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Experiments on Grid-Supporting (economic) Model Predictive Control of a Trigeneration System

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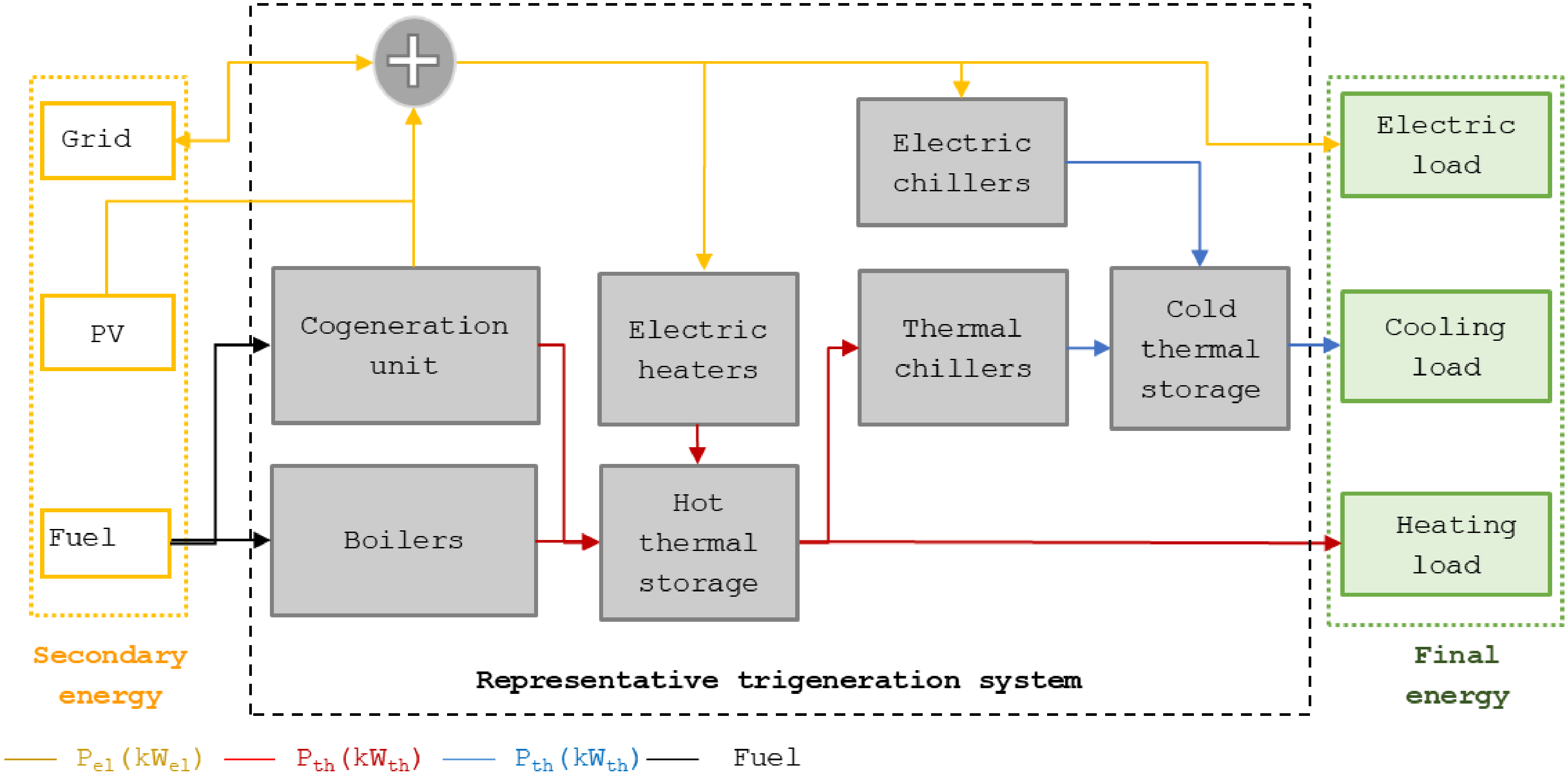
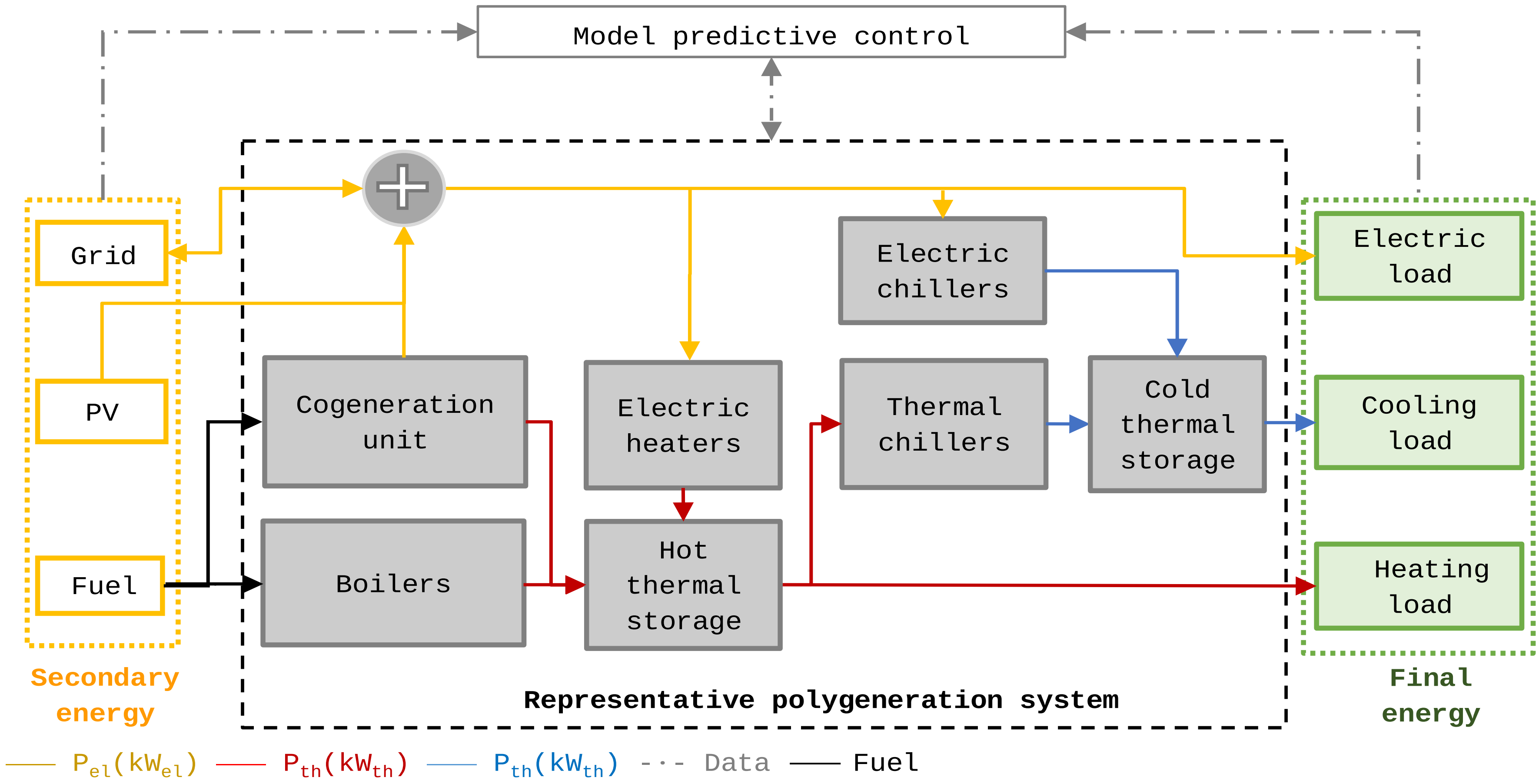
Trigeneration Systems and Motivation for Experimental Tests

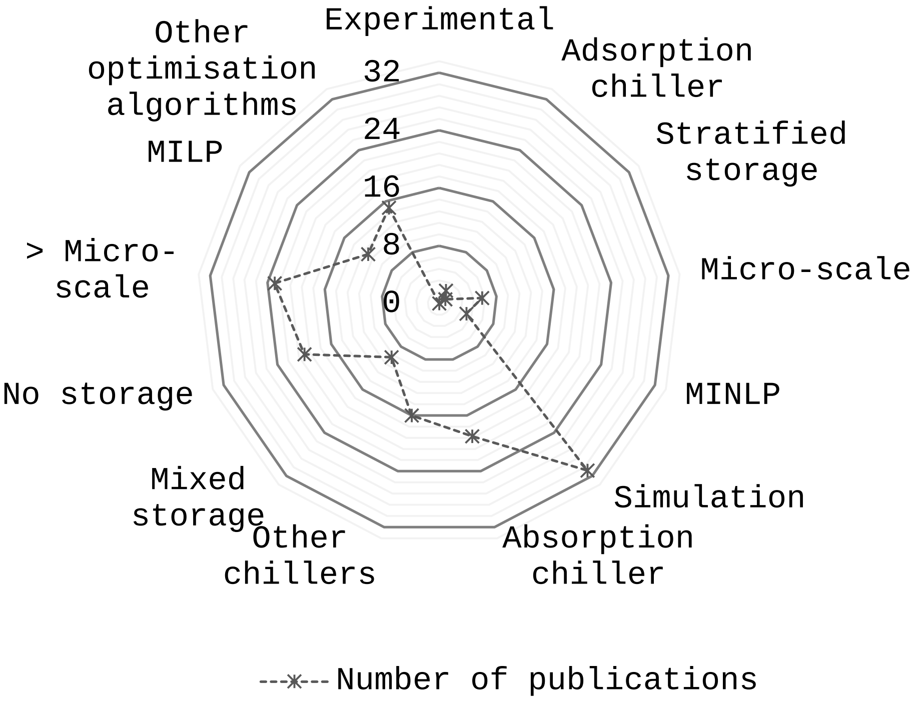


Grid
PV
Fuel
Secondary energy
Cogeneration unit
Boilers
Electric heaters
Hot thermal storage
Electric chillers
Thermal chillers
Cold thermal storage
Representative trigeneration system
Electric load
Cooling load
Heating load
Final energy
P_{el} (kW_{el})
P_{th} (kW_{th})
P_{th} (kW_{th})
Fuel


