Innovative thermal machines for waste heat recovery in industry

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3rd Winter School for PhD students

FLUID MACHINES AND ENERGY SYSTEMS

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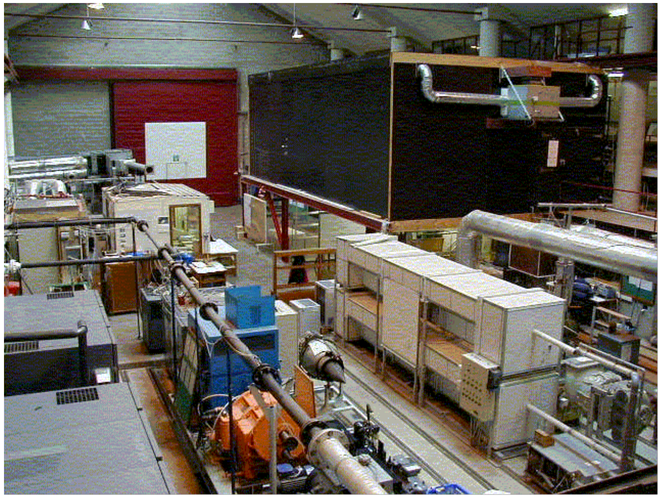
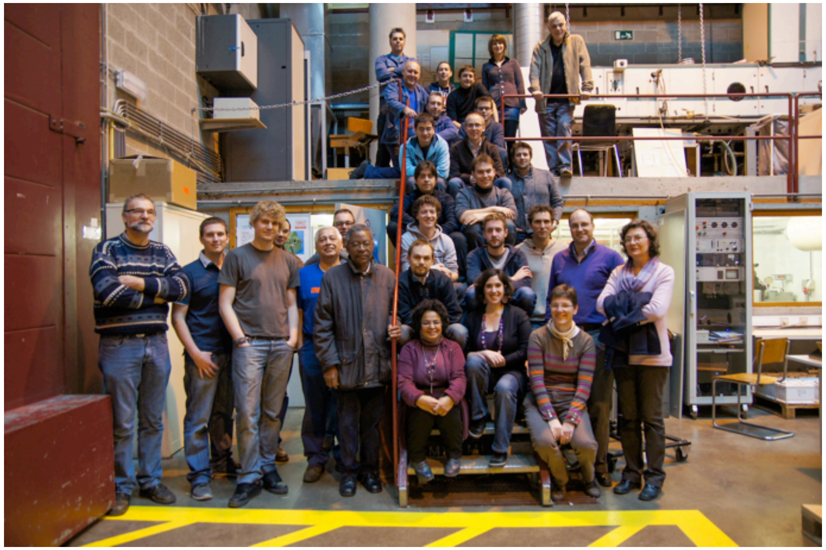
LIÈGE université

LABORATOIRE DE THERMODYNAMIQUE UNIVERSITE DE LIEGE

About our group

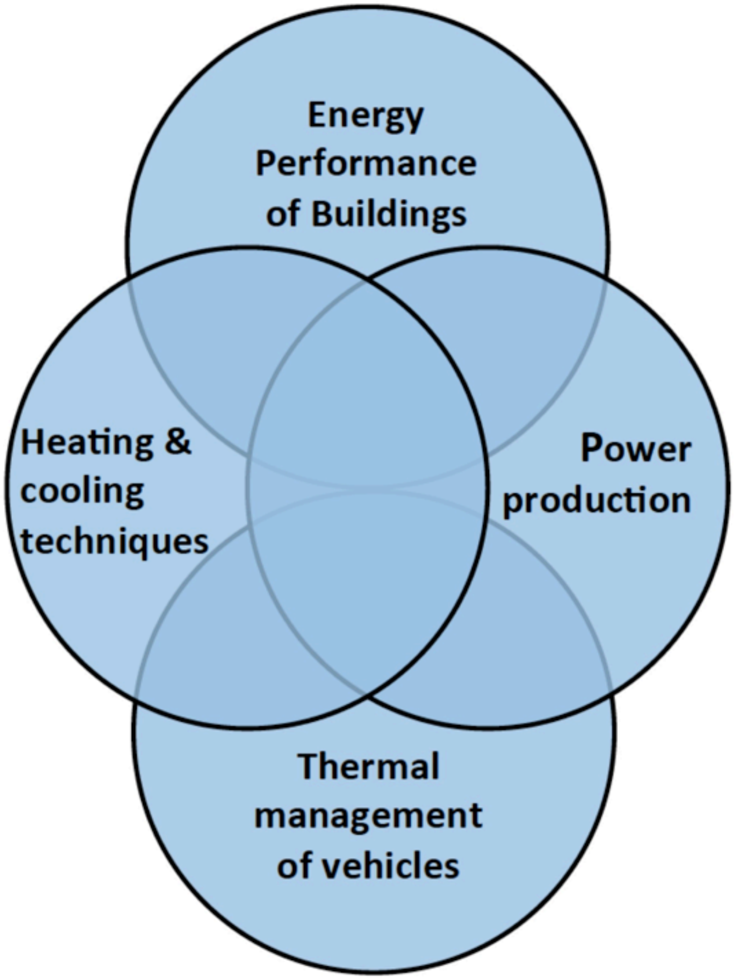
- Thermodynamics Laboratory
- Aerospace and Mechanical Engineering Department
- Engineering School of University of Liège
- Team of approx. **30 people**: 4 professors (1 emeritus), 3 postdoc, 12 PhD students, 4 technicians, 1 secretary, 5 invited researchers, 2 scientific collaborators





About our group

- Research activities aim at developing innovative and efficient **thermal energy systems**
    - ✓ Design of components/systems
    - ✓ Integration
    - ✓ Control
- Address 4 different sectors
- Good equilibrium between **experimental** and **numerical** research
- Large proximity with **industrial world**

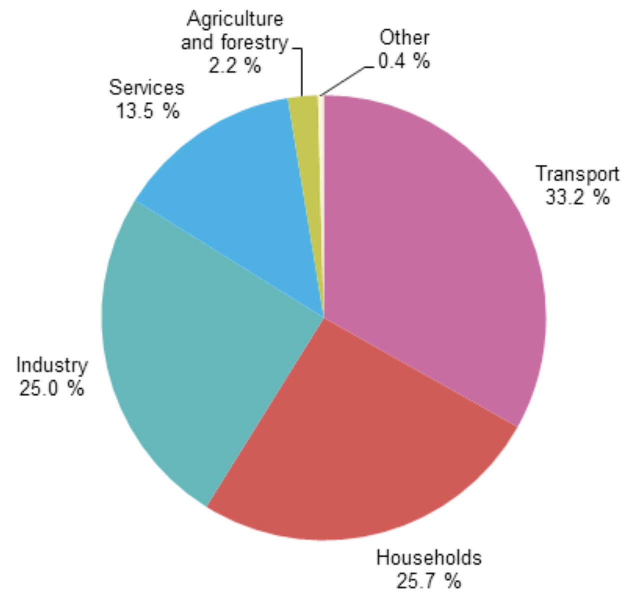


Introduction

Context – Industrial sector energy consumption

- Industry and services are responsible for more than 1/3 of the final energy consumption.
- Energy consumption of industry is similar to that of households

Final energy consumption by sector, EU-28, 2016
(% of total, based on tonnes of oil equivalent)



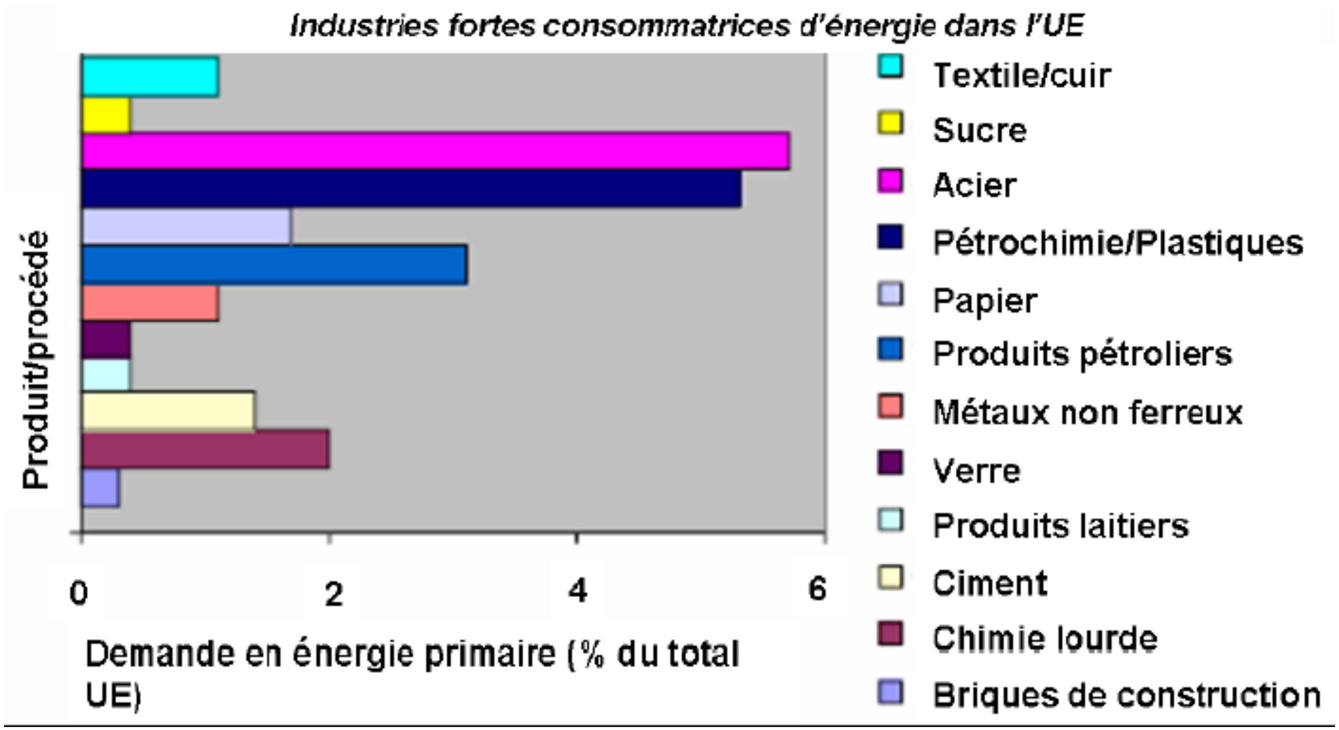
Source: Eurostat (online data code: nrg_100a)

eurostat

Introduction

Context – Industrial sector energy consumption

- Some industry sectors consume more energy than others…



Primary energy demand in industry in Europe by sector (source: TOTAL Ademe)

Introduction
Context – Energy efficiency in Industry

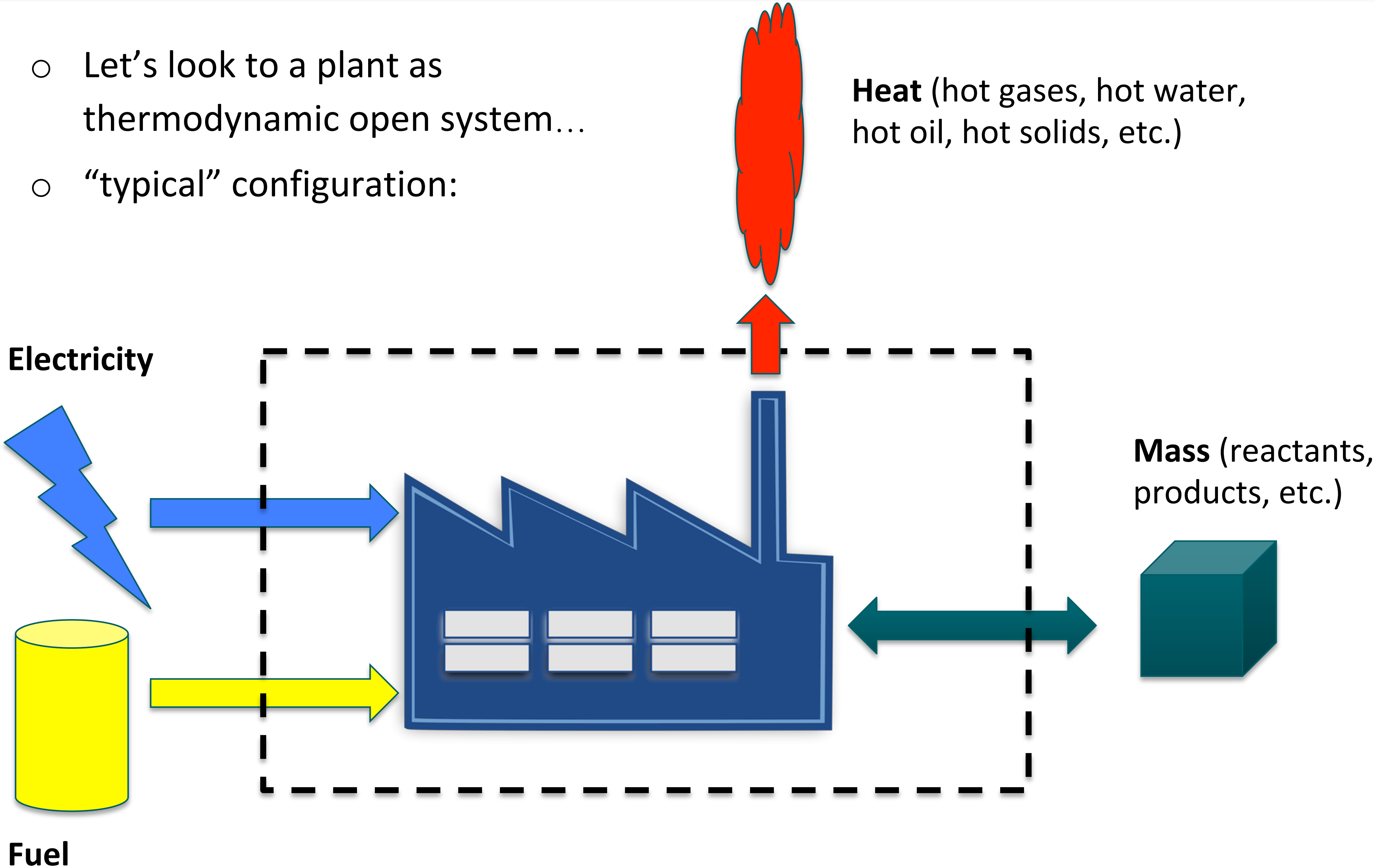
- Increasing energy efficiency of Industry causes:
  - A reduction of the CO_2 emissions (and other pollutants)
  - An increase of local industry competitiveness (e.g. energy represents from 20 to 40 % of total production cost of cement)

How could Energy Efficiency of Industry be improved?

Introduction

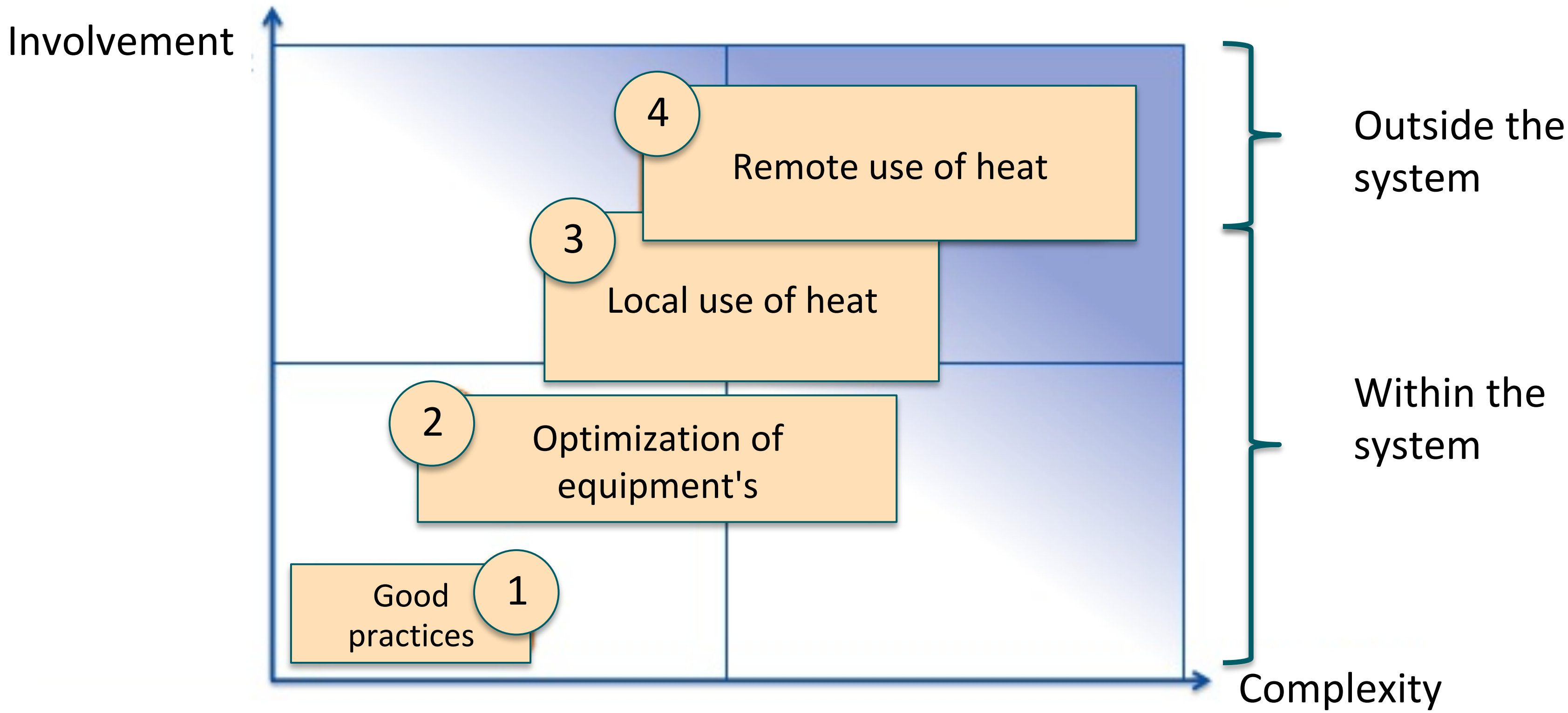
Context – Energy efficiency in Industry

- Let's look to a plant as thermodynamic open system…
- "typical" configuration:



