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BRAYTON BATTERIES FOR COMBINED ELECTRICITY AND HEAT AND COOLING PRODUCTION: SYSTEMATIC CONCEPT STUDY

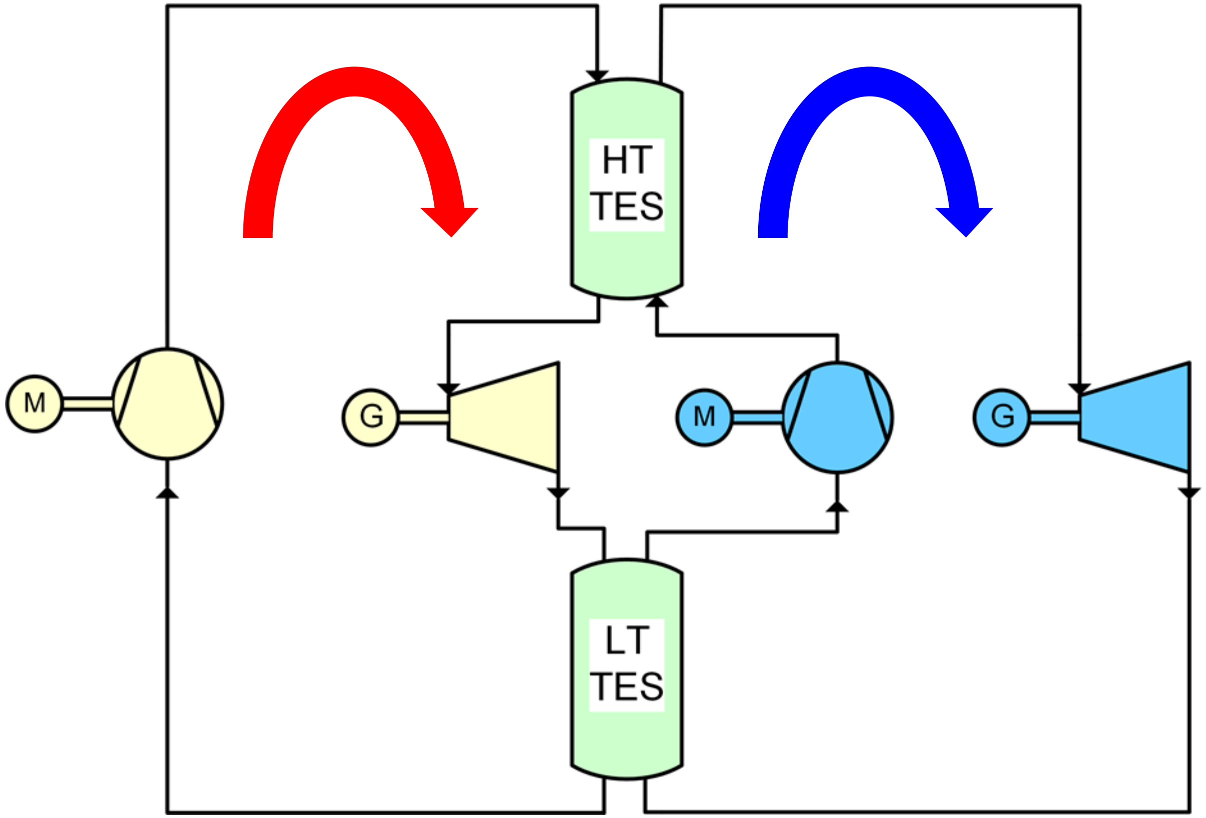
Dr.-Ing. Michael Krüger

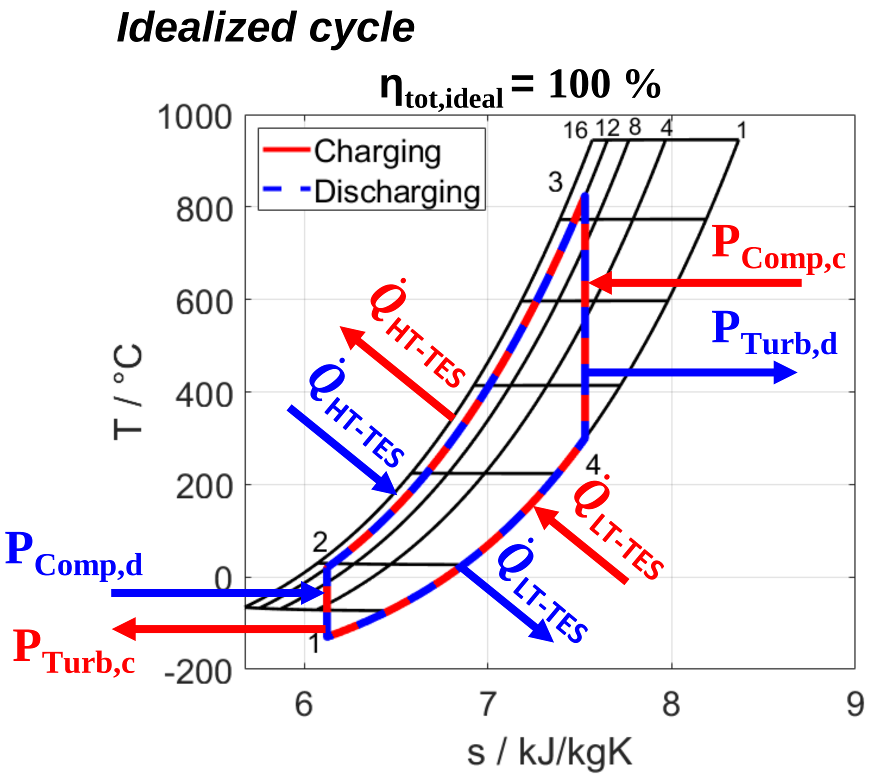
German Aerospace Center (DLR) - Institute of Engineering Thermodynamics

