# Optimal operation of energy storage in buildings: The use of hot water system

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# Agenda

- Project description
- Work done
- Model validation
- Further work

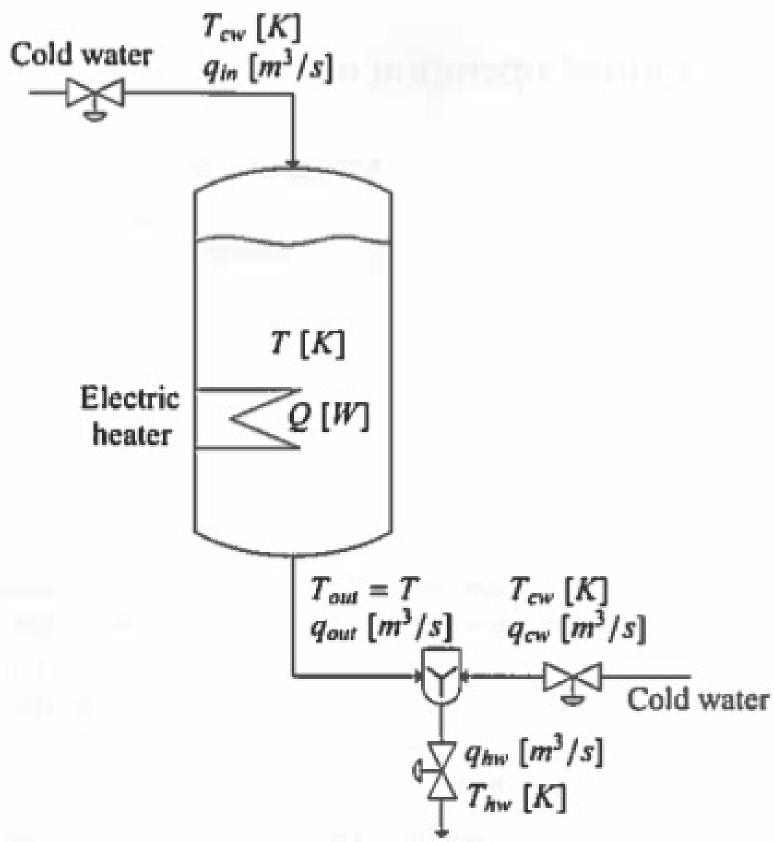
# Project description

- Optimal operation of energy storage in buildings with focus on the optimization of an electrical water heating system.
- Objective is to minimize the energy cost of heating the water
- Main complications: Electricity price and future demand
- Goal: To propose, implement and compare different simple policies that result in near-optimal operation of the system.

# Proposed policies

- Should be robust in some to-be-defines sense (e.g. must be feasible for at least 95% of the cases)
- Should result in significant savings compared to trivial solution
- Should be simple to implement in practice.

# Process flow scheme




Dynamic model:

$$\frac{dV}{dt} = q_{in} - q_{out}$$

$$\frac{dT}{dt} = \frac{1}{V}[q_{in}(T_{in} - T) + \frac{Q}{\rho c_p}]$$

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# Model assumptions

- qhw and Thws controlled directly by the consumer
- Perfect control when feasible

