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2024

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ETH zürich

CO_2-neutral process steam for industry: Model-based analysis of technologies and strategies

Steam generating heat pumps, OST Webinar, 18 March 2024

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ENERGY & PROCESS SYSTEMS ENGINEERING

CO2-neutral process steam: Model-based analysis of technologies and strategies

Niklas Nolzen, Luisa Evering, Claudio Schmid, André Bardow, Dennis Roskosch

Steam-generating heat pumps, OST Webinar
18 March 2024

Starting point: Steam supply of industrial sites

How to decarbonize?

Steam

Images: Colourbox

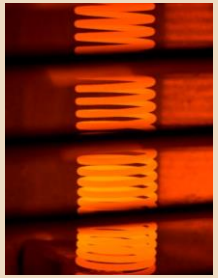
Technologies for decarbonizing steam production

Renewable electricity

Green hydrogen

Heatpumps

Direct electrical

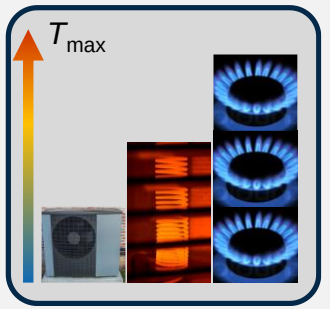


Boiler

CHP

Efficiency

Economics



Feasibility

Flexibility

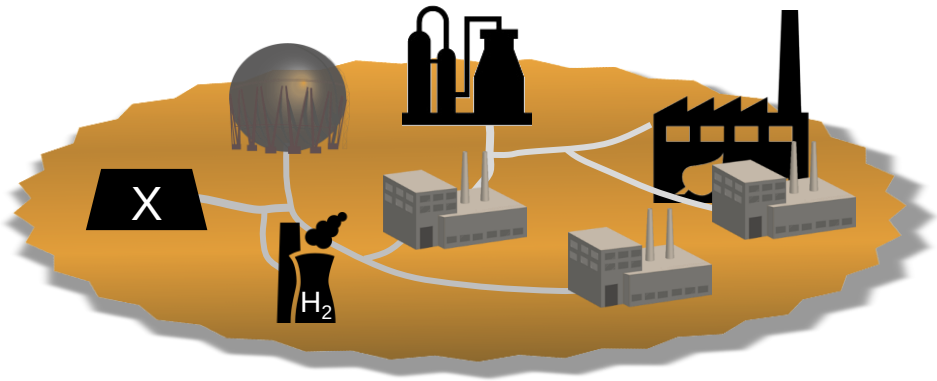
System analysis required!

Images: Colourbox

From process to system optimization

Technologies are not market-ready!

Process specifications

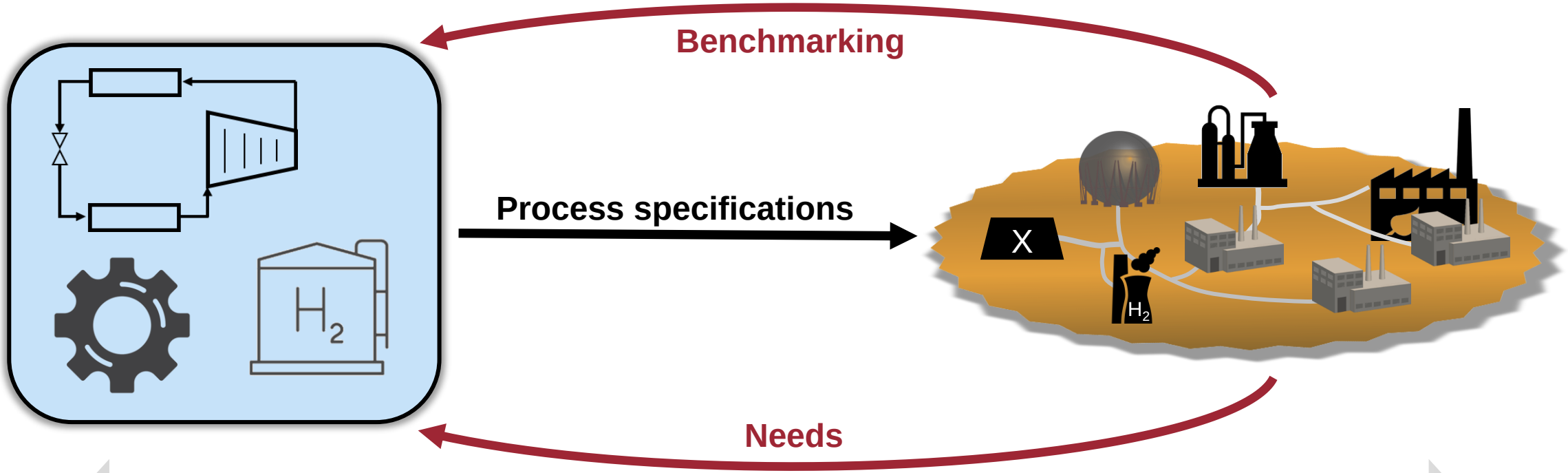


System design

Cover the trade-offs

Images: Colourbox

From process to system optimization



Images: Colourbox

From process to system optimization

Nat. gas
5.4 TWh/a

Alternative technologies for decarbonisation

M. Prenzel, T. Bauer, S. Kirschbaum, A. Reimer; Definition der idealtypischen Chemieparkversorgungsstruktur für TOP-Energy; DLR, GF_aI; 2021