Stuttgart

DLR

Introduction: Brayton Battery
Working principle, with gas as a working medium





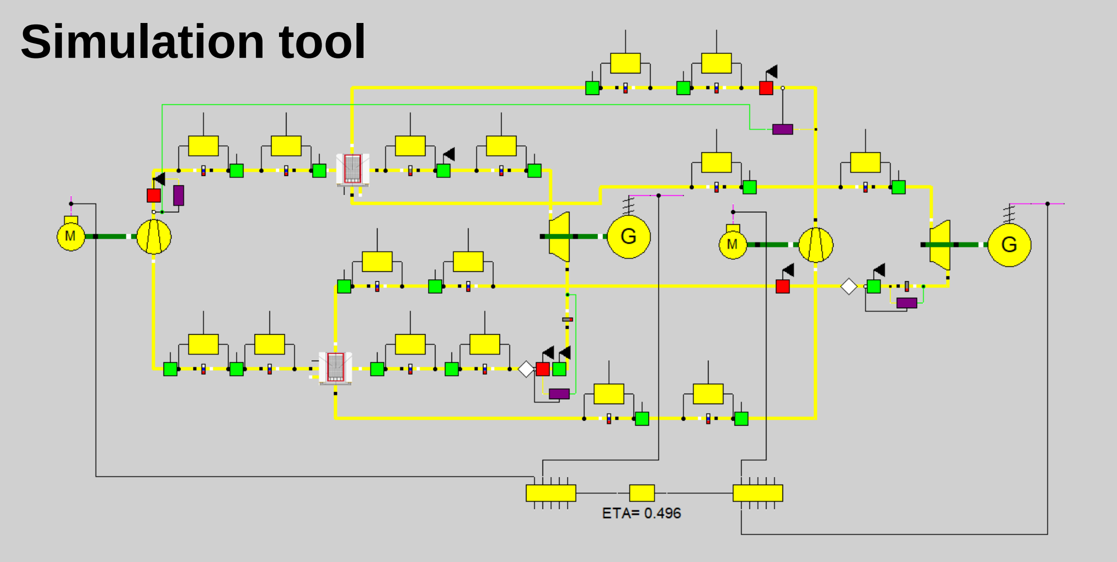
Motivation

- Carnot batteries can have potentially very high power-to-power efficiency.
- However, in the case of Brayton batteries, there exists a considerable disparity between theoretically attainable efficiency and what is realistically achievable.
- Throughout both charging and discharging cycles, a notable portion of the energy undergoes conversion into heat, which is either unusable or only partially utilized, especially when generating electricity alone.

→ As a result, in this concept study, the focus is on varying the topology and coupled generation with the primary goal of maximizing energy efficiency.

Methods

- To extend the plant benefits, the following options are considered:
  - pure electricity generation w/wo waste heat integration,
  - coupled generation of electricity/heat w/wo waste heat integration,
  - coupled generation of electricity/cooling w/wo waste heat integration,
  - coupled generation of electricity/heat/cooling.
- All theoretically possible integration points for heat exchangers for the input or output of heat into the plant were systematically investigated by system simulations (software Ebsilon Professional®).



Methods

- Variants:
  - Closed and open circuits were considered.
  - The compressor discharge temperature CDT of the charging line was set to 450 °C or 625 °C as a manipulated variable with the compressor discharge pressure as a controlled variable.
  - For the closed concepts, CO_2 and argon were considered as working fluids in addition to air.
  - For the air-driven system, variants with a recuperator to shift heat from the hot to the cold side of the charging line (and discharging line) were also looked at.
  - Choosen combinations for coolers & heaters: 1C∨1H, 2C∨2H, 1C∧1H, 1C∧2H, 2C∧1H, 2C∧2H

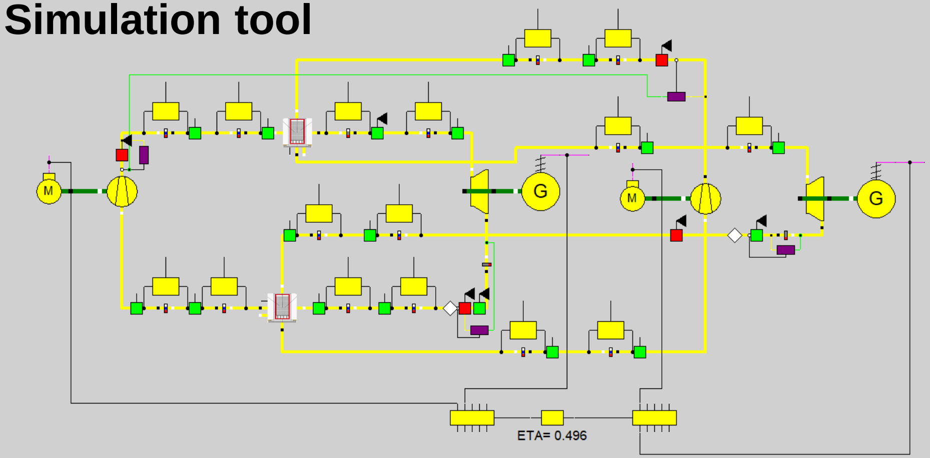
$$\binom{n}{k} = \frac{n!}{(n-k)!k!}$$

→ Almost 200,000 concepts were calculated.

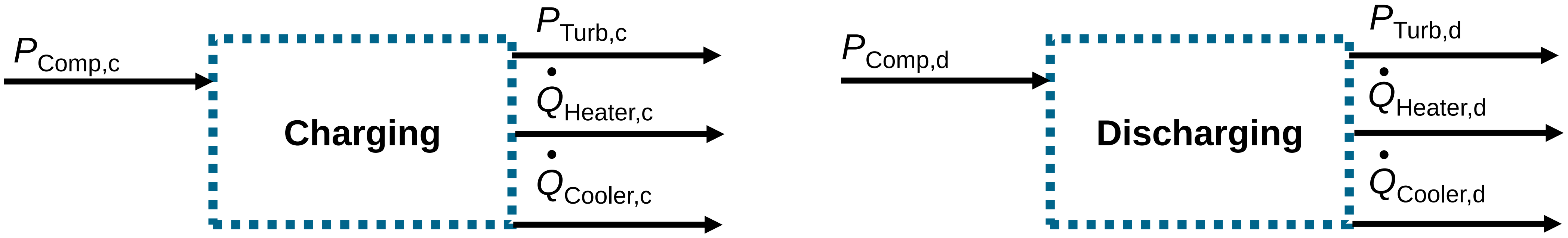
Boundary conditions

- Calculation of the states according to the ideal gas law
- Temperature level of the integrated waste heat (WHI): 90 °C
- Temperature level of the supplied heat (CHP): 250 °C
- Temperature level of the supplied cold (CCP): 6 °C
- Temperature gradient of external HEX: 10 K
- Temperature after compressor (controlled variable): 450 °C / 625 °C
- Pressure after compressor / turbine: manipulated variable / 1 bar
- Thermal energy storage efficiency: 0.95
- Recuperator efficiency: 0.9
- Isentropic efficiency TM: 0.9
- Mechanical Efficiency TM: 0.99
- Electrical efficiency motor: 0.97
- Mechanical efficiency motor: 0.998
- Generator electrical efficiency: 0.99
- Ambient temperature: 15 °C