Perfect control: $T_{hw} = T_{hw,s} \quad and \quad q_{hw} = q_{hw,s}$

else $T < T_{hw,s} \quad and \quad q_{hw} = q_{hw,s}$

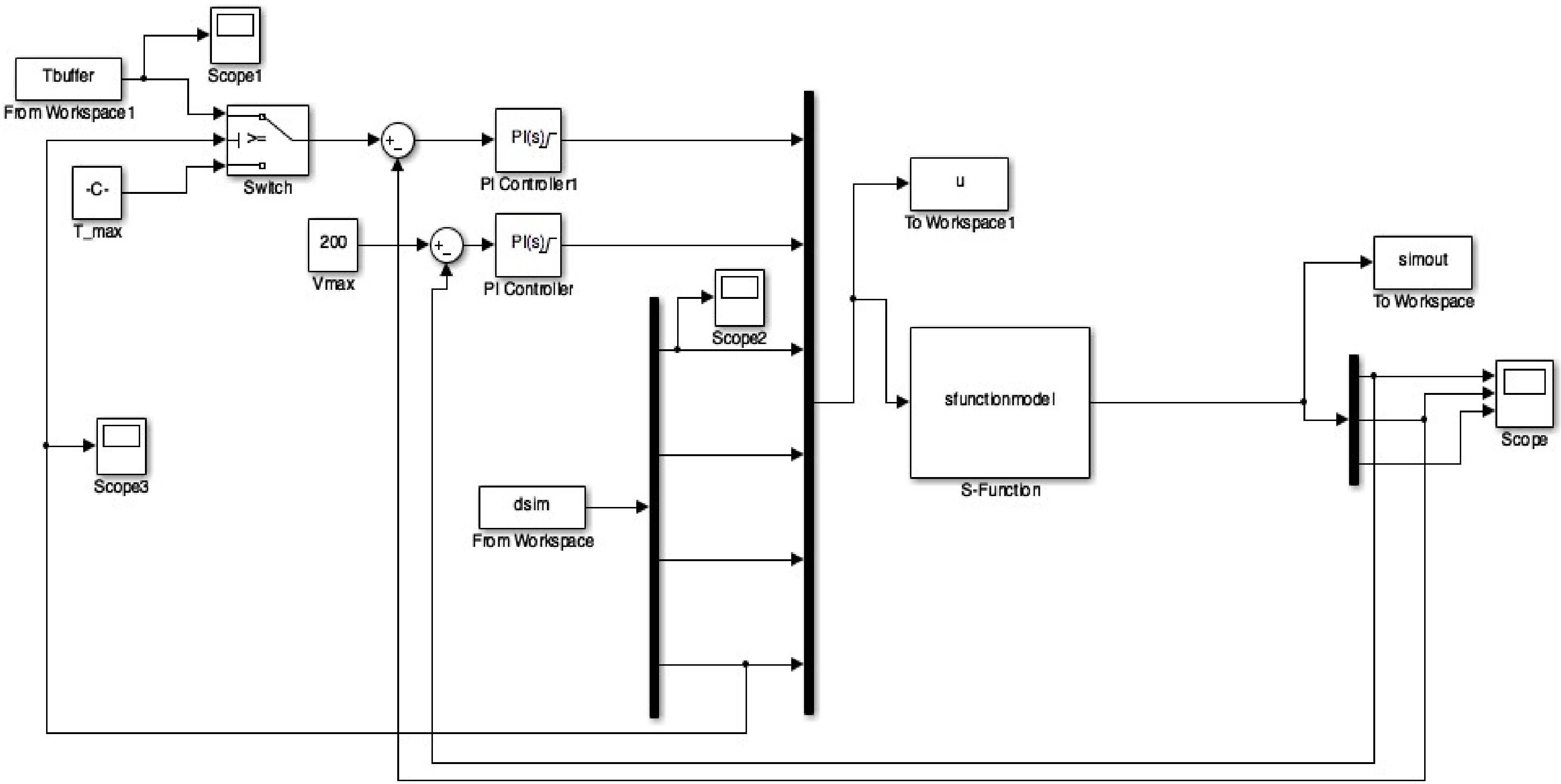
# Model equation

$$\frac{dx}{dt} = f(x, u, d)$$

Definition of the state, input and disturbance vectors.

$$x = \begin{bmatrix} V \\ T \end{bmatrix}, u = \begin{bmatrix} Q \\ q_{in} \end{bmatrix}, d = \begin{bmatrix} q_{hw} \\ T_{hw,s} \\ T_{in} \\ p \end{bmatrix}$$

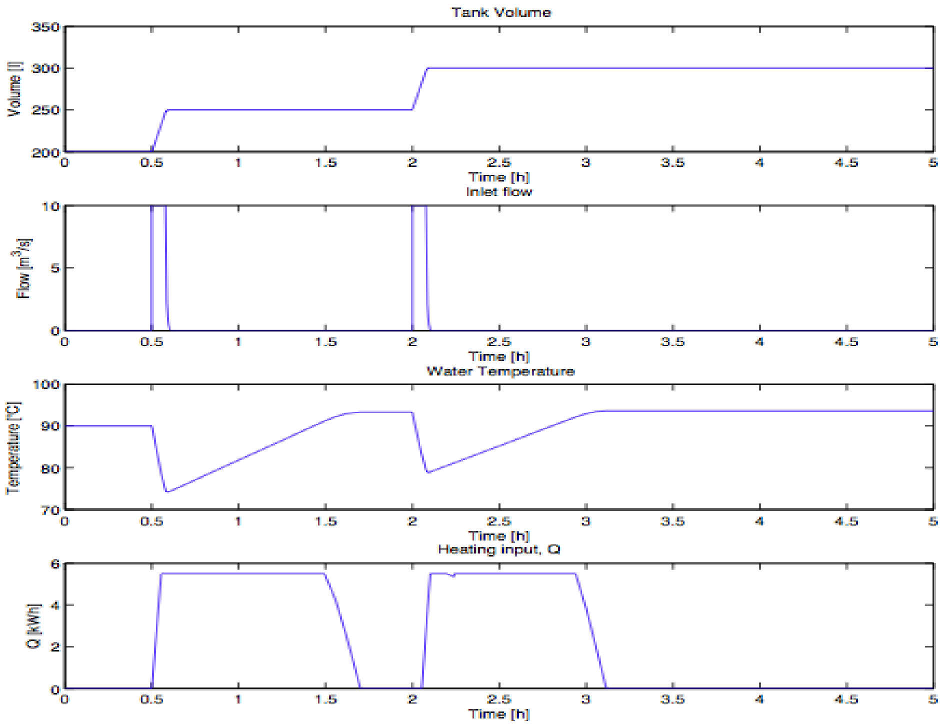
# Model validation



# PID controller

$$p(t) = p + K_c(e(t) + \frac{1}{\tau_I}\int_0^t e(t*)\,\mathrm{d}t + \tau_D \frac{de(t)}{dt})$$

