Application of Optimization-based Energy Management Systems for Interconnected District Heating Networks

22nd Styrian Workshop on Automatic Control

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Agenda

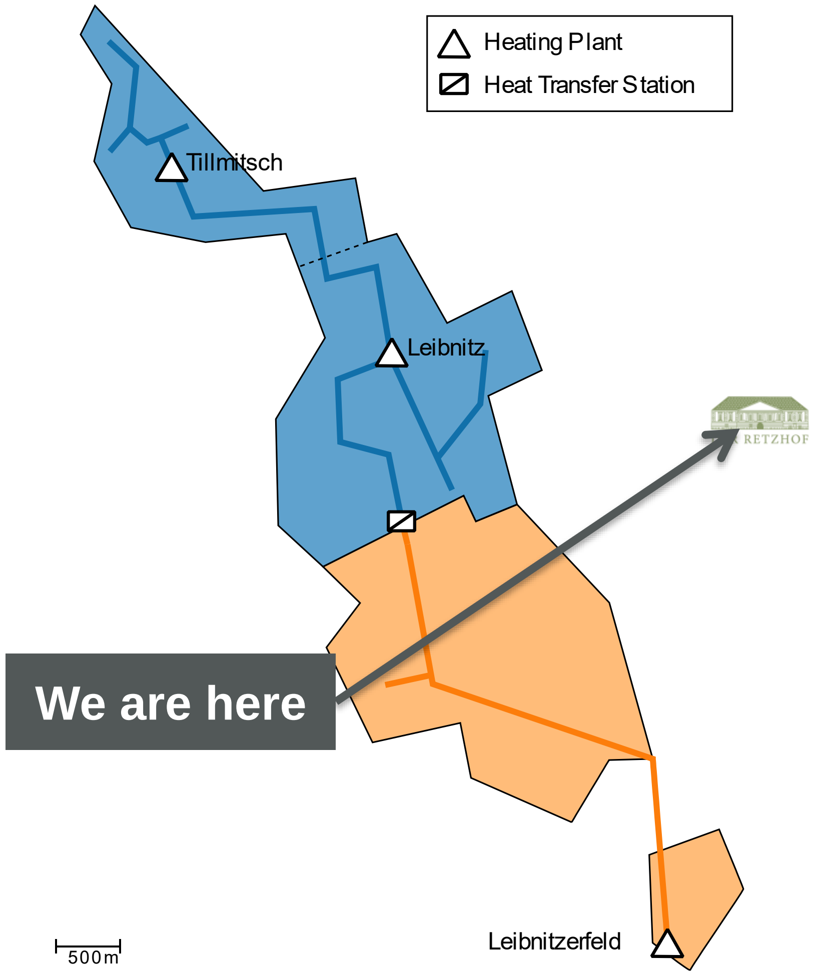
- Project Overview and Motivation
- Representation of Thermal Systems in Energy Management System (EMS)
- Handling Low-Level Controllers
- Hybrid Coupling of Energy Systems
- Results

Motivation
Project ThermaFLEX

ThermaFLEX

- **Interconnected DH networks** at and around Leibnitz
  - Different production technologies, costs, storage sizes, waste heat potential,…
  - Bidirectional heat transfer
- Goal
  - **Minimization of CO_2 emissions**/costs
  - High-level coordination of all networks

Optimization-based Energy Management System



https://greenenergylab.at/projects/100-renewable-district-heating-leibnitz/

Motivation
Energy Management System (EMS)

- What we mean with energy management system (EMS)?
  - **Supervisory controller** coordinating producers, storage and consumers in an energy network

- Applications
  - Building energy management
  - Control of district heating (DH) networks
  - ...

Bildquellen: Lunghammer – TU Graz

Bildquellen: thermaflex.greenenergylab.at

Motivation
Optimization-based EMS

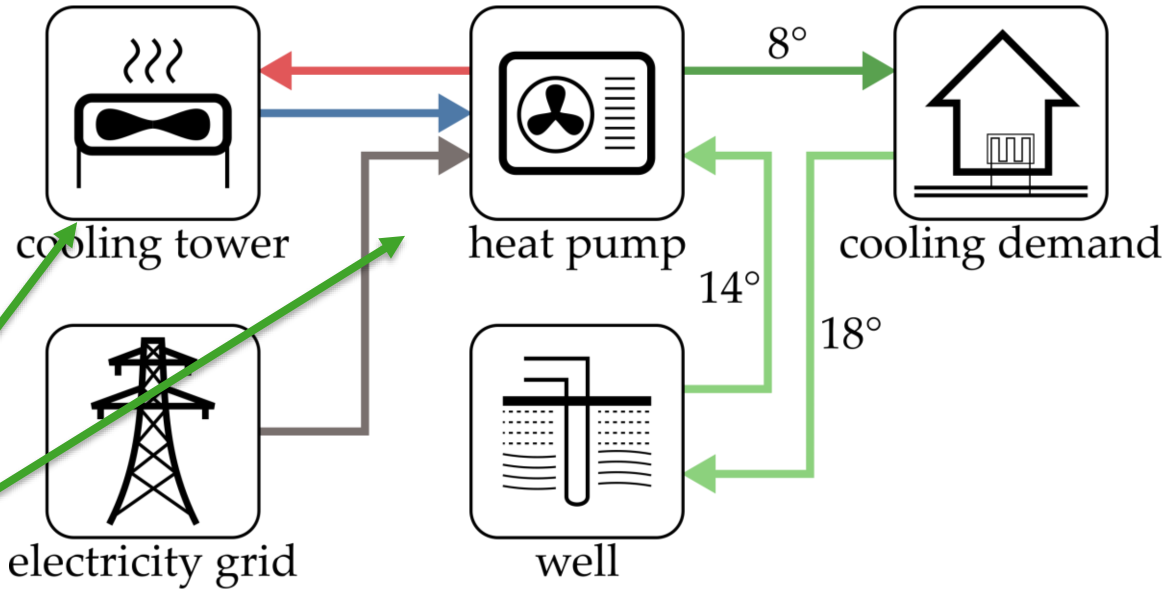
- **Prosumers**
  Models the physical behavior and constraints
- **Connections**
  Ensures conservation of mass and energy
- **MPC problem**