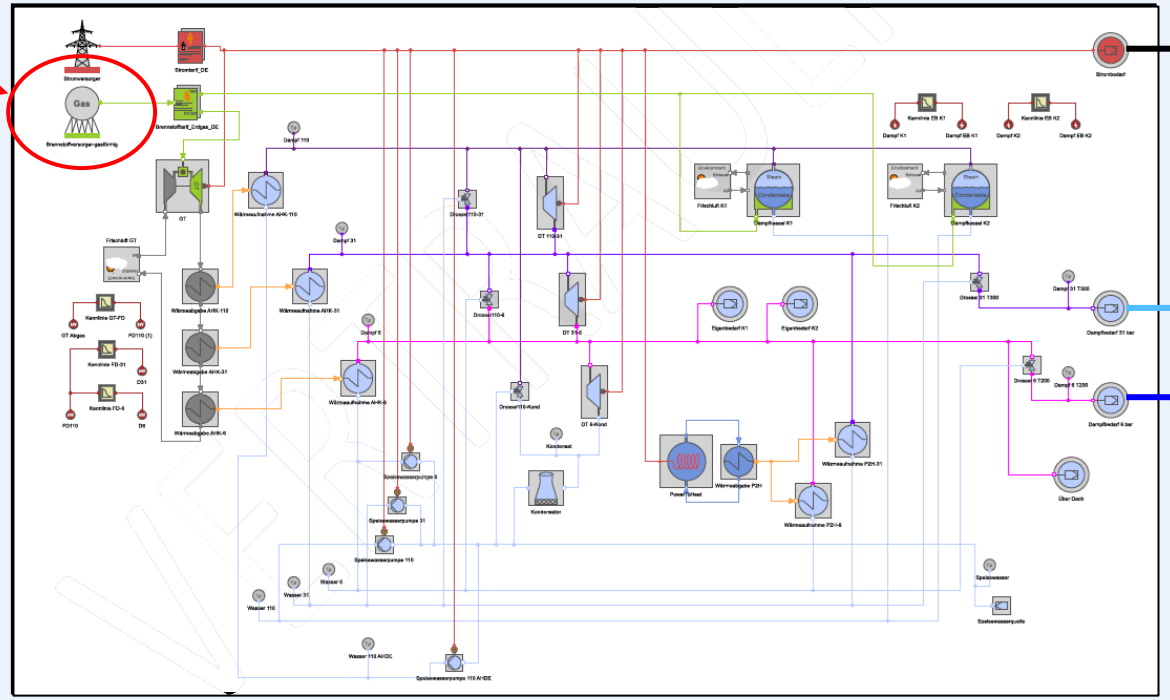
Images: Colourbox

From process to system optimization

Nat. gas
5.4 TWh/a

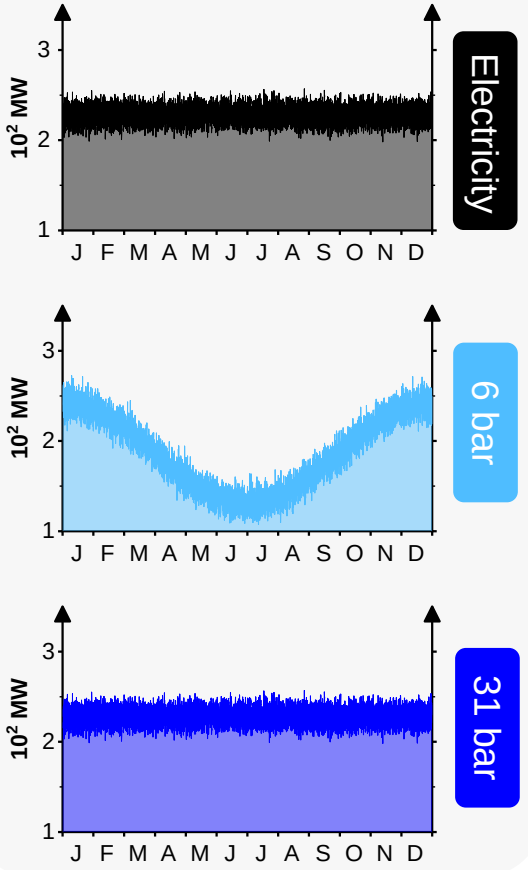
Alternative technologies for decarbonisation

Energy system



Fossil-based (natural gas) steam production of a typical chemical park

Demands



M. Prenzel, T. Bauer, S. Kirschbaum, A. Reimer; Definition der idealtypischen Chemieparkversorgungsstruktur für TOP-Energy; DLR, GF_aI; 2021