$$G(s) = K_p(1 + \frac{1}{\tau_I s} + \tau_D s)$$

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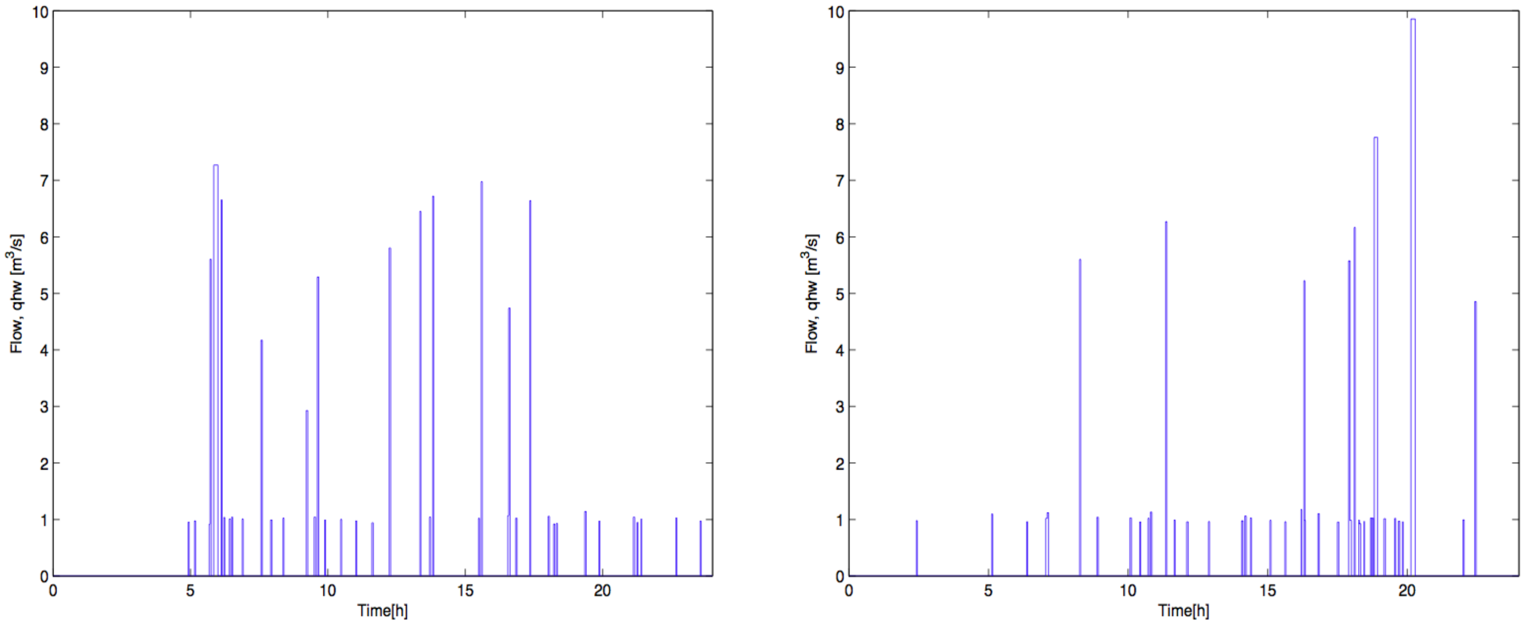
# Demand profile

- Randomly generated demand profiles from MATLAB script, qhw.

