Efficient heat pump operation:
A comparative analysis of model-predictive and rule-based heat pump control

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Bernd Riederer, Daniel Muschick, Astrid Leitner,
Mathias Schwendt, Valentin Kaisermayer, Markus Gölles

BEST – Bioenergy and Sustainable Technologies GmbH

Operation of hybrid energy systems

- **Flexibility is increasing**
  - Volatile renewable energy sources and storage systems
  - Increased sector coupling
  - New pricing models for flexibility (time-variable tariffs) in various sectors
  - Integration of storage systems (battery, heat storages, building mass)

Increasing complexity and range of energy carriers requires
a flexible and efficient control of all components

- Heat-pumps provide a central component of hybrid energy systems

What to expect from different control approaches?

Requirements for controlling hybrid energy systems

optimal operation
(efficiency, CO_2 emissions, …)

→ **optimization-based**
ensures optimal operation of the system
by targeted utilization of the different technologies

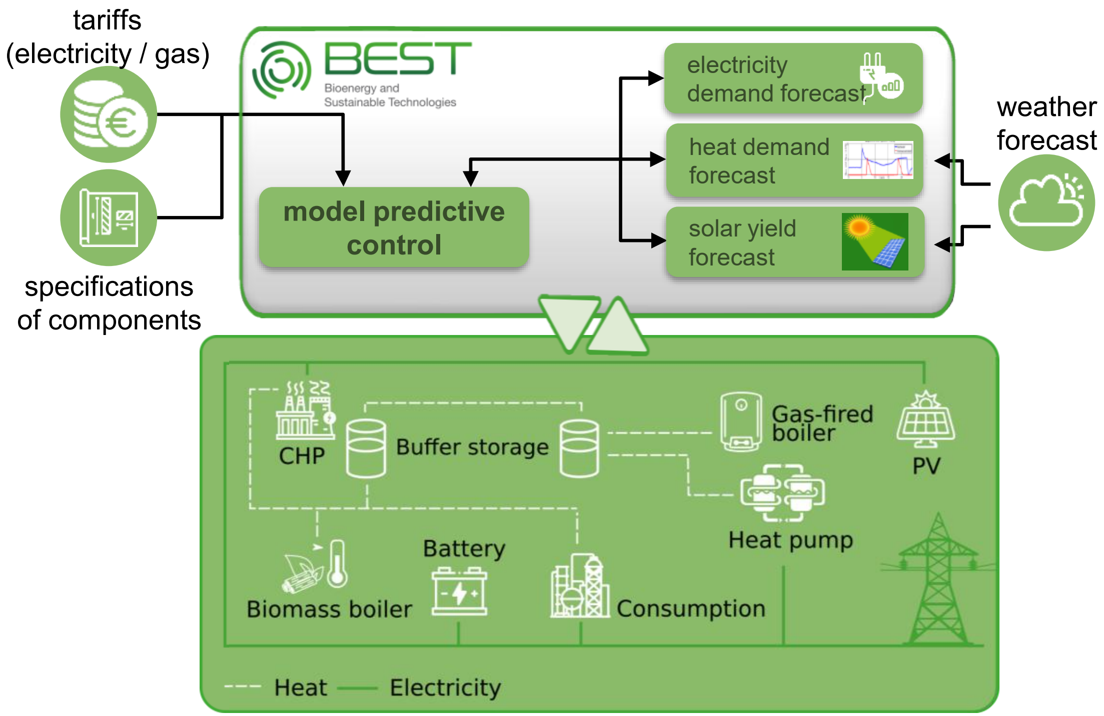
volatility
of production and consumption

→ **predictive**
integration of weather and price forecasts
calculation of forecasts for yields and consumptions

variation range
of the configurations

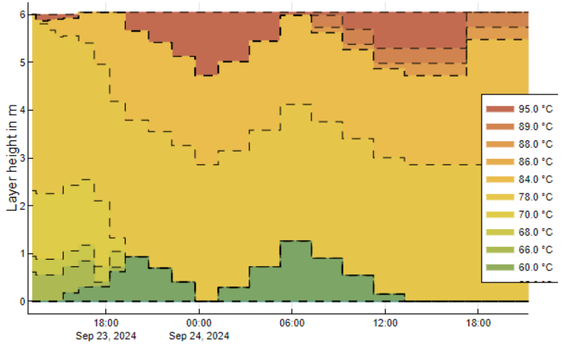
→ **modular**
automatic (re)formulation of the optimization problem
based on the specifications of the components