Simulation tool



Efficiency definitions



- <u>Pure electricity generation:</u> Roundtrip efficiency

$$RTE = \frac{P_{\text{Turb,d}} - P_{\text{Comp,d}}}{P_{\text{Comp,c}} - P_{\text{Turb,c}}}$$

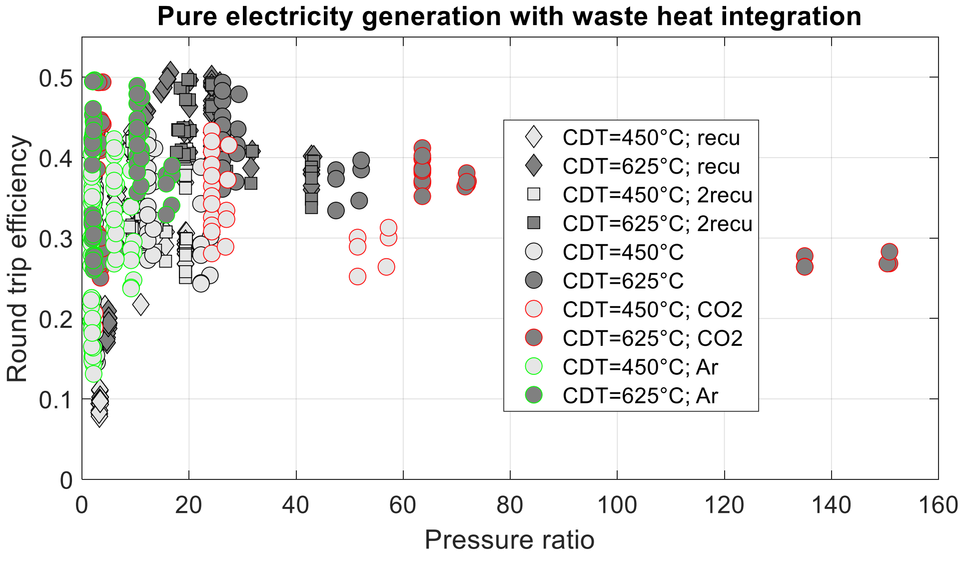
- <u>Coupled generation:</u> Roundtrip utilization

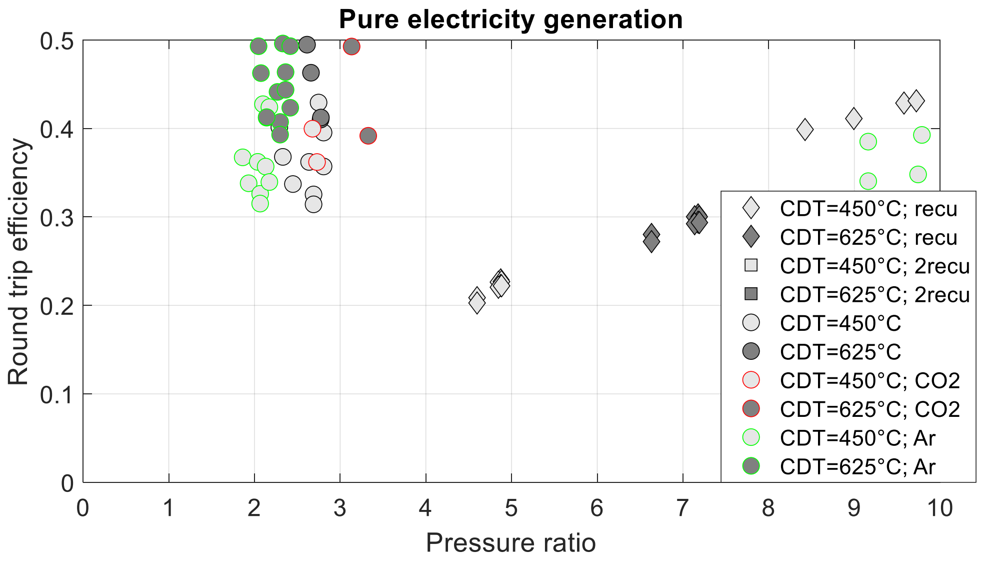
$$RTU = \frac{P_{\text{Turb,d}} - P_{\text{Comp,d}} + \dot{Q}_{\text{Heater,d}} + \dot{Q}_{\text{Cooler,d}}}{P_{\text{Comp,c}} - P_{\text{Turb,c}} - \dot{Q}_{\text{Heater,c}} - \dot{Q}_{\text{Cooler,c}}}$$

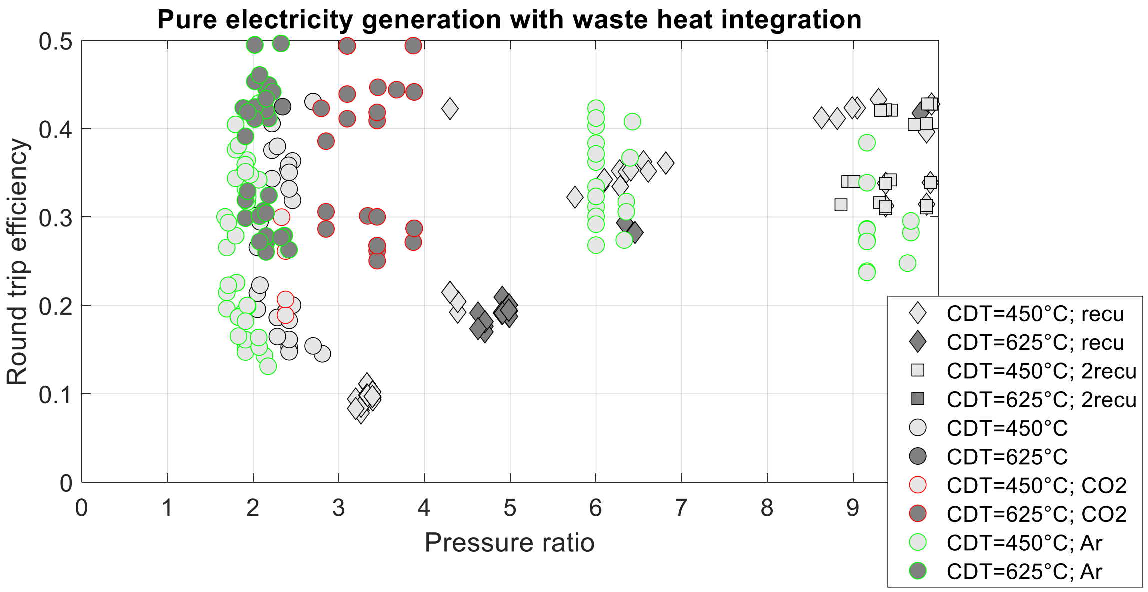
Only usable heat flows are included in the balance!

