Optimal design and operation of large-scale heat pumps in district heating and cooling systems

Marco Wirtz, Lukas Kivilip, Peter Remmen, Dirk Müller

ECOS Conference, Wrocław, Poland
23.-28. June 2019

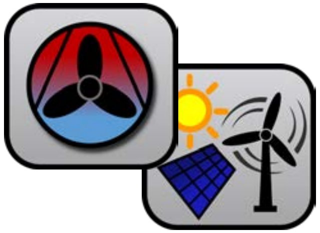
ECOS 2019

EBC | Institute for Energy Efficient Buildings and Indoor Climate
E.ON Energy Research Center
RWTH AACHEN UNIVERSITY

Motivation

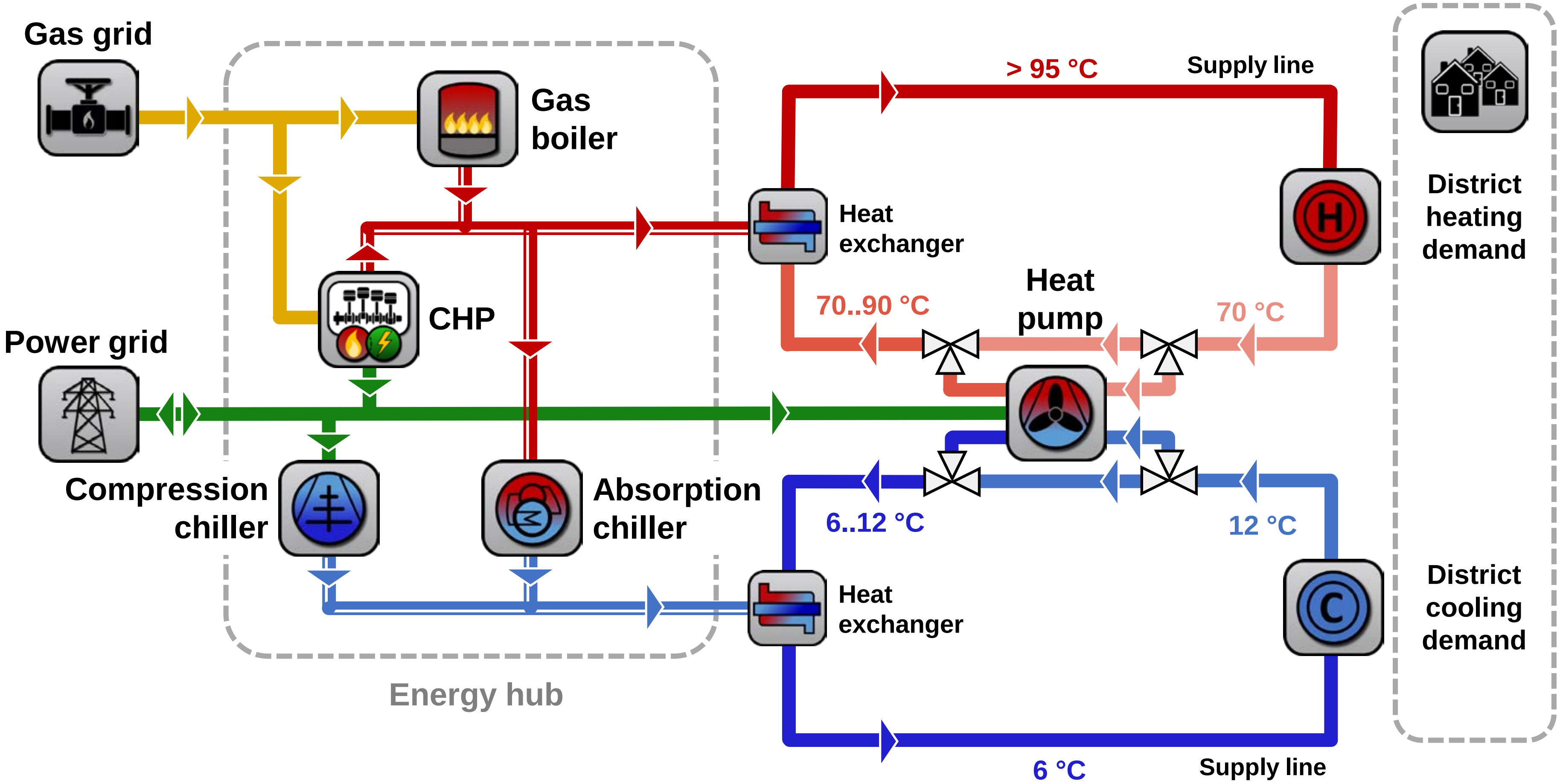
- **Decarbonization** of heating and cooling

- Key technology: **Heat pumps**
  - Most **efficient** power-to-heat technology
  - Support integration of renewable energies



- **Integration** in district heating networks
  - Heat sources: Sea water, ground, air or **return line of district cooling network**
    - How does a large-scale heat pump affect the energy system?
    - Effect on costs and carbon emissions?