A modular, predictive, optimization-based supervisory control framework

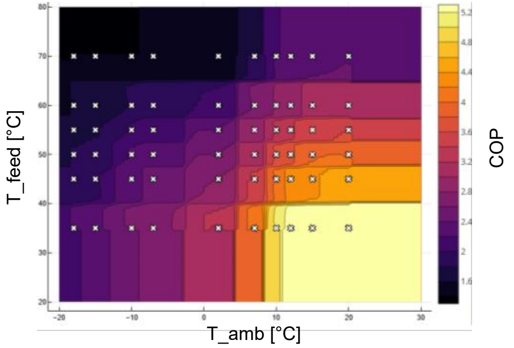


Optimization based approach

- **Mixed-integer linear models**
  - Can directly be considered in optimisation problems (MILP)
  - Easily adaptable and configurable
- **Consideration of temperature levels**
  - Different temperature requirements and efficiencies included
  - Needed for all applications with varying heat demand (e.g. heating)
- **Multi-linear heat pump model**
  - COP depends on ambient and return temperature



thermal buffer temperature prediction for MPC



interpolated heat pump COP

[1] **Moser, Andreas et.al**. (**2020**).
DOI: 10.1016/j.apenergy.2019.114342.
[2] **Muschick, Daniel et.al**. (**2022**).
DOI: 10.1016/j.apenergy.2022.118890.

One Framework – Many Applications

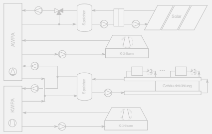
Simulation studies

Using the controller as a stepwise simulation tool for scenario analysis and control strategy evaluation

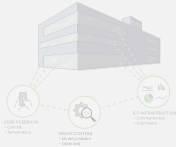
Single Family Homes
Managing the energy of homes, increasing comfort and efficiency

Energy Communities
Incentivize synchronization of electricity export and import

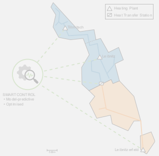
Solar Thermal
Solar cooling, process heat or district heating



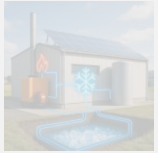
Office Buildings
Provision of heating and cooling while maximizing comfort



District Heating
Heating of whole cities with hundreds of consumers

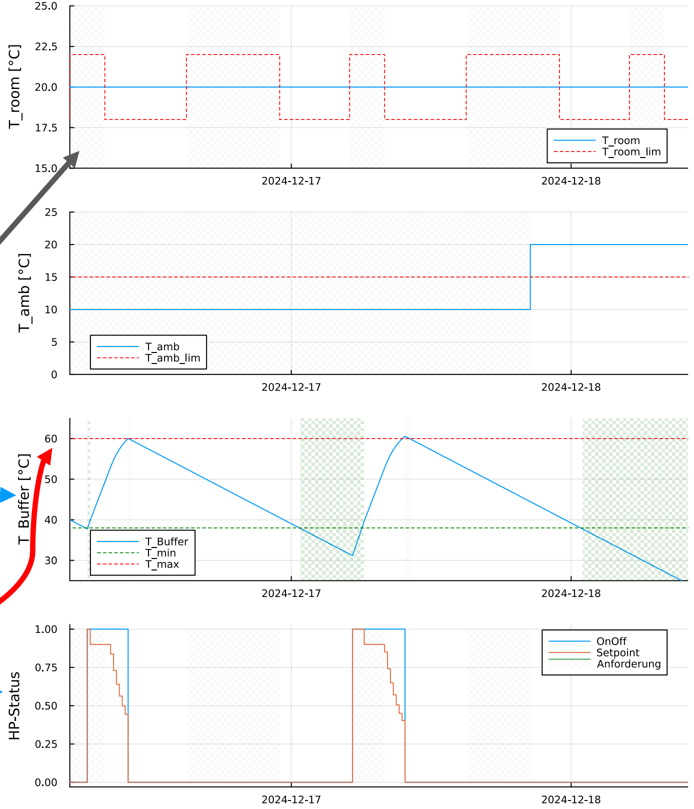


Business & Industry
Orchestration of energy production, storage and consumption



Rule-based control

- Implemented as additional constraints
- RBC logic
  - 🕒 Time-dependent operational constraints
    - ➢ Operation restricted or adapted during predefined periods
  - 🌡️ Buffer-driven on/off control
    - ➢ Heat pump activation based on internal thermal state
  - 🌞 Surplus-driven setpoint adaptation
    - ➢ Temporary extension of buffer target levels

