Online MPC of a heat-booster substation for ultra-low temperature district heating

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MOTIVATION

- **ULTDH** (T = 40-45°C) is too cool for safe **DHW production**
- Need an auxiliary energy source (**electricity**)
- Increasing share of **intermittent renewable sources**: requires demand-side flexibility
- Peak boilers expensive and polluting: shave **peak loads**

Integration of heat and electricity sectors

- Heat pumps can absorb excess electricity and store heat in **tanks**
- **Smart control** can shift the load and reduce costs and emissions

OBJECTIVES

System model

- Model of the substation with Modelica
- Validation with real data from measurements

Energy demand

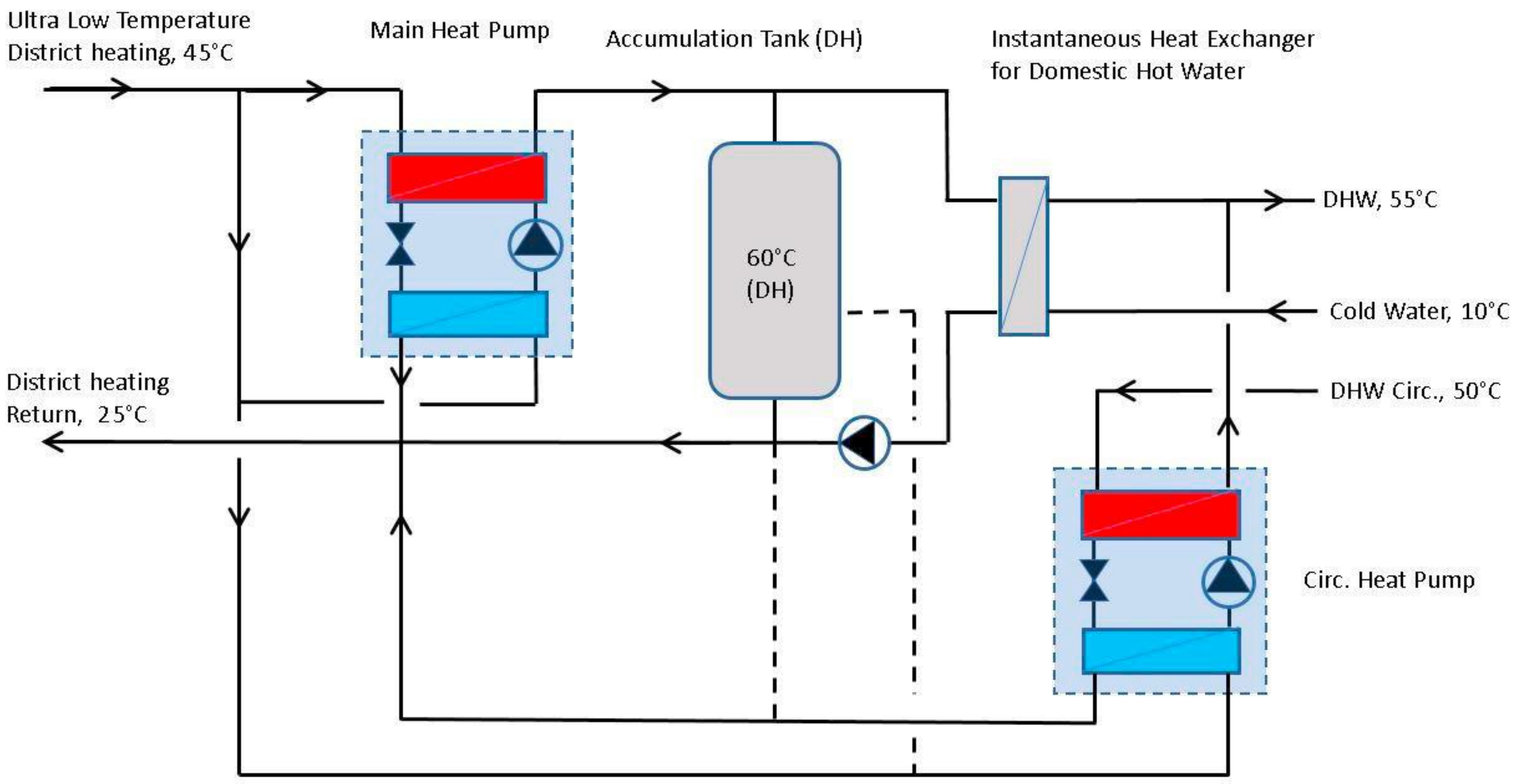
- Prediction through statistical time series models
- Test the forecasting methods with real data

Energy cost

- Construction of a time-varying energy tariff

Optimal control problem

CASE STUDY



DHW for 22 flats

Two storage stanks in series

Total storage volume: **1500 l**

Main heat pump:

Condenser capacity: **15 kW**

Electricity consumption: **3 kW**

On-off operation

Circulation heat pump:

