Optimal Dispatch for CHP Units under Solar Production Uncertainty

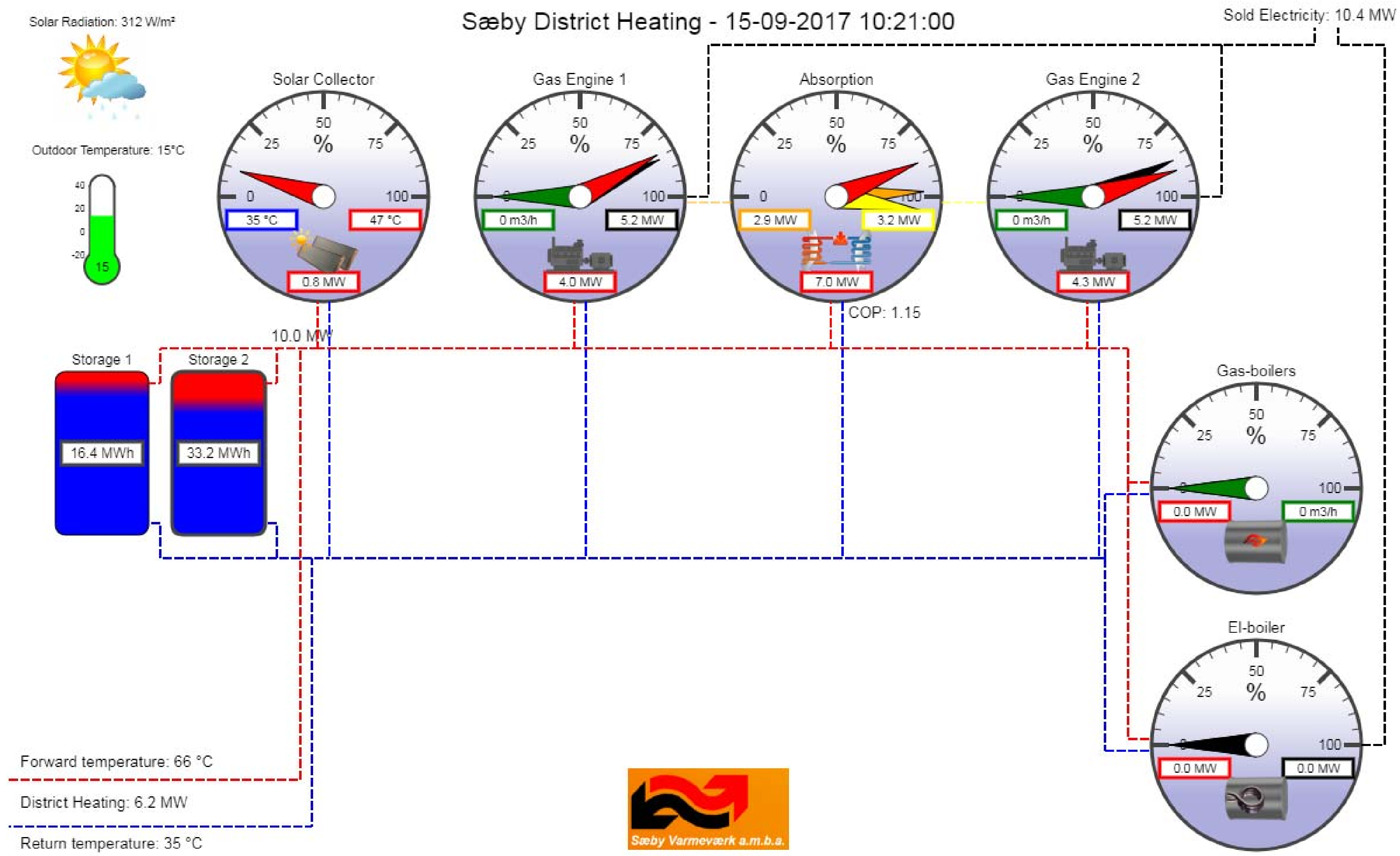
CITIES

Ignacio Blanco
Daniela Guericke
Henrik Madsen
Anders N. Andersen

EMD International A/S
www.emd.dk

ENFOR

DTU Compute
Department of Applied Mathematics and Computer Science



Sæby District Heating - 15-09-2017 10:21:00
Solar Radiation: 312 W/m²
Outdoor Temperature: 15°C
15
Sold Electricity: 10.4 MW
Solar Collector
35 °C
47 °C
0.8 MW
Gas Engine 1
0 m3/h
5.2 MW
4.0 MW
Absorption
2.9 MW
3.2 MW
7.0 MW
COP: 1.15
Gas Engine 2
0 m3/h
5.2 MW
4.3 MW
10.0 MW
Storage 1
16.4 MWh
Storage 2
33.2 MWh
Gas-boilers
0.0 MW
0 m3/h
El-boiler
0.0 MW
0.0 MW
Forward temperature: 66 °C
District Heating: 6.2 MW
Return temperature: 35 °C
Sæby Varmeværk a.m.b.a.

Sæby District Heating

Sæby District Heating has installed a natural gas fired engine made by Caterpillar. The engine has the following capacity:

Electricity:	6 MW, efficiency: 42,5%
Heat:	7 MW, efficiency: 49,6%

In 2015 Sæby District Heating installed an absorption heat pump made by Thermax. The hottest part of the exhaust gas from the engines is used run to the absorption heat pump, which subtract the remaining heat out of the exhaust gas, cooling it down to below 20°C:

COP:	1.7
Net Heat	3.2 MW

A COP of 1.7 means that by using 1 MW of the hot heat the heat pump can subtract another 0.7 MW from the cold part of the exhaust gas. The Net Heat is what the heat pump subtract from the cold part of the exhaust gas.

Further, Sæby District Heating has an electric boiler:

Heat:	12 MW
Electricity consumption:	12 MW

Sæby District Heating has a large-scale solar heating plant:

Area of solar panels:	11.900 m^2
Heat:	8.2 MW

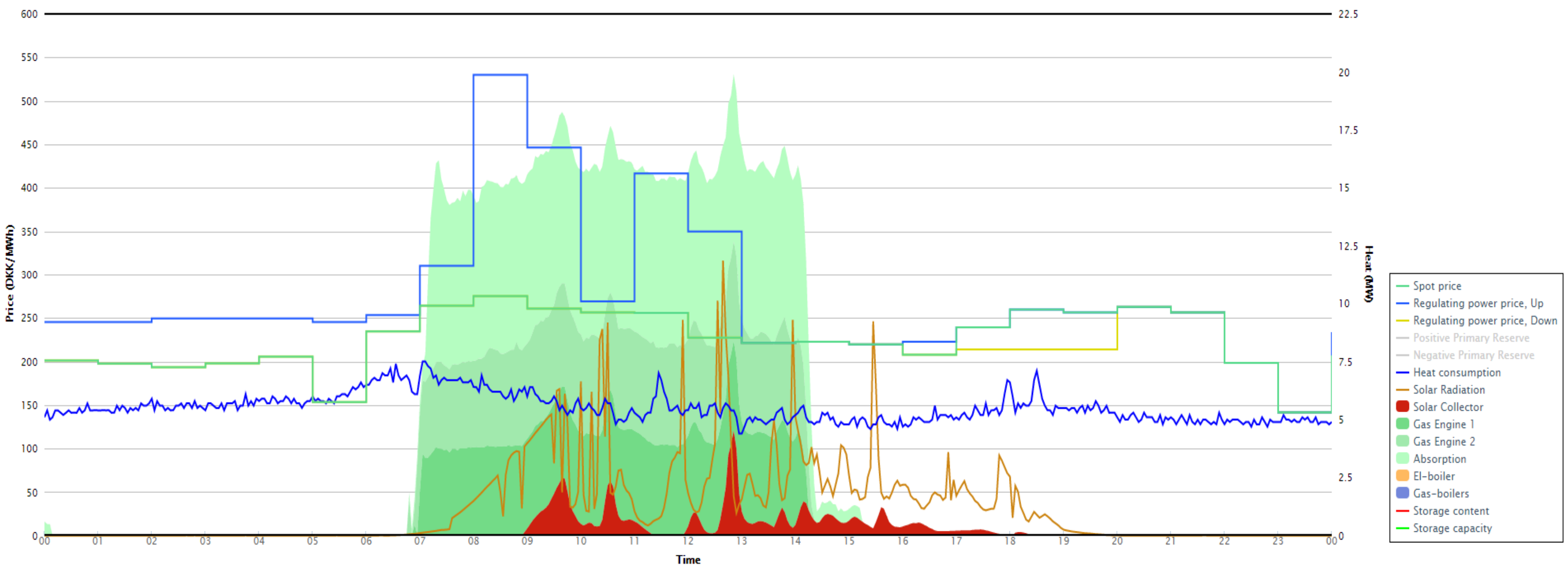
Sæby District Heating has two gas boilers with the following capacities and efficiencies:

Boiler 3:	11.6 MW, efficiency: 102% (secondary peak and reserve boiler)
Boiler 4:	17.5 MW, efficiency: 105% (primary peak and reserve boiler)

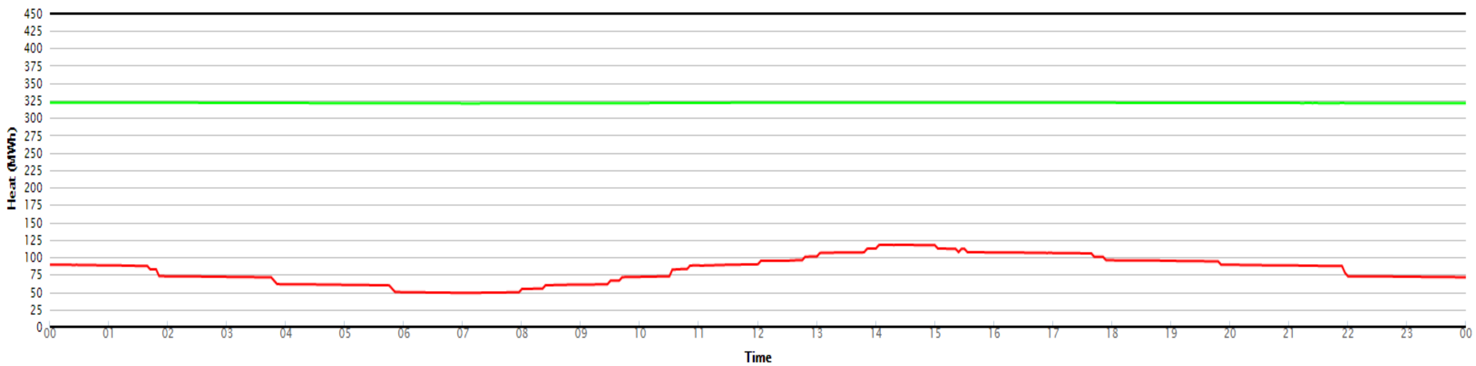
The current gas consumption is calculated from the above efficiencies. That is, the current gas consumption shown is not a measured value.

Sæby District heating has two heat storage tanks, each of 2700 m^3, total capacity app. 280 MWh.

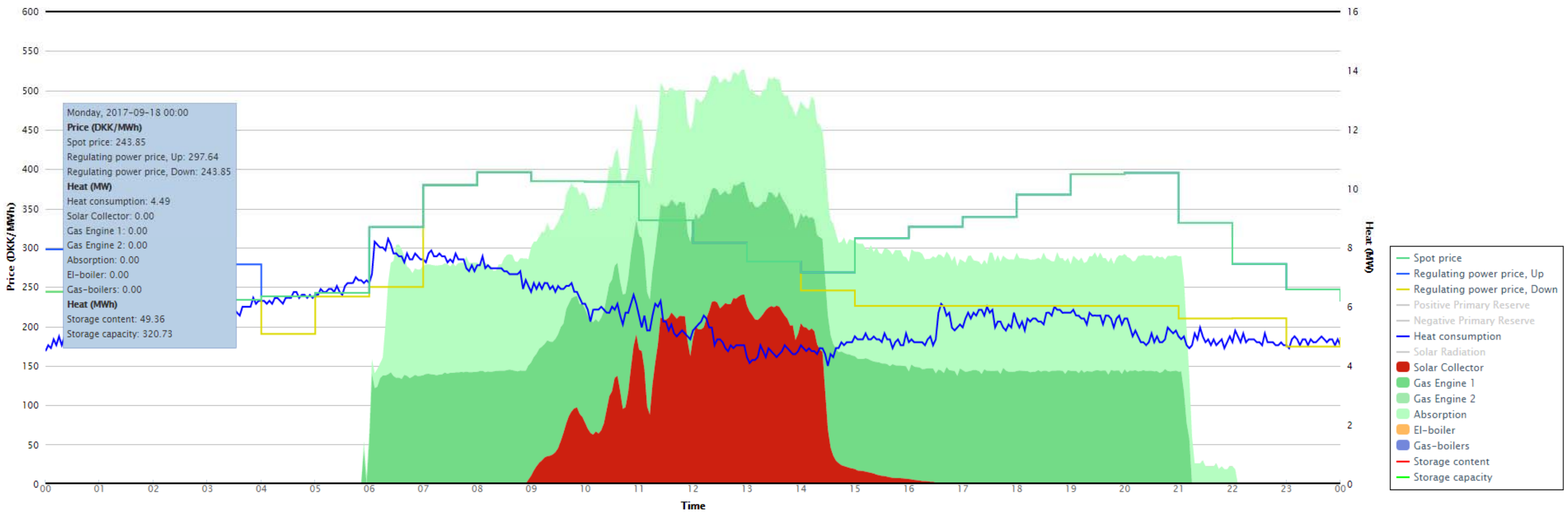
2015-16 the total heat deliverance to the district heating network was app. 80000 MWh. The gas engines supplied 69%, the gas boilers 17% and the electric boiler and solar heating app. 7% each of the total heat production. The loss in the district heating network is app. 25% of the total deliverance.

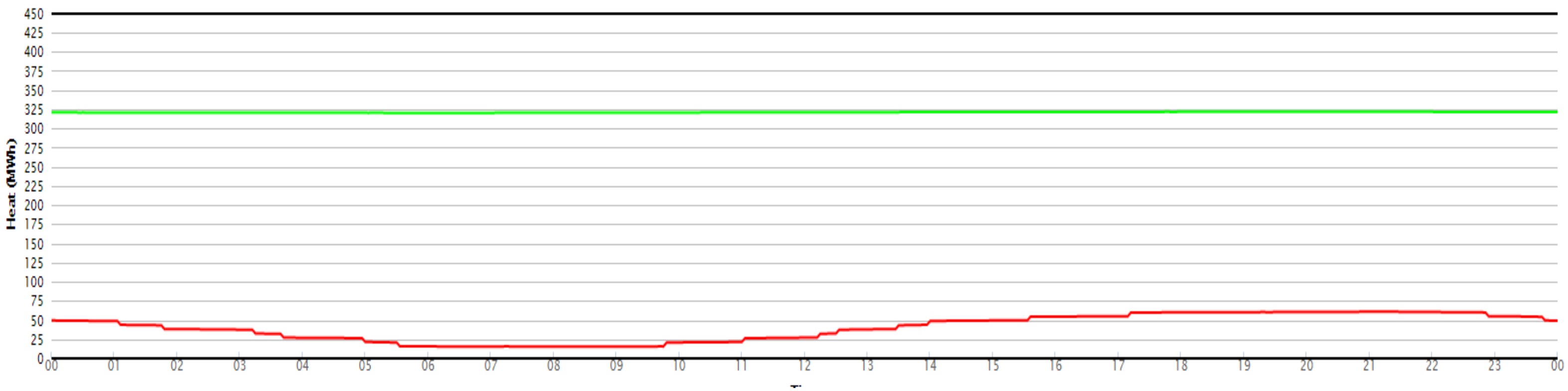


Price (DKK/MWh)
Heat (MW)
Time
Spot price
Regulating power price, Up
Regulating power price, Down
Positive Primary Reserve
Negative Primary Reserve
Heat consumption
Solar Radiation
Solar Collector
Gas Engine 1
Gas Engine 2
Absorption
El-boiler
Gas-boilers
Storage content
Storage capacity