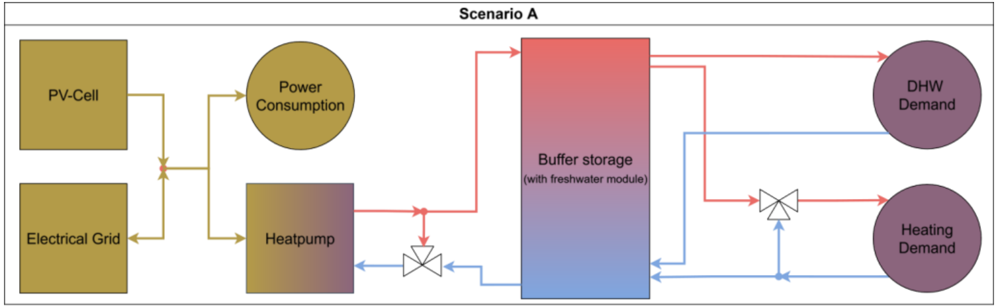


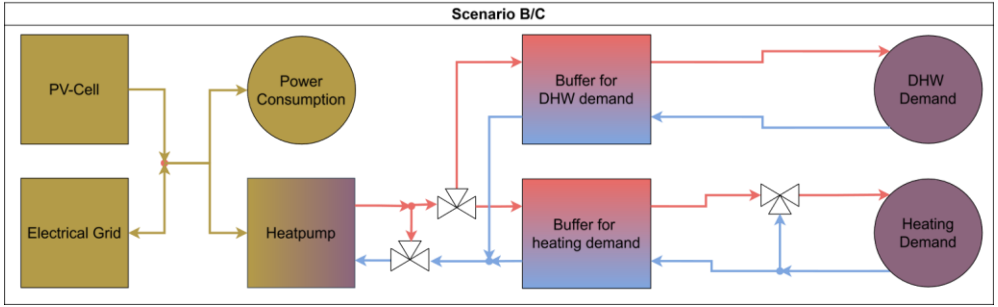
Sample illustration of a possible RBC logic

Scenarios for analysis and setup

- **Data**
  - Demand and weather from single family home
  - PV: calculated from weather data
  - Reference time: 2023
- **Electricity tariffs**
  - **Variable**: SPOT 2023 (excl. taxes and grid fees)
  - **Fixed**: import 12 ct/kWh / export 8 ct/kWh

Name	HP	PV	Buffer	DHW	Electricity tariff
A-1	13 kW_{th}	15 kW_p	1500 l	-	variable
A-2	13 kW_{th}	15 kW_p	500 l	-	variable
B-1	8 kW_{th}	10 kW_p	300 l	300 l	variable
B-2	8 kW_{th}	10 kW_p	500 l	300 l	variable
B-3	8 kW_{th}	10 kW_p	750 l	300 l	variable
C-1	8 kW_{th}	10 kW_p	300 l	300 l	fixed
C-2	8 kW_{th}	10 kW_p	500 l	300 l	fixed
C-3	8 kW_{th}	10 kW_p	750 l	300 l	fixed