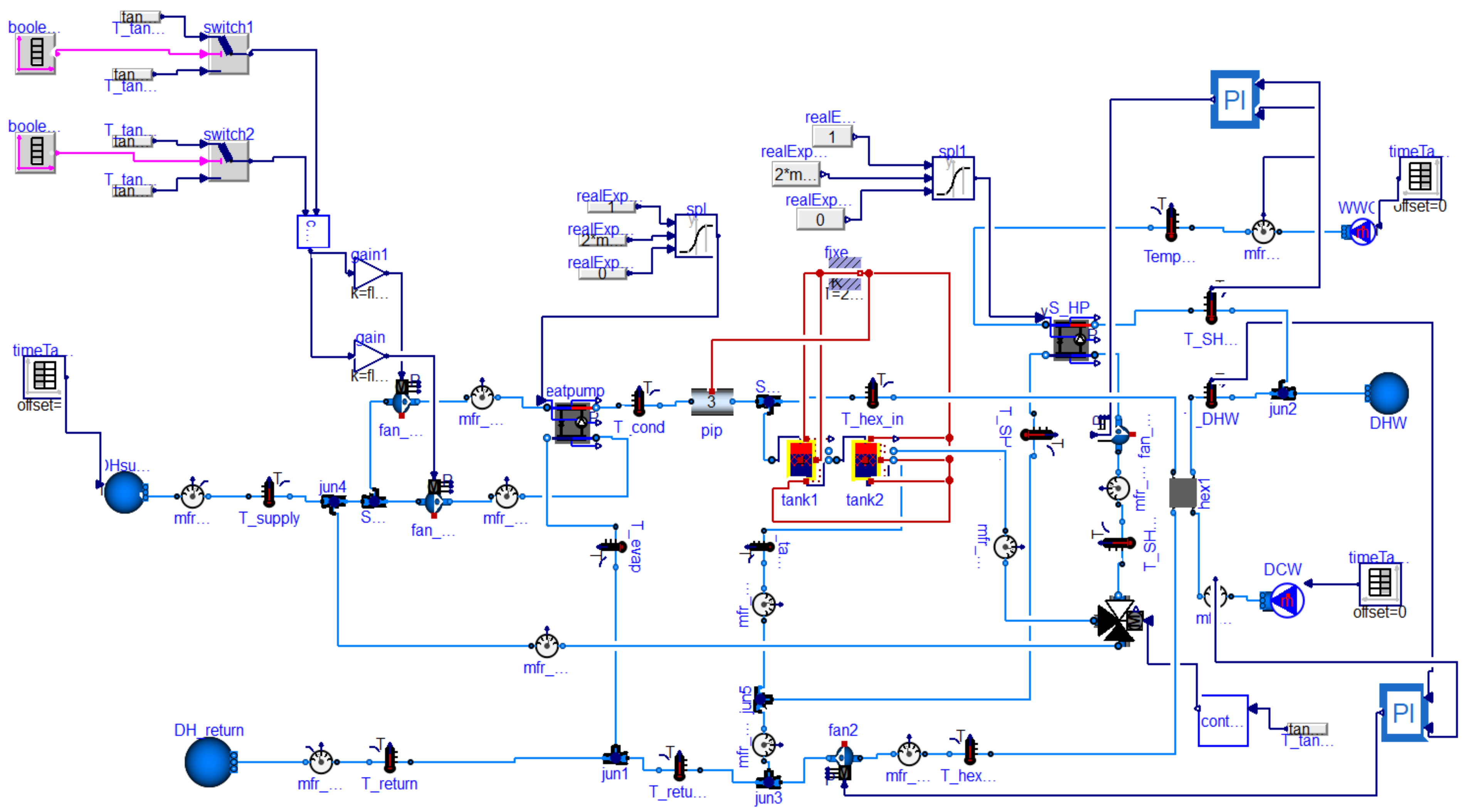
Condenser capacity: **3 kW**

Electricity consumption: **0.6 kW**

Always on

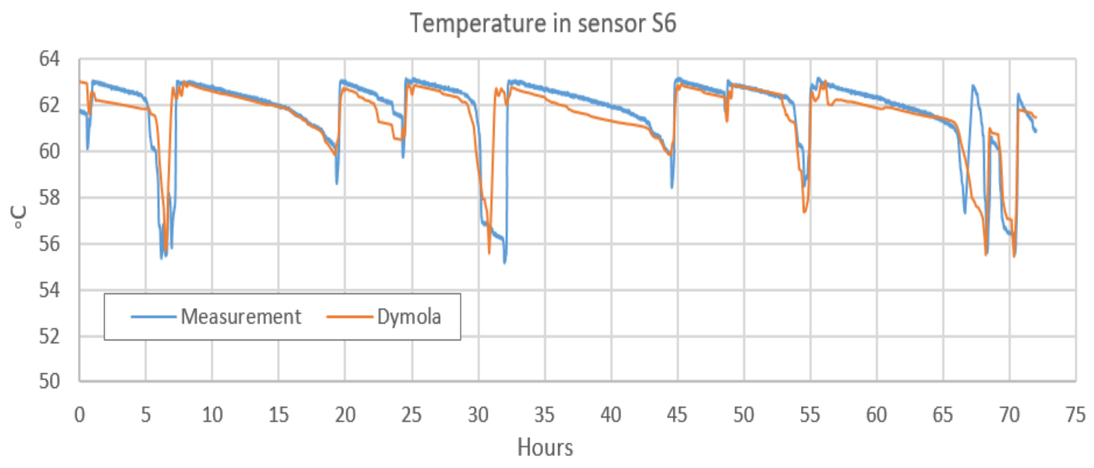
SUBSTATION MODEL

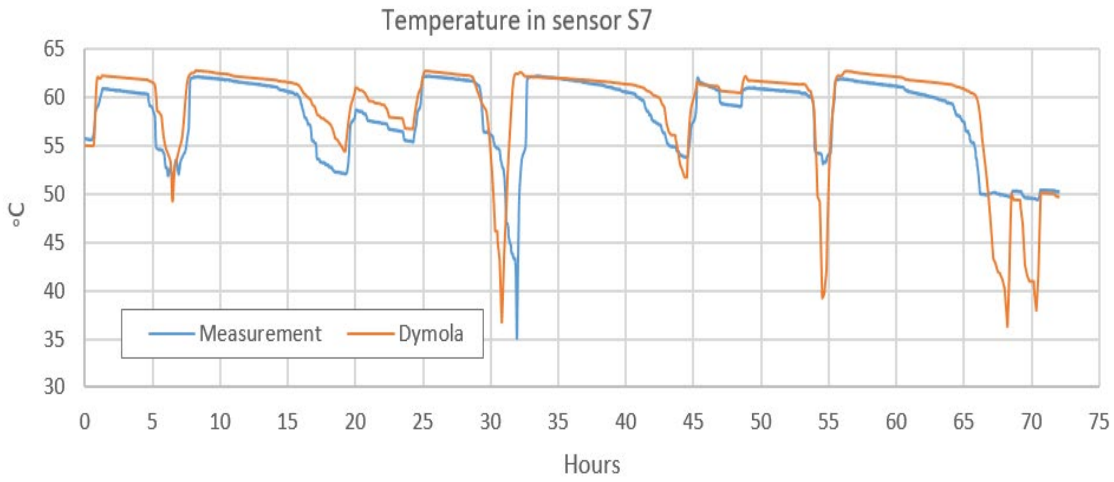
Components included in the Modelica Buildings Library v5.1

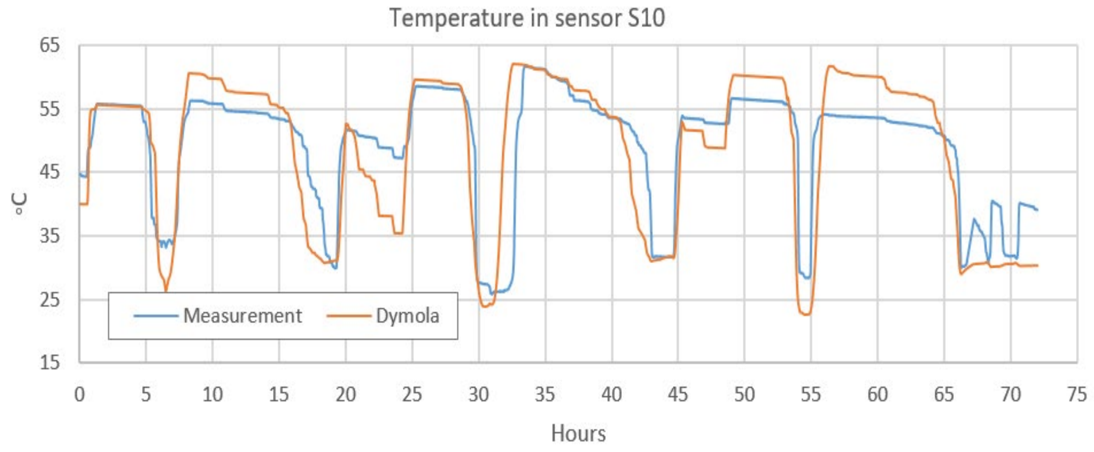


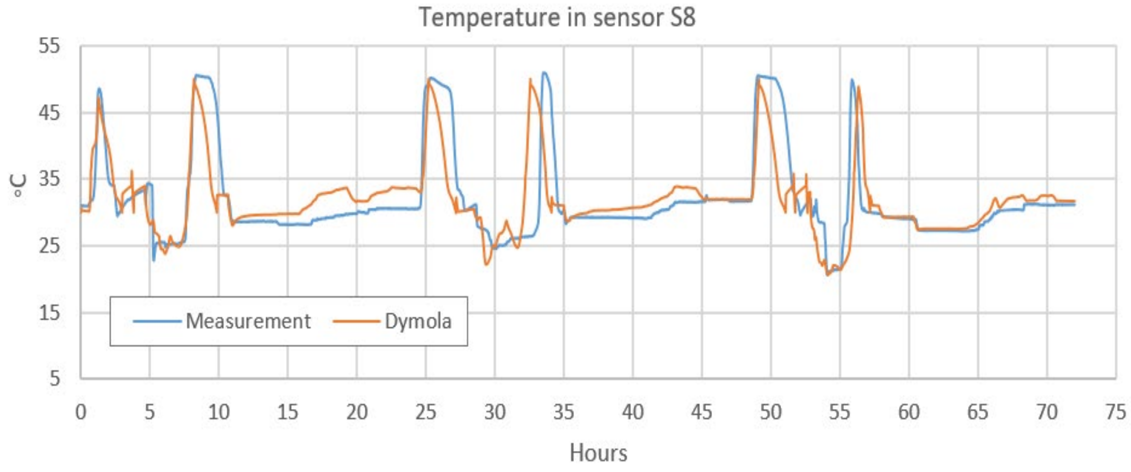
MODEL VALIDATION

Temperature measured in different sensors of the tank VS temperature from Dymola simulation



