Aggregators, Modelling, Forecasting and Control for Flexible Buildings and Districts

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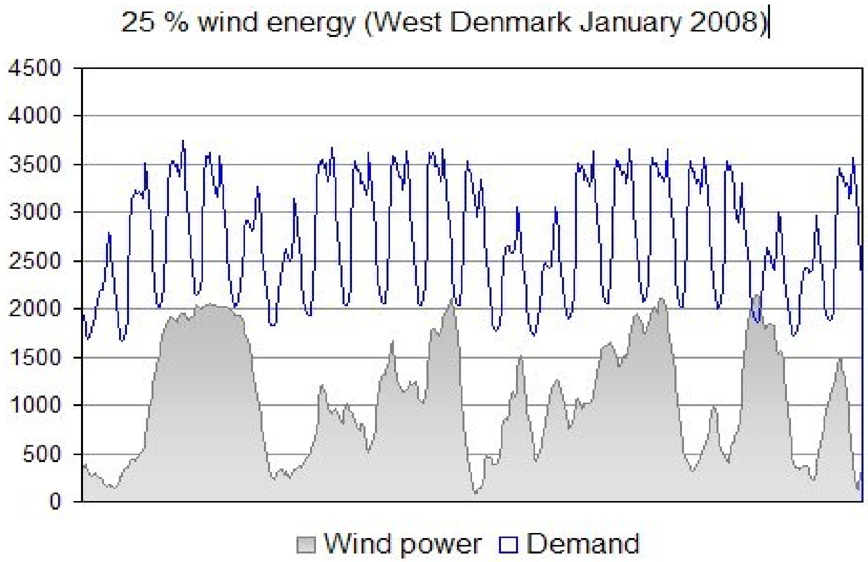
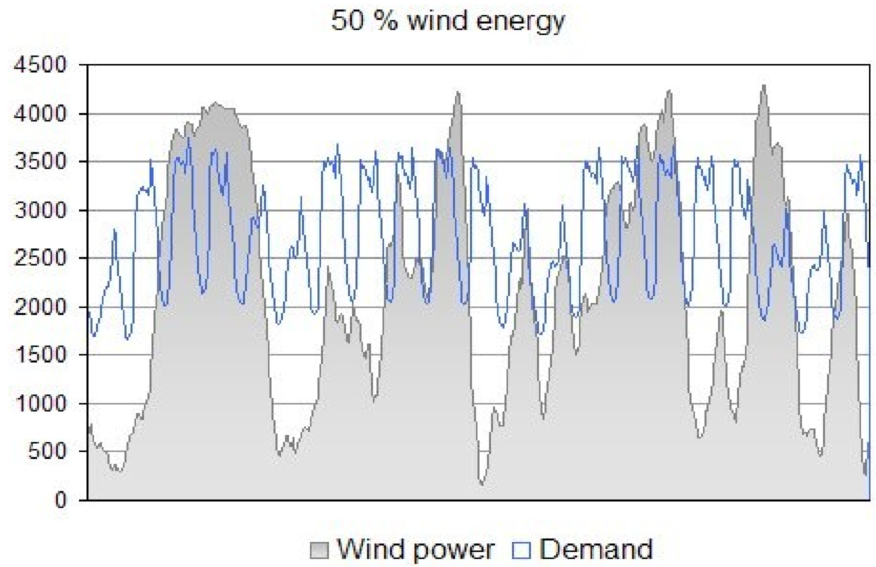
IEA EBC Annex 67 meeting, Lisbon, October 2015

The Danish Wind Power Case

.... balancing of the power system





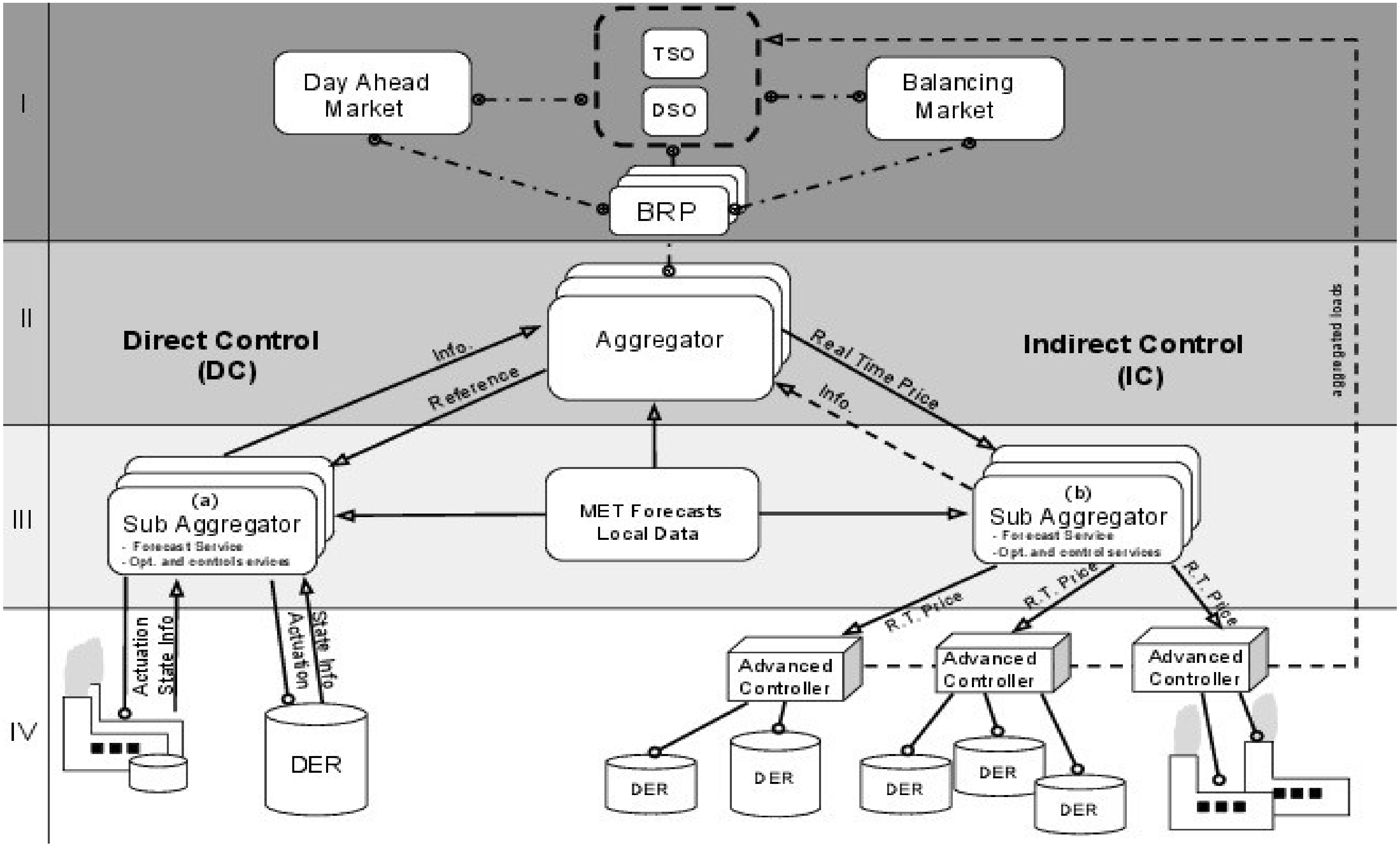
In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

In 2014 more than 40 pct of electricity load was covered by wind power.