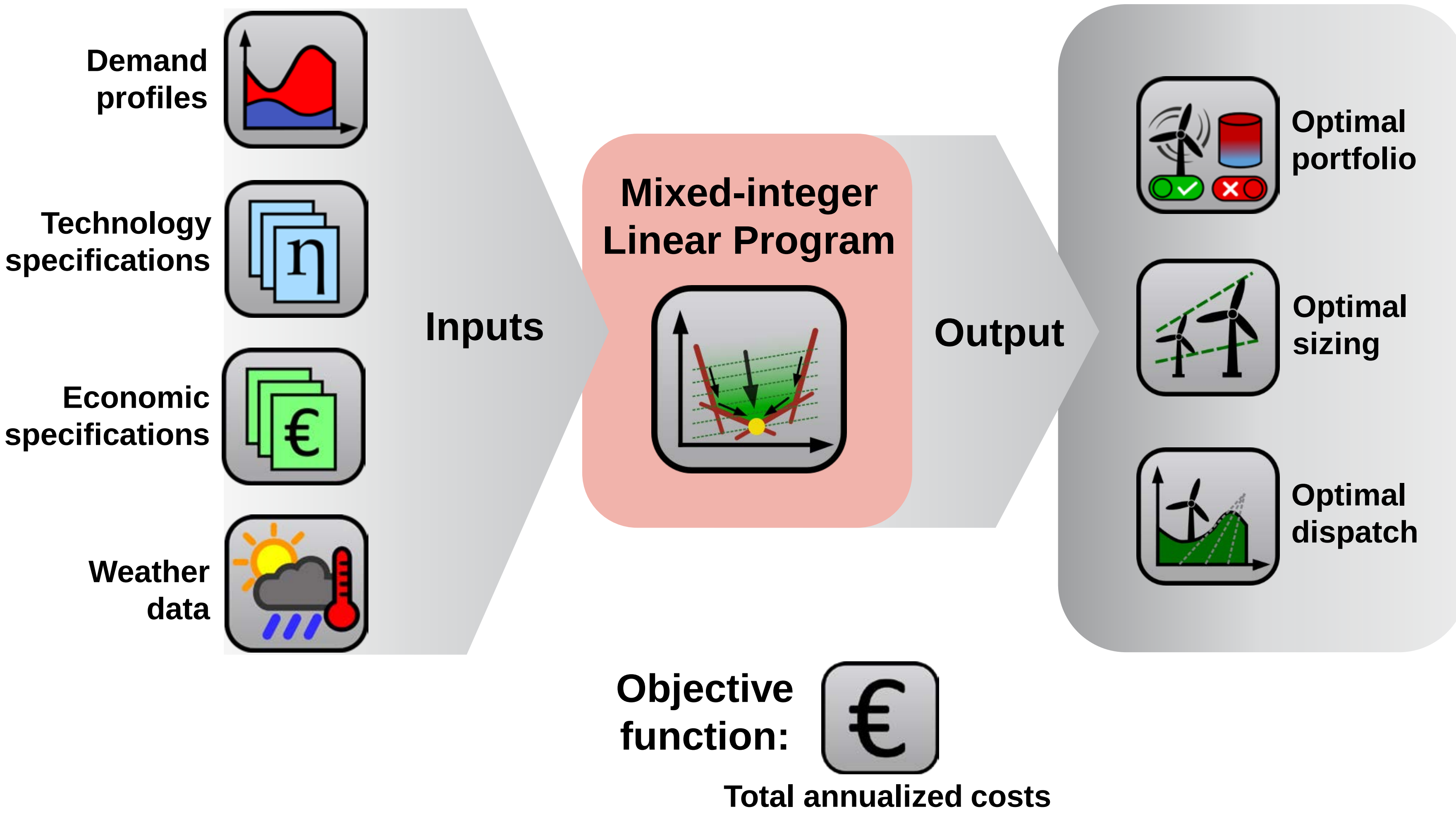
Energy system structure



Temperatures exemplary for 2nd Generation District Heating

Marco Wirtz

Methodology



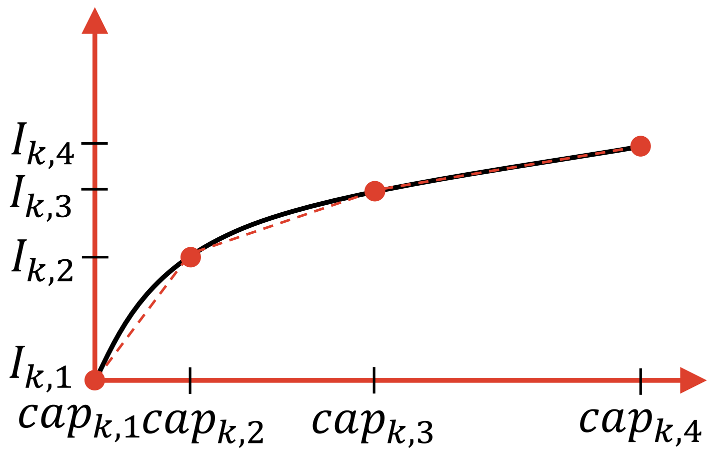
Marco Wirtz

Mixed-integer linear program (MILP)

- Objective function:
  - **Total annualized costs**

$$\min C^{\mathrm{TAC}} = C^{\mathrm{inv,tot}} + C^{\mathrm{o\&m}} + C^{\mathrm{el}} + C^{\mathrm{gas}}$$

$$C^{\mathrm{inv,tot}} = \sum_{k} \sum_{i=1}^{N_k} \xi_{k,i} I_{k,i} + C^{\mathrm{inv}}_{\mathrm{netw}}$$



Piece-wise linear approximation

Marco Wirtz
ECOS Conference, Wrocław, Poland
23.-28. June 2019

Mixed-integer linear program (MILP)