Results: Electricity generation with or w/o heat integration

- Less than 1% of the calculated concepts lead to physically feasible results.
- For pure electricity generation, round trip efficiencies in the range of 20 to 50 % are obtained.
- Concepts operating at CDT=450 °C exhibit lower round trip efficiencies compared to those at CDT=625 °C.
- There is no discernible trend concerning working fluids, and the same holds true for the inclusion or exclusion of recuperators.
- The incorporation of additional waste heat integration does not lead to significantly higher values.







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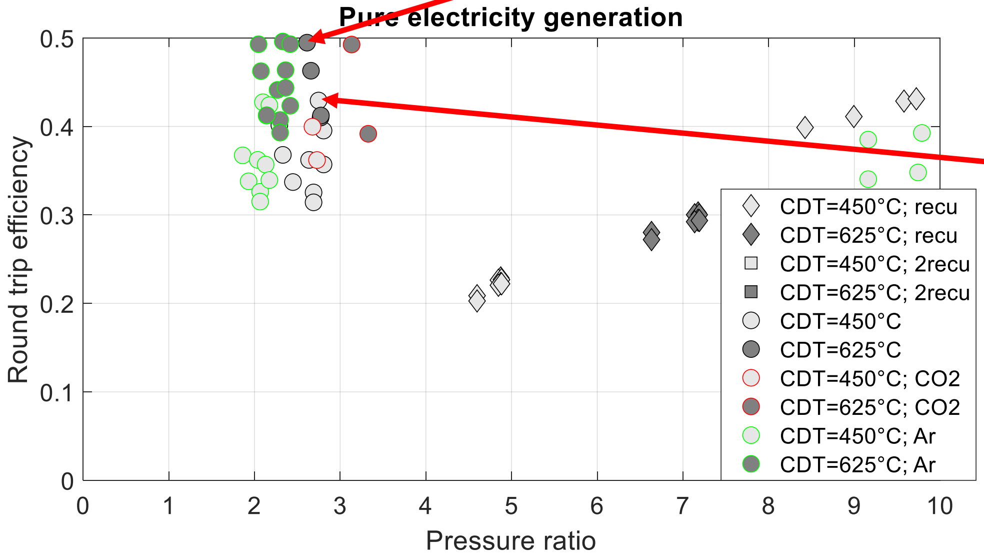
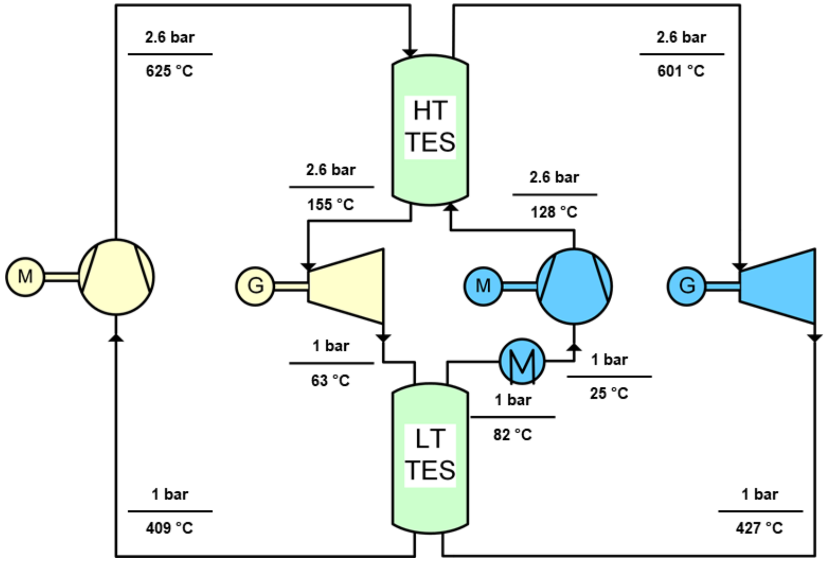