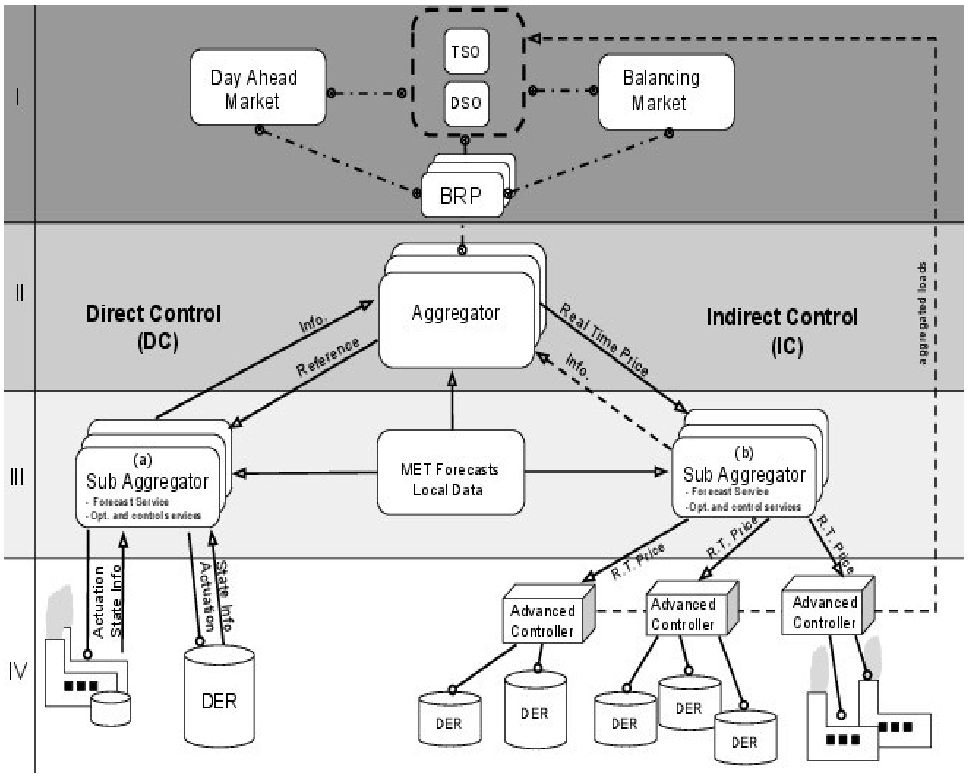
For several days in 2014 the wind power production was more than 120 pct of the power load.

July 10th, 2015 more than 140 pct of the power load was covered by wind power

Control and Optimization



Control and Optimization



In New Wiley Book: Control of Electric Loads in Future Electric Energy Systems, 2015

Day Ahead:

Stoch. Programming based on eg. Scenarios

Cost: Related to the market (one or two levels)

Direct Control:

Actuator: **Power**

Two-way communication

Models for DERs are needed

Constraints for the DERs (calls for state est.)

Contracts are complicated

Indirect Control:

Actuator: **Price**

Cost: E-MPC at **low (DER) level**, One-way communication

Models for DERs are not needed

Simple 'contracts'

Direct vs Indirect Control

Level	Direct Control (DC)	Indirect Control (IC)
III	$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$	$\min_{\hat{z},p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$ s.t. $\hat{z}_{k+1} = f(p_k)$
IV	$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$ s.t. $x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$	$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$ s.t. $x_{k+1} = f_j(x_k, u_k)$

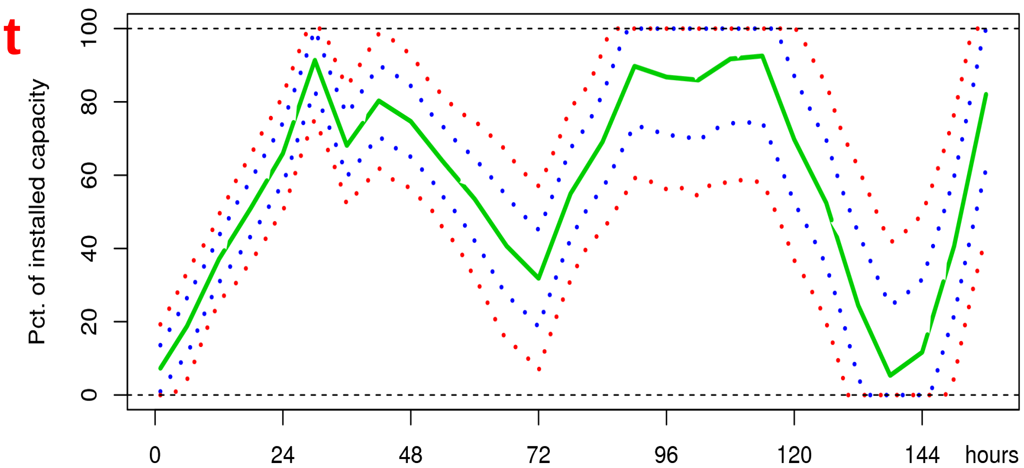
Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals u_j are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes the optimal prices p which are sent to the J-units at level IV. Hence the J DERs optimize their own energy consumption taking into account p as the actual price of energy.

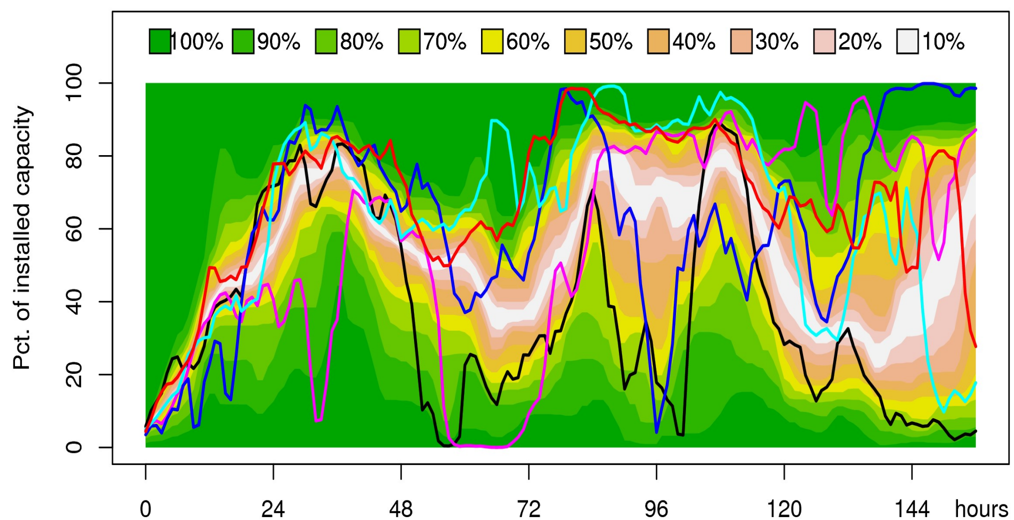
Forecasting ….

Forecasting is very important

Type of forecasts:

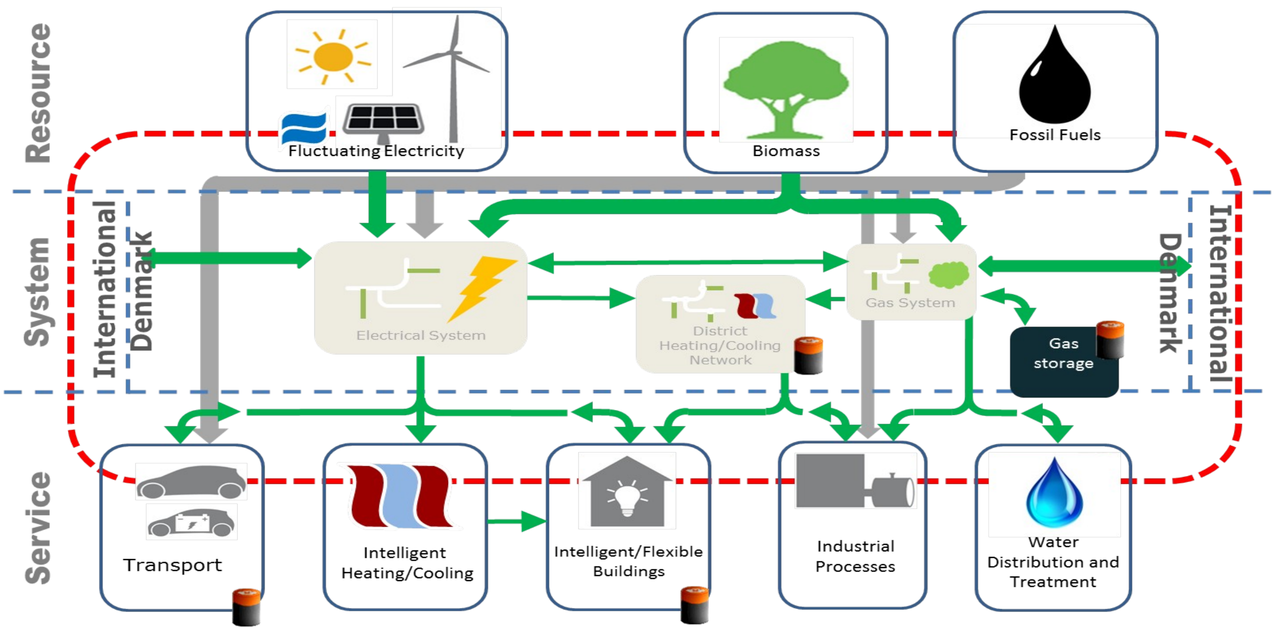
- Point forecasts
- Conditional mean and covariances
- Conditional quantiles
- Conditional scenarios
- Conditional densities
- Stochastic differential equations