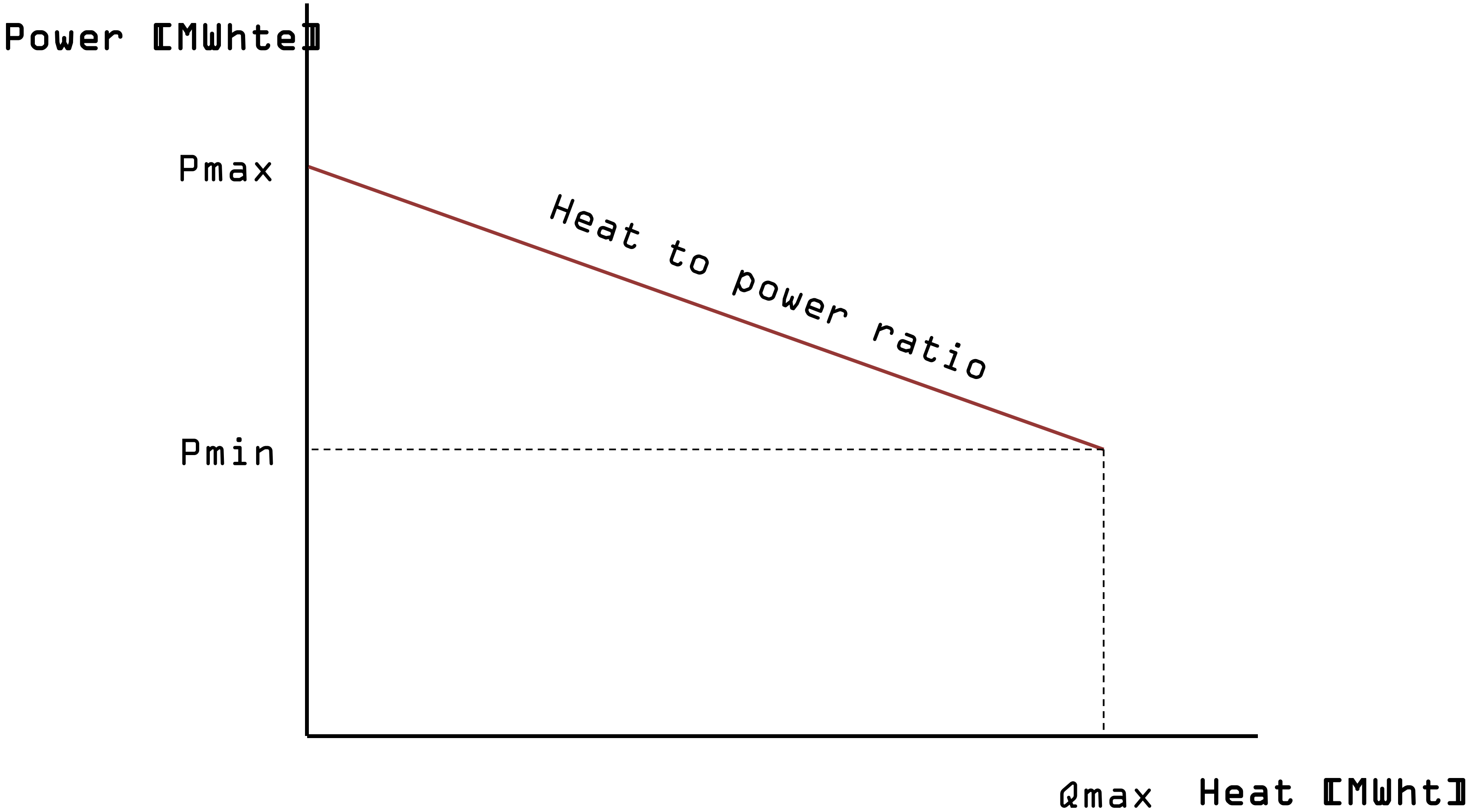


Heat (MWh)
Time

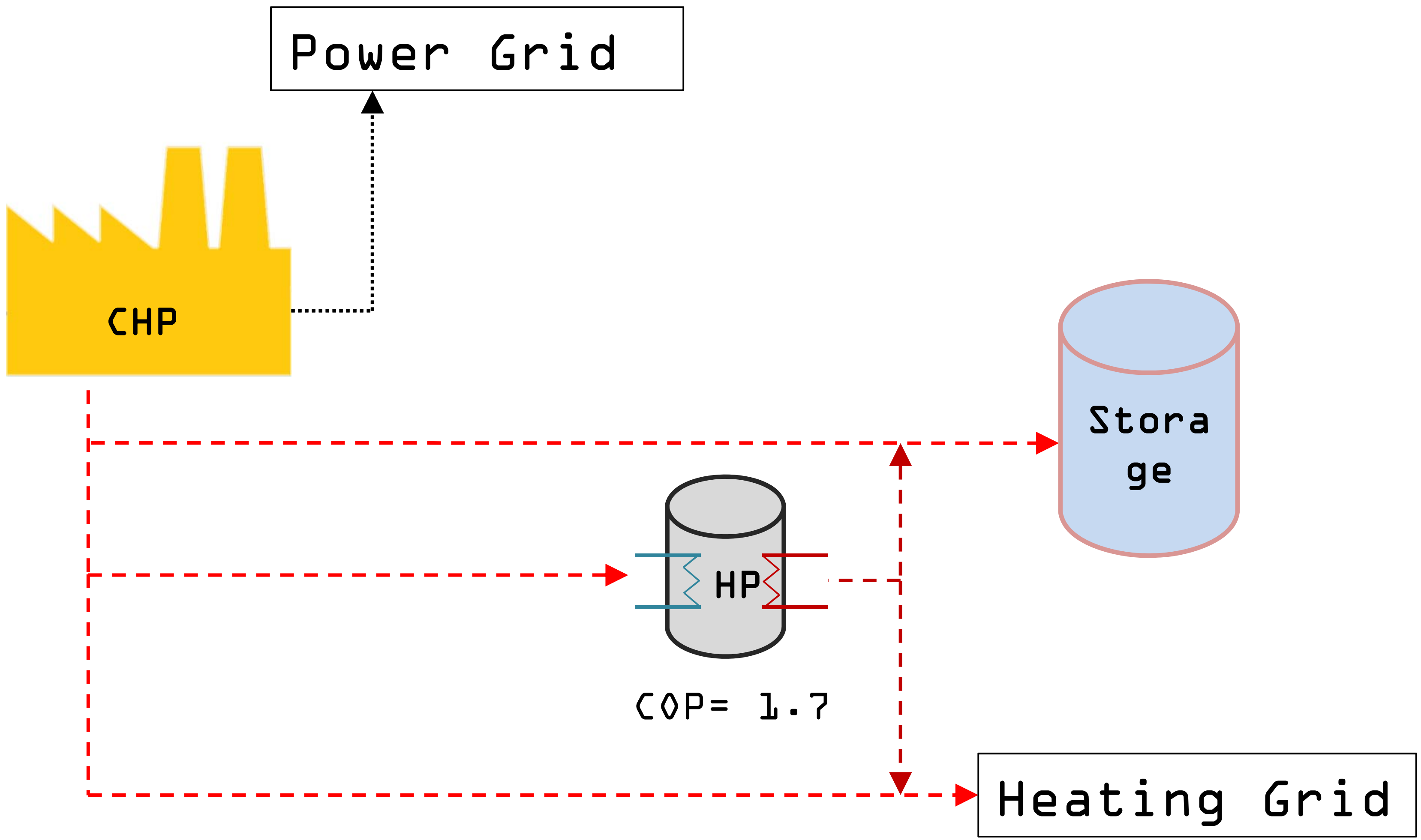

Monday, 2017-09-18 00:00
Price (DKK/MWh)
Spot price: 243.85
Regulating power price, Up: 297.64
Regulating power price, Down: 243.85
Heat (MW)
Heat consumption: 4.49
Solar Collector: 0.00
Gas Engine 1: 0.00
Gas Engine 2: 0.00
Absorption: 0.00
El-boiler: 0.00
Gas-boilers: 0.00
Heat (MWh)
Storage content: 49.36
Storage capacity: 320.73
Price (DKK/MWh)
Heat (MW)
Time
Spot price
Regulating power price, Up
Regulating power price, Down
Positive Primary Reserve
Negative Primary Reserve
Heat consumption
Solar Radiation
Solar Collector
Gas Engine 1
Gas Engine 2
Absorption
El-boiler
Gas-boilers
Storage content
Storage capacity