Model predictive control
Grid
PV
Fuel
Secondary energy
Cogeneration unit
Boilers
Electric heaters
Hot thermal storage
Electric chillers
Thermal chillers
Cold thermal storage
Representative polygeneration system
Electric load
Cooling load
Heating load
Final energy
$P_{el}(kW_{el})$
$P_{th}(kW_{th})$
$P_{th}(kW_{th})$
Data
Fuel

Three Levels of CCHP Optimisation*

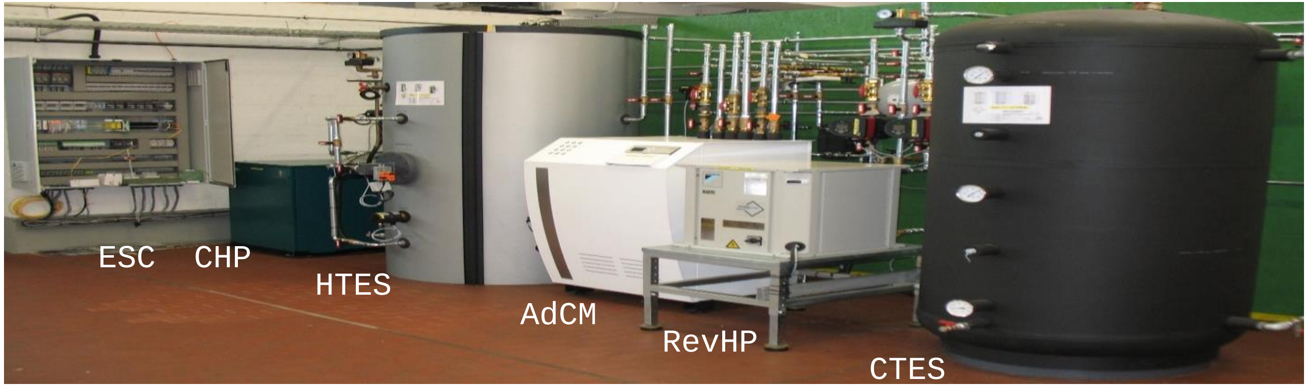
Literature Analysis

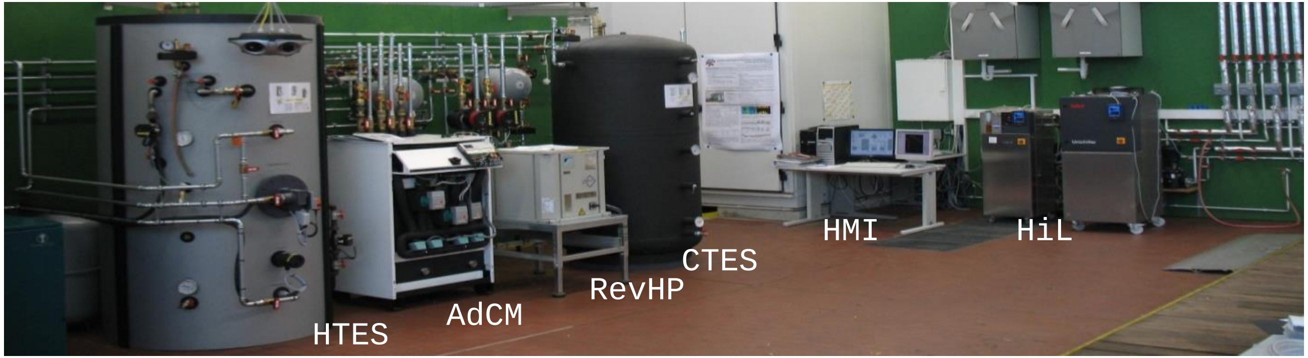


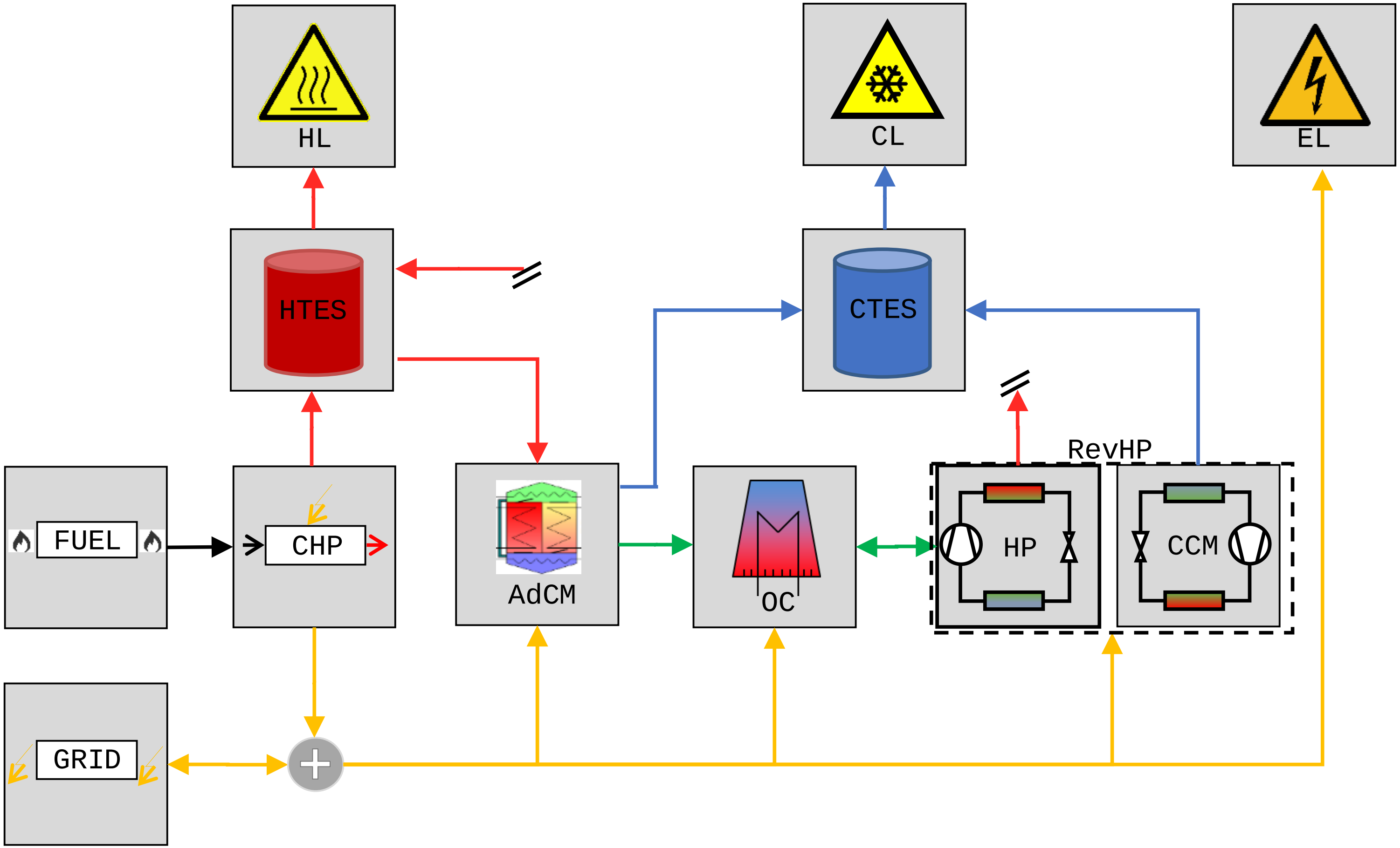
*Urbanucci, L., 2018. Energy Procedia 148, 1199–1205. https://doi.org/10.1016/j.egypro.2018.08.021