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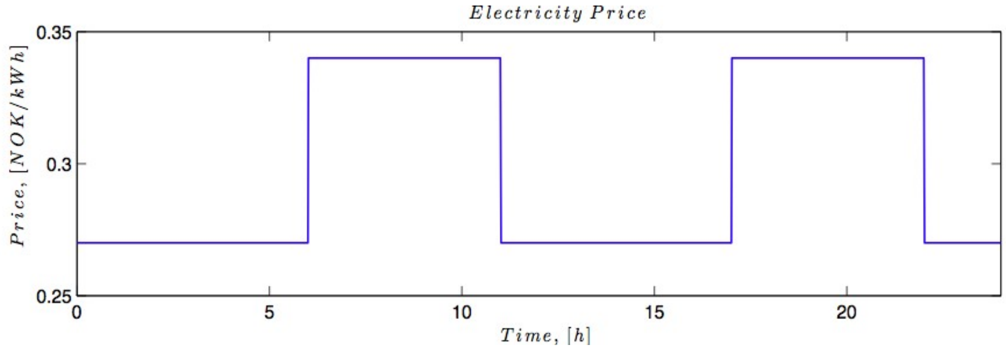
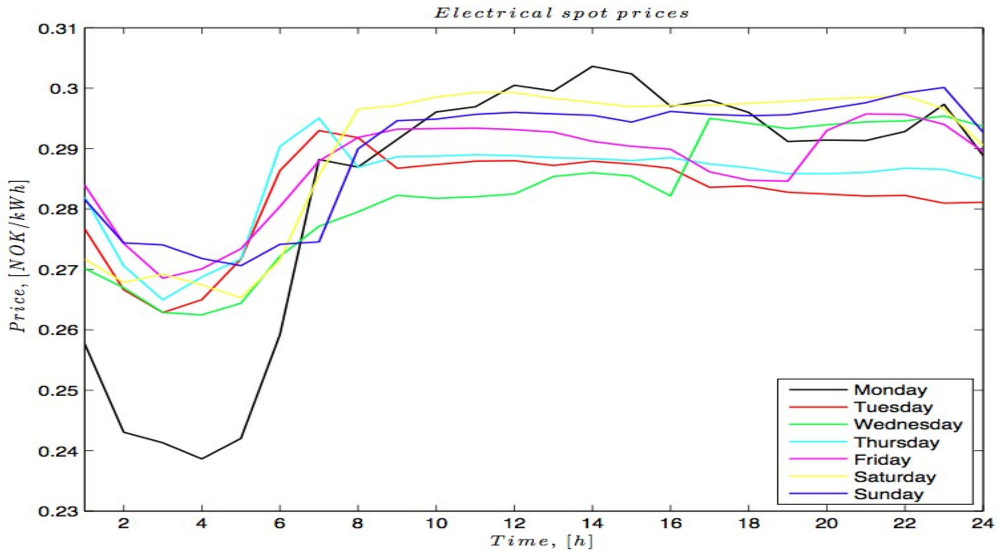
# Electricity Price




- On-off peak price
- Time varying price

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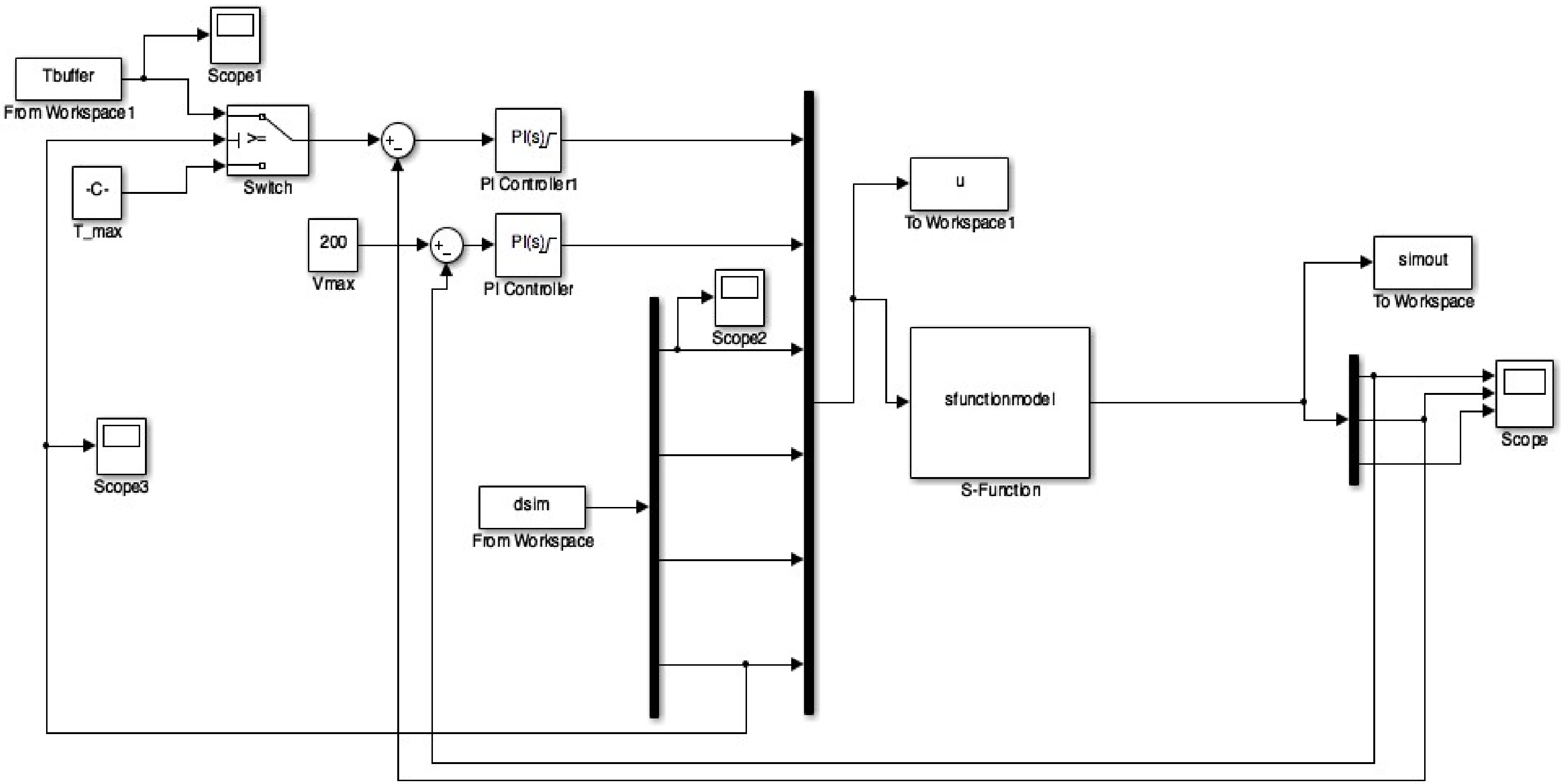
# Implementing a switch