Flexibility Concepts

Energy Systems Integration using **ICT and Grey-Box models for operating future flexible energy systems.**



Case study

Control of Power Consumption (DSM) using the Thermal Mass of Buildings

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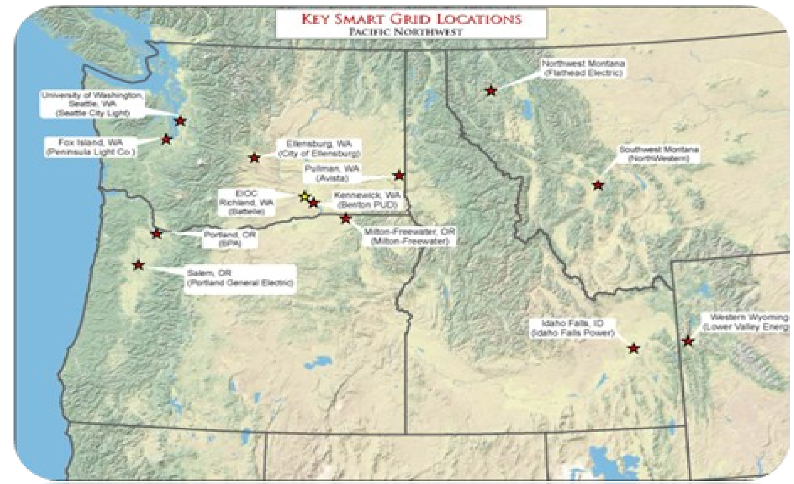
Data from BPA

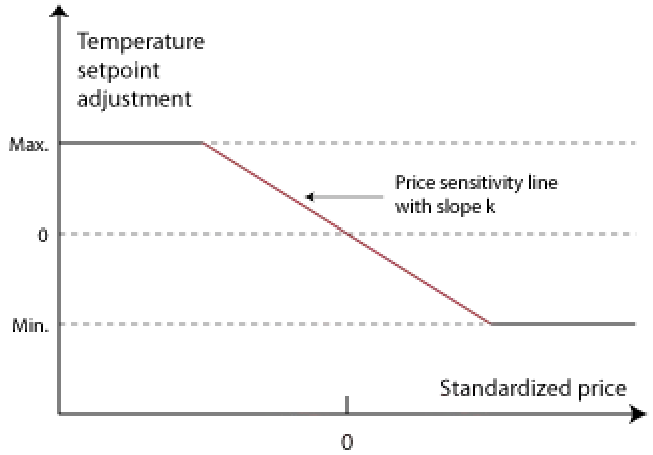
Olympic Pensinsula project

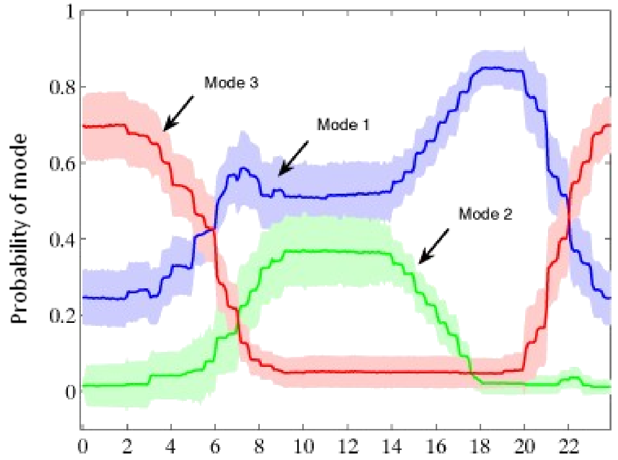
- 27 houses during one year
- Flexible appliances: HVAC, cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption

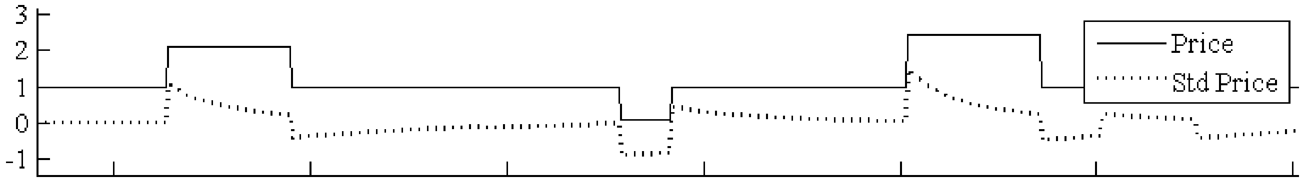


Price responsivity

Flexibility is activated by adjusting the temperature reference (setpoint)