Heat (MWh)

Back pressure CHP unit

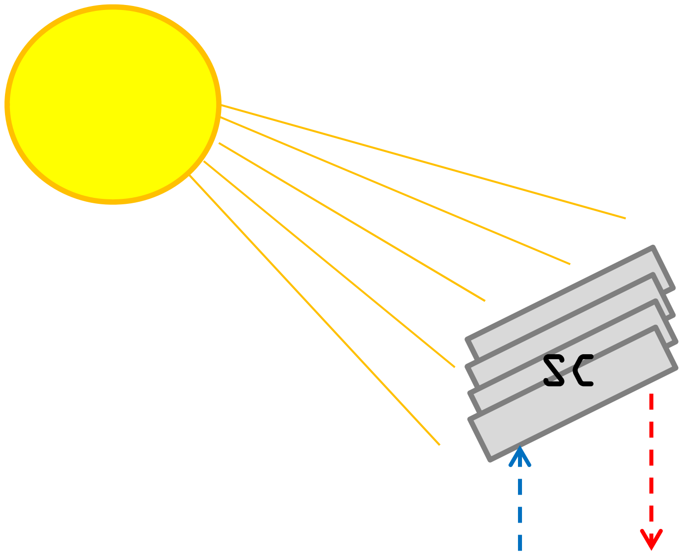


Absorption Heat Pump



Solar Collector

Directly affected by the solar radiation but with a certain lag. Maybe a **state-space model** could be the optimal to describe the dynamics of the system.



HEAT ECONOMIC DISPATCH

$$\left.\begin{aligned} \mathbf{H} &= \{\text{CHP}, \text{GB1 and GB2}\} \\ \mathbf{T} &= \{t_1, t_2, \ldots, |T|\} \end{aligned}\right\} \text{Sets}$$

$$\text{minimize} \quad \sum_{t \in \mathbf{T}} \sum_{h \in \mathbf{H}} \left(\frac{C^{F(h)}}{\varepsilon_{(h)}} + C^{T}_{(h)} + C^{O\&M}_{(h)} + C^{CO_2}_{(h)} \right) \cdot q_{(h,t)}$$

$$\text{subject to} \quad \sum_{h \in \mathbf{H}} q_{(h,t)} + q^{SC}_{(t)} = L^{H}_{(t)} \; : \lambda^{H}_{(t)} \quad \forall t \in \mathbf{T}$$

$$q_{(h,t)} \leq \overline{Q}_{(h)} \quad \forall t \in \mathbf{T}, \forall h \in \mathbf{H}$$

Blue box: Parameters

Green box: Marginal Value

Red box: Variables

Yellow box: Uncertainty

BIDDING PRICE FOR CHP [DKK\MWh]

$$\lambda_{(t)}^{\mathrm{CHP}} = \frac{C_{\mathrm{CHP}}^{\mathrm{F}}}{\varepsilon_{(\mathrm{CHP})}} + C_{\mathrm{CHP}}^{\mathrm{T}} + C_{\mathrm{CHP}}^{\mathrm{O\&M}} + C_{\mathrm{CHP}}^{\mathrm{CO_2}} - \lambda_{(t)}^{\mathrm{H}}$$

UNIT COMMITMENT OF THE SYSTEM

Bidding price

$$\text{minimize} \sum_{t \in \mathbf{T}} \left(\lambda^{\text{CHP}}_{(t)} - \lambda^{\text{P}}_{(t)} \right) p^{\text{CHP}}_{(t)} + C^{\text{GB}}_{(t)} q^{\text{GB}}_{(t)}$$

subject to

$$q_{(h,t)} \leq \overline{Q}_{(h)} \quad \forall t \in \mathbf{T}, \forall h \in \mathbf{H}$$

Maximum heat production

$$q^{\text{CHP}}_{(t)} = \Xi \cdot p^{\text{CHP}}_{(t)} \quad \forall t \in \mathbf{T}$$

$$p^{\text{CHP}}_{(t)} \leq \overline{P} \cdot x_{(t)} \quad \forall t \in \mathbf{T}$$

$$\underline{R} \leq p^{\text{CHP}}_{(t)} - p^{\text{CHP}}_{(t-1)} \leq \overline{R} \quad \forall t \in \mathbf{T}$$

$$\sum_{t-UT+1}^{t} y_{(\tau)} \leq x(t) \quad \forall t \in \mathbf{T}$$

$$\sum_{t-DT+1}^{t} z(\tau) \leq 1 - x(t) \quad \forall t \in \mathbf{T}$$

$$y_{(t)} - z(t) = x(t) - x(t-1) \quad \forall t \in \mathbf{T}$$

Technical operation of CHP

$$q_{(h,t)} = s^{\text{IN}}_{(t)} + q^{\text{DH}}_{(t)} \quad \forall t \in \mathbf{T}, \forall h \in \{GB, SC\}$$

$$q^{\text{CHP}}_{(t)} = s^{\text{IN,CHP}}_{(t)} + q^{\text{DH,CHP}}_{(t)} + q^{\text{HP}}_{(t)} \quad \forall t \in \mathbf{T}, \forall h \in \{GB, SC\}$$

$$s_{(t)} = s_{(t-1)} + \sum_{h} s^{\text{IN}}_{(h,t)} + q^{\text{HP}}_{(t)} - s^{\text{OUT}}_{(t)} \quad \forall t \in \mathbf{T}$$