Introduction

Energy efficiency in industry – Actions to undertake

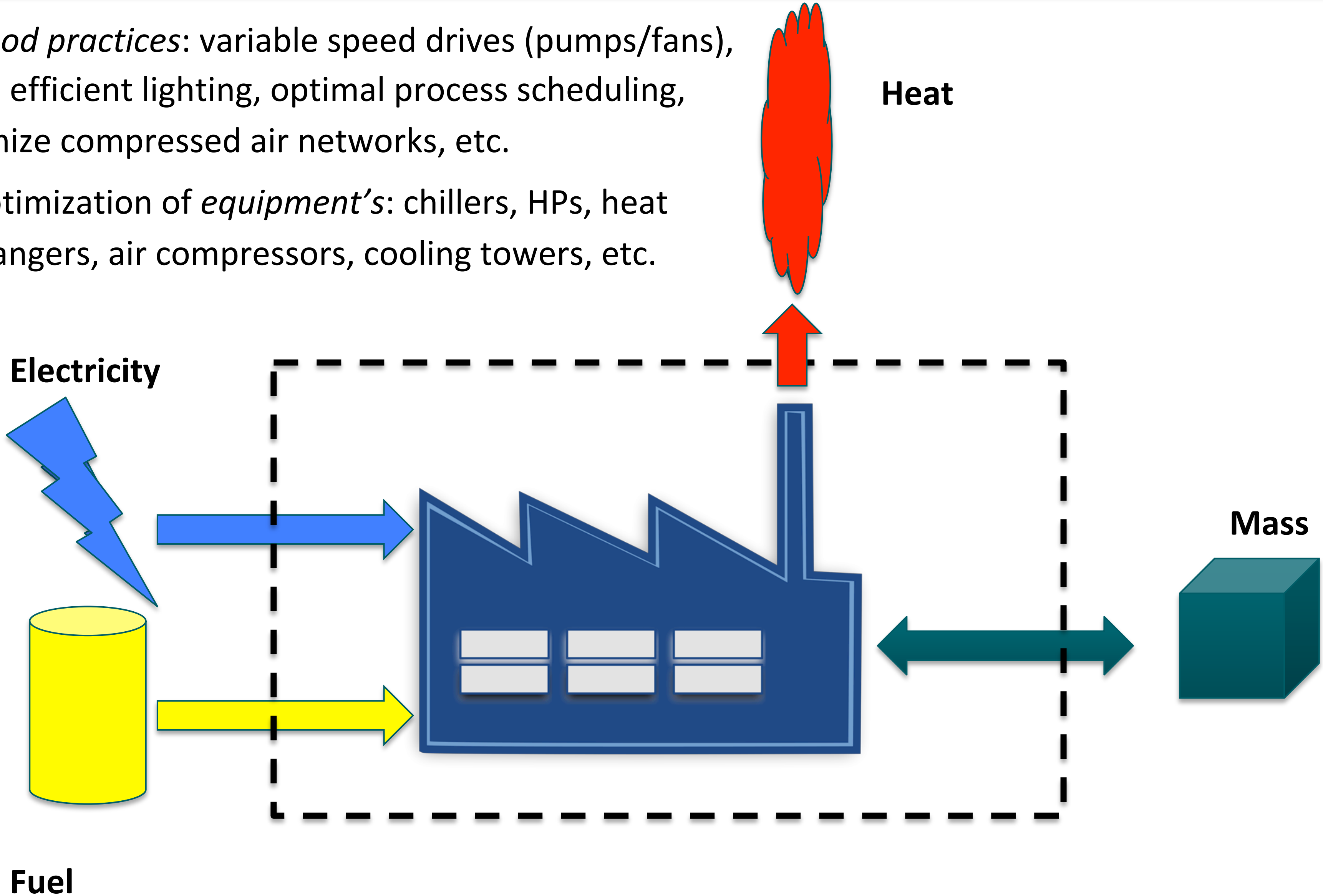


(Adapted from Ludovic Ferrand – CMI)

Introduction

Energy efficiency in industry – Actions to undertake

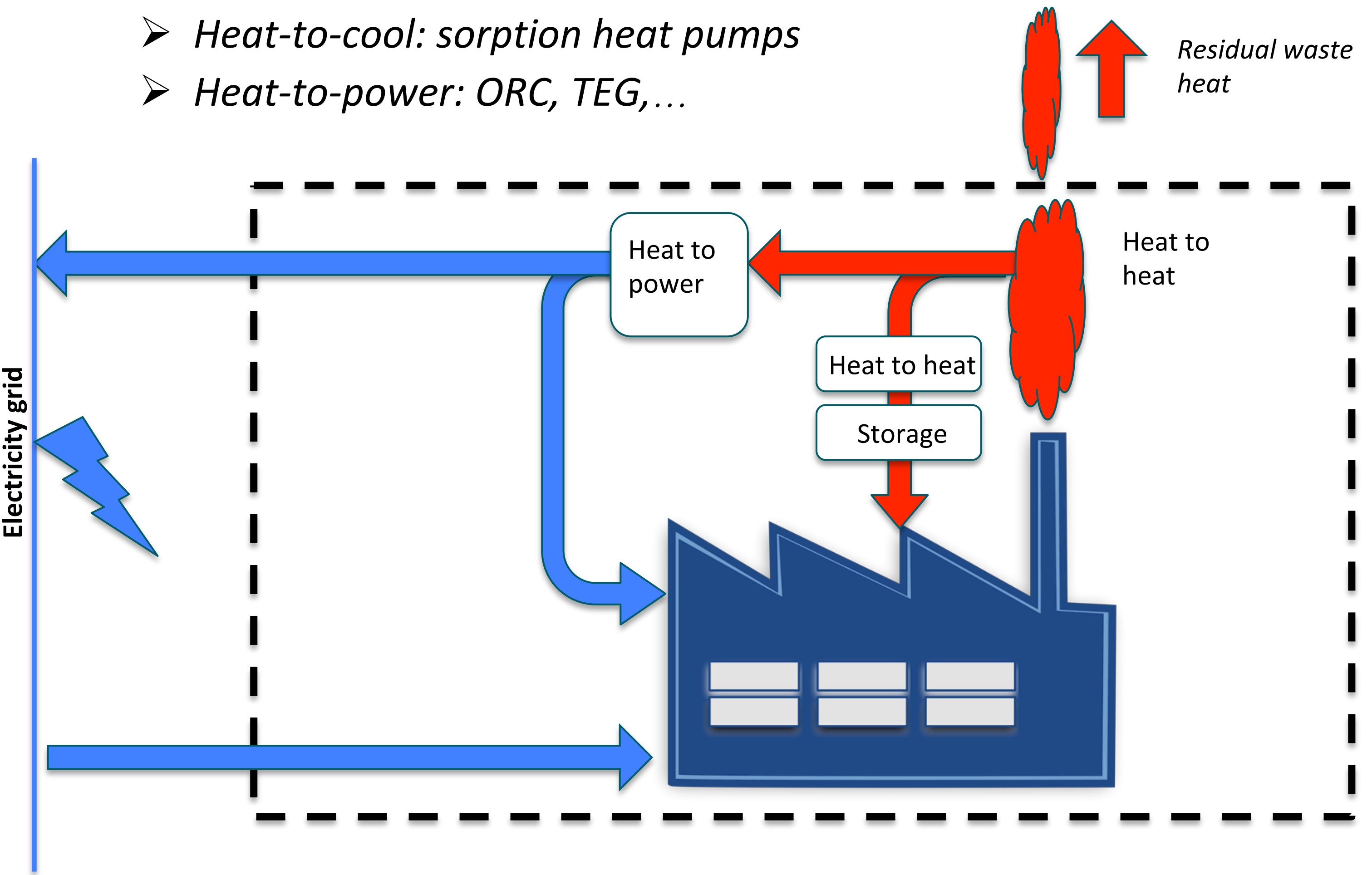
- *1. Good practices*: variable speed drives (pumps/fans), more efficient lighting, optimal process scheduling, optimize compressed air networks, etc.
- 2. Optimization of *equipment's*: chillers, HPs, heat exchangers, air compressors, cooling towers, etc.



Introduction

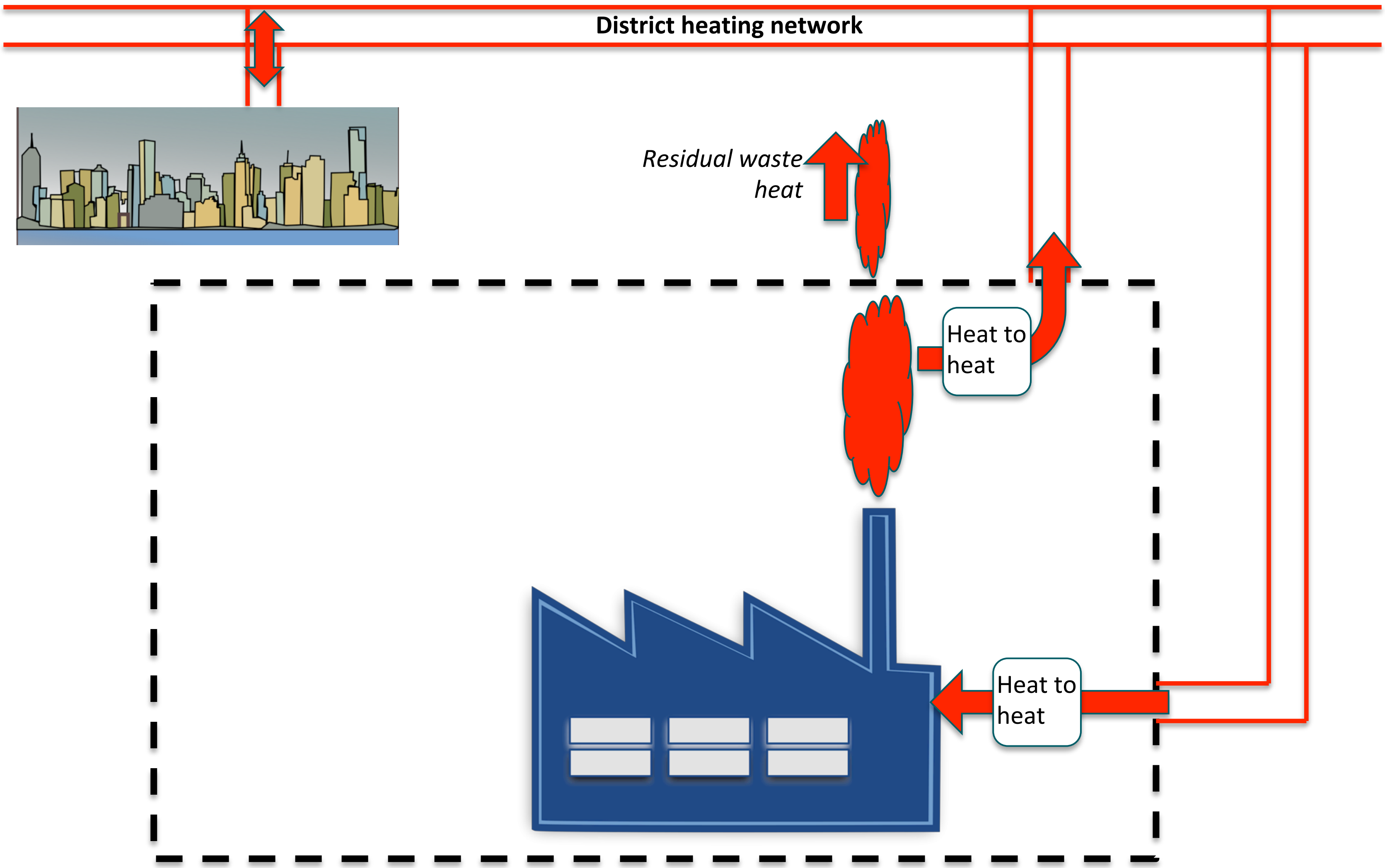
Energy efficiency in industry – Actions to undertake

- *3. Local use of heat:*
  - *Heat-to-heat: HEX, Heat pipes, HP (t° upgrade)*
  - *Heat-to-cool: sorption heat pumps*
  - *Heat-to-power: ORC, TEG,…*



Introduction

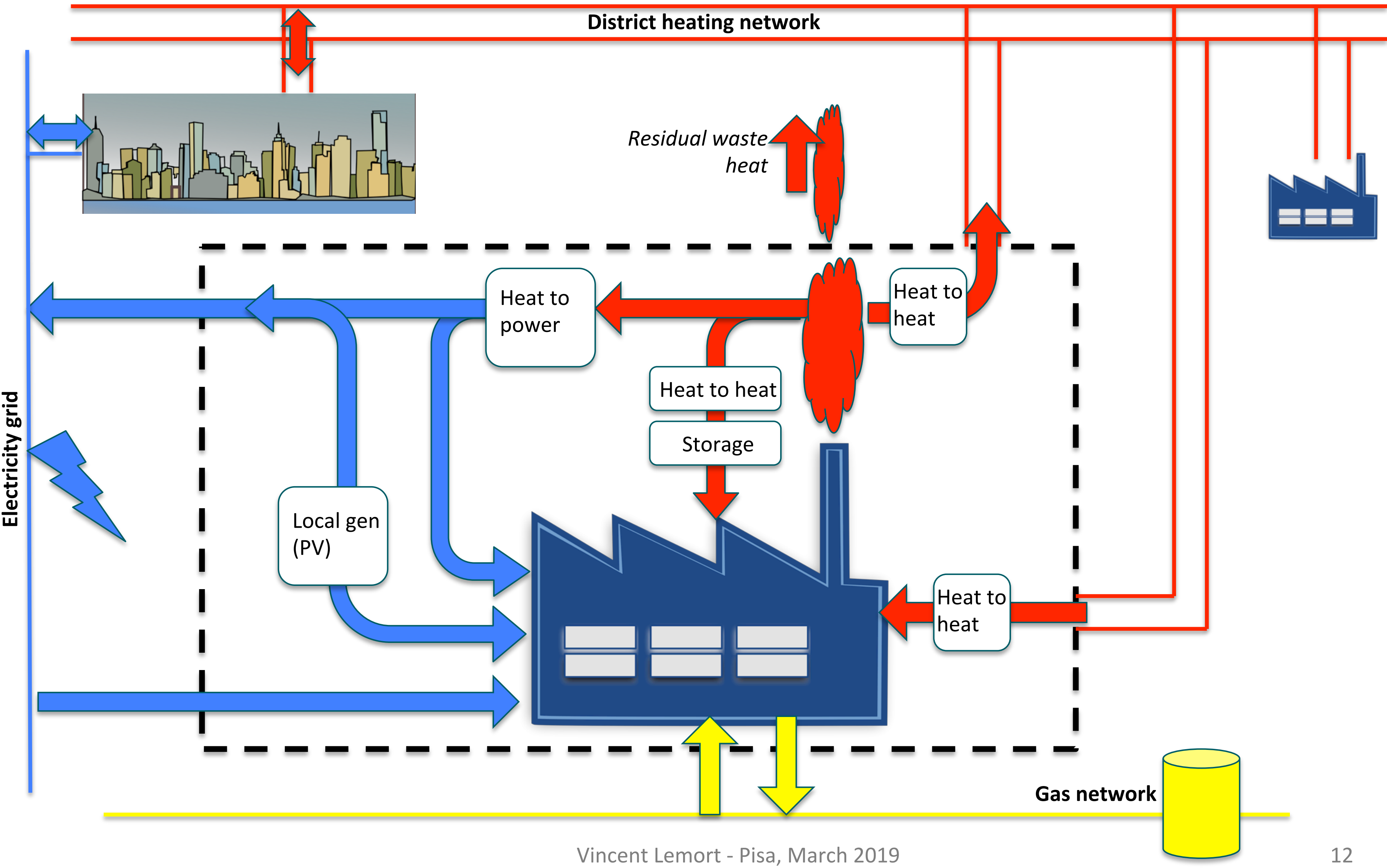
Energy efficiency in industry – Actions to undertake



✧ *4. Remote use of heat through DHN (ideally low t° DHN)*

Introduction

Energy efficiency in industry – Actions to undertake



Introduction

Energy efficiency in industry – Focus on WHR

- Actions 3 and 4 are based on waste heat recovery (WHR)
- WHR techniques should
  - ✓ Be efficient
  - ✓ Be cost effective
  - ✓ Be reliable (environment could be severe: acids, soot,…)
  - ✓ Not impact the process (quality of the product, performance of process)
  - ✓ Dynamic and intermittent heat sources
  - ✓ …

- ➢ Existing techniques must be adapted/improved and **innovative techniques** must be proposed
- ➢ Ideas don't come only from thermodynamics (**multi fields of physics**)
- ➢ New modeling tools/experimental approaches must be developed

Introduction
Purpose of this talk

- Present some past and ongoing research projects dealing with advanced thermal systems (for industry)
- Stress the technical challenges to cope with
- Point out the scientific/technical innovation

Content of the presentation

1. About our research group
2. Introduction
3. **Heat-to-heat with heat exchangers**
4. Heat-to-heat with vapor compression heat pumps
5. Heat-to-heat with absorption heat pumps
6. Heat-to-power with (Organic) Rankine Cycle systems
7. Pumped thermal energy storage
8. Conclusions

Use of heat exchangers
Context and challenges

Context

- Many heat sources are available at temperatures high enough for direct use for heating (w/o temperature upgrade)
- Heat could be used for space heating, process pre-heating, etc.

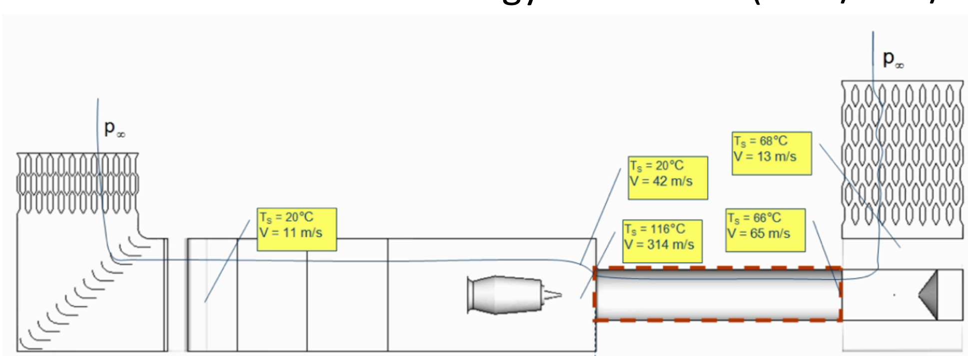
Technical challenges

- Backpressure created by the heat exchanger must be limited
- Acid condensation/fooling by soot can occur
- Transfer of humidity (in addition to heat) can also be interesting
- Performance should be high enough for meet economic profitability
- …

Use of heat exchangers

Waste heat recovery from plane engines

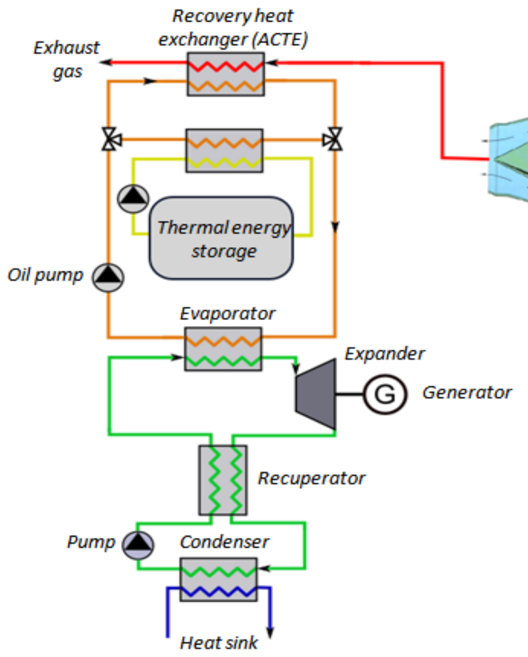
- Context:
  - Market of engines test benches: OEM, engines manufacturers, maintenance companies, aeronautics companies, armies.
  - Waste heat recovery on engine test benches
    - Turbofan: exhaust gases (1240-1450 kg/s and 55-70°C: 47 MW)
    - Turbojet: exhaust gases (550 kg/s and approx. 300°C: 161 MW)
    - Turboprop: brake cooling water (30-70°C) and gas (35-60 kg/s and approx. 300°C: 17 MW)
    - Turboshaft: brake cooling water (30-70°C) and gas (35-60 kg/s and approx. 317°C: 11 MW)
  - Test benches close to energy consumers (heat/cold/electricity)



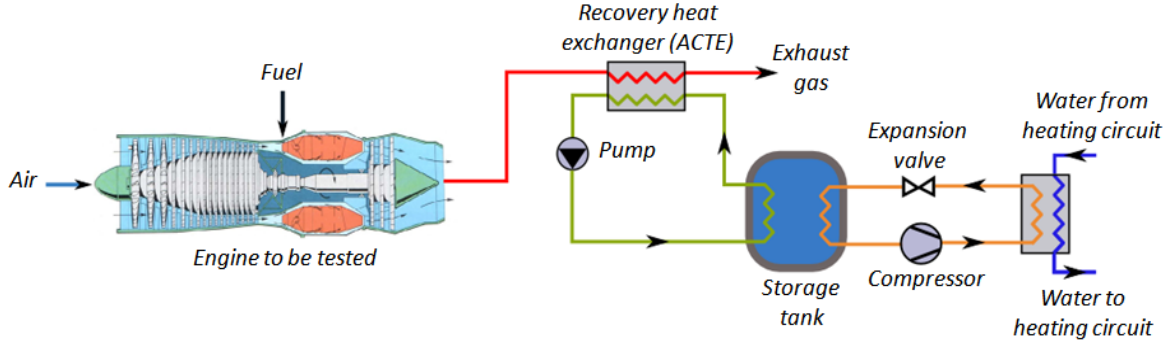
Use of heat exchangers

Waste heat recovery from plane engines

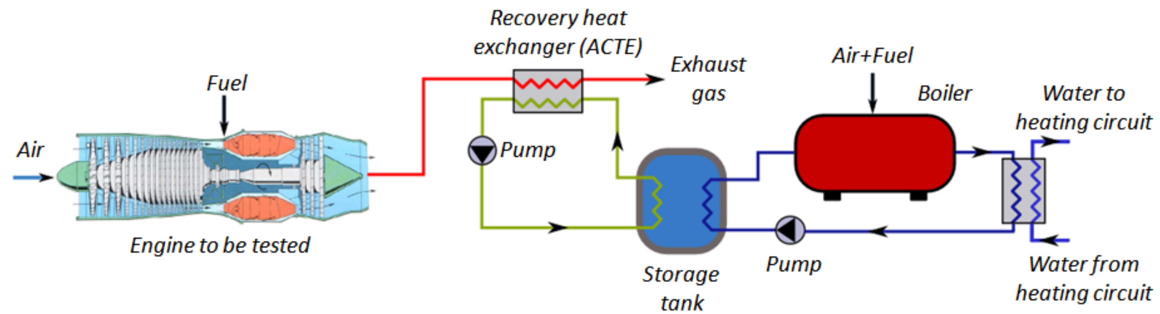
- Comparison of different waste heat recovery techniques.



