ANALYSIS OF A PUMPED THERMAL ELECTRICITY STORAGE SYSTEM WITH THE INTEGRATION OF LOW TEMPERATURE HEAT SOURCES

UNIVERSITY OF PISA

PhD course in:

Energy, Systems, Territory and Construction Engineering

XXXII cycle

Candidate:

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Outline

- Thesis content
- Introduction
    - Study context and motivation
- Preliminary study on Pumped Thermal Electricity Storage (PTES) technology
    - Use of low grade heat sources
- Focus on High Temperature Vapour Compression Heat Pumps (HT-VCHPs)
    - Working fluids and performance
- Multi- criteria analysis of a PTES system
    - More realistic assessment of PTES performance
- Focus on trade-off between cost and performance for HT-VCHPs

- Conclusion, Future development, List of publications

Thesis content

- Six chapters

i. Introduction on grid scale storage technologies
  - Why storage is needed
  - What kind of storage is needed
  - Storage technology overview

ii. Preliminary analysis of a PTES system
  - Integration of low-grade heat sources
  - Vapour compression heat pumps and ORC
  - Several fluid simulated

iii. Focus on High Temperature Vapour Compression Heat Pumps (HT-VCHP)
  - Vapour compression systems
  - Fluid applicability ranges
  - Performance trade-off

iv. PTES Multi-objective analysis
  - Multi-objective optimized design
  - Performance trade-off
  - Realistic assessment of practically achievable KPIs

v. HT-VCHP Multi-objective economic analysis
  - HT-VCHP cost model
  - Cycle design influence on cost and performance
  - Economic feasibility assessment

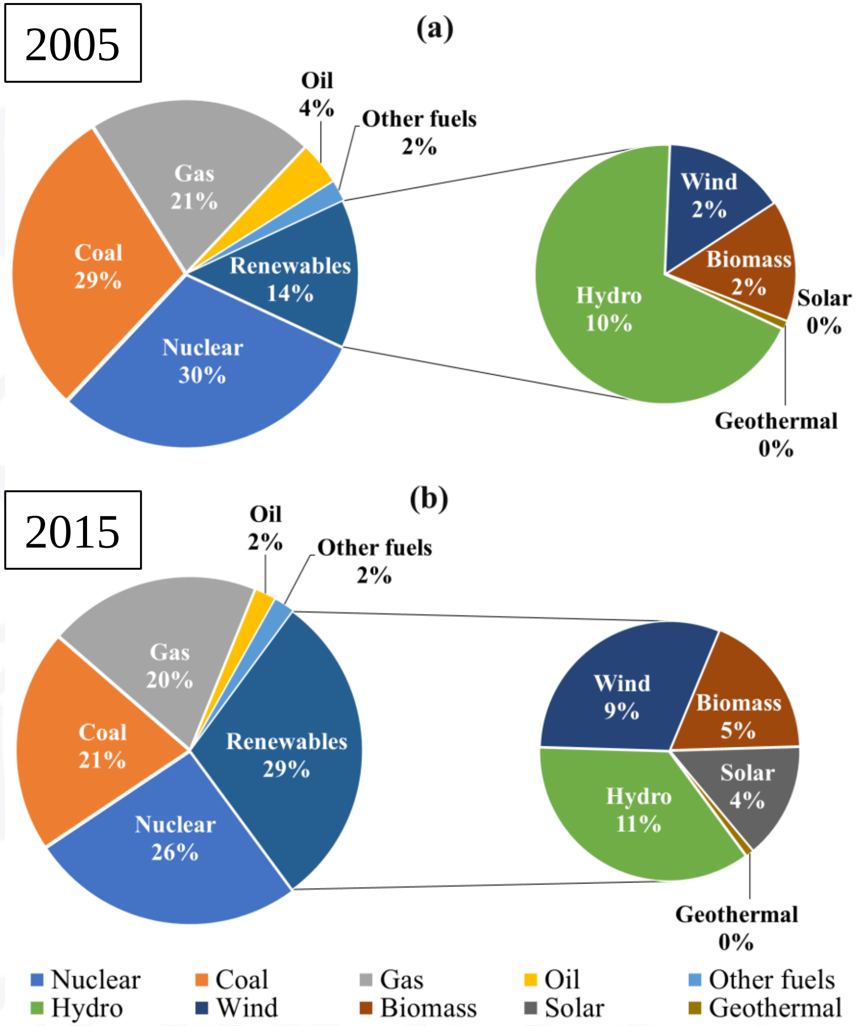
vi. Conclusion
  - Contributions and Future development
  - List of publications

Introduction

Chapter 1

Do we need storage?

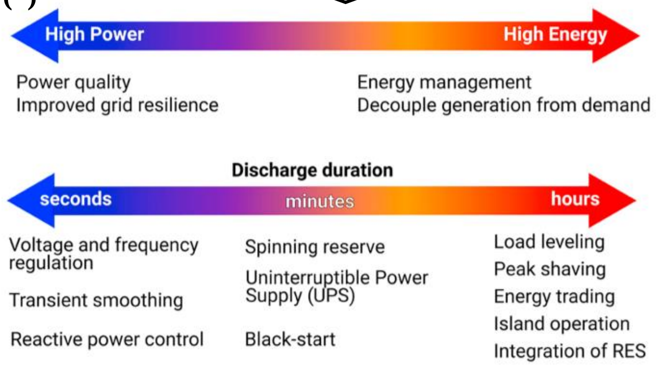
(*) artwork from: *M.C. Argyrou, P. Christodoulides, S.A. Kalogirou, Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications, Renew. Sustain. Energy Rev. 94 (2018) 804–821. doi:10.1016/j.rser.2018.06.044.*



RES growth is mostly sustained by non-dispatchable sources

Rigid production → flexibility issues

(*)

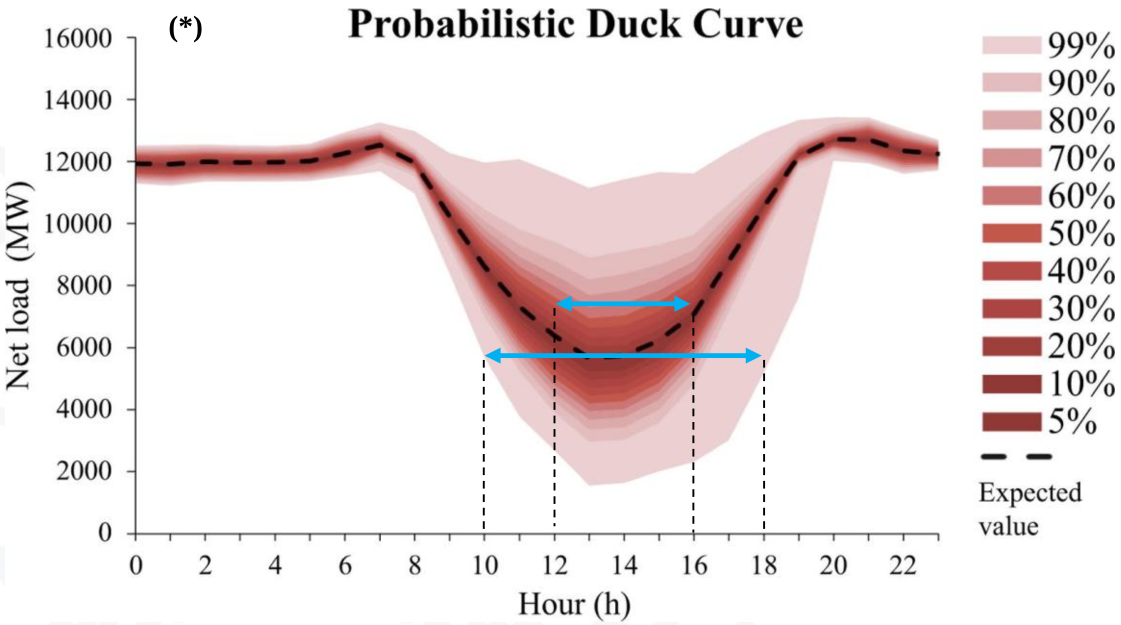


Occupied niches:
- ≤ 1 second
- Seconds
- Minutes
- ≤ 1 hour

Available niches:
- > 1 hour

PTES

Do we need several hour-capacity storage?



(*) Artwork from: *Q. Hou, N. Zhang, E. Du, M. Miao, F. Peng, C. Kang, Probabilistic duck curve in high PV penetration power system: Concept, modeling, and empirical analysis in China, Appl. Energy. 242 (2019) 205–215. doi:10.1016/j.apenergy.2019.03.067.*

Great potential in Solar resources, which impose characteristic profiles to residual electric demand

Power-to-capacity ratio from 1/4 to 1/8 h^{-1}

Low cost per kWh

Technology	**Power-related cost [$/kW]**	**Capacity-related cost [$/kWh]**
PHES	400/600 – 1000/2000	1/5 – 100
UPHES	400/600 – 1000/2000	85
SWPHES	720 – 2200	25 – 30
CAES	400/500 – 800/1000	1/2 – 50/100/200
ACAES	700 – 1000	40 – 80
UWCAES	750 – 2000	40 – 200
ICAES	500 – 1000	10 – 100
LAES	900/1000 –2000	260 – 530
Br-PTES	600 – 800	20/90 – 60/180
Ra-PTES	225/390 – 450	45 – 95/120
NaS Batteries	150/200 – 300/900	100/200/300 – 500/600
Flow Batteries	300/600 – 500/1500	150/400 – 750/1000