- Objective function:
  - **Total annualized costs**

$$\min C^{\mathrm{TAC}} = C^{\mathrm{inv,tot}} + C^{\mathrm{o\&m}} + C^{\mathrm{el}} + C^{\mathrm{gas}}$$

$$C^{\mathrm{inv,tot}} = \sum_{k} \sum_{i=1}^{N_k} \xi_{k,i} I_{k,i} + C^{\mathrm{inv}}_{\mathrm{netw}}$$

$$C^{\mathrm{o\&m}} = \sum_{k} f_k^{\mathrm{o\&m}} \, C_k^{\mathrm{inv}}$$

O&M as share of investment[1]:

CHP

8 %

Heat pump

2.5 %

Compr. chiller

3.5 %

3 %

Gas boiler

3 %

Abs. chiller

[1] according VDI 2067

Marco Wirtz
ECOS Conference, Wrocław, Poland
23.-28. June 2019

Mixed-integer linear program (MILP)

- Objective function:
  - **Total annualized costs**

$$\min C^{\mathrm{TAC}} = C^{\mathrm{inv,tot}} + C^{\mathrm{o\&m}} + C^{\mathrm{el}} + C^{\mathrm{gas}}$$

$$C^{\mathrm{inv,tot}} = \sum_{k} \sum_{i=1}^{N_k} \xi_{k,i} I_{k,i} + C_{\mathrm{netw}}^{\mathrm{inv}}$$

$$C^{\mathrm{o\&m}} = \sum_{k} f_k^{\mathrm{o\&m}}\, C_k^{\mathrm{inv}}$$

$$C_{\mathrm{el}} = \overline{P_{\mathrm{el,grid}}}\, p_{\mathrm{el,peak}} +$$

$$\overline{P_{\mathrm{el,grid}}} \geq P_{\mathrm{el,grid},t} \quad \forall\, t$$

$$\overline{P_{\mathrm{el,grid}}} \geq P_{\mathrm{el,feed-in},t} \quad \forall\, t$$

$59.7\ \frac{EUR}{kW}$ $\quad 0.145\ \frac{EUR}{kWh}$ $\quad 0.064\ \frac{EUR}{kWh}$

Marco Wirtz
ECOS Conference, Wrocław, Poland
23.-28. June 2019

Mixed-integer linear program (MILP)

- Objective function:
  - **Total annualized costs**

$$\min C^{\mathrm{TAC}} = C^{\mathrm{inv,tot}} + C^{\mathrm{o\&m}} + C^{\mathrm{el}} + C^{\mathrm{gas}}$$

$$C^{\mathrm{inv,tot}} = \sum_{k} \sum_{i=1}^{N_k} \xi_{k,i} I_{k,i} + C^{\mathrm{inv}}_{\mathrm{netw}}$$

$$C^{\mathrm{o\&m}} = \sum_{k} f_k^{\mathrm{o\&m}} C_k^{\mathrm{inv}}$$

$$C_{\mathrm{el}} = \overline{P_{\mathrm{el,grid}}}\, p_{\mathrm{el,peak}} + \Delta t \left(\sum_t P_{\mathrm{el,grid},t}\, p_{\mathrm{el,work}} - \sum_t P_{\mathrm{el,feed-in},t}\, p_{\mathrm{el,feed-in}} \right)$$

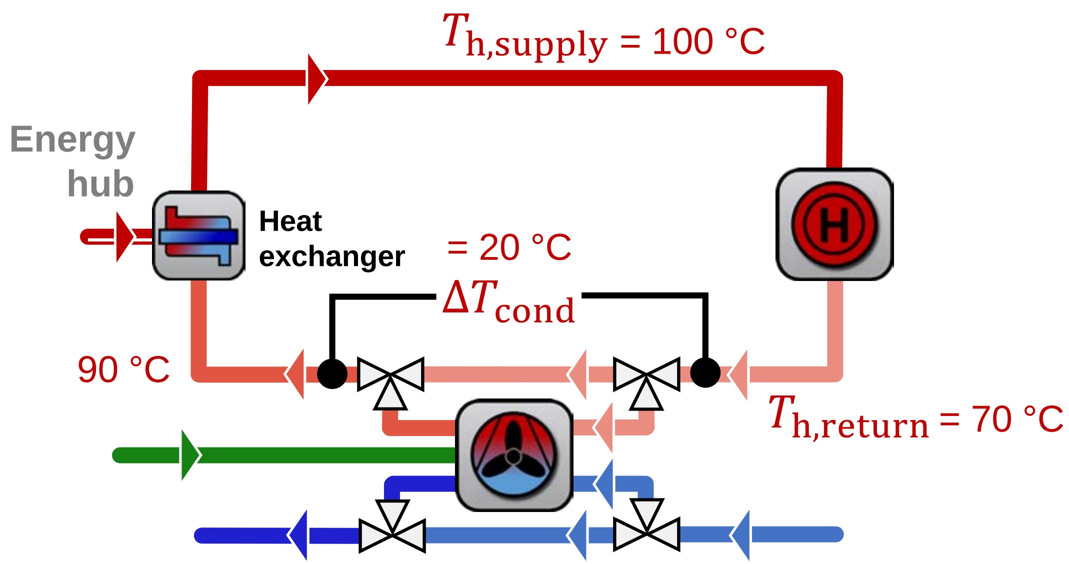
$$C^{gas} = \overline{G_{\mathrm{grid}}}\, p_{\mathrm{gas,peak}} + \Delta t \left(\sum_t \dot{G}_{\mathrm{BOI},t} + \sum_t \dot{G}_{\mathrm{CHP},t} \right) p_{\mathrm{gas,work}}$$