INES Trigeneration System

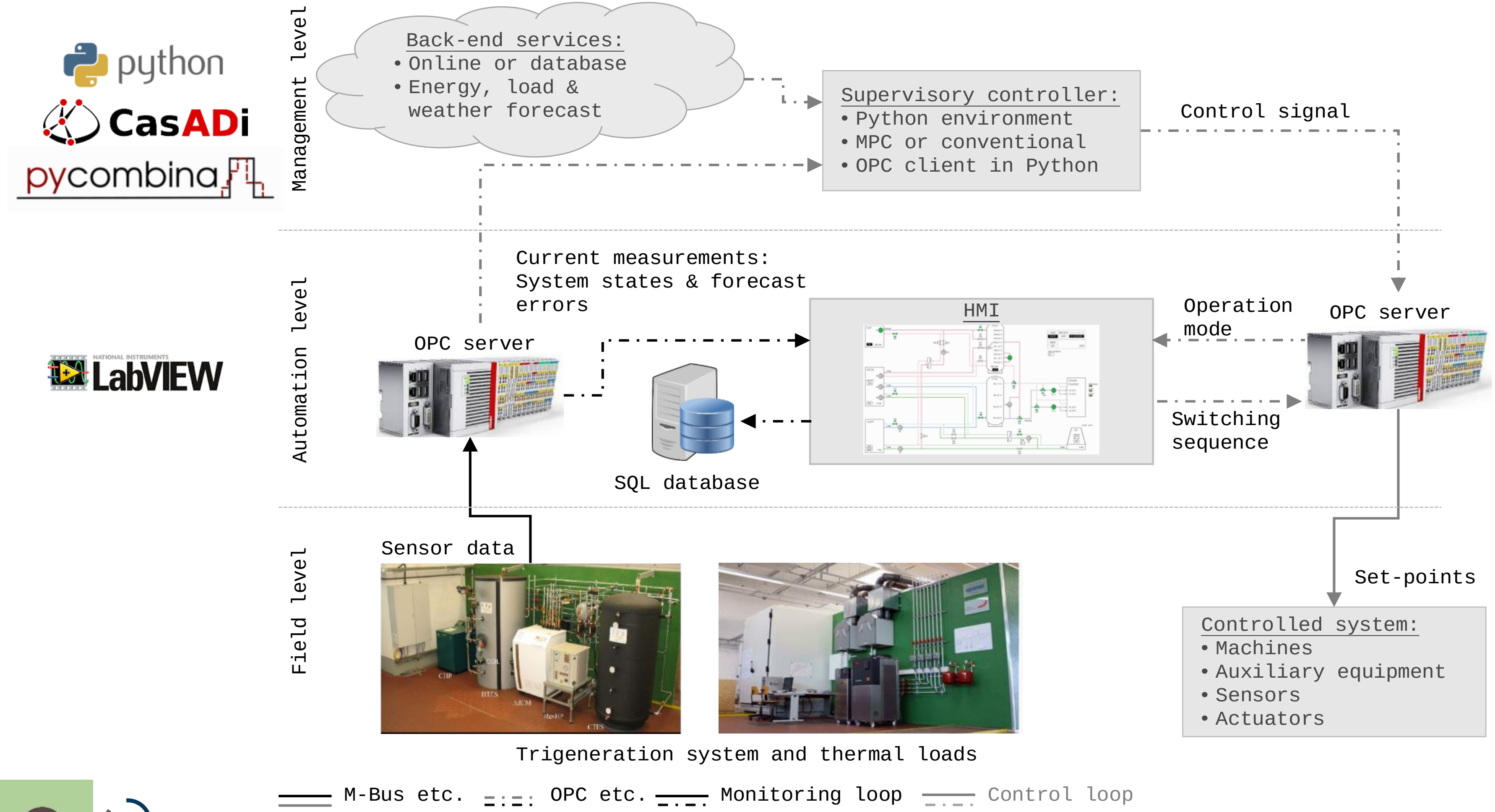
INES Trigeneration System

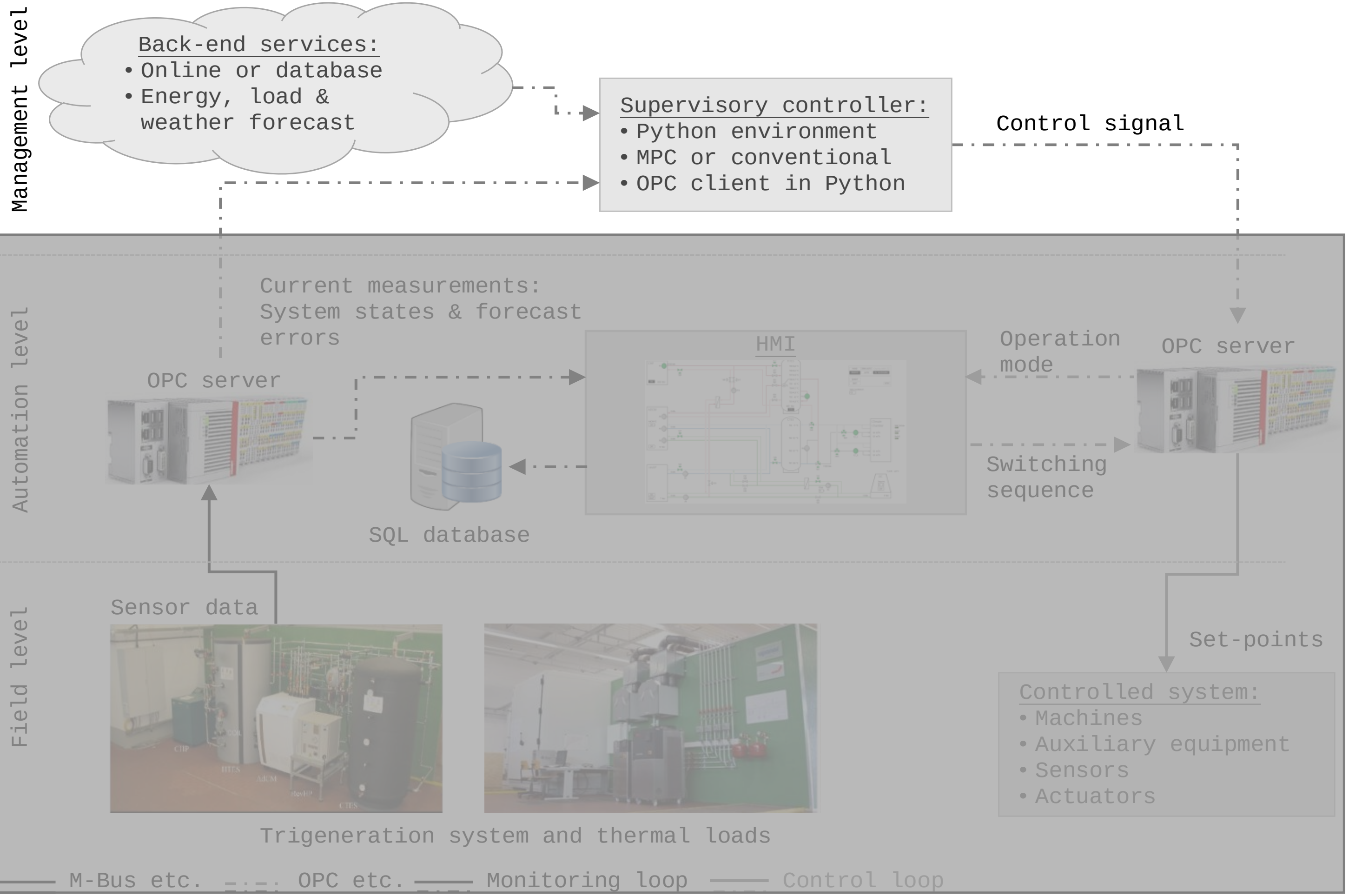






HL
CL
EL
HTES
CTES
RevHP
FUEL
CHP
AdCM
OC
HP
CCM
GRID


python
CasADi
pycombina
LabVIEW
Management level
Automation level
Field level
Back-end services:
• Online or database
• Energy, load & weather forecast
Supervisory controller:
• Python environment
• MPC or conventional
• OPC client in Python
Control signal
Current measurements:
System states & forecast errors
OPC server
HMI
Operation mode
OPC server
Switching sequence
SQL database
Sensor data
Set-points
Controlled system:
• Machines
• Auxiliary equipment
• Sensors
• Actuators
Trigeneration system and thermal loads
M-Bus etc.
OPC etc.
Monitoring loop
Control loop


Management level
Back-end services:
• Online or database
• Energy, load & weather forecast
Supervisory controller:
• Python environment
• MPC or conventional
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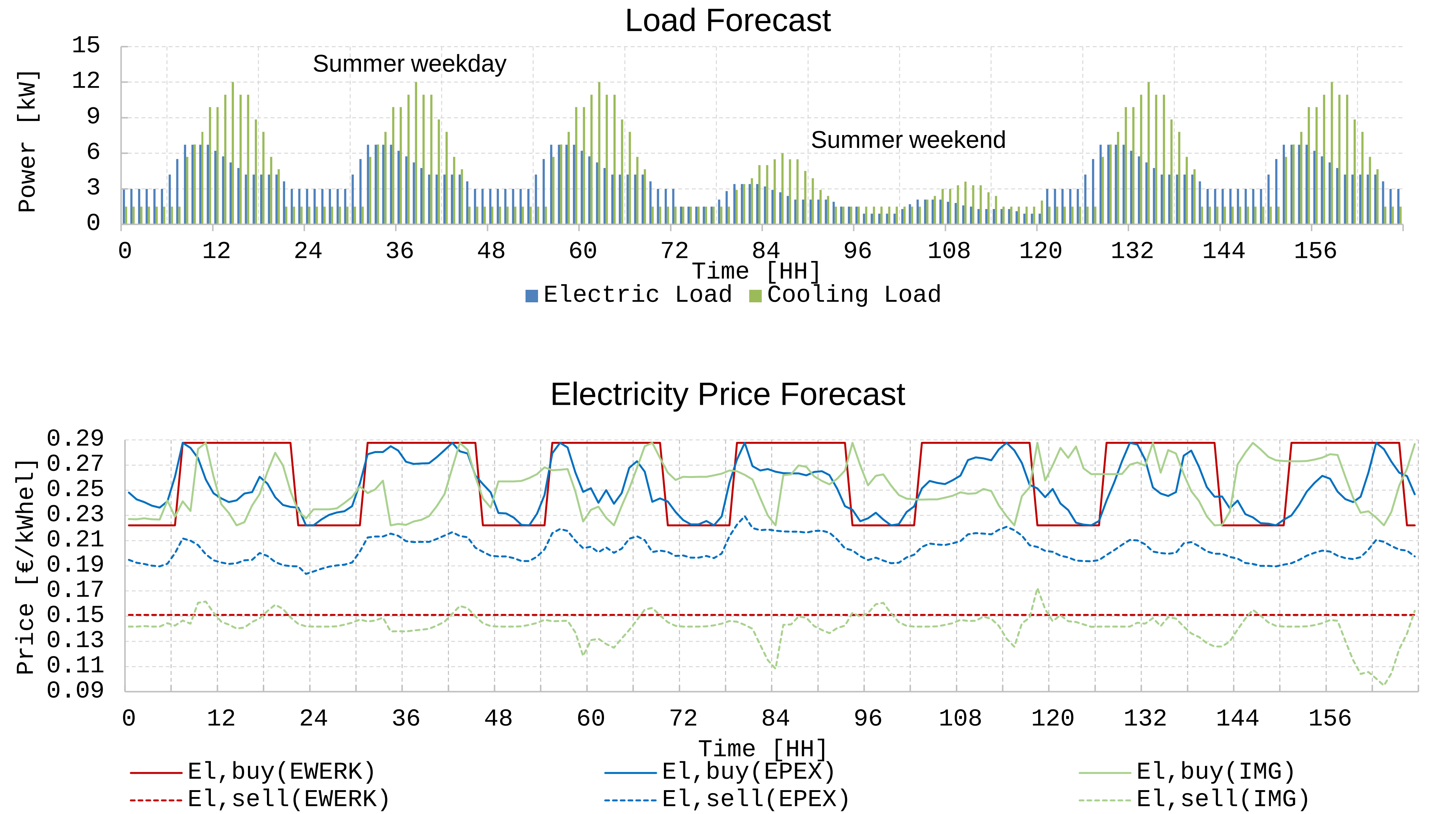


