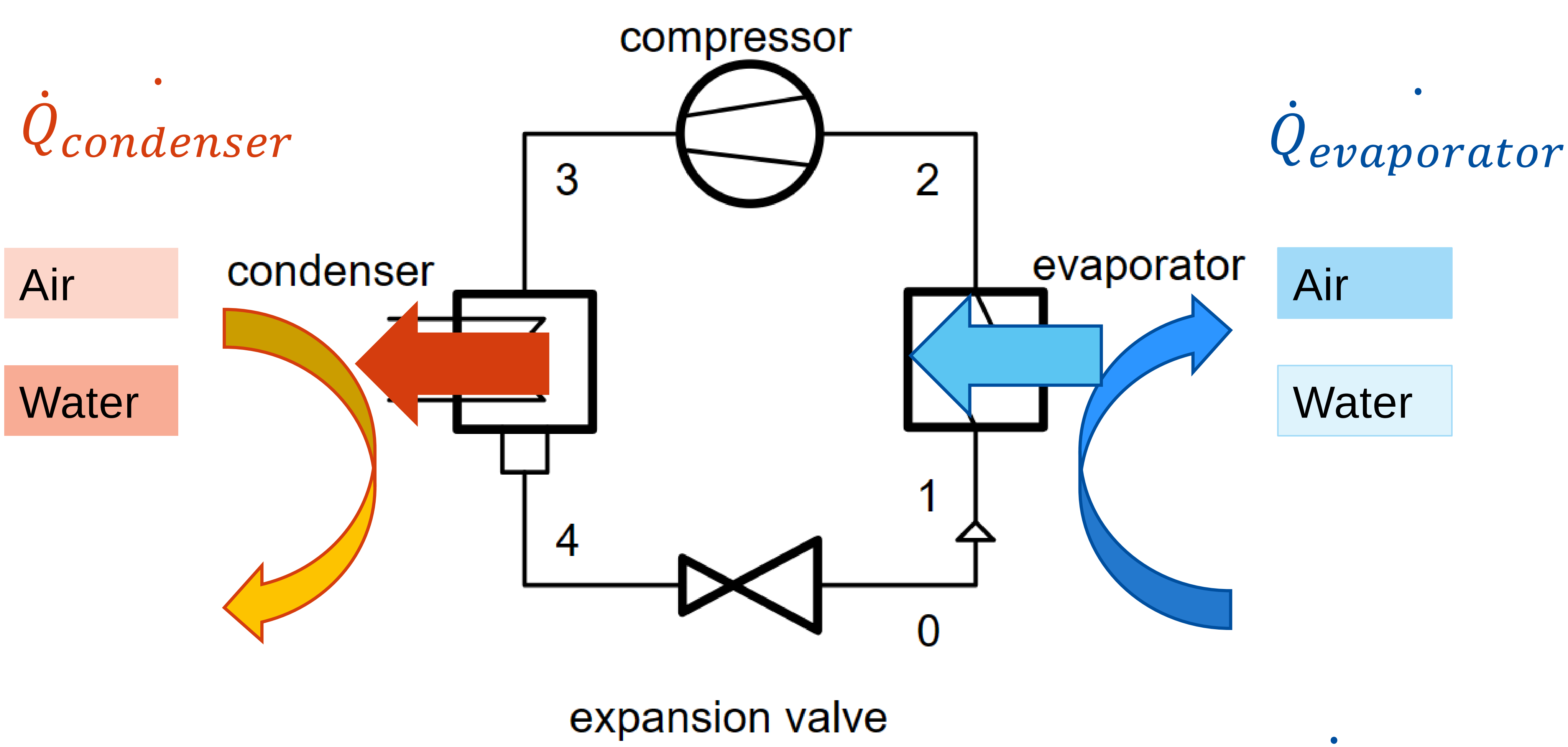
Heat pump overview

The heat pump cycle

Operation - Real behaviour (simluated)
Constant mass flow vs. Constant temperature difference
(in the secondary sides of both evaporator and condenser)