MILP formulation

- Constraints:
  - Energy balances (losses in the power grid neglected)
  - Operation of components: conversion efficiencies, temperature dependencies, e.g.:
    - Heat pump cannot cover full heat demand (condenser temperature of HP ≤ 90 °C)

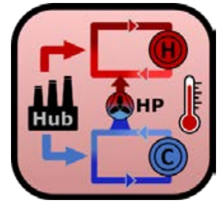
$$\dot{Q}_{\mathrm{h,HP},t} \leq \frac{\Delta T_{\mathrm{cond}}}{T_{\mathrm{h,supply}} - T_{\mathrm{h,return}}} \dot{Q}_{\mathrm{h,dem},t} \quad \forall t$$

20 °C; 100 °C; 70 °C; 66 %



Marco Wirtz
ECOS Conference, Wrocław, Poland
23.-28. June 2019

Supply scenarios



	No heat pump	*High temp. network*	*Low temp. network*
Heat pump	✗	✓	✓
Supply & return temp. heating network	**95 – 140 °C** **70 °C**		**60 °C** **30 °C**
Supply & return temp. cooling network		**6 °C** **12 °C**	
	2nd Gen DH		**4th Gen DH**

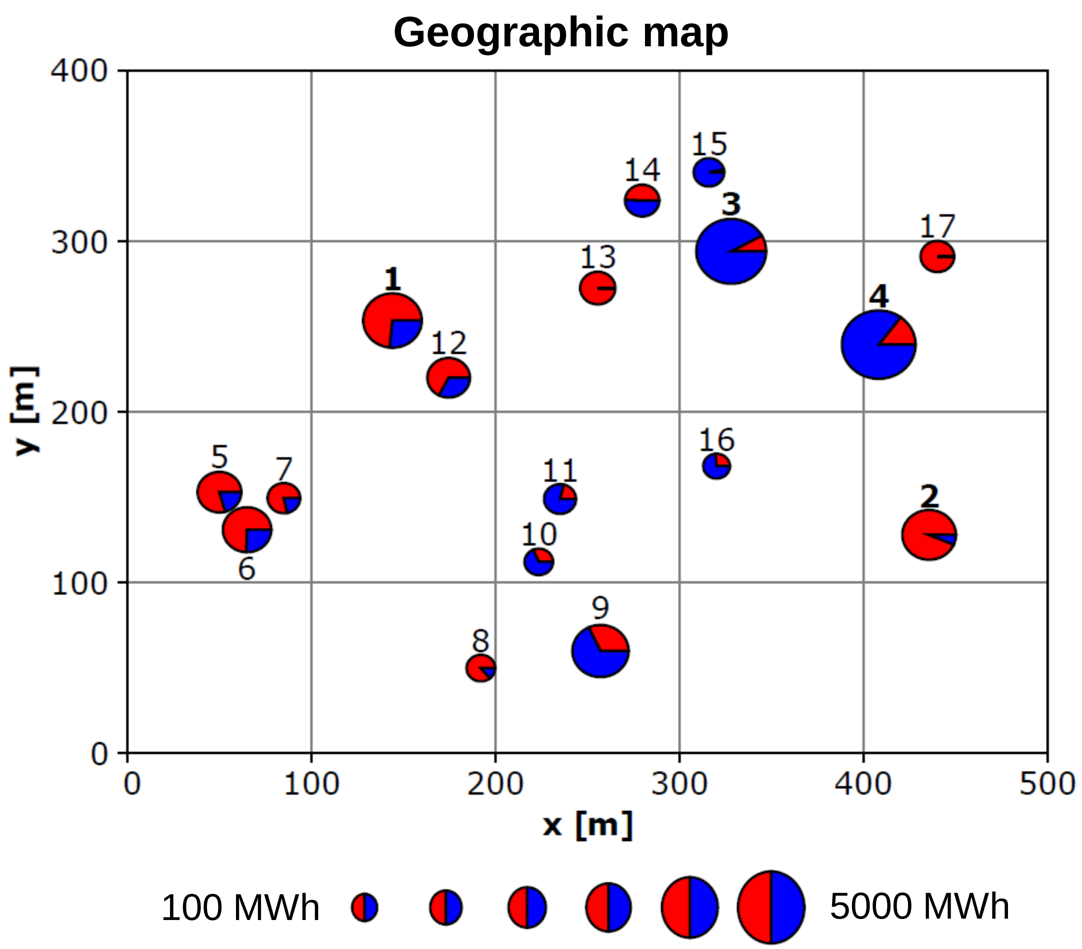
Case study

- Hourly demands for 17 buildings of research campus in Germany
  - *Office buildings and laboratories*
  - *Data centers (building 3 and 4)*