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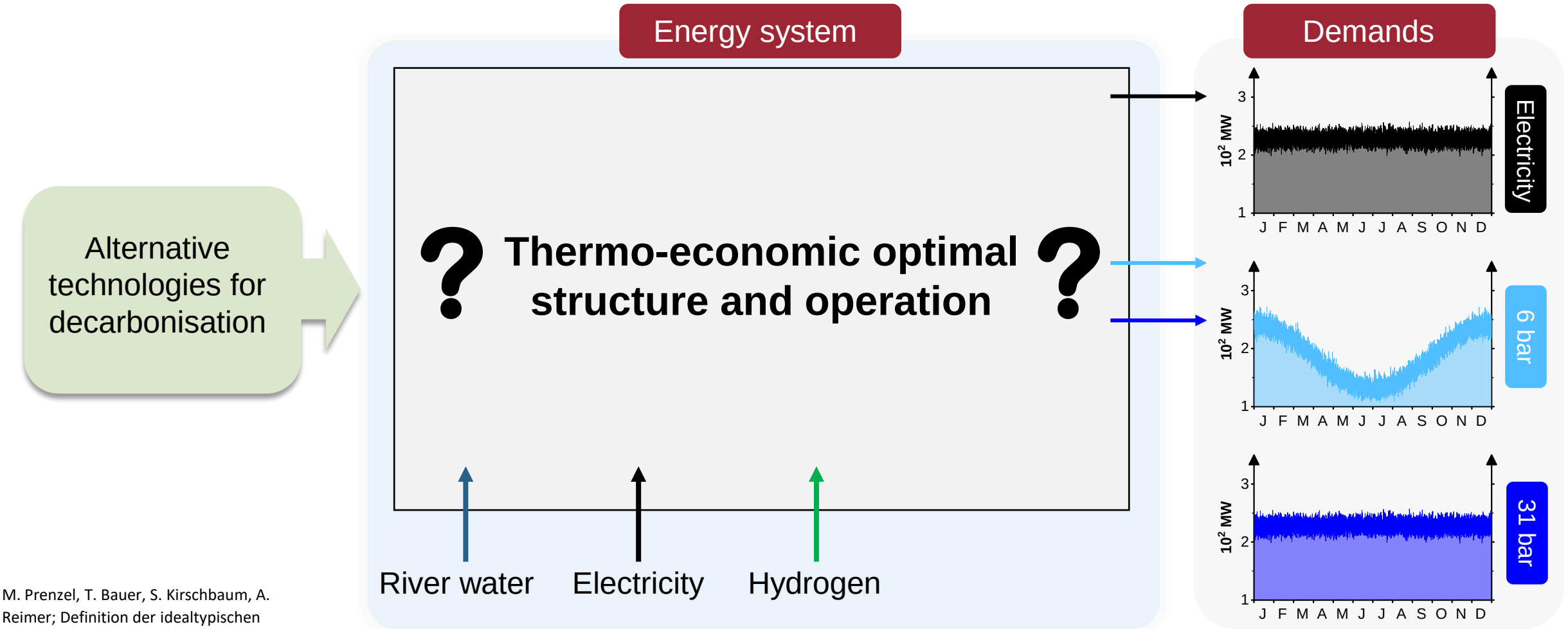
From process to system optimization

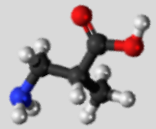


M. Prenzel, T. Bauer, S. Kirschbaum, A. Reimer; Definition der idealtypischen Chemieparkversorgungsstruktur für TOP-Energy; DLR, GF_aI; 2021

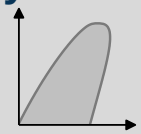
Images: Colourbox

Heat pump modeling
Refrigerant selection and process optimization

457 refrigerants
- **337 pure**
- **120 mixtures**



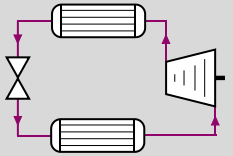
Thermo-dynamics



Components

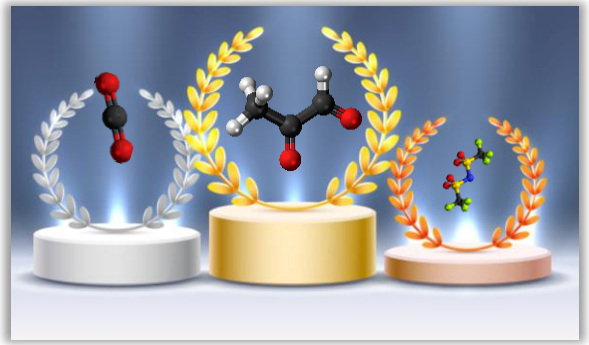
x

Process



$$\max_x \mathrm{COP}(x)$$
$$\text{s.t. } g_1(x) \le 0$$
$$x_{\mathrm{lb}} \le x \le x_{\mathrm{ub}}$$