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# Price threshold, $p_B$

- Defining set-points for the temperature at the switch

$$T_{set} = \begin{cases} \text{if } p > p_B \text{ then } T_{set} = T_{max} \\ \text{if } p \leq p_B \text{ then } T_{set} = T_{buffer} \end{cases}$$

$$T_{set} = \begin{cases} \text{if } p > p_B \text{ then } V_{set} = V_{max} \\ \text{if } p \leq p_B \text{ then } V_{set} = V_{max} \end{cases}$$

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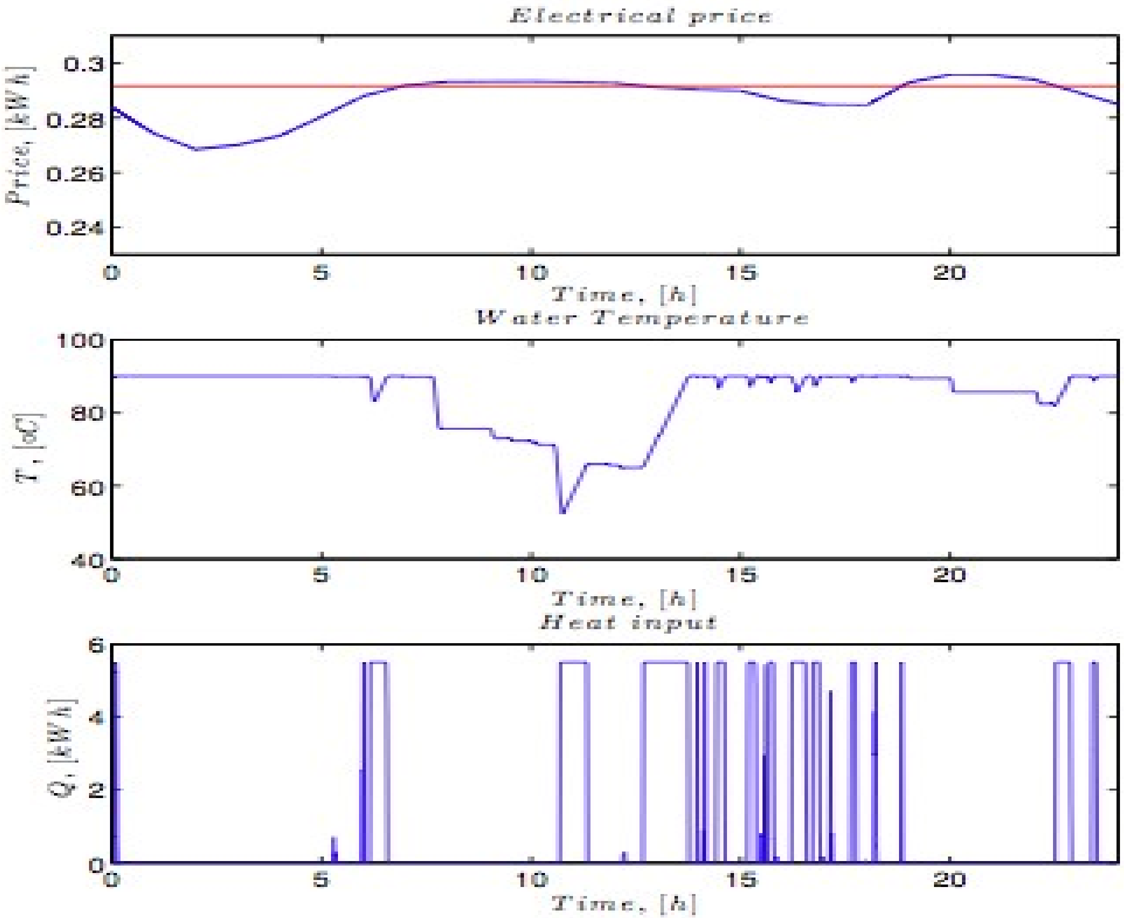
# Results




(b) Friday

- Switching between set-points as the price is higher or lower than the price threshold $P_B$.