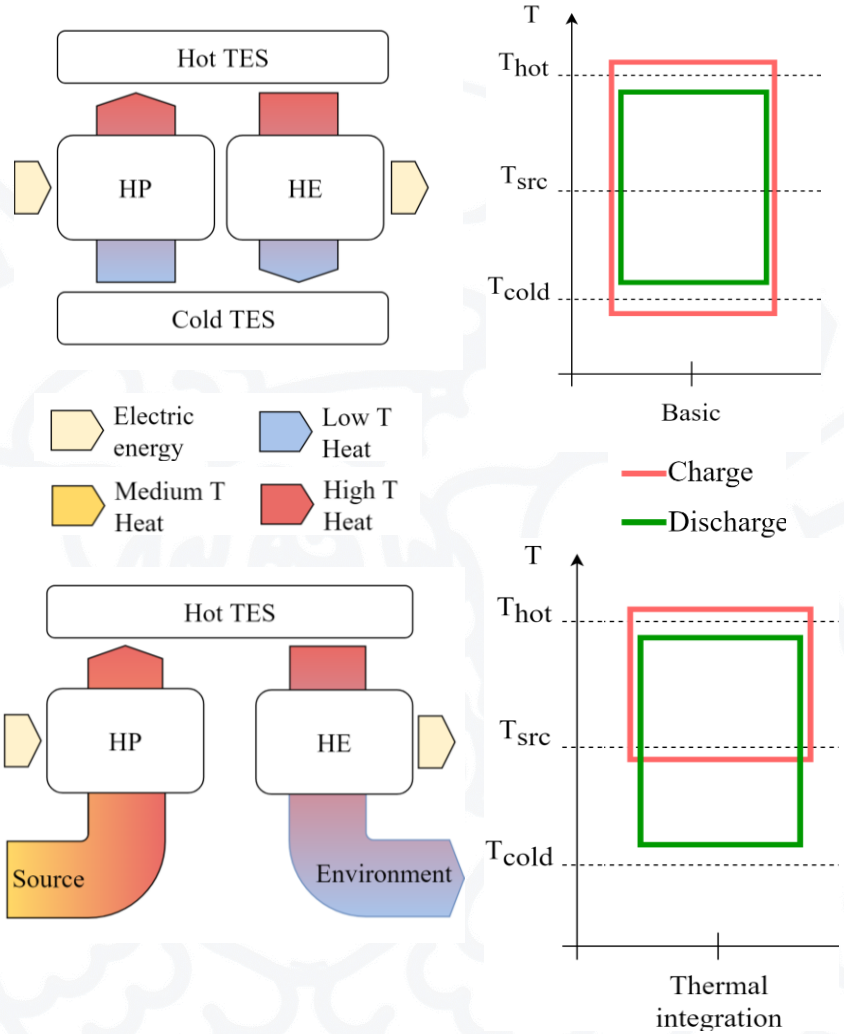
Desired features:

- Environmentally sustainable
- Low scarce material usage
- Limited land and water usage

Preliminary analysis of PTES

Chapter 2

PTES technology



- Pumped Thermal Electricity Storage (PTES) stores electric energy in form of thermal energy
- The investigated system features:

High TRL

- ○ High Temperature Vapour Compression Heat Pumps (HT-VCHP) and ORC

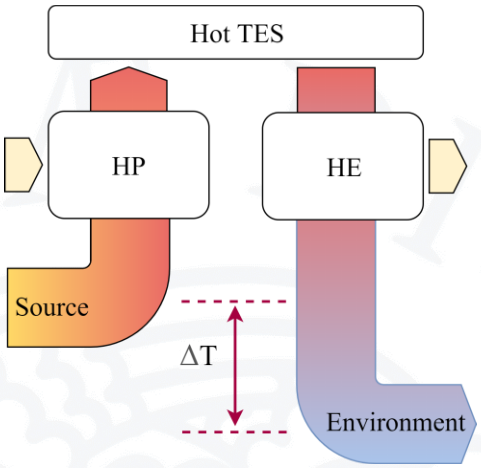
Low cost, Common materials

- ○ Inexpensive storage medium (thermal oil, water,…)

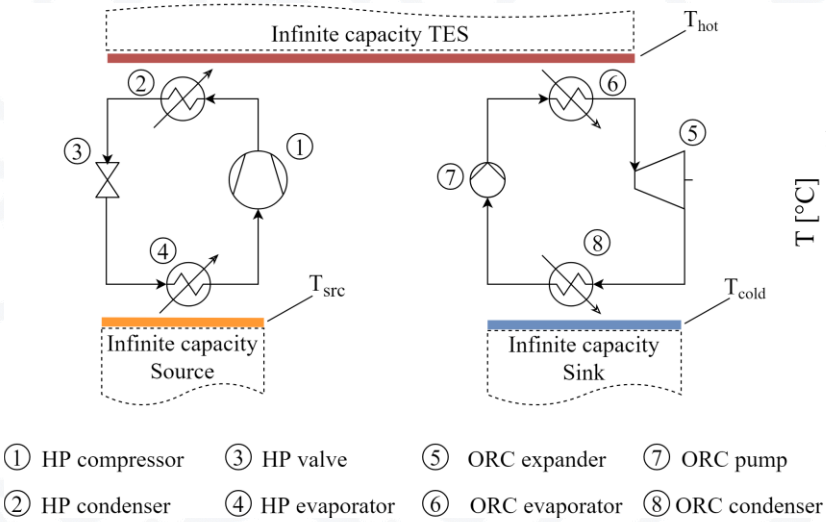
Integration between energy vectors

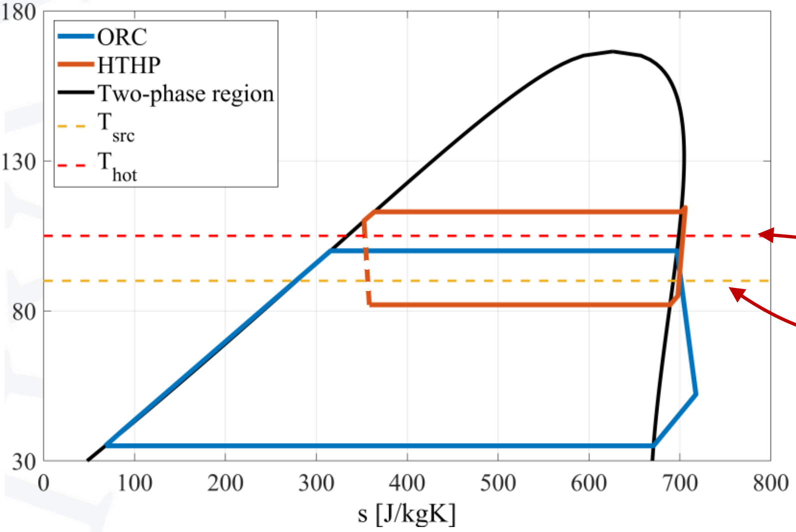
- ○ Low temperature ($T_{max} \leq 180$ °C)
- ○ It takes advantage of low grade heat sources (waste heat, solar, geothermal)

Effect of additional thermal sources



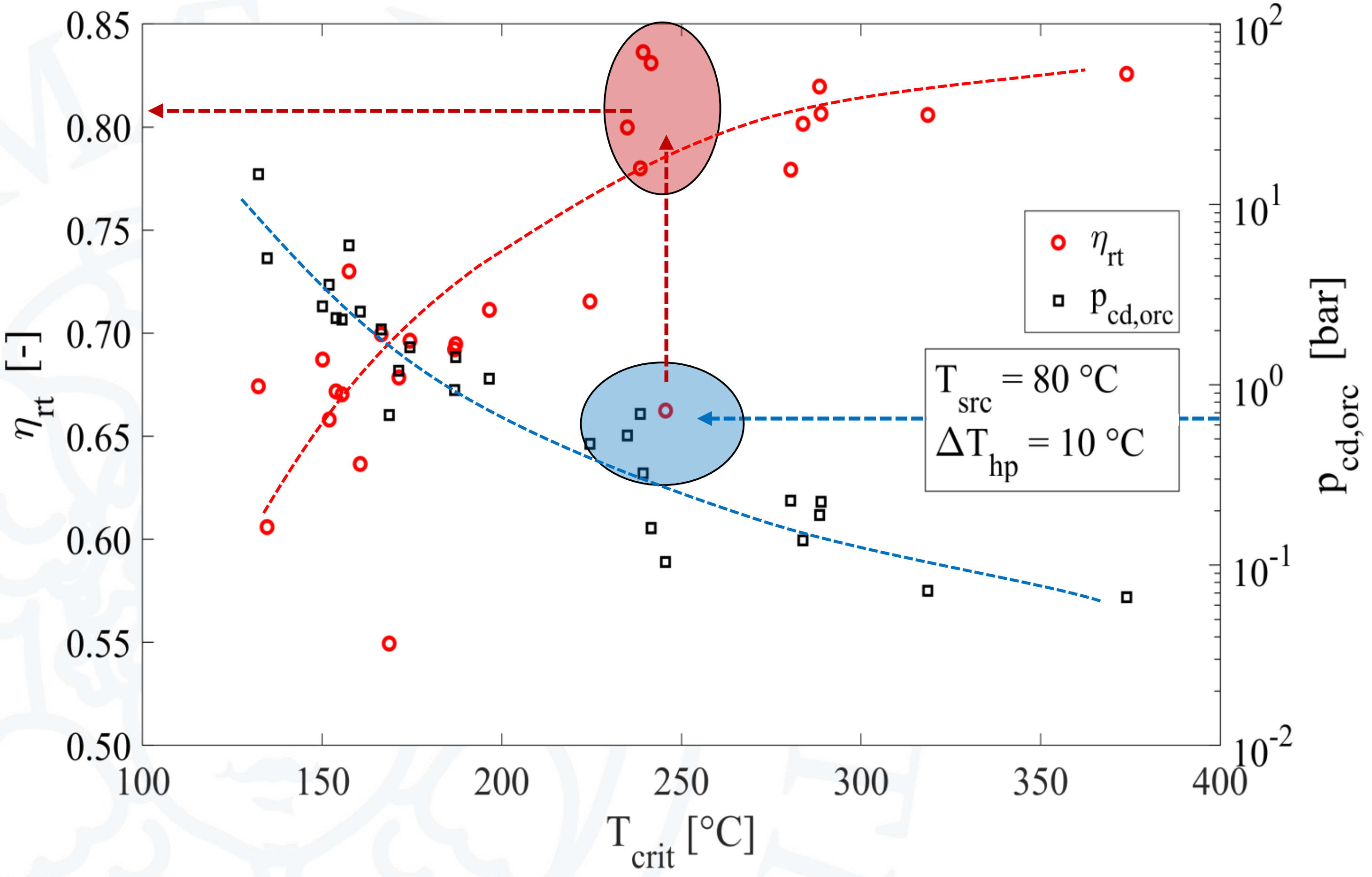
- The use of low grade heat sources improves *electric* efficiency of the system
- In extreme (but realistic) cases the ratio between absorbed and returned *electric* energy can be higher than 1
- The system is powered by both electric and thermal energy → exergy analysis to take this into account