ORC: turbojet



Heat pump: turbofan

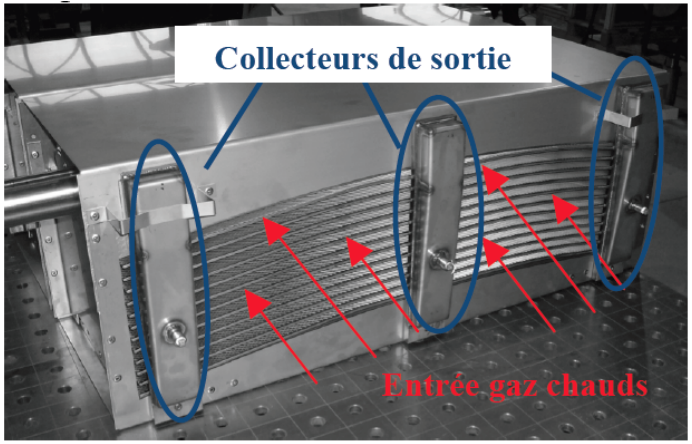


Preheating of boiler: turbofan

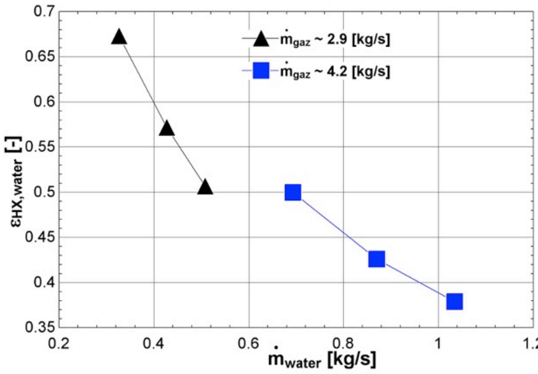
Use of heat exchangers

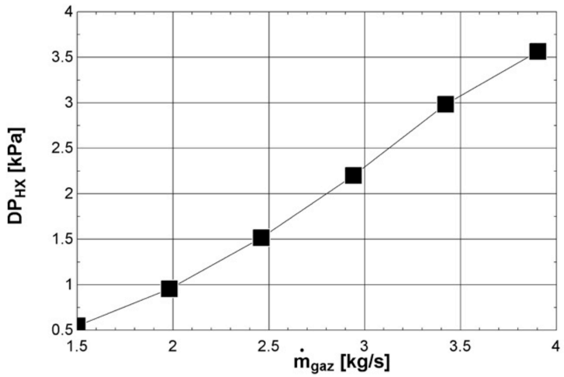
Waste heat recovery from plane engines

- Testing and modeling a scaled-down prototype of heat exchanger (Reynolds similitude).



- Exchanger: tubular plates, 14 m^2
- Test bench: gas burner of 465kW (vs 46 MW), air flow: 0-4.2 kg/s and temperature: 20-450°C





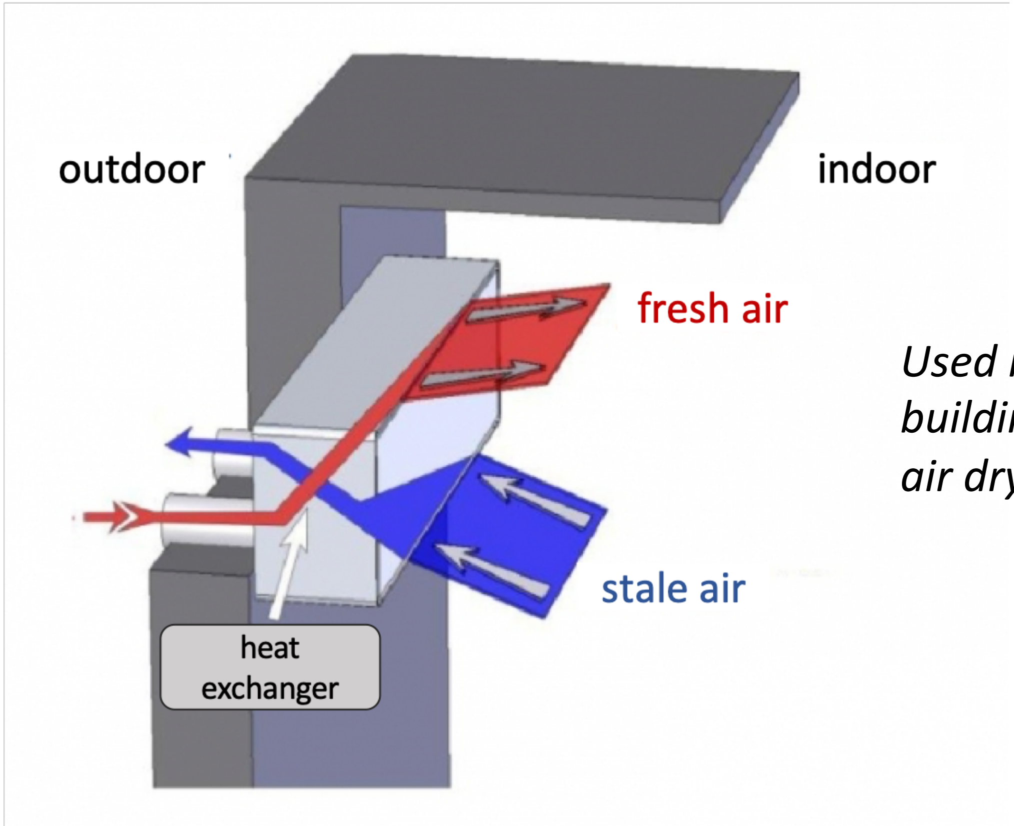
→ Accepted pressure drop on the gas side

Use of heat exchangers

Heat exchangers wih humidity transfer

- Classical heat exchangers : only heat recovery between the two streams
- **Enthalpy** exchangers : recovery **of heat + water** between the two streams

  => Reduce condensation issues and delays frost formation problems

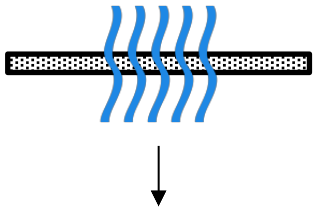


Used in large buildings too limit air drying

Use of heat exchangers

Heat exchangers wih humidity transfer

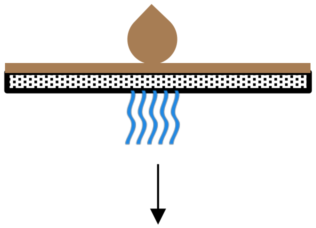
VAPOUR transfer



No state change

Transfer of vapour through a membrane (typically in paper)

LIQUID transfer



State change in the process

Transfer of liquid through a membrane

=> More robust enthalpy exchanger with a high enlargement factor (i.e. ratio between developed and flat surfaces) allowing an efficient heat, vapor and liquid water transfer

http://www.labothap.ulg.ac.be/cmsms/index.php?page=silenthalpic

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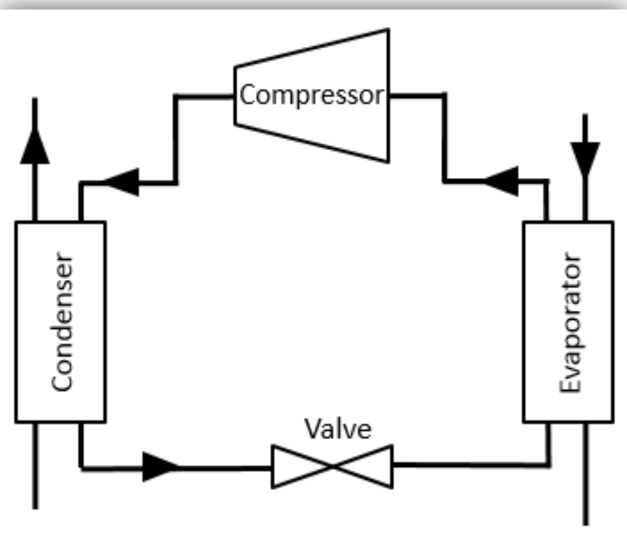
Vapor compression heat pumps

Context and challenges

Context

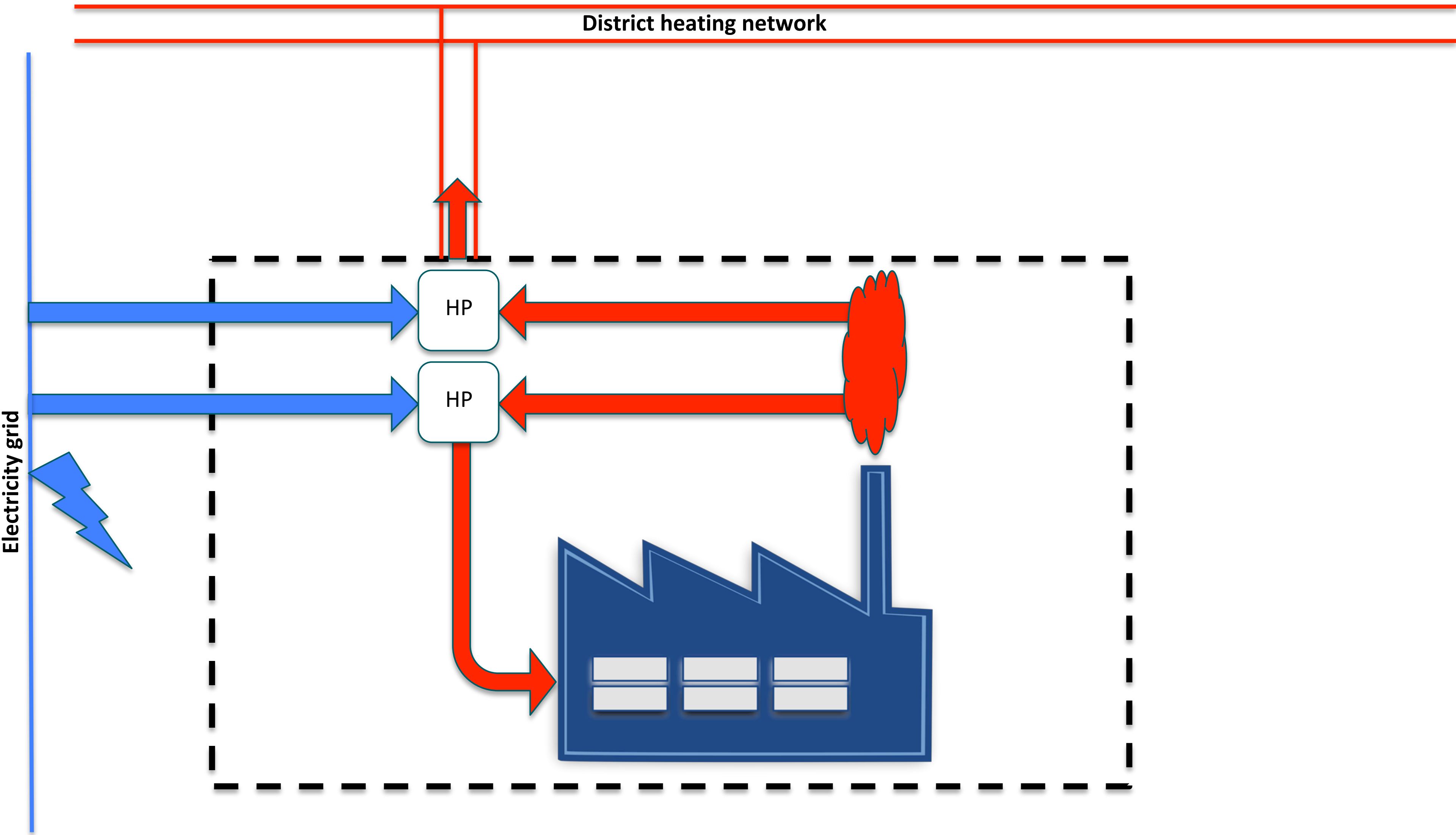
- Can yield large CO_2 savings
- Connected to thermal/electrical storages, can play a role in the management of the electricity grid.
- Mature technology for building applications



Technical challenges

- To be competitive, keep on increasing COP
- “New” refrigerants (HFO, hydrocarbons)
- Integration into buildings, processes (high level control, good coupling with distribution/emission systems)
- High temperature heat pumps for waste heat recovery
- Integration in smart grids (“smart grid ready”)