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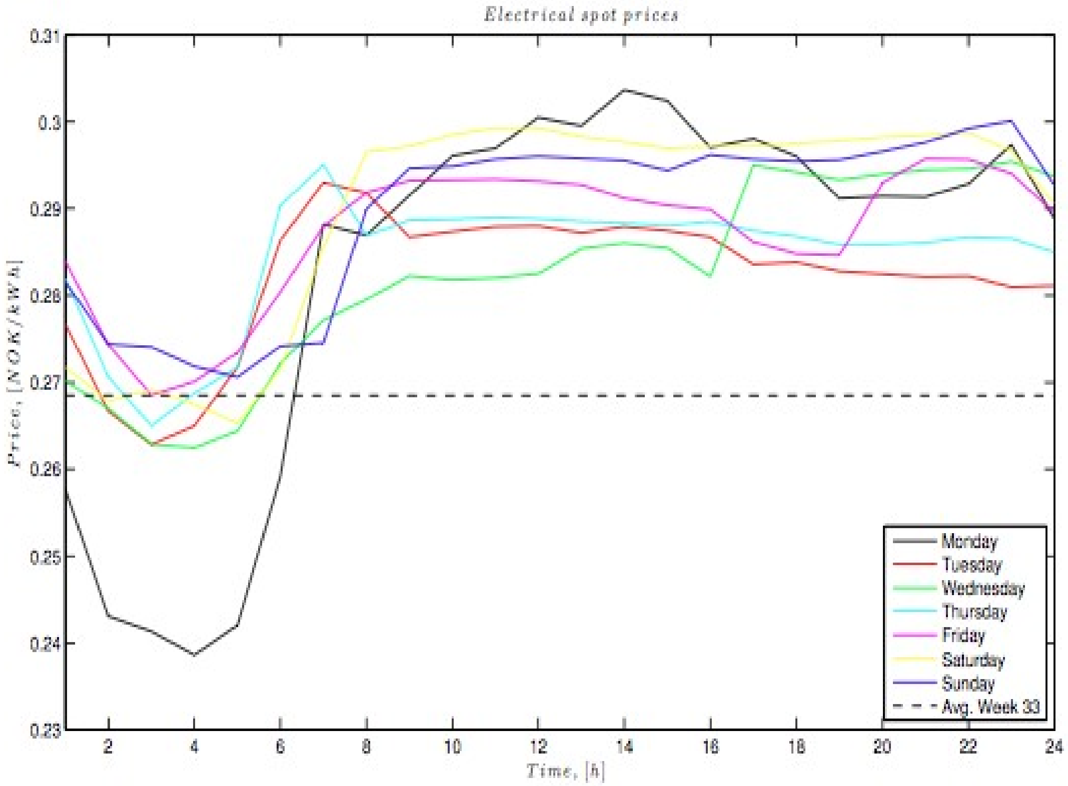
# Weekly average




