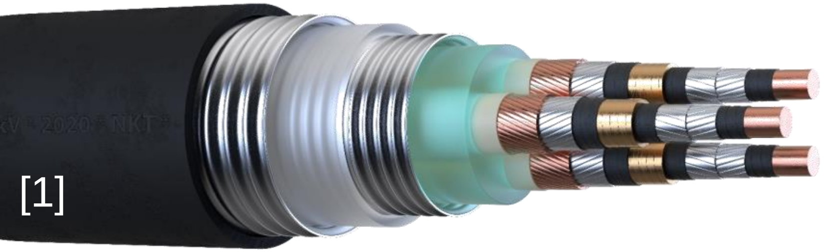
Optimization of cryogenic mixed-refrigerant cascades for intermediate cooling stations of the long-distance superconducting power cable SuperLink

F. Boehm, W. Batista de Sousa, S. Grohmann, International Cryogenic Engineering Conference, July 25, 2024

SuperLink – 15 km sc. HV cable in Munich

- Progressing electrification due to energy transition
- Upgrading power grid is imperative (age, performance)


[1]

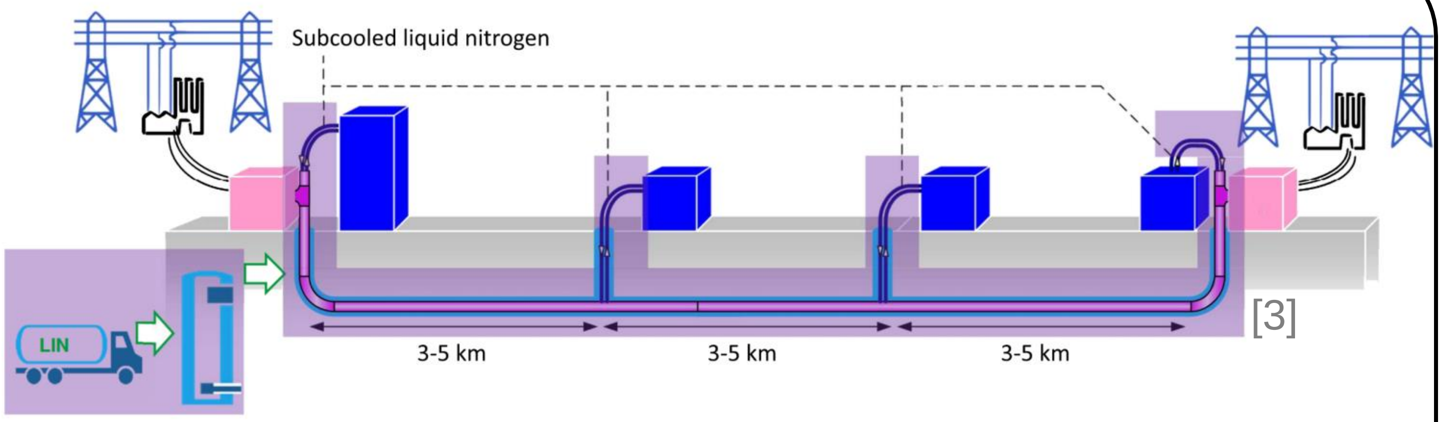
[1] www.nkt.de

- Lower space demand
- No electromagnetic emissions
- No joule heating
- Higher transmission performance

[2] NKT

SuperLink – Closed cycle cooling stations

- Cooling temperature below 77 K
- 15-30 kW per cooling station
- Low-maintenance → reliability
- Low space requirement
- Low energy demand