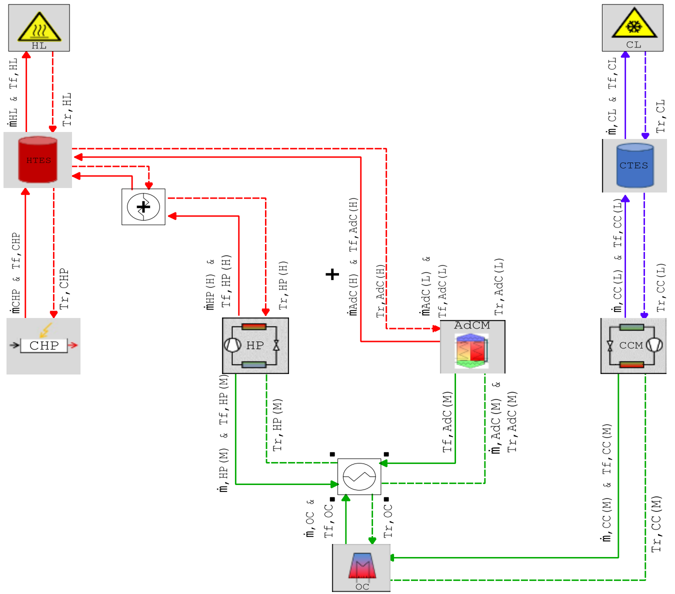
Load Forecast
Summer weekday
Summer weekend
Power [kW]
15
12
9
6
3
0
0
12
24
36
48
60
72
84
96
108
120
132
144
156
Time [HH]
Electric Load
Cooling Load
Electricity Price Forecast
Price [€/kWhel]
0.29
0.27
0.25
0.23
0.21
0.19
0.17
0.15
0.13
0.11
0.09
Time [HH]
El,buy(EWERK)
El,buy(EPEX)
El,buy(IMG)
El,sell(EWERK)
El,sell(EPEX)
El,sell(IMG)

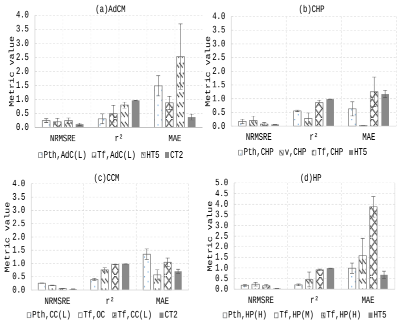
Characteristics of Models for MPC

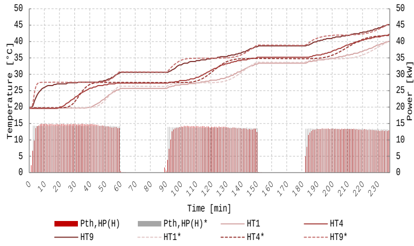
Sought after characteristics

Application in:

- 1. Field level control
  - 1a. Capture dynamic characteristics
  - 1b. Capture part-load behaviour / internal control logic
  - 1c. Practical parameterisation capabilities
  - 1d. Adaptability to component design
- 2. Optimisation
  - 2a. Lower complexity (more stability)
  - 2b. Sufficient accuracy
  - 2c. Continuous differentiability

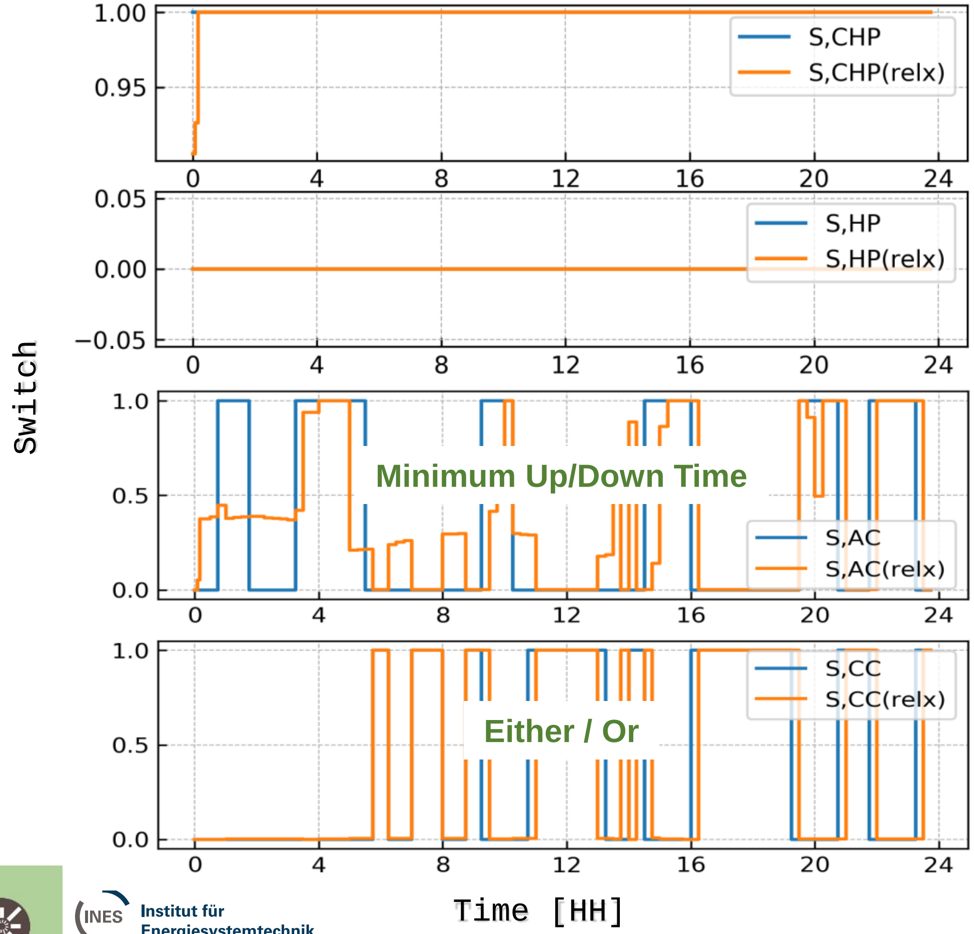






*Sawant P., Bürger, A. *et al.*, 2019. Energy and Buildings (In Press). https://doi.org/10.1016/j.enbuild.2019.109725

Results of One MPC Iteration



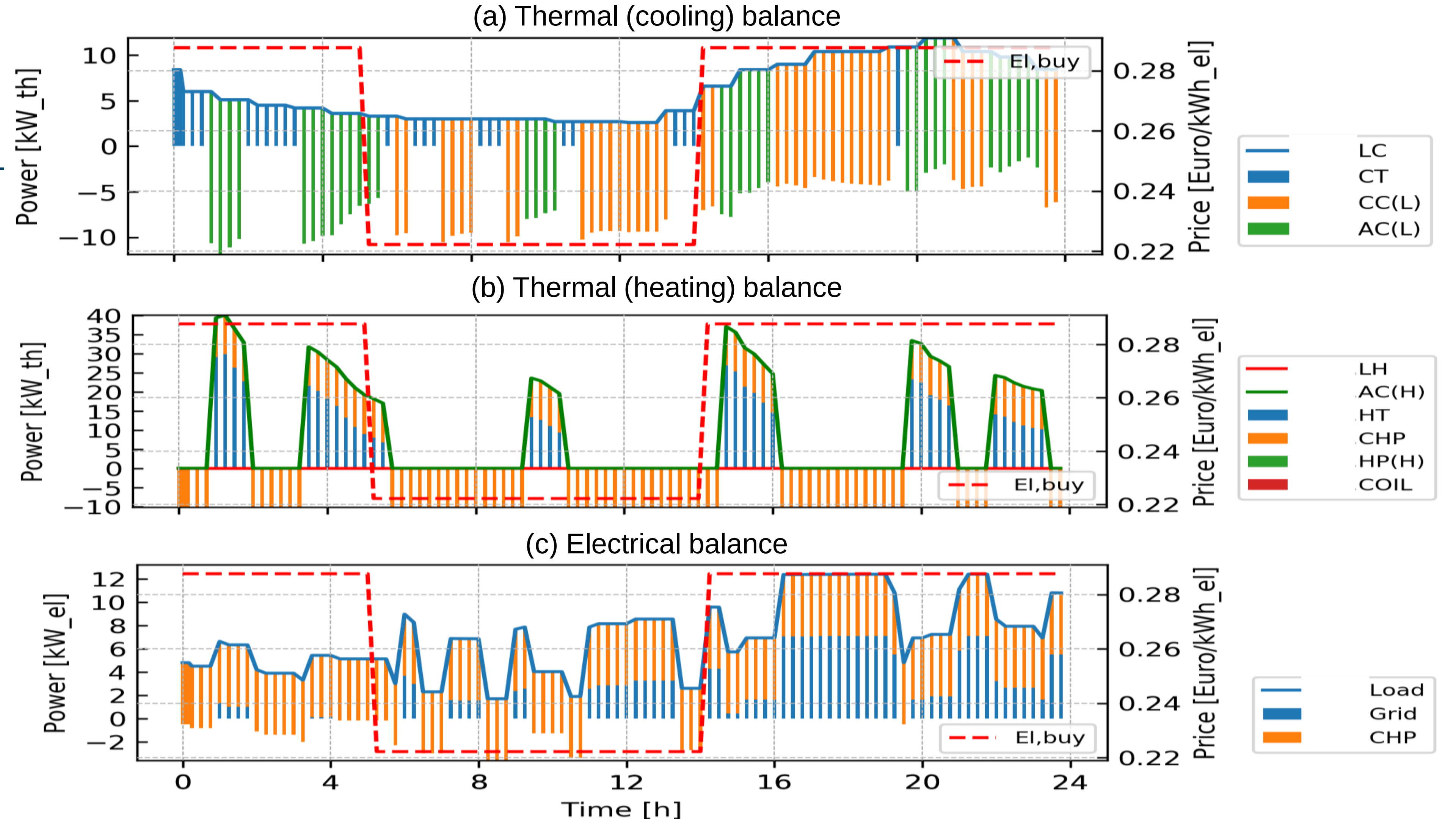
NLP Solution

↓ Relaxed solution ∈[0,1]

