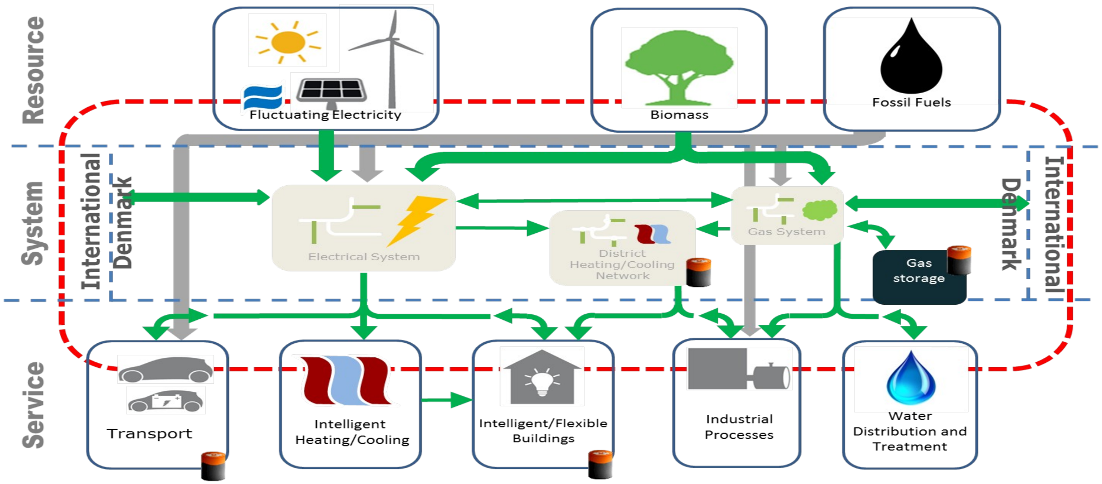
Grey-Box Models and Controllers for ESI



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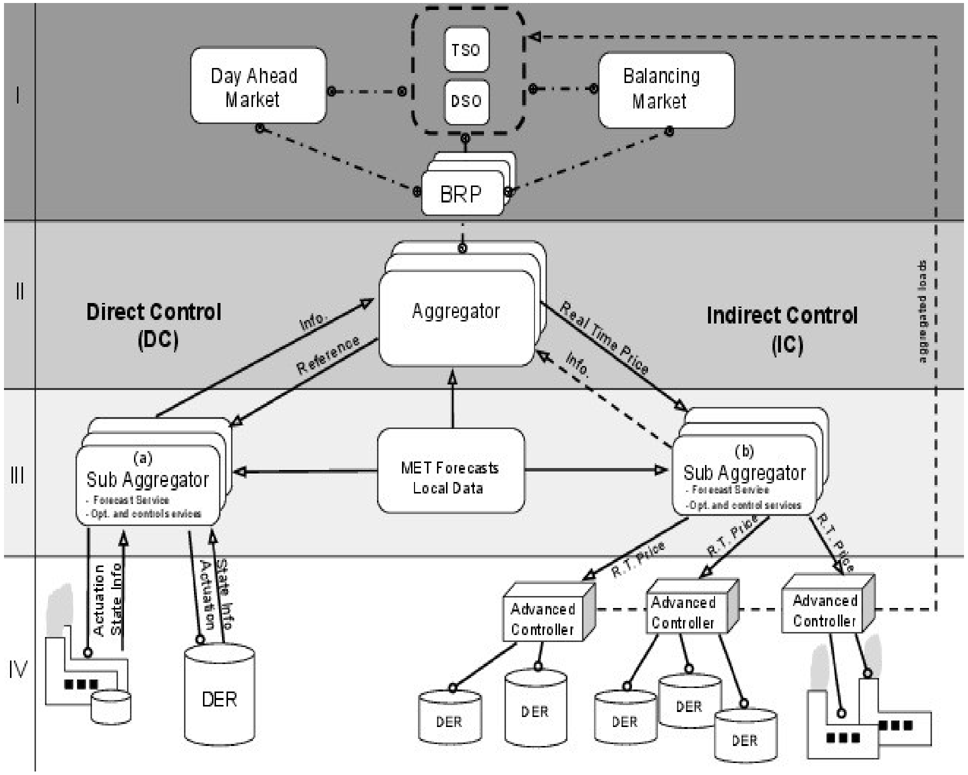
Principles for Demand Side Management