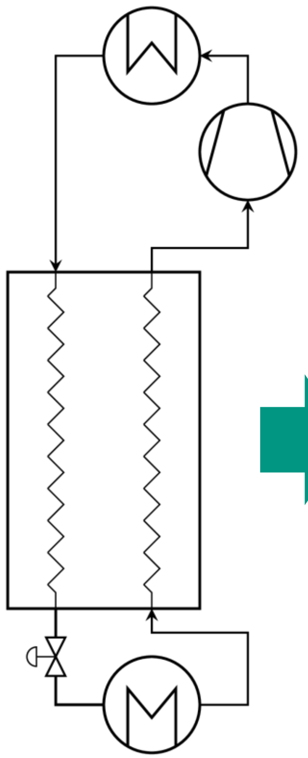


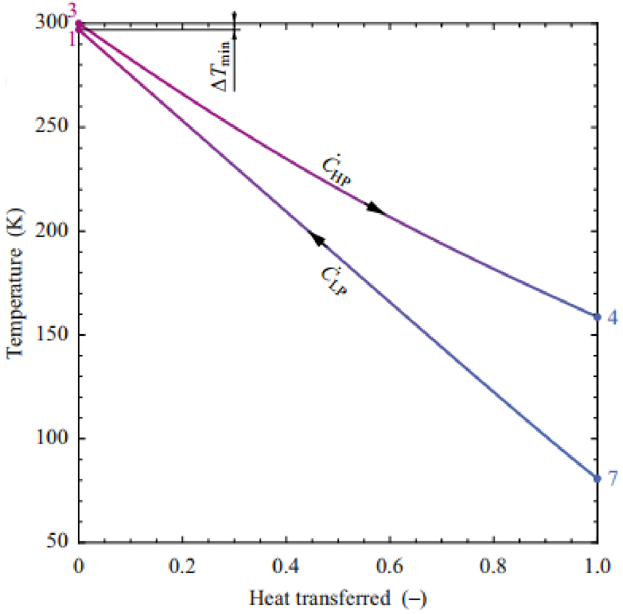
[3] Alekseev et al. 2020

- Cooling systems are the main contributor to energy demand
  - 1st and 2nd law of thermodynamics → $P = \sum T_U \cdot \dot{S}_{i,\mathrm{irr}}$
  - Δp: $\dot{S}_{i,\mathrm{irr}} \propto -\frac{v}{T}\mathrm{d}p$
  - ΔT: $\dot{S}_{i,\mathrm{irr}} \propto \frac{T_1 - T_2}{T_1 \cdot T_2}$

Influence of ΔT and Δp increases at cryogenic temperatures

Why mixed refrigerants? – The Linde Hampson Cycle





- Easiest cryogenic cooling cycle
  - Capacity flows do not match for pure refrigerants
    → ΔT increases entropy production

$$\Delta s_{\mathrm{irr}} = \int \frac{T_{\mathrm{h}} - T_{\mathrm{c}}}{T_{\mathrm{h}} T_{\mathrm{c}}} \mathrm{d}q$$

- Improvement by matching capacity flows
  → constant ΔT along inner CFHX
  - … by adjusting massflows in CFHX
    - e.g. Claude process
  - … by using wide boiling refrigerant mixtures
    - Cryogenic mixed-refrigerant cycle (CMRC)