Binary approximation

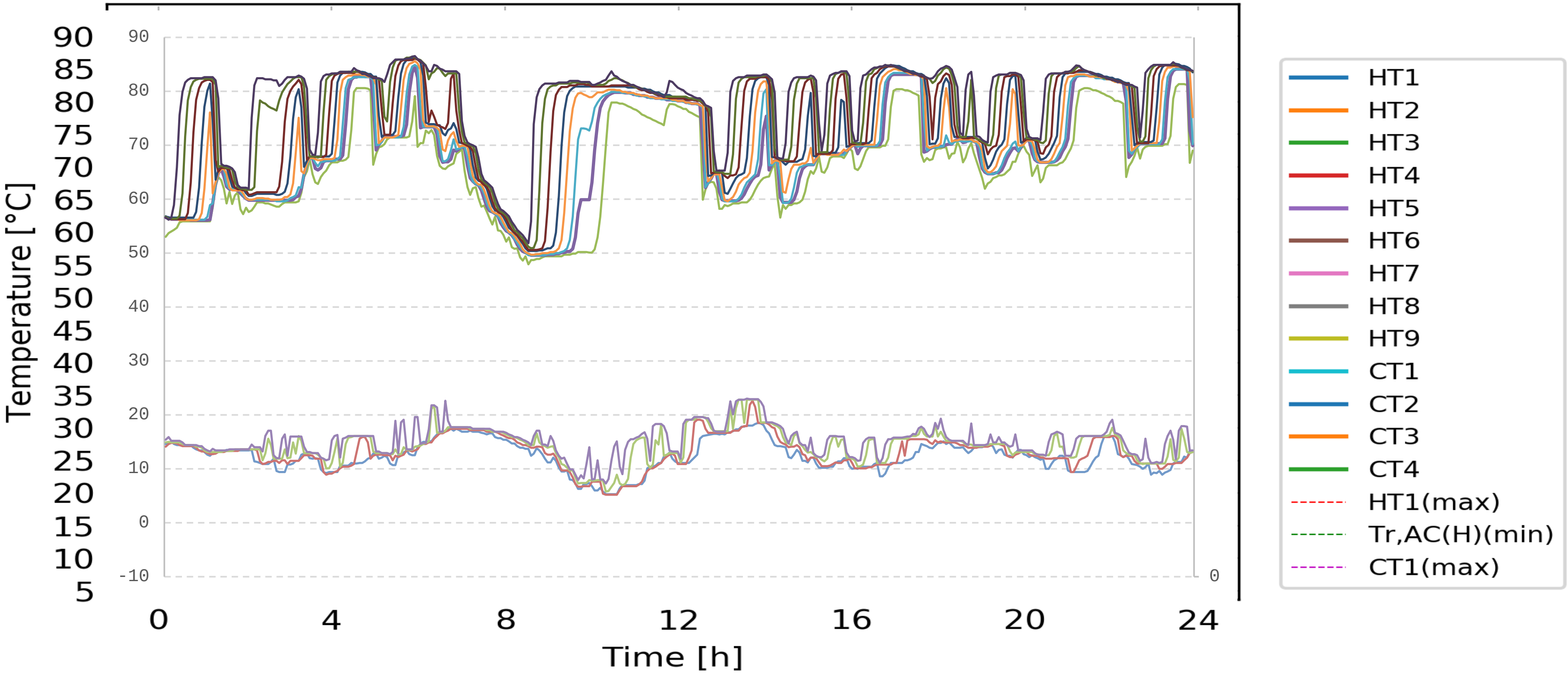
↓ Binary solution ∈{0,1}

On / Off Schedule

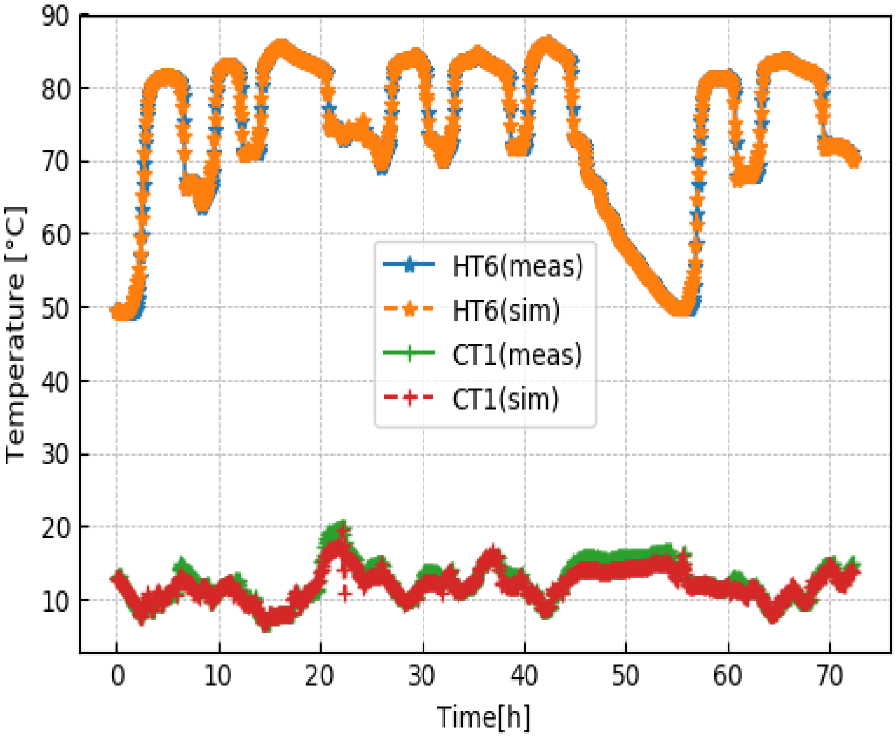


(a) Thermal (cooling) balance
Power [kW_th]
Price [Euro/kWh_el]
El,buy
LC
CT
CC(L)
AC(L)
(b) Thermal (heating) balance
Power [kW_th]
Price [Euro/kWh_el]
El,buy
LH
AC(H)
HT
CHP
HP(H)
COIL
(c) Electrical balance
Power [kW_el]
Price [Euro/kWh_el]
El,buy
Load
Grid
CHP
Time [h]

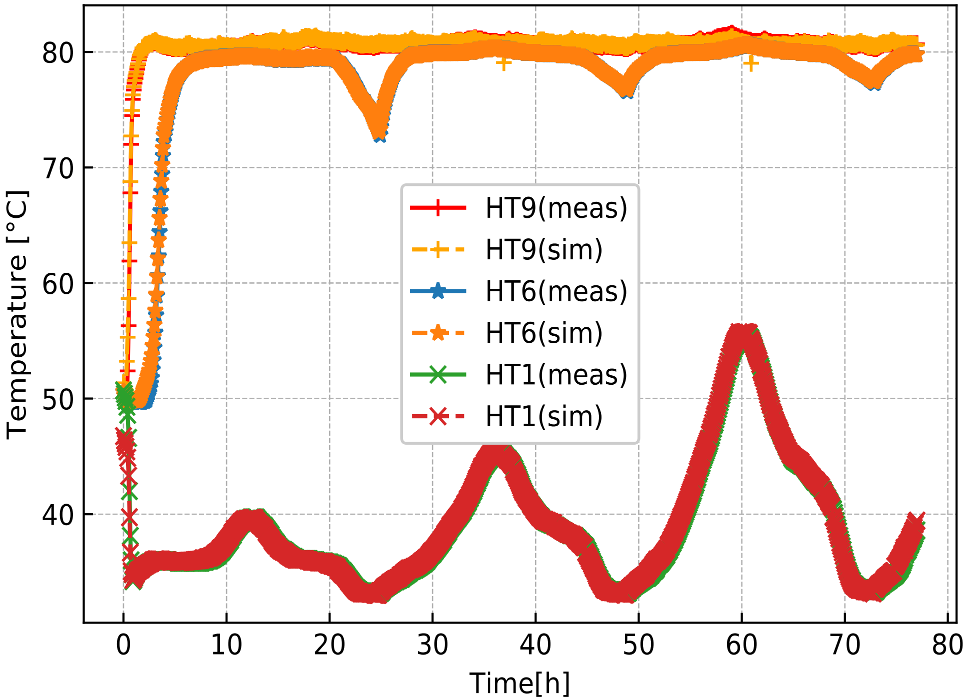
Stratified Tank Temperatures (System States)