- 28 Working fluids
- Several values of storage and source temperatures

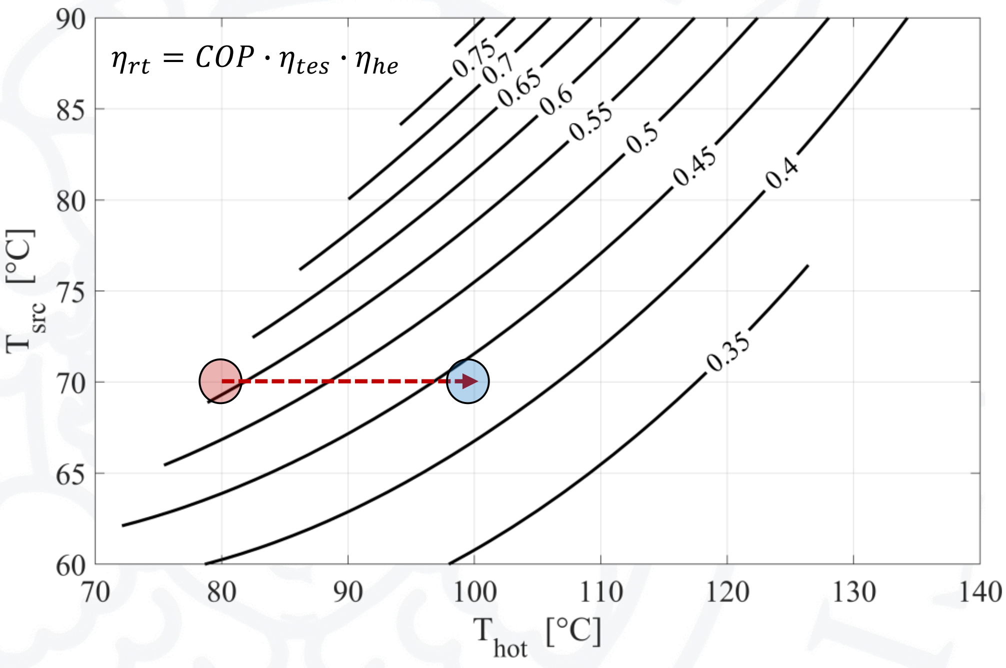
Expected performance

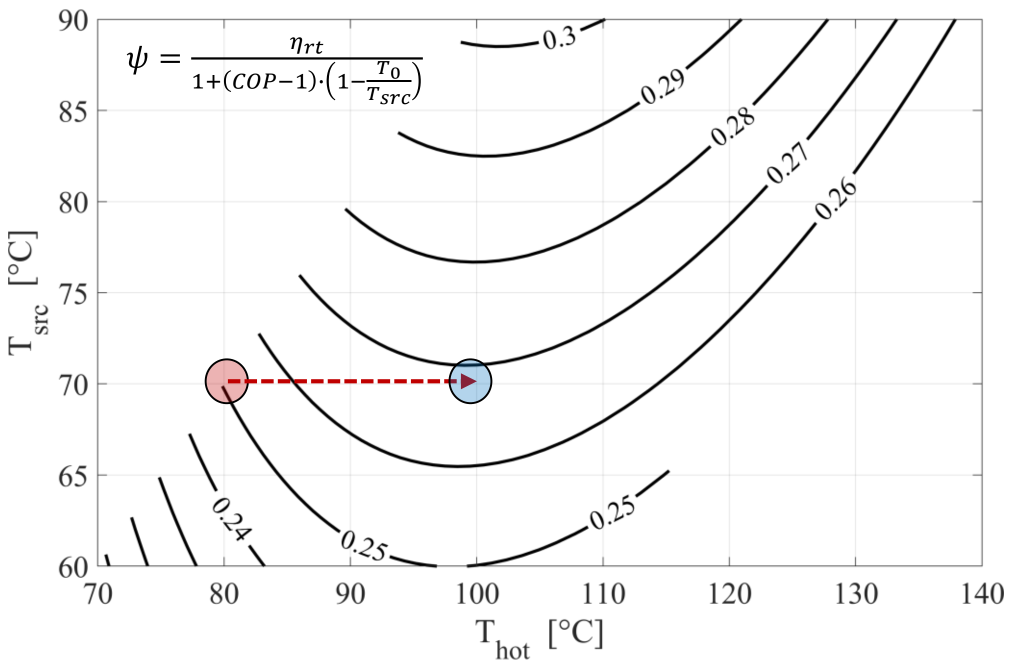


- Too high and too low pressure must be avoided to resort on standard equipment
- Both pressure and roundtrip efficiency are correlated with critical temperature
- From the chart, the most suited fluids may be selected

The R1233zd(E) case

- Performance variations in function of source and storage temperatures
- Roundtrip efficiency and exergy efficiency do not have the same behaviour
- Design trade off may be searched



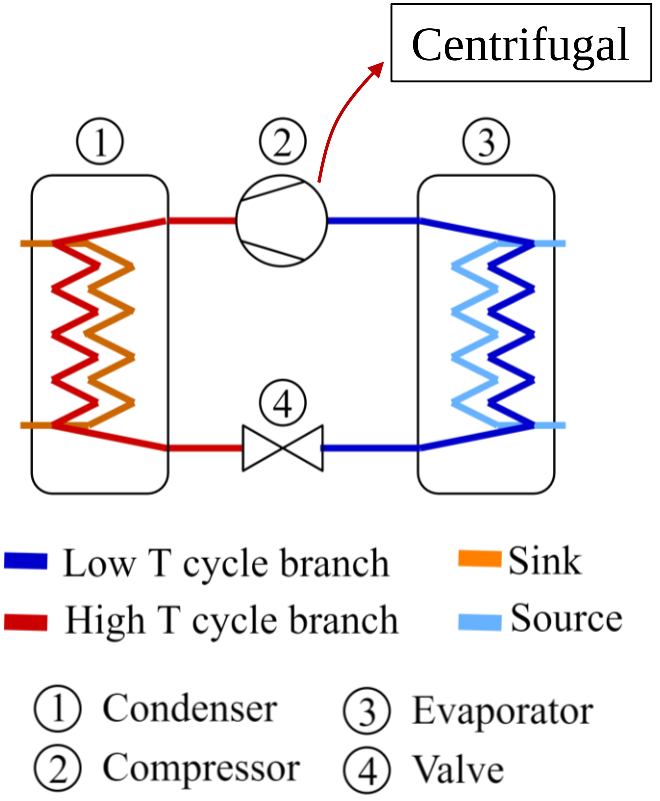


Fluid suitability ranges for HT-VCHP

Chapter 3

Role of HT-VCHP

- HT-VCHPs are *identical* to regular VCHP from layout point of view
- HT-VCHPs work on completely different temperature range and different fluids must be used:
  - VCHP T_{env} → 60 °C – 90 °C
  - HT-VCHP 60°C – 90 °C → 110°C – 150 °C
- HT-VCHPs may be used as waste heat *upgrading* technology (stand alone use) or in PTES systems
- An open question is the choice of the fluid, considering also the compressor technology