Why mixed refrigerants? – Refrigerant Design

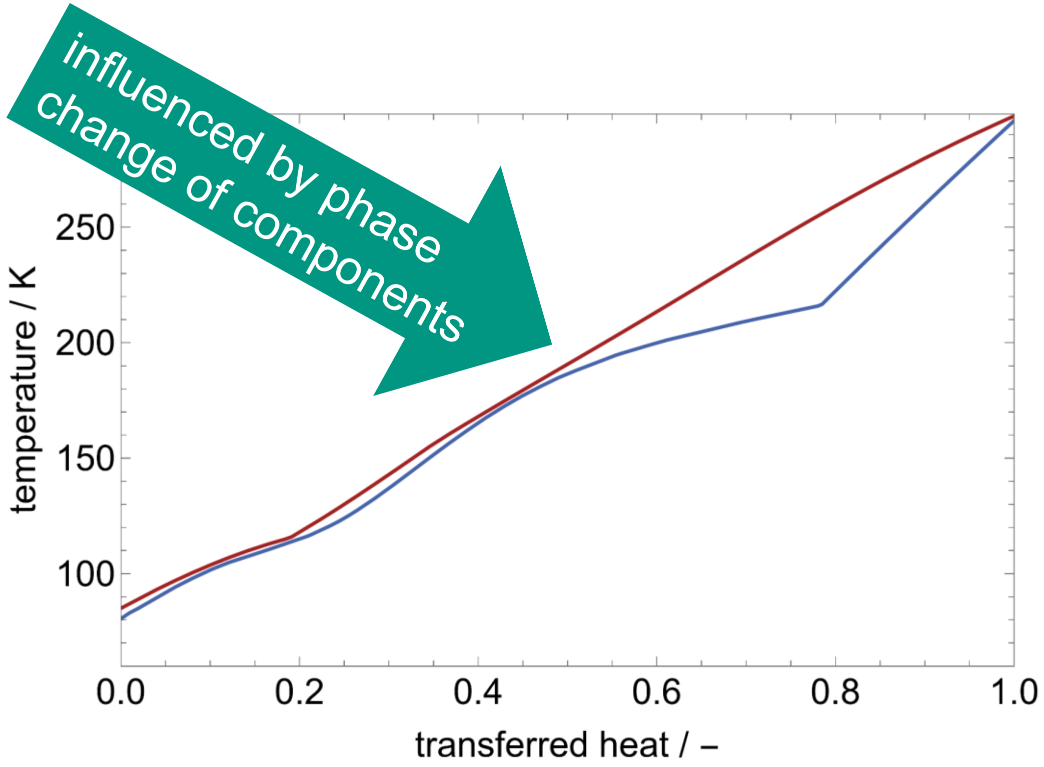
Cooling task
$\dot{Q}_0, T_0$

Process Design

- Pure refrigerant which is the „best match“ to requirements
- ↓
- Optimize for efficiency through more complex process topology