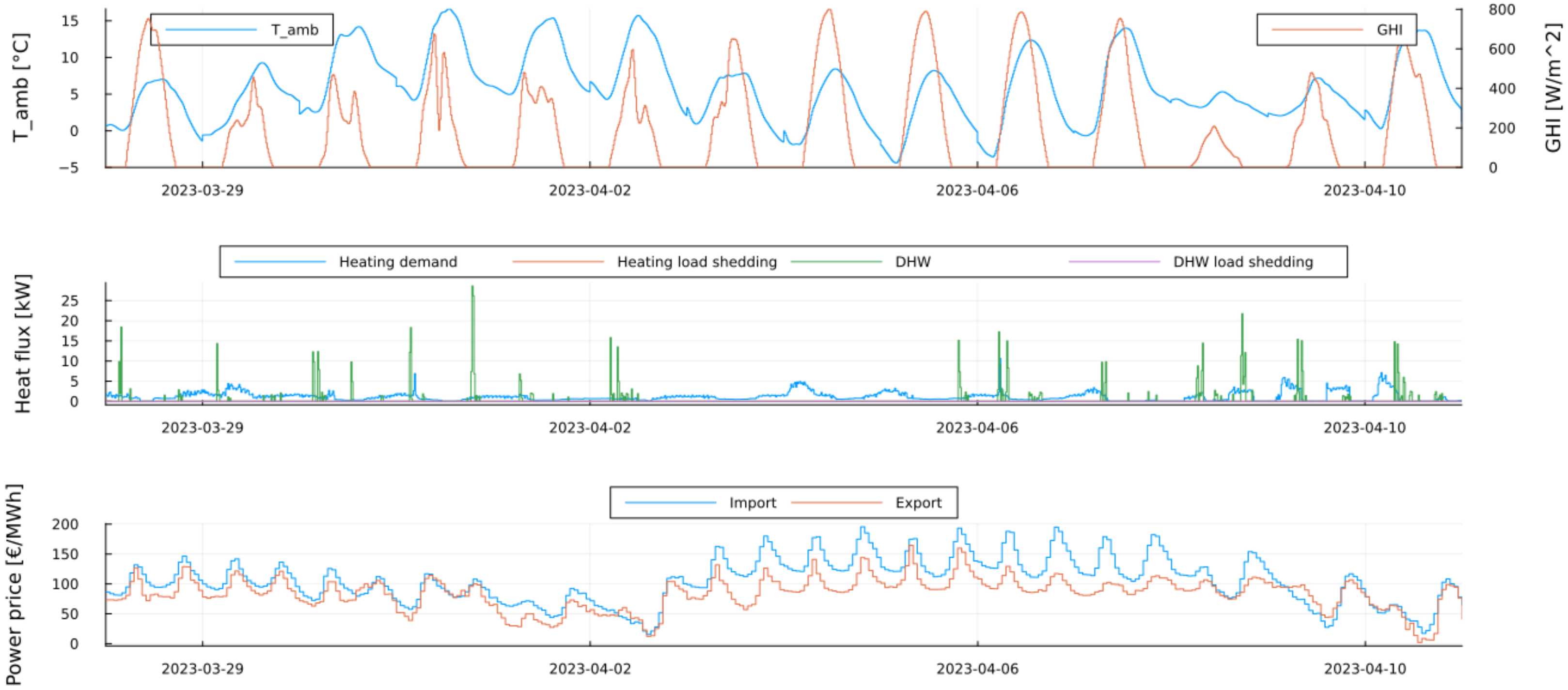


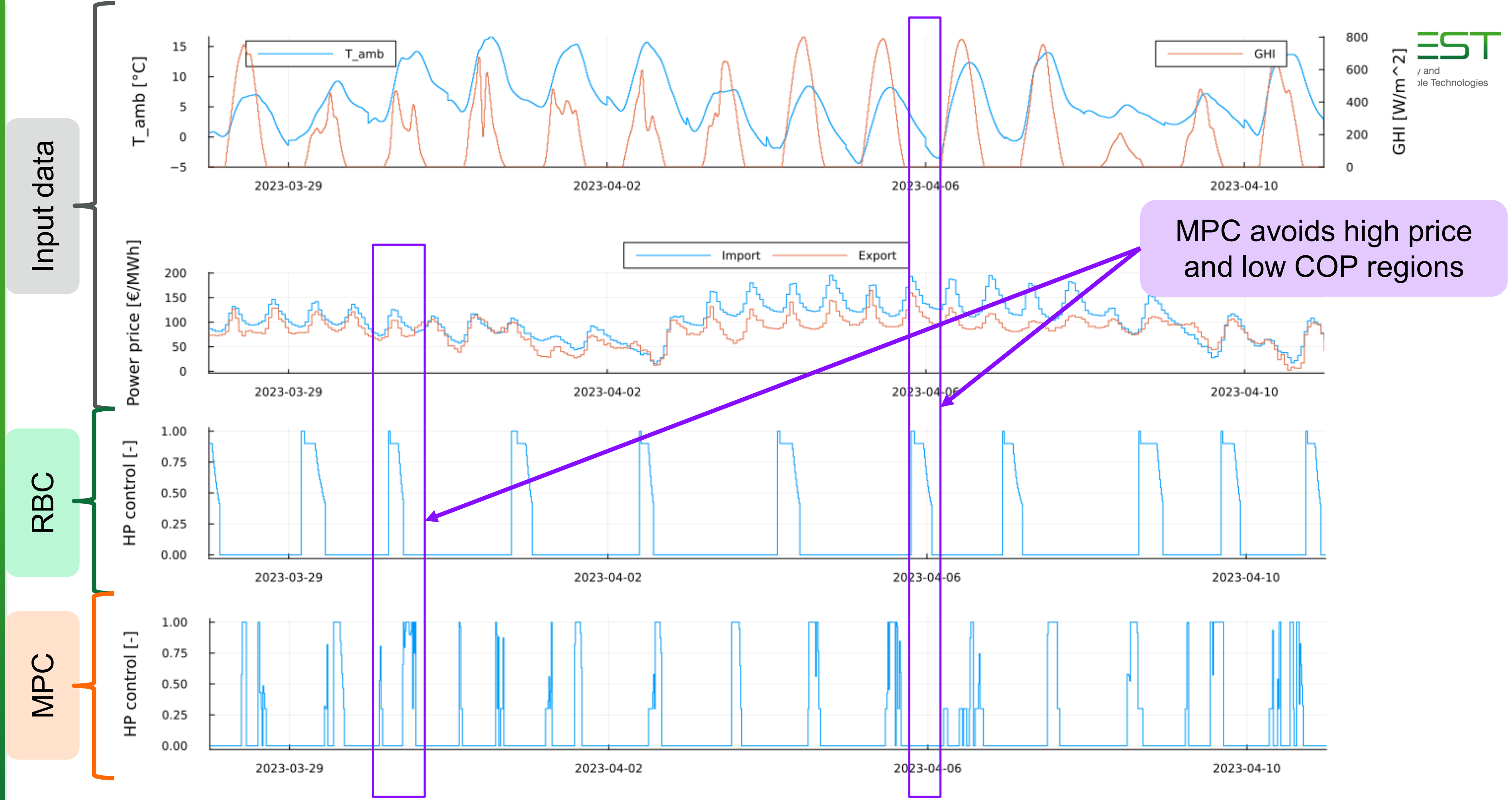


Results