GWP<150
ODP = 0
Low toxicity

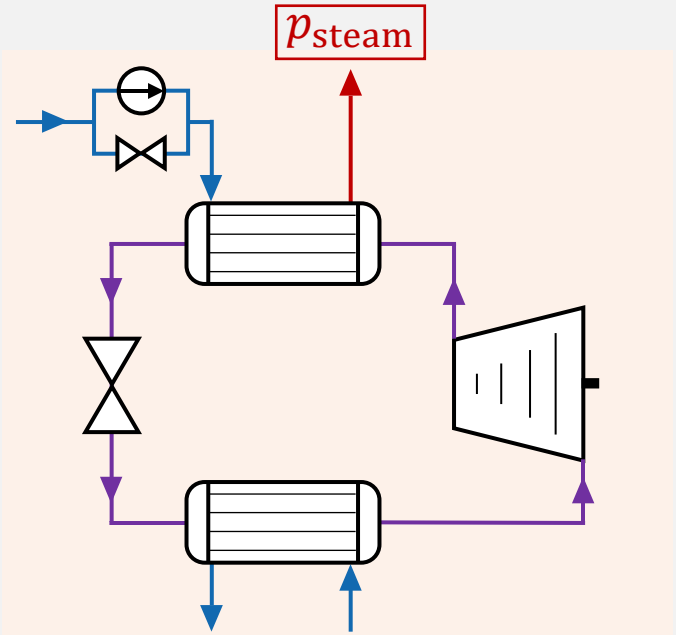


D. Roskosch, B. Atakan, Energy 2015, 81, 202–212.

D. Roskosch, V. Venzik, B. Atakan, Renewable Energy 2020, 147, 2865–2873.

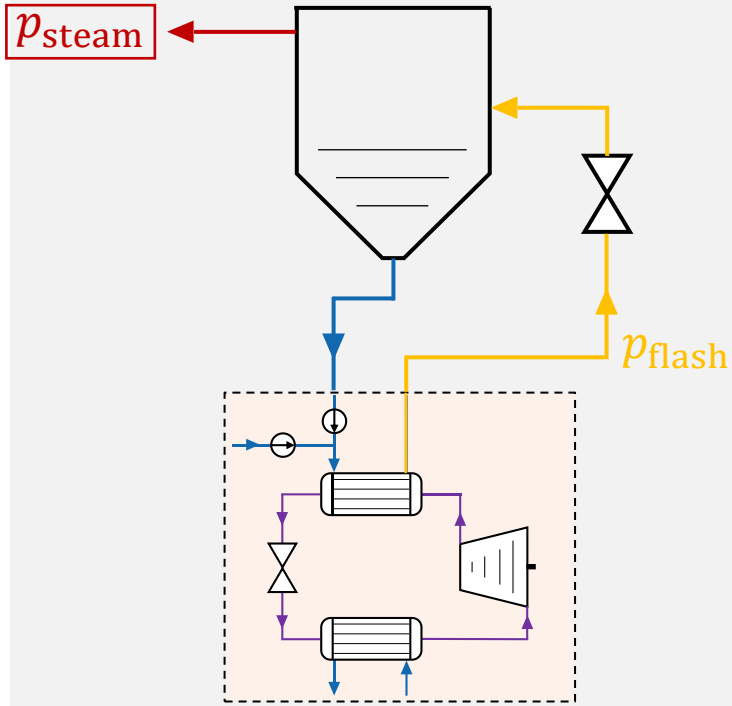
Various types of steam-generating heat pumps