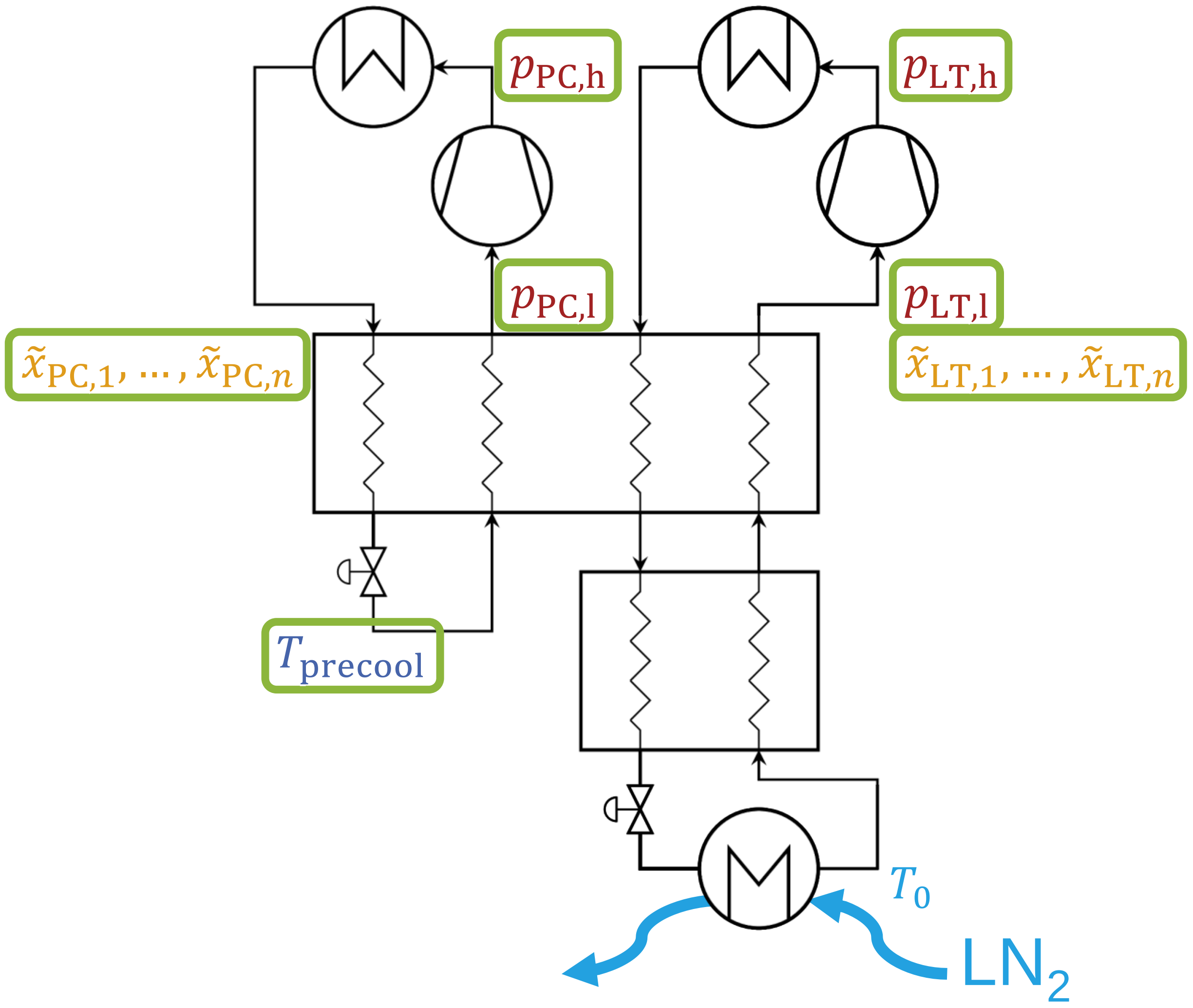
Refrigerant Design

- „Design“ of desired refrigerant behavior
- ↓
- Simple process with high efficiency



Key component of every cooling system is the refrigerant!

CMRC cascade



- Single-stage CMRC inefficient for very low temperatures (70 K)
  - Amount of high boiling components must be drastically reduced to avoid freeze-out

→ CMRC cascade

- precooling (PC) stage
  - cooling down to T_{precool}
- low temperature (LT) stage
  - cooling at T_0