Simulation and Measured Results



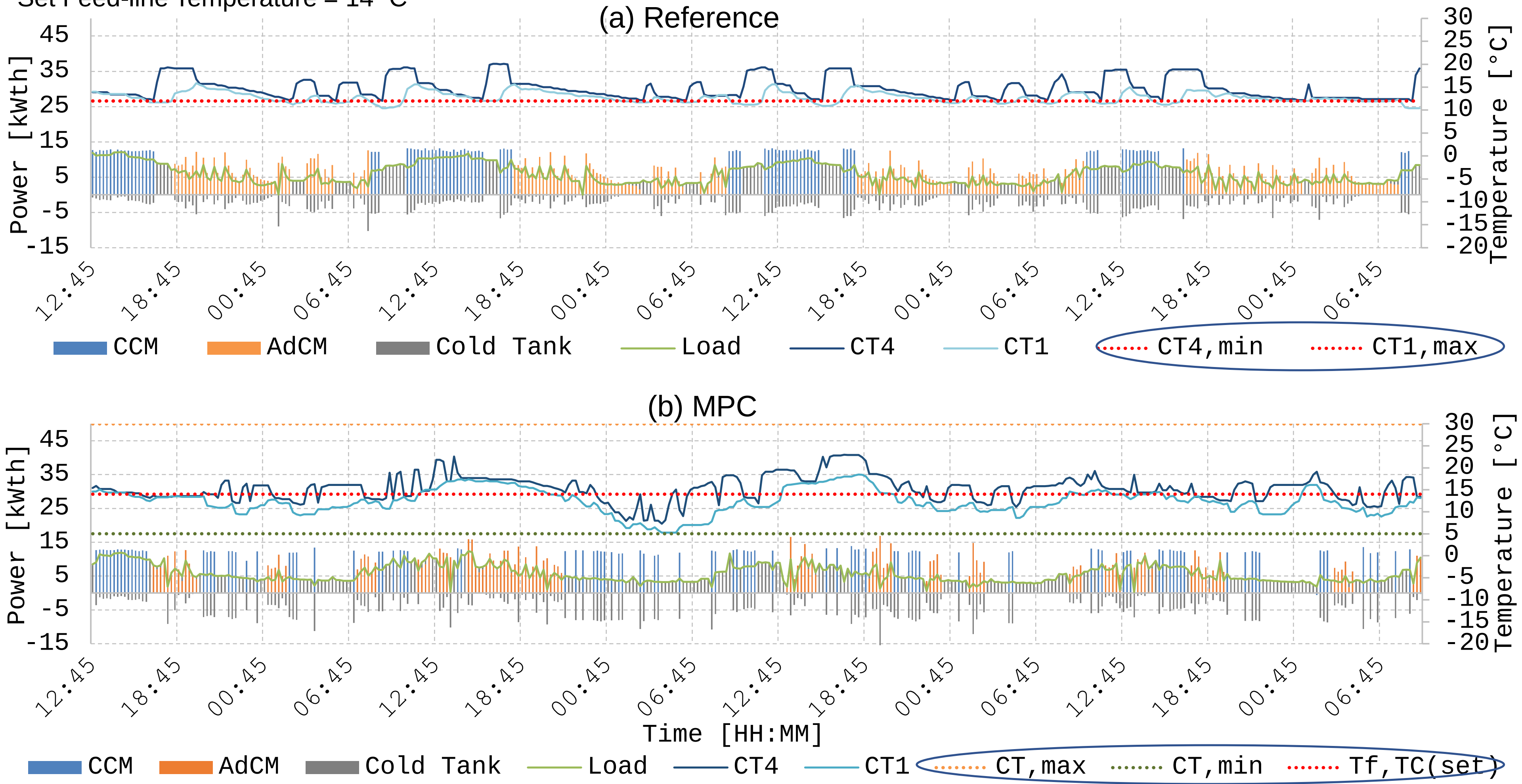
(a) Summer test



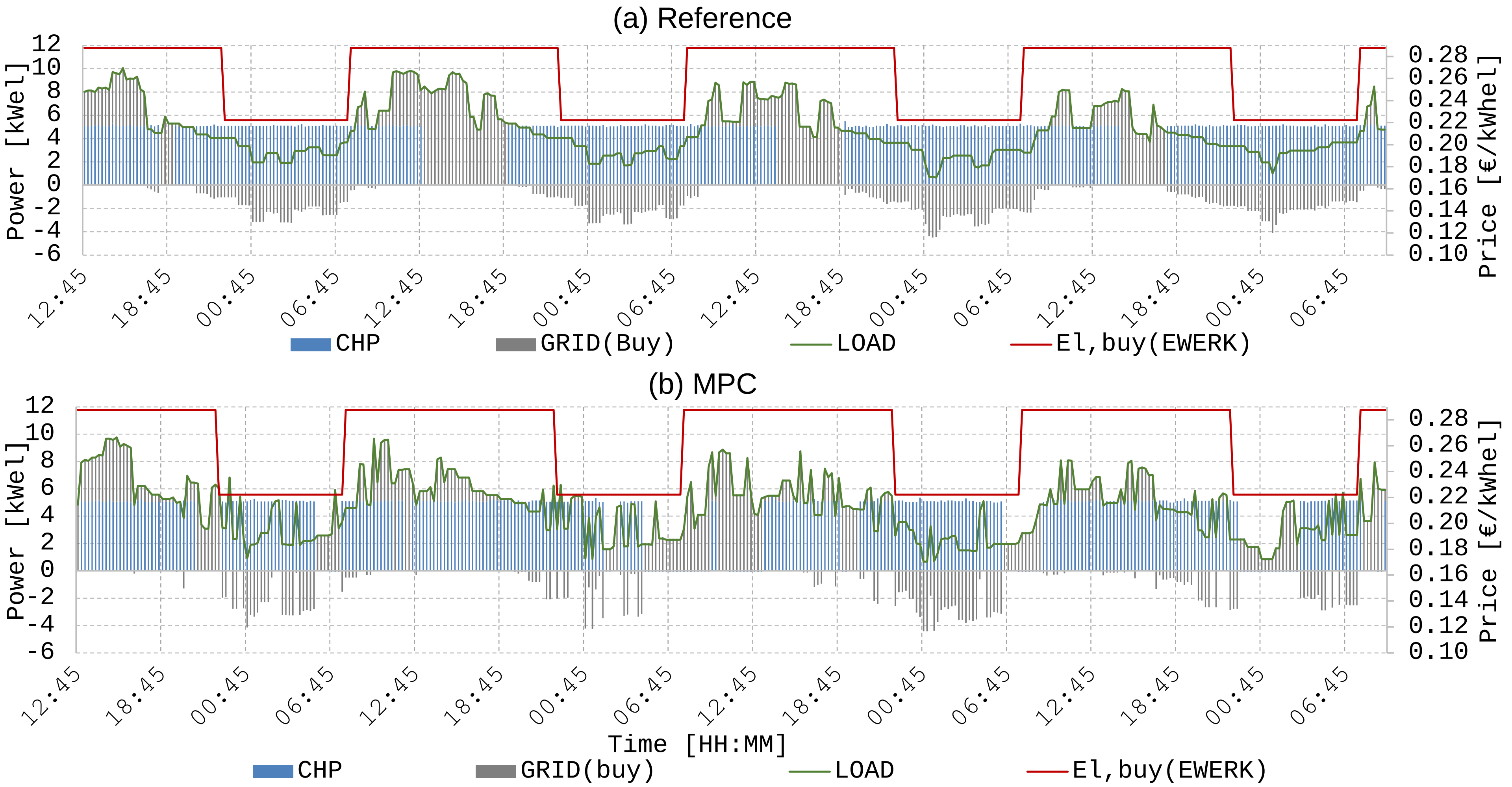
(b) Winter test

Measured Data: Reference Controller and MPC (Cooling energy balance)

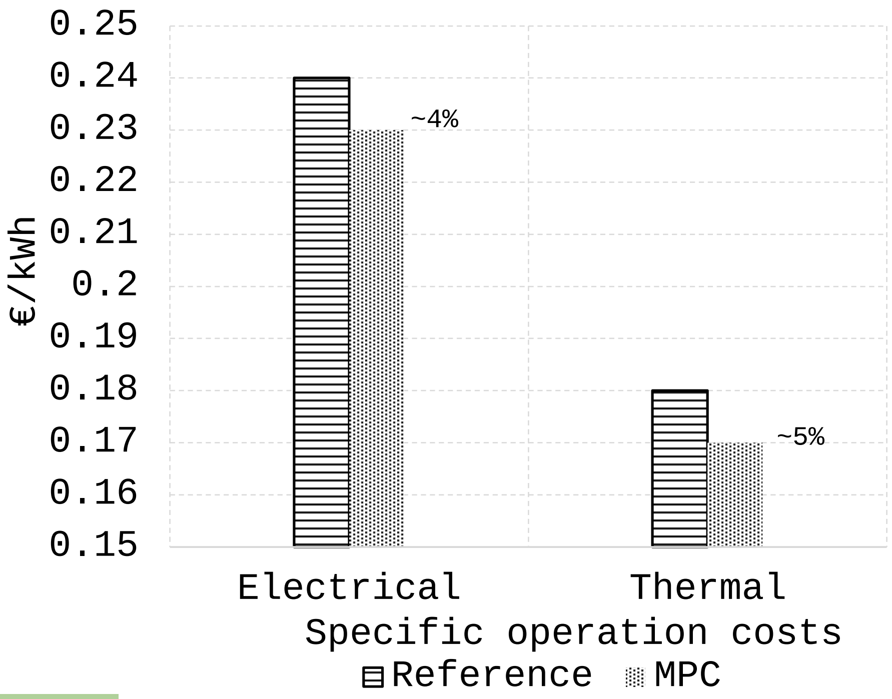
Set Feed-line Temperature = 14°C



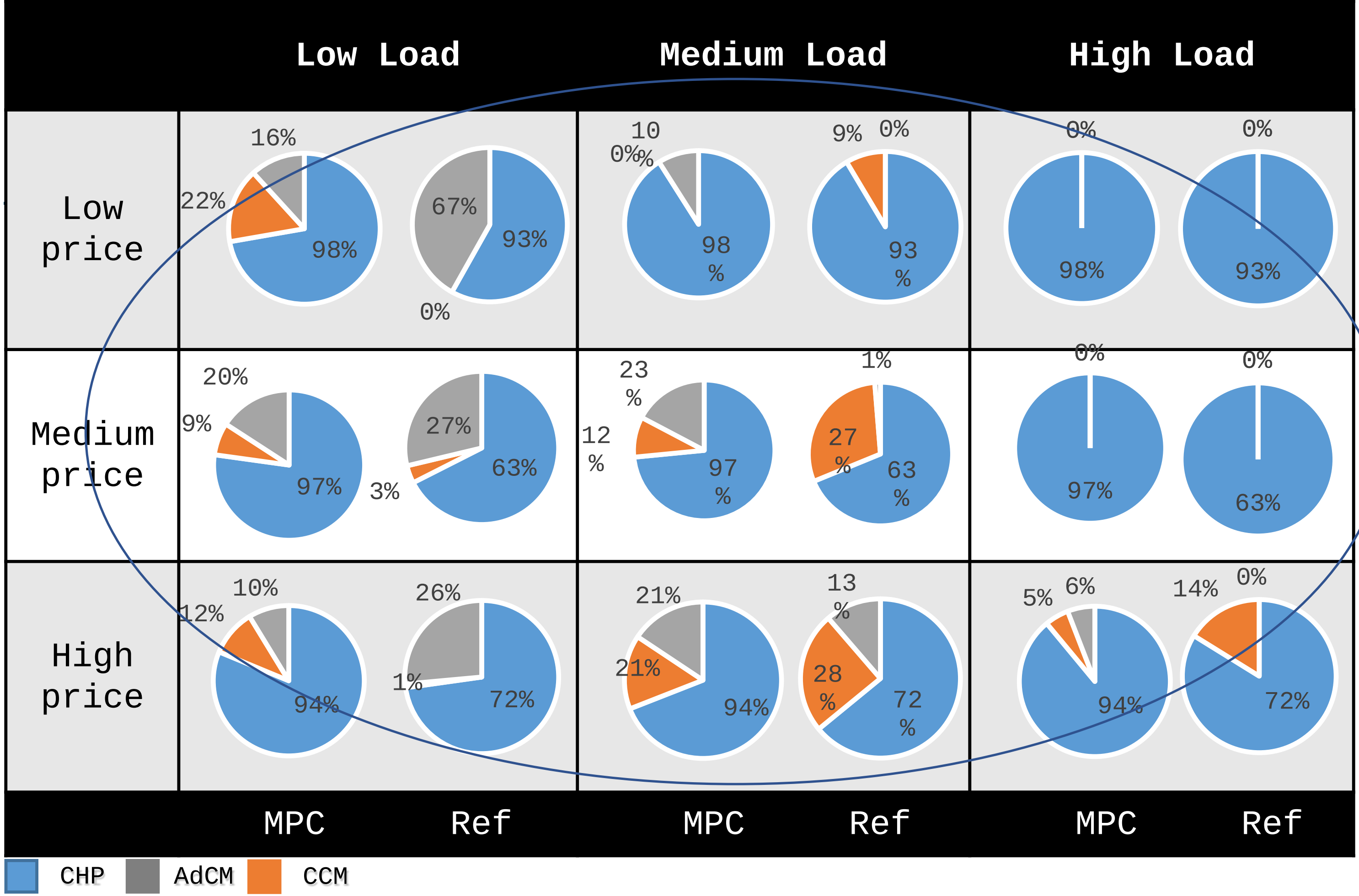
Measured Data: Reference Controller and MPC (Electrical balance)