Direct evaporation HP



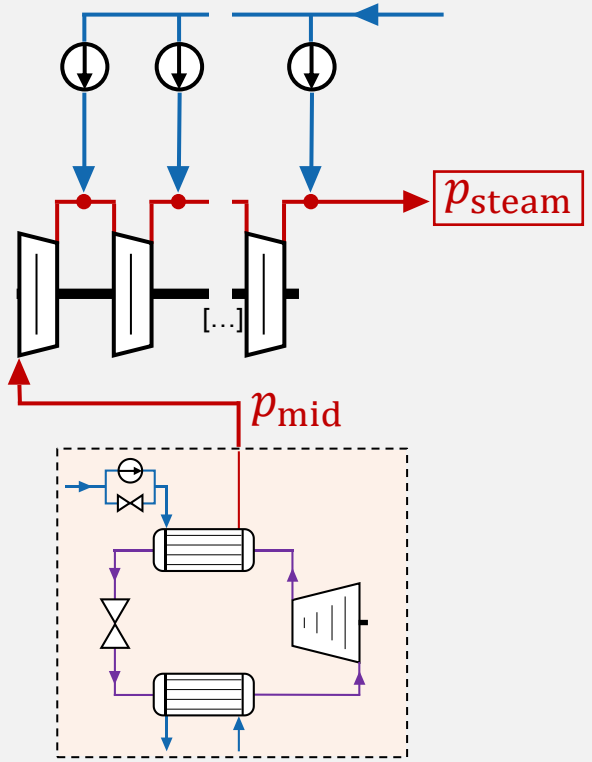
Sub-crit | Trans-crit

Flash evaporation HP



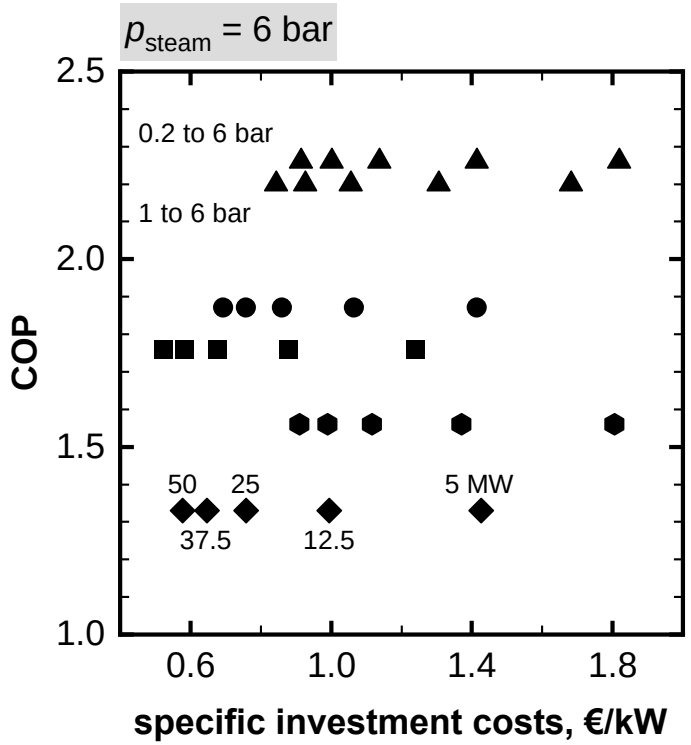
Sub-crit | Trans-crit

Direct evaporation HP + MVR

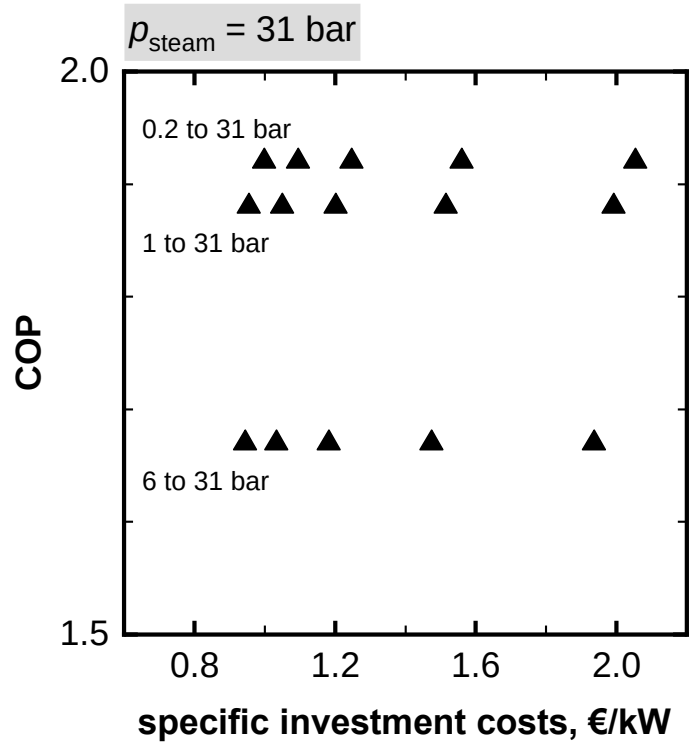


Subcrit. direct+ MVR

Heat pump COP and investment costs



- subcritical, direct evaporation
- subcritical, flash evaporation
- transcritical, direct evaporation
- transcritical, flash evaporation
- subcritical, direct evaporation + MVR