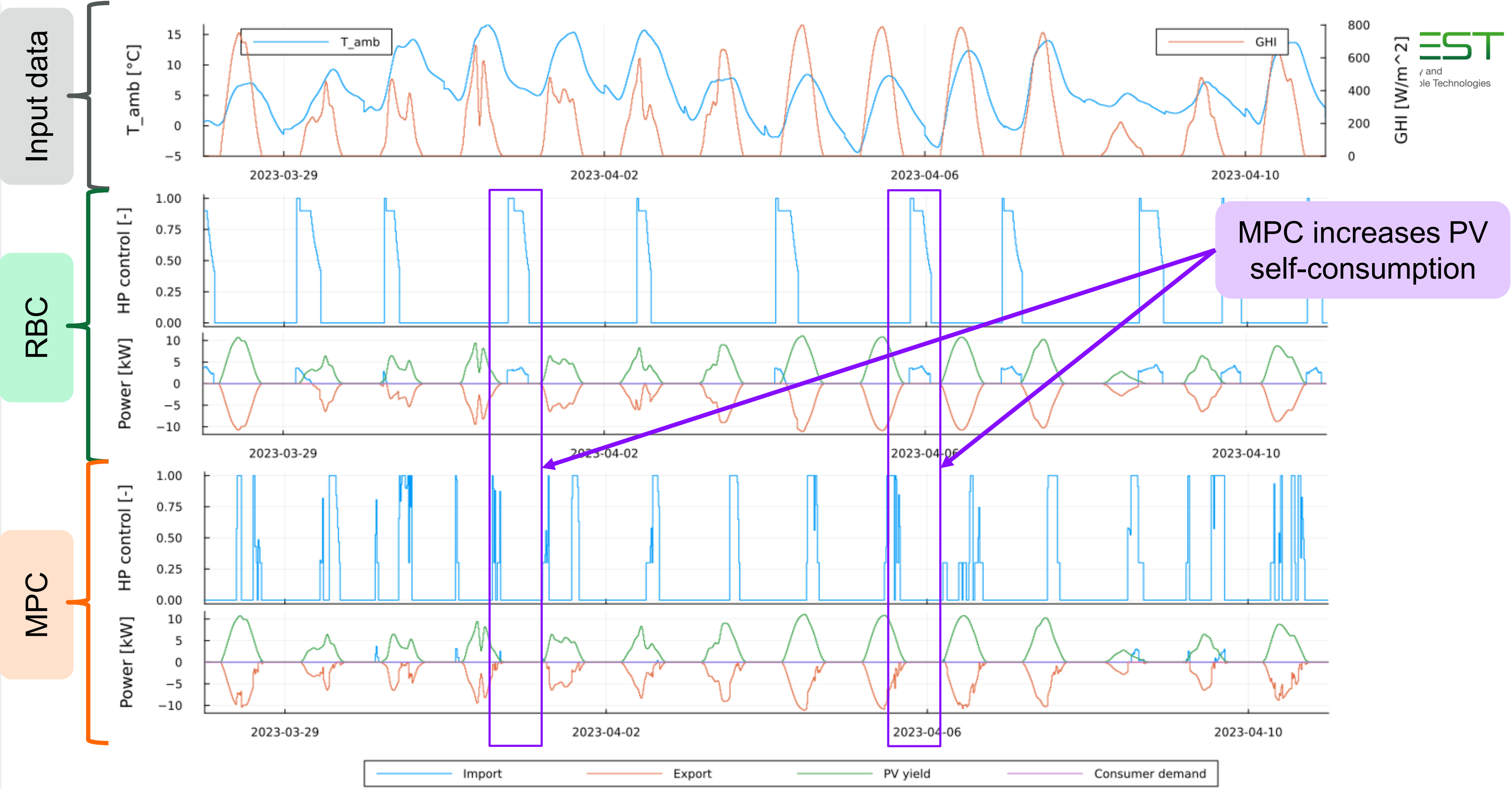
Single Buffer scenarios – Operation schedules