$$\dot{Q}_{evaporator} = \dot{m} c_p \Delta T$$

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Heat pump overview

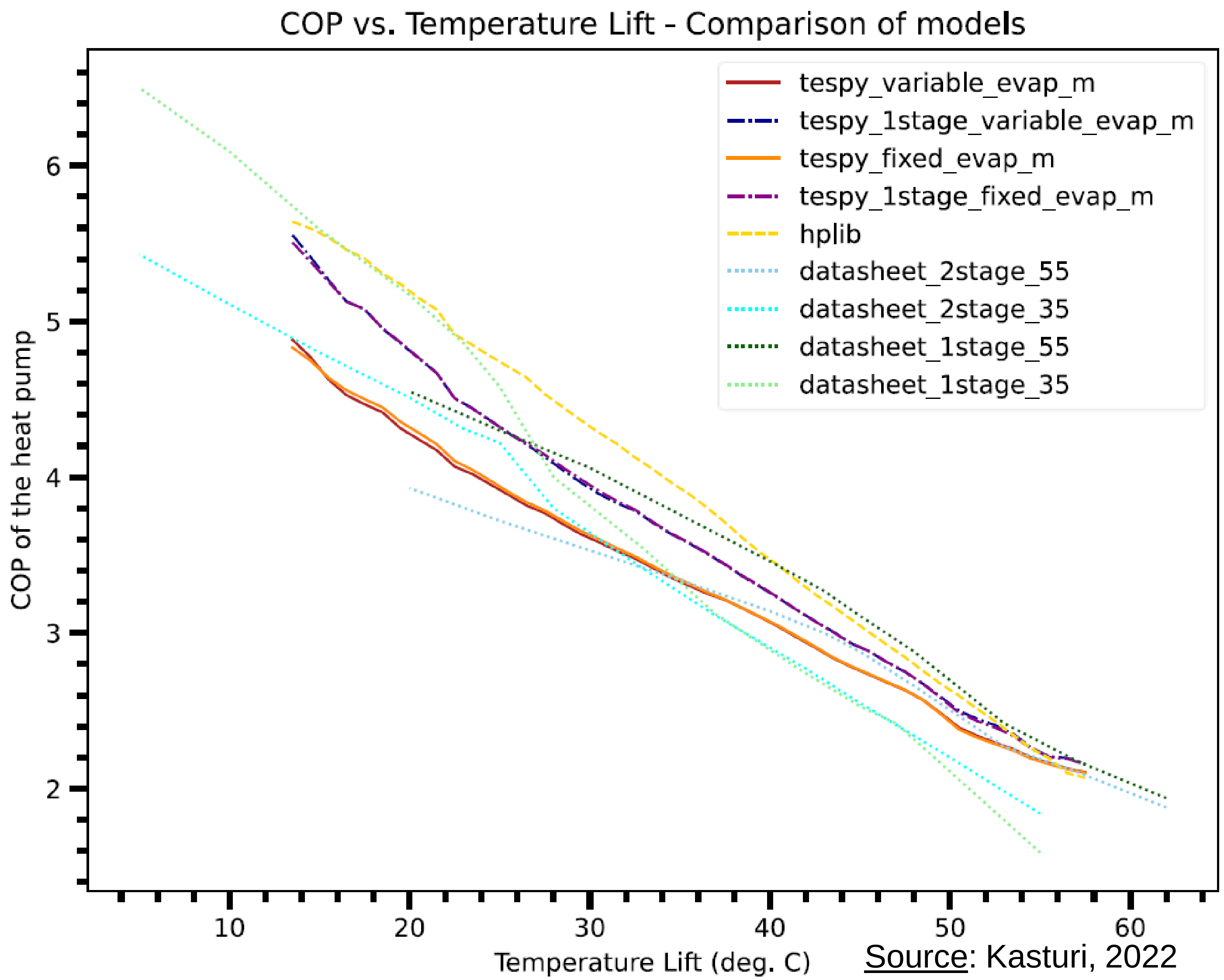
The heat pump cycle

Operation

Constant mass flow vs. Constant temperature difference

(in the secondary sides of both evaporator and condenser)