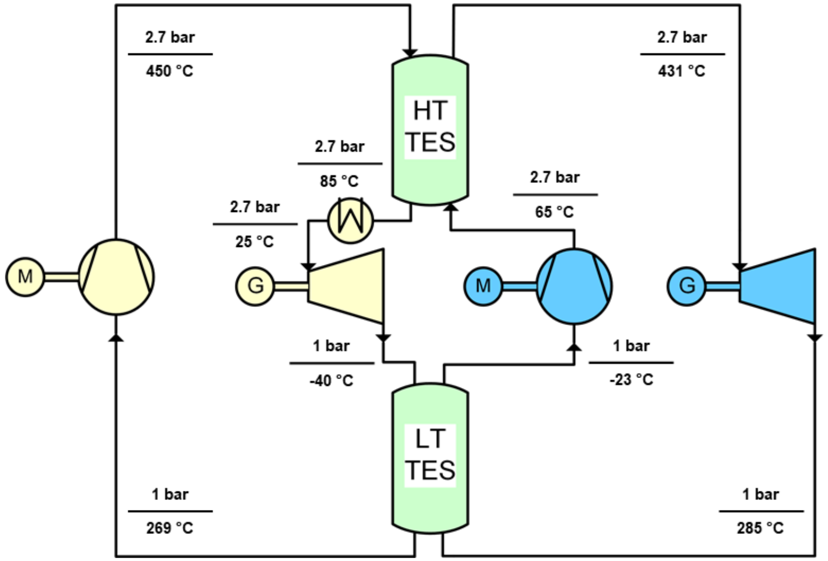


Lead concept

PEG 1

ϑ_{max}=625 °C; Π=2.6

RTE=49.5 %



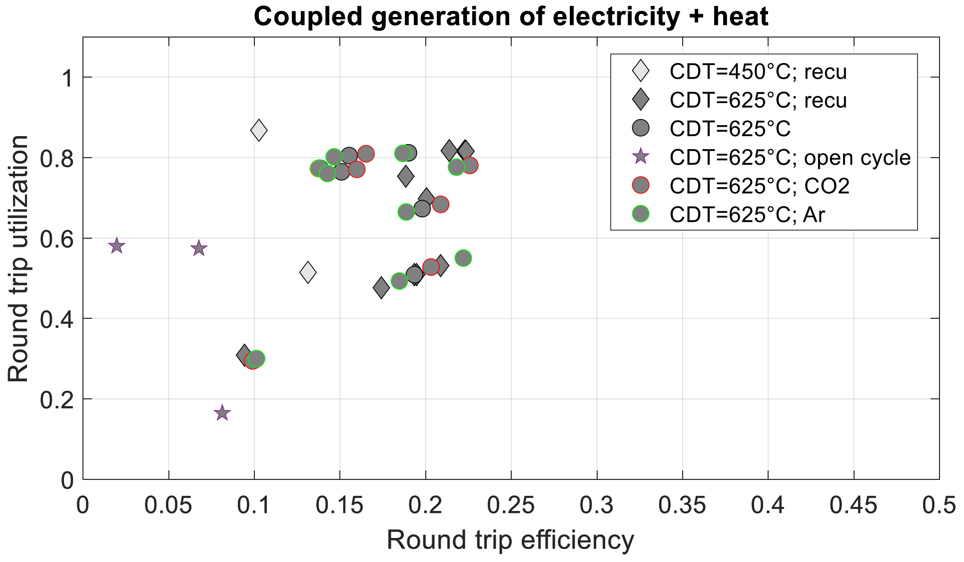
Lead concept

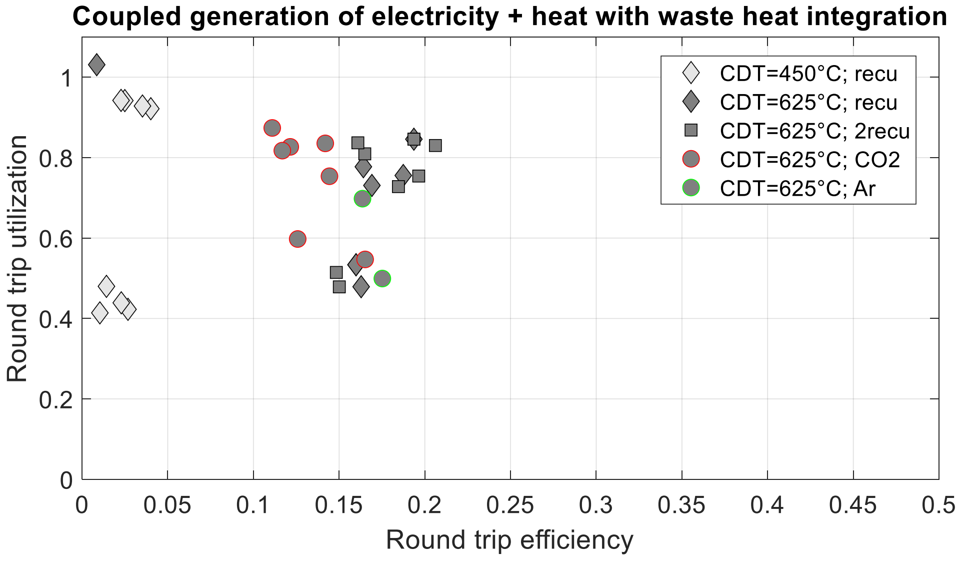
PEG 2

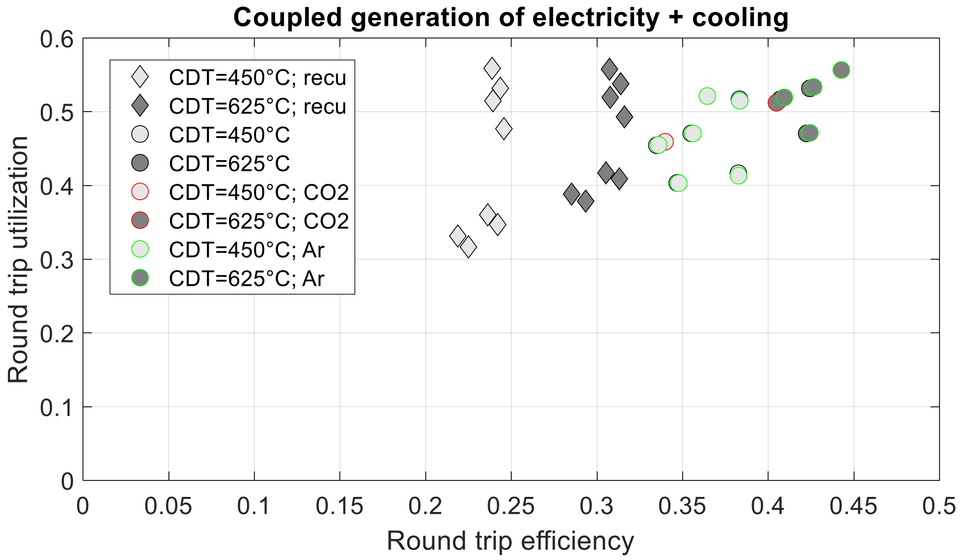
ϑ_{max}=450 °C; Π=2.7

RTE=42.9 %

Results: Coupled generation

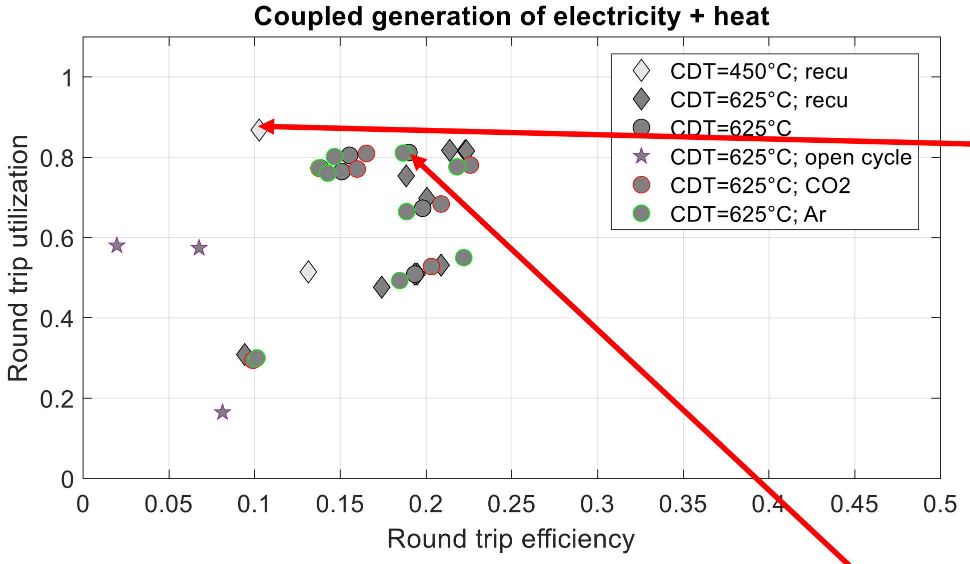


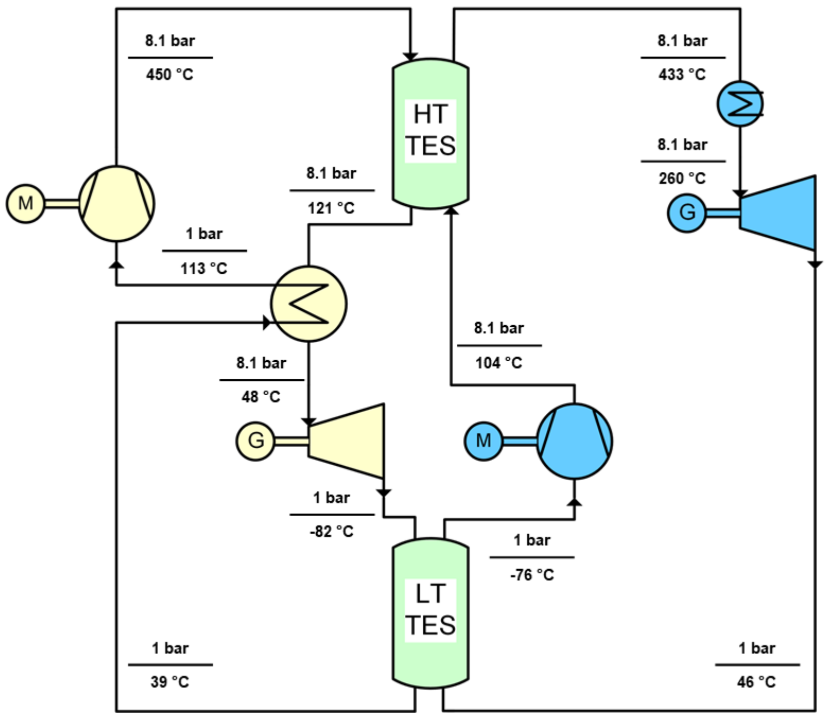




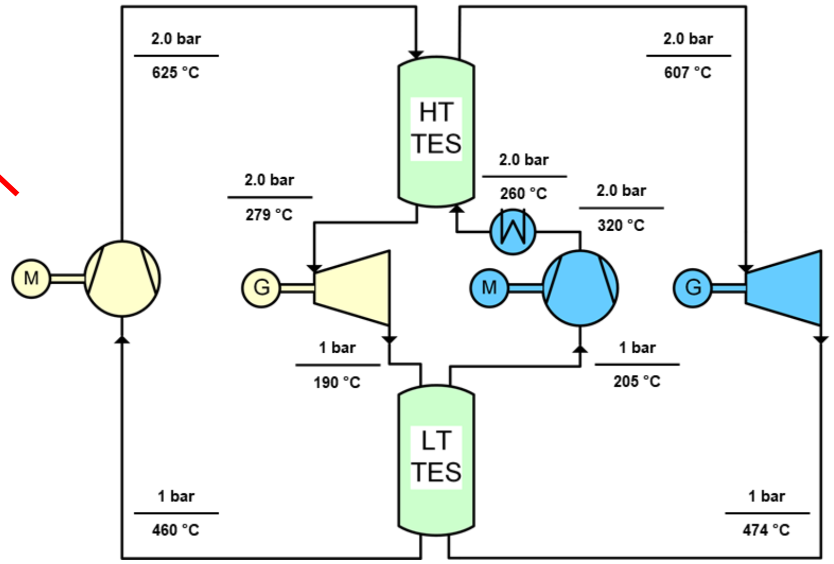
- Integrating additional waste heat results in concepts with increased values for heating but not for cooling.
- The coupled generation of electricity and heat or cooling enhances overall efficiency, reflected in elevated values for RTU. However, this comes at the expense of RTE.
- Concepts operating at CDT=450 °C exhibit lower RTE than those at CDT=625 °C, although RTU rates do not necessarily have to be lower.
- With regard to open concepts, very few solutions were achieved, and those that were attained exhibited low efficiencies.
- No clear trend can be observed with regard to the working fluids.
- The inclusion of a recuperator in the charging line enables the development of concepts for the coupled generation of electricity and heat at CDT=450 °C.