Process simulation

Karlsruhe Institute of Technology

Analysis

- Energy demand
- Temperature profiles

Process Modeling

- Steady-state calculation
- T_0, T_c, ΔT, p, Δp are given

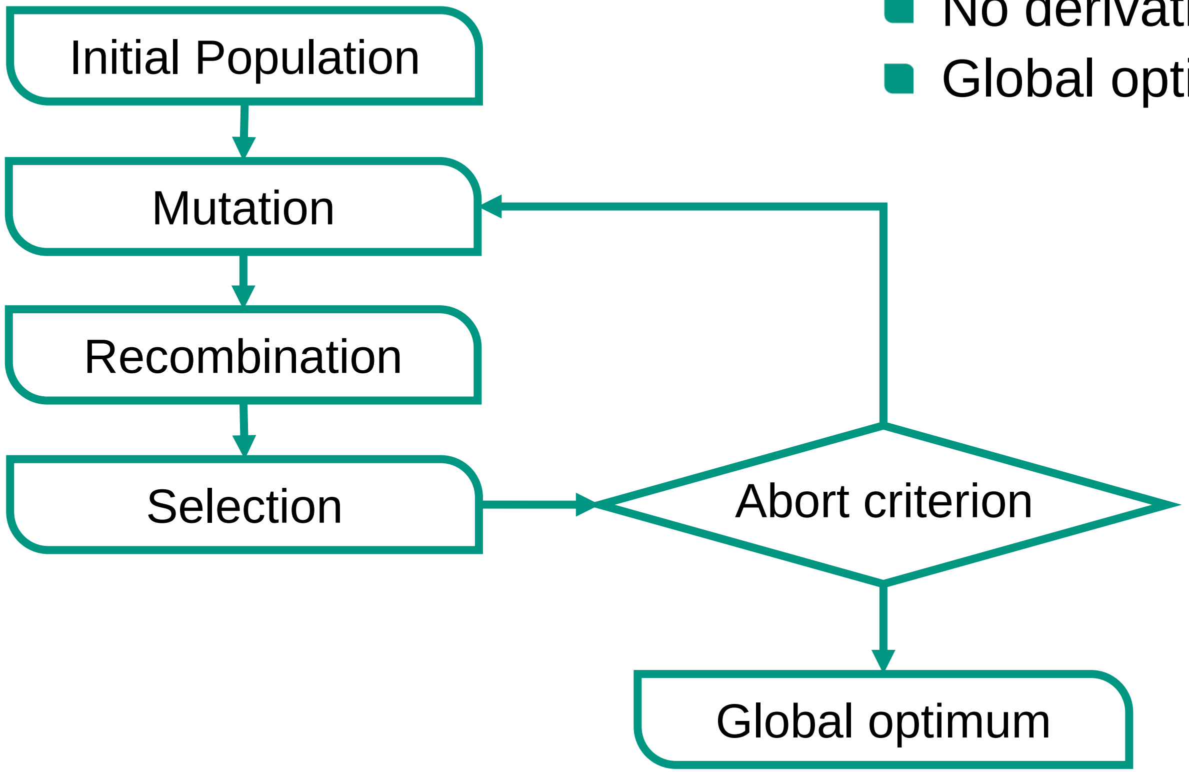
Thermodynamic Property Data

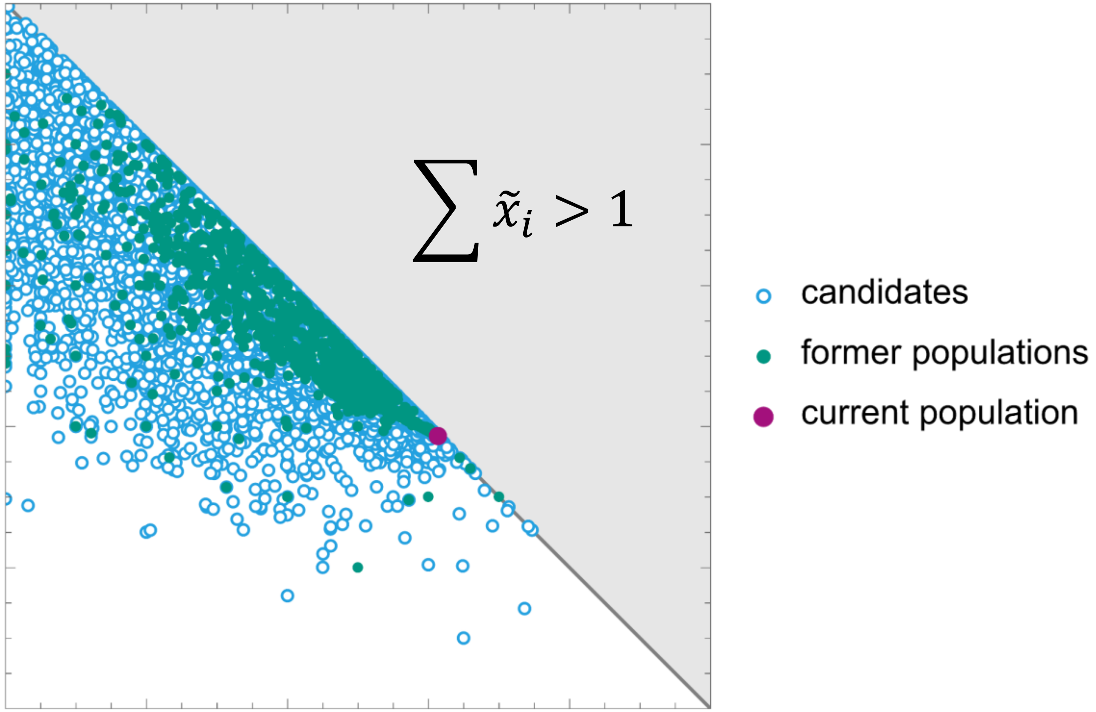
- Open-Source Tool CoolProp[4]
- EoS: Peng-Robinson

[4] I.H. Bell et al. 2014

Optimization by genetic algorithm[5]

- Differential Evolution (DE) [6,7]
  - No derivatives needed
  - Global optimization → „Exploration & Exploitation“