$$\underline{S} \leq s_{(t)} \leq \overline{S} \quad \forall t \in \mathbf{T}$$

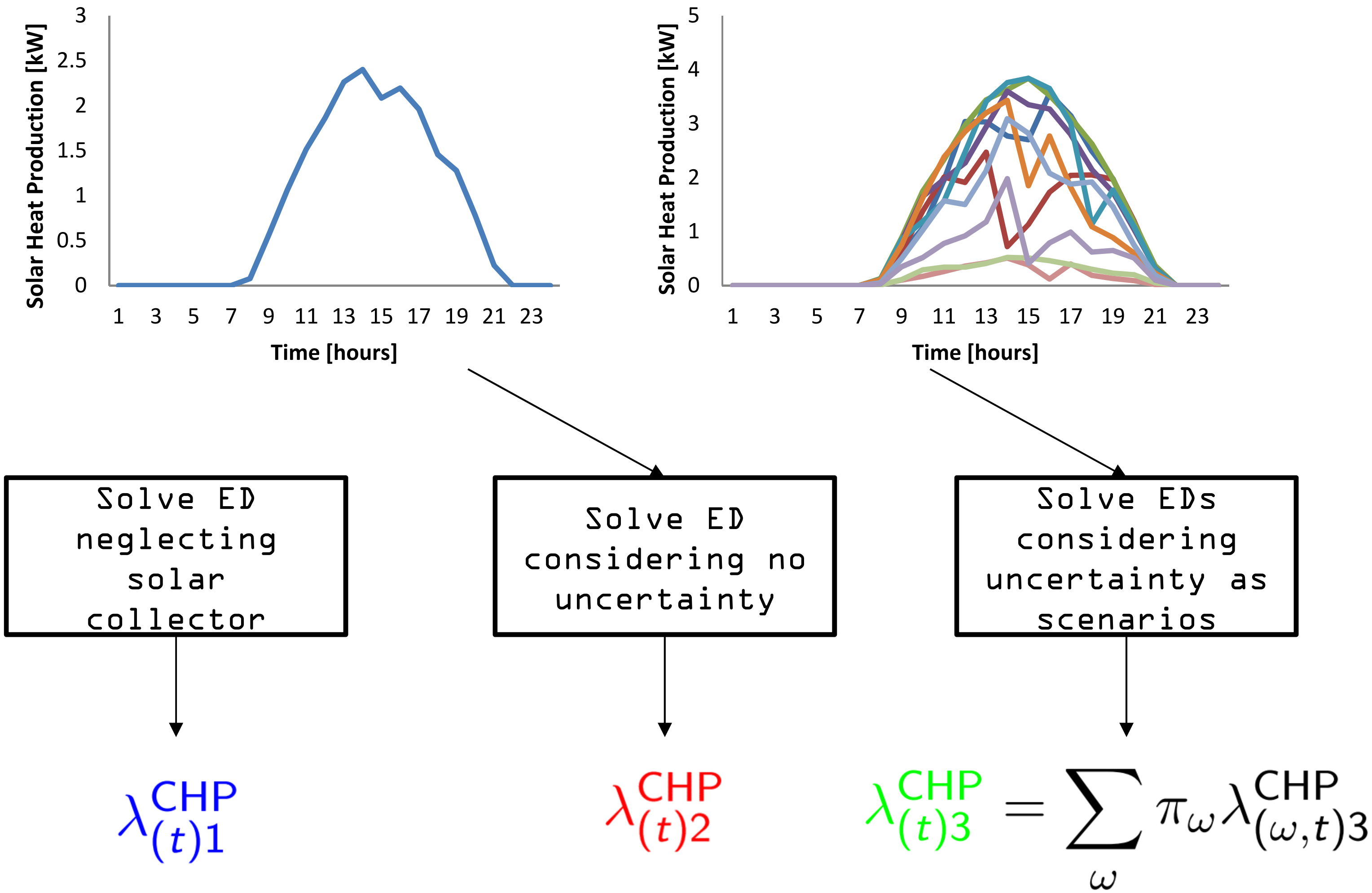
Storage and DH operati on

$$\sum_{h} q^{\text{DH}}_{(h,t)} + s^{\text{OUT}}_{(t)} = L^{\text{H}}_{(t)}$$

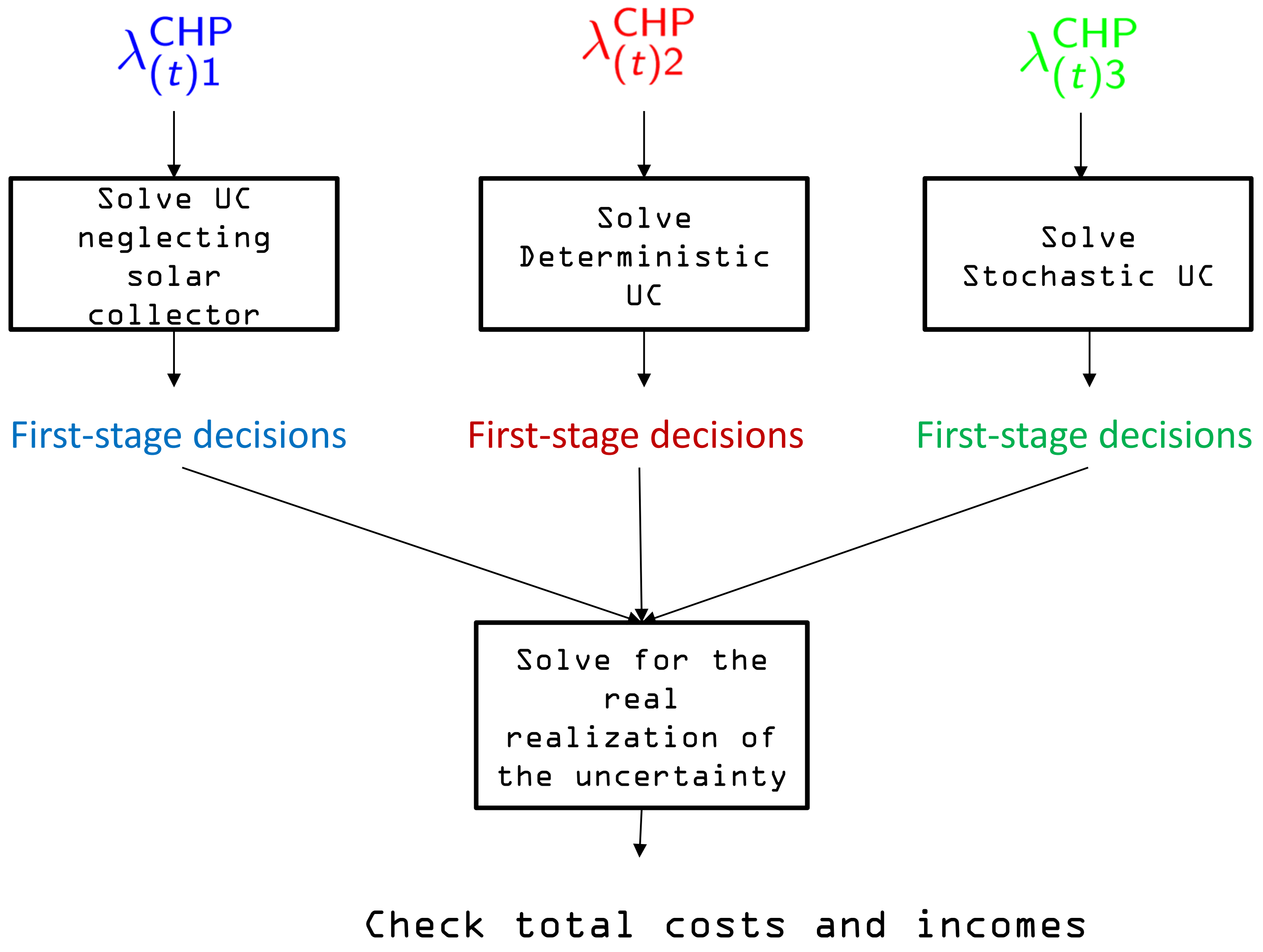
Balance

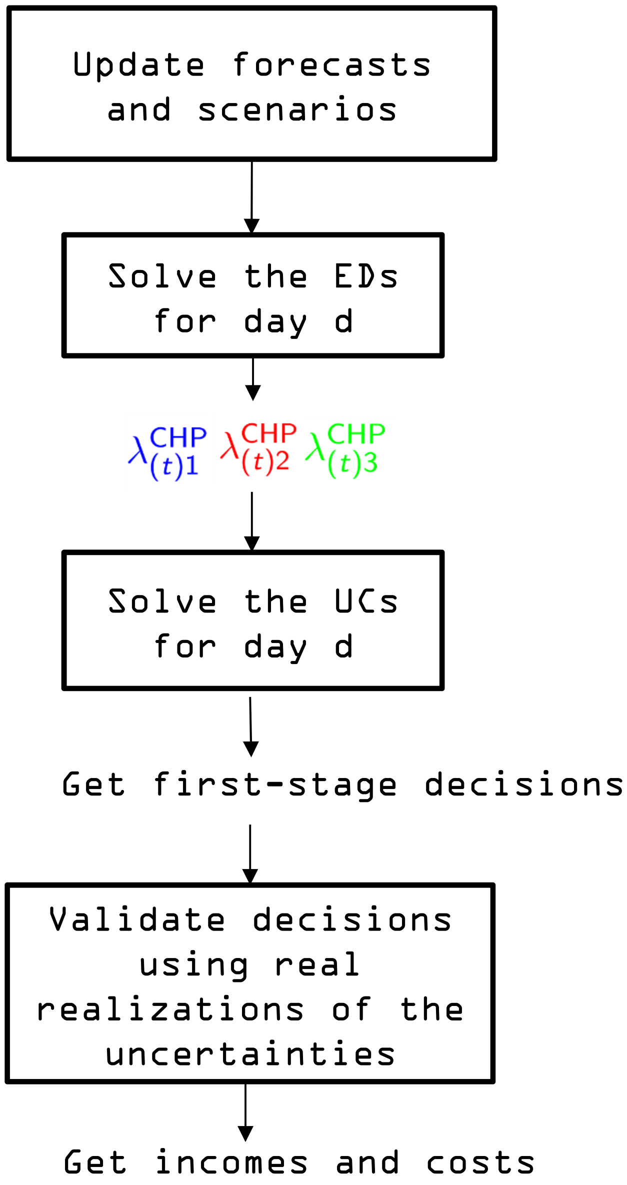
STOCHASTIC UNIT COMMITMENT

First-stage Decisions	Power bid to the DA market
Uncertainty	Heat produced by solar collectors
Second-stage Decisions	Operation of the DH system