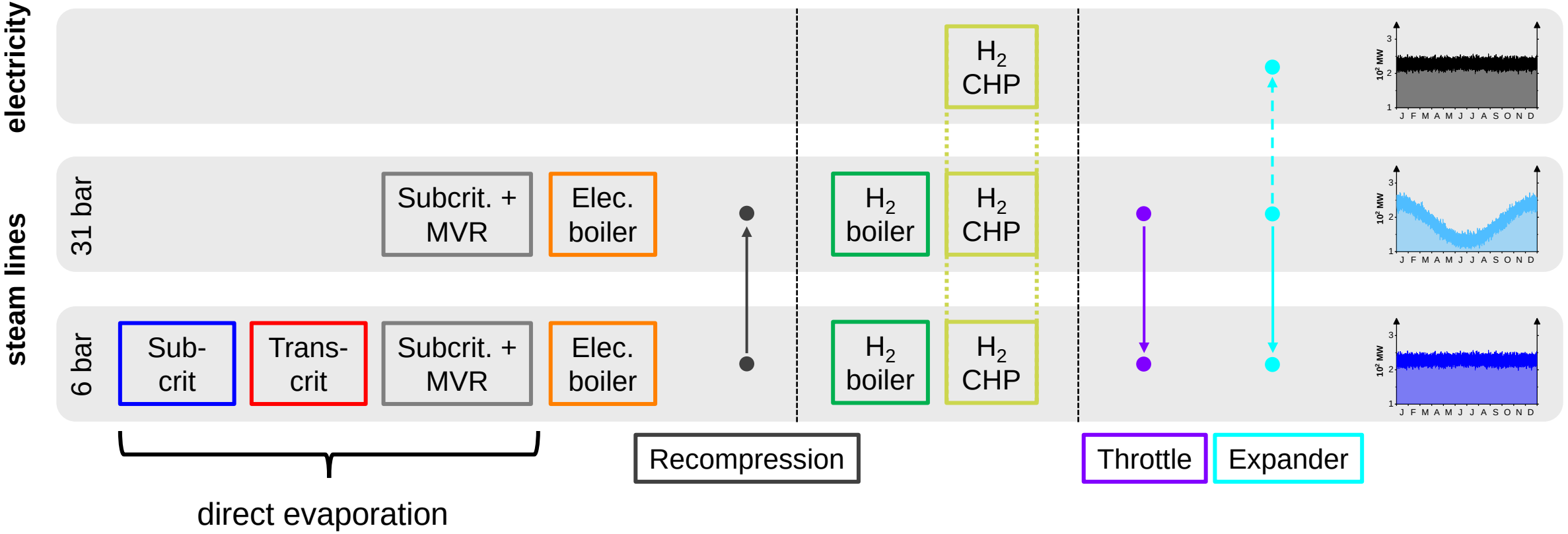


Subcrit vs. transcrit
- higher COP
- higher costs

Flash vs. direct evaporation
- lower COP
- higher costs

Subcrit + MVR
- highest COP
- highest costs
- small mid pressure → higher COP

Technology options



Energy system optimization

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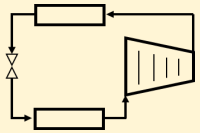
Technologies

Technology X



- Capacities
- Efficiency
- Part-load behavior
- Investment costs
- Maintenance costs
- Lifetime

Electricity costs

Hydrogen costs

Structural and operational optimization

What is built?

How many and how large?

How is operated?