Vapor compression heat pumps
Integration in industry

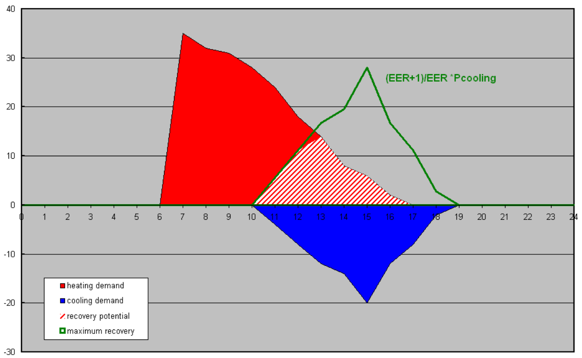


Vapor compression heat pumps

Vapor injection heat pumps

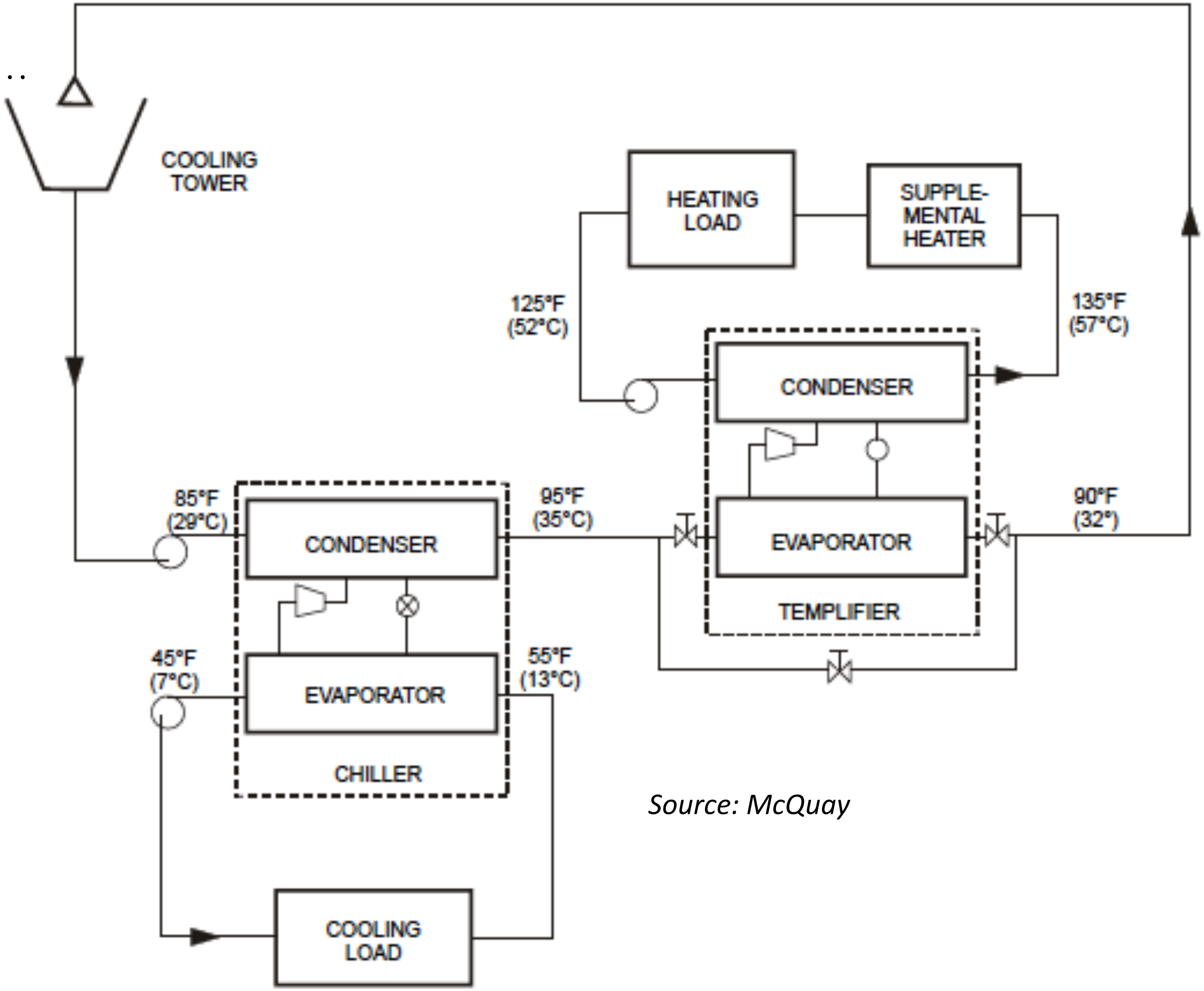
Simultaneous Heating/cooling…

Often chillers and boilers are working simultaneously



Source: IEA ECBCS Annex 48

Source: Baltimore Aircoil



Source: McQuay

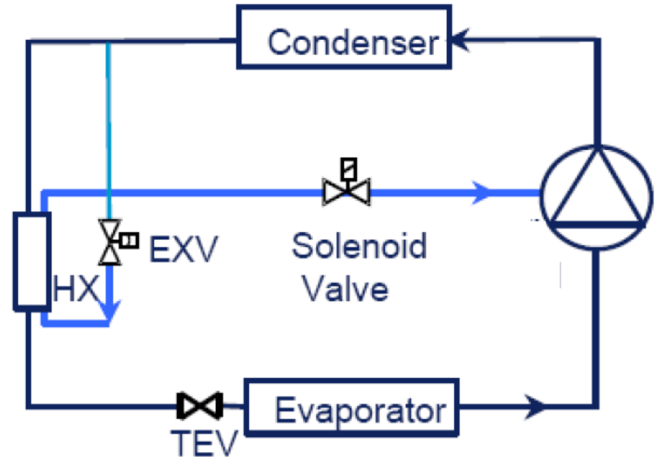
Vapor compression heat pumps

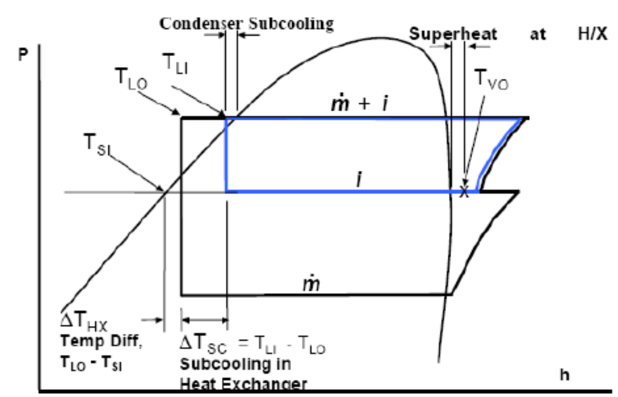
Vapor injection heat pumps

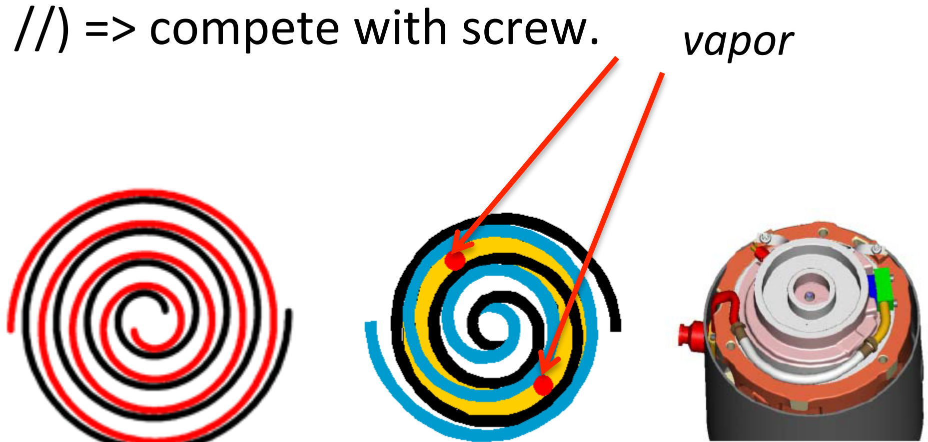
- For high temperature lift, vapor injection heat pumps are suitable (it increases the performance and decreases the discharge temperature)
- Vapor injection in scroll compressor combined with variable speed is the SoA

  But still improvement in the control.

- Note that scroll compressor capacity increase (and several compressors can be used in //) => compete with screw.







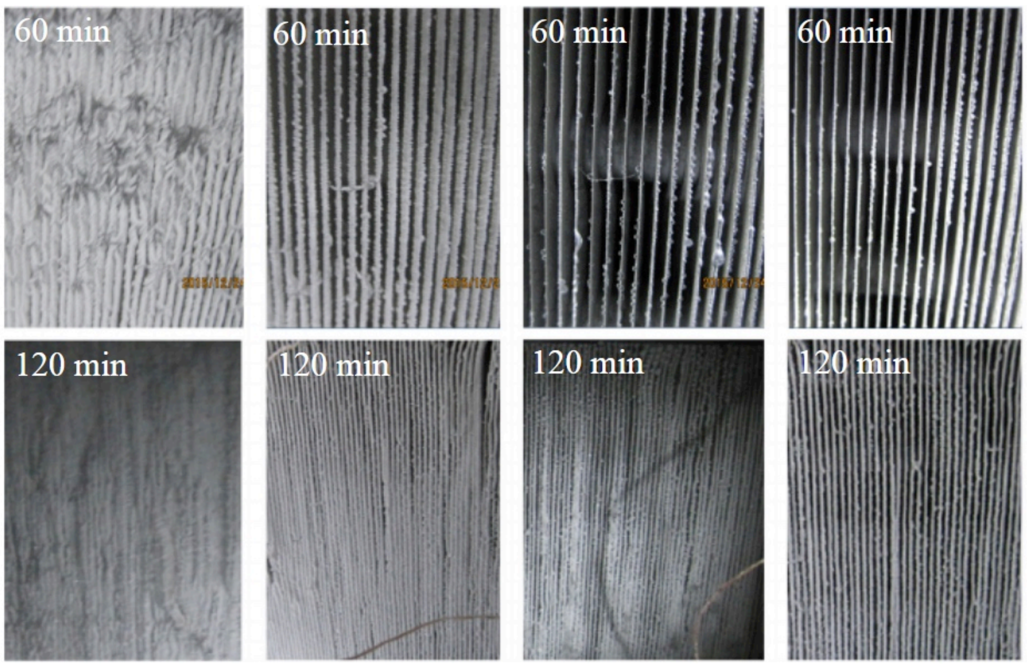
Vapor compression heat pumps

Frost limitation on evaporators

Not fully related to WHR, but interesting "hot" topic: coatings for frost formation limitation

(Wang et al., 2018)

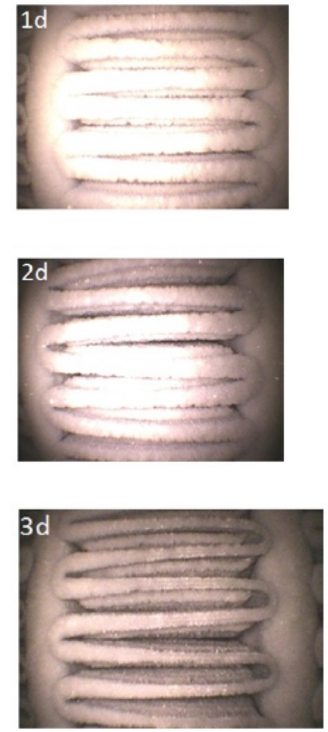
Super-hydrophobic coating



0 m/s 5 m/s 10 m/s 15 m/s

↗ velocity

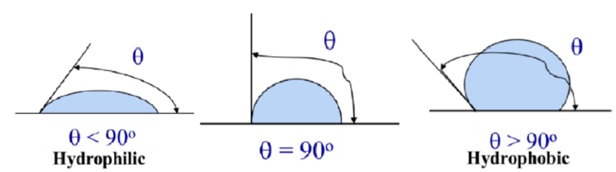
↘ frost layer thickness



neutral

hydrophilic

hydrophobic



(Simpson, 2015)

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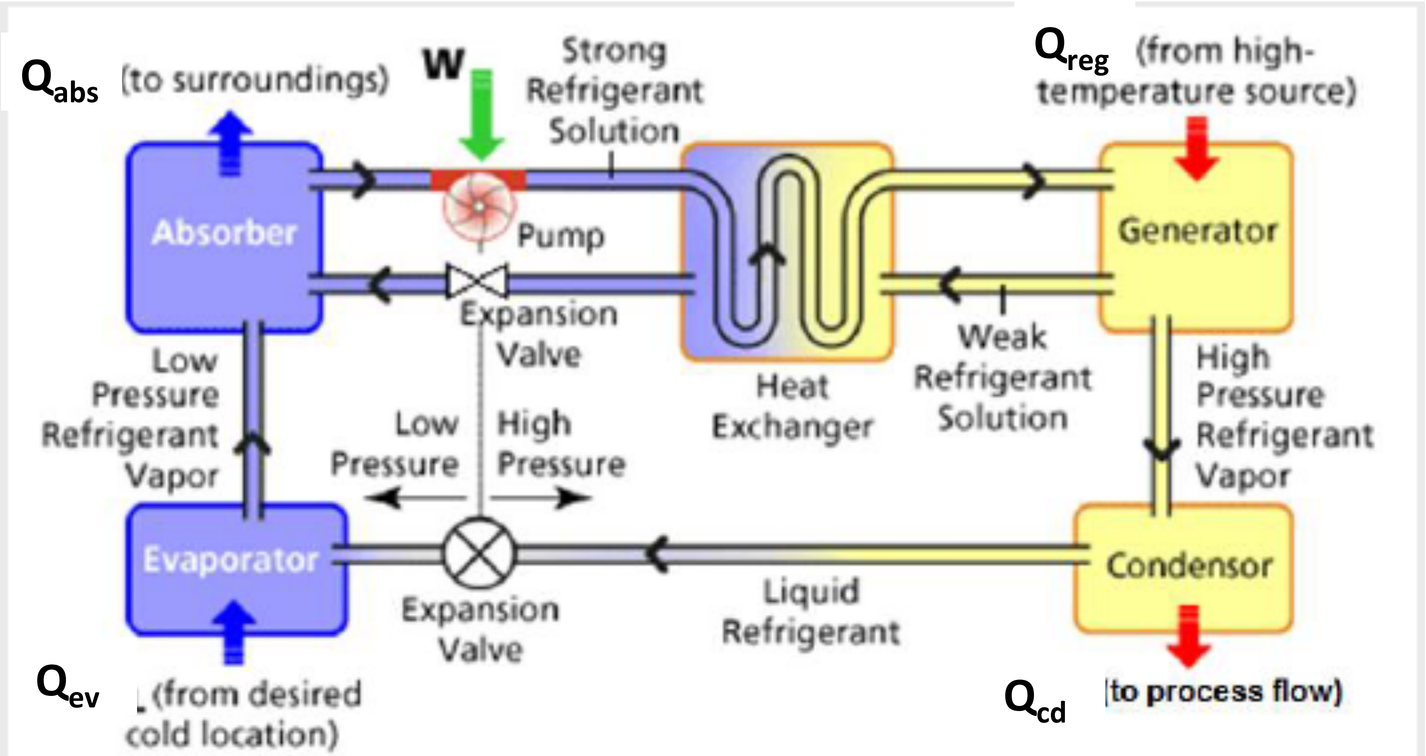
Absorption heat pumps

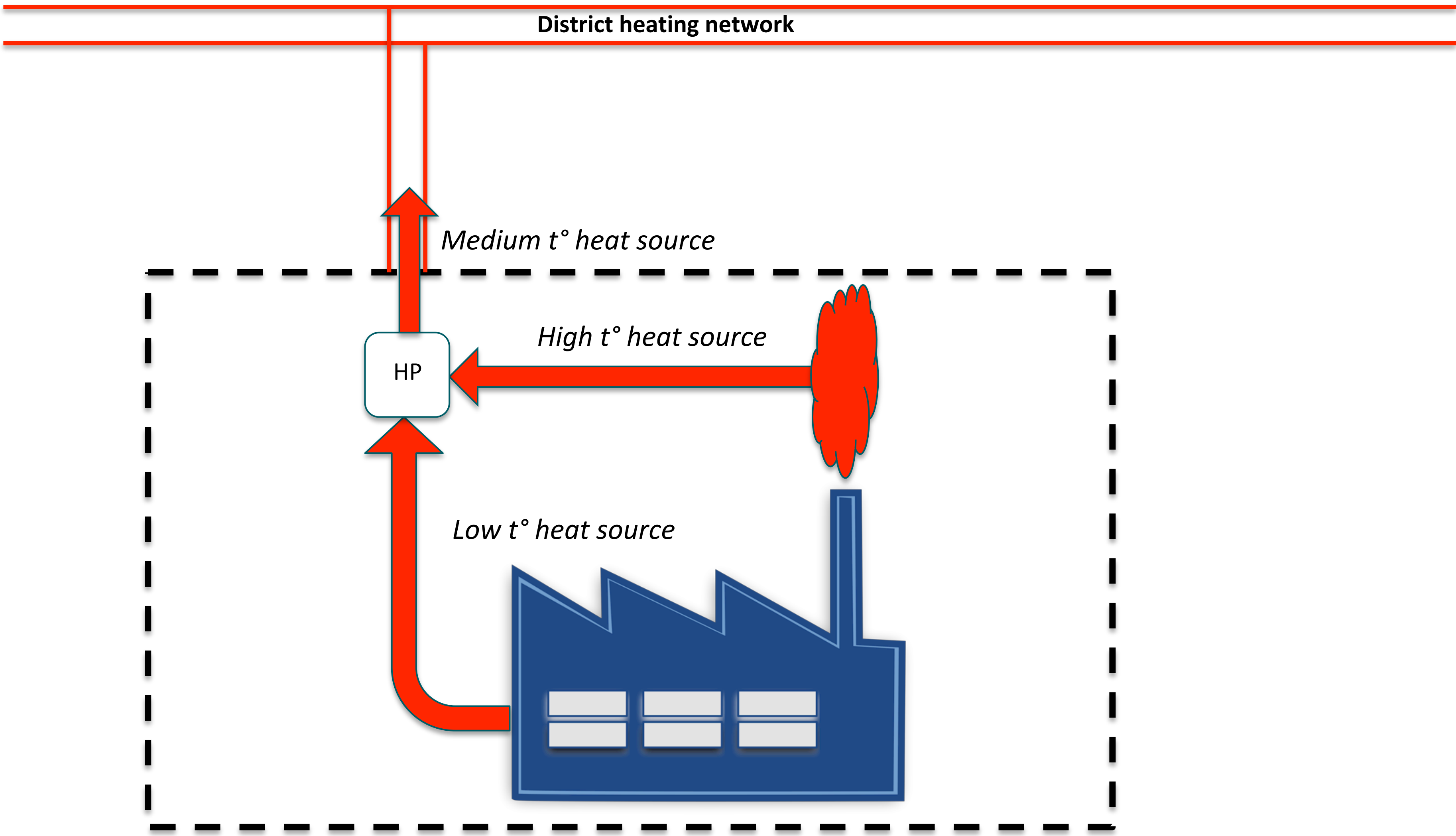
Working principle



$$COP = \frac{\dot{Q}_{cd} + \dot{Q}_{abs}}{\dot{Q}_{reg}}$$

Absorption heat pumps

Integration in industry

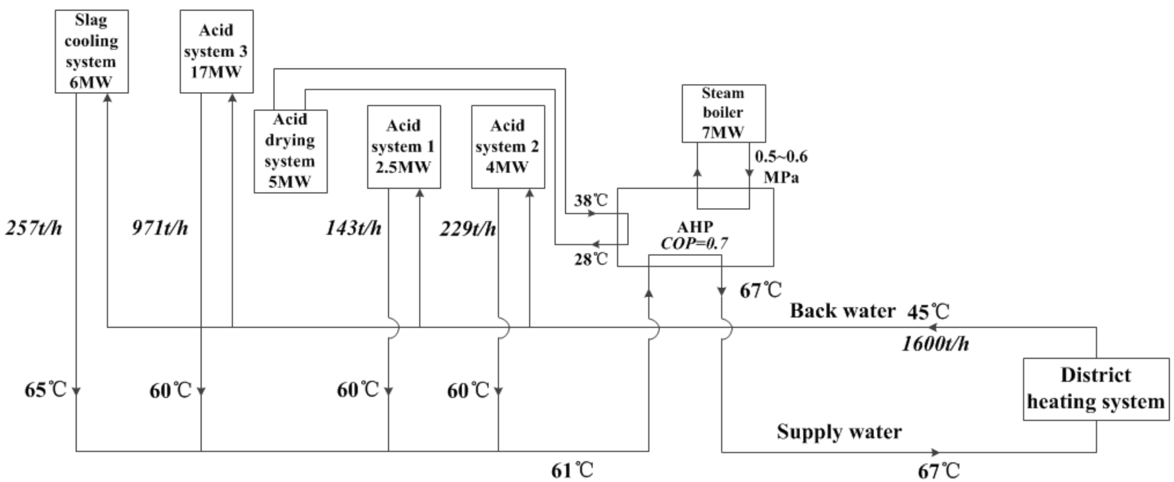


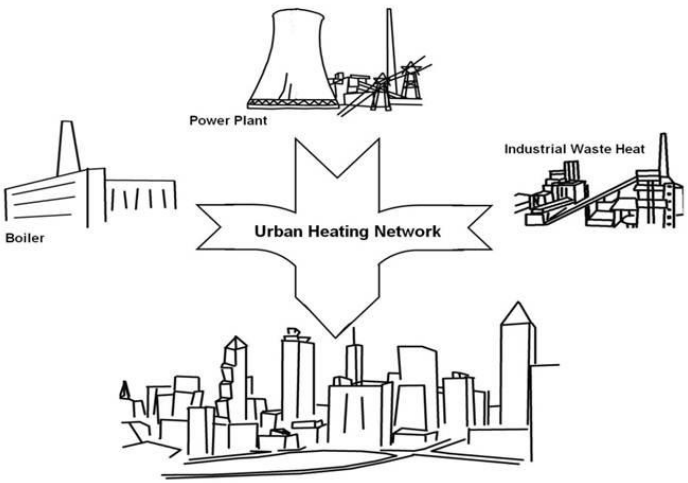
Absorption heat pumps

Residential applications of absorption heat pumps

Example: District heating network of city of Chiffeng (Mongolia): 4.6 millions habitants

- The capacity of the district heating network doesn't cover anymore the increasing heating demand.
- Low temperature heating demand of the plant (domestic hot water) often lower than heat rejection.
- The district heating network, initially connected to CHP units/boilers , now recovers the heat from a copper foundry and from a cement plant.





Source: BERC Tsinghua University

Absorption heat pumps

Residential applications of absorption heat pumps

HEATING MODE (1)

ErP enegy class (55 °C application)			**A++**
Working point A7/W35 (2)	G.U.E. gas utilization efficiency (3)	%	169
	heating capacity	kW	18.9
Working point A7/W50 (4)	G.U.E. gas utilization efficiency (5)	%	157
	heating capacity	kW	17.6
Max outlet water temperature	heating	°C	65
	domestic hot water (DHW)	°C	70

Source: Robur K18

Absorption heat pumps (absorption machine + gas burner) have also applications in buildings.