- Thermal demand

	Total	Peak
Heating	**6.4 GWh**	**2.01 MW**
Cooling	**10.0 GWh**	**2.42 MW**

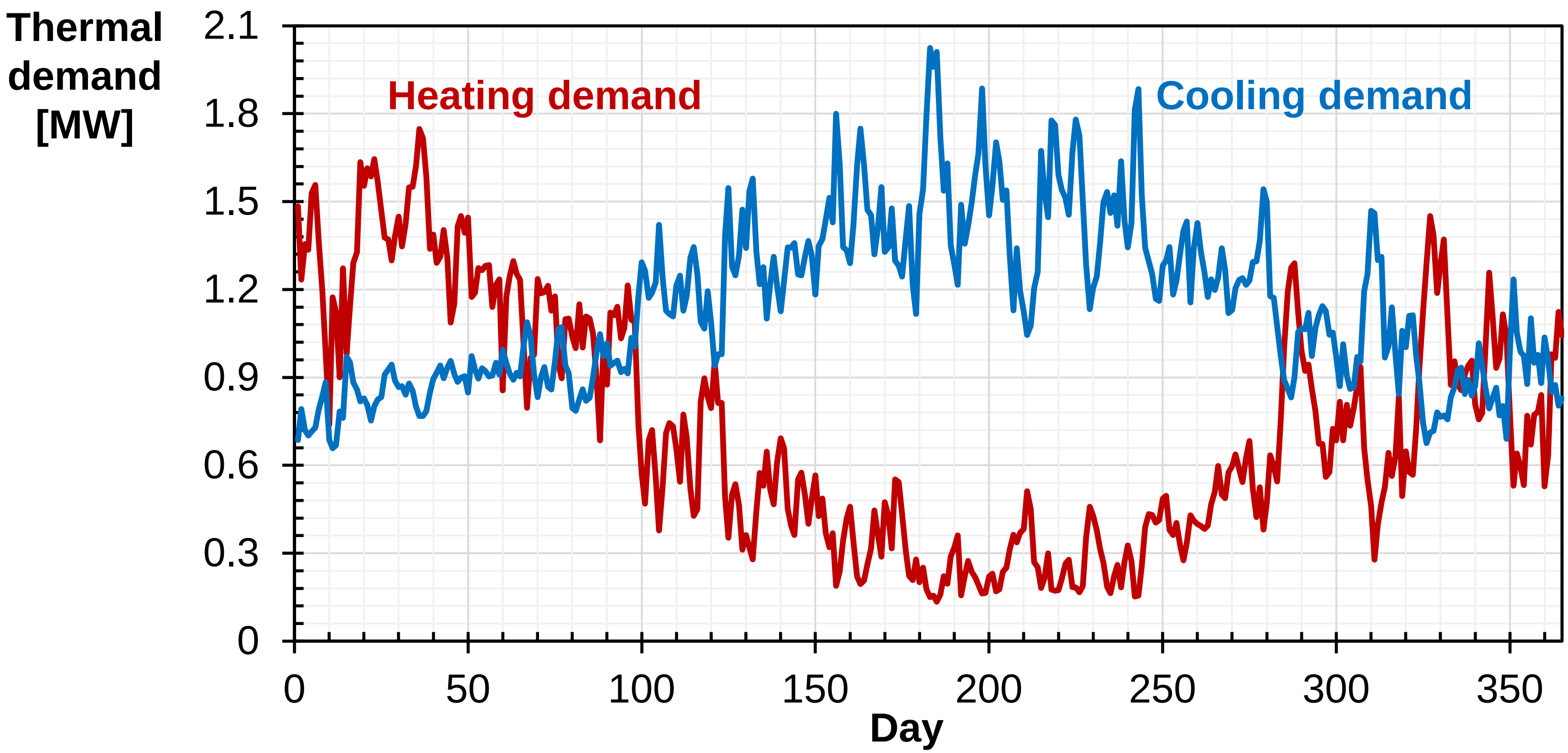
- 73 % of cooling demand results from data centers