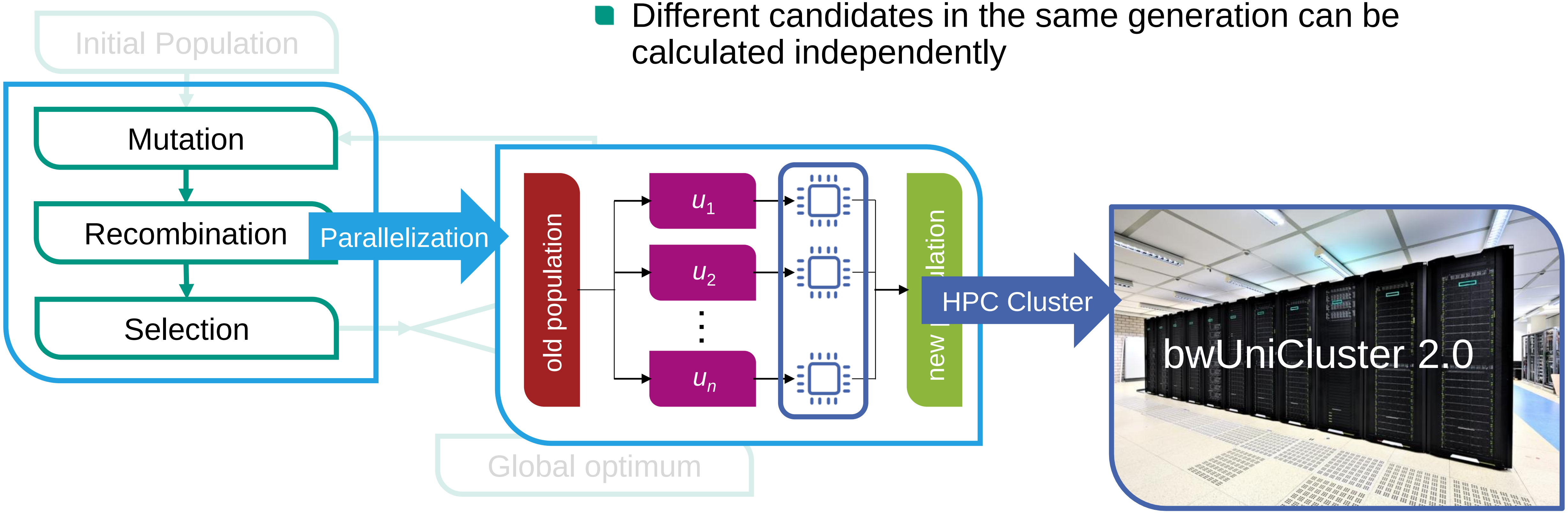


[6] R. Storn und K. Price 1997
[7] K. Price et al. 2005

Optimization by genetic algorithm[5]

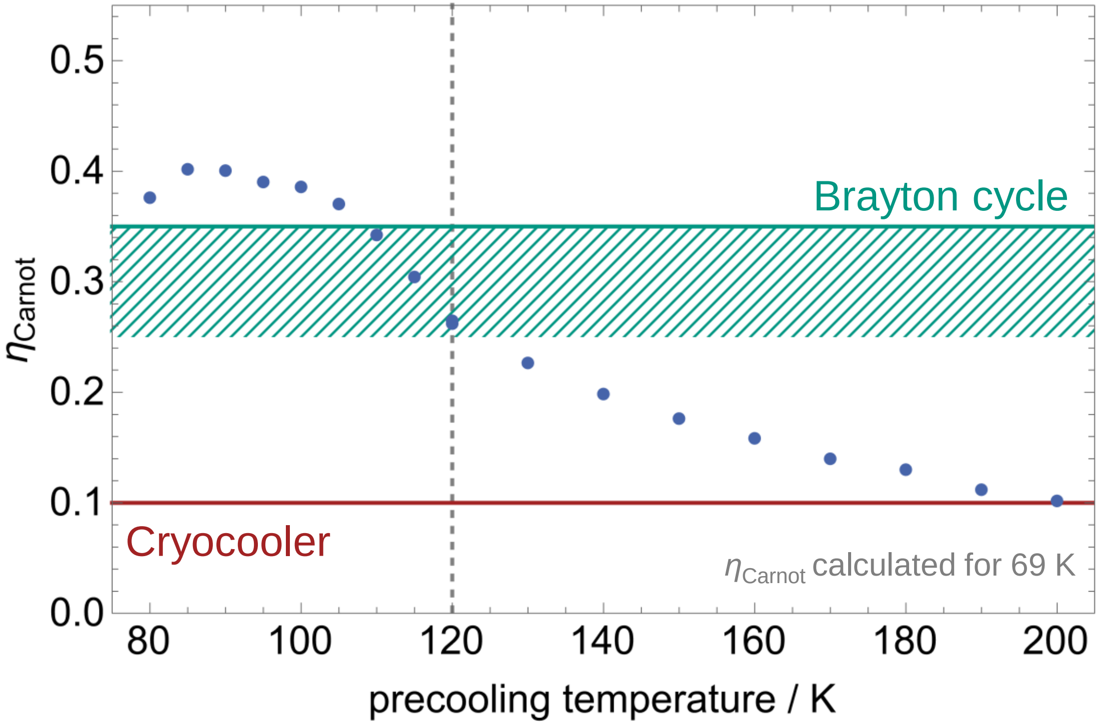
Karlsruhe Institute of Technology

- DE is predestined to parallelization
  - Different candidates in the same generation can be calculated independently