$$\min_{x,y} \ \text{CAPEX} + \text{OPEX}$$

$$s.t. \ h(x,y) = 0$$

$$g(x,y) \leq 0$$

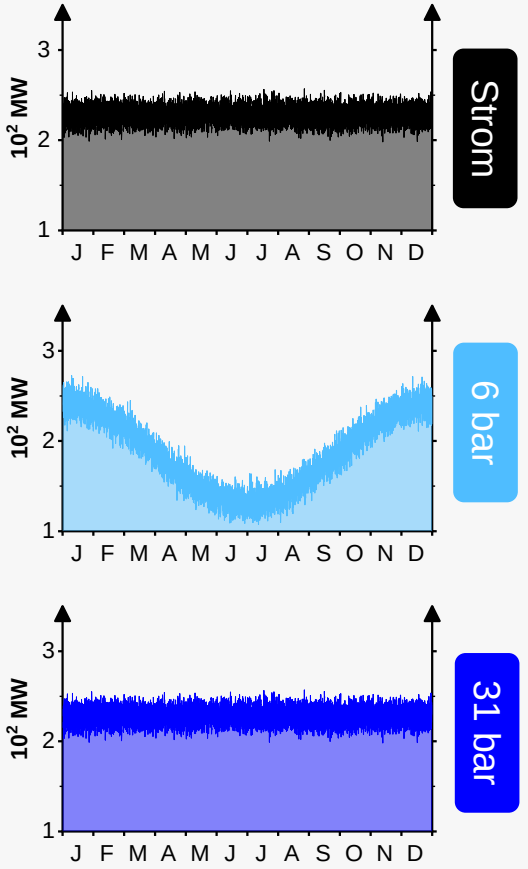
$$x \in X \subseteq \mathbb{N}_0$$

$$y \in Y \subseteq \mathbb{R}$$

Mixed-integer linear optimization

SecMOD

Demands



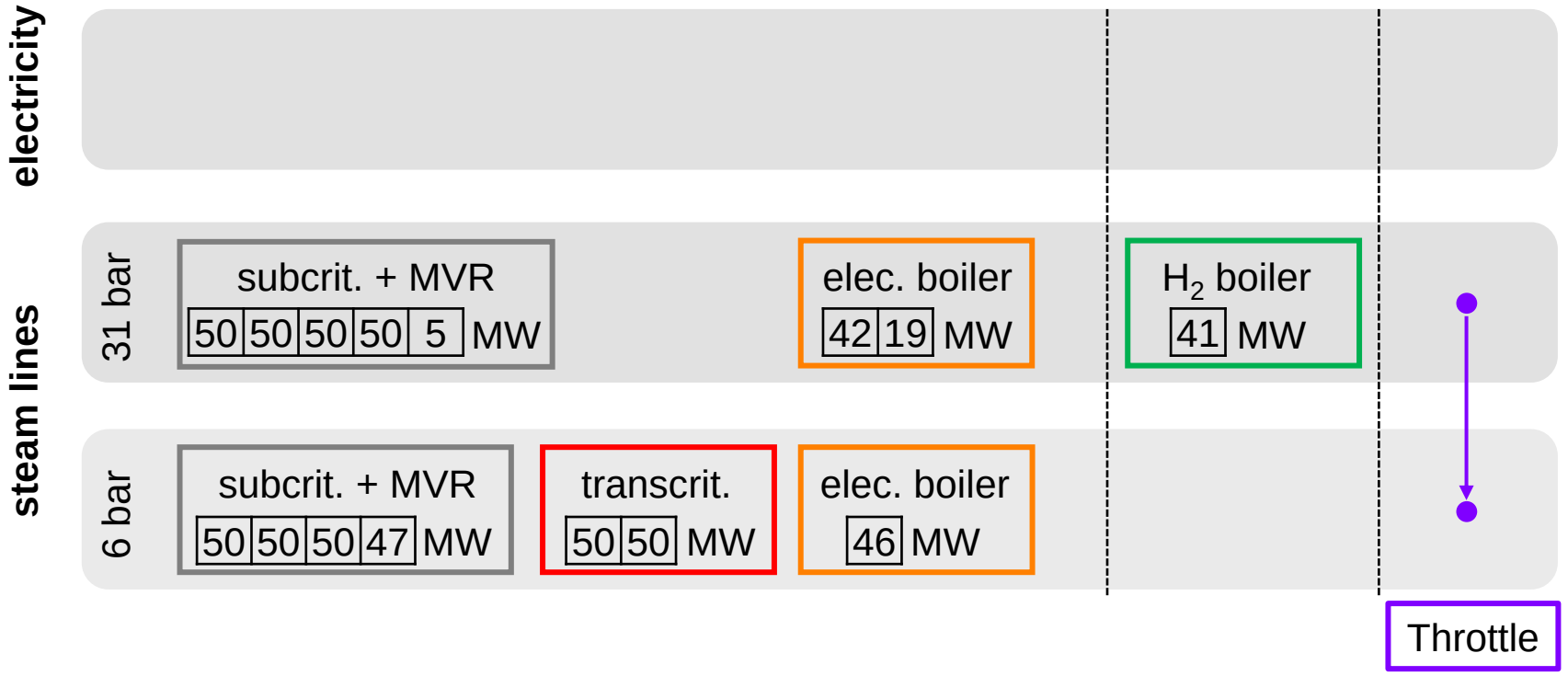
6 typical days

C. Reinert, L. Schellhas, J. Mannhardt, D. Y. Shu, A. Kämper, N. Baumgärtner, S. Deutz, A. Bardow, Front. Energy Res. 2022, 10.

C. Reinert, N. Nolzen, J. Frohmann, D. Tillmanns. A. Bardow, Com & Chem Eng. 2023,04.

Optimal structure

Base case (2021): $\bar{C}_{\mathrm{elec}} = 96.85\ €/\mathrm{MWh}$, $C_{\mathrm{H_2}} = 144\ €/\mathrm{MWh}$