Marco Wirtz

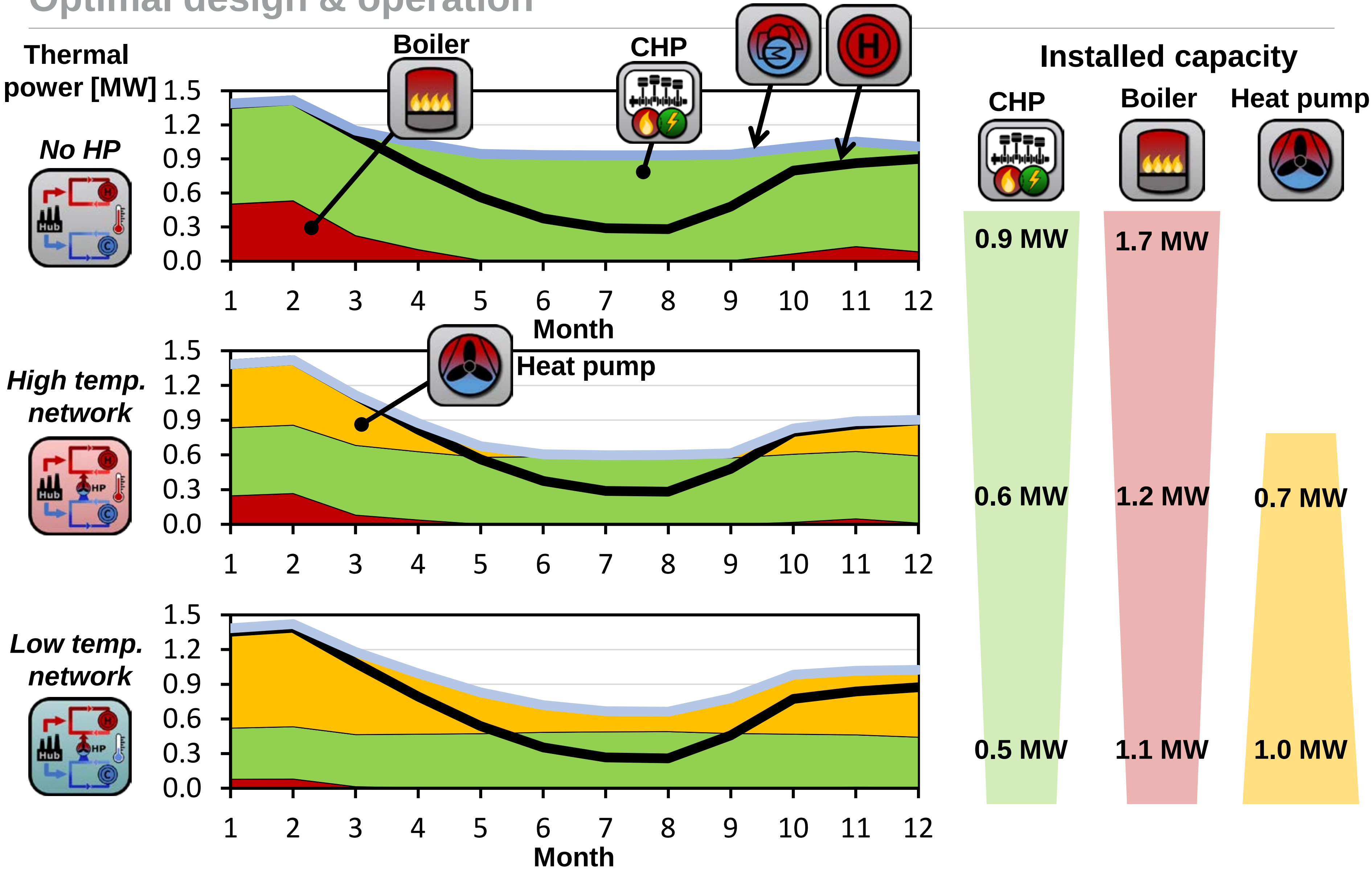
Case study

- Hourly demands for 17 buildings of research campus in Germany



Marco Wirtz

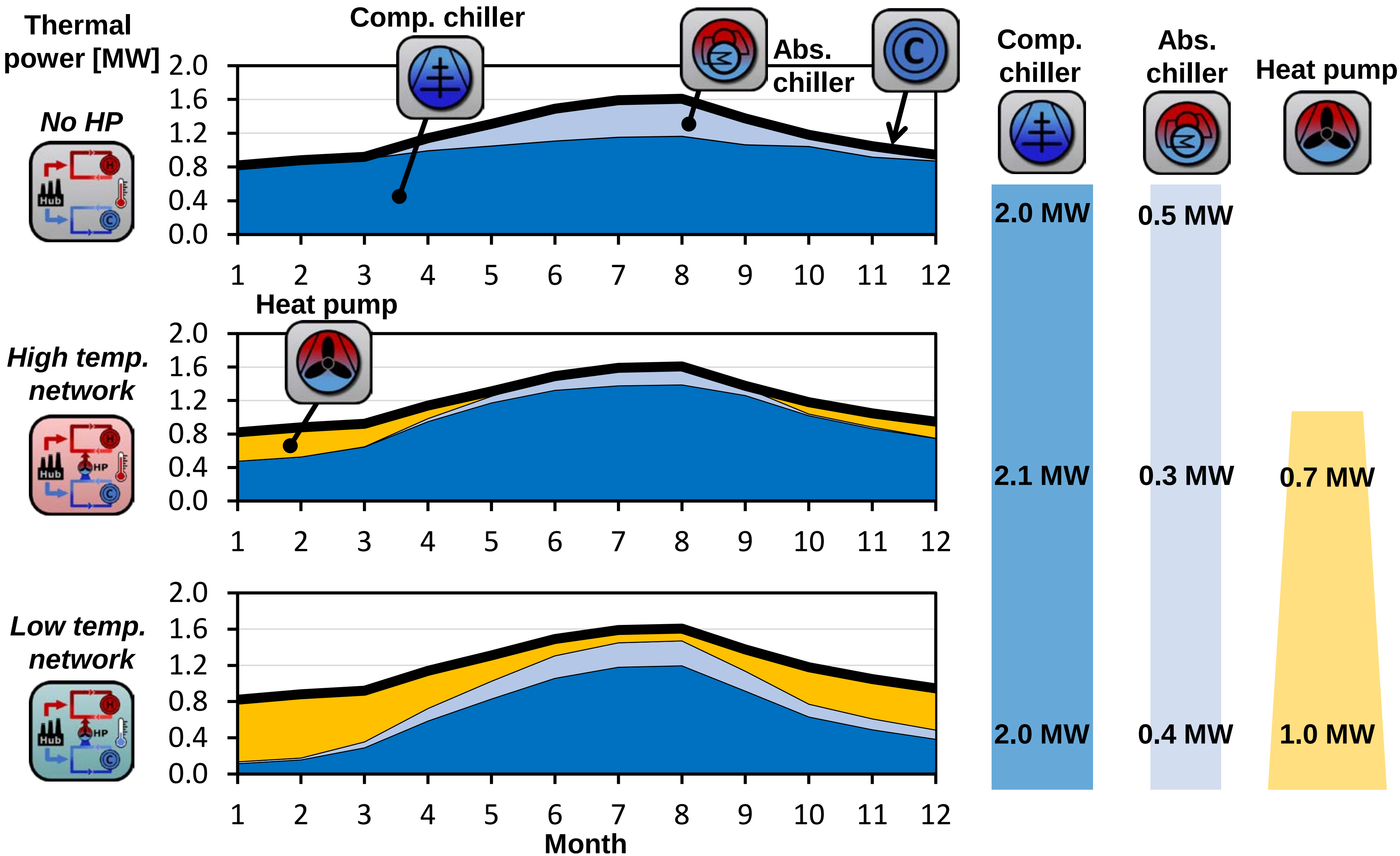
Optimal design & operation



Marco Wirtz

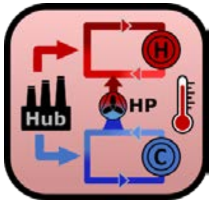
ECOS Conference, Wrocław, Poland
23.-28. June 2019