Fluid selection

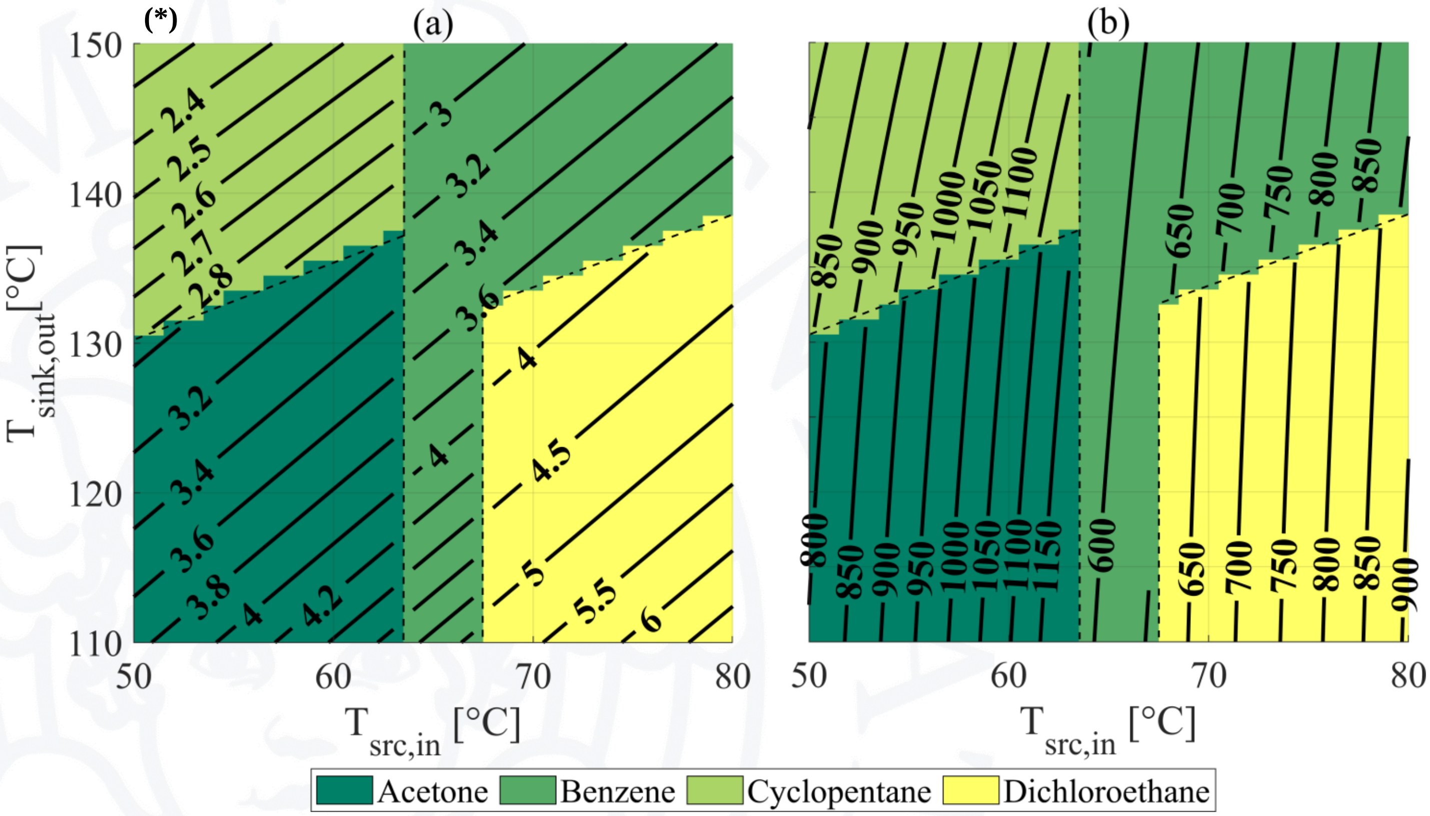
Fluid	T_{crit} [°C]	$p_{sat,40\,°C}$ [bar]	GWP_{100}	Health	Flammability	ASHRAE	CS compatibility	T_{auto} [°C]	$T_{dec,min}$ [°C]
Acetone	234.95	0.57	< 1	1	3	N/A	✓	527	N/A
Ammonia	132.25	15.55	< 1	3	1	B2L	✓	630	N/A
Benzene	288.87	0.24	N/A	2	3	N/A	✓	555	315
Cyclopentane	238.57	0.74	< 6	1	3	N/A	✓	320	275 – 325
Cyclopropane	125.15	10.64	N/A	1	4	N/A	✓	495	N/A
Cyclohexane	280.45	0.25	< 6	1	3	N/A	✓	260	N/A
Dichloro-Ethane(DCE)	288.45	0.21	< 1	2	3	N/A	× - (SS)	440	300
Dimethyl-Carbonate (DMC)	283.85	0.15	N/A	3	3	N/A	× - (SS)	458	N/A
Ethanol	241.56	0.18	1	2	3	N/A	✓	400	N/A
Iso-Butane	134.67	5.31	3	0	4	A3	✓	460	300^{f}
Iso-Hexane	224.55	0.51	< 6	1	3	N/A	✓	265	N/A
Iso-Pentane	187.20	1.52	2 ÷ 6	1	4	A3	× - (SS)	420	275 – 290
Methanol	239.35	0.35	2.8	1	3	N/A	✓	440	N/A
MM	245.60	0.11	N/A	1	3	N/A	N/A	310	300^{g}
n-Butane	151.98	3.78	4	1	4	A3	✓	405	300 – 310
n-Pentane	196.55	1.16	5	1	4	A3	× - (SS)	260	280
Neopentane	160.59	2.70	N/A	2	4	N/A	✓	450	315
Novec649	168.66	0.73	< 1	N/A	0	N/A	N/A	N/A	300
R1224yd(Z)	155.5	2.45	< 1	N/A	0	A1	✓	N/A	175
R1233zd(E)	166.45	2.16	1	N/A	0	A1	✓	N/A	200
R1234ze(Z)	150.12	2.90	< 1	1	0	A2L	N/A	368	N/A
R13336mzz(Z)	171.3	1.28	2	N/A	0	A1	✓	N/A	200
R245ca	174.42	1.73	726	1	1	N/A	N/A	412	350
R365MFC	186.85	1.01	804	3	0	A2	N/A	594	N/A
Sulfur-Dioxide	157.49	6.30	< 1	3	0	N/A	× - (SS)	N/A	N/A
Toluene	318.60	0.08	3	2	3	N/A	✓	480	315
Water	373.95	0.07	< 1	0	0	A1	× - (SS)	N/A	N/A

Trade-off between COP and VHC

- Objectives:
  - COP measures the amount of electric energy per unit of useful thermal energy. It is relevant for operating cost
  - VHC measures the volumetric flow rates required for a given useful thermal power. It is relevant for capital cost
  - The trade-off between capital cost and efficiency is investigated

- Methodology:
  - HT-VCHP design for a given couple of source and sink temperatures is *optimized*
  - Physical constraints (heat exchanger approach and component mass balances) are enforced through optimization constraints
  - COP is assumed as objective function (single objective optimization)
  - Other limitations:
    - Minimum pressure
    - Maximum temperature
    - Maximum number of stages

Fluid selection based on efficiency



- Most efficient fluids are all highly flammable
- VHC is too low as in refrigeration 3000 – 6000 *kJ/m*^{3} are common
- What is the trade-off if fluids with higher VHC are used?

(*) Artwork from: *G.F. Frate, L. Ferrari, U. Desideri, Analysis of suitability ranges of high temperature heat pump working fluids, Appl. Therm. Eng. 150 (2019) 628–640. doi:10.1016/j.applthermaleng.2019.01.034.*

COP vs. VHC

α = 0.75
β = 0.25

α = 0.50
β = 0.50

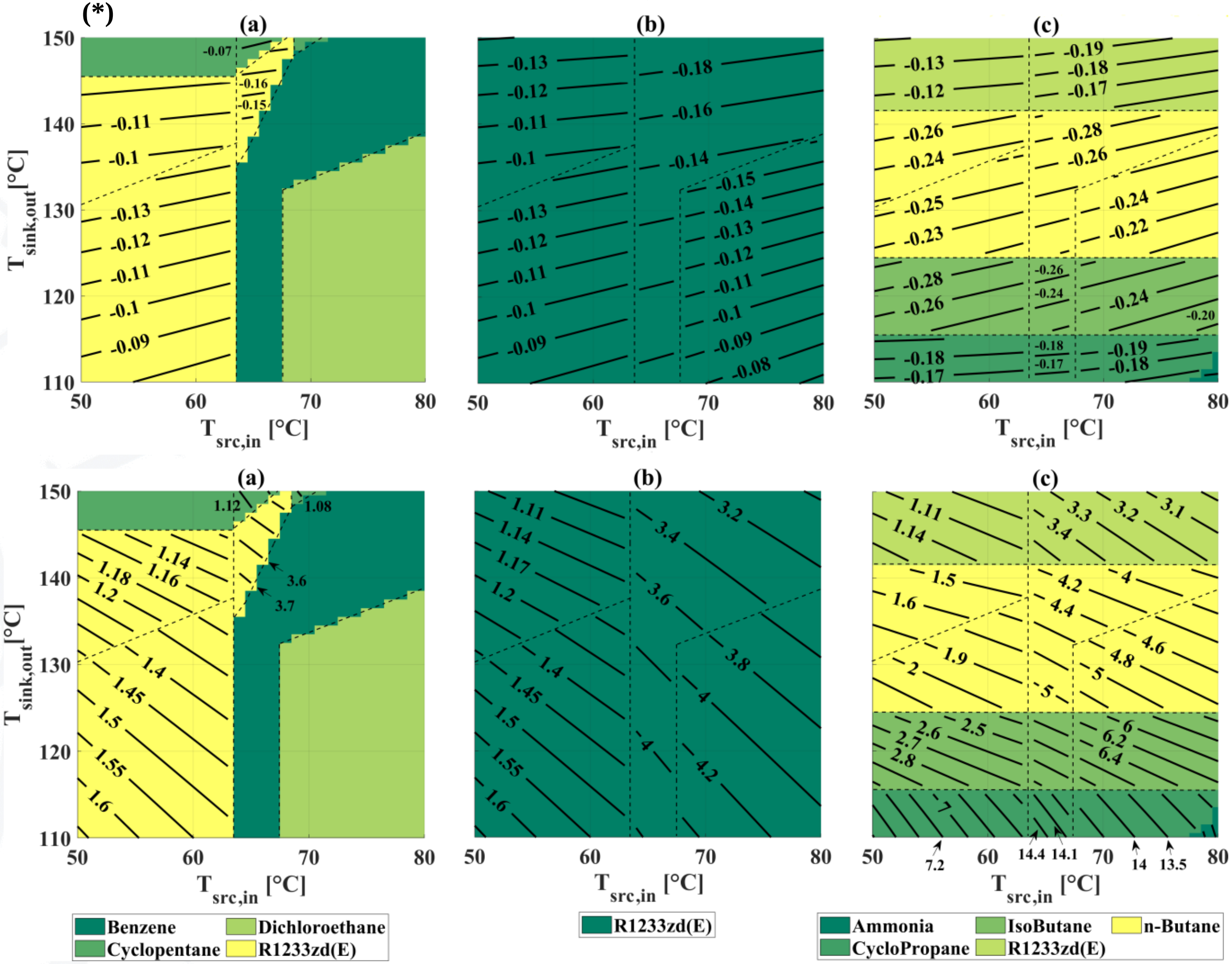
α = 0.00
β = 1.00

COP losses

VHC increments

Score = α · COP + β · VHC

(*)