Solar Heat Production [kW]
Time [hours]
Solar Heat Production [kW]
Time [hours]
Solve ED neglecting solar collector
Solve ED considering no uncertainty
Solve EDs considering uncertainty as scenarios
$\lambda^{\text{CHP}}_{(t)1}$
$\lambda^{\text{CHP}}_{(t)2}$
$\lambda^{\text{CHP}}_{(t)3} = \sum_{\omega} \pi_{\omega} \lambda^{\text{CHP}}_{(\omega,t)3}$

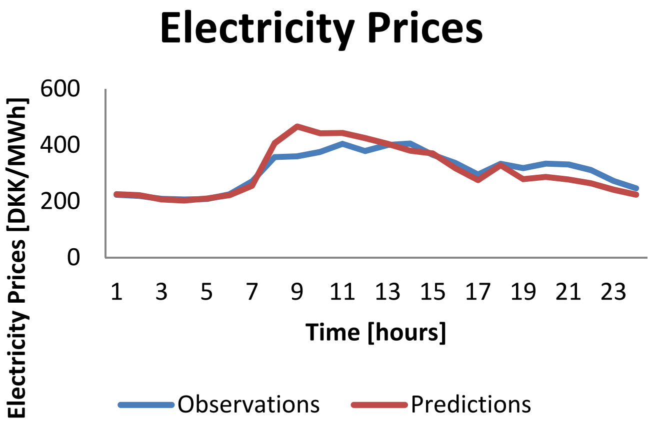

$\lambda^{CHP}_{(t)1}$
$\lambda^{CHP}_{(t)2}$
$\lambda^{CHP}_{(t)3}$
Solve UC neglecting solar collector
Solve Deterministic UC
Solve Stochastic UC
First-stage decisions
First-stage decisions
First-stage decisions
Solve for the real realization of the uncertainty
Check total costs and incomes

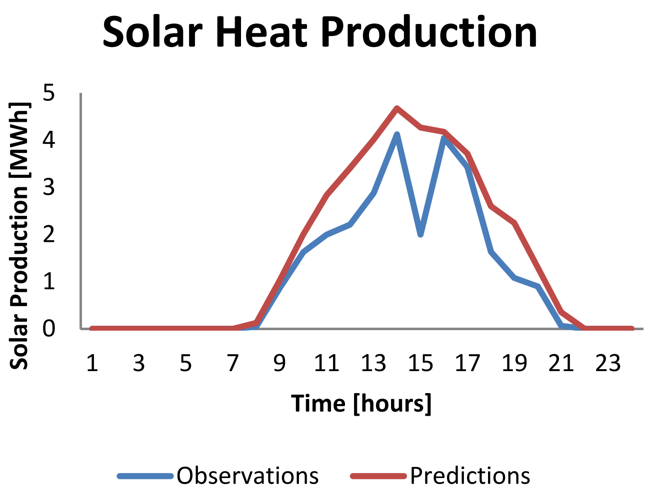

Update forecasts and scenarios
Solve the EDs for day d
$\lambda^{CHP}_{(t)1}$ $\lambda^{CHP}_{(t)2}$ $\lambda^{CHP}_{(t)3}$
Solve the UCs for day d
Get first-stage decisions
Validate decisions using real realizations of the uncertainties
Get incomes and costs

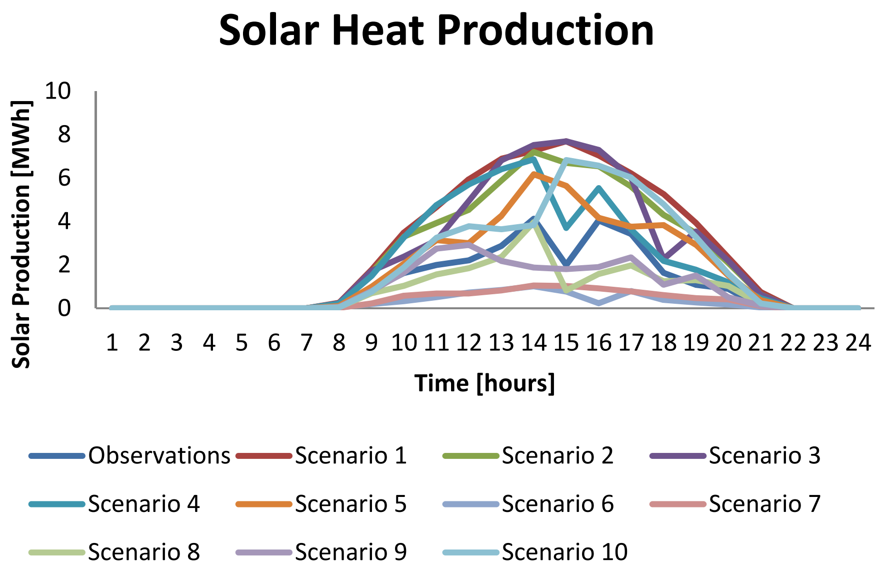
5 Days Study

	Non Uncertainty	Deterministic	Stochastic
Day 1	22106,82	14176,98	20646,87
Day 2	24347,25	20962,1	18145,23
Day 3	42229,16	41193,59	28147,14
Day 4	24647,91	21702,36	25342,36
Day 5	26555,22	18886,29	24871,04
	139886,36	**116921,32**	**117152,64**

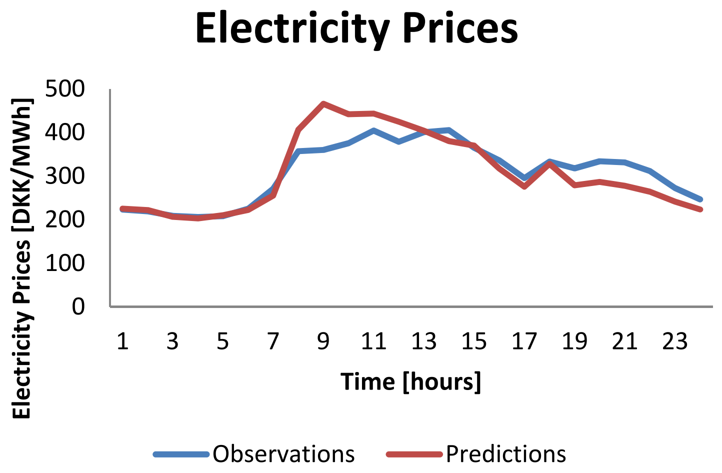
Day 1

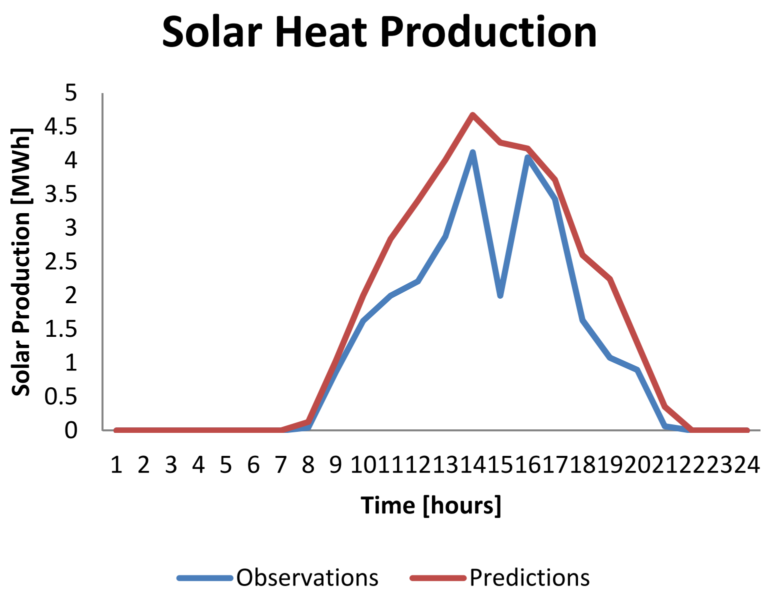

Electricity Prices
Electricity Prices [DKK/MWh]
600
400
200
0
1 3 5 7 9 11 13 15 17 19 21 23
Time [hours]
Observations
Predictions