$$\begin{aligned} \min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad & \sum_{i=1}^{N} f_i(\boldsymbol{x}_i) \\ \text{subject to} \quad & \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b} \end{aligned}$$

Prosumers

Connections

In our case a MILP



Motivation
Challenges

- **Representing thermal systems in an MPC**
  Temperature levels are important

- **Dealing with low-level controllers**
  EMS is often only added during a retrofit
  and only able to control a subset of the production units

- **Non-cooperative coupling**
  Typically multi-owner setting for interconnected DH networks

Representation of Thermal Systems in EMS

Representation of Thermal Systems for EMS
Motivation: Simple boiler model

- Typical EMS only consider energy flows
  - In the case of thermal energy this means constant temperatures

$$\dot{Q}(t) = c_{\mathrm{p}}\dot{m}(t)(T_{\mathrm{in}} - T_{\mathrm{out}})$$

- In reality the temperatures vary; model is **non-linear**

$$\dot{Q}(t) = c_{\mathrm{p}}\dot{m}(t)(T_{\mathrm{in}}(t) - T_{\mathrm{out}})$$

If outlet is controlled at e.g. 90 °C

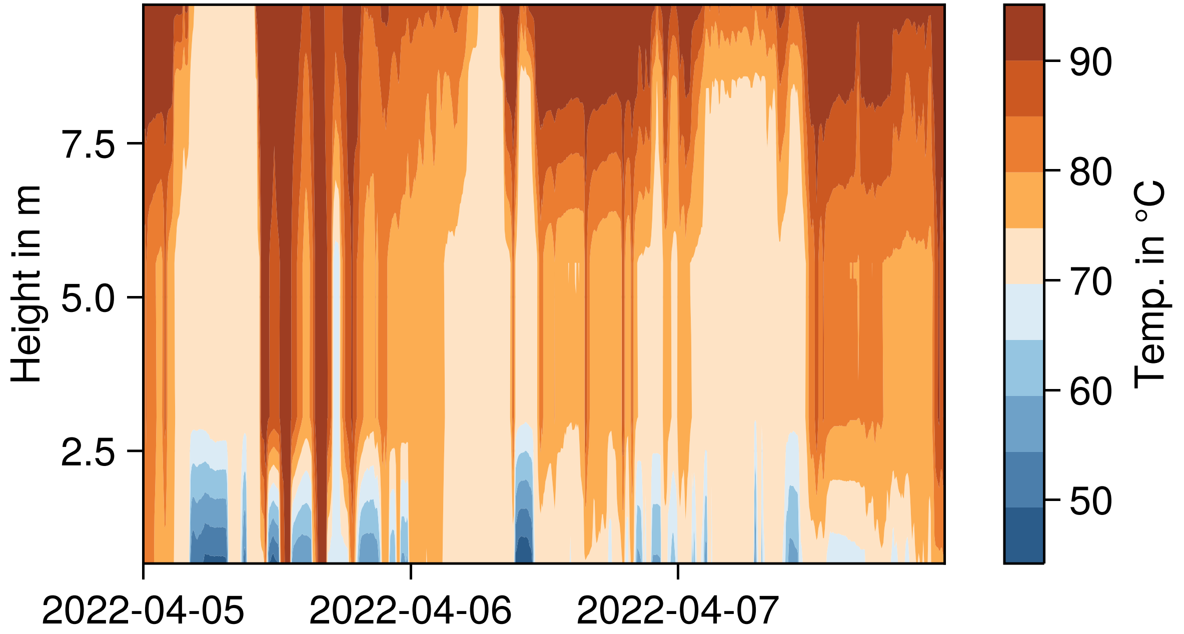
- Solution: “multi-temperature” model; model is **still linear**

$$\dot{Q}(t) = \sum_i c_{\mathrm{p}}\dot{m}_{\mathrm{in},i}(t)T_{\mathrm{in},i} + c_p\dot{m}_{\mathrm{out}}(t)T_{out}$$

$$\dot{m}_{\mathrm{in},i}(t) \in \mathrm{SOS2}$$

Representation of Thermal Systems for EMS
Thermal Energy Storage (TES) Model

- The constant temp. model would only allow for two layers (hot and cold)
- In reality no ideal stratification between a hot and cold layer
- Does not fit with well with const. temp. model