- Very similar COP - performance for both operation strategies



Source: Kasturi, 2022

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Heat pump overview

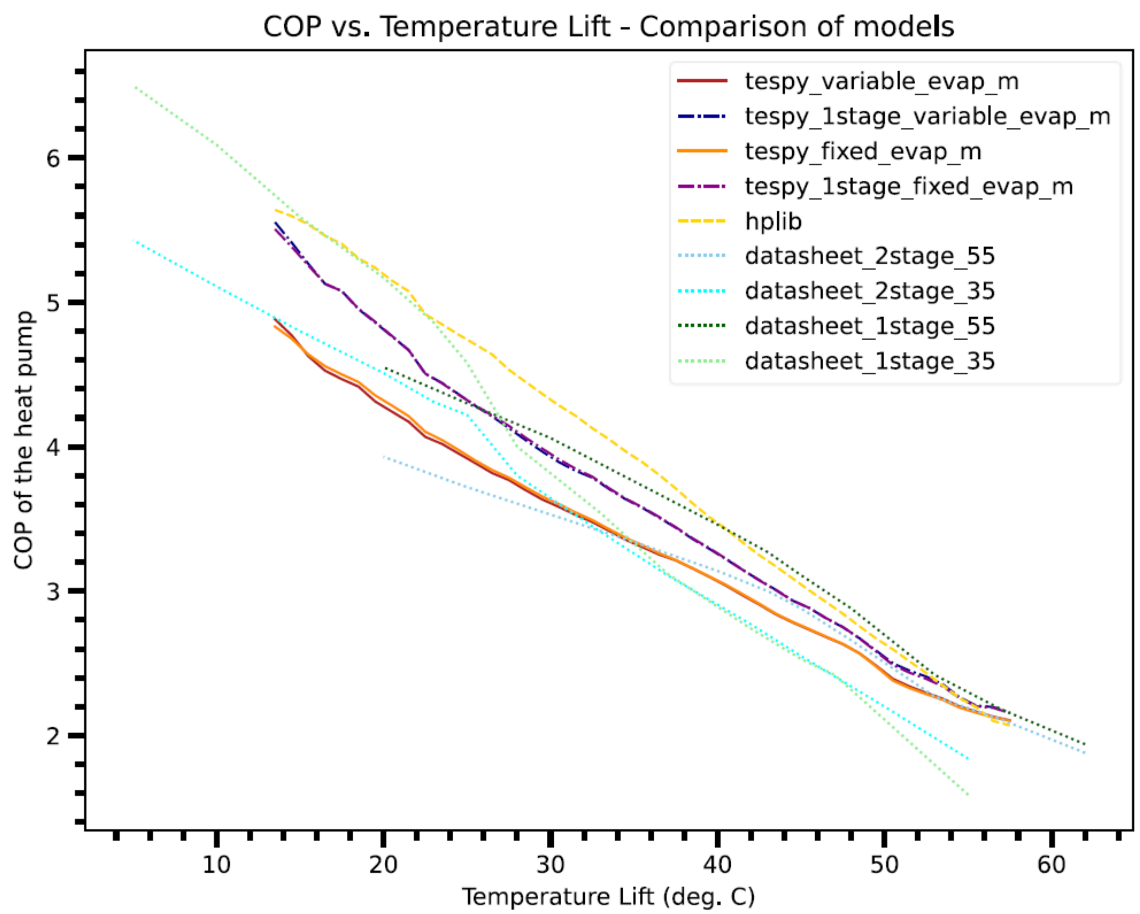
The heat pump cycle

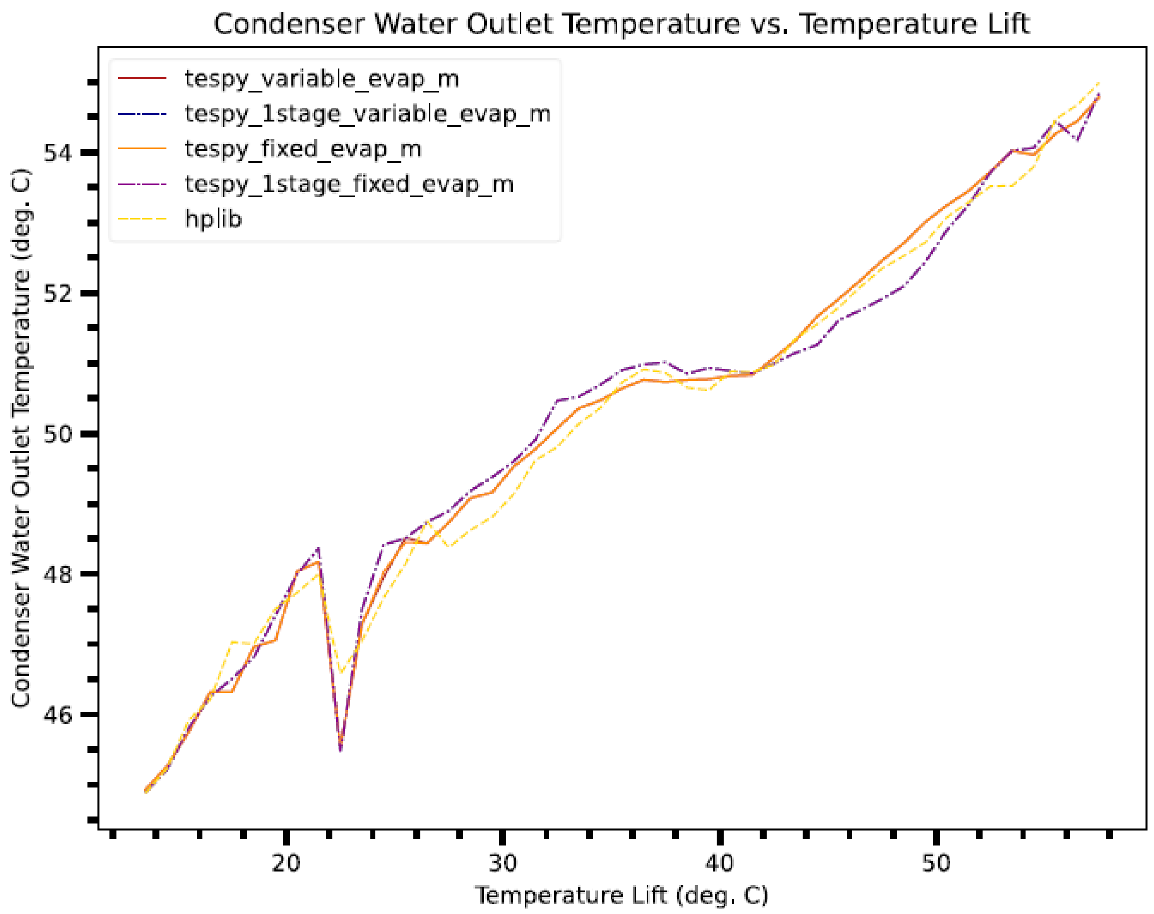
Operation

Constant mass flow vs. Constant temperature difference

(in the secondary sides of both evaporator and condenser)

- Very similar COP performance for both operation strategies
- Very similar condenser outlet temperatures





Source: Kasturi, 2022

References

Grassi 2018. Heat pump fundamentals and applications. Green Energy and Technology, Springer Ed. Link: https://link.springer.com/book/10.1007/978-3-319-62199-9, Last accessed: Oct. 2023

Kasturi 2023. *Simulation of photovoltaic-thermal (PV-T) solar assisted heat pump (SAHP) systems for building thermal demands.* Master thesis at the UOL.

Hervas Blanco. 2020. Low temperature waste water heat recovery for Domestic Hot Water production based on heat pumps. PhD Thesis. Instituto Ingenieria Energetica. Universidad Politecnica de Valencia. Link: Aprovechamiento del calor residual a baja temperatura mediante bombas de calor para la producción de agua caliente (upv.es), Last accessed: 03.11.2023