Results: Coupled generation



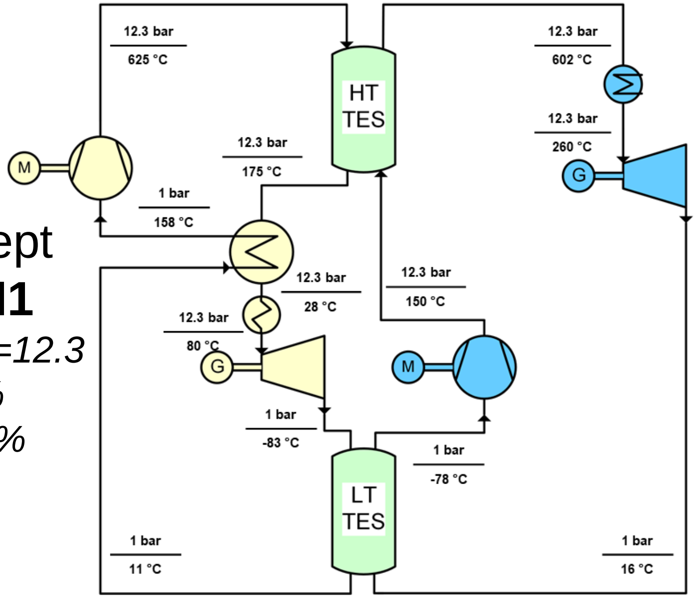


Lead concept
CHP1
ϑ_{max}=450 °C; Π=8.1
RTE=10.3 %
RTU=86.8 %

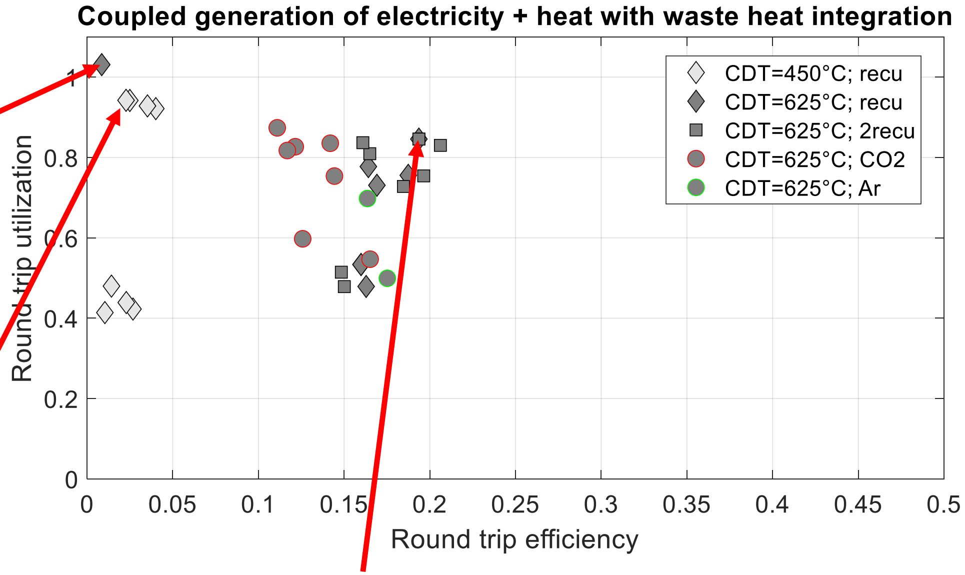


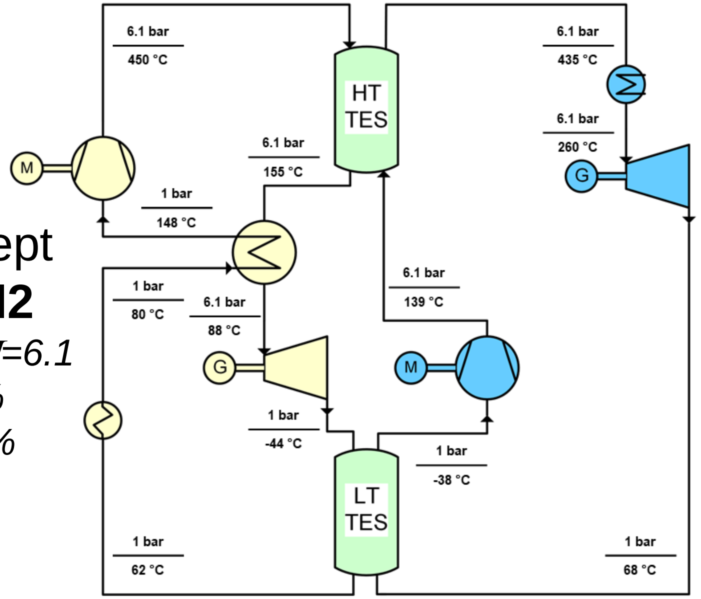
Lead concept
CHP2
ϑ_{max}=625 °C; Π=2.0
RTE=19.0 %
RTU=81.2 %