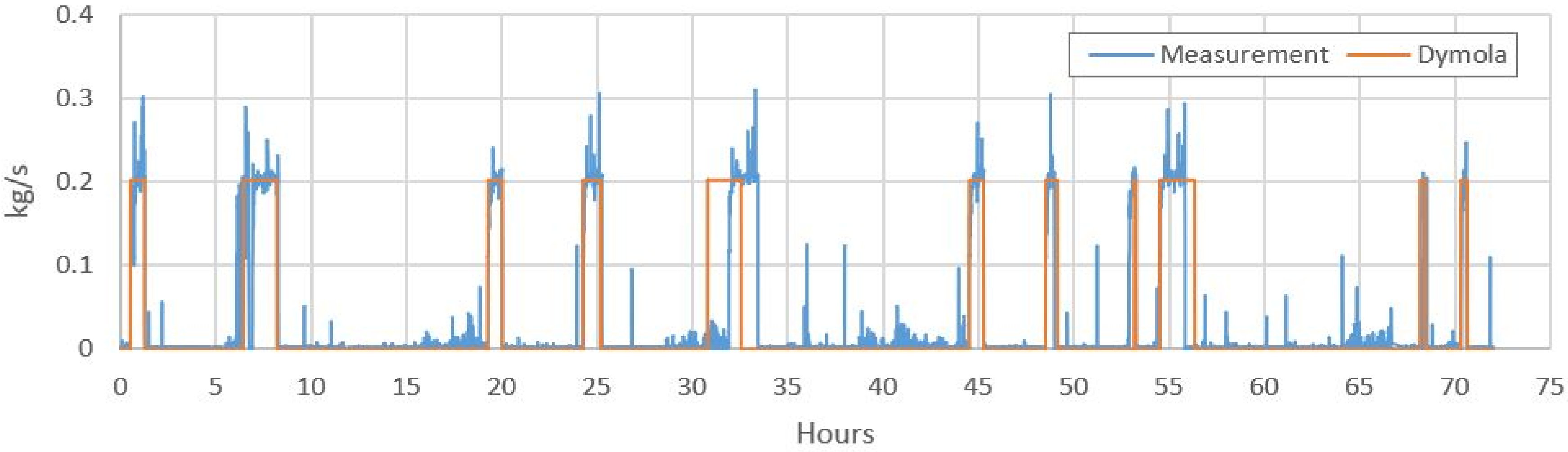




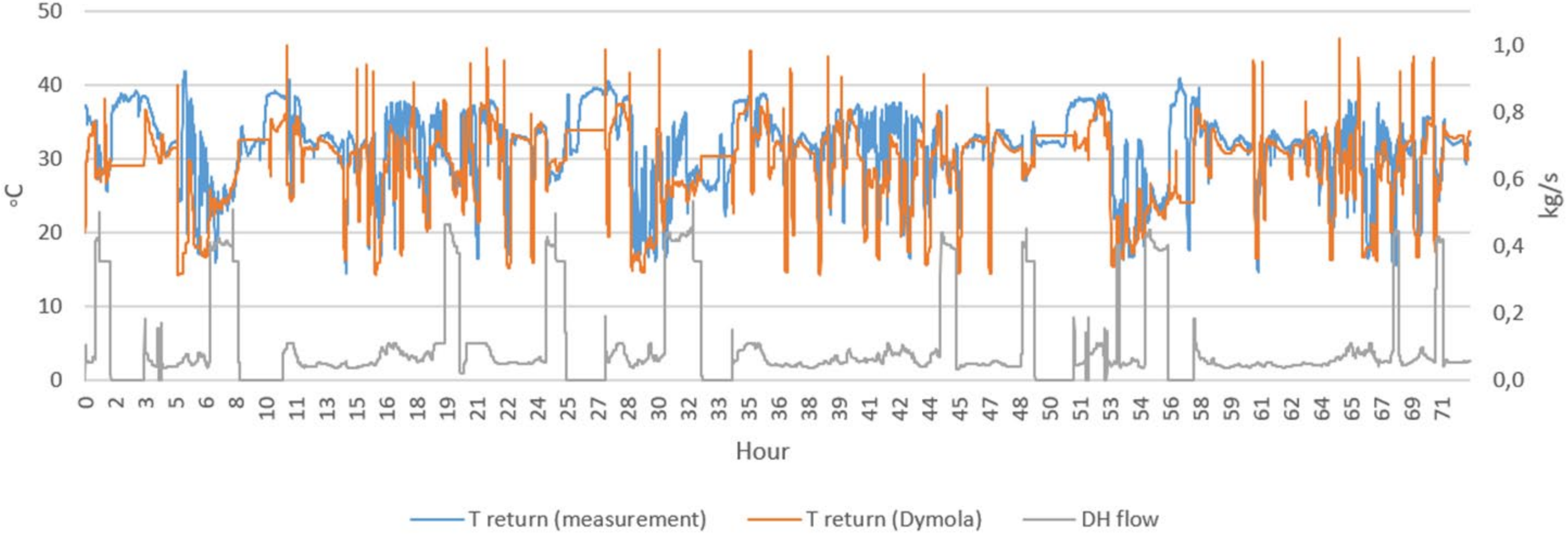


MODEL VALIDATION

Mass flow in the condenser of the main heat pump



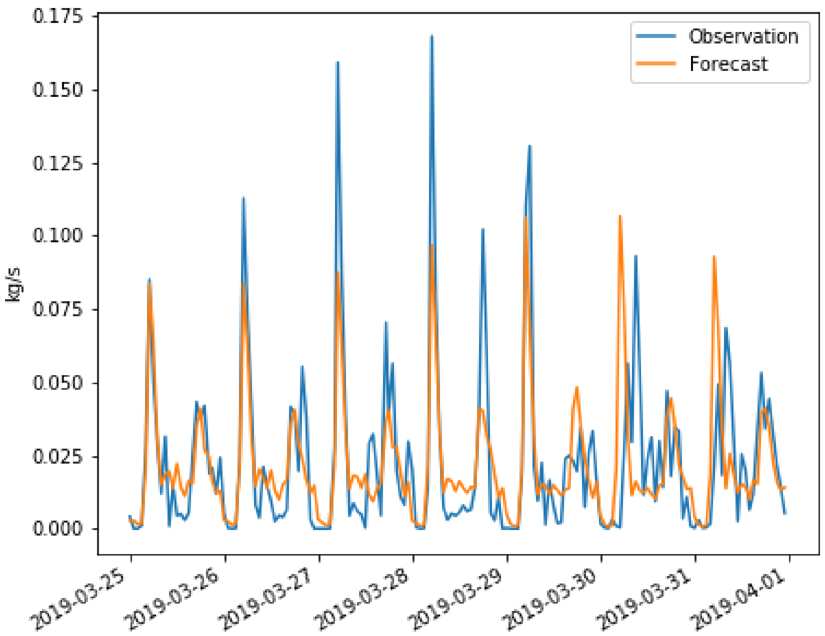
DH return temperature



DHW CONSUMPTION FORECASTING

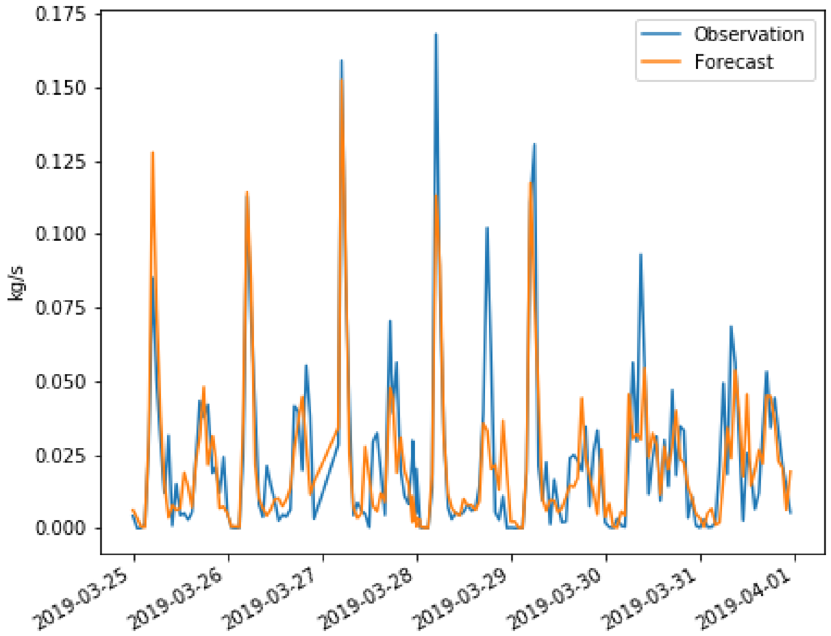
- **Triple exponential smoothing (Holt-Winters):** Weighted sum of the seasonal and non-seasonal past observations, where w**eight** of the past observations **decreases exponentially** over time

Model with daily seasonality (period = 24)