- $P_B$ average from previous week

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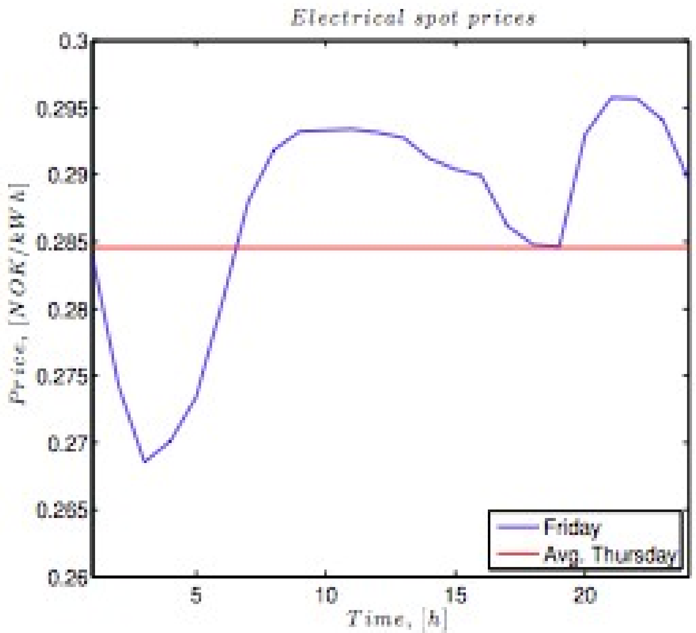
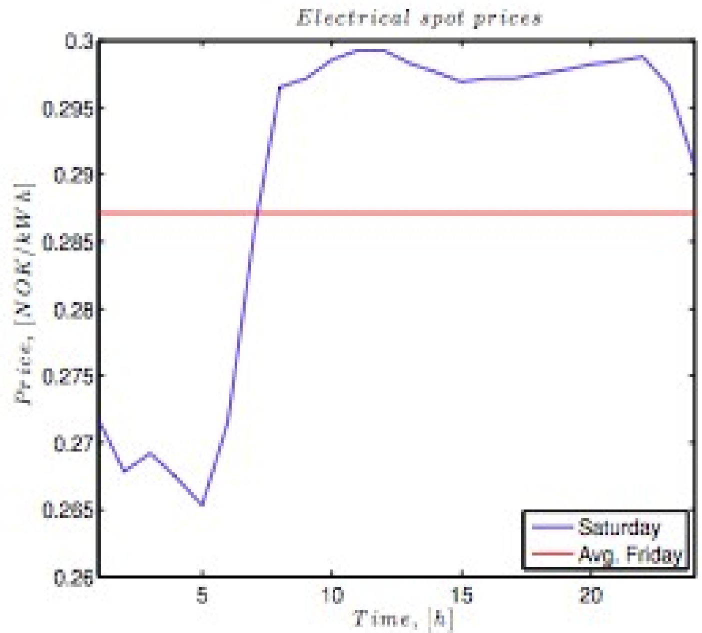
# Average from previous day




(c) Friday




(d) Saturday

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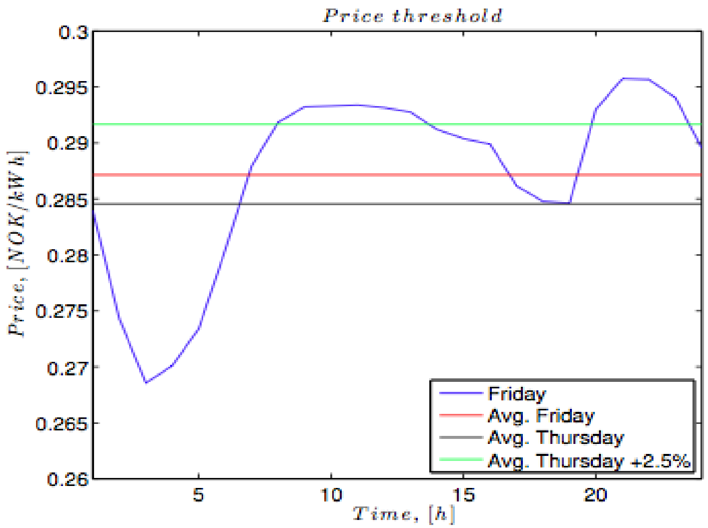
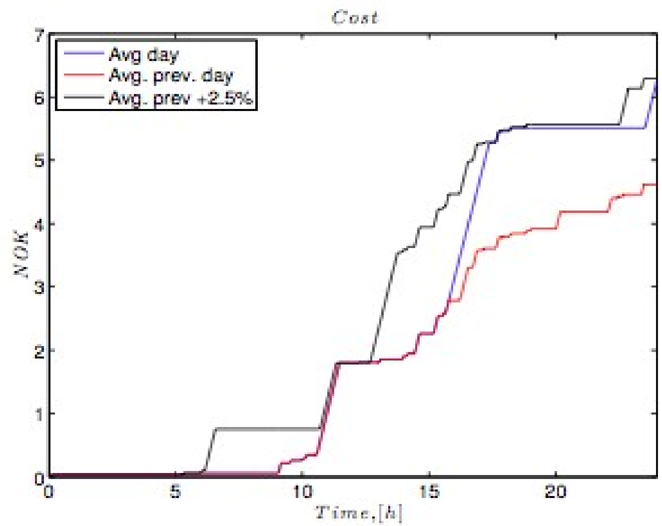
# Average current day

- Comparing the total cost with different boundaries, also assuming the electricity price for the current day is known, and the average of this day can be used.