Optimal design & operation



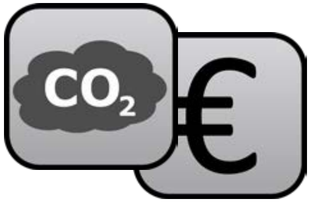
Marco Wirtz
ECOS Conference, Wrocław, Poland
23.-28. June 2019

Performance results

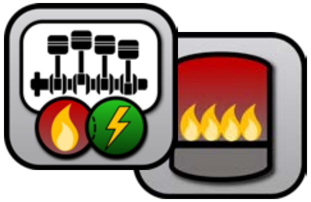
	No heat pump 	*High temp. network* 	*Low temp. network* 
Total annualized costs	**421.2 kEUR/a**	**396.3 kEUR/a** **(– 5.9 %)**	**349.2 kEUR/a** **(– 17.1 %)**
CO_2 emissions	**3879 t/a**	**2408 t/a** **(– 38 %)**	**1853 t/a** **(– 52 %)**
Heating SCOP HP	**—**	**2.73**	**4.82**
SCOP HP (Heating and cooling power as benefit)	**—**	**4.46**	**8.64**

Conclusions

- Large potential for **cost and emission savings**



- CHP and gas boiler are not replaced completely
  - **CHP** produces power for heat pump at low costs
  - **Gas boiler** needed for peak demands



- Heat pump can be **profitable for high temperature district heating networks** (> 100°C) as well

- **Demand structure** affects profitability (simulteanous heating and cooling demand)

- **Outlook:**
  - Thermo-hydraulic simulation model for further analysis of operation

Thank you for your attention.

Questions? Inspiration?

Marco Wirtz, M.Sc.

RWTH Aachen University
Institute for Energy Efficient Buildings
and Indoor Climate

marco.wirtz@eonerc.rwth-aachen.de

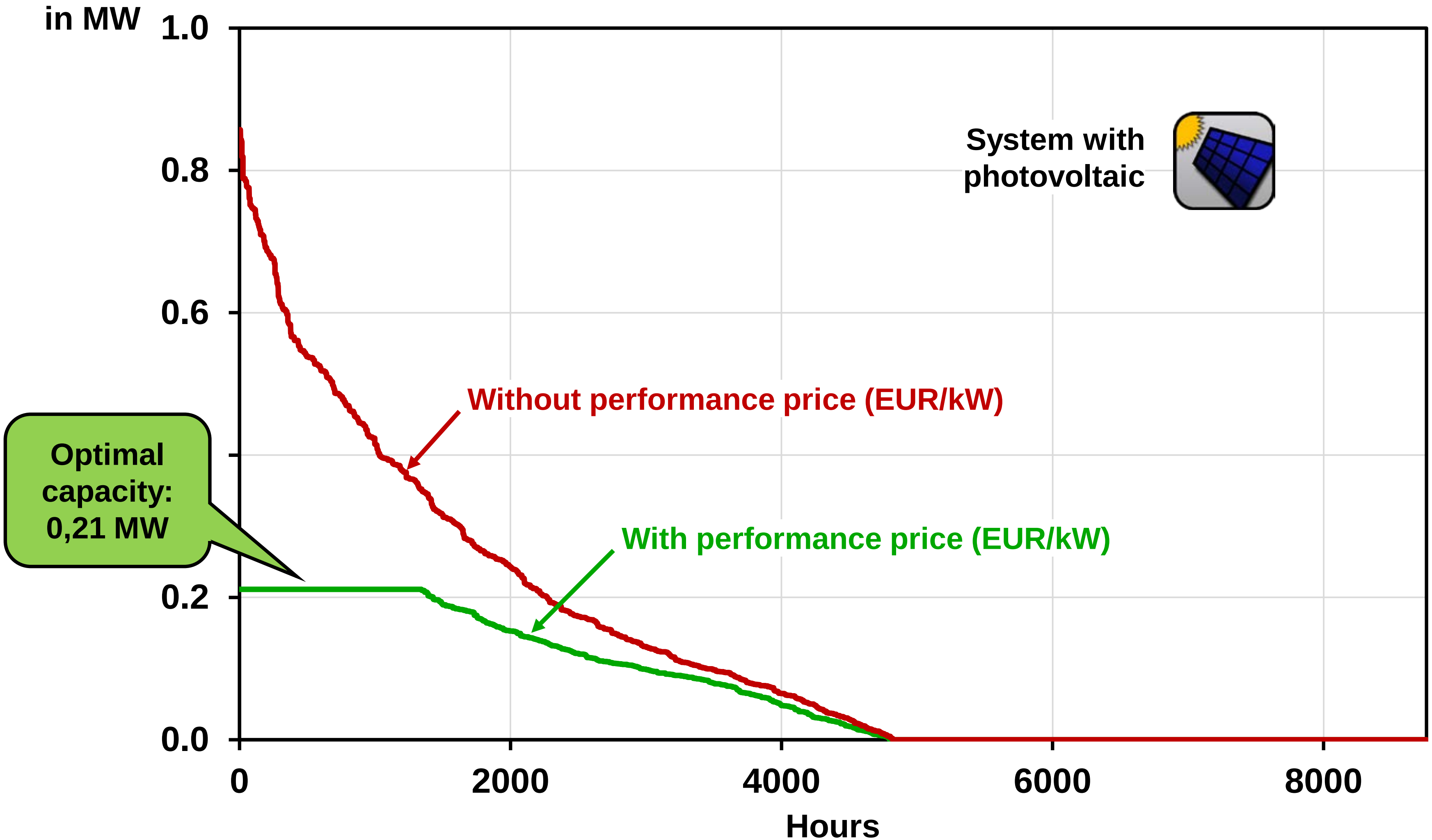
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