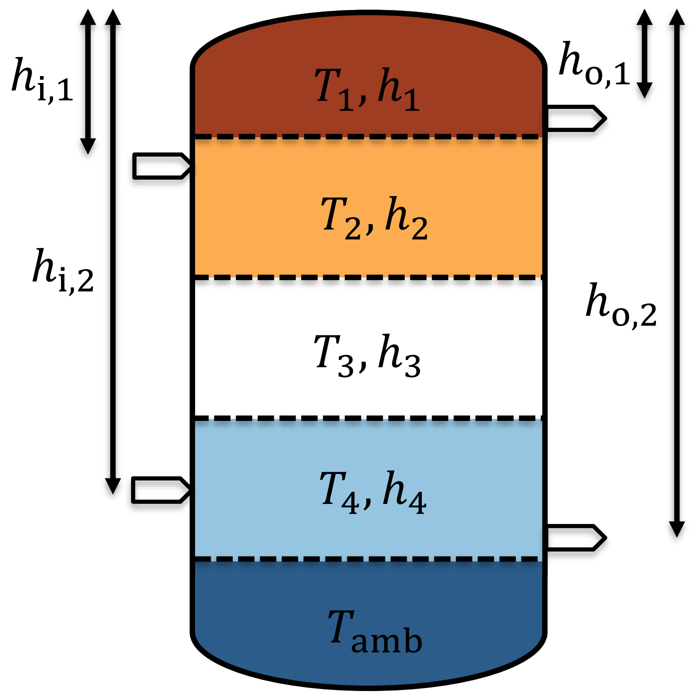
This is a problem if we have low-level controllers that operate on temperatures

Representation of Thermal Systems for EMS
Thermal Energy Storage (TES) Model

Idea [1]

- Layers of constant temperature T_i
- States: Layer heights h_i

Accurately represent temp. distribution in TES in MILP



Why do we need this level of detail?
e.g. accurately predicting low-level TES controllers

[1] Muschick, D., Zlabinger, S., Moser, A., Lichtenegger, K., & Gölles, M. (2022). A multi-layer model of stratified thermal storage for MILP-based energy management systems. *Applied Energy*, *314*, 118890. https://doi.org/10.1016/j.apenergy.2022.118890

Handling Low-Level Controllers

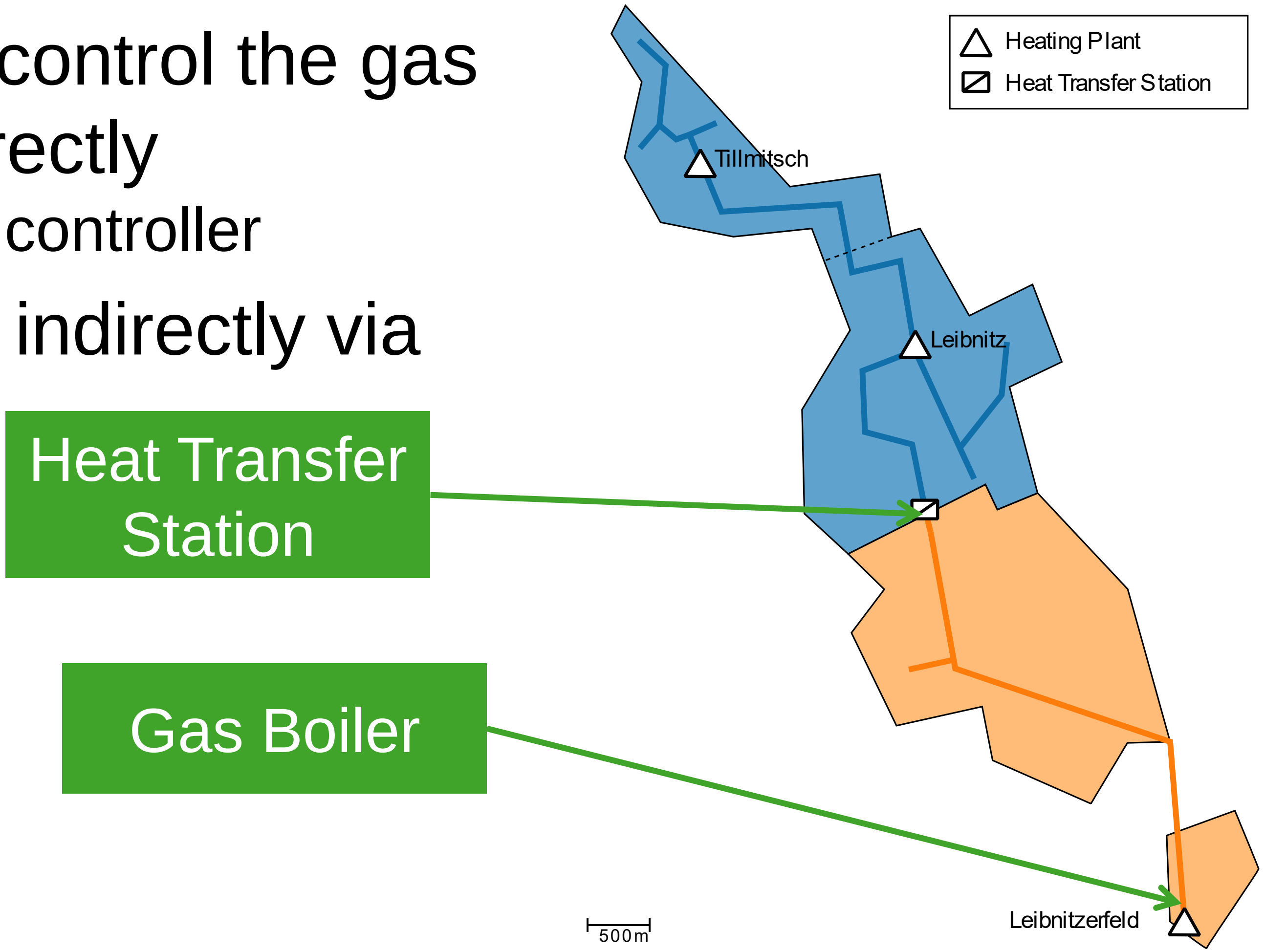
Handling Low-Level Controllers
Motivation