- Tests will start in our laboratory to measure performance performance outside nominal operating conditions (t° air<7°C)
- In situ monitoring in houses

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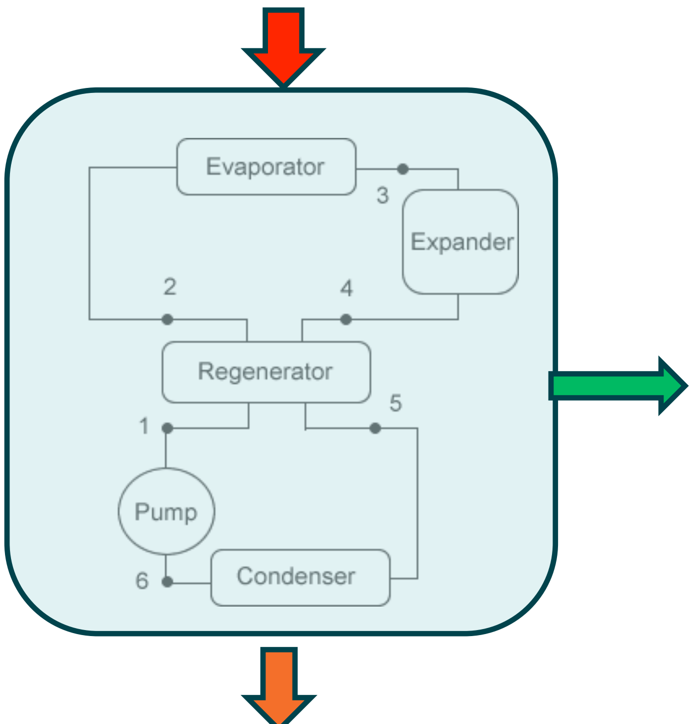
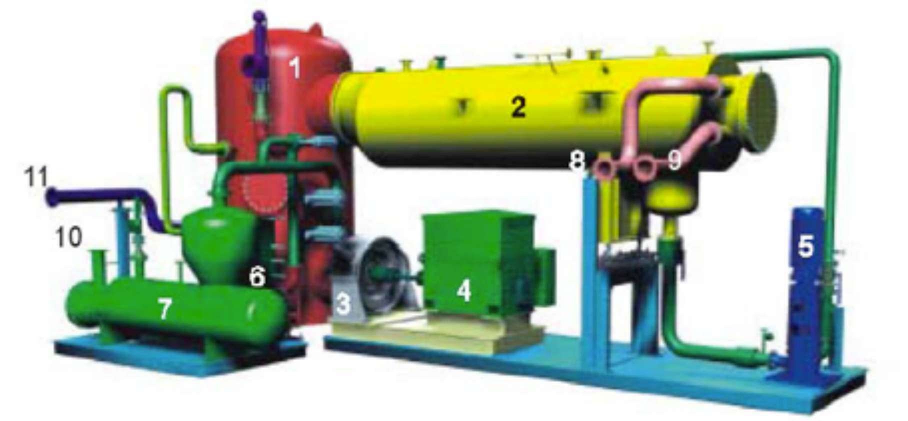
Organic Rankine Cycles
Working principle

Waste heat recovery or renewable energies: solar, biomass, geothermal



Electricity/ mechanical power

Heat



1 Regenerator
2 Condenser
3 Turbine
4 Electric generator
5 Circulation pump
6 Pre-heater
7 Evaporator
8 Hot water inlet
9 Hot water outlet
10 Thermal oil inlet
11 Thermal oil outlet

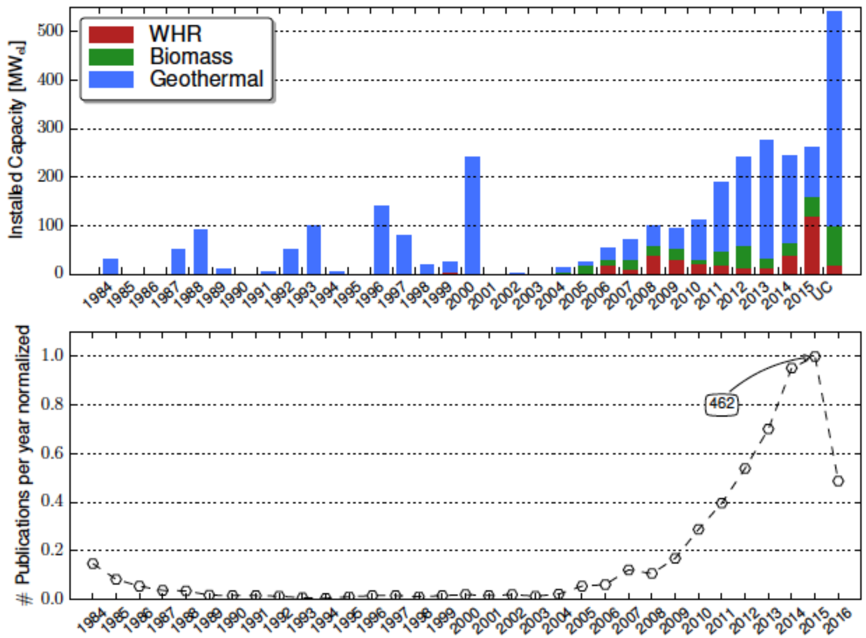
- External combustion engine
- CHP operation by recovering heat from the condenser

Organic Rankine Cycles

Context and challenges

Context

- Large regain of interest for ORC
- External combustion engine: can valorize a wide range of heat sources: biomass CHP, waste heat recovery (and solar)

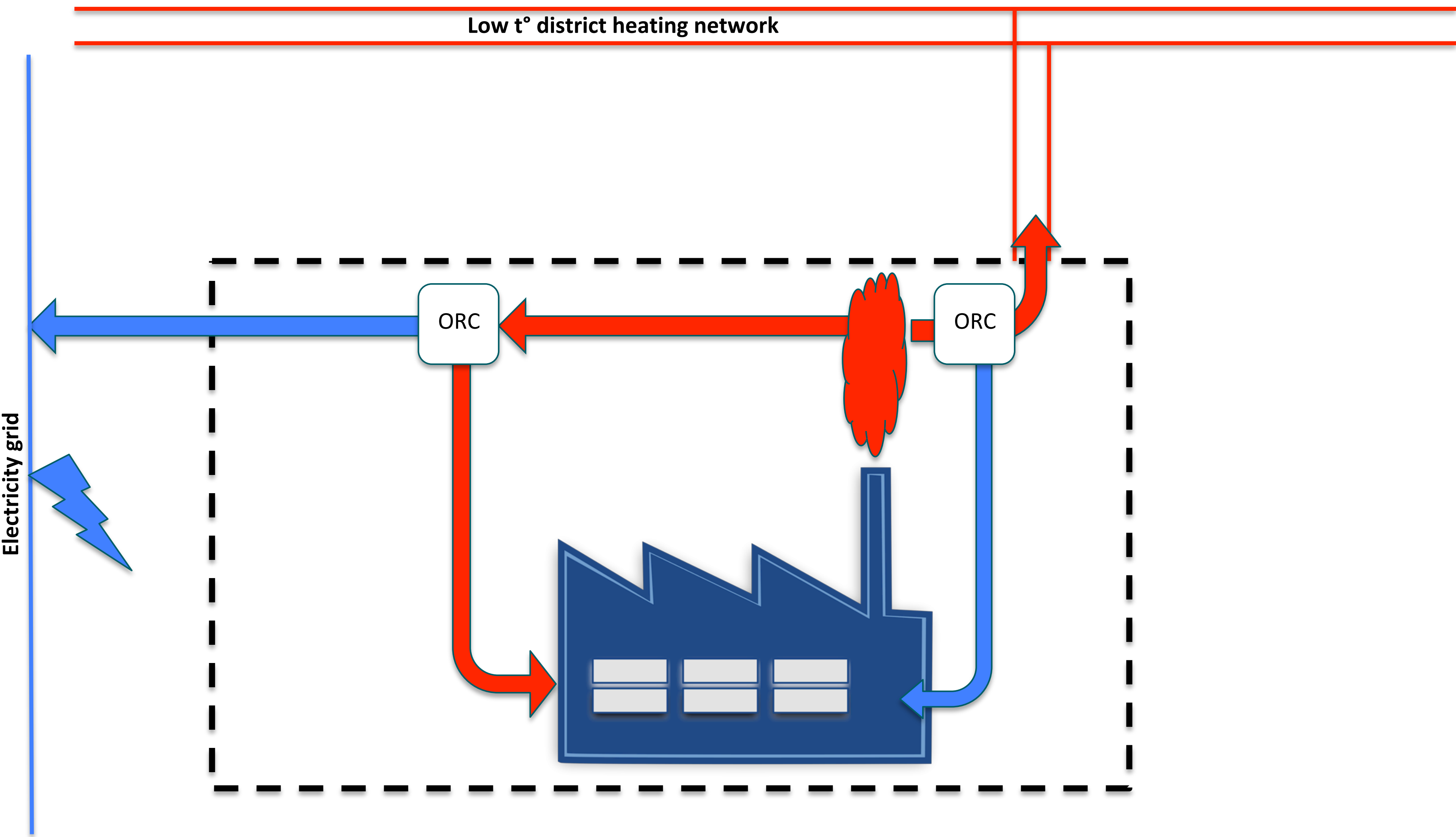


Technical challenges in industry

- Recovering heat without impacting process
- Increase ORC performance (€):
  - Innovative architecture, optimized components, pumpless, improved control…
- Increase robustness/reliability

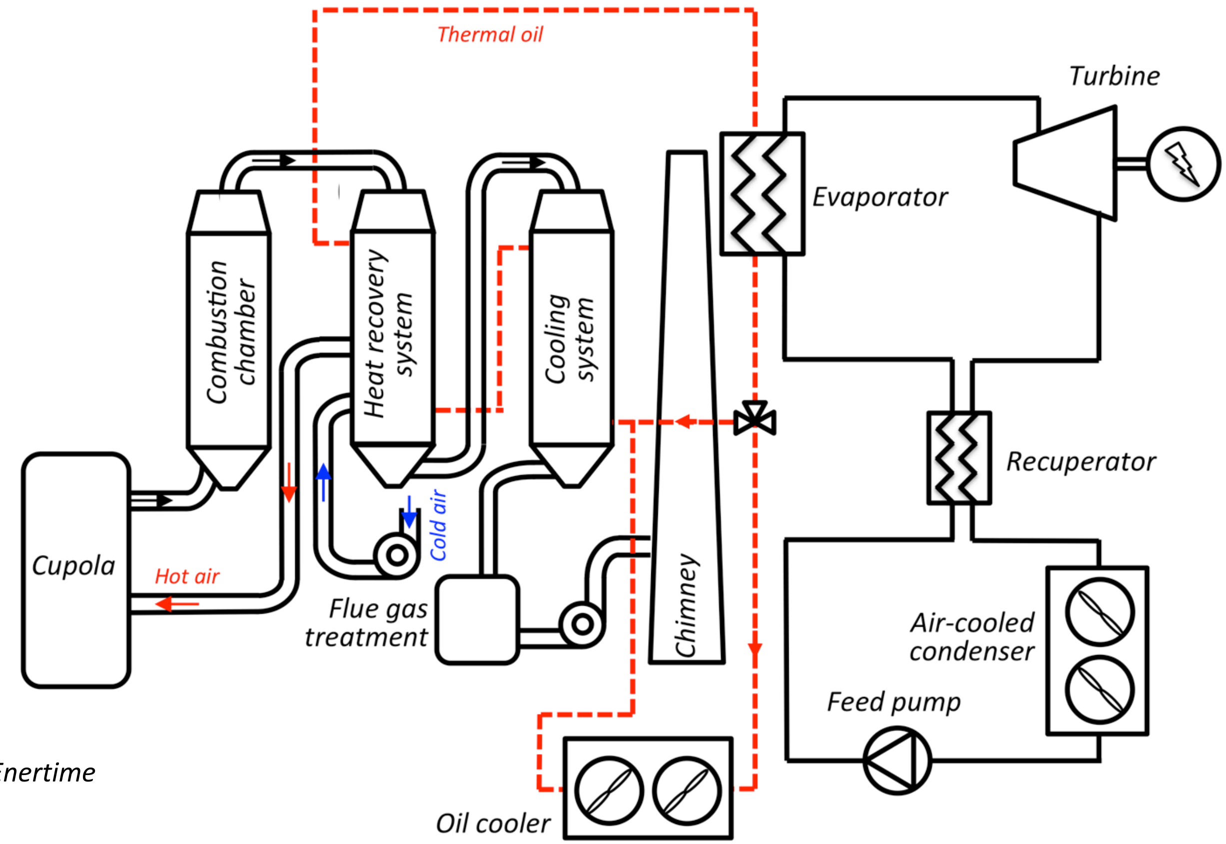
Organic Rankine Cycles

Integration in industry



Organic Rankine Cycles

Integration in industry

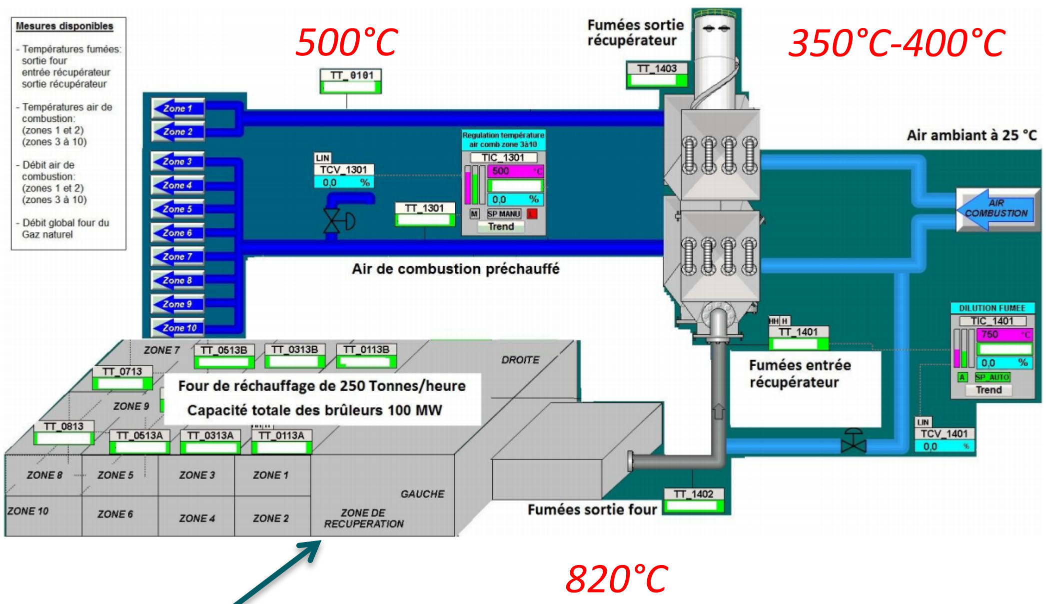


Source Enertime

- ✧ 5.6 MW_{th} recovered from exhaust gases
- ✧ Net power production: 870 kW_e
- ✧ 30 % of the factory electricity consumption can be covered by the ORC

Organic Rankine Cycles

Waste heat recovery from slab reheating furnace



Source: Comeca

- Gas consumption: 350 kWh per ton of produced steel.
- Furnaces are already equipped with a heat recovery heat exchanger
- 25-35% lost in fumes.
- Additional potential of waste heat recovery through ORC.

http://www.labothap.ulg.ac.be/cmsms/index.php?page=orcal

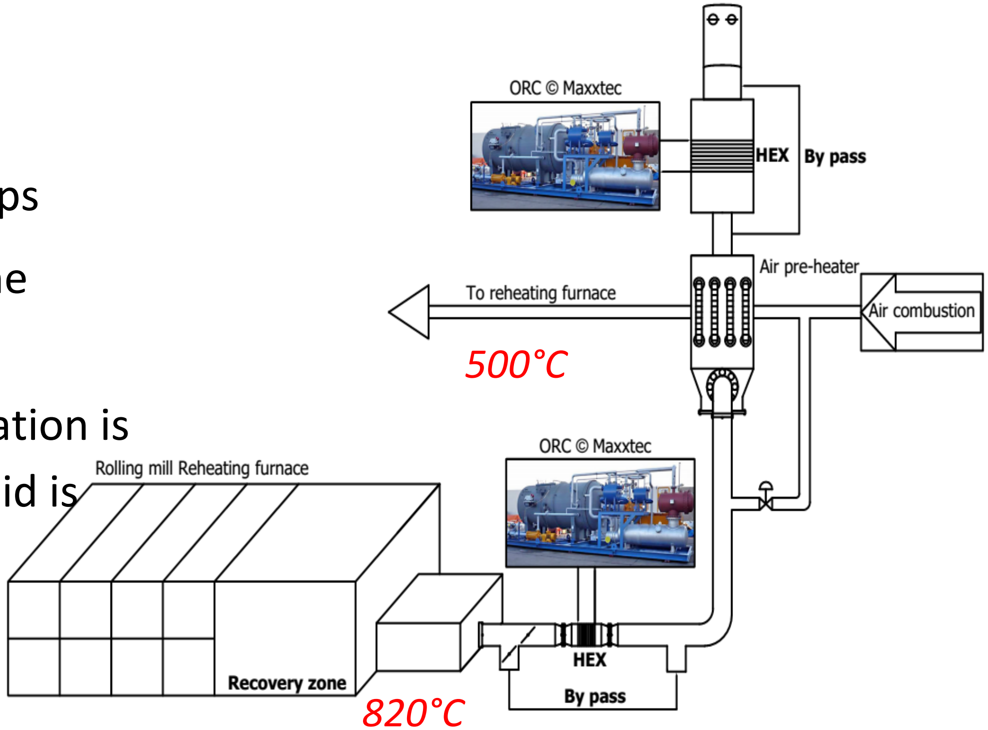
Organic Rankine Cycles

Waste heat recovery from slab reheating furnace

- Position of the additional waste heat recovery heat exchanger

- Downwards recuperator:
  - ✔ Direct evaporation is feasible (no intermediate fluid)
  - ✖ Heat transfer under a low ΔT: large heat transfer area and pressure drops

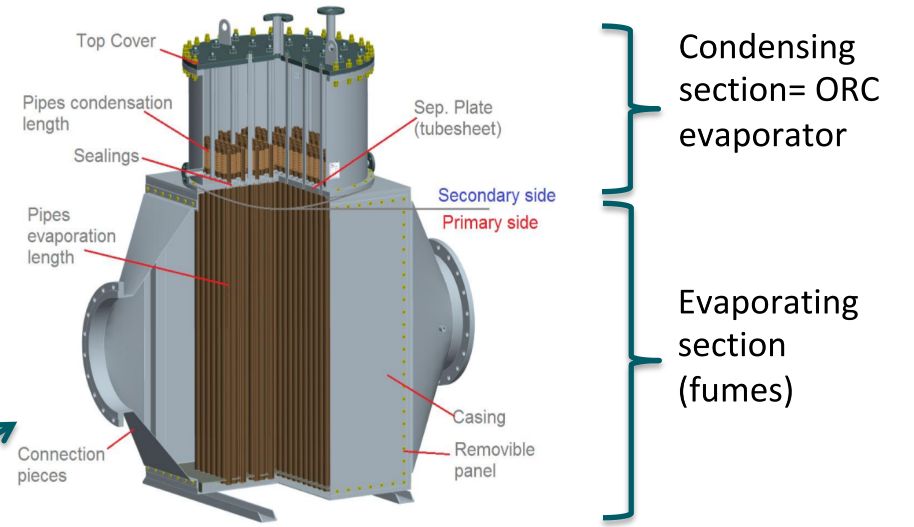
- Upwards recuperator:
  - ✔ Large ΔT: limitation of pressure drops
  - ✖ Temperature drop ➔ sizing again the recuperator
  - ✖ High temperature ➔ direct evaporation is impossible /choice of the heat carrier fluid is limited