BIAS [kg/s]	- 0.0012
MAE [kg/s]	0.0127
RMSE [kg/s]	0.0205

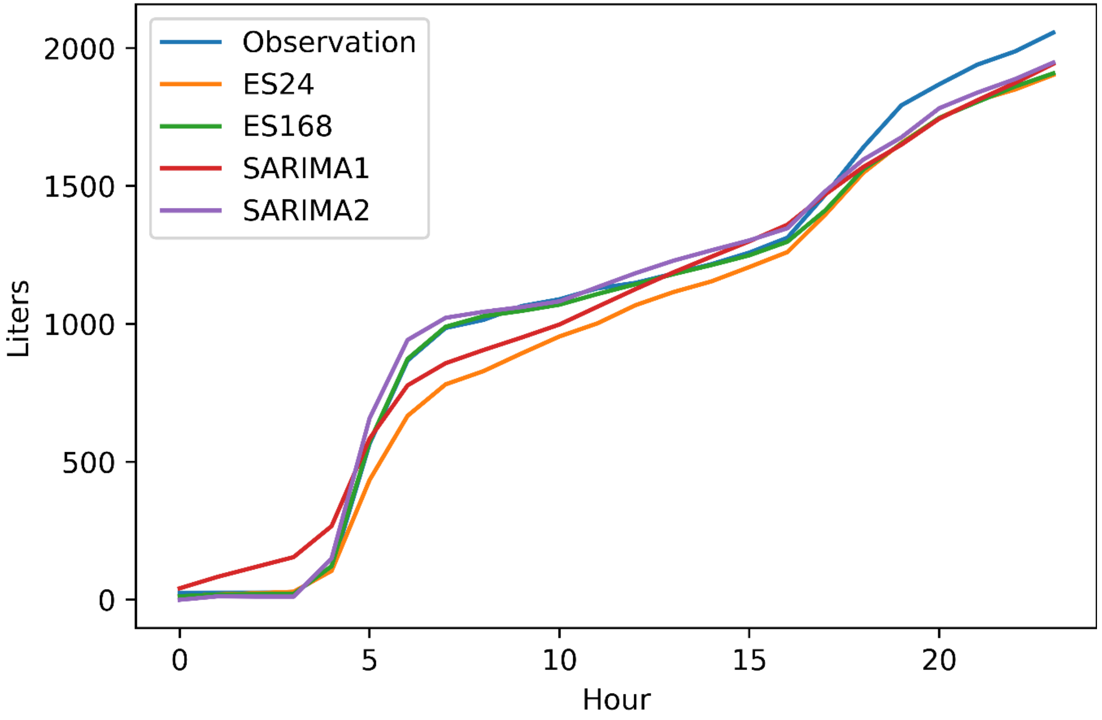
Model with weekly seasonality (period = 168)



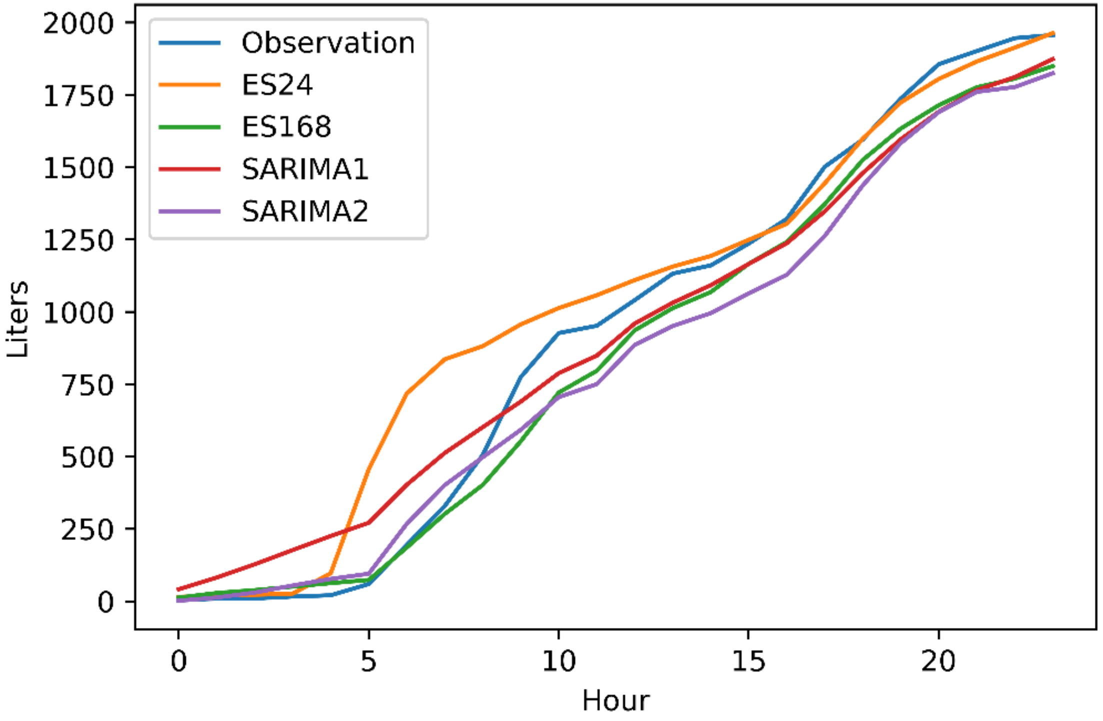
BIAS [kg/s]	- 0.0015
MAE [kg/s]	0.0108
RMSE [kg/s]	0.0162

CUMULATIVE ERROR

Observation and forecast of the cumulative volume consumed in one day

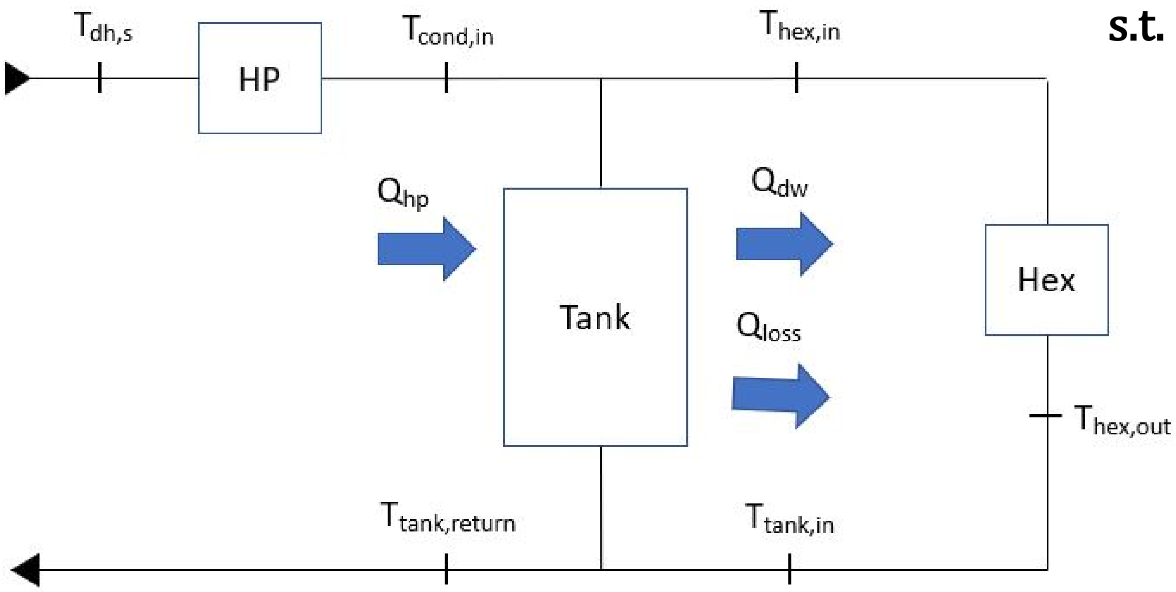


Weekdays



Weekend

OPTIMAL CONTROL MODEL



min $Z = \sum_{t=t_0}^{Np} (Pdh(t) \cdot cdh(t) + P_{el}(t) \cdot cel(t) + w(t) \cdot c_w(t))$

s.t. $s(t) = s(t\text{-}1) + q_{hp}(t\text{-}1) - q_{dw}(t\text{-}1) - q_{loss}(t\text{-}1)$