[8] SCC, KIT

Total Carnot efficiency for different $T_{precool}$

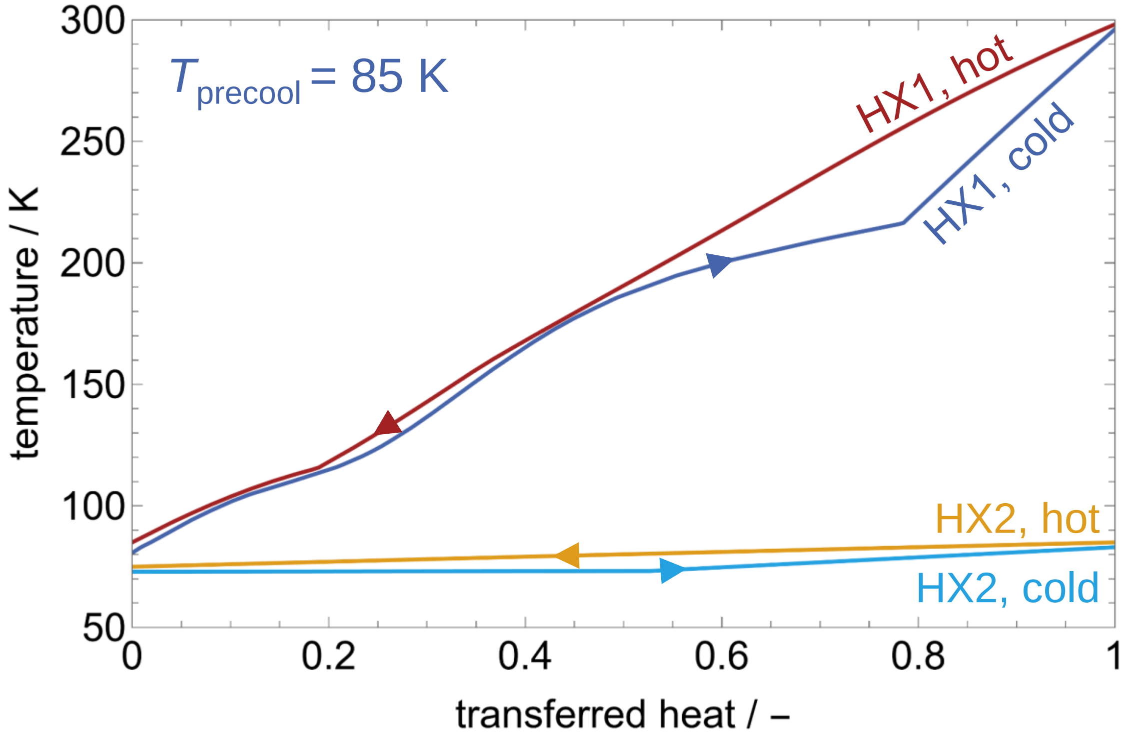


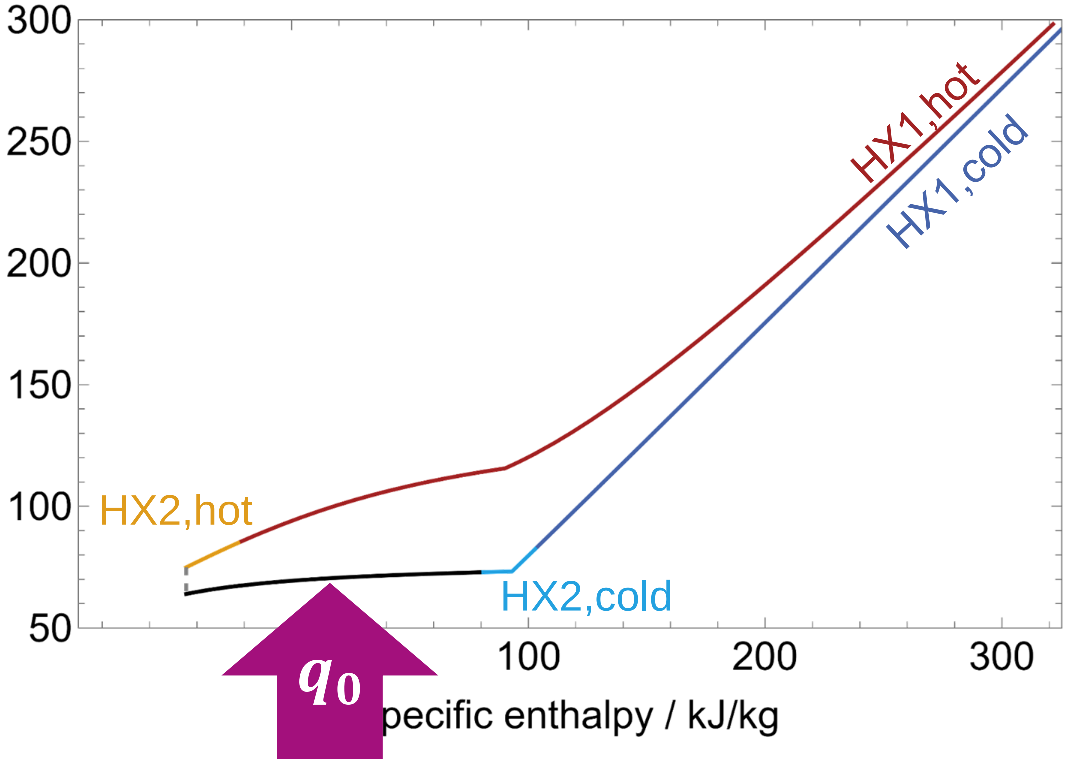
T_0	64 K – 74 K
T_a	293.15 K
ΔT_a	5 K
ΔT_{min}	2 K
η_{is}	0.7