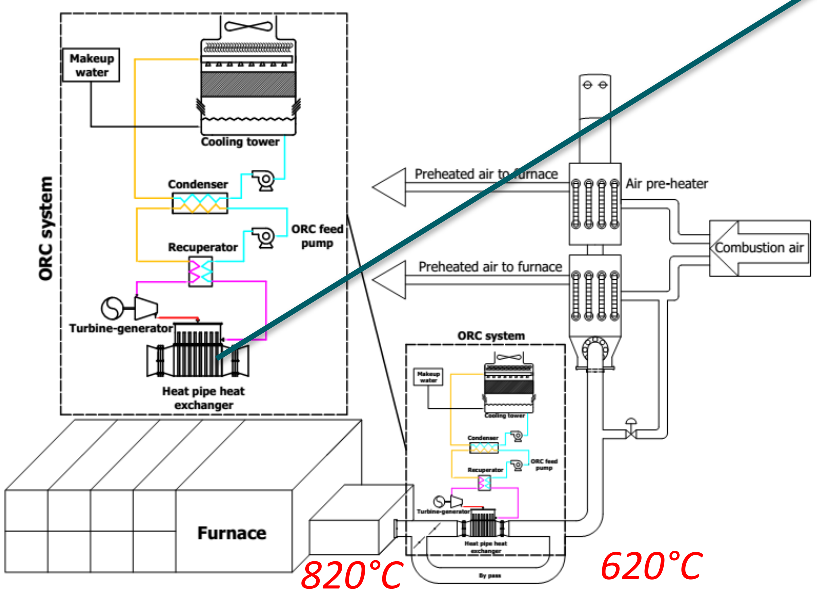
Organic Rankine Cycles

Waste heat recovery from slab reheating furnace

- Use of gravity heat pipes (« thermosyphons »)
  - ✓ Natural heat carrier fluid
  - ✓ Low temperature gradient
  - ✓ Low cost, few maintenance, compact, reliable
  - ✓ Now circulating pump



Source: Amini A., 2013

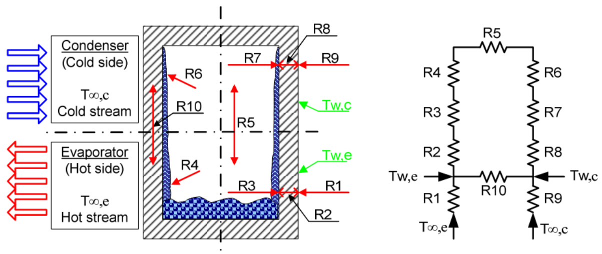


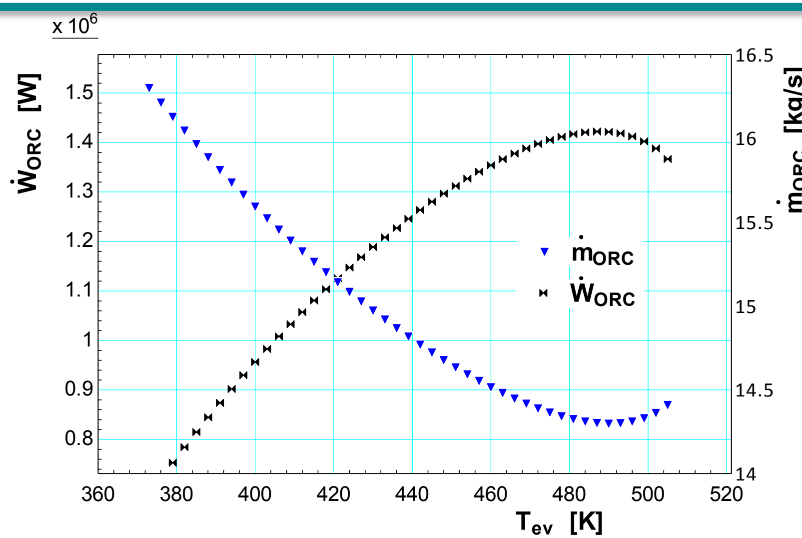
- Use of an ORC vs steam cycle: more interesting economically and thermodynamically

Organic Rankine Cycles

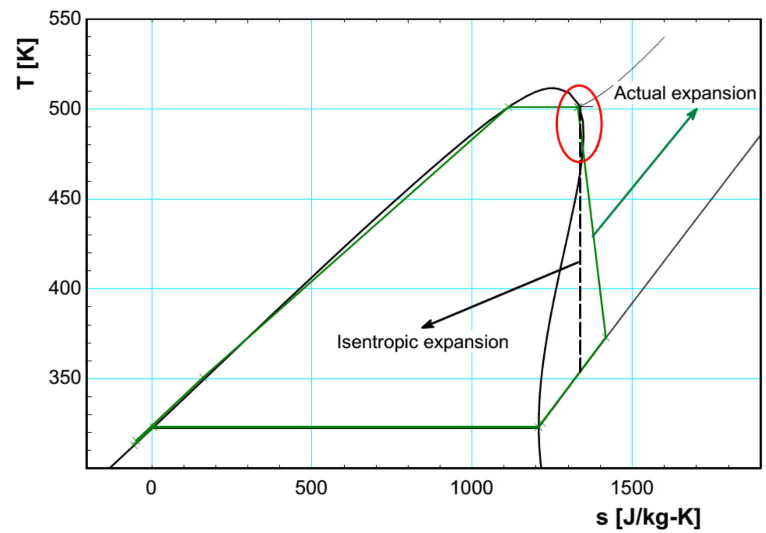
Waste heat recovery from slab reheating furnace

- Sizing of heat pipes (heat transfer limitations are taken into account), selection of fluid (water)/material (water)





- Pre-sizing of ORC: use of cyclopentane, turbine, recuperator hex
- Assessed performance:
  - ✓ 7,435 MWth recovered
  - ✓ 1.42 MWe produced
  - ✓ ORC efficiency: 19.1%
  - ✓ Payback > 4 years

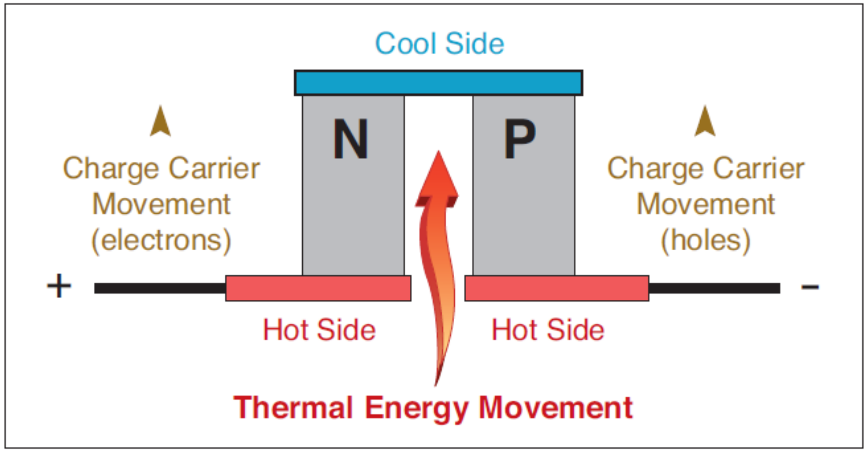


Organic Rankine Cycles

Waste heat recovery from slab reheating furnace

- Experimental set-up to investigate the ORC fluid evaporation in the annular section around the heat pipe condensing section.

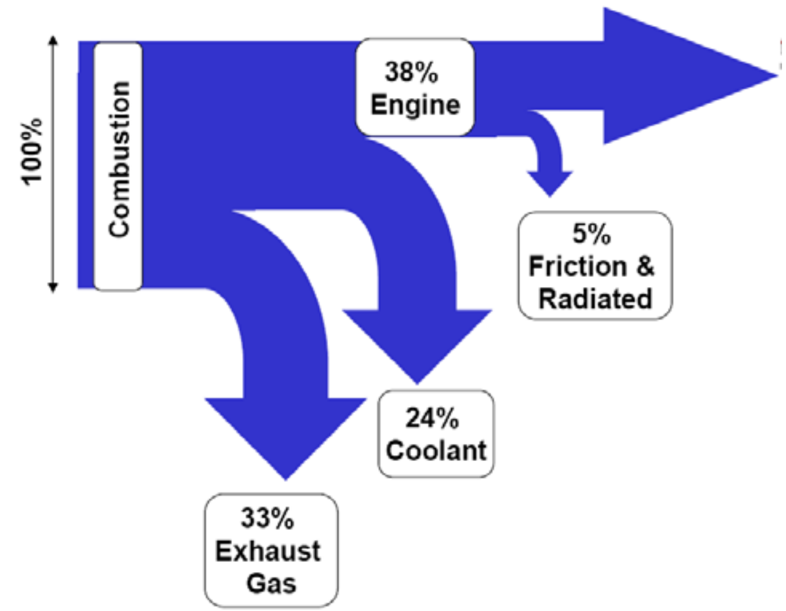
- Other project dealing with the connection of heat pipes and Thermoelectric generators (TEG)

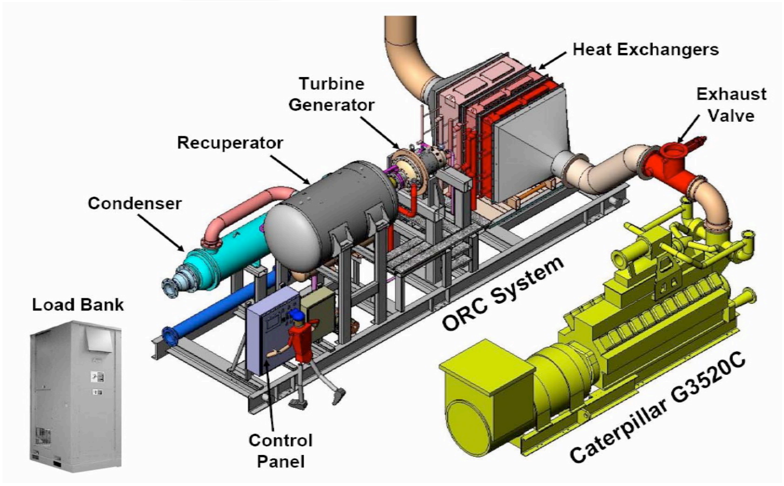


Organic Rankine Cycles

Waste heat recovery from internal combustion engines

- ORC systems can be used to upgrade the performance of internal combustion engines CHP plants.
- Current research on mobile applications (marine ships, trucks, cars) could be a driver.





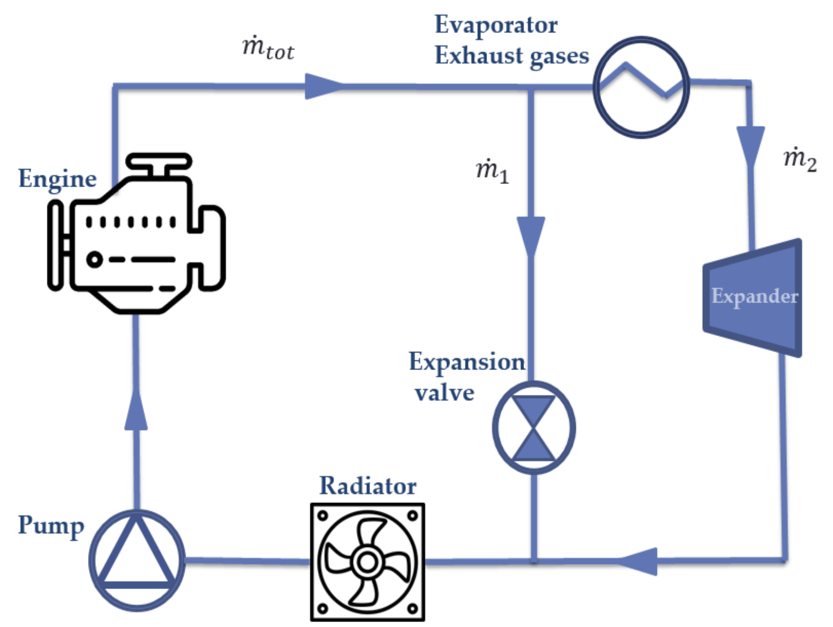
Organic Rankine Cycles

Waste heat recovery from internal combustion engines

<u>Current research on passenger car with potential applications for CHP</u>:

- Price of (O)RC systems are still too large for being installed on cars
- Other constraints than on trucks: weight, volume, additional working fluid,…
- Both engine coolant and exhaust gas show pros and cons
- New idea: combine the Rankine cycle and the engine coolant loop.
- (Rem: by-pass m1 is necessary to ensure enough engine cooling and to optimize the expander supply state).

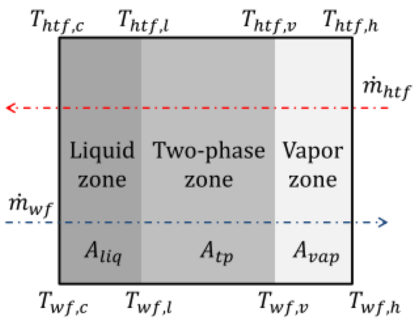
Architecture	Exhaust gas (EG)	Cooling Engine (CE)
Energy on a driving cycle	-	+
Part load performance	-	+
Pumping losses produced with the additional heat exchanger in the exhaust gases	-	+
Higher temperature (exergy/efficiency)	+	-
Cold start	+	-

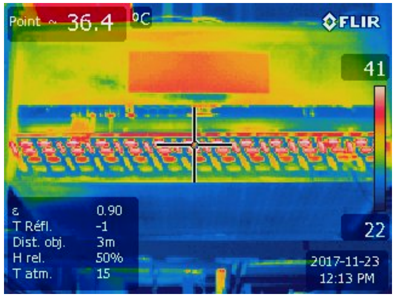


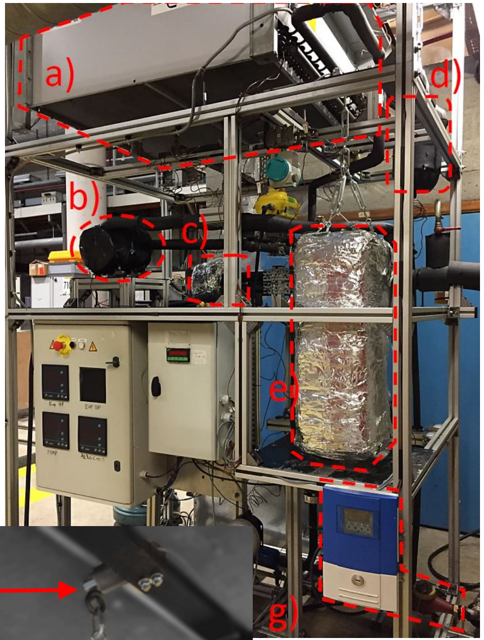
Organic Rankine Cycles

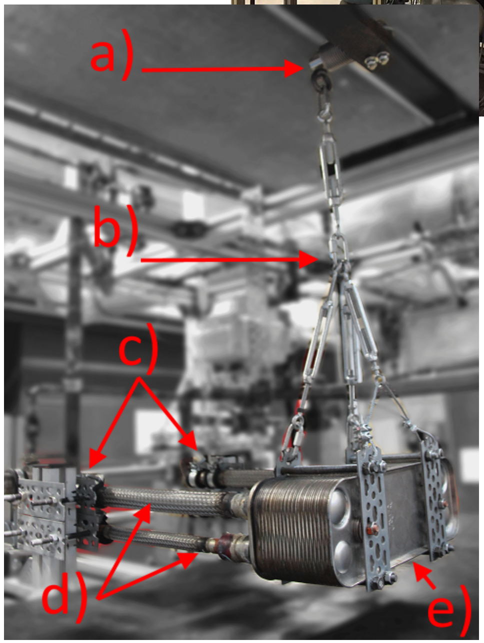
Working fluid repartition in small-scale ORC systems

- Versatile nature of the operating conditions of ORC systems (**off-design**)
- Both energy and **mass balances** must be taken into account to correctly describe the off-design performance.





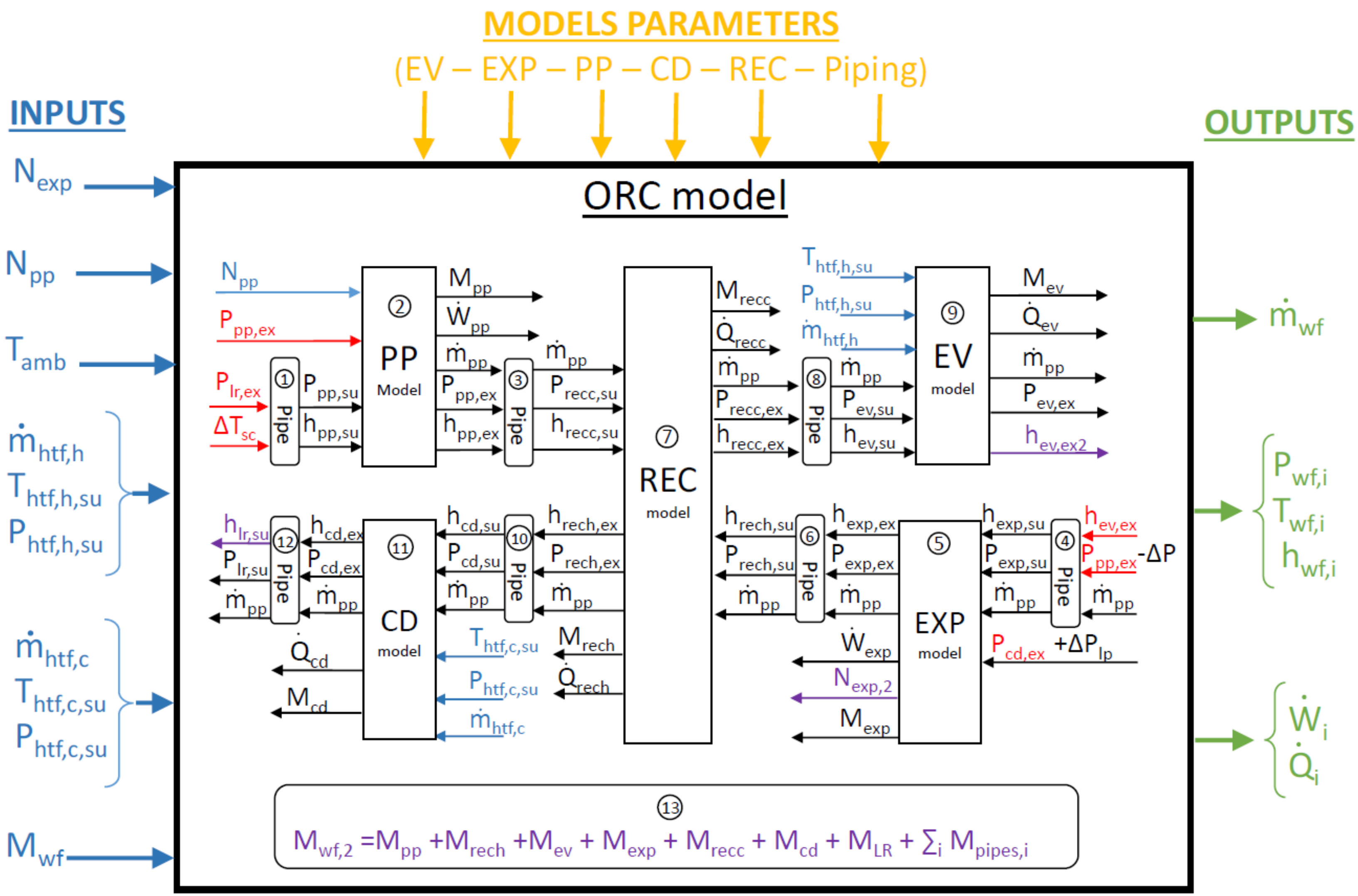




- Limited literature on repartition of fluid among components.
- **Online measurement method** versus quick closing of valve (major components are hung to loads cells)
- Calibration of the measurement apparatus to account for operating **pressure**