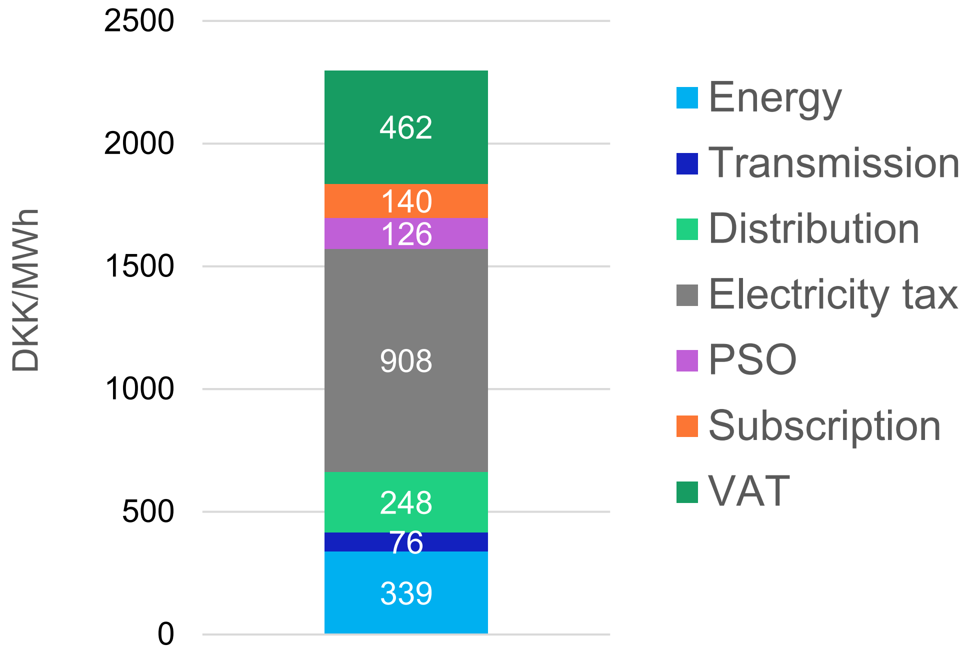
$s_{max} + w(t) \geq s(t) \geq s_{min} - w(t)$

$qmax \geq q_{hp}(t) \geq q_{min}$

1. Solve the optimization problem with initial state from measurements
2. Apply control in Dymola for 24 hours
3. Use results from Dymola as initial state for the next optimization time horizon

ELECTRICITY TARIFF CONSTRUCTION

Electricity price in 2017



Spot/load-based tariff

- Energy cost weighted with the **spot price**
- Transmission and distribution cost weighted with the **grid load level**

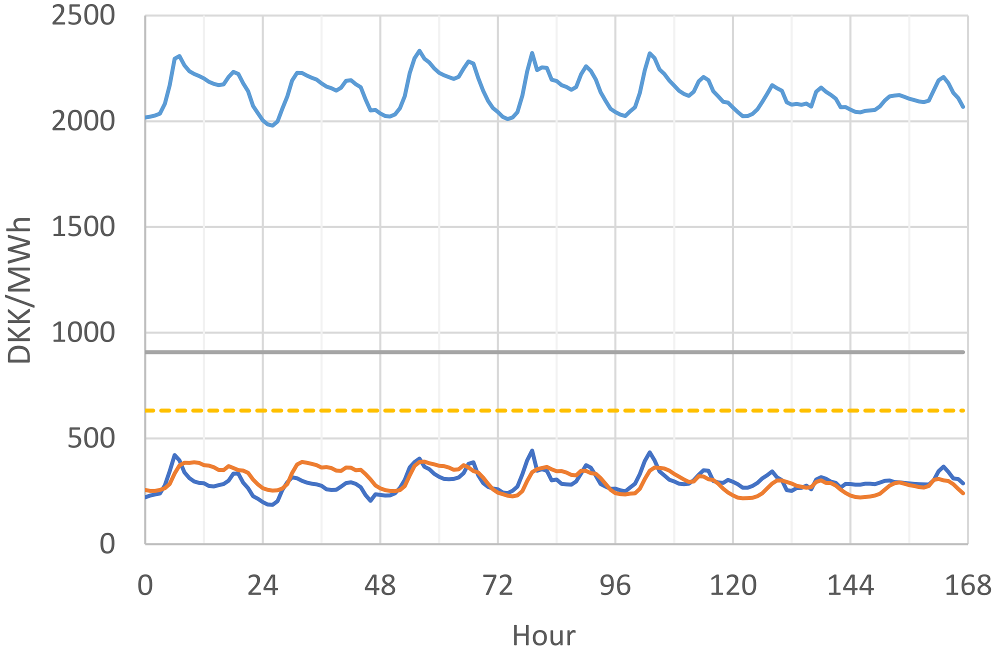
(Ulbig, 2010)

$$C_{el}(t) = C_{energy} \cdot \frac{spot(t)}{spot_{avg}} + C_{system} \cdot \frac{load(t)}{load_{avg}} + C_{other}$$