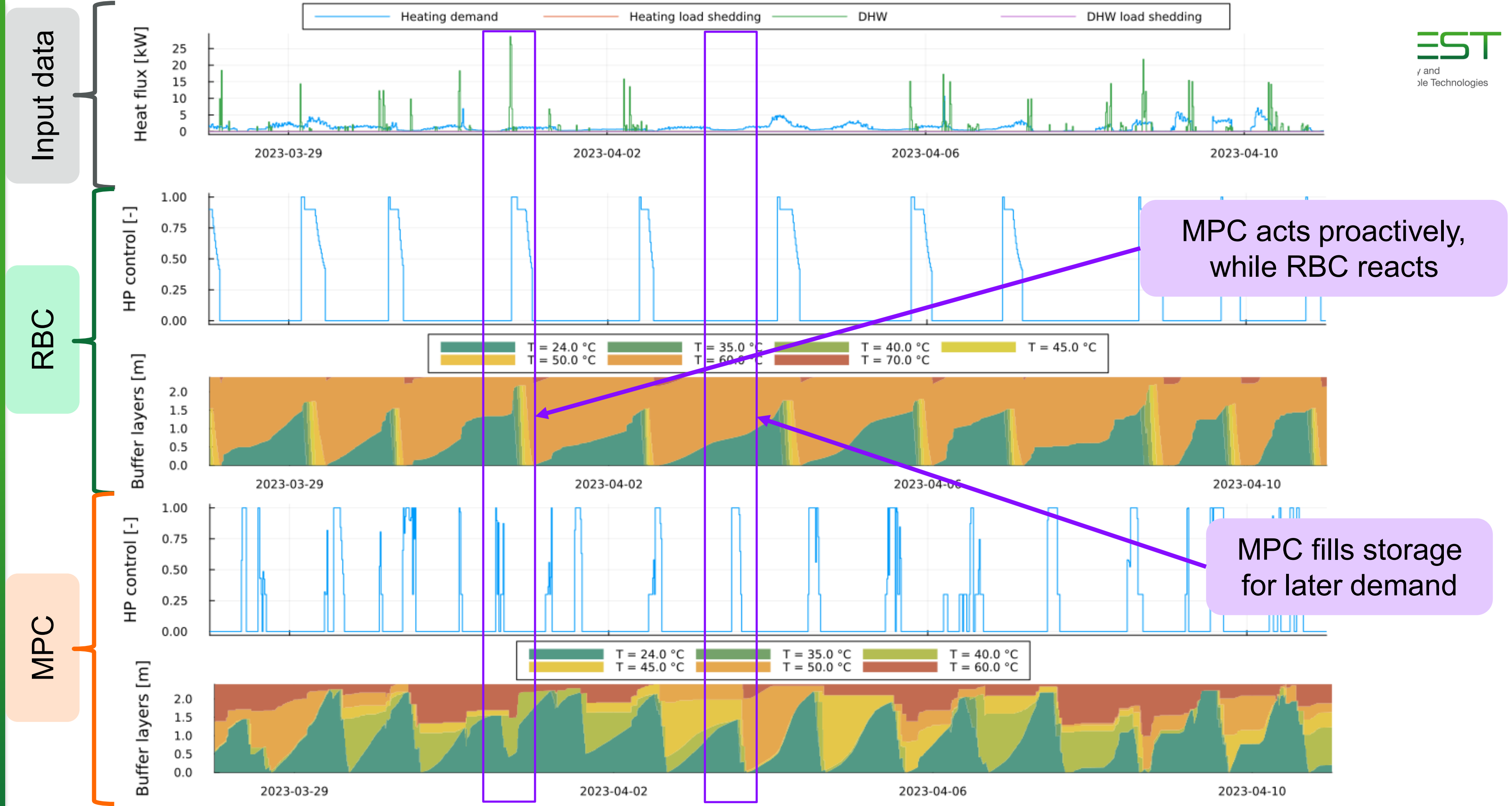
Input data





Input data
RBC
MPC
T_amb [°C]
T_amb
GHI
GHI [W/m^2]
Power price [€/MWh]
Import
Export
HP control [-]
2023-03-29
2023-04-02
2023-04-06
2023-04-10
MPC avoids high price and low COP regions


Input data
RBC
MPC
T_amb [°C]
T_amb
GHI
GHI [W/m^2]
HP control [-]
Power [kW]
2023-03-29
2023-04-02
2023-04-06
2023-04-10
MPC increases PV self-consumption
Import
Export
PV yield
Consumer demand



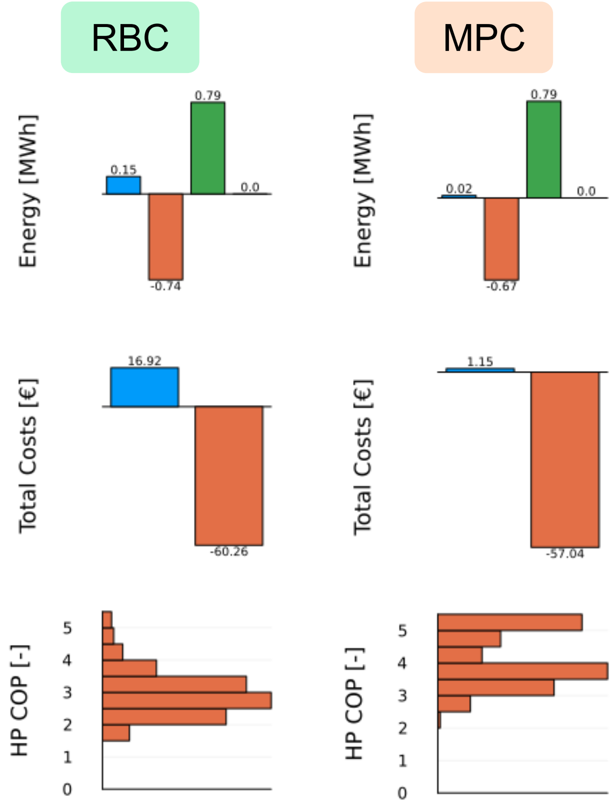
Input data
RBC
MPC
Heating demand
Heating load shedding
DHW
DHW load shedding
Heat flux [kW]
HP control [-]
Buffer layers [m]
2023-03-29
2023-04-02
2023-04-06
2023-04-10
T = 24.0 °C
T = 35.0 °C
T = 40.0 °C
T = 45.0 °C
T = 50.0 °C
T = 60.0 °C
T = 70.0 °C
MPC acts proactively, while RBC reacts
MPC fills storage for later demand