- EMS is often only added during a **retrofit**
- EMS may at first be only allowed to...
  - provide **optimal setpoints** for low-level controllers
  - control a **subset of the production units**
- Needs to **gain trust** first

Represent low-level controllers in EMS

Handling Low-Level Controllers
Motivation

- EMS was not allowed to control the gas boiler in Leibnitzerfeld directly
  Still controlled via a low-level controller
- Could only be influenced indirectly via the imported heat



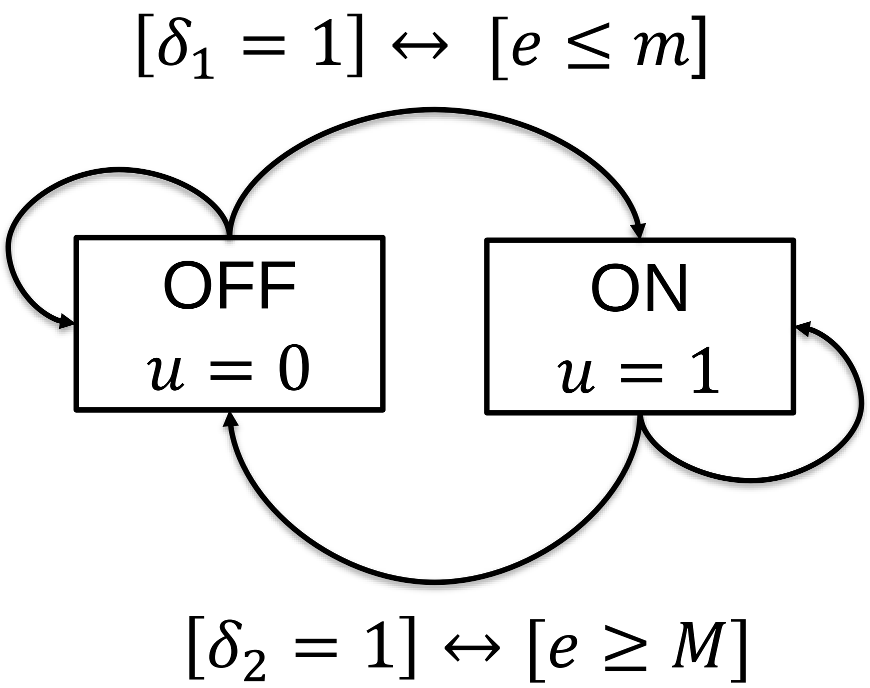
Handling Low-Level Controllers
Motivation

- Low-level controllers are very often “simple” but **highly non-linear**
  - Two-point controller
  - PI with anti-windup
  - IF-THEN-ELSE logic
- How to represent them in a **MILP** optimization problem?
  - Mixed logical-dynamical system [1]

[1] Bemporad, A., & Morari, M. (1999). Control of systems integrating logic, dynamics, and constraints. *Automatica*, *35*(3), 407–427. https://doi.org/10.1016/S0005-1098(98)00178-2

Handling Low-Level Controllers
Example: Two-Point Controller with hysteresis

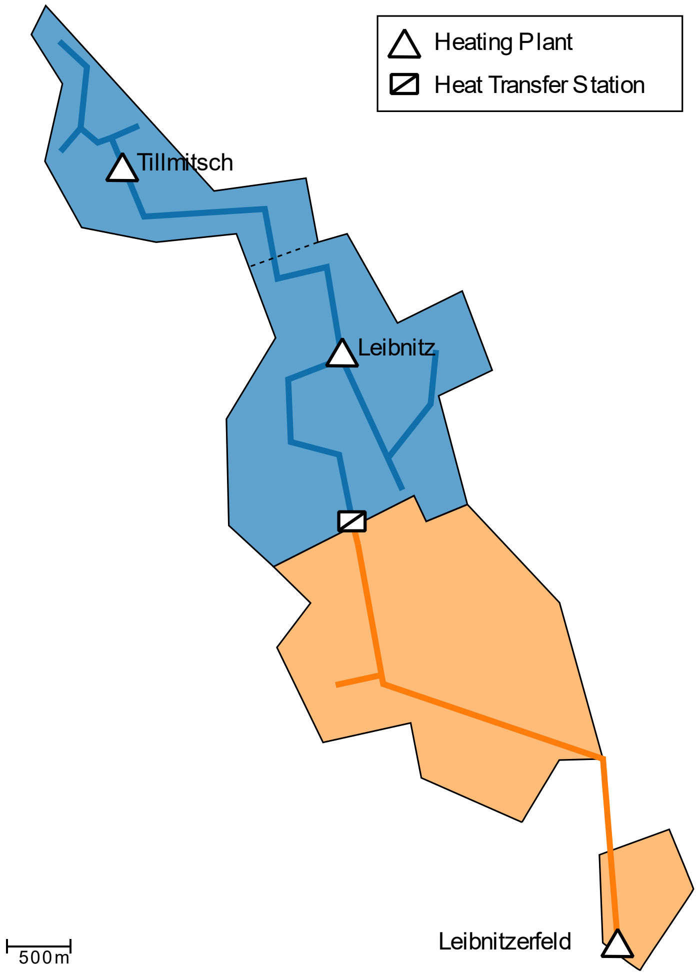
- "When are we in state ON?"
- $[u_{k+1}] \leftrightarrow [(\neg u_k \wedge \delta_{1,k}) \vee (u_k \wedge \neg \delta_{2,k})]$
- MILP formulation?
- **Idea** (logic to inequality):
  - $\delta_1 \vee \delta_2$ is equivalent to $\delta_1 + \delta_2 \geq 1$
  - $\delta_1 \vee \neg\delta_2$ is equivalent to $\delta_1 + (1 - \delta_2) \geq 1$
- Convert to CNF and incorporate as inequality constraints