ELECTRICITY TARIFF CONSTRUCTION

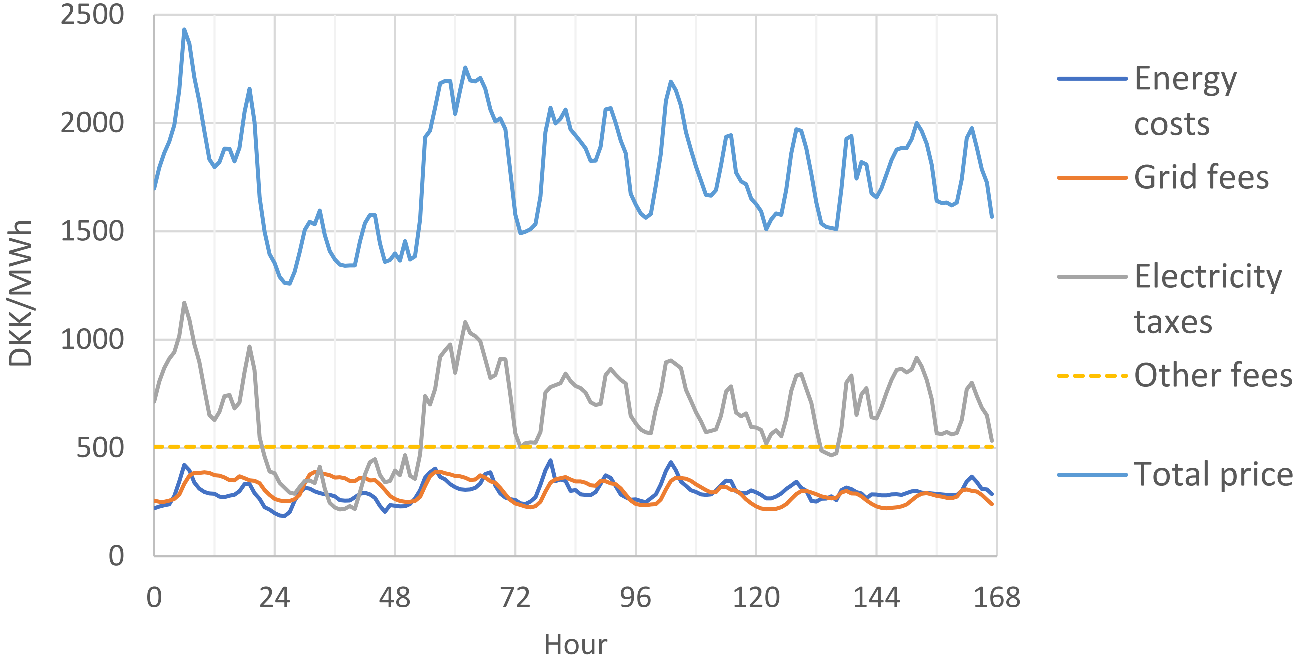
Approach 1

- Constant electricity taxes



Approach 2

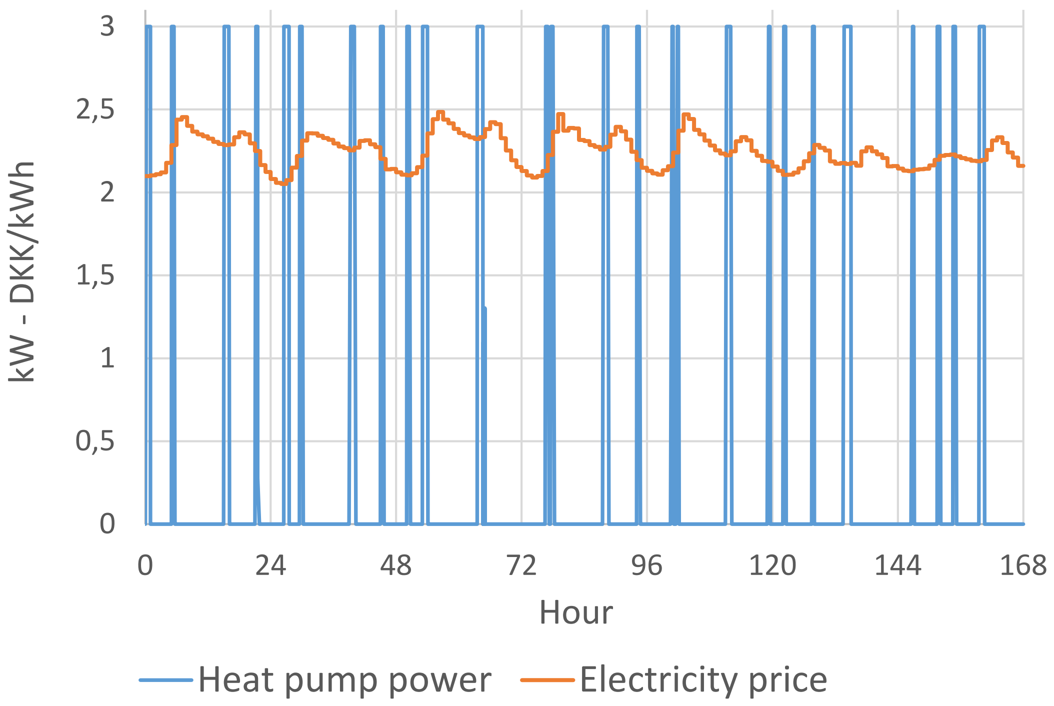
- Electricity taxes weighted with **CO_2 intensity signal** (*Knudsen and Petersen, 2016*)
- Average electricity tax reduced
- PSO eliminated



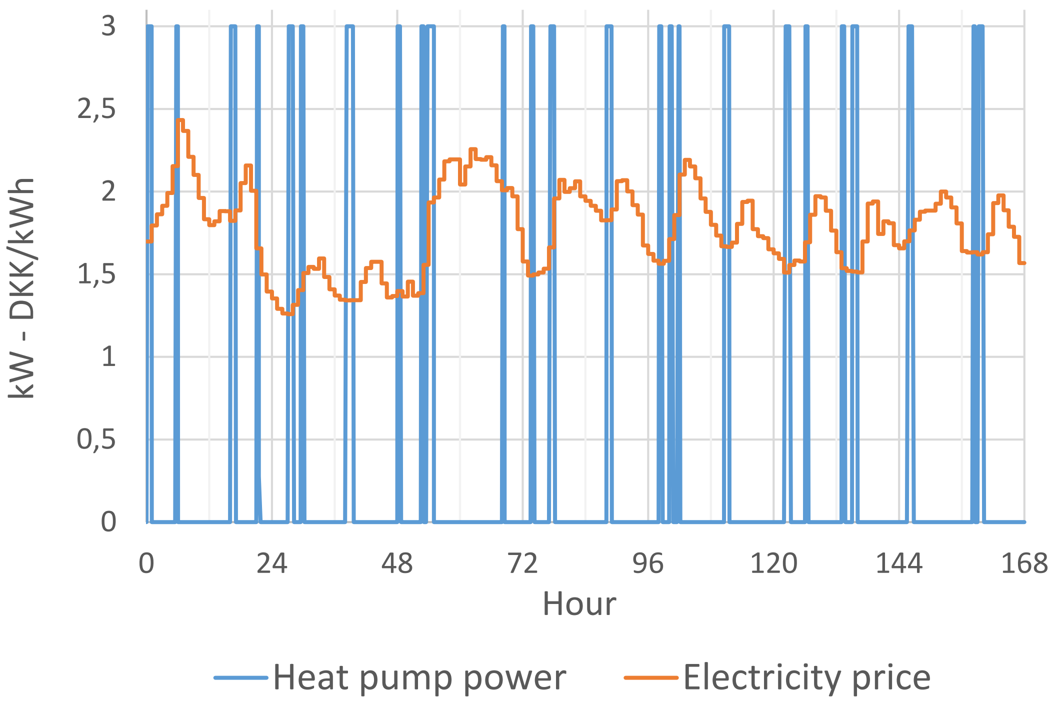
OPTIMIZATION RESULTS

The two different tariffs were used in the objective function of two optimization programs. The district heating price was first assumed to be constant.