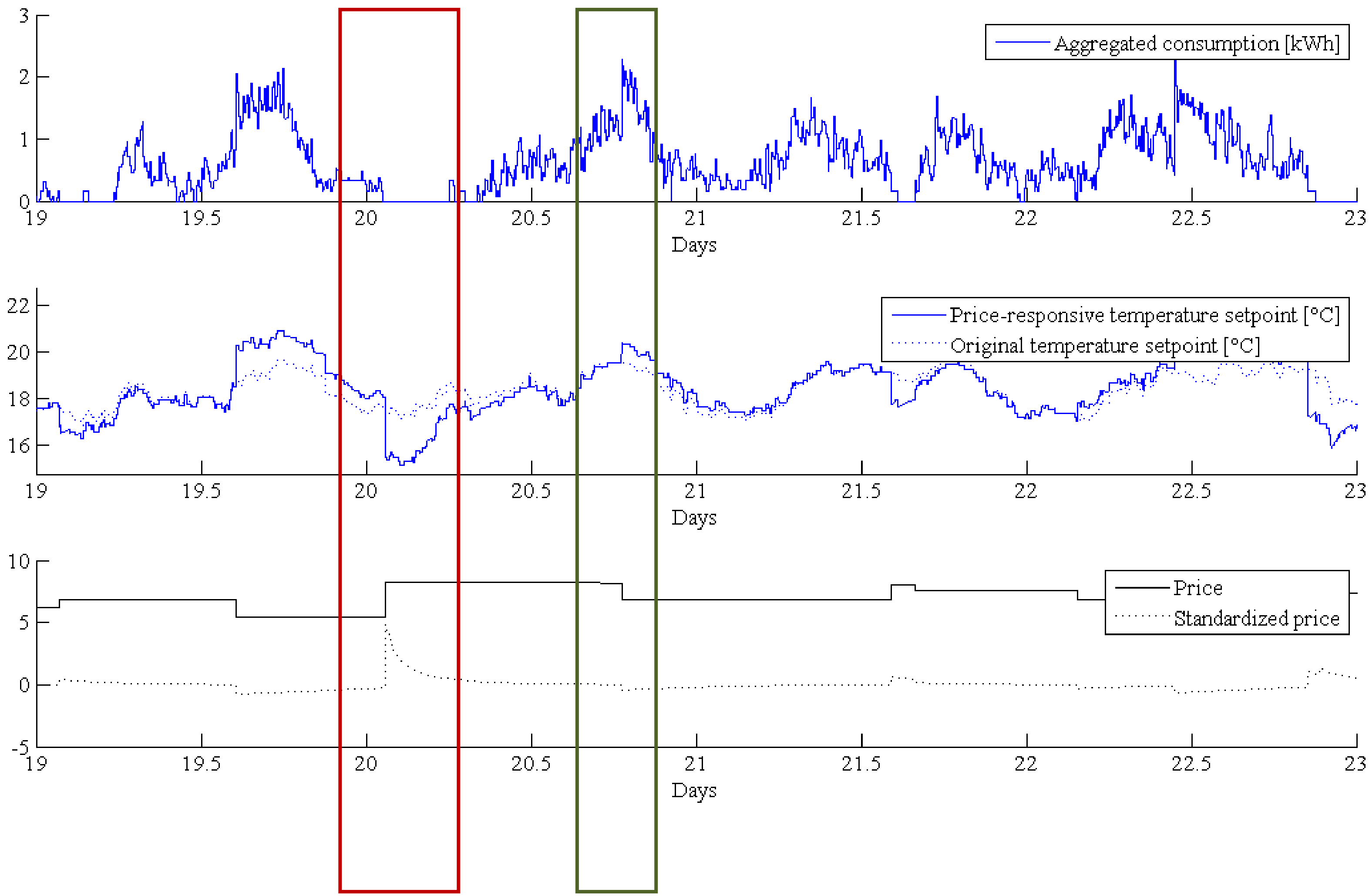






- **Standardized price** is the % of change from a price reference, computed as a mean of past prices with exponentially decaying weights.
- **Occupancy mode** contains a price sensitivity with its related comfort boundaries. 3 different modes of the household are identified (work, home, night)

Aggregation (over 20 houses)



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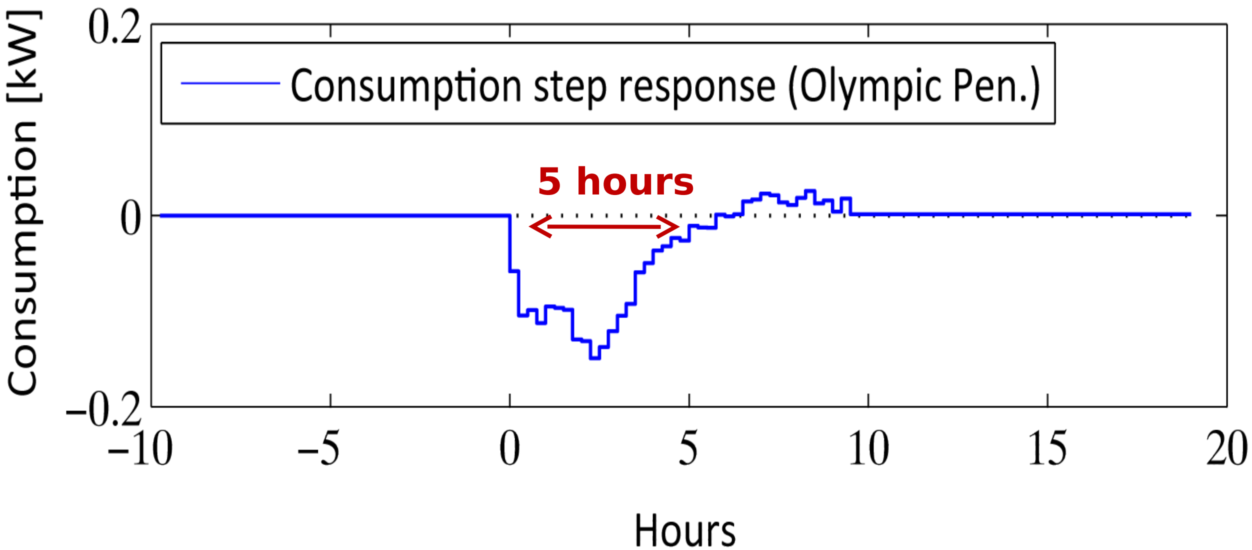
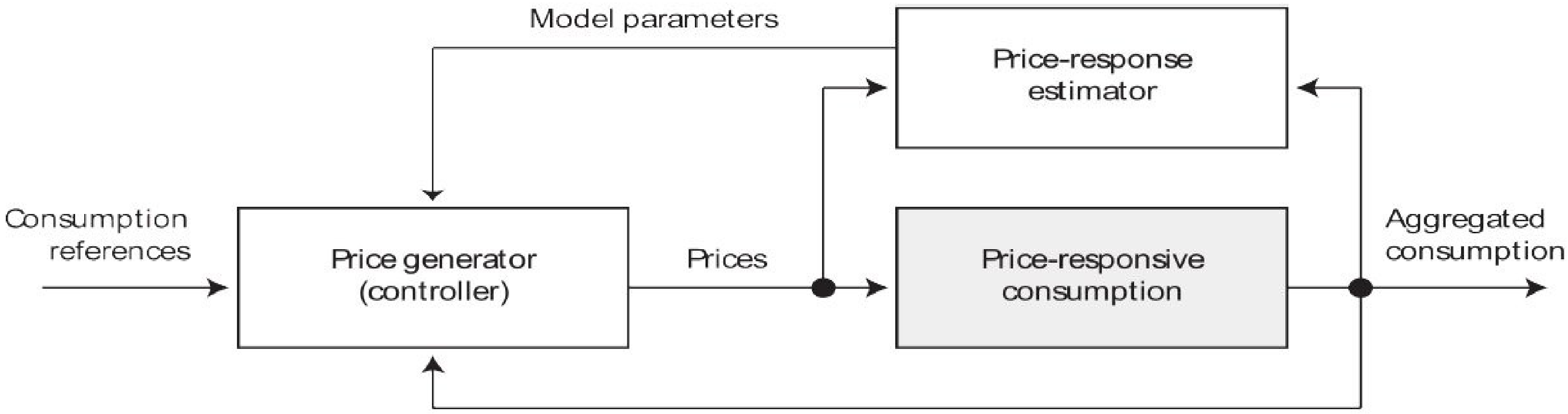
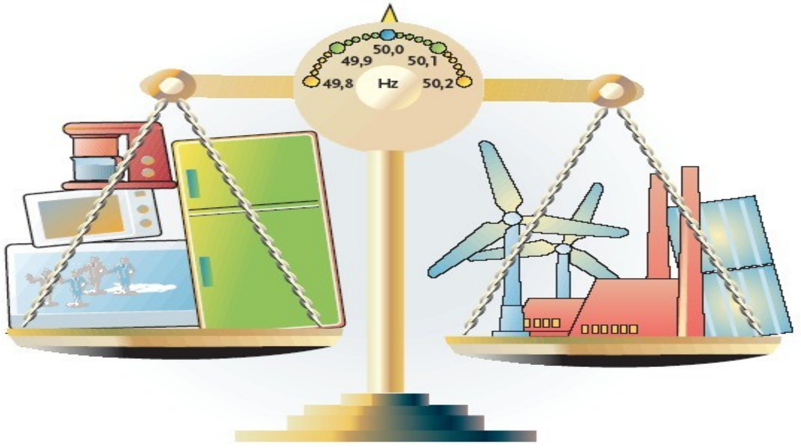
Response on Price Step Change