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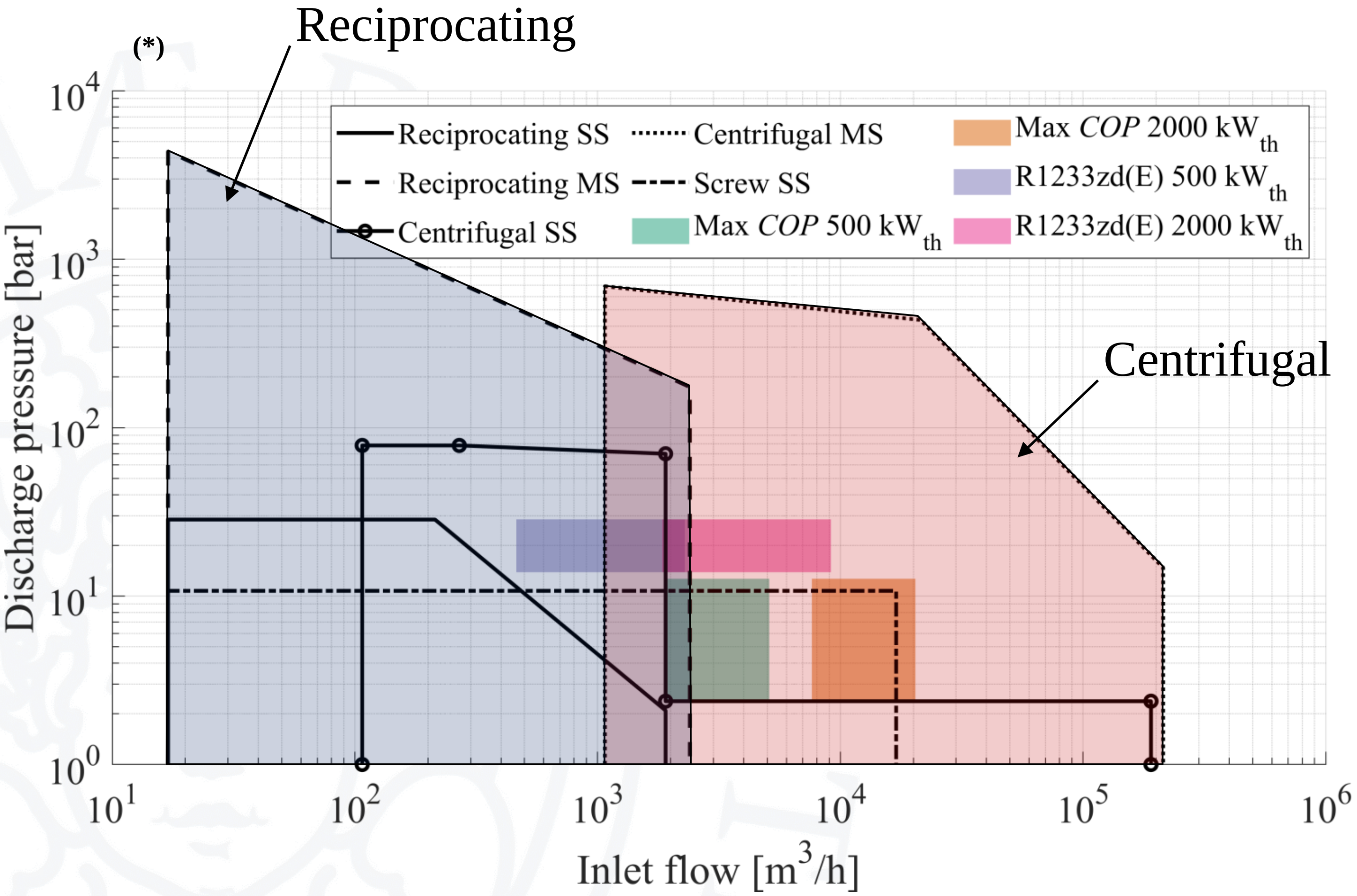
Recommended compressor technology



- Multi-stage compressors are the most suited ones
- Other compressor technology might suffer for large size HT-VCHP applications
- If high VHC fluids are used, cheaper compressors (i.e. reciprocating) could be used

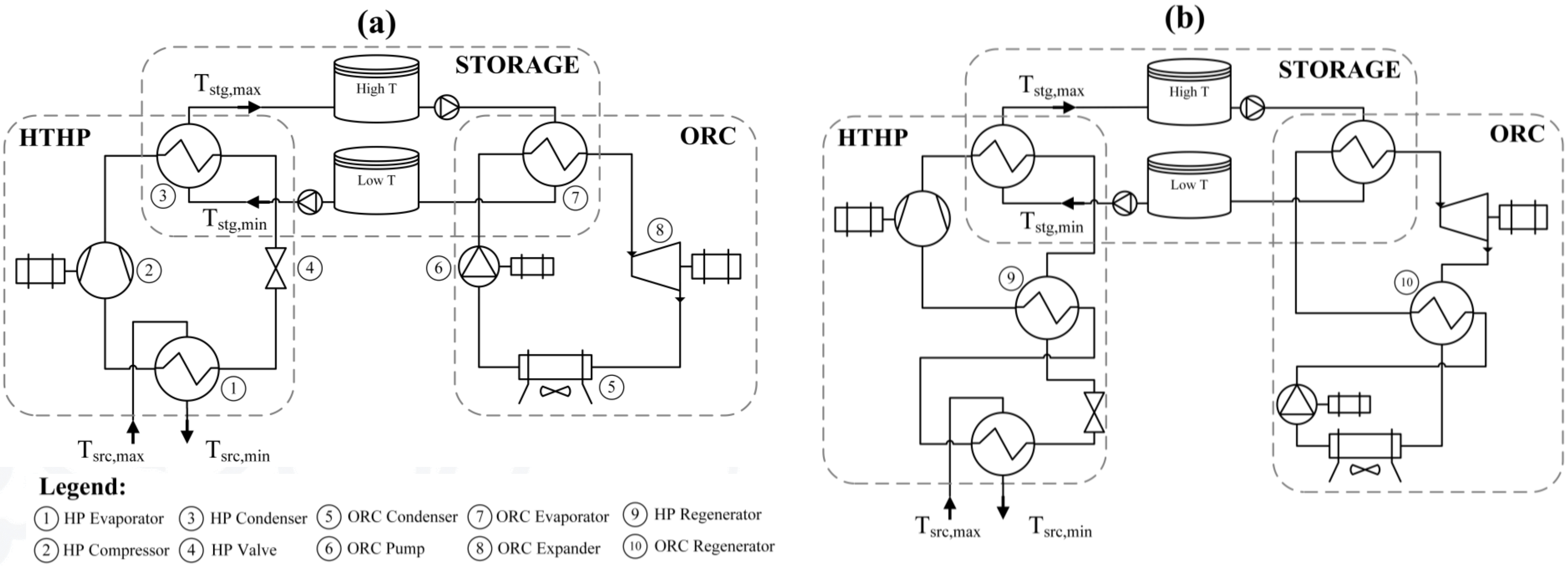
(*) Artwork from: *G.F. Frate, L. Ferrari, U. Desideri, Analysis of suitability ranges of high temperature heat pump working fluids, Appl. Therm. Eng. 150 (2019) 628–640. doi:10.1016/j.applthermaleng.2019.01.034.*

PTES multi-objective design optimization

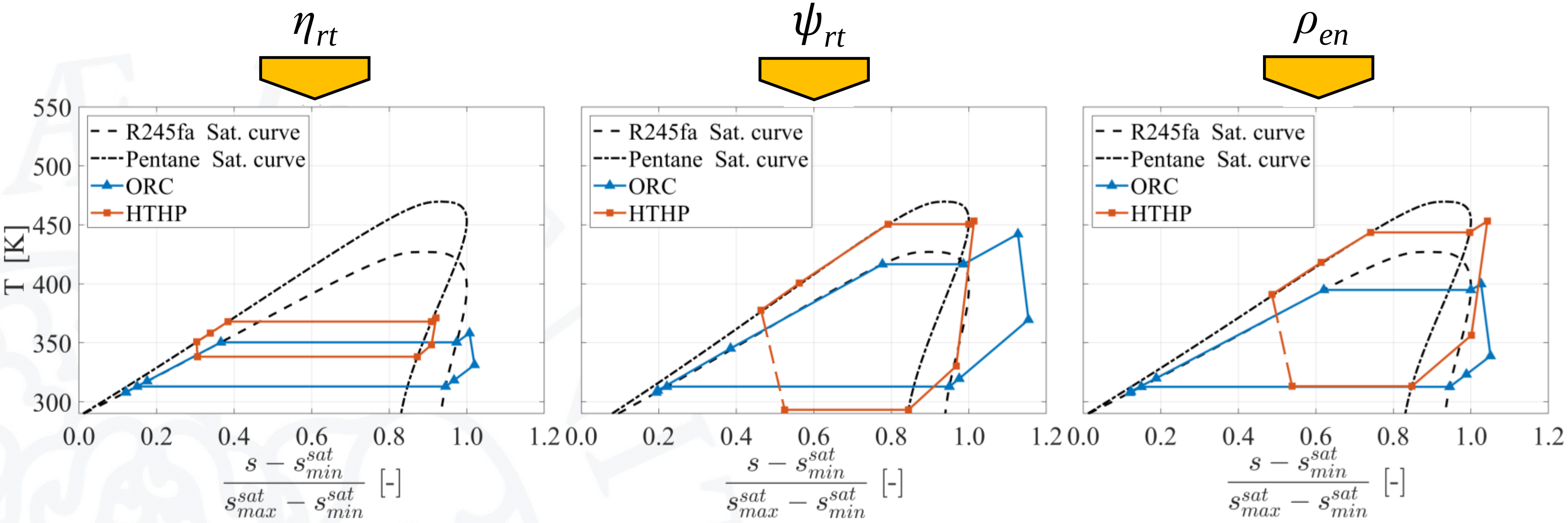
Chapter 4

Layout and KPIs

- Variable source, sink and storage temperature
- Regenerated and non-regenerated layouts
- Fluid pool selected based on previous analyses
- Two set of boundary conditions (Pessimistic vs. Optimistic)
- Multi-objective design:
    - Roundtrip efficiency
    - Exergy efficiency (modified)
    - Energy density