Results

Single Buffer scenarios

- **Operational behaviour**
  - MPC utilizes flexibility
  - Higher COP
  - Lower Costs
  - Increased PV self-sufficiency
- **Annual net costs**

Scenario	RBC	MPC	Relative change
A-1	-384 €	-538 €	-40%
A-2	-334 €	-496 €	-48%
A-1 (no PV)	1083 €	913 €	-16%
A-2 (no PV)	1111 €	959 €	-14%



Results

Double Buffer scenarios

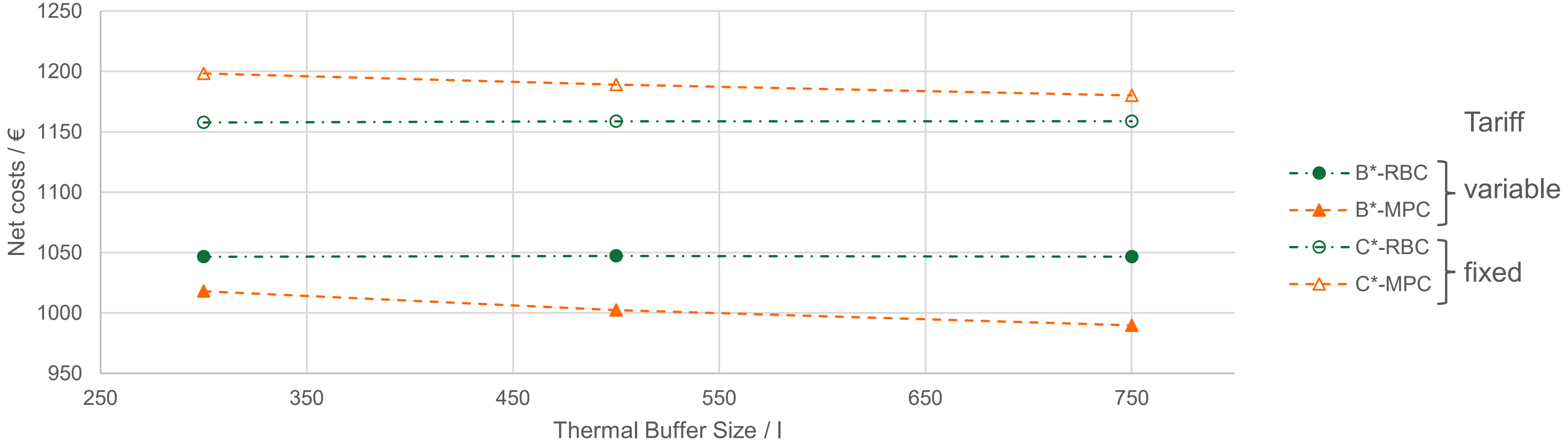
- Double buffer scenarios requires switching between filling
  → reduces flexibility

- Operational benefits reduced compared to single buffer scenarios
  - Lower flexibility
  - Smaller buffers
  - Smaller heat pump

Does the **MPC** strategy pay off, or is RBC sufficient?
If so, under **which conditions**?

Results

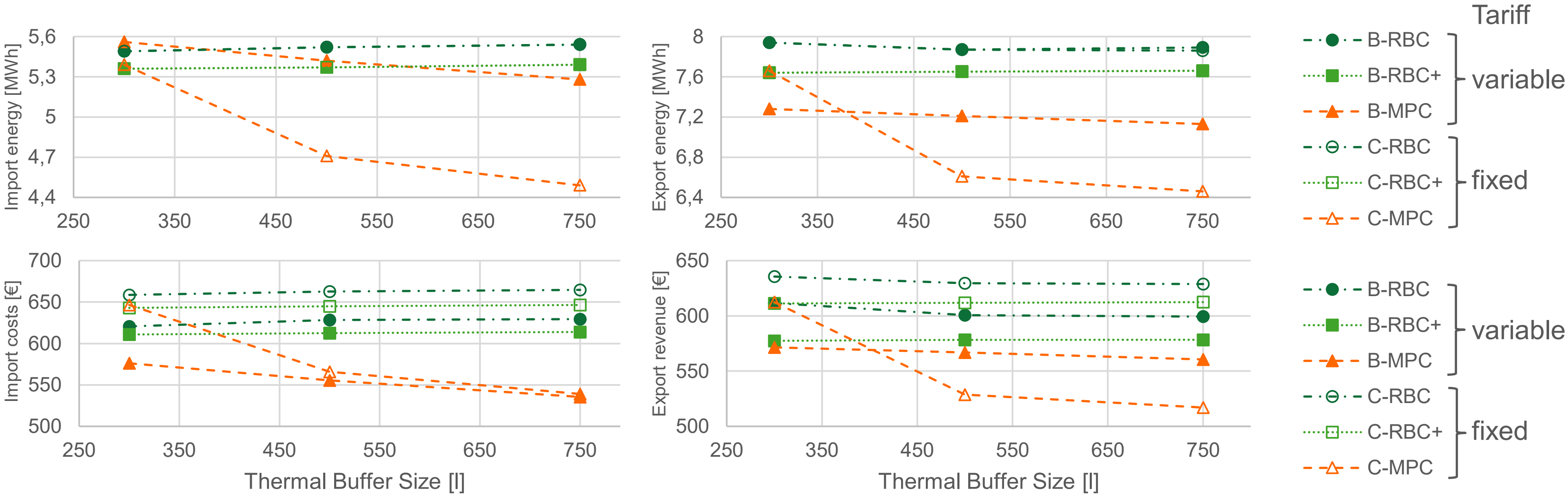
Double Buffer scenarios without PV – Annual net costs