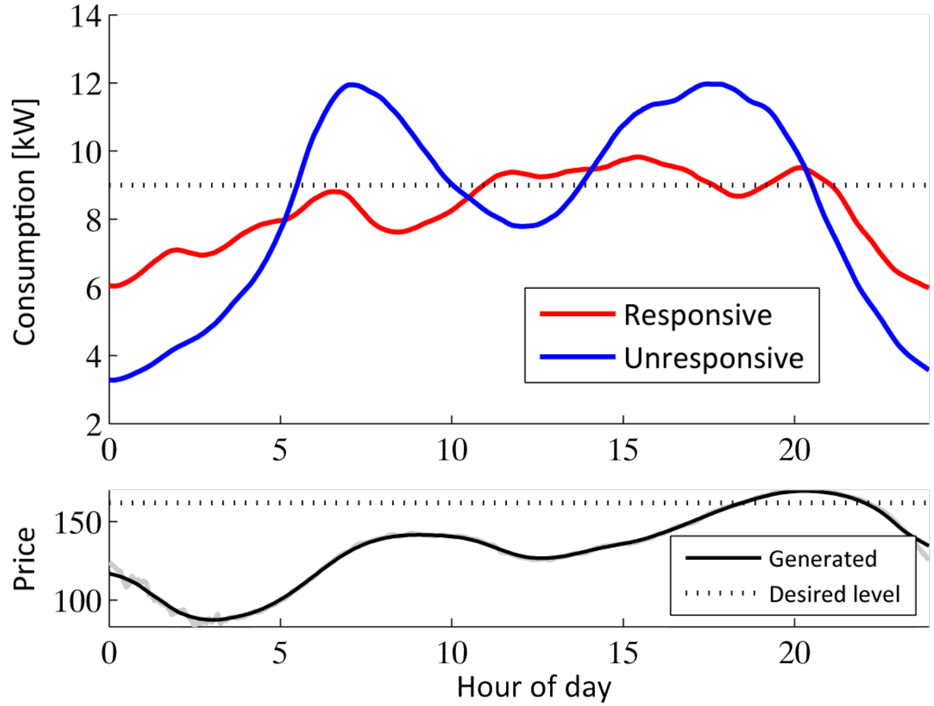
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**



Case study

Super Market Cooling

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The physical system

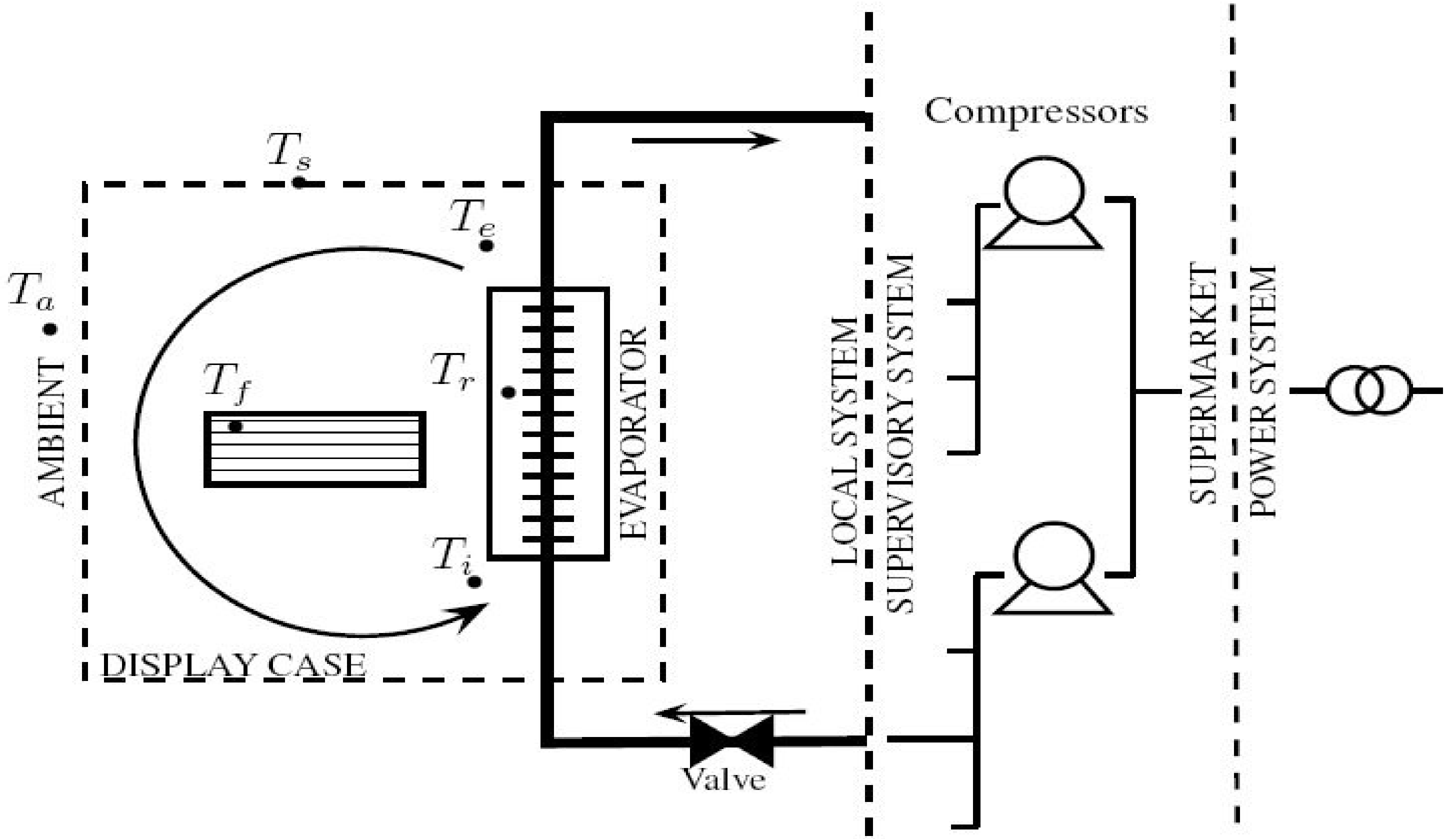


Fig. 2: Simplified graphical representation of the display case system

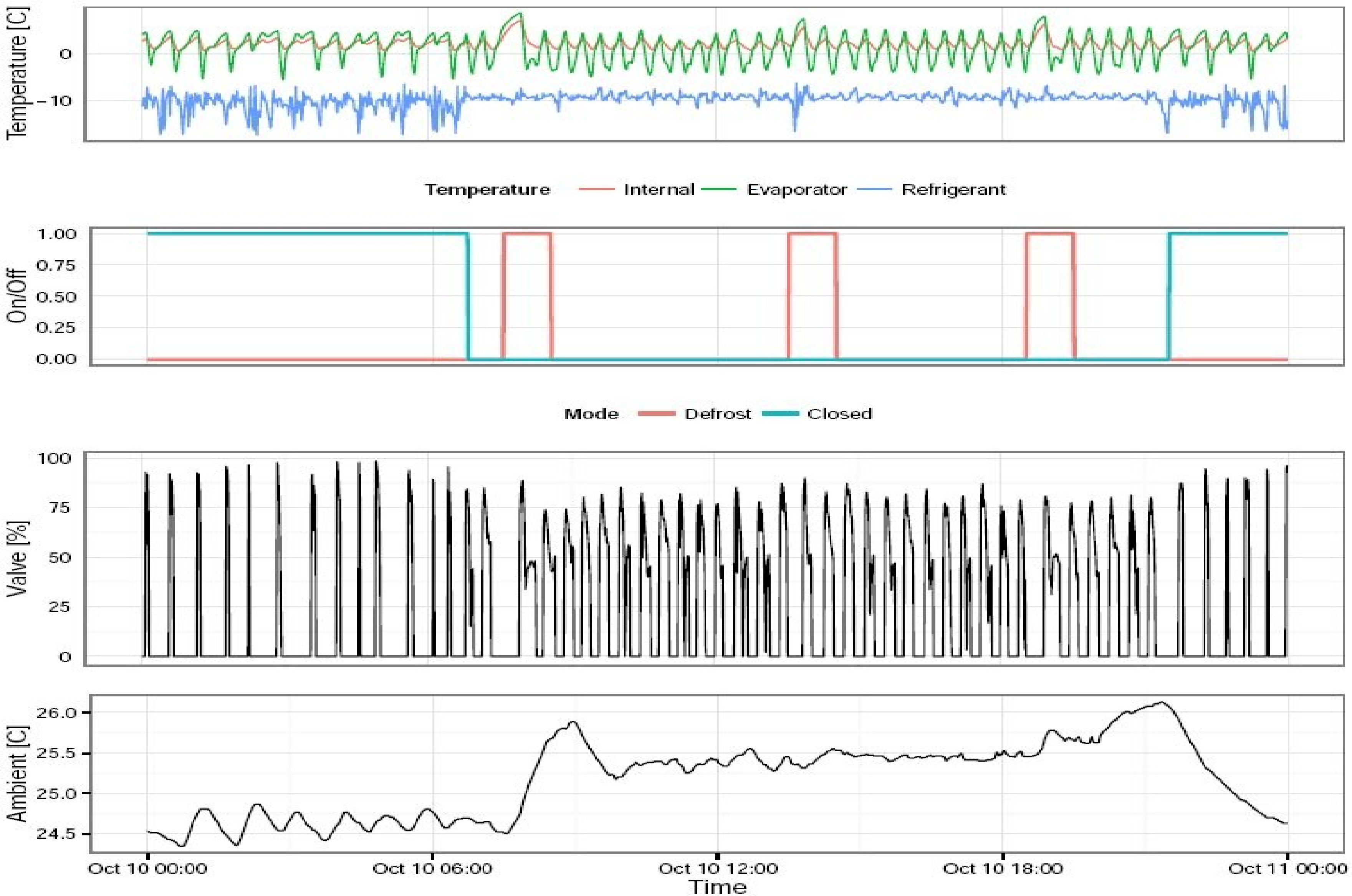


Fig. 3: Temperature, environmental (open/closed status, defrost status, ambient temperature) and control input (valve) data for an open medium temperature display case in a supermarket in Funen, Denmark