Organic Rankine Cycle

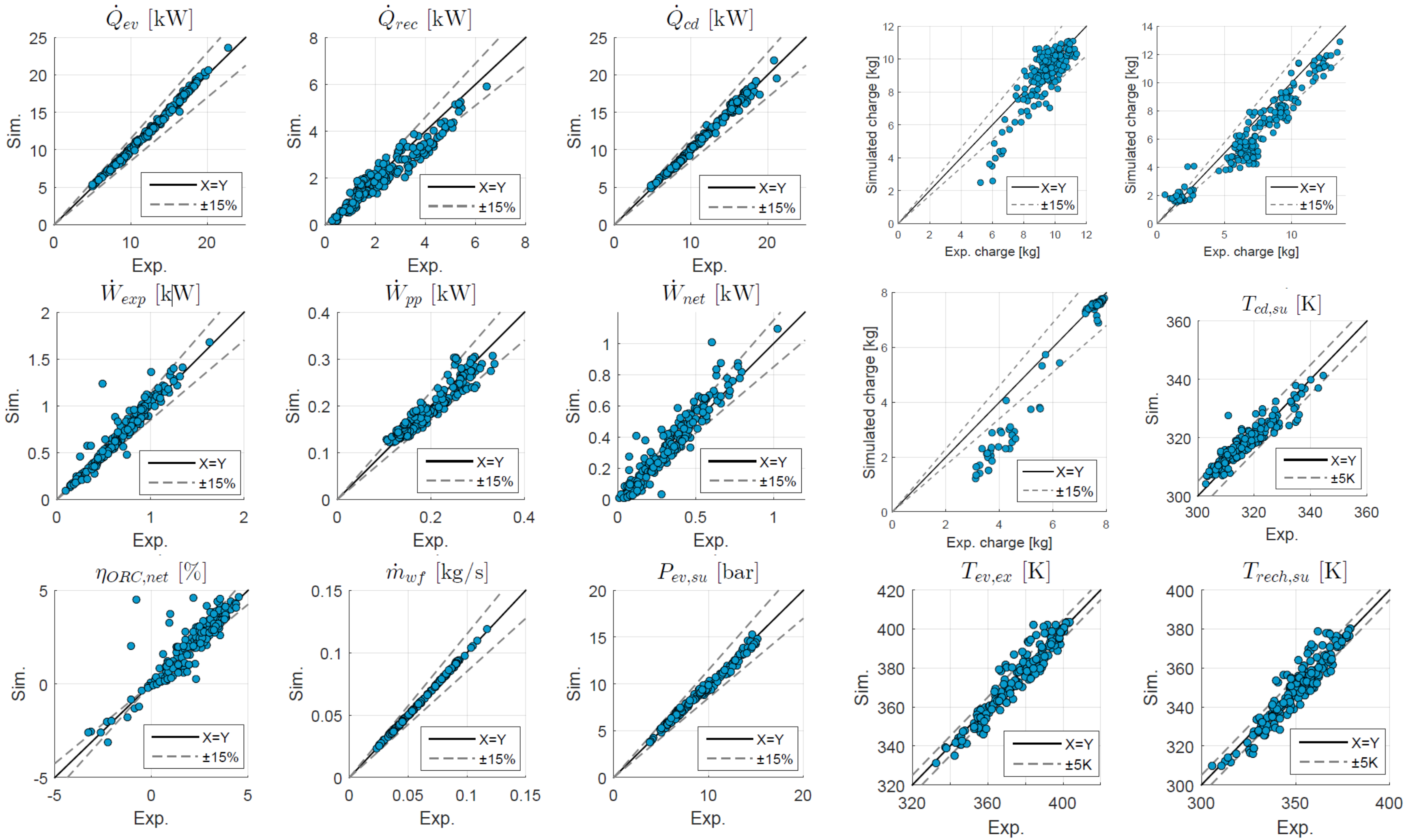
Working fluid repartition in small-scale ORC systems



Organic Rankine Cycle

Working fluid repartition in small-scale ORC systems

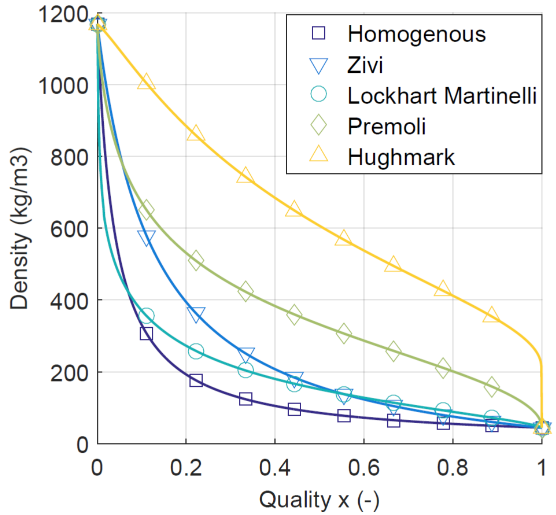
Variation of the working fluid charge, heat source supply temperature/flow rate, working fluid flow rate => 304 points

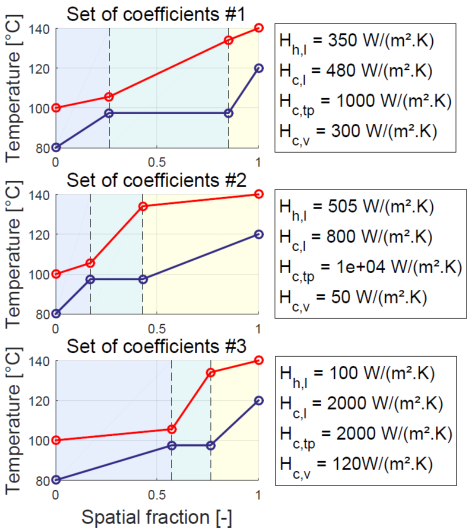


Organic Rankine Cycle

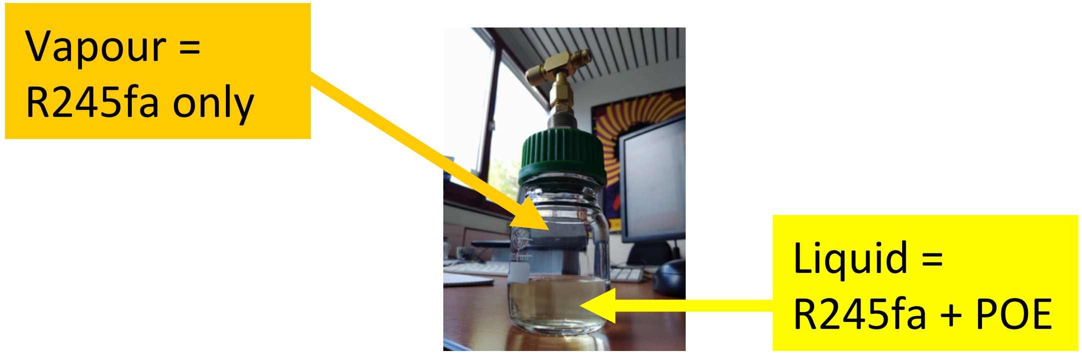
Working fluid repartition in small-scale ORC systems

- Measurements are also used to
  - ✓ improve void fraction and heat transfer models



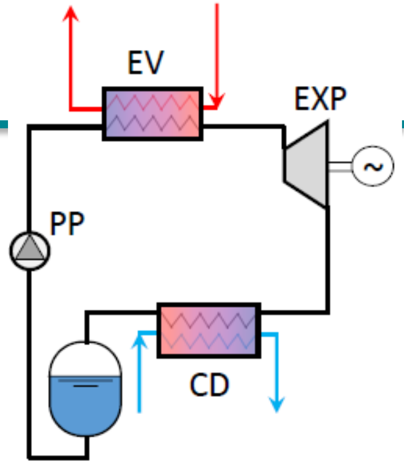


  - ✓ Better characterize the impact of oil on the working fluid state

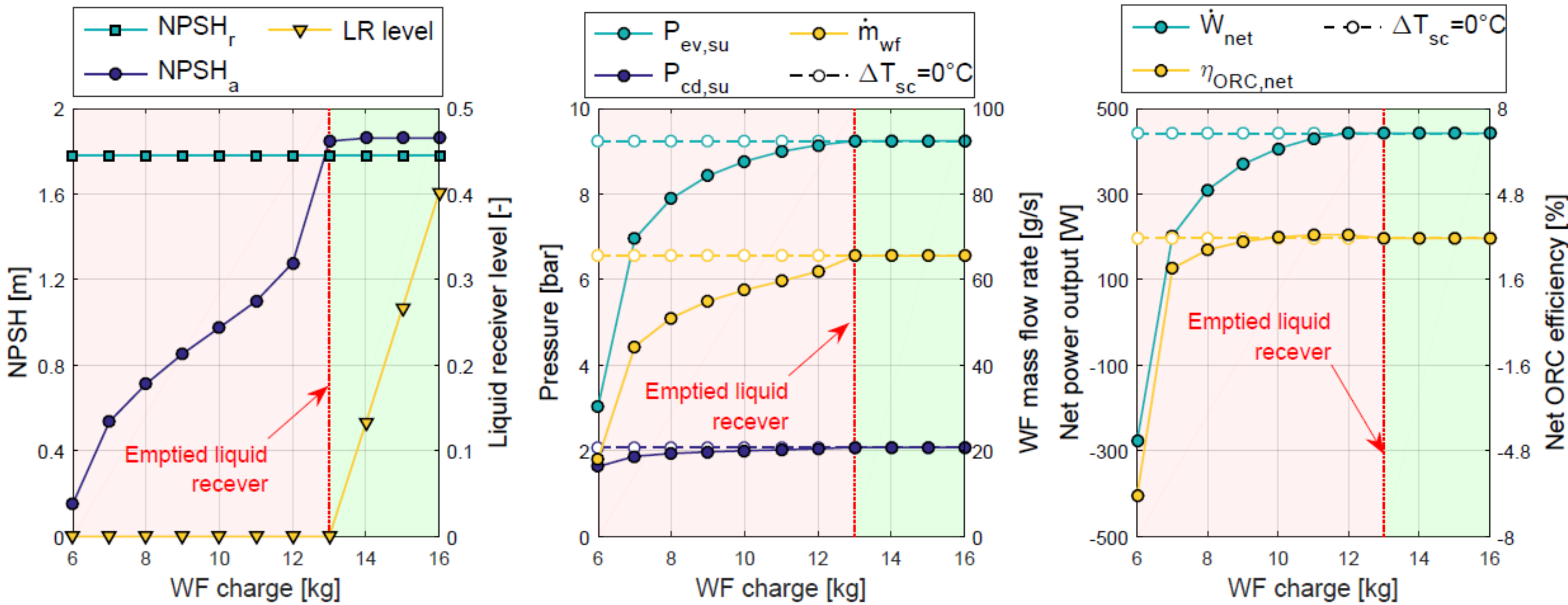


Organic Rankine Cycles

Working fluid repartition in small-scale ORC systems

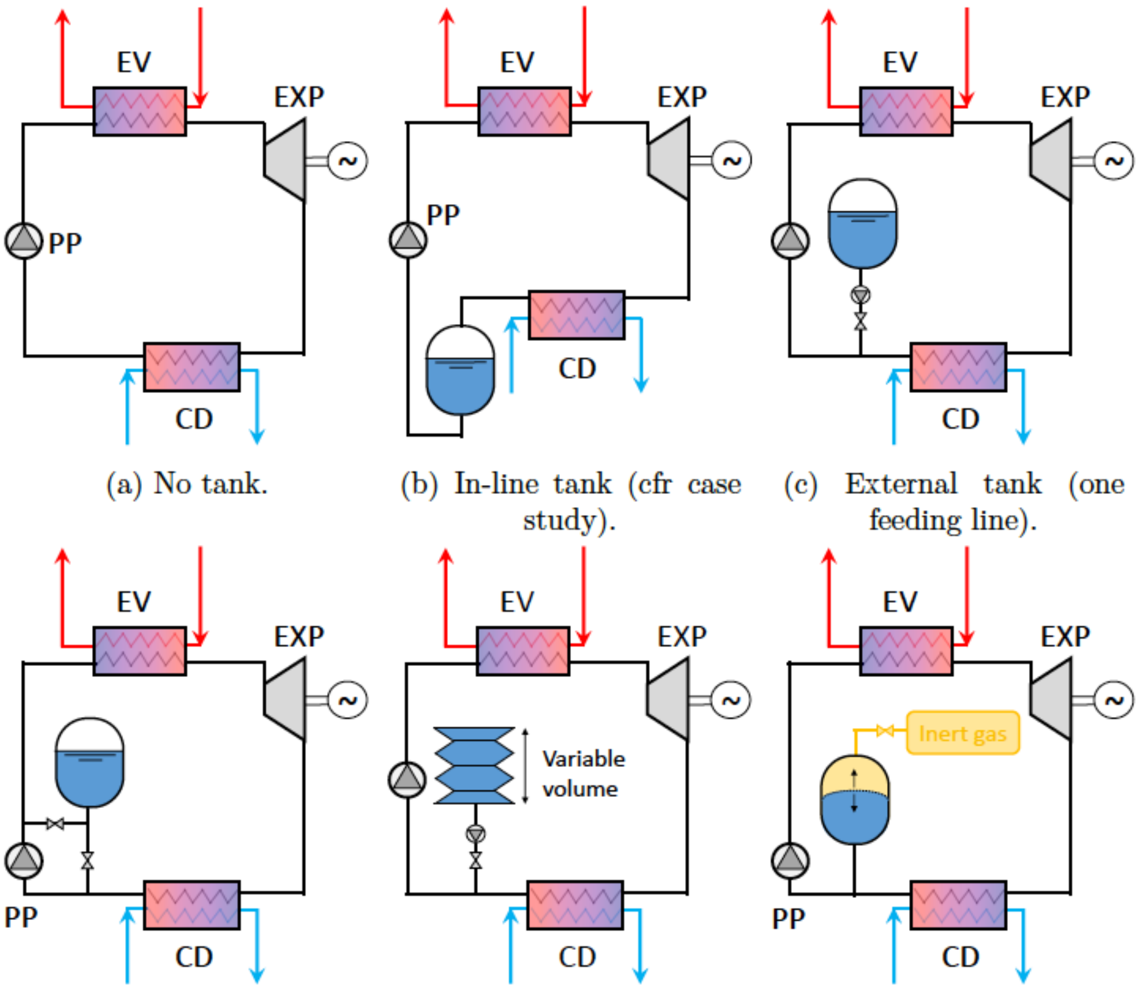


Identification tools for conditions where the reservoir gets emptied!



Organic Rankine Cycles

Working fluid repartition in small-scale ORC systems



(a) No tank.

(b) In-line tank (cfr case study).

(c) External tank (one feeding line).

(d) External tank (dual feeding lines without feeding pump).

(e) External tank (with variable volume).

(f) Two-chamber pressure-regulated tank.

- In (a): subcooling increased by decreasing condensing pressure…
- A receiver ((b) to (f)) removes the dependency between the condensing pressure and the subcooling (circulating mass flow rate is adjusted) => Better performance
- Active charge methods ((c) to (f)) allows for reduced time response, more control versatility and space savings

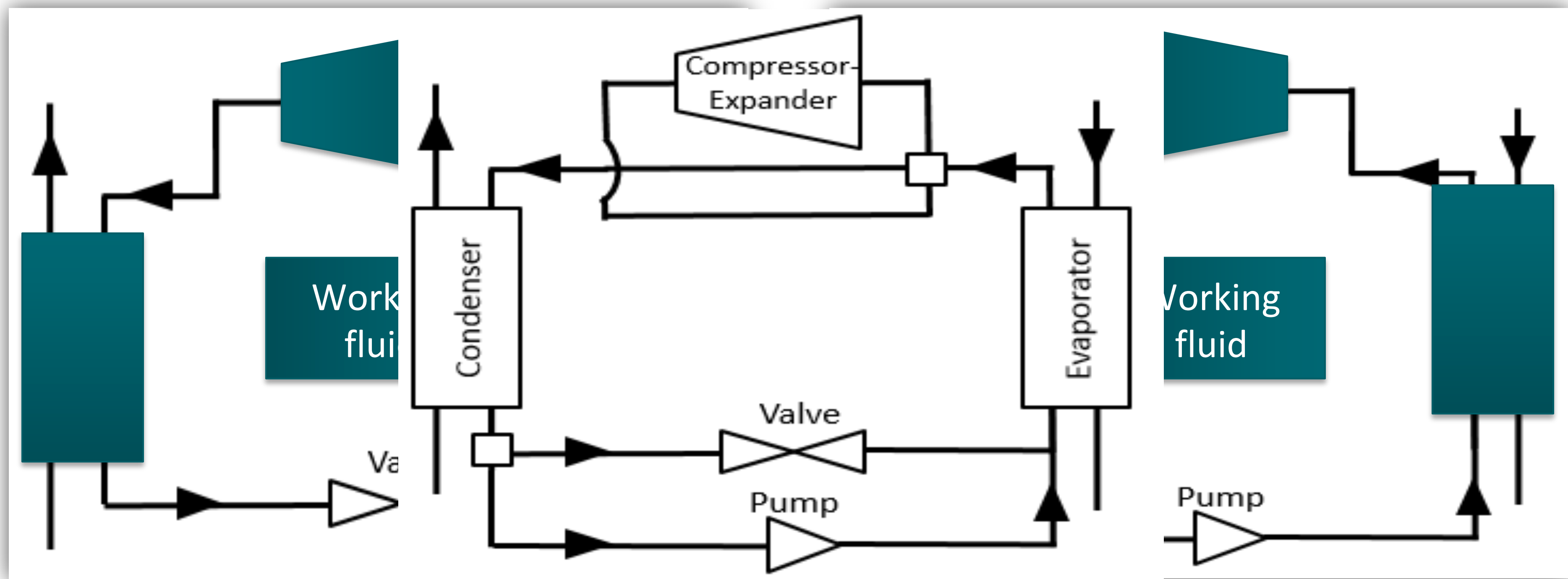
Content of the presentation

1. About our research group
2. Introduction
3. Heat-to-heat with heat exchangers
4. Heat-to-heat with vapor compression heat pumps
5. Heat-to-heat with absorption heat pumps
6. Heat-to-power with (Organic) Rankine Cycle systems
7. **Pumped thermal energy storage**
8. Conclusions

Pumped Thermal Energy Storage

Reversibility of ORC into HP

Heat Pump → ORC → Reversible HP/ORC

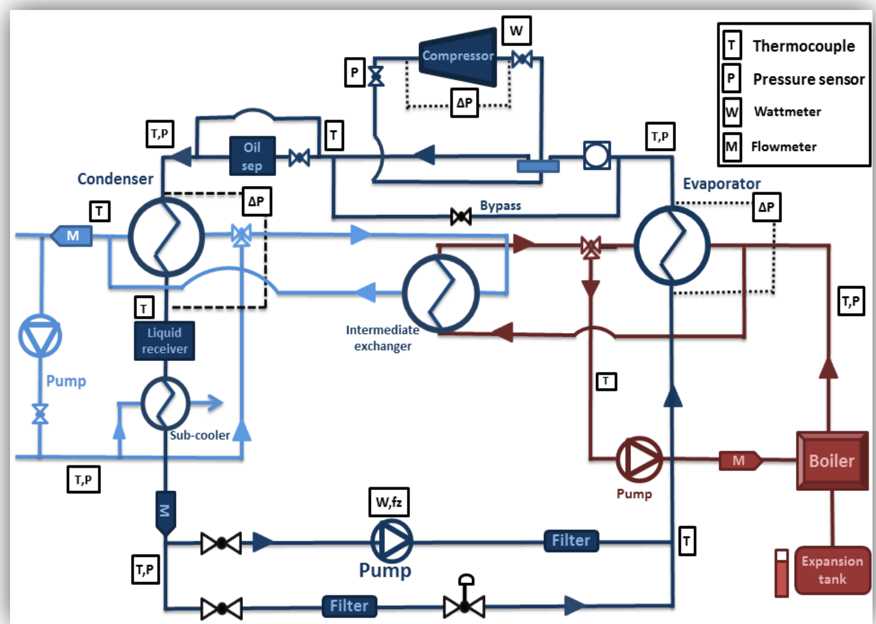


Cheap & flexible the system!