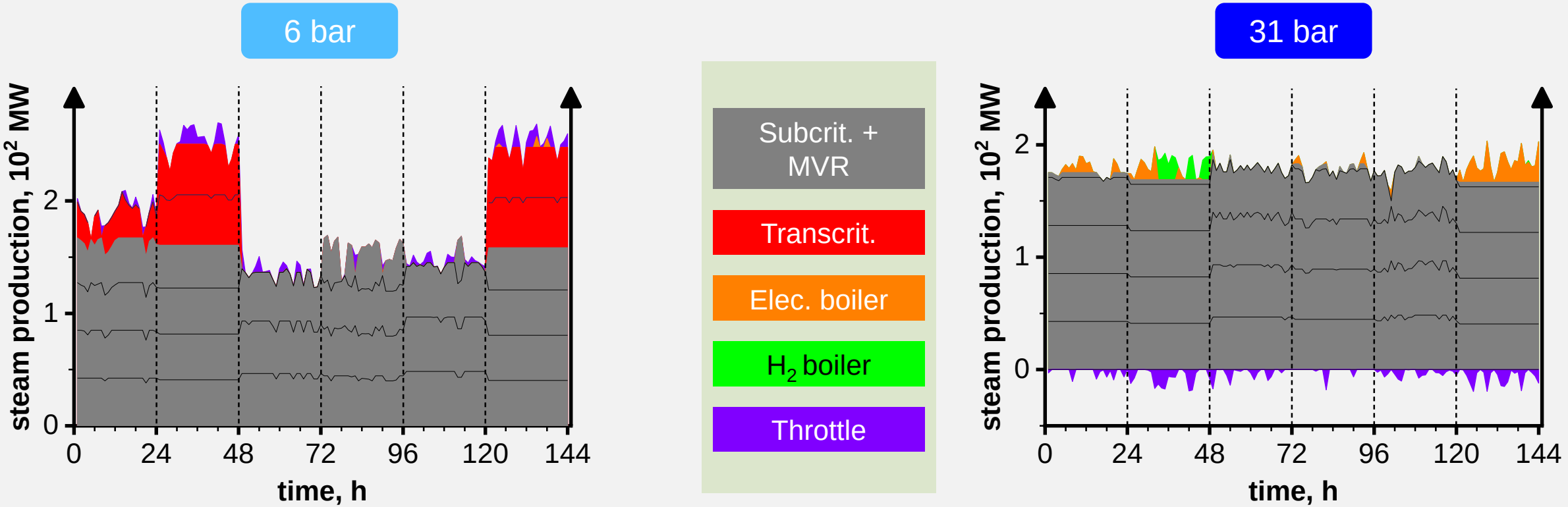
Highly-efficient heat pumps dominate

H_2 und elec. boiler: only small capacities

Throttle instead of expander

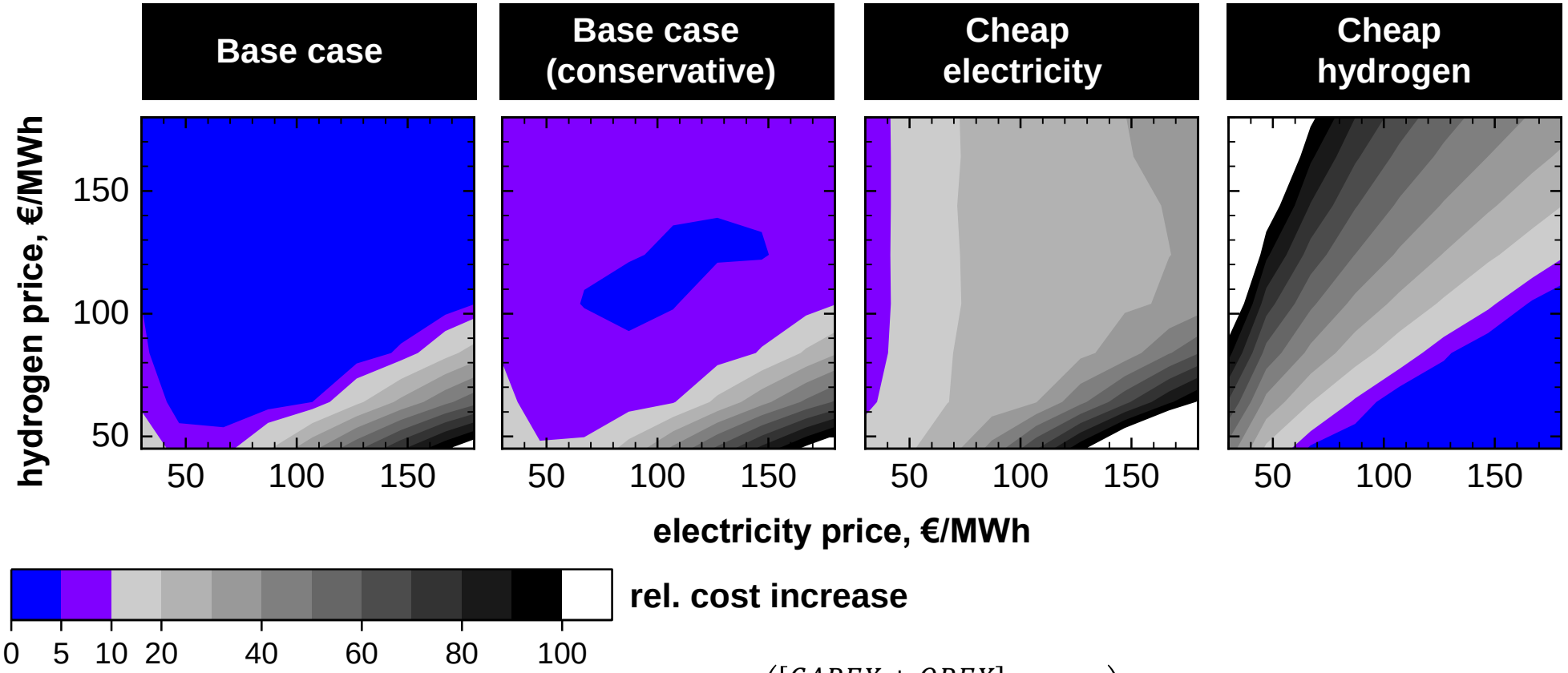
Optimal operation

Base case (2021): $\bar{C}_{\mathrm{elec}} = 96.85\ €/\mathrm{MWh}$, $C_{\mathrm{H_2}} = 144\ €/\mathrm{MWh}$



- **Highly efficient heat pumps provide base load**
- **Transcritical heat pumps for medium load**
- **H_2 and electric boiler only for peak loads**

Place your bet – Which system is more robust?



$$\Delta C_{\mathrm{rel}} = \left(\frac{[CAPEX + OPEX]_{case}}{[CAPEX + OPEX]_{opt}} - 1 \right) \cdot 100$$

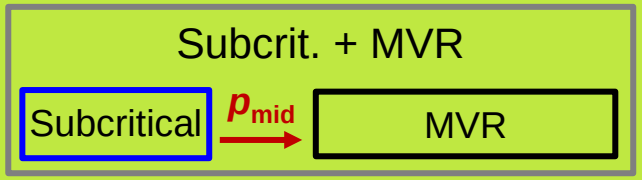
Conclusions

How to decarbonize?

Base case

- Base load: Highly efficient heat pumps
- Medium load: less-efficient but cheaper heat pumps
- Peak load: H_2 and electric boiler

The best high-temperature heat pump is a low-temperature heat pump!



A bet on future developments

Cheap electricity? cheap hydrogen? similar prices?

Heat pump dominated energy system is most robust!

Thank You!

Funding

“High efficiency high-temperature heat pumps with temperature glide”

Innosuisse BRIDGE Schweizerischer Nationalfonds