The grey-box model

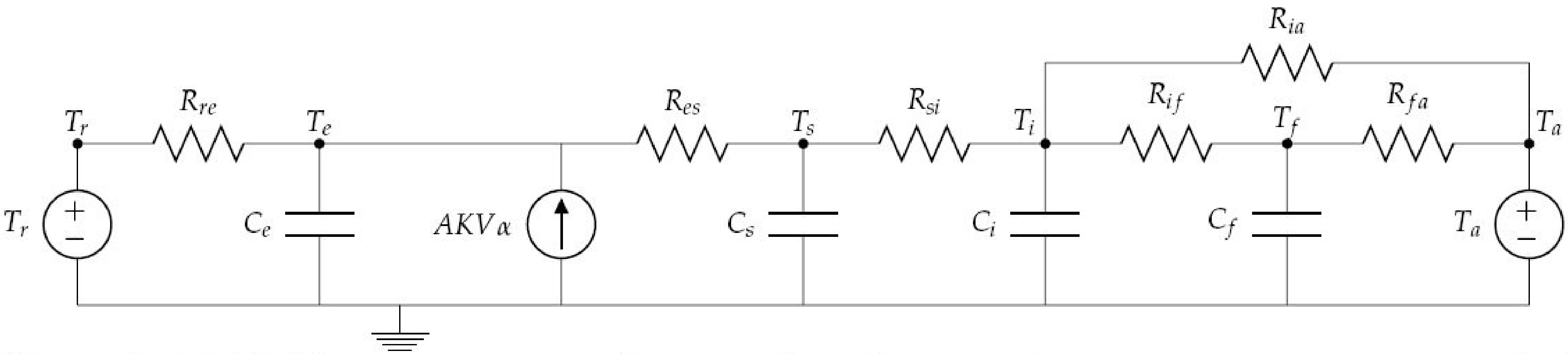


Fig. 6: RC-Representation of a four time constant model ($T_i T_e T_f T_s$)

Direct and Indirect Controllers

- Direct Control
  - **Temperature Reference Tracking**

$$\min \sum_{n=1}^{N} \left(T_n - T_n^{ref}\right)^2 + \gamma_1 \Delta P_{1,t-1}$$

s.t:

- System Temperature/Power Dynamics from ARMAX model
- $T_{max}, T_{min}, P_{max}$

  - **Power Reference Tracking**

$$\min \sum_{n=1}^{N} \left(P_n - P_n^{ref}\right)^2$$

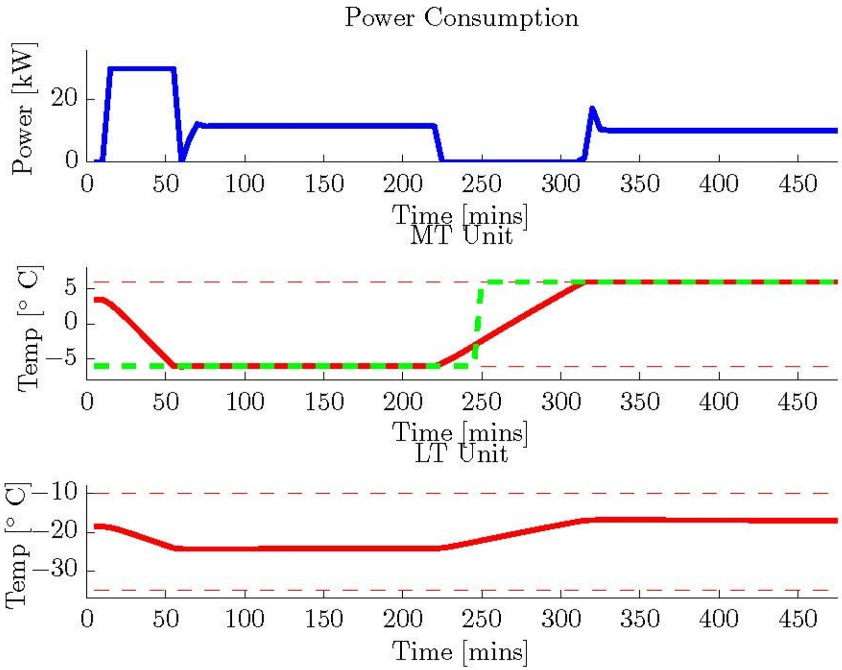
- Indirect Control
  - **Economic MPC**

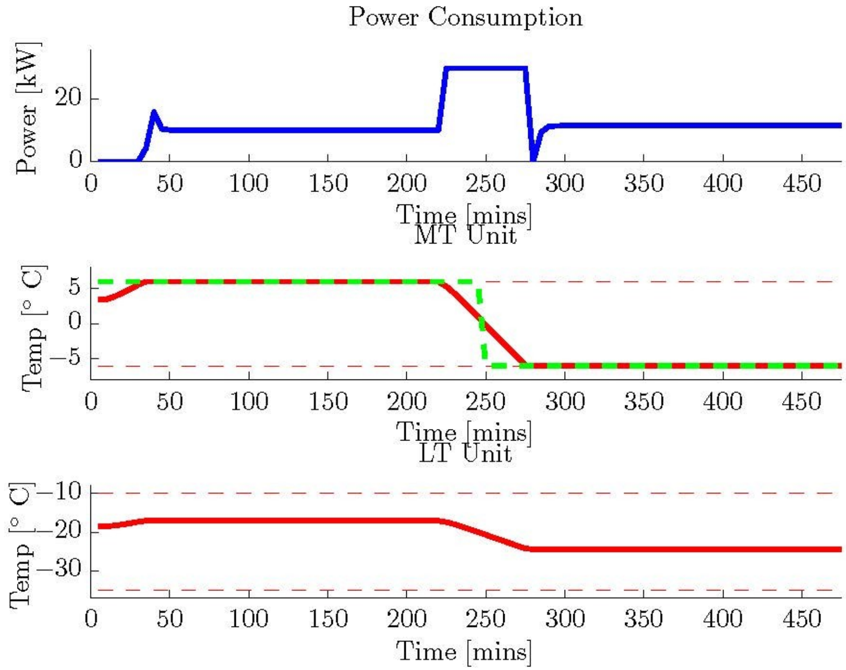
$$\min \sum_{n=1}^{N} \lambda_n P_n + \gamma_1 T_N^{MT} + \gamma_2 T_N^{LT}$$

- Note all controller formulations are “MPC” – i.e. forecasts of price/references only available up to a fixed horizon – control consists of a sequence of receding horizon optimisations