(a) Cost

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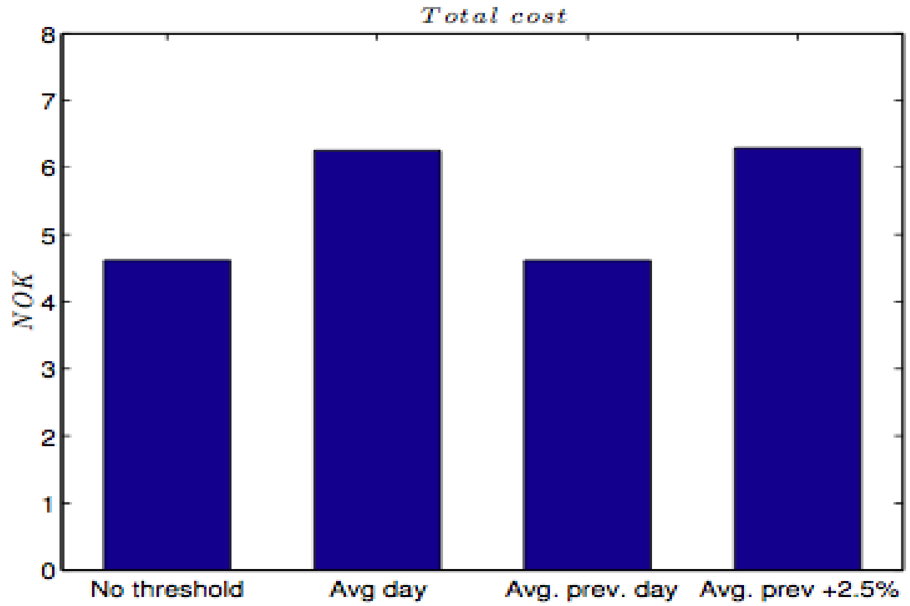
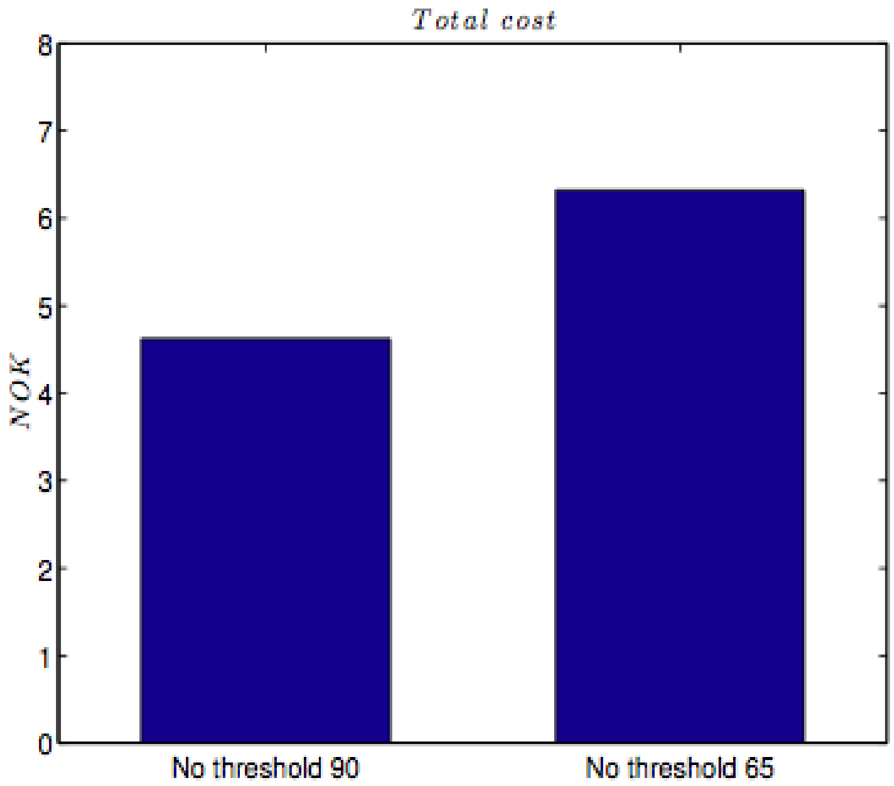
# No boundary?

- The lowest price threshold resulted in the lowest cos, what are the result with no boundary?



# No boundary?




- $T_{start}$ = 90 °C, low total cost.
- $T_{start}$ = 65 °C, higher total cost.

# Cost function

- Original cost function: $J(t) = \int_0^t p(t)Q(t)\mathrm{d}t$
- Implementing a penalty into the cost function:

$$J = \int_{t_0}^{\infty} p(t)Q\mathrm{d}t + \int_{t_0}^{\infty} p*(T)Q_{demand}\mathrm{d}t$$

$$p*(T) = \begin{cases} 0 & \text{if} T \geq T_{hw,s} \\ p_1 * (T_{hw,s} - T)^2 + p_2 * (T_{hw,s} - T) & \text{if} T < T_{hw,s} \end{cases}$$

# Further work

- Optimization problem: min $J(P_B, T_{buffer})$
  - Decision variables: $P_B$ and $T_{buffer}$

Finding the optimal $P_B$ and $T_{buffer}$ which provides the lowest total cost.

Simulate for longer periodes and generalizing the simulation

Find near optimal policies