Hybrid Coupling of Energy Systems

Hybrid Coupling of Energy Systems
Motivation

- Control of **interconnected DH networks** with different owners
- **Different economic interests** (non-cooperative)
- Global (social) optimum, not adequate
- **Mixture** of cooperative and non-cooperative coupling; “Coalitions”



Hybrid Coupling of Energy Systems
Mathematical Representation

Cooperative coupling

- Each agent has local constraints and a local objective function
- Agents minimize the global objective function

$$\min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad \sum_{i=1}^{N} f_i(\boldsymbol{x}_i)$$
$$\text{subject to} \quad \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b}$$

One opt. problem
Social optimum

Non-cooperative coupling

- Each agent has local constraints and a local objective function
- Each agent minimizes only its local cost function

$$\min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad f_i(\boldsymbol{x}_i), \quad i = 1, \ldots, N$$
$$\text{subject to} \quad \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b}$$

N coupled opt. problems
Nash equilibrium

Hybrid Coupling of Energy Systems

Mathematical Representation – Cooperative Coupling

$$\min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad \sum_{i=1}^{N} f_i(\boldsymbol{x}_i)$$

$$\text{subject to} \quad \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b}$$

- Separable Programme
- Solution is **social optimum**

Apply augmented Lagrangian method

- Augmented Lagrange function

$$\mathcal{L}(\boldsymbol{x}, \boldsymbol{\lambda}) = \sum_{i=1}^{N} f_i(\boldsymbol{x}_i) + \boldsymbol{\lambda}^T \left(\sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i - \boldsymbol{b} \right) + \frac{\rho}{2} \left\| \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i - \boldsymbol{b} \right\|_2^2$$

- Dual ascent

$$\boldsymbol{x}^{(k+1)} = \operatorname*{argmin}_{\boldsymbol{x} \in \mathcal{X}_1 \times \dots \times \mathcal{X}_N} \mathcal{L}\left(\boldsymbol{x}, \boldsymbol{\lambda}^{(k)}\right)$$

$$\boldsymbol{x}_i^{(k+1)} = \operatorname*{argmin}_{\boldsymbol{x}_i \in \mathcal{X}_i} \mathcal{L}_i\left(\boldsymbol{x}_i, \boldsymbol{\lambda}^{(k)}, \boldsymbol{x}_{-i}^{(k)}\right)$$

$$\boldsymbol{\lambda}^{(k+1)} = \boldsymbol{\lambda}^{(k)} + \rho \left(\sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i^{(k+1)} - \boldsymbol{b} \right)$$

Hybrid Coupling of Energy Systems

Mathematical Representation – Non-cooperative coupling

$$\min_{\boldsymbol{x}_i \in \mathcal{X}_i} \quad f_i(\boldsymbol{x}_i), \quad i = 1, \dots, N$$

$$\text{subject to} \quad \sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i = \boldsymbol{b}$$

- N-player game
- Solution is a **Nash equilibrium**

N coupled opt. problems

Apply augmented Lagrangian method for each

- Augmented Lagrange functions

$$\mathcal{L}_i(\boldsymbol{x}_i, \boldsymbol{\lambda}_i) = f_i(\boldsymbol{x}_i) + \boldsymbol{\lambda}_i^T \left(\boldsymbol{A}_i \boldsymbol{x}_i + \sum_{j \neq i} \boldsymbol{A}_j \boldsymbol{x}_j - \boldsymbol{b} \right) + \frac{\rho}{2} \left\| \boldsymbol{A}_i \boldsymbol{x}_i + \sum_{j \neq i} \boldsymbol{A}_j \boldsymbol{x}_j - \boldsymbol{b} \right\|_2^2$$