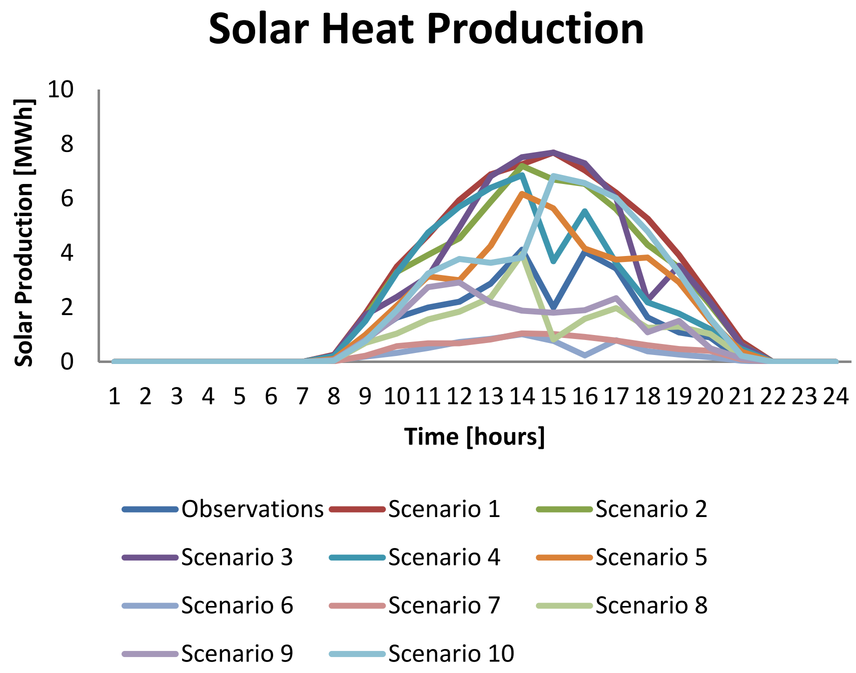

Solar Heat Production
Solar Production [MWh]
5
4
3
2
1
0
1 3 5 7 9 11 13 15 17 19 21 23
Time [hours]
Observations
Predictions

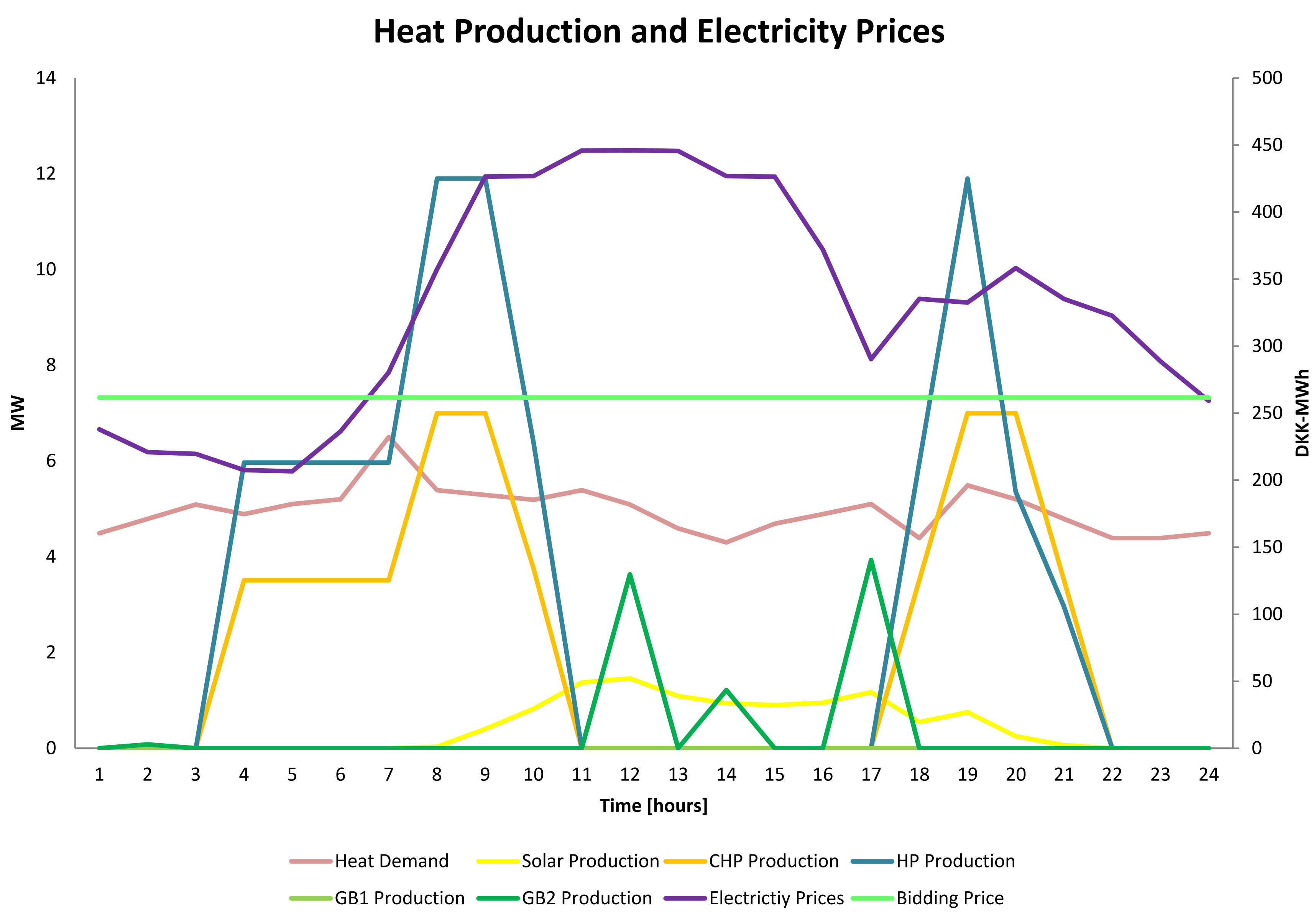

Solar Heat Production
Solar Production [MWh]
10
8
6
4
2
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time [hours]
Observations
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9
Scenario 10