Simulations – Temperature Tracking

Asymmetry





Case study

Control of Heat Pumps

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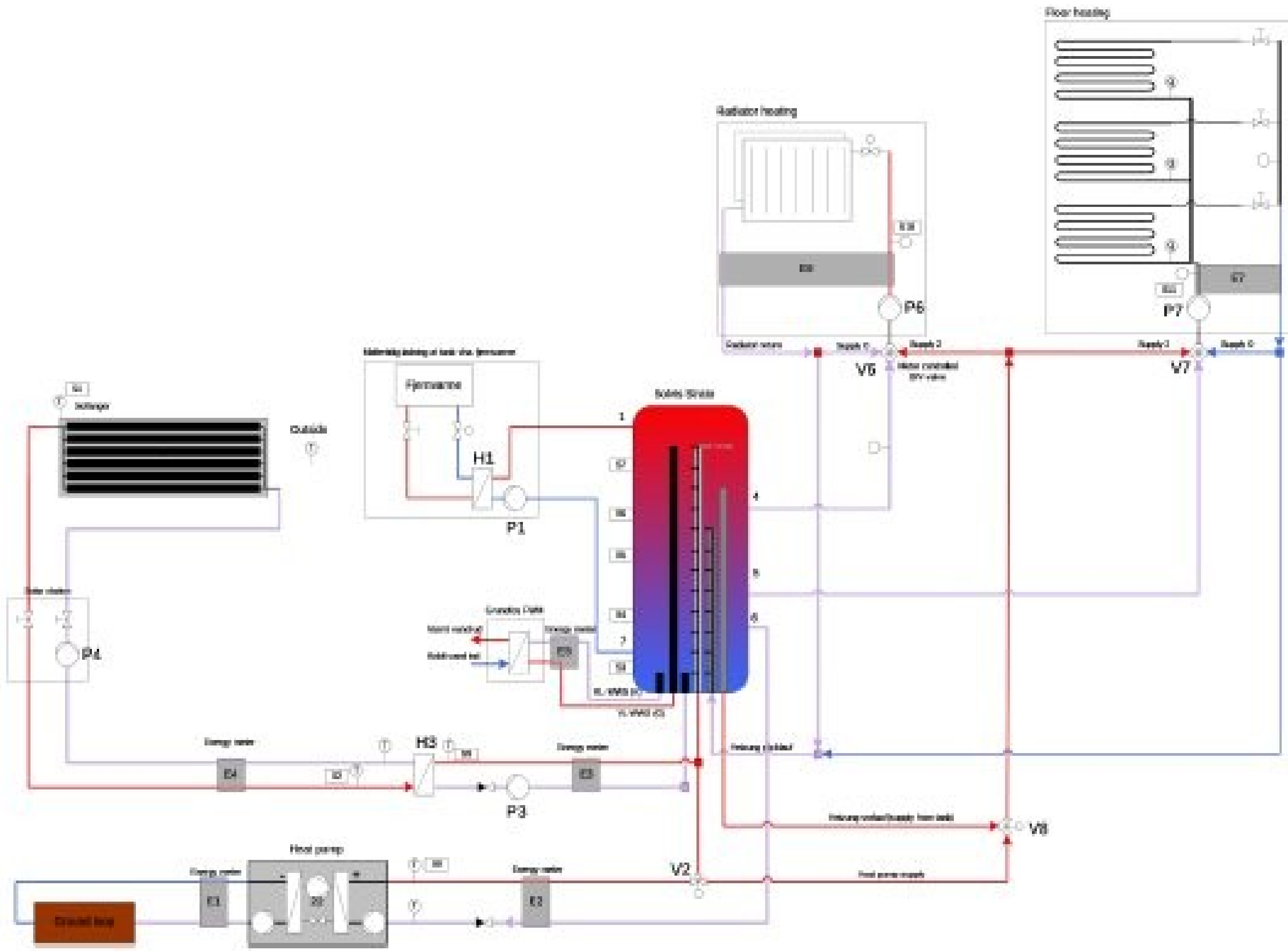
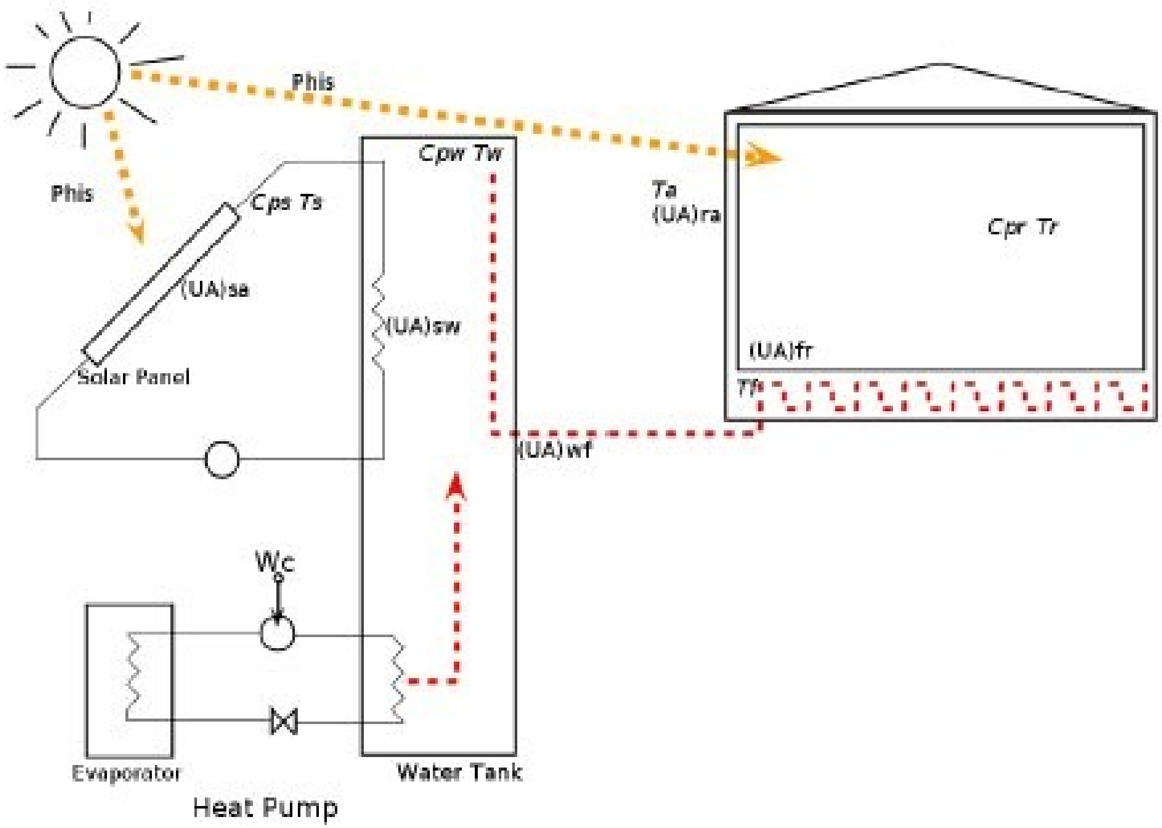
Grundfos Case Study