- Dual ascent

$$\boldsymbol{x}_i^{(k+1)} = \operatorname*{argmin}_{\boldsymbol{x}_i \in \mathcal{X}_i} \mathcal{L}_i(\boldsymbol{x}_i, \boldsymbol{\lambda}_i^{(k)}, \boldsymbol{x}_{-i}^{(k)})$$

$$\boldsymbol{\lambda}_i^{(k+1)} = \boldsymbol{\lambda}_i^{(k)} + \rho \left(\boldsymbol{A}_i \boldsymbol{x}_i^{(k+1)} + \sum_{j \neq i} \boldsymbol{A}_j \boldsymbol{x}_j^{(k)} - \boldsymbol{b} \right)$$

Hybrid Coupling of Energy Systems

Mathematical Representation - Comparison

ALM for cooperative coupling

$$\boldsymbol{x}_i^{(k+1)} = \underset{\boldsymbol{x}_i \in \mathcal{X}_i}{\operatorname{argmin}} \; \mathcal{L}\left(\boldsymbol{x}_i, \boldsymbol{\lambda}^{(k)}, \boldsymbol{x}_{-i}^{(k)}\right)$$

$$\boldsymbol{\lambda}^{(k+1)} = \boldsymbol{\lambda}^{(k)} + \rho\left(\sum_{i=1}^{N} \boldsymbol{A}_i \boldsymbol{x}_i^{(k+1)} - \boldsymbol{b}\right)$$

ALM for non-coop. coupling

$$\boldsymbol{x}_i^{(k+1)} = \underset{\boldsymbol{x}_i \in \mathcal{X}_i}{\operatorname{argmin}} \; \mathcal{L}_i(\boldsymbol{x}_i, \boldsymbol{\lambda}_i^{(k)}, \boldsymbol{x}_{-i}^{(k)})$$

$$\boldsymbol{\lambda}_i^{(k+1)} = \boldsymbol{\lambda}_i^{(k)} + \rho\left(\boldsymbol{A}_i \boldsymbol{x}_i^{(k+1)} + \sum_{j \neq i} \boldsymbol{A}_j \boldsymbol{x}_j^{(k)} - \boldsymbol{b}\right)$$

Very similar $\Rightarrow$ Idea: Combination for **hybrid coupling**

Hybrid Coupling of Energy Systems

Mathematical Representation – Hybrid Coupling

$$\boldsymbol{x}_i^{(k+1)} = \underset{\boldsymbol{x}_i \in \mathcal{X}_i}{\operatorname{argmin}} \, \mathcal{L}\left(\boldsymbol{x}_i, \boldsymbol{x}_{j \neq i}^{(k)}, \boldsymbol{\lambda}_i^{(k)}\right)$$

$$\boldsymbol{\lambda}_{i,c}^{(k+1)} = \boldsymbol{\lambda}_{i,c}^{(k)} + \rho \left(\boldsymbol{A}_i \boldsymbol{x}_i^{(k+1)} + \boxed{\sum_{j \neq i}^{N} \boldsymbol{A}_i \boldsymbol{x}_j^{(k)}} - \boldsymbol{b} \right), \quad i = 1, \dots, N, \; c \in \mathcal{C}_{\text{non-coop}}$$

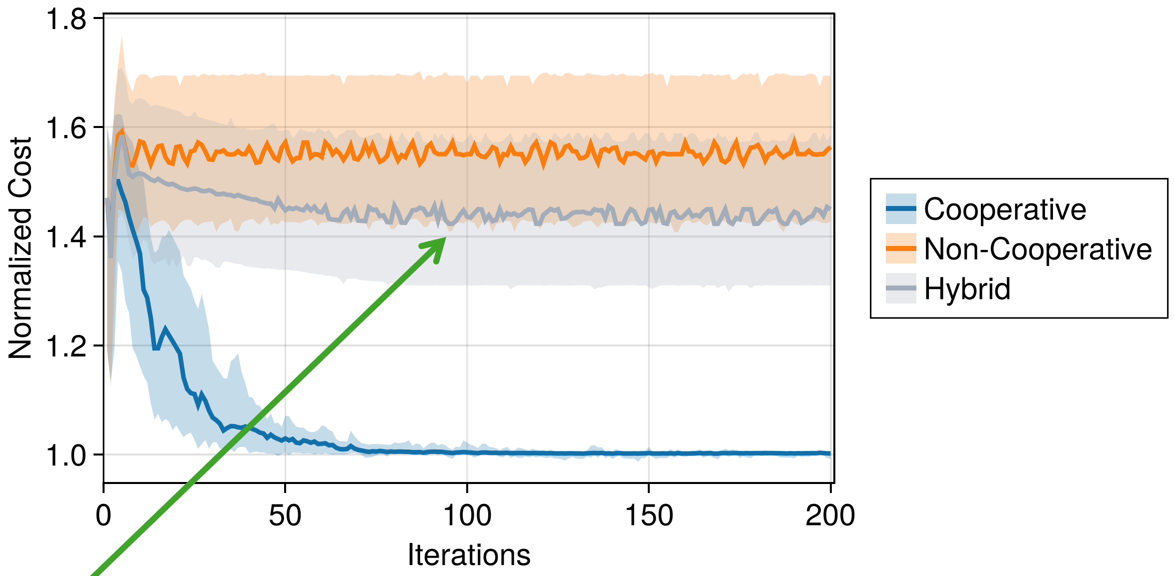
$$\boldsymbol{\lambda}_{i,c}^{(k+1)} = \boldsymbol{\lambda}_{i,c}^{(k)} + \rho \left(\boldsymbol{A}_i \boldsymbol{x}_i^{(k+1)} + \boxed{\sum_{j \neq i}^{N} \boldsymbol{A}_i \boldsymbol{x}_j^{(k+1)}} - \boldsymbol{b} \right), \quad i = 1, \dots, N, \; c \in \mathcal{C}_{\text{coop}}$$

V. Kaisermayer, D. Muschick, M. Horn, and M. Gölles, “Operation of Coupled Multi-Owner District Heating Networks via Distributed Optimization,” Energy Reports, vol. 7, pp. 273–281, Oct. 2021.