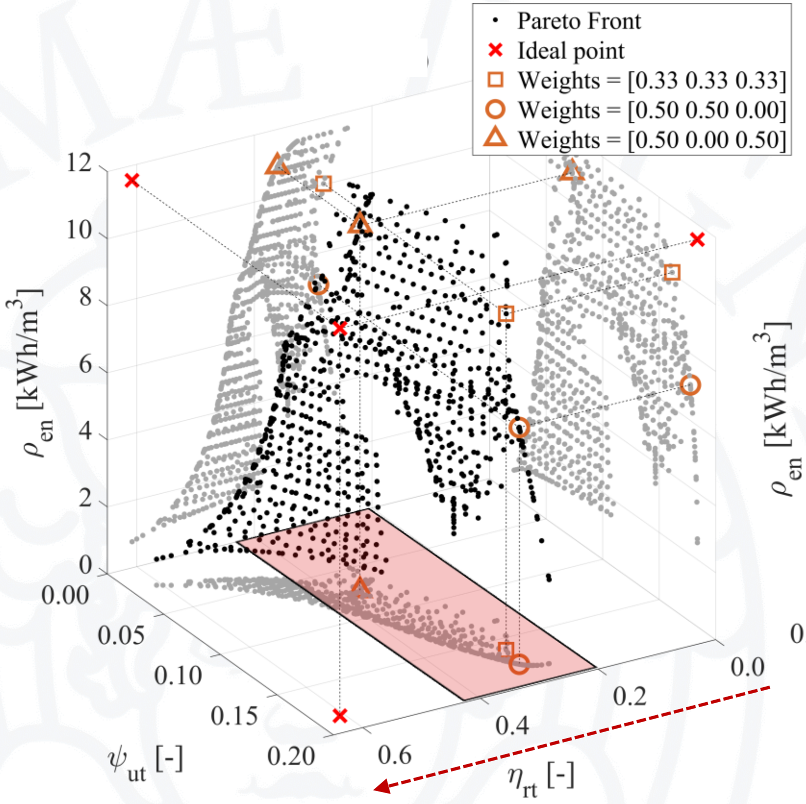


Single objective analysis

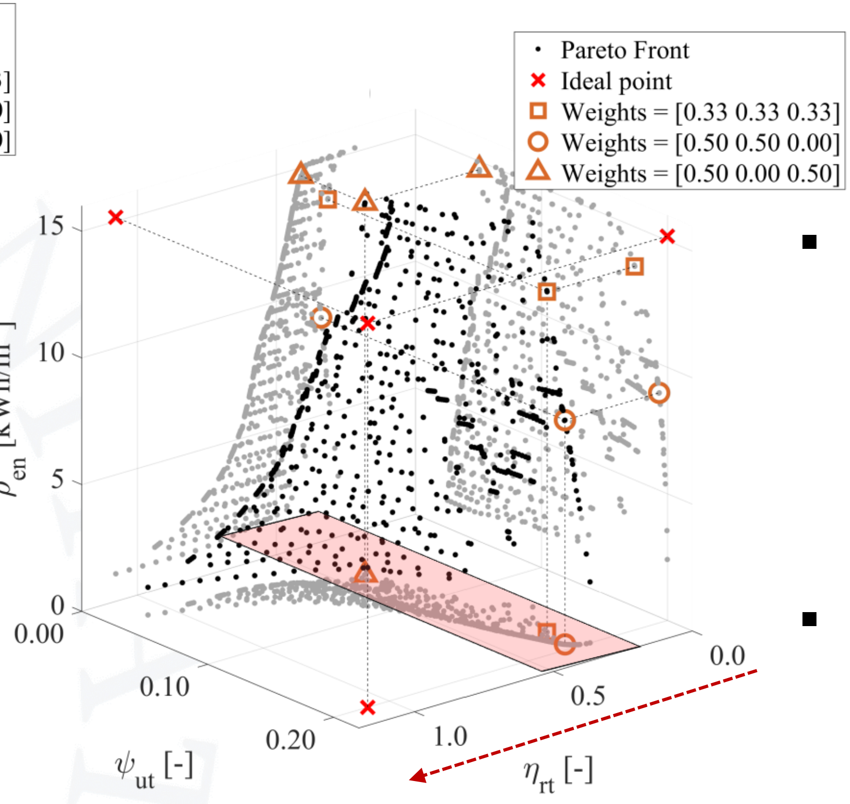


	Maximized Parameter:	Non-regenerated			Regenerated		
		η_{rt} [-]	ψ_{ut} [-]	ρ_{en} [kWh/m^3]	η_{rt} [-]	ψ_{ut} [-]	ρ_{en} [kWh/m^3]
Pessimistic	η_{rt} [-]	**0.61**	**0.02**	**0.78**	**0.59**	**0.02**	**0.78**
	ψ_{ut} [-]	**0.25**	**0.18**	2.31	0.38	**0.19**	9.34
	ρ_{en} [kWh/m^3]	0.26	0.06	**11.55**	**0.23**	0.08	**13.21**
Optimistic	η_{rt} [-]	**1.08**	**0.03**	**1.09**	**1.02**	**0.03**	**1.08**
	ψ_{ut} [-]	**0.28**	**0.20**	2.32	**0.33**	**0.21**	11.64
	ρ_{en} [kWh/m^3]	0.29	0.06	**15.17**	0.34	0.09	**17.28**

Pareto fronts

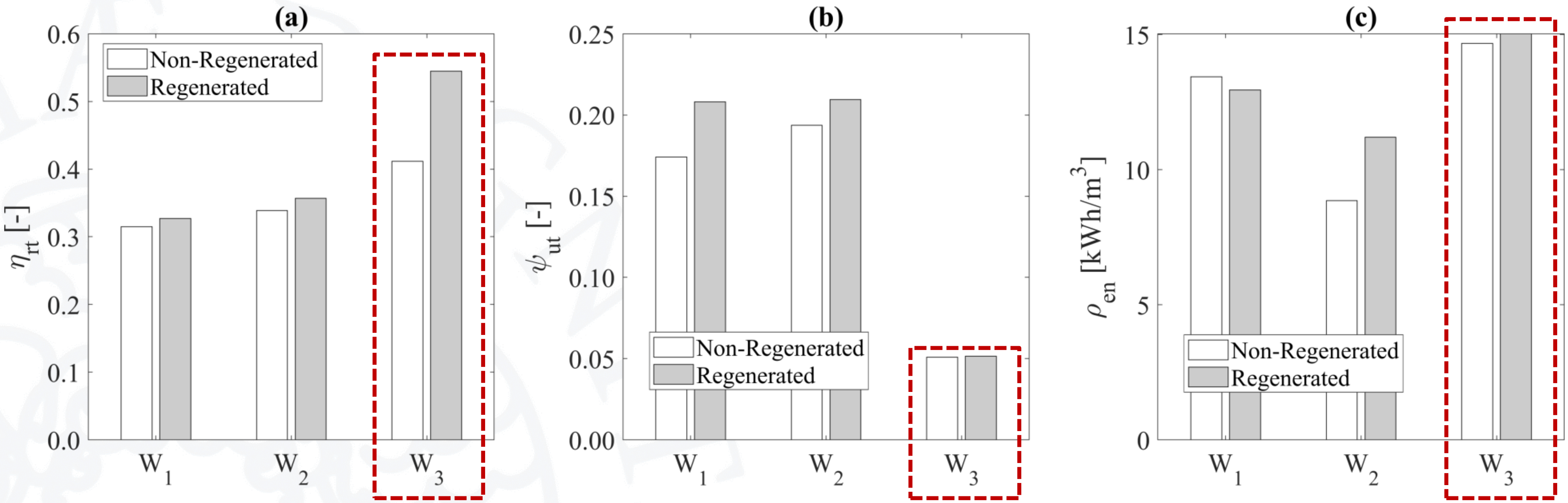


Pessimistic



Optimistic

- Maximum efficiency points are never selected (penalization to other objectives is too strong)
- Multi-objective frame work is the right one to design such systems

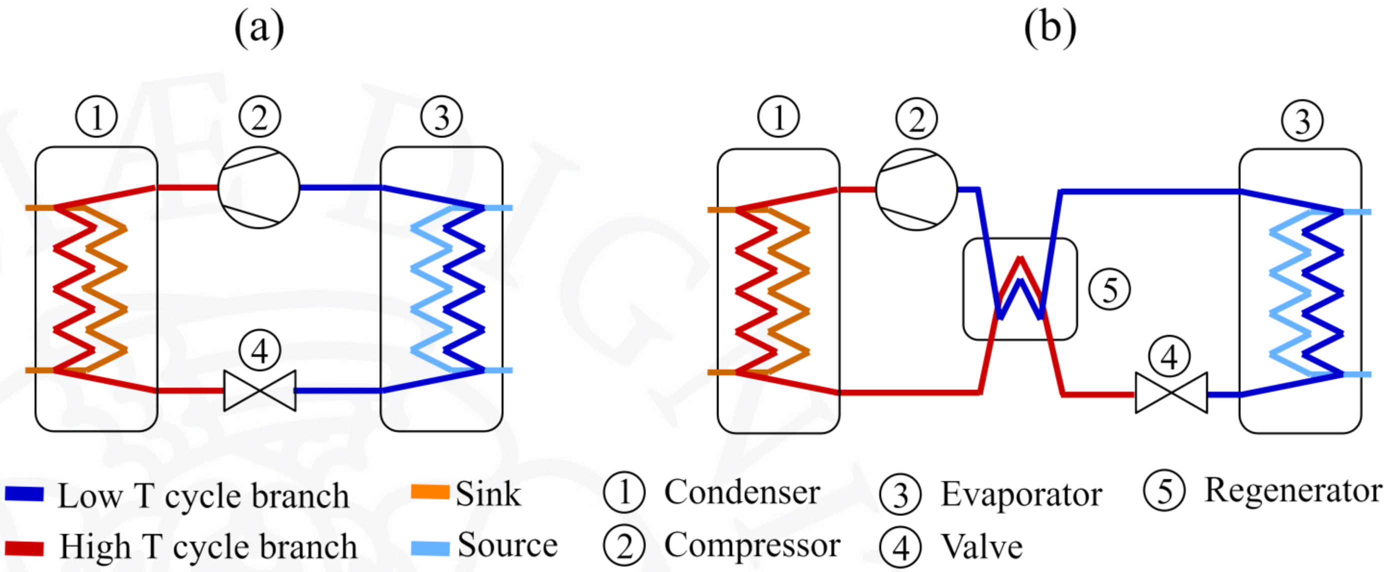


- Satisfactory performance are found if the source is inefficiently exploited
- Impressive results for a system that operates below 180 °C and with practically commercial components

HT-VCHP multi-objective economic analysis

Chapter 5

Investigated layout



- HT-VCHPs are investigated for stand alone applications (waste heat upgrading)

- Regenerated vs. non-regenerated
- Lower size → reciprocating compressor
- Cost functions from vendor data

- Trade off between COP and cost (between capex and opex):
  - Subset of Chapter 3 fluids
  - Useful temperature 130 °C – 150 °C
  - Source Temperature 80 °C
  - Sink temperature difference 10 °C – 30 °C