Pumped Thermal Energy Storage

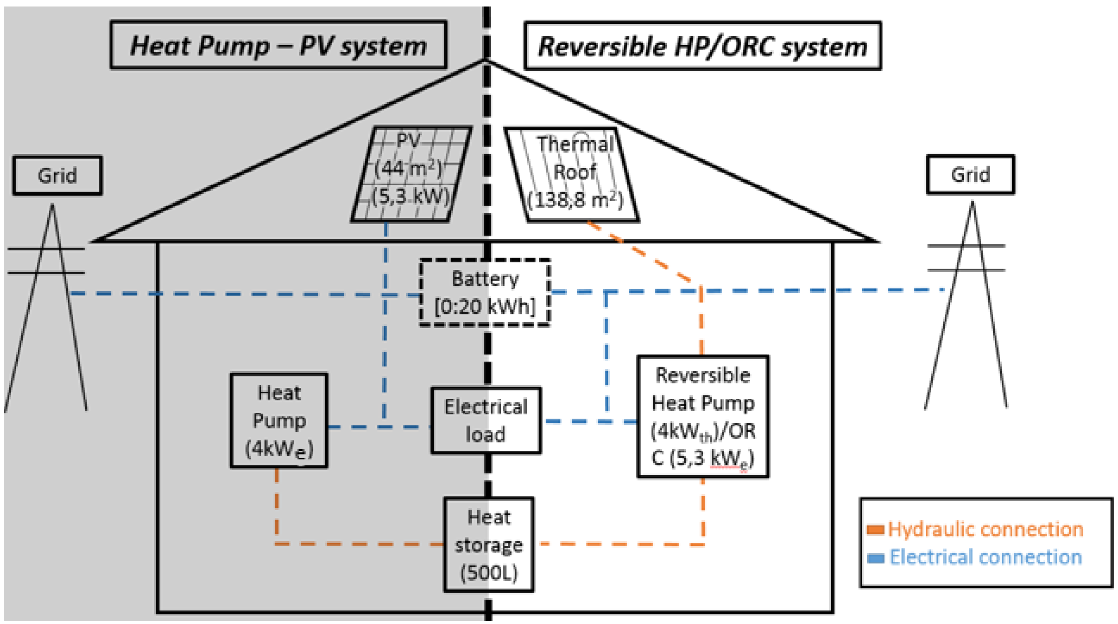
Reversibility of ORC into HP

- 1st prototype:
  - Sized to produce 4030 kWhe per year
  - COP of 4.21 (Tev=21°C/Tcd=61°C)
  - ORC efficiency of 5.7% (Texcd=25°C/ Tsuev=88°C)



Pumped Thermal Energy Storage

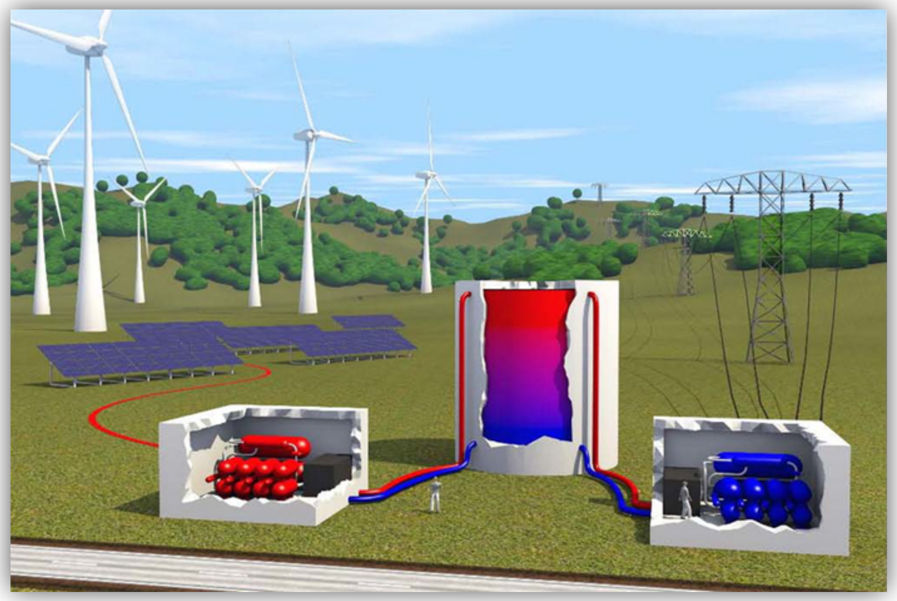
Reversibility of ORC into HP



- Initially, the HP/ORC system (coupled to solar collectors) was seen as an alternative to PV panels+HPs… but not economically profitable.
- Pumped Thermal Energy Storage (PTES) seems a better application

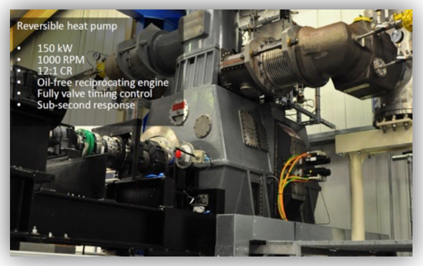
Pumped Thermal Energy Storage

Working principle



BOSCH

Google



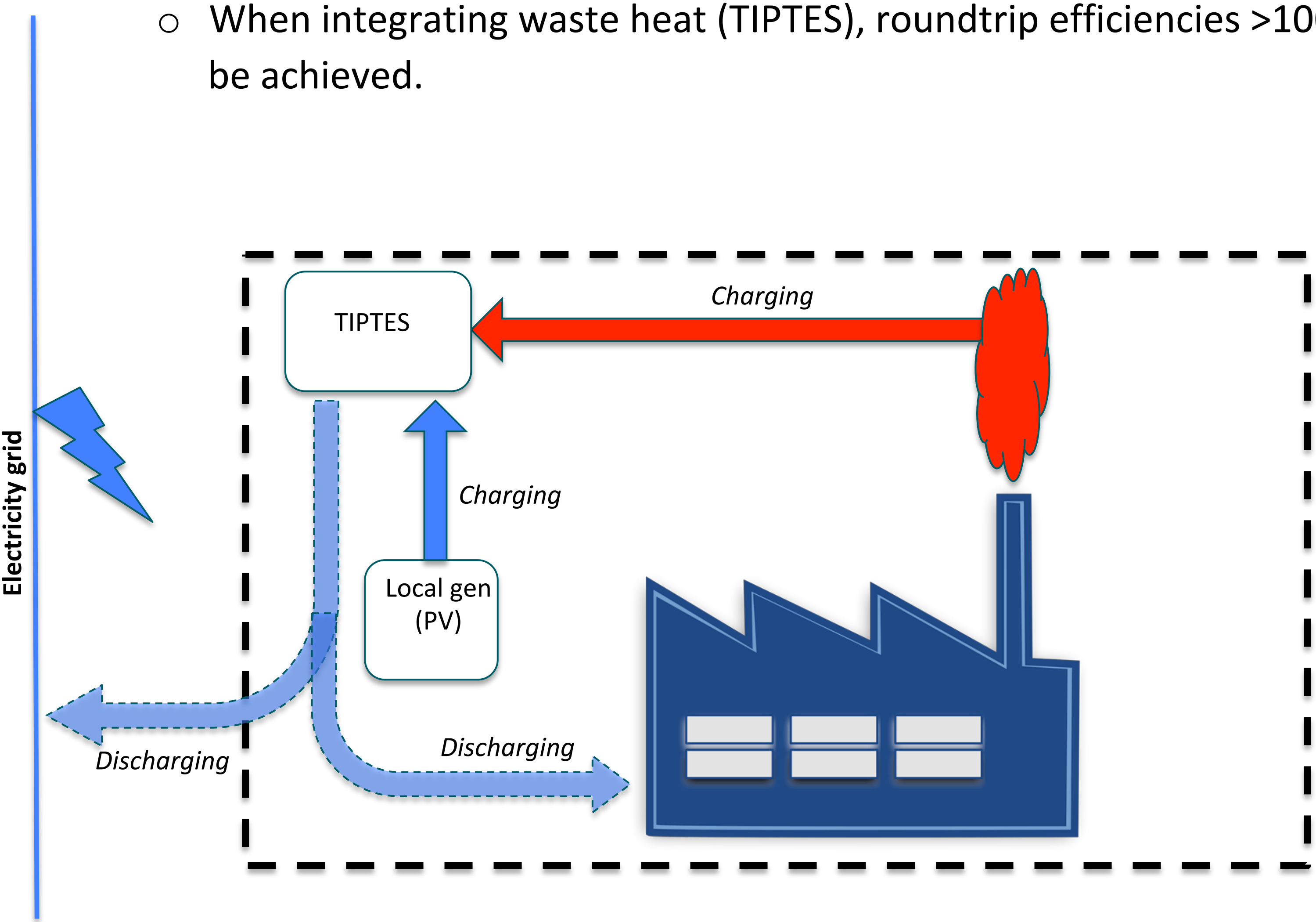
- Promising technology to store electricity from intermittent power production.

$$\eta_{roundtrip} = \frac{E_{el,out}}{E_{el,in}} < 70\%$$

Pumped Thermal Energy Storage

Integration in industry

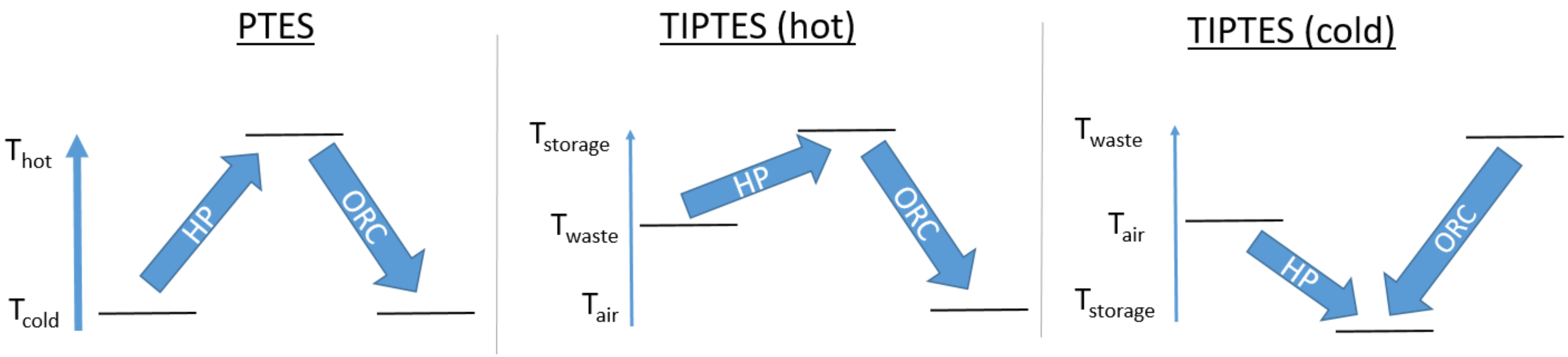
- When integrating waste heat (TIPTES), roundtrip efficiencies >100% could be achieved.



Pumped Thermal Energy Storage

TIPTES configurations

- Two different configurations of TIPTES can be achieved: hot and cold configurations



Hot thermal storage

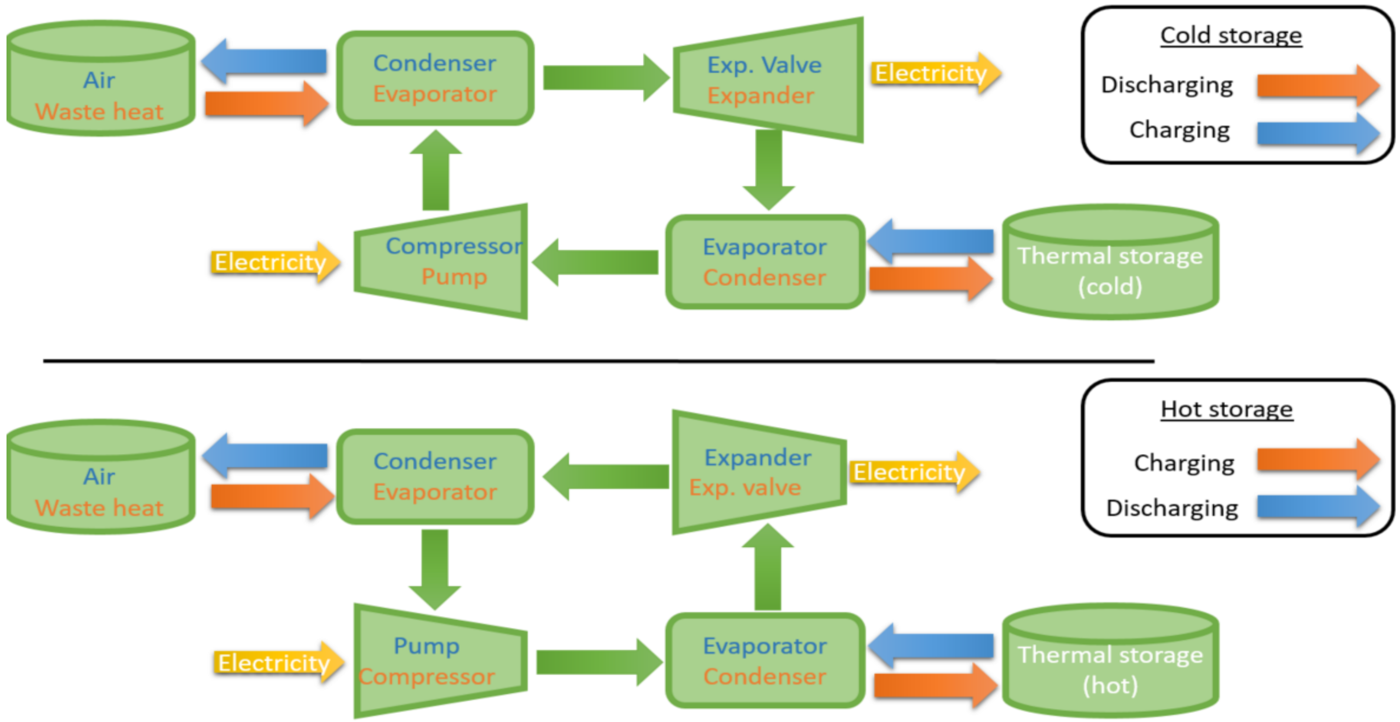
Cold thermal storage

Pumped Thermal Energy Storage

TIPTES with a reversible HP/ORC system

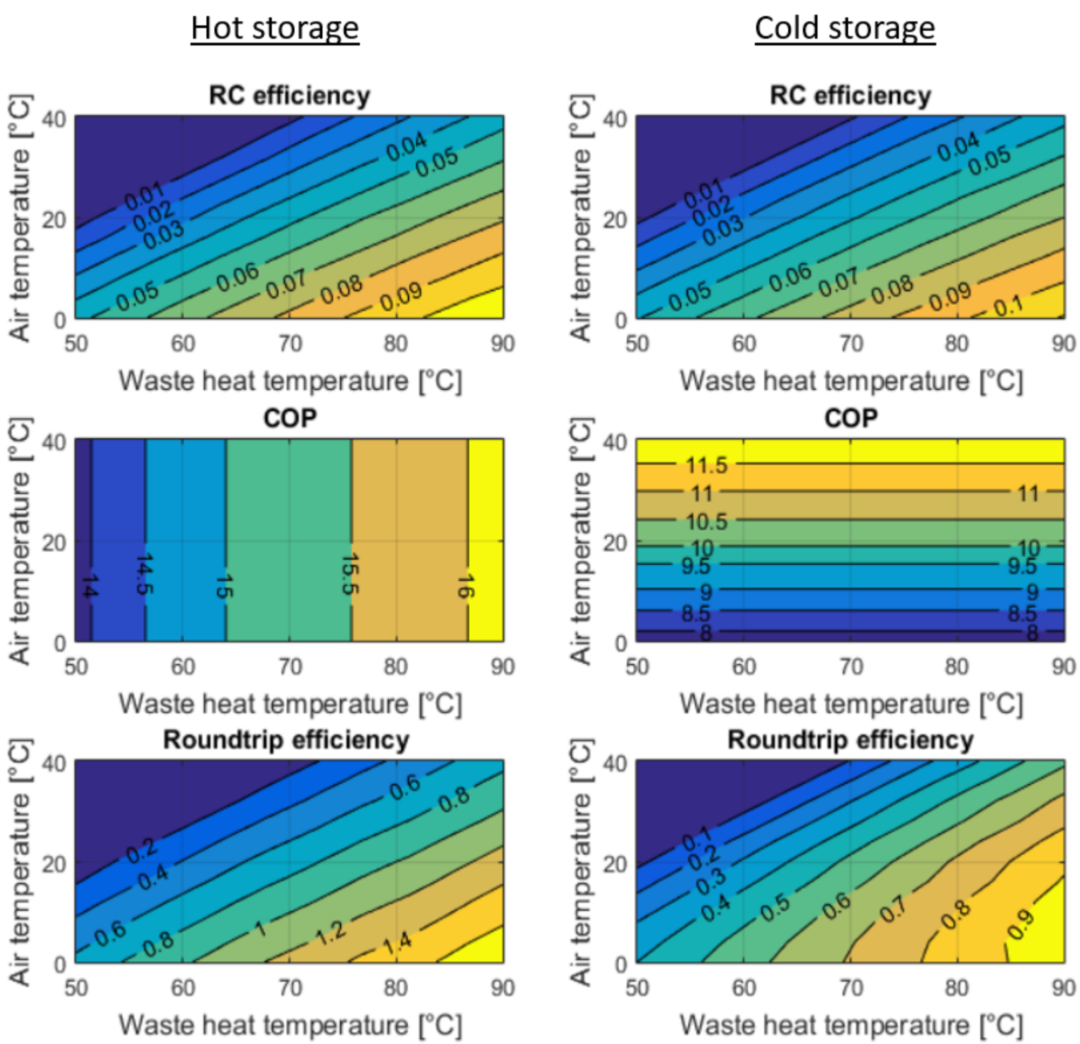
- For low and mid-scale systems: similarities between fluids/components of ORC and HPs.

  => 1 unique reversible machine reduces cost and increases compactness and easiness of operation



Pumped Thermal Energy Storage

TIPTES with a reversible HP/ORC system



- Heat pump should work with a low temperature lift to maximize COP (≠ classical PTES)
- Large zone with high roundtrip efficiency => promising technology
- => We're building a prototype.

Conclusions

- Waste heat recovery potential in industry is far from being totally valorized. Some solutions exist, but there is room for innovation and improvement:
  - ✓ Cheap, efficient, robust solutions
  - ✓ Flexible (heating/cooling/electricity production) solutions

- In the current energy transition, we need to develop innovative thermal machines that are
  - ✓ Integrate energy storage solutions (for intermittent RE sources)
  - ✓ Able to ensure the connections between the electricity, gas and thermal grids

- Large R&D potential at the thermal system component level. Some elementary physical phenomena still need to be better described through experimental/ numerical research.

Thank you for your attention!

Thank you to all contributors to this presentation

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