$T_{precool}$	80 … 200 K
p_{ND}	1 … 20 bar
p_{HD}	10 … 60 bar
$\tilde{x}_i$	0 … 1

- liquid refrigerant supply (LRS) to HX2 for $T \leq 120$ K
  → significantly improves efficiency of low temperature stage

HX temperature profiles and T-h plot for LT stage





Conclusions and outlook

Simulation results

- Successful implementation of genetic CMRC cascade optimization algorithm
- Precooling temperatures below 120 K improve efficiency
- Very good match of capacity flow rates within heat exchangers

Technology outlook

- Compared to Turbo-Brayton cycles, **CMRC cascades** have
  - higher Carnot efficiency (> 40 %)
  - higher power density (2-phase)
  - no cold expanders
  - scalable technology
- **Next steps**
  - Prototype development?
  - Test facility COMPASS[9] available

Thank you for your attention!

Karlsruhe Institute of Technology

Bibliography

[1] https://www.nkt.de/presse-events/nkt-entwickelt-den-prototyp-fuer-das-weltweit-laengste-supraleitende-stromkabel, last checked: 17 July 2024,

[2] NKT, private communication

[3] A. Alekseev, S. Grohmann and L. Decker, „Anforderungen an das Kühlsystem für lange HTSL-Leistungskabel“, german, 2020. DKV Tagung 2020 online, A I.11, 19-20 November 2020

[4] I.H. Bell, J. Wronski, S. Quoilin and V. Lemort, “Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp”, Industrial & Engineering Chemistry Research 53, S. 2498–2508, ISSN 0888-5885. 2014.

[5] F. Boehm and S. Grohmann, "Modelling and optimization of cryogenic mixed-refrigerant cycles for the cooling of superconducting power cables." IOP Conference Series: Materials Science and Engineering. Vol. 1301. No. 1. IOP Publishing, 2024. doi: 10.1088/1757-899X/1301/1/012132

[6] R. Storn and K. Price, „Differential Evolution - A Simple and Efficient Heuristic for global Optimization over Continuous Spaces“, Journal of Global Optimization, 11, S. 341-359, 1997. doi: 10.1023/A:1008202821328

[7] K. Price, R. Storn and J. Lampinen, „Differential Evolution - A Practical Approach to Global Optimization“, Springer Berlin, Heidelberg. ISBN: 978-3-540-20950-8. 2005.

[8] https://www.scc.kit.edu/dienste/bwUniCluster_2.0.php, last checked: 17 July 2024

[9] J. Arnsberg, M. Stamm, and S. Grohmann. “Design of a High-Current Cryogenic Test Stand for Compact Accelerator Systems”. In: 26th IIR International Congress of Refrigeration - Refrigeration Science and Technology Proceedings. 26th IIR International Congress of Refrigeration. Vol. 1. Paris, France, Aug. 21, 2023, pp. 231–239. DOI: 10.18462/iir.icr.2023.0290.