Economic analysis



- Highly tuned reference controller
- Lesser On / Off Flanks but not monetised



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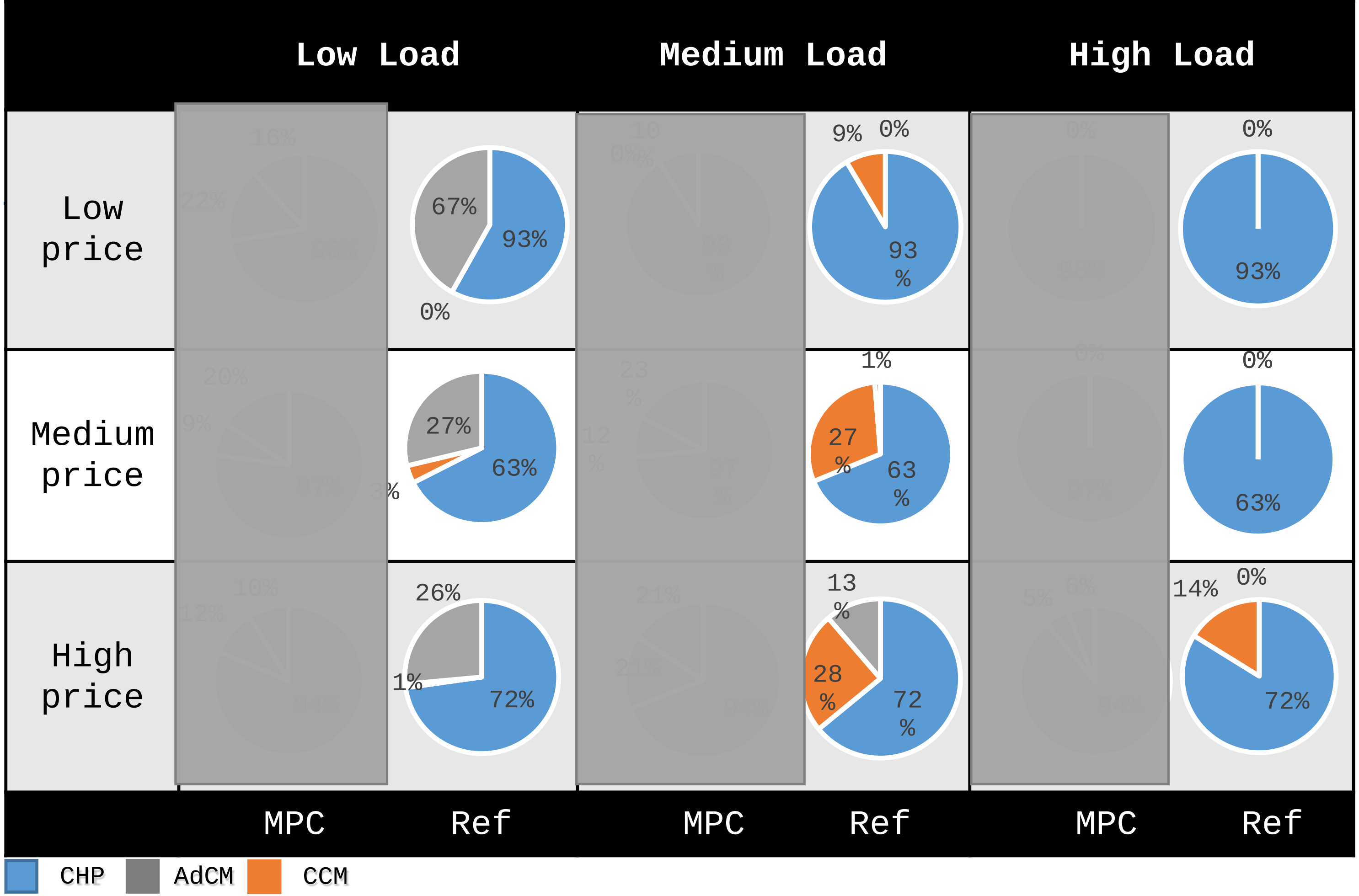
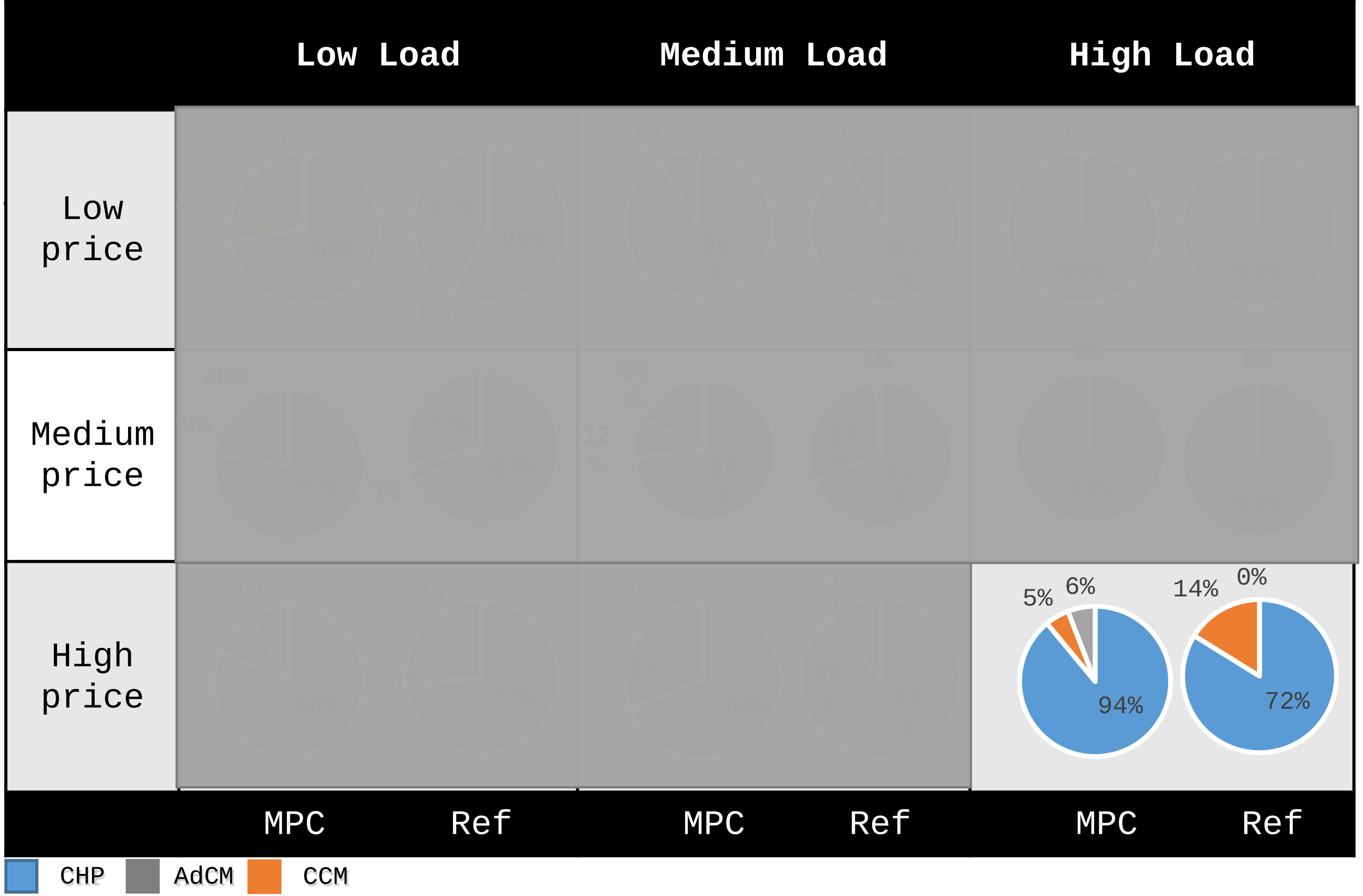
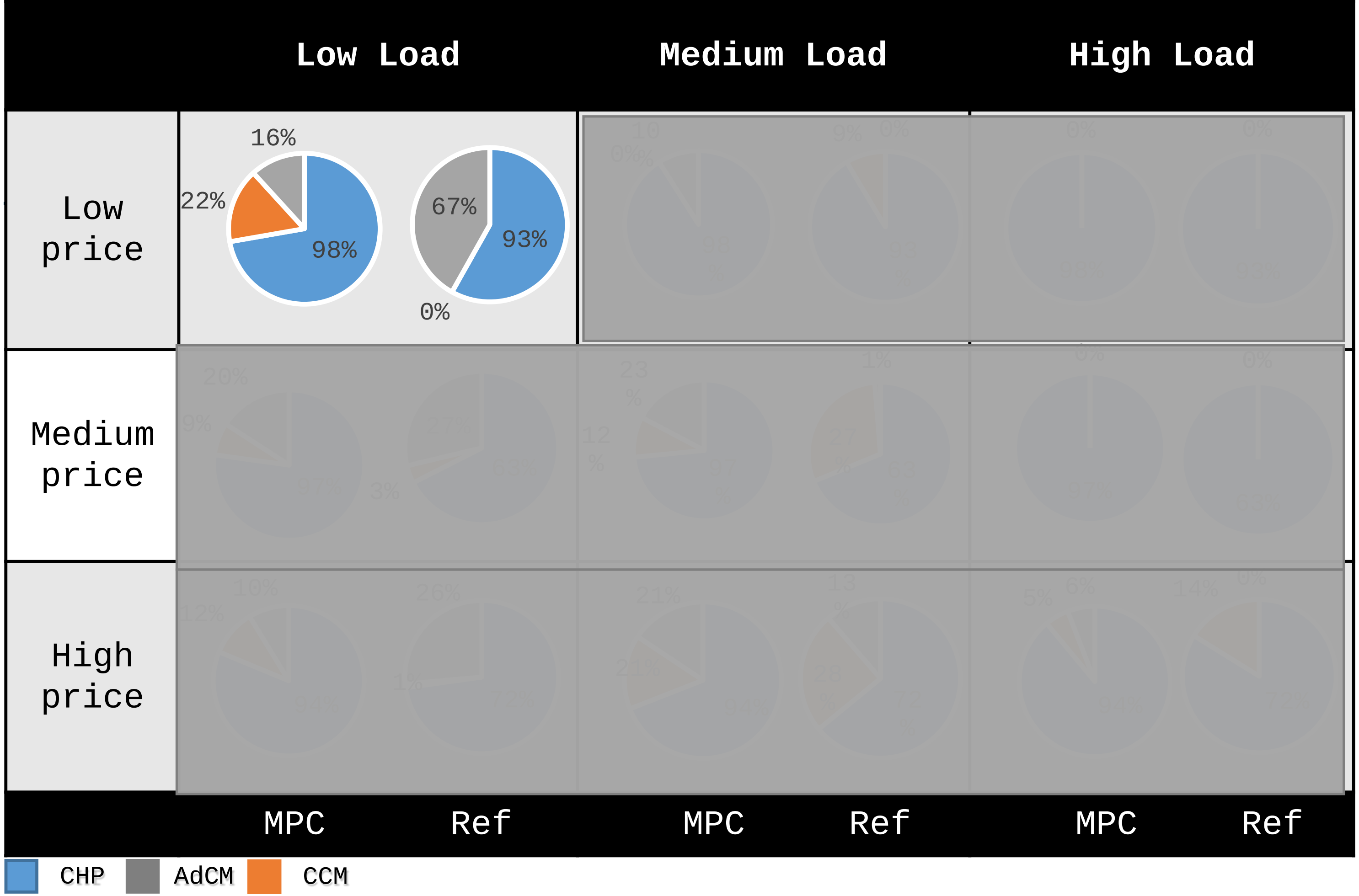
Operational Analysis