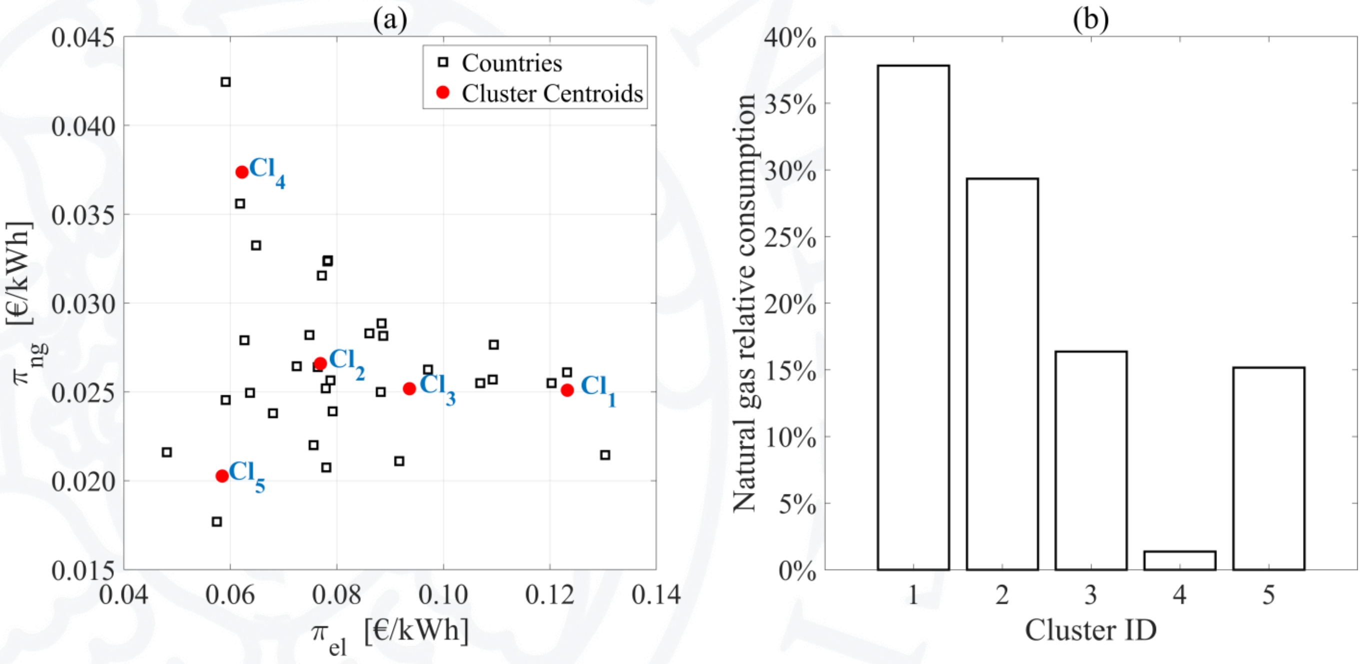
Why don’t we use an aggregated indicator?

- Levelized Cost Of Heat (LCOH) is function of both cost and COP:

$$LCOH = \alpha \cdot TCI + \beta \cdot \frac{1}{COP}$$

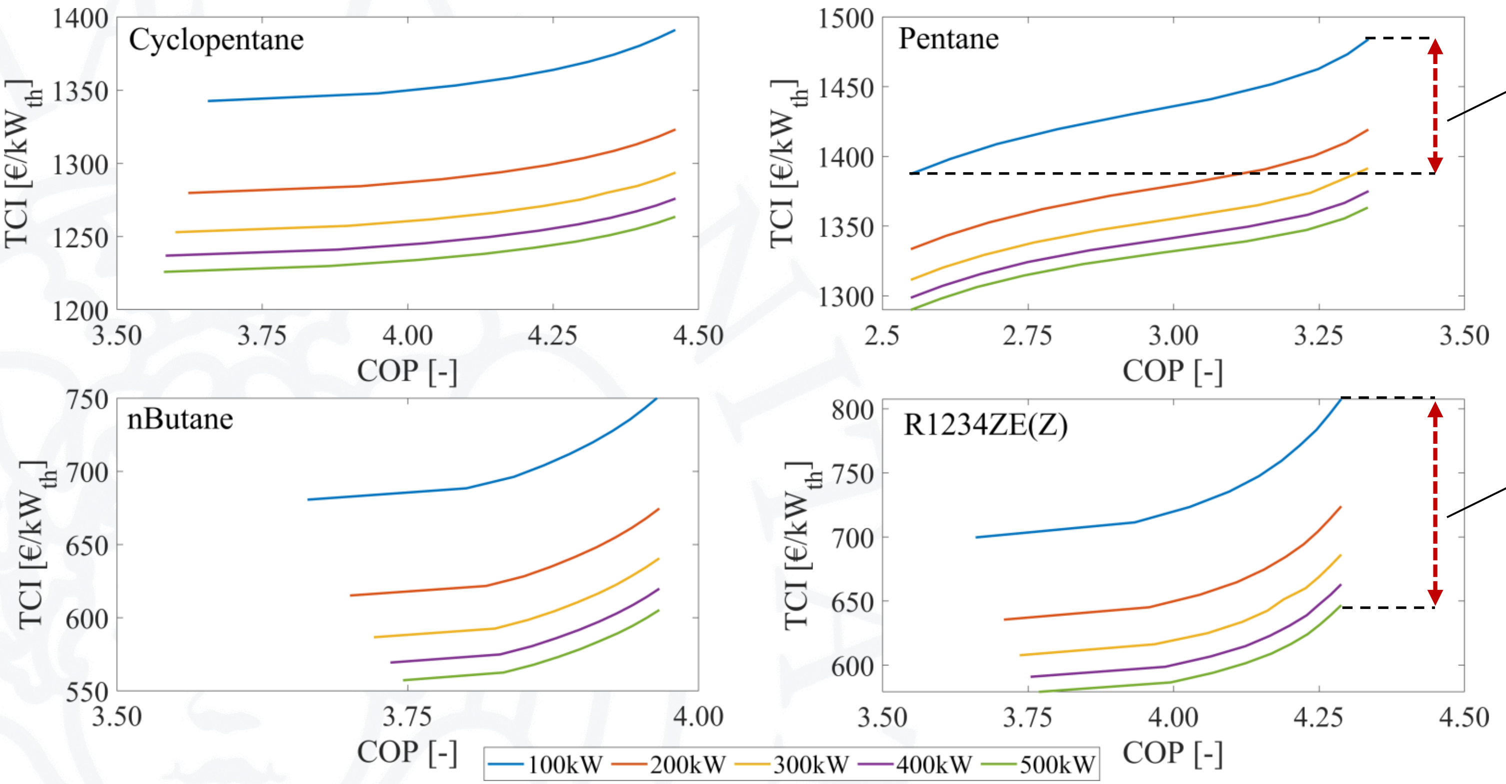
α and β are function of electric energy and natural gas price

- LCOH is country dependant, design might not be robust:



- European area countries have been clustered and 5 representative groups have been considered
- Not all the groups have the same weight