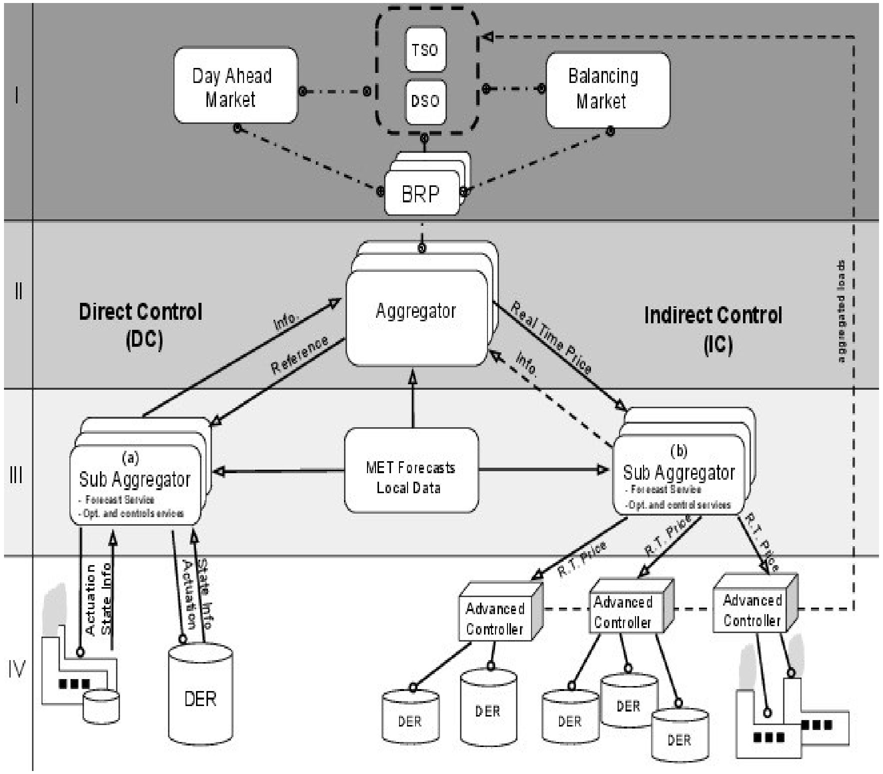
- **Day Ahead:**
  - Stoch. Programming based on eg. Scenarios
  - Cost: Related to the market (one or two levels)
  - Operational optimization – also for the grid
- **Direct Control:**
  - Actuator: **Power**
  - Cost: eg. MV, LQG, EMPC, ... (a single large problem)
  - Two-way communication
  - Models for DERs are needed
  - Constraints for the DERs (calls for state est.)
  - Contracts are complicated
- **Indirect Control:**
  - Actuator: **Price**
  - Cost: GPC, LQG at **high level**, VaR-alike
  - 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. $\quad \hat{z}_{k+1} = f(p_k)$
IV	$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$ s.t. $\quad x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$	$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$ s.t. $\quad x_{k+1} = f_j(x_k, u_k)$

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.