Approach 1

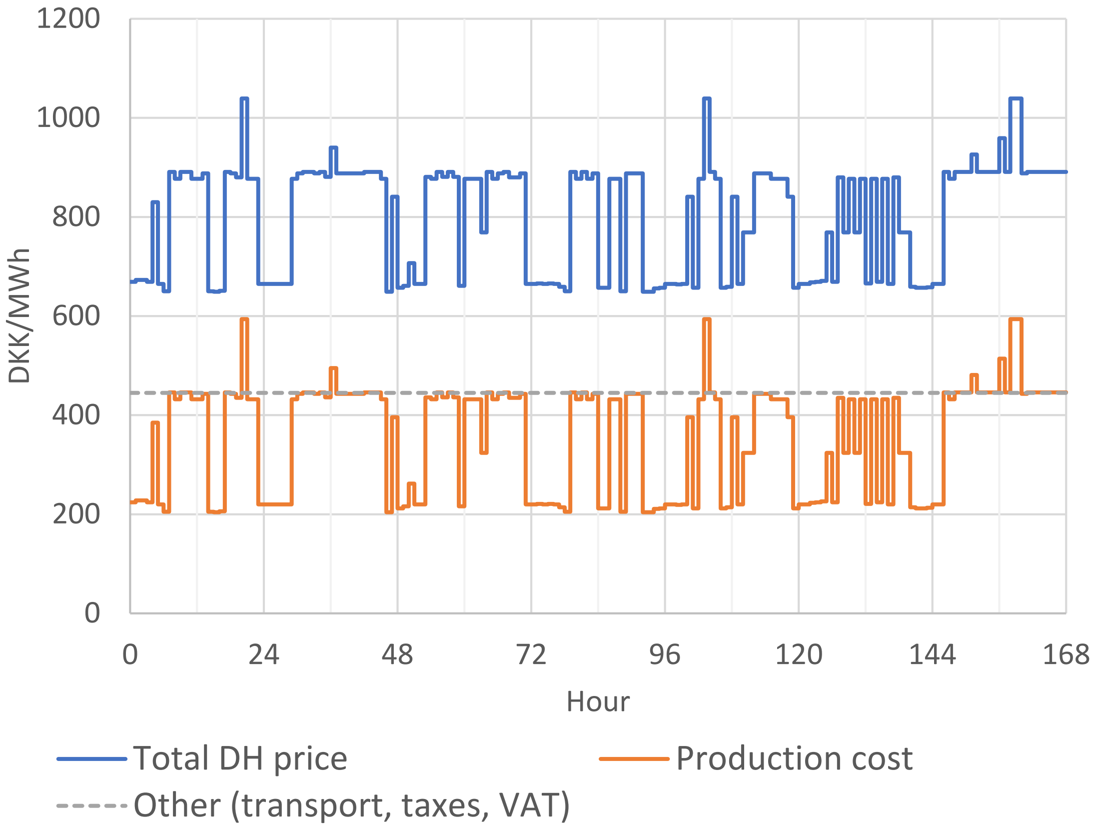


Approach 2

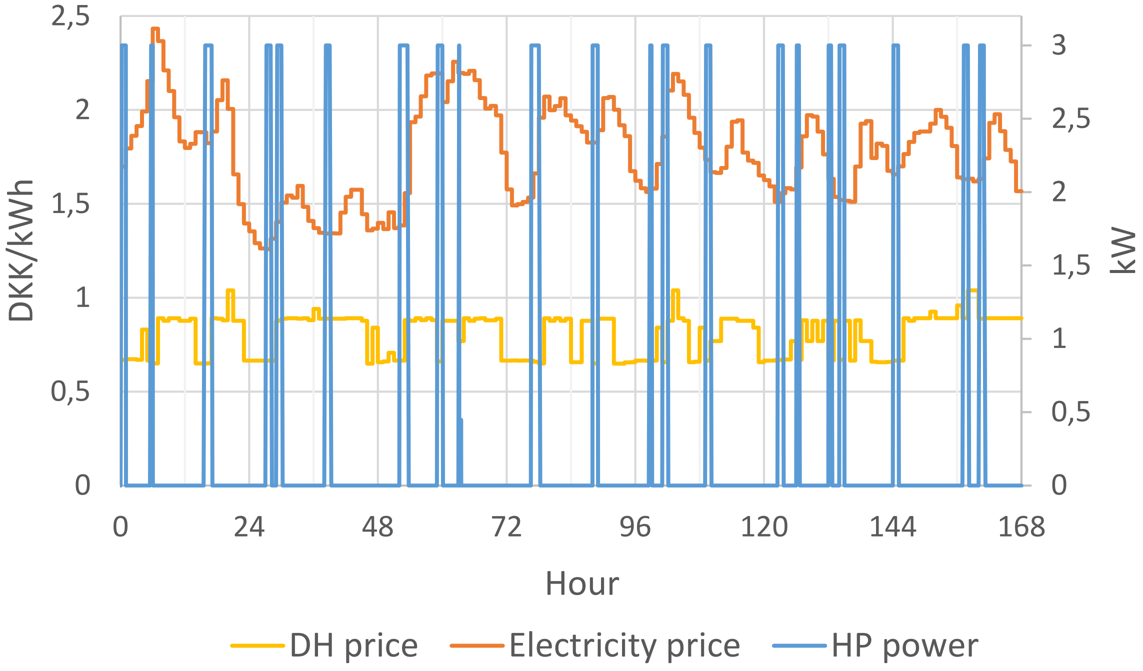


DH TARIFF

- DH energy cost weighted with the data about **marginal production costs** available

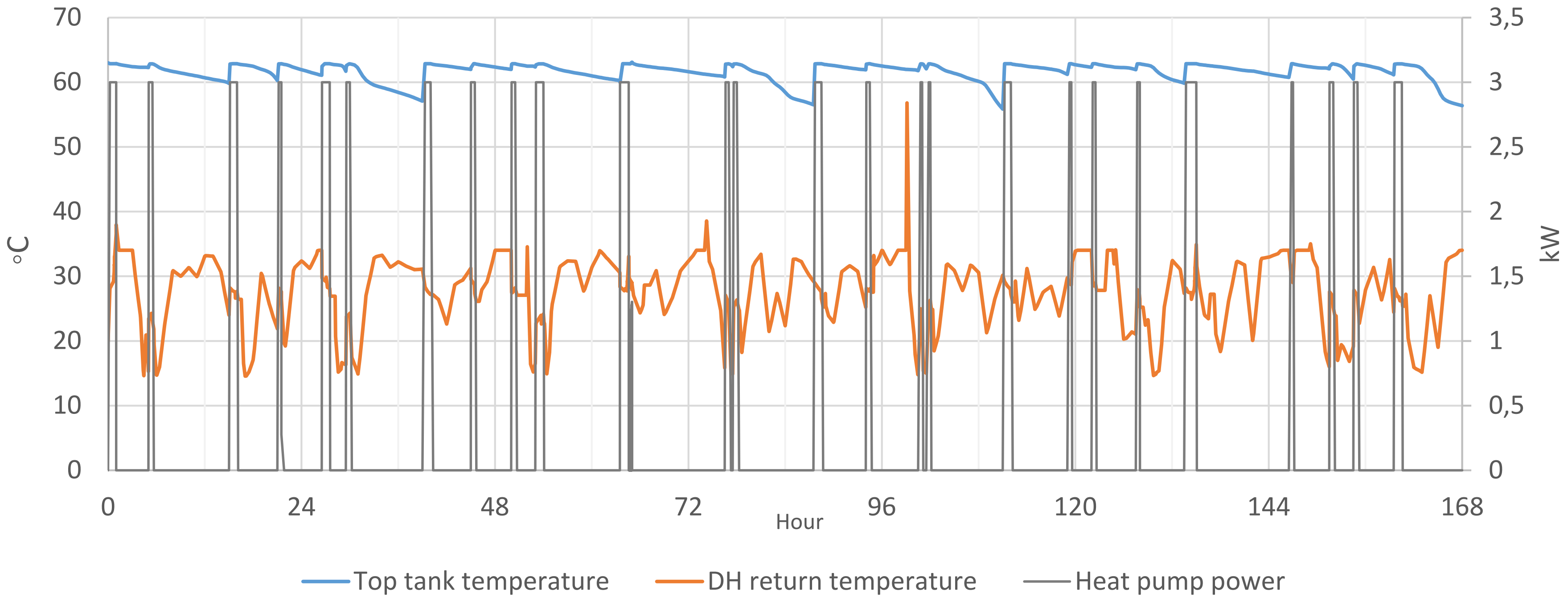


- DH tariff combined with electricity tariff in the objective function



SYSTEM OPERATION

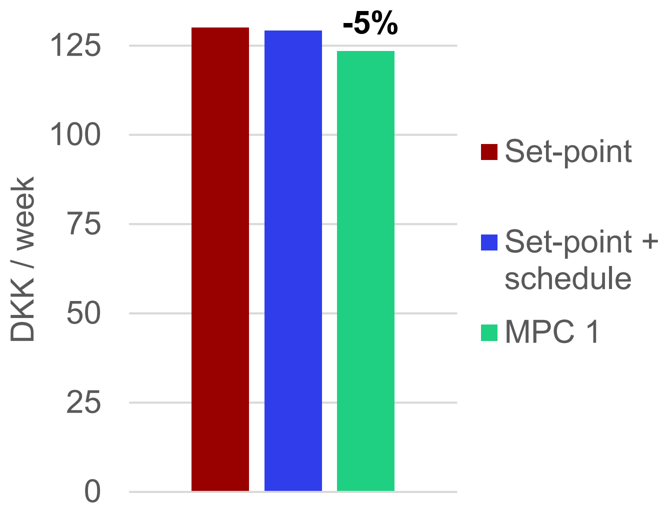
- Security of DHW supply: top tank temperature > 55° C
- No overcharging: mass-weighted DH return temperature ≈ 30 ° C



ECONOMIC PERFORMANCE

Scenario 1

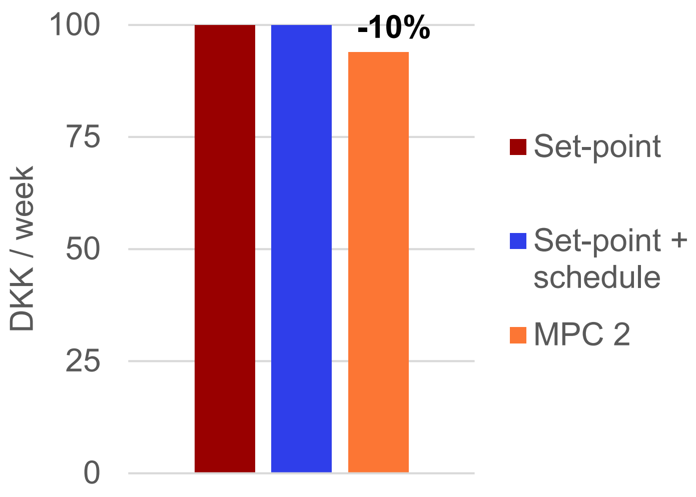
Electricity tariff with constant taxes, constant DH price