Performance trade-off

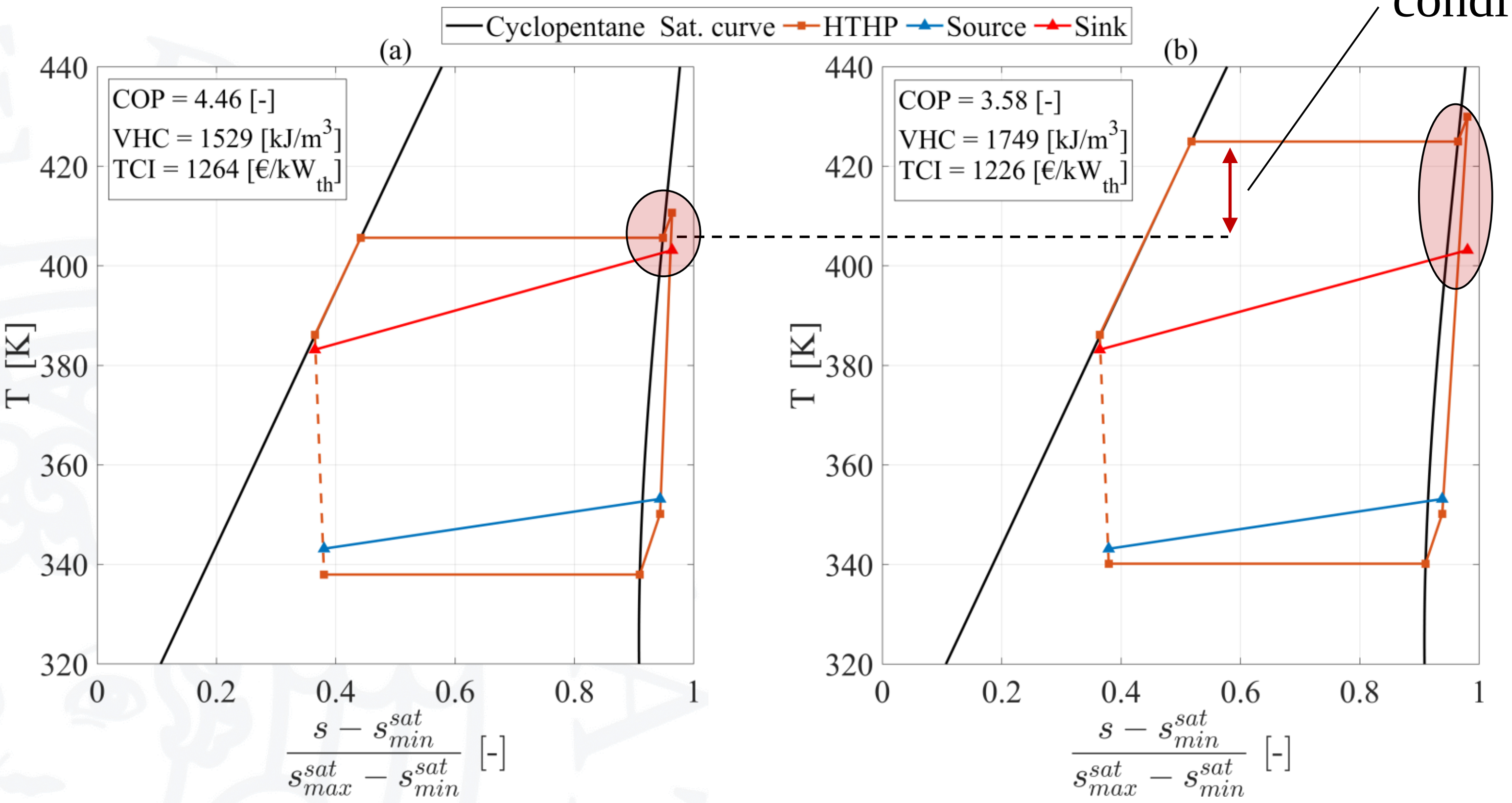


Effect of the cycle design

Effect of the thermal size

Cycle design

Condensation conditions



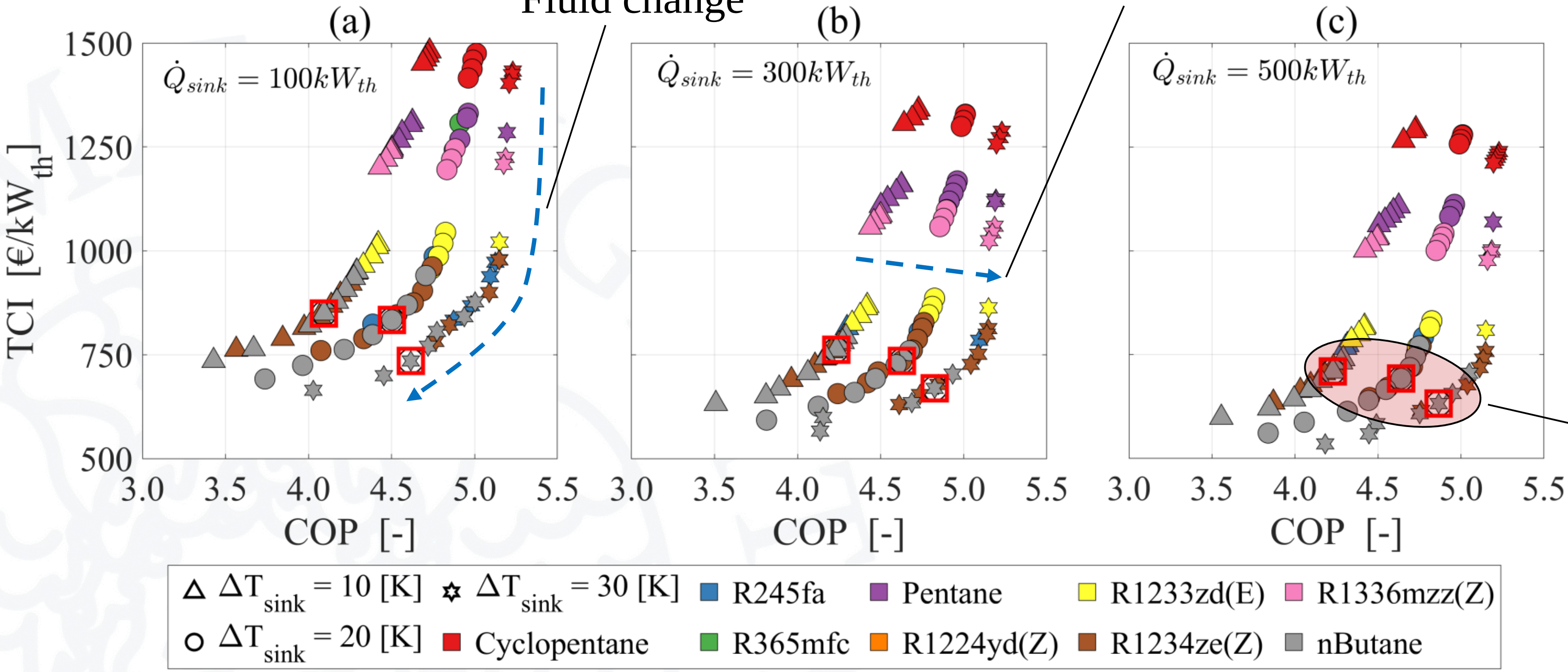
Max COP

Min cost

COP vs. Cost

Fluid change

Sink temperature difference



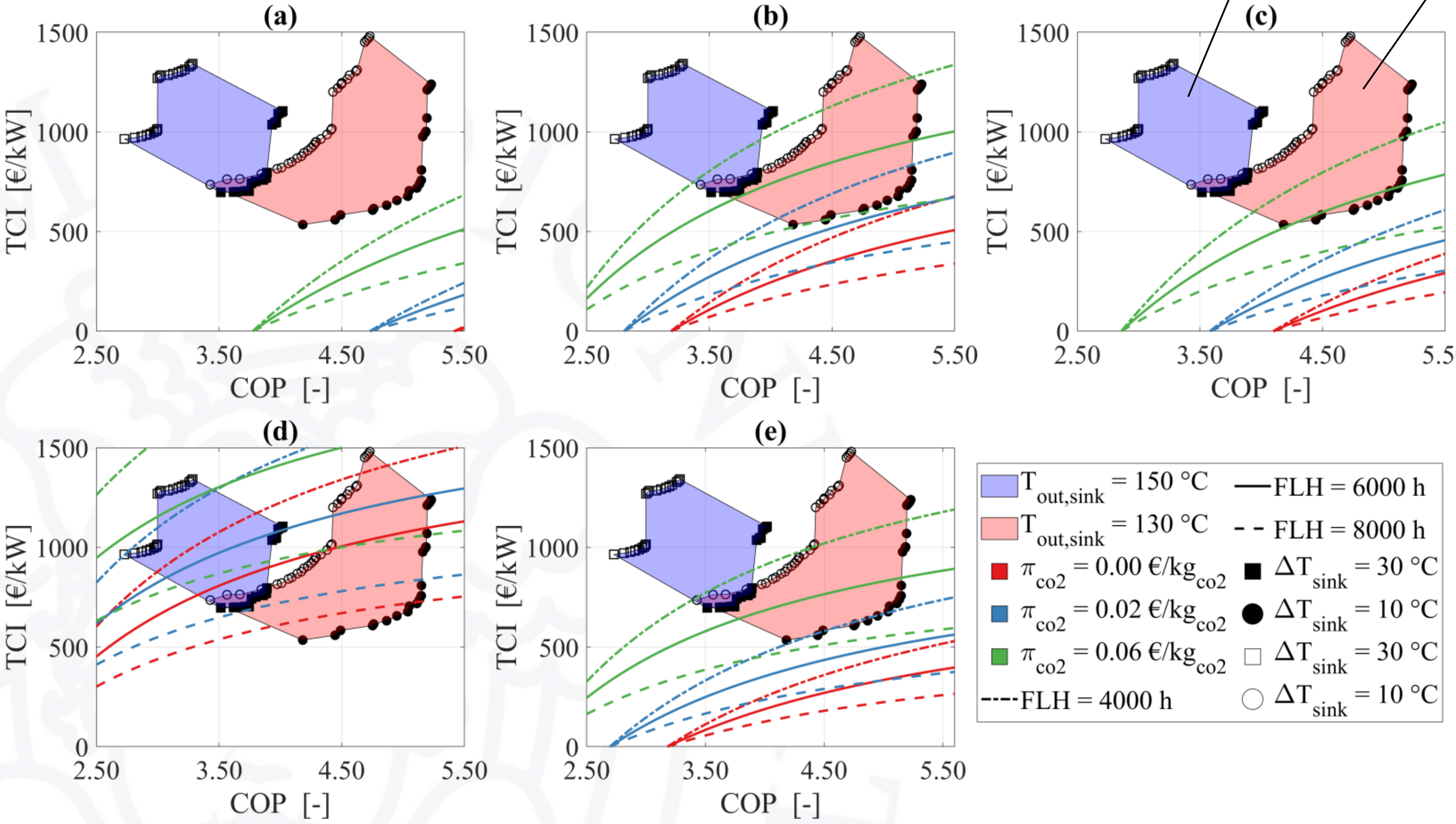
Minimum LCOH

- High VHC fluids yield lower COP but also lower cost
- From LCOH point of view low cost are better than high efficiency

Assessing feasibility

T useful 150 °C

T useful 130 °C



Increasing carbon tax

- Current estimated prices exclude economic feasibility in most scenarios

Conclusion

Chapter 6

Main contributions

- In depth thermodynamic analysis of a novel EES technology
    - Potentiality of exploiting additional low grade thermal sources have been assessed
- Realistic assessment of performance in light of the trade-offs that must be assumed between KPIs
    - Some designs feature satisfactory performance
    - Performance comparable with other more complex / lower TRL technologies
- Most critical (and less studied) subcomponent (HT-VCHP) has been analysed from thermodynamic and economic point of view
    - Design guide lines have been provided both for working fluid choice and for impact of cycle specifications
    - Economic feasibility has been assessed, by demonstrating that a cost reduction must be pursued
- First building block for PTES cost model have been developed

Future development

- Experimental validation
- Completing the cost model
- Use of supercritical fluid and mixtures to improve thermal integration between HT-VCHP, thermal storage and ORC
- Off-design model (to test the storage in real-life case studies)

List of publications

- Journal
    - Guido Francesco Frate, Marco Antonelli, and Umberto Desideri. 2017. “A Novel Pumped Thermal Electricity Storage (PTES) System with Thermal Integration”. *Applied Thermal Engineering* 121: 1051-1058. doi:10.1016/j.applthermaleng.2017.04.127.
    - Guido Francesco Frate, Lorenzo Ferrari, and Umberto Desideri. 2019. “Analysis of suitability ranges of high temperature heat pump working fluids”. *Applied Thermal Engineering* 150: 628-640. doi:10.1016/j.applthermaleng.2019.01.034.
    - Guido Francesco Frate, Lorenzo Ferrari, and Umberto Desideri. 2019. “Multi-criteria investigation of a Pumped Thermal Electricity Storage (PTES) system with thermal integration and sensible heat storage”. *Energy Conversion and Management* 208, 112530. doi:10.1016/j.enconman.2020.112530.
- Conference proceedings
    - Guido Francesco Frate, Marco Antonelli, and Umberto Desideri. 2017. “Pumped Thermal Electricity Storage: An Interesting Technology for Power-To-Heat Applications”. 30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2017.

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