Hybrid Coupling of Energy Systems
Simulation Study

Test Problems

- All three grids **cooperative**
- All three grids **non-cooperative**
- The two grids that belong to the same owner cooperate; the third does not (**hybrid**)



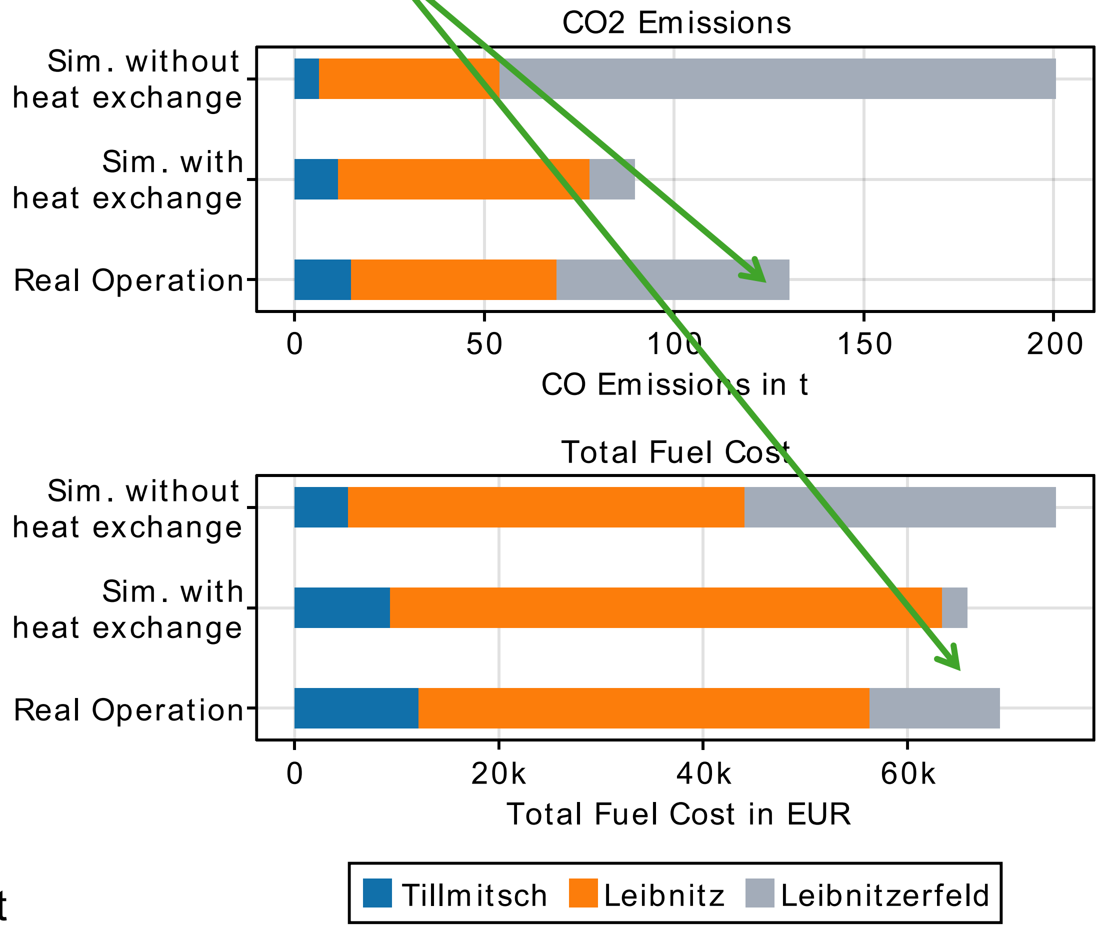
Shaded area is range of solutions for different input datasets

Real Operation

Real Operation
Pre-Simulation Study

- **Cooperative EMS** was implemented
  - “Fair” contract between owners
- Simulation study as a best-case scenario
  - With and without (base case) heat exchanger
- Real operation

35% reduction in CO_2 emissions
7% fuel cost reduction
during 1 month (April 2021)