RBC ➔ benefits from **variable tariffs** but is unchanged by buffer size
MPC ➔ benefits from rising **flexibility** (buffer size/variable tariffs)

Results

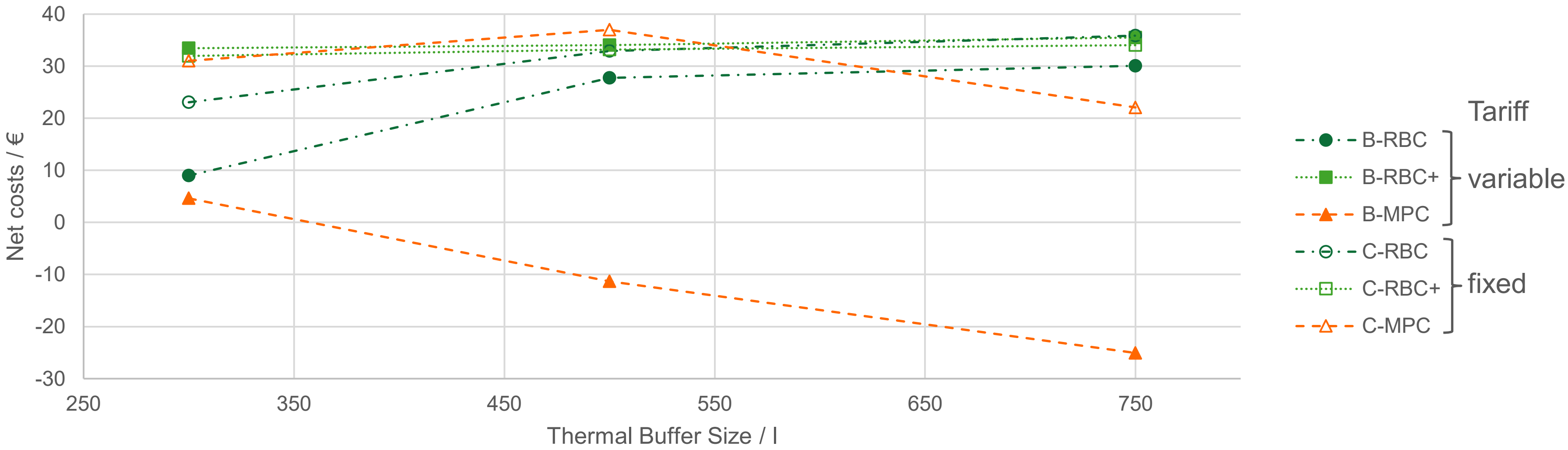
Double Buffer scenarios with PV – Annual Import/Export



RBC ➔ import energy and costs **increase** / **export** stays **constant**
MPC ➔ reduced import and **export** / variable tariff **reduces import costs**

Results

Double Buffer scenarios with PV – Annual net costs



RBC ➔ benefits from **variable tariffs** for small buffers
MPC ➔ significantly **reduces costs** with **increasing flexibility**

Conclusion

- **Rule-based control** works well for **standard systems**
  - → no benefit from flexibility
- **Model-predictive control** shows high **cost-saving potential**
  - → up to 48% reduction in high-flexibility systems
- **Flexibility is key**:
  Larger buffers, PV, or variable tariffs boost MPC performance significantly

Outlook and ongoing improvements

- **Expand simulations to complex systems**
  - → batteries, thermal building mass as additional storage, hybrid setups …
- Study **heat pump size dependence** in more detail

Bernd Riederer
Senior Researcher
Automation and Control
T +43 5 02378-9229
bernd.riederer@best-research.eu

Markus Gölles
Area Manager
Automation and Control
T +43 5 02378-9208
markus.goelles@best-research.eu

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