Results: Coupled generation

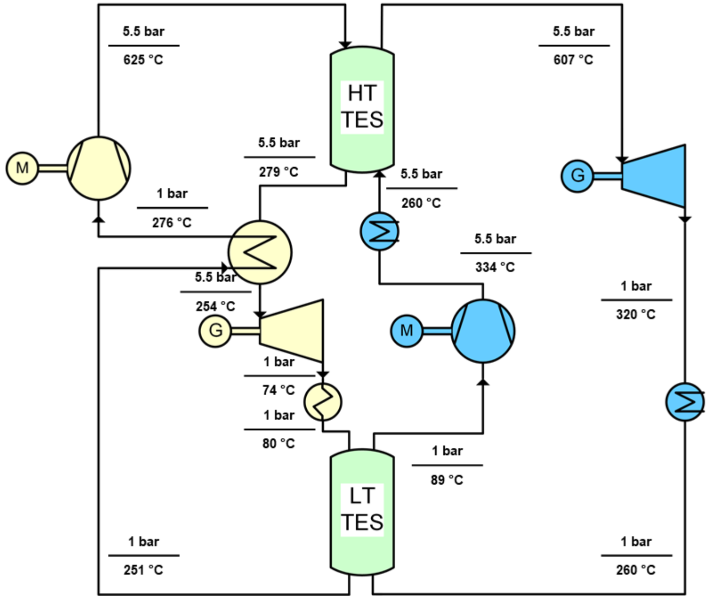


Lead concept
CHP+WHI1
ϑ_{max}=625 °C; Π=12.3
RTE=0.9 %
RTU=103.1 %



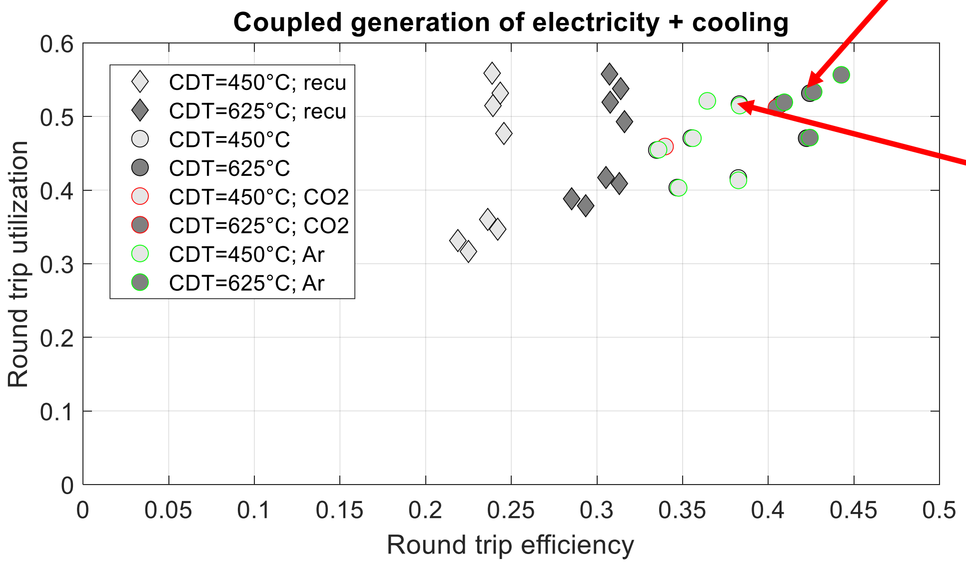


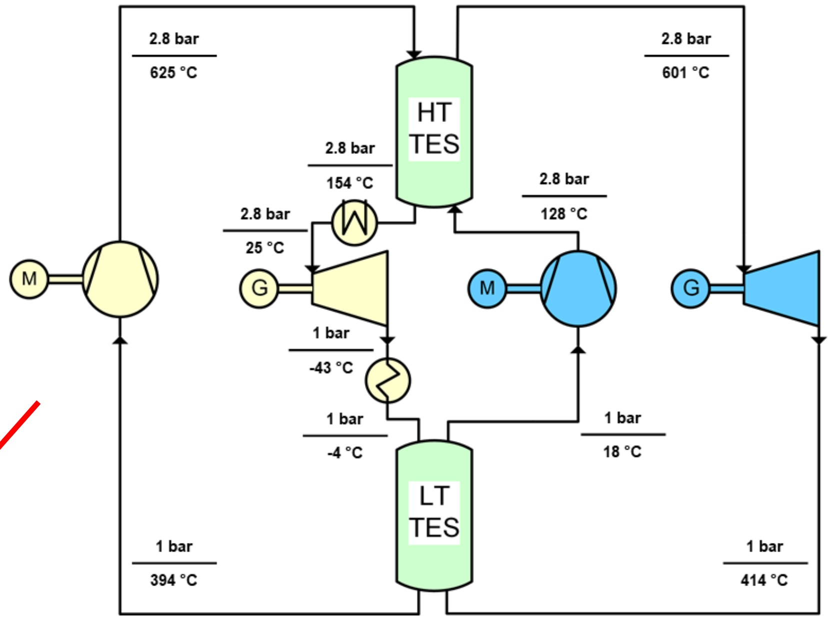
Lead concept
CHP+WHI2
ϑ_{max}=450 °C; Π=6.1
RTE=2.5 %
RTU=94.2 %



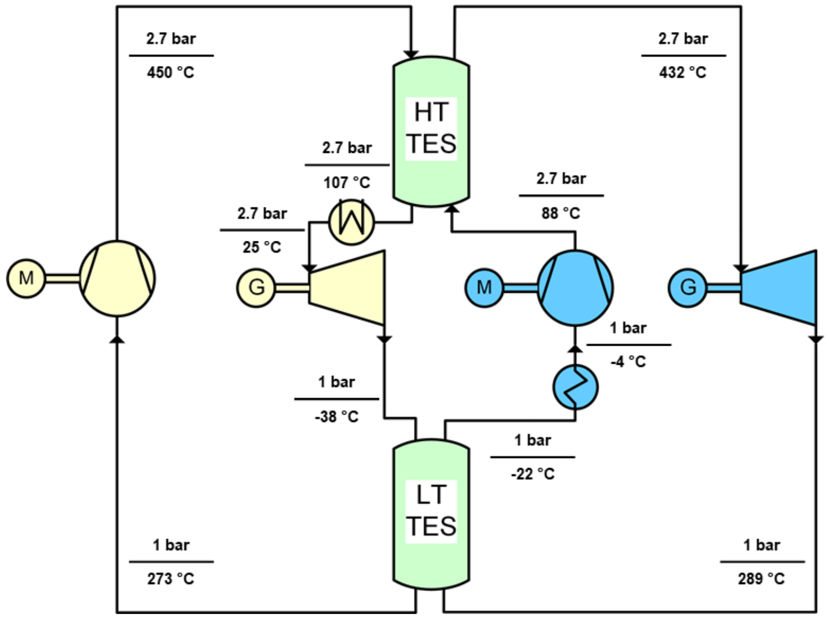
Lead concept
CHP+WHI3
ϑ_{max}=625 °C; Π=5.5
RTE=19.4 %
RTU=84.6 %

Results: Coupled generation



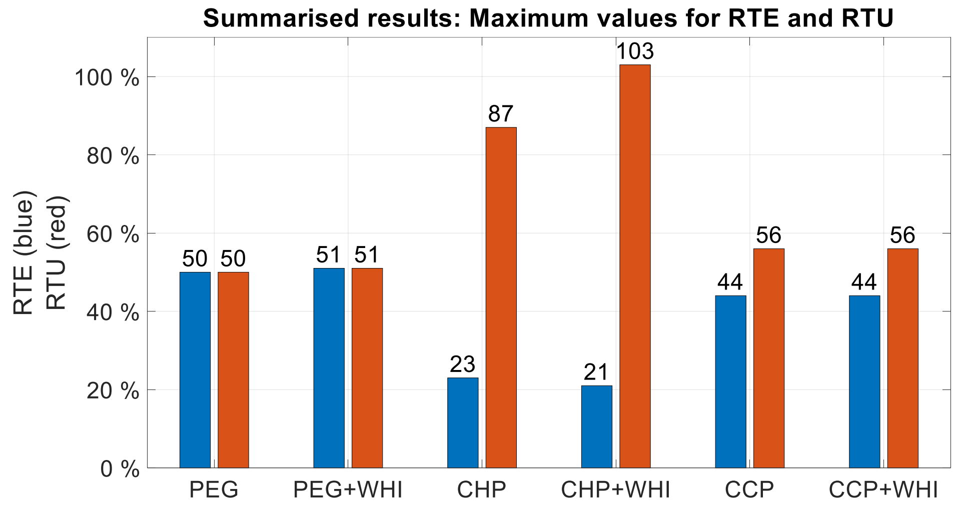


Lead concept
CCP1
ϑ_{max}=625 °C; Π=2.8
RTE=42.4 %
RTU=53.2 %



Lead concept
CCP2
ϑ_{max}=450 °C; Π=2.7
RTE=38.3 %
RTU=51.7 %

Summary & Outlook



- A universal simulation tool was created for a systematic structural analysis of Brayton batteries.
- For a specific set of boundary conditions, a concept study was conducted for various applications, resulting in the computation of over 200,000 concepts
- This allowed us to identify lead concepts that demonstrate exceptional efficiency for these applications.
- The identified lead concepts are all air-driven systems at relatively low pressures (<13 bar) with or without a recuperator in the charging line, and with heat supply or removal at different points in the process, whereby CDT of 450°C or 625°C were considered.
- These lead concepts are currently being investigated in more detail through dynamic system simulations, including the design of the components, particularly focusing on thermal energy storage units.

Thank you for your interest!

German Aerospace Center (DLR)
Institute of Engineering Thermodynamics | Thermal Process Technology |
Pfaffenwaldring 38-40 | 70569 Stuttgart | Germany

Dr.-Ing. **Michael Krüger** | Project leader
Telefon 0711/6862-417 | Telefax 0711/6862-747 | michael.krueger@dlr.de
www.DLR.de

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