Day 3

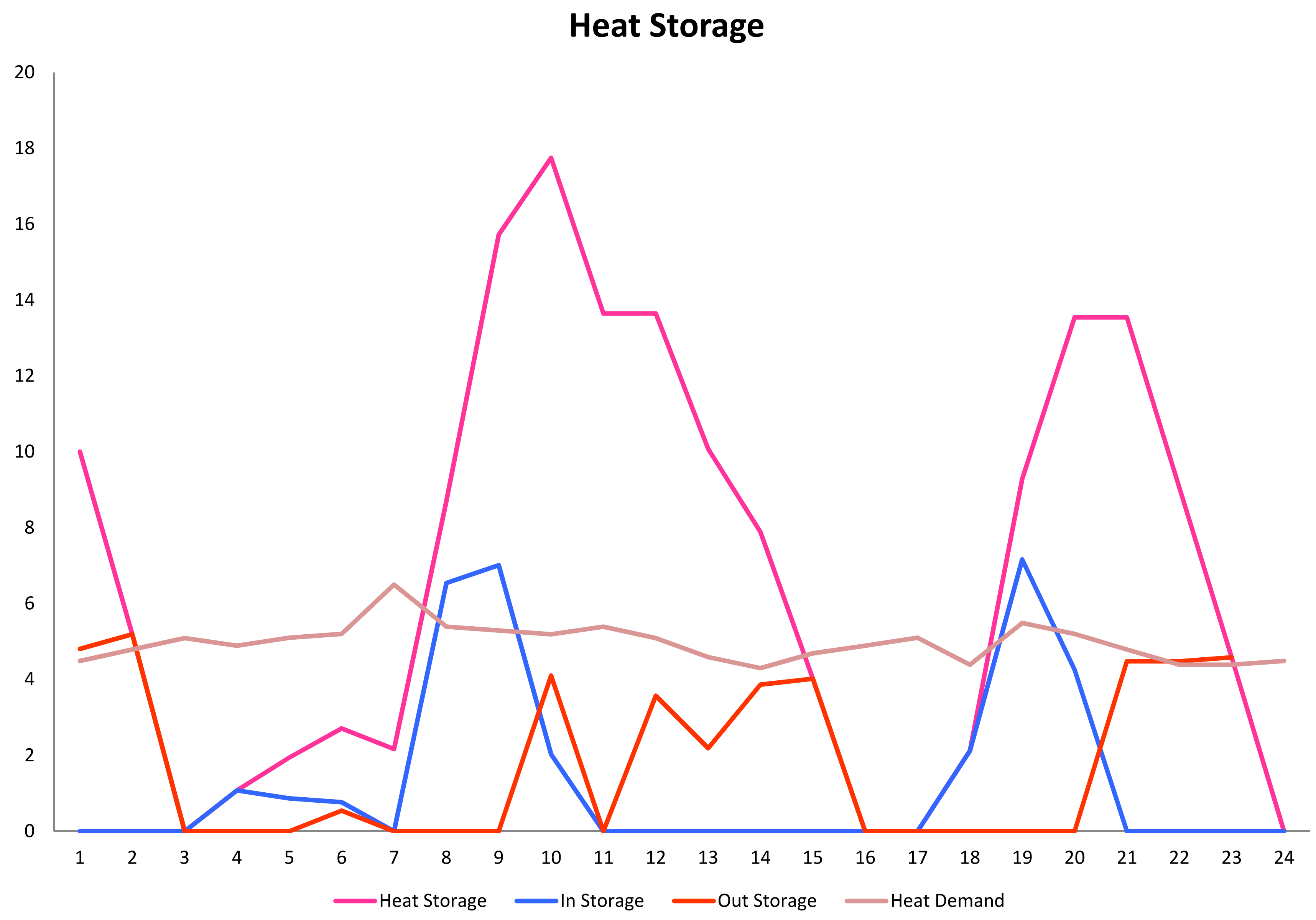

Electricity Prices
Electricity Prices [DKK/MWh]
500
400
300
200
100
0
1 3 5 7 9 11 13 15 17 19 21 23
Time [hours]
Observations
Predictions

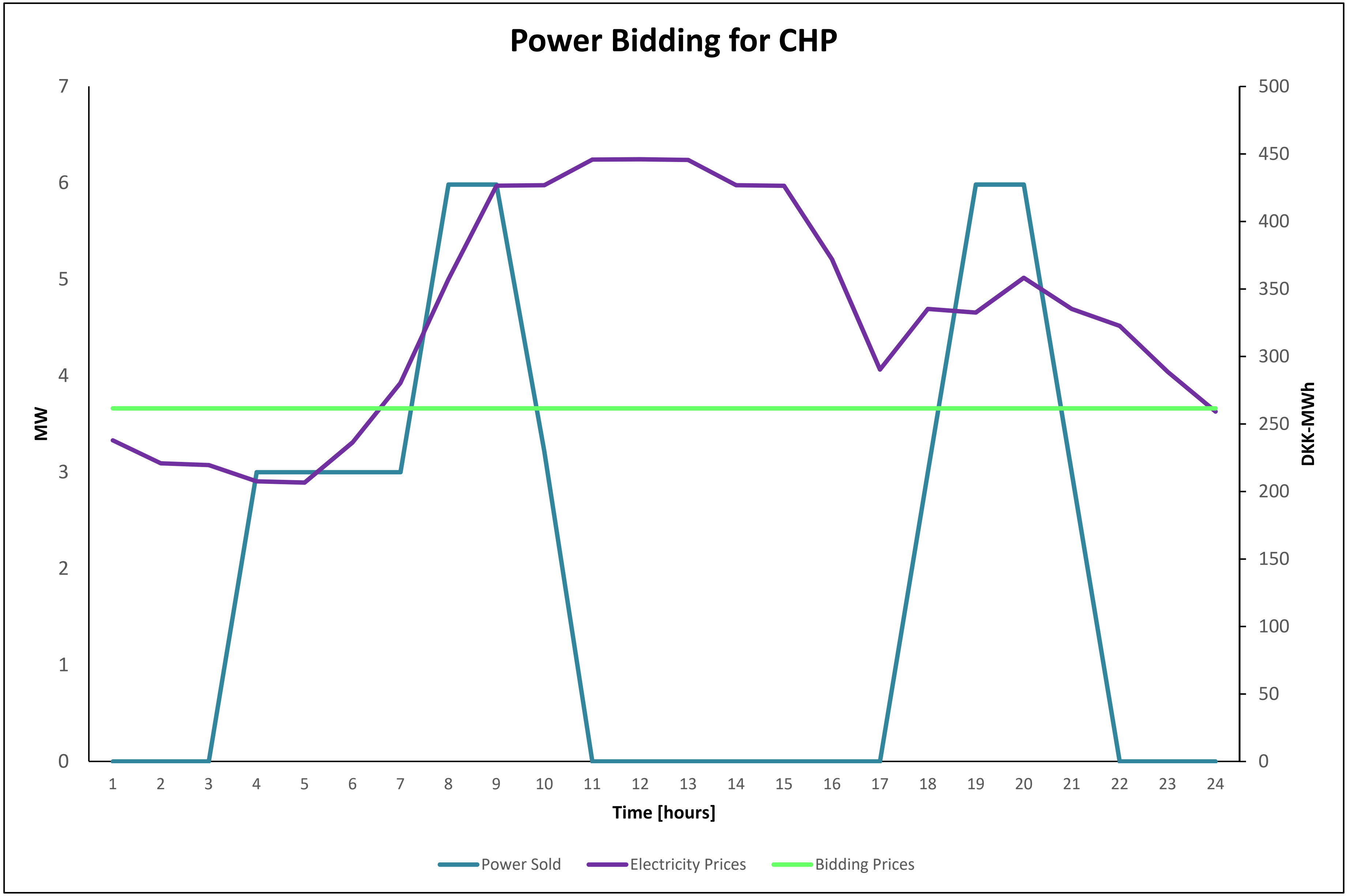

Solar Heat Production
Solar Production [MWh]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time [hours]
Observations
Predictions


Solar Heat Production
Solar Production [MWh]
10
8
6
4
2
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time [hours]
Observations
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9
Scenario 10



Heat Production and Electricity Prices
MW
DKK-MWh
Time [hours]
0
2
4
6
8
10
12
14
0
50
100
150
200
250
300
350
400
450
500
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Heat Demand
Solar Production
CHP Production
HP Production
GB1 Production
GB2 Production
Electrictiy Prices
Bidding Price


Heat Storage
20
18
16
14
12
10
8
6
4
2
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Heat Storage
In Storage
Out Storage
Heat Demand


Power Bidding for CHP
MW
DKK-MWh
Time [hours]
0
1
2
3
4
5
6
7
0
50
100
150
200
250
300
350
400
450
500
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Power Sold
Electricity Prices
Bidding Prices

THANK YOU

CITIES

Ignacio Blanco
Daniela Guericke
Henrik Madsen
Anders Andersen

EMD International A/S
www.emd.dk

ENFOR

DTU Compute
Department of Applied Mathematics and Computer Science