Electricity costs

Scenario 2

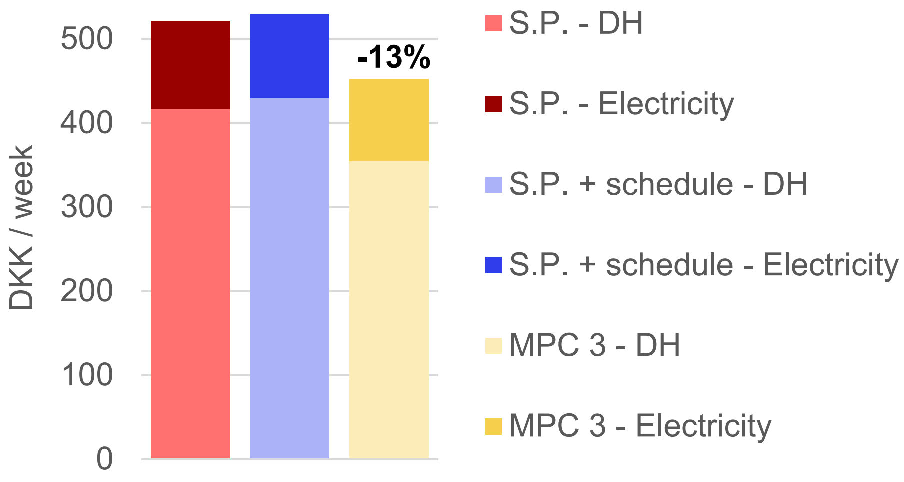
Electricity tariff with variable taxes, constant DH price



Electricity costs

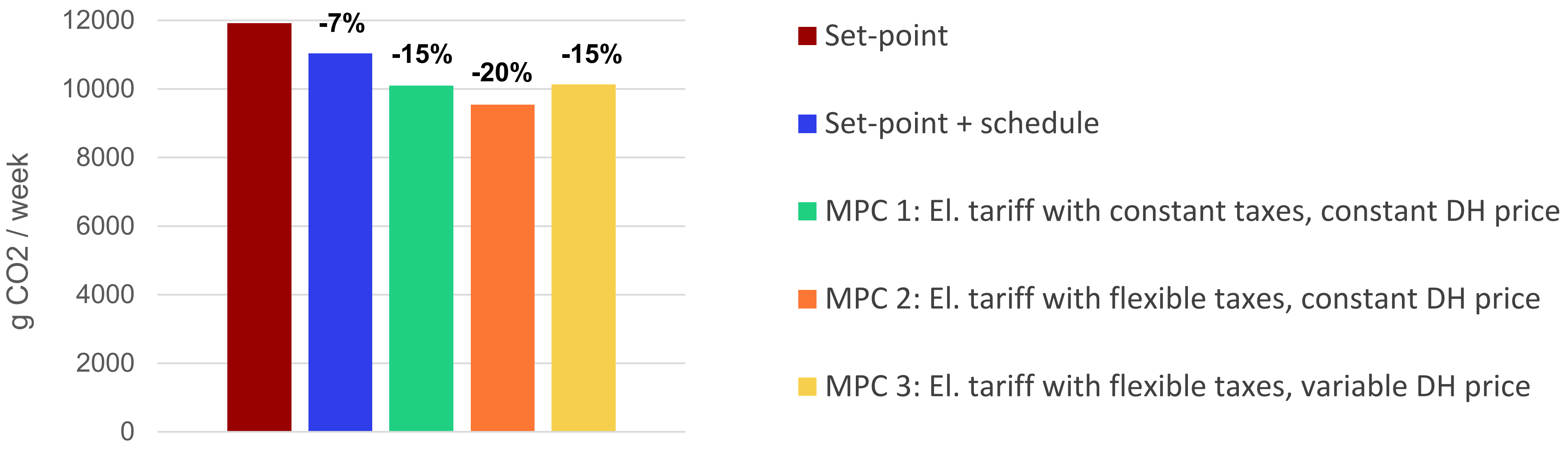
Scenario 3

Electricity tariff with variable taxes, variable DH price



Electricity and DH costs

CO_2 EMISSIONS FROM ELECTRICITY



CONCLUSIONS

- The optimal control model using consumption forecasts is able to supply enough energy to fulfill **comfort and health requirements** for DHW production
- The consumption can be shifted almost entirely from **peak hours**
- The optimal control is superior to standard control systems based on set-points and fixed schedules in **minimizing emissions and costs**
- The economic incentive becomes relevant if **time-varying energy tariffs with flexible taxes** are applied

FUTURE WORK

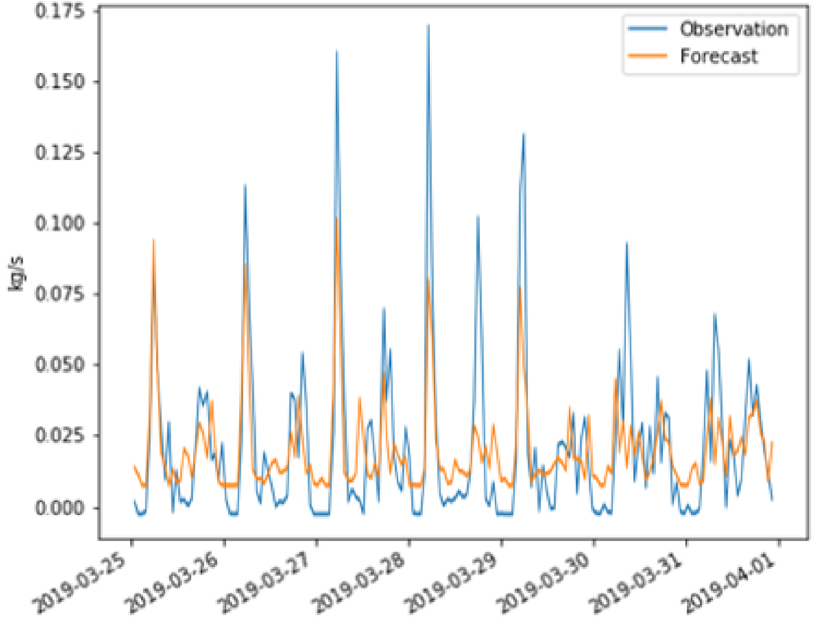
- **Optimize the control in Jmodelica.org using MPCPy:** optimization based on state estimation of the model in Dymola (stratified storage tank, return DH temperature)
- **Circulation heat pump:** optimization of the heat source used for the evaporator, including return DH (model of the space heating system needed)
- **DH tariff:** hourly data about marginal costs for ULTDH, grid load level and carbon intensity

Thank you for your attention

DHW CONSUMPTION FORECASTING

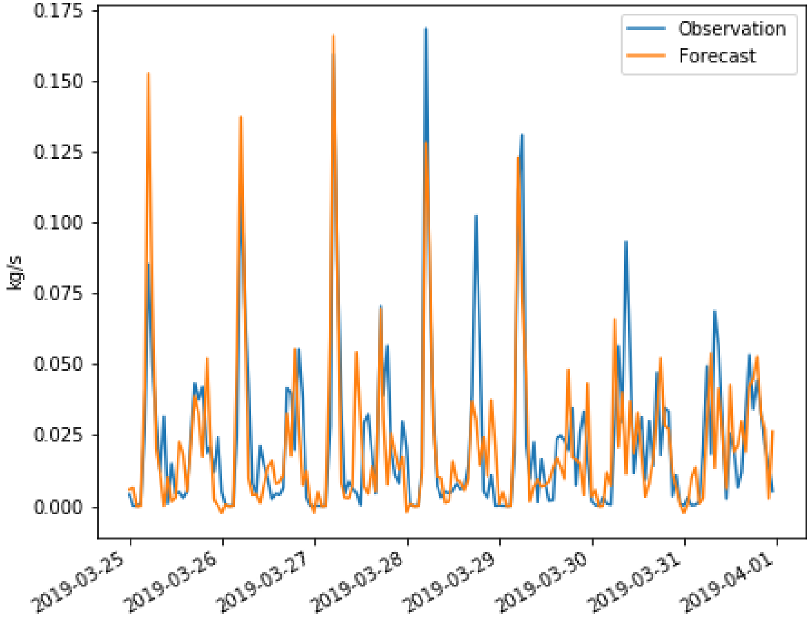
- **Seasonal ARIMA:** The forecast is a linear combination of its seasonal and non-seasonal **lagged values** and of the past forecast **errors,** where the data are are transformed using **differencing**.

Model 1: SARIMA $(1,1,2)\mathrm{x}(1,0,0)_{168}$



BIAS [kg/s]	- 0.0010
MAE [kg/s]	0.0144
RMSE [kg/s]	0.0199

Model 2: SARIMA $(1,0,1)\mathrm{x}(0,1,0)_{168}$



BIAS [kg/s]	- 0.0012
MAE [kg/s]	0.0132
RMSE [kg/s]	0.0197