This work was supported by the Helmholtz Association under the Joint Initiative "Energy System 2050 – A Contribution of the Research Field Energy".

E.ON Energy Research Center | RWTH AACHEN UNIVERSITY

Backup

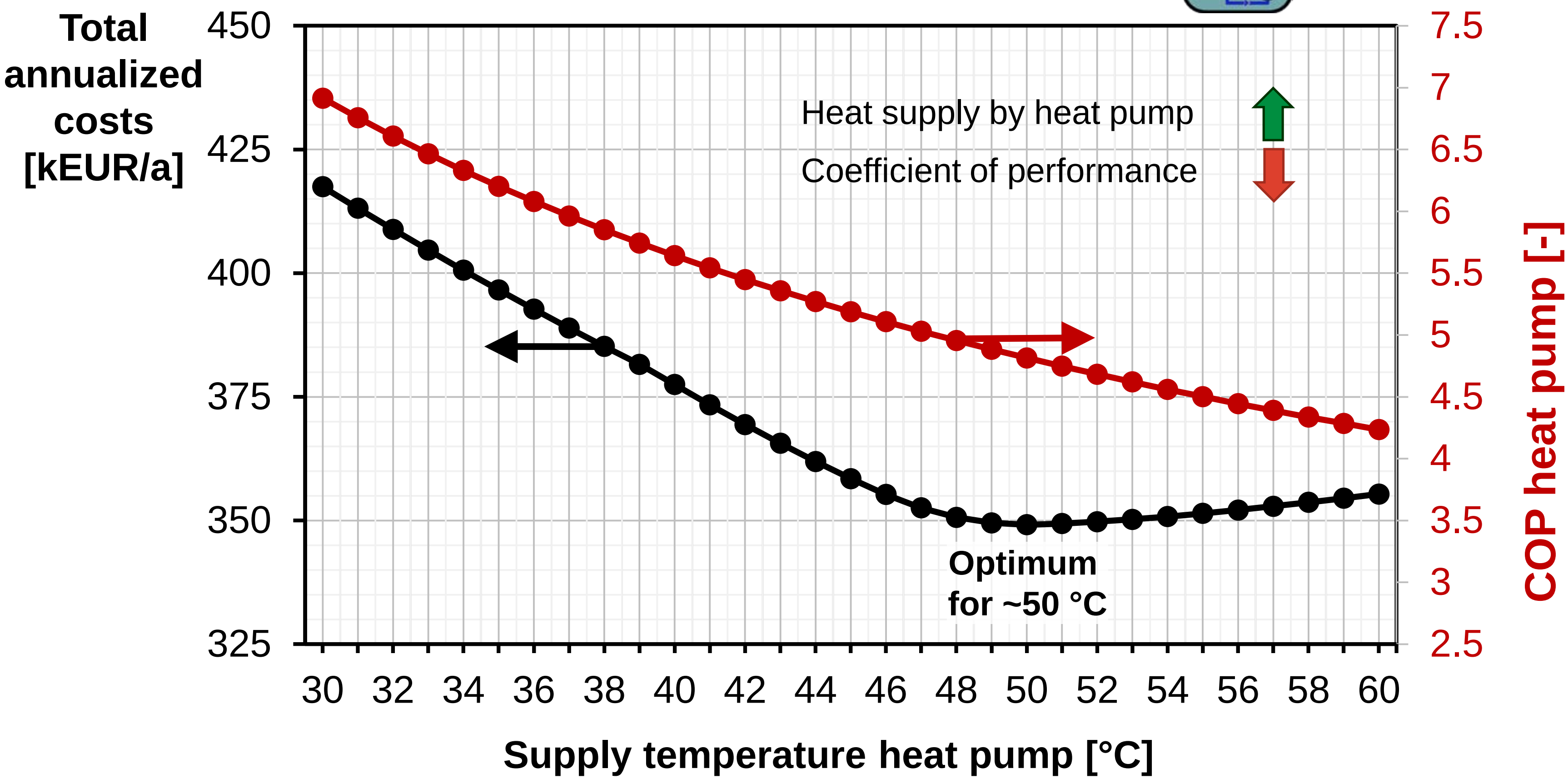
Effect of performance price



Marco Wirtz
ECOS Conference, Wrocław, Poland
23.-28. June 2019

Optimal condenser temperature

- For high temperature network: 90 °C (largest possible)
- For low temperature network:



Marco Wirtz
ECOS Conference, Wrocław, Poland
23.-28. June 2019
E.ON Energy Research Center
RWTH AACHEN UNIVERSITY