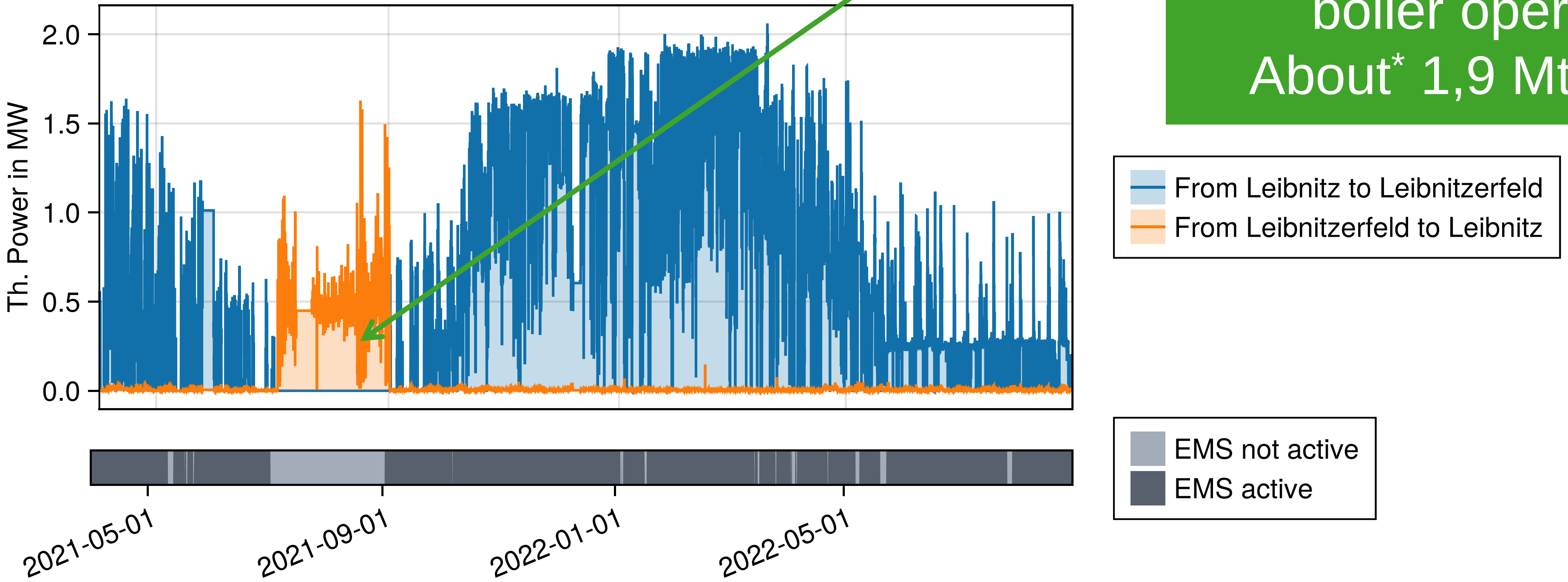
V. Kaisermayer *et al.*, “Smart control of interconnected district heating networks on the example of ‘100% Renewable District Heating Leibnitz,’” *Smart Energy*, vol. 6, May 2022.

Real Operation
Heat Transfer Station

- **Running since April 2021**

Maintenance during summer

Saved 7537 MWh of gas boiler operation
About* 1,9 Mt of CO_2



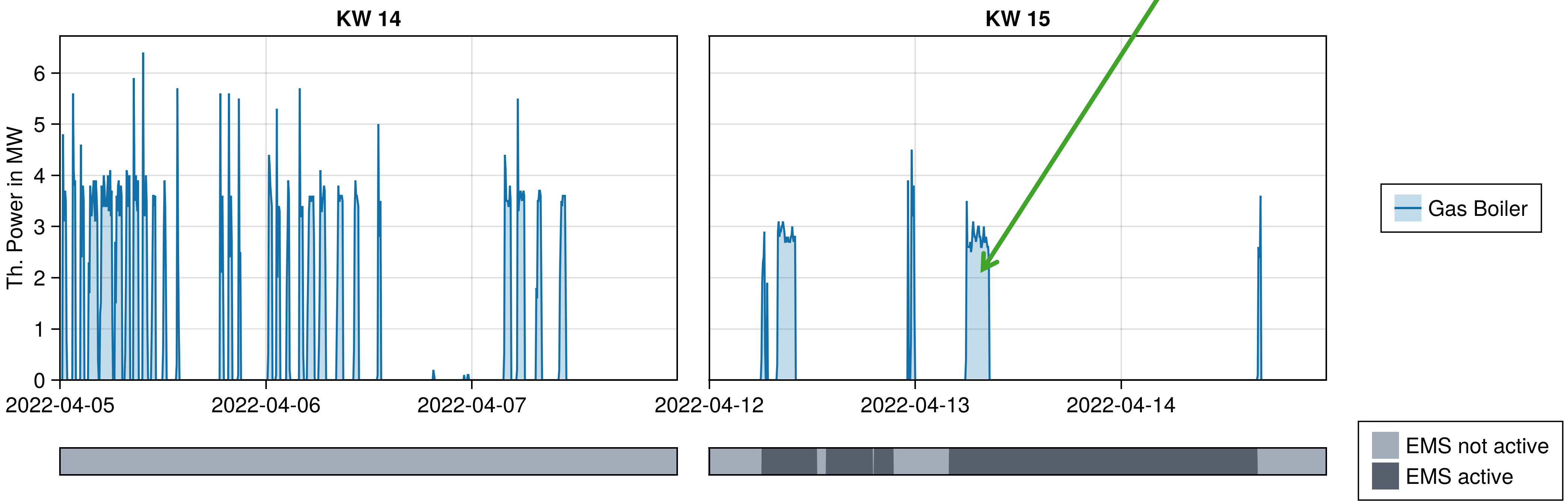
* 0,201 tCO_2/MWh @ 80% efficiency

Real Operation

Gas Boiler Operation

- During KW15 the EMS was given full control

Reduced Gas Boiler Operation by 70%
Better Operating Conditions:
(longer run time, lower power level)



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