Low Load
Medium Load
High Load
Low price
Medium price
High price
67%
93%
0%
9%
0%
93 %
0%
93%
27%
63%
3%
1%
27 %
63 %
0%
63%
26%
1%
72%
13 %
28 %
72 %
14%
0%
72%
MPC
Ref
MPC
Ref
MPC
Ref
CHP
AdCM
CCM

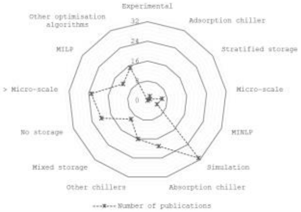


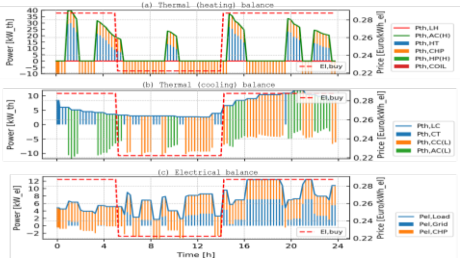
Low Load
Medium Load
High Load
Low price
Medium price
High price
5%
6%
94%
14%
0%
72%
MPC
Ref
MPC
Ref
MPC
Ref
CHP
AdCM
CCM

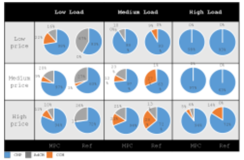

Low Load
Medium Load
High Load
Low price
Medium price
High price
16%
22%
98%
67%
93%
0%
MPC
Ref
MPC
Ref
MPC
Ref
CHP
AdCM
CCM

Summary and Outlook

- Motivation for experimental demonstration established
- Control-oriented models made available in project consortium
- MPC benefits:
  - 3-5% economic benefit over highly tuned reference controller
  - Ease of tuning and adapting to other plants
  - Less frequent machine switching
- Five years outlook:
  - Communication with other plants
  - Provide flexibility through economic optimisation
  - Industrial operation







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MINISTERIUM FÜR WISSENSCHAFT, FORSCHUNG UND KUNST
Rheinland-Pfalz
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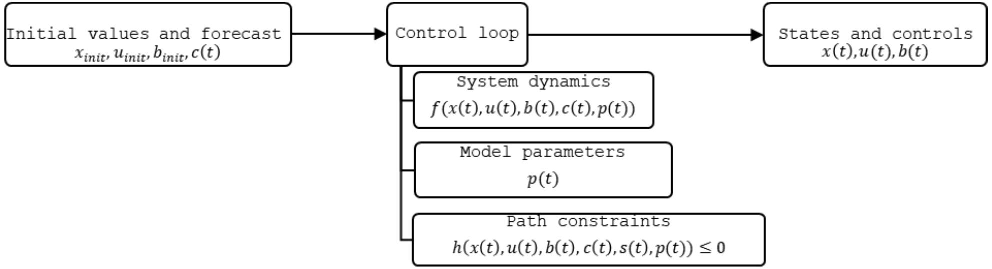
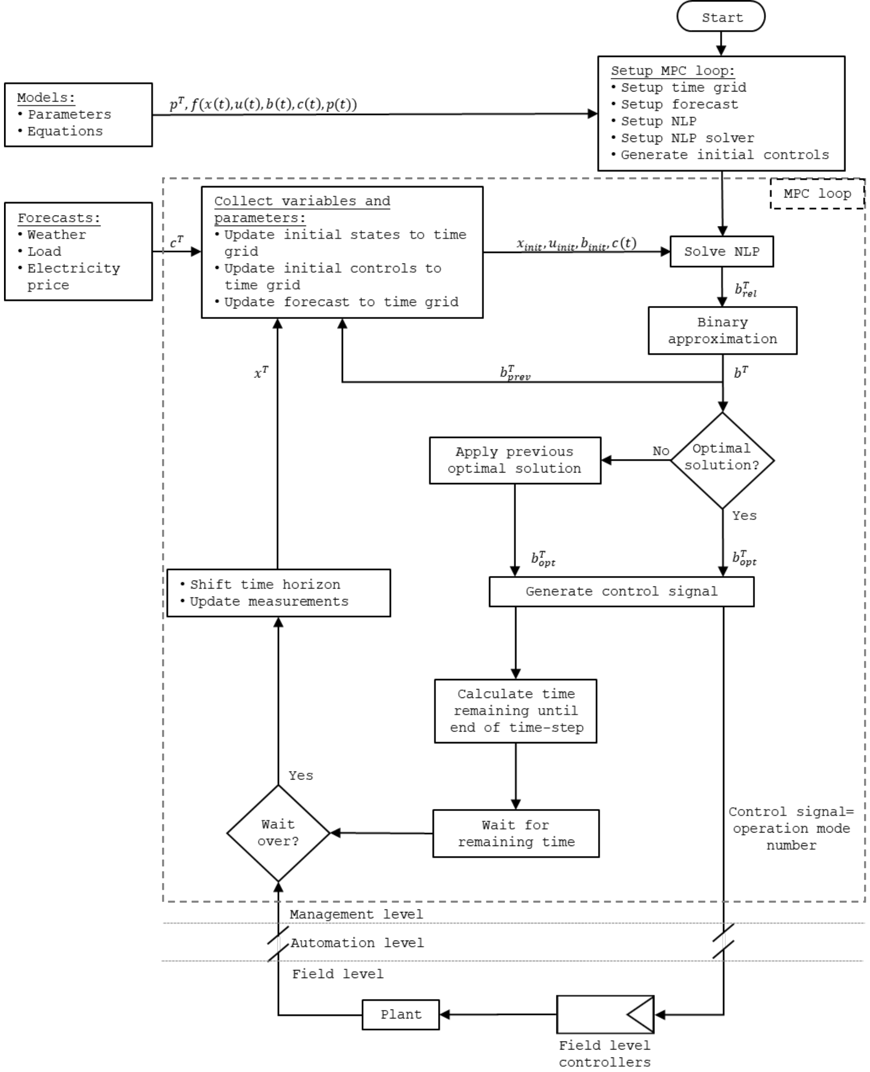


Initial values and forecast
$x_{init}, u_{init}, b_{init}, c(t)$
Control loop
States and controls
$x(t), u(t), b(t)$
System dynamics
$f(x(t), u(t), b(t), c(t), p(t))$
Model parameters
$p(t)$
Path constraints
$h(x(t), u(t), b(t), c(t), s(t), p(t)) \leq 0$



Start
Models:
• Parameters
• Equations
$p^T, f(x(t), u(t), b(t), c(t), p(t))$
Setup MPC loop:
• Setup time grid
• Setup forecast
• Setup NLP
• Setup NLP solver
• Generate initial controls
MPC loop
Forecasts:
• Weather
• Load
• Electricity price
c^T
Collect variables and parameters:
• Update initial states to time grid
• Update initial controls to time grid
• Update forecast to time grid
$x_{init}, u_{init}, b_{init}, c(t)$
Solve NLP
b^T_{rel}
Binary approximation
b^T
b^T_{prev}
x^T
Optimal solution?
No
Yes
Apply previous optimal solution
b^T_{opt}
b^T_{opt}
Generate control signal
• Shift time horizon
• Update measurements
Calculate time remaining until end of time-step
Yes
Wait over?
Wait for remaining time
Control signal= operation mode number
Management level
Automation level
Field level
Plant
Field level controllers

For $t \in [0, T]$:

$$\min_{\substack{x(\cdot),u(\cdot),\\ b(\cdot),s(\cdot)}} \int_{t_0}^{t_f} (\dot{v}_{Fuel}(t) Fuel_{price} + P_{el,Grid(buy)}(t) El_{buy}(t) - P_{el,Grid(sell)}(t) El_{sell}(t) + s(t)^T W_s s(t)) dt \tag{6.32a}$$

subject to:

$$\dot{x}(t) - f(x(t), u(t), b(t), c(t), p(t)) = 0, \tag{6.32b}$$

$$h(x(t), u(t), b(t), c(t), s(t), p(t)) \leq 0, \tag{6.32c}$$

$$x(t_0) - x_0 = 0, \tag{6.32d}$$

$$u_{lb} \leq u(t) \leq u_{ub}, \tag{6.32e}$$

$$s(t) \leq 0, \tag{6.32f}$$

$$b(t) \in \{0,1\}. \tag{6.32g}$$