Schematic of the heating system



Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

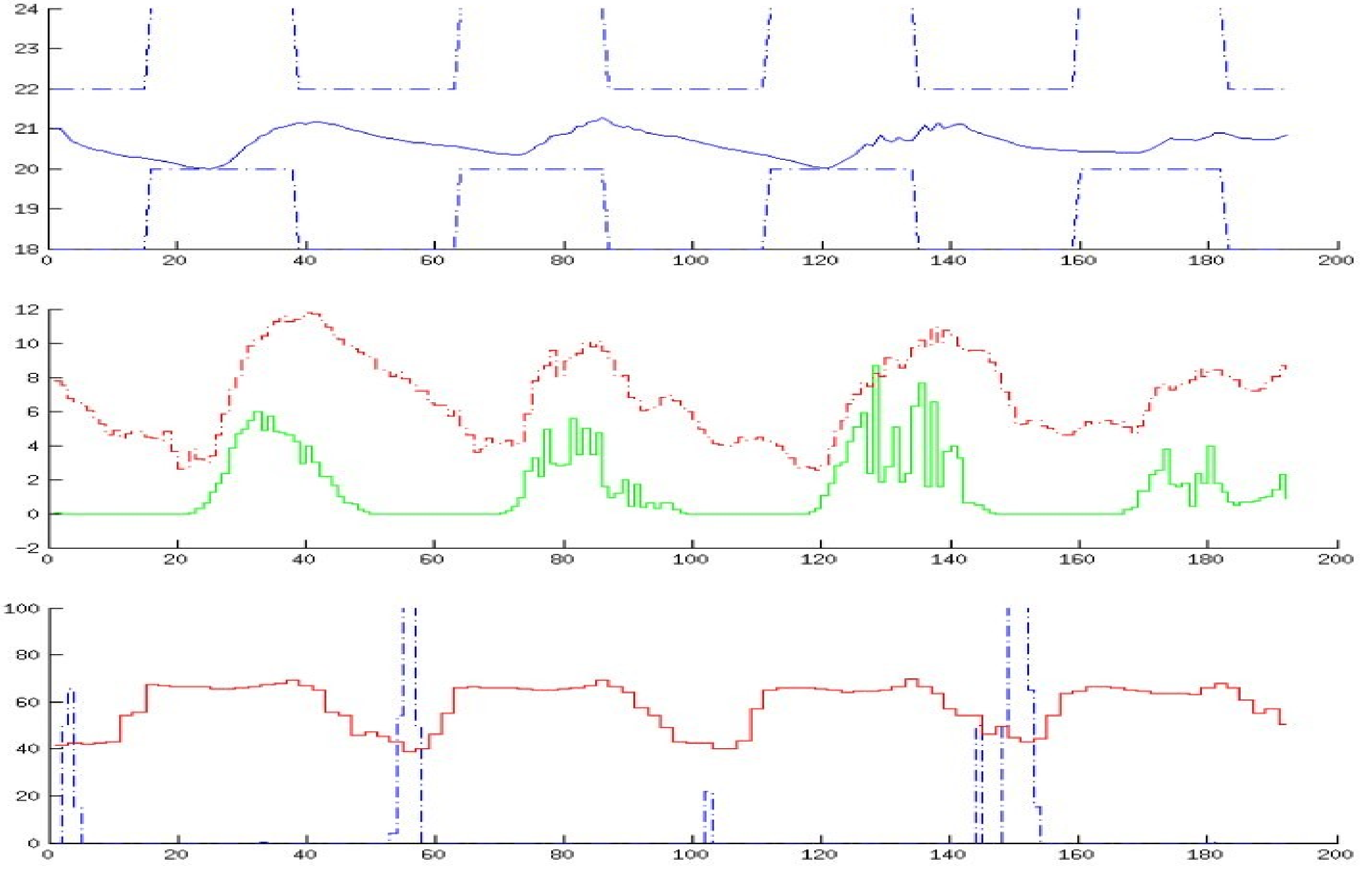
Formulation

The Economic MPC problem, with the constraints and the model, can be summarized into the following formal formulation:

$$\min_{\{u_k\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c' u_k \tag{4a}$$

$$\begin{aligned}
\text{Subject to} \quad & x_{k+1} = Ax_k + Bu_k + Ed_k & k = 0, 1, \ldots, N-1 \quad & (4b) \\
& y_k = Cx_k & k = 1, 2, \ldots, N \quad & (4c) \\
& u_{min} \leq u_k \leq u_{max} & k = 0, 1, \ldots, N-1 \quad & (4d) \\
& \Delta u_{min} \leq \Delta u_k \leq \Delta u_{max} & k = 0, 1, \ldots, N-1 \quad & (4e) \\
& y_{min} \leq y_k \leq y_{max} & k = 0, 1, \ldots, N \quad & (4f)
\end{aligned}$$

EMPC for heat pump with solar collector (savings 35 pct)



Activities in Annex 67

- System setup
- Modelling – incl. Library of dynamic models
- Forecasting
- Control
- Software Tools – eg Grey-Box Modelling and MPC
- A.2.6
- B.1.1, B.1.3, B.3.8
- C.2.5

Conclusions

- A hierarchi of optimization/control problems with integrated grey-box modelling for both direct and indirect control have been described.
- Examples considered:
    - Control of heat accumulated in the thermal mass
    - Control of supermarket cooling (both direct and indirect control)
    - Control of heat pump and thermal solar collector system for a family house
- All examples have illustrated the used of forecasts

For more information ...

See for instance

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...or contact

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Acknowledgement CITIES (DSF 1305-00027B)

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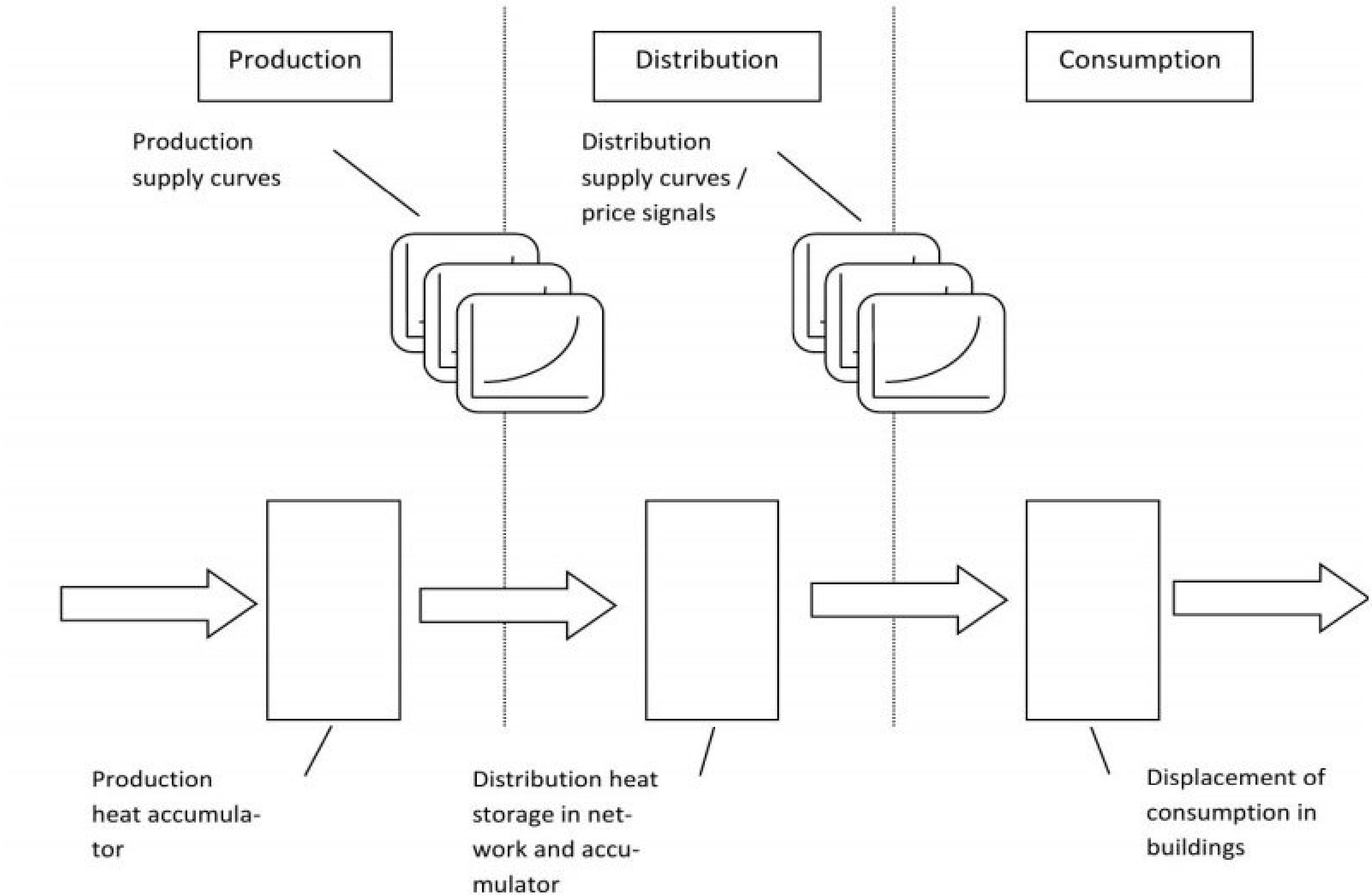
Flexibility in District Heating



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