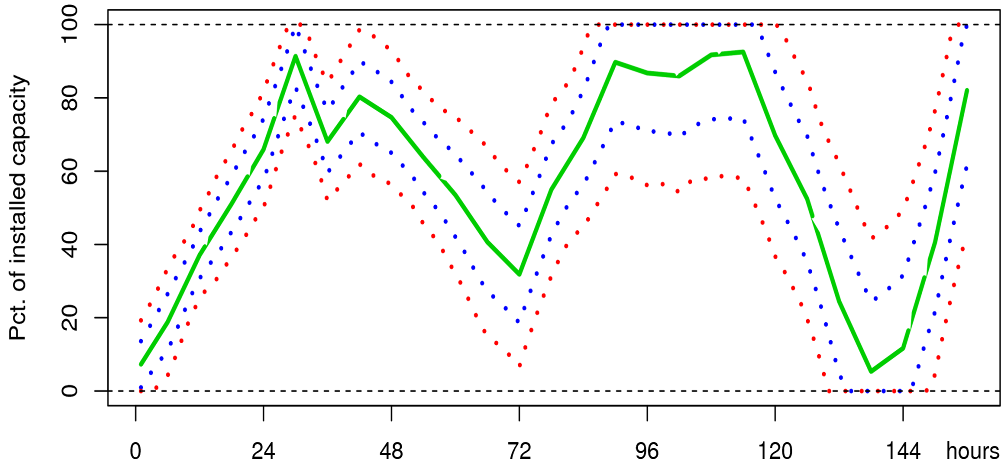
Forecast requirements

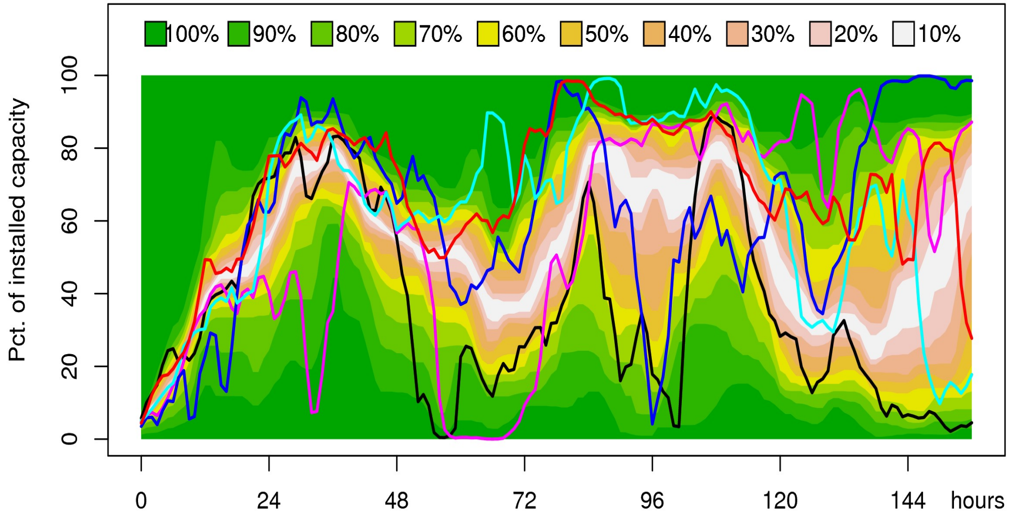


- **Day Ahead:**
  - Forecasts of loads
  - Forecast of Grid Capacity (using eg. DLR)
  - Forecasts of production (eg. Wind and Solar)
- **Direct Control:** .
  - Forecasts of states of DERs
  - Forecasts of load
- **Indirect Control:**
  - Forecasts of prices
  - Forecasts of load

Which type of forecast to use?

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



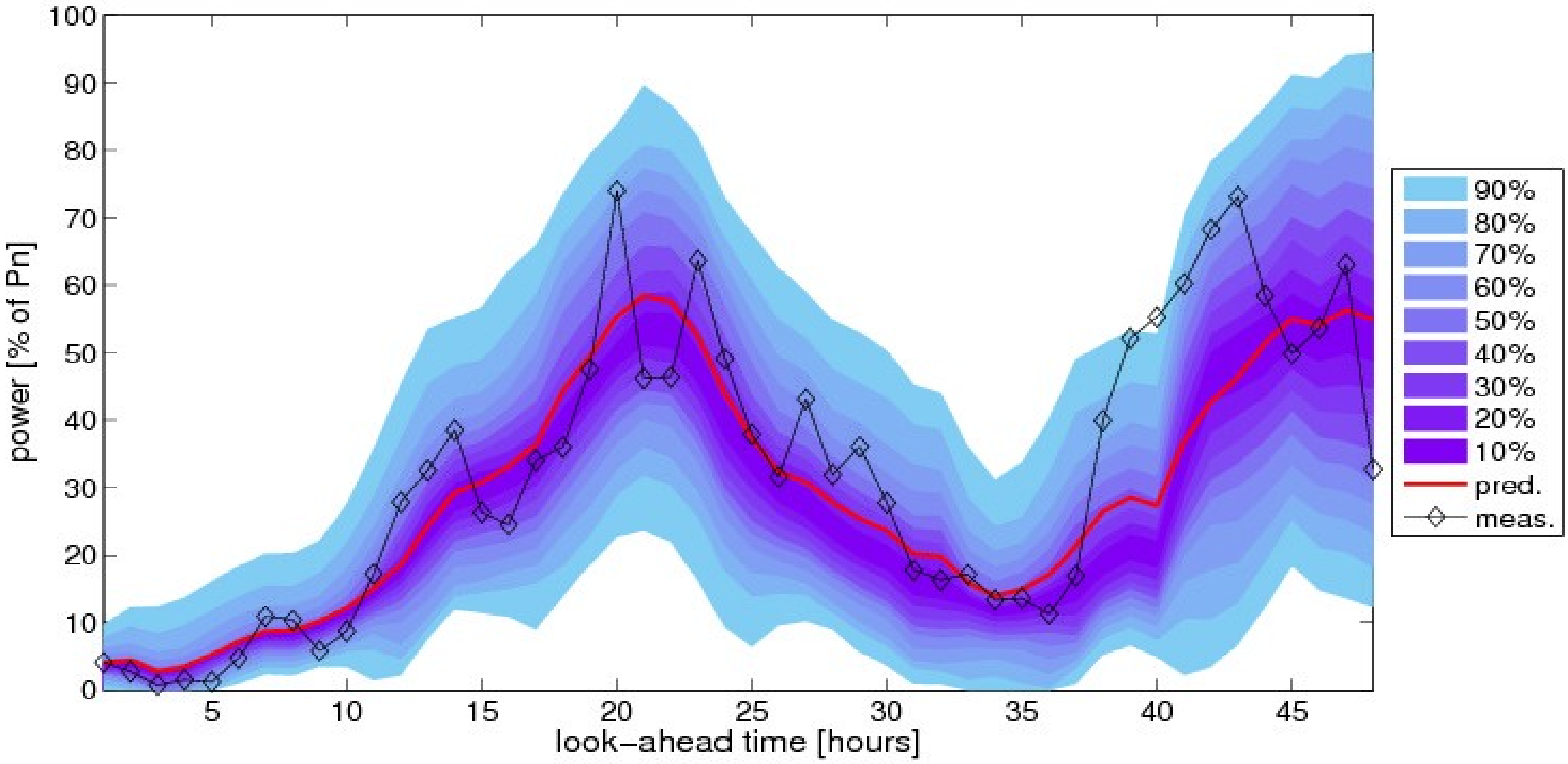


Important aspects for integrating RE

- **Adaptive and probabilistic forecasts become essential**
- **Methods for using prob. forecasts in decision making**
- **Correlation of forecast errors must be described**
- **Stochastic grey-box models are needed (for state estimation and for developing model predictive control schemes)**
- **Modeling of flexibility (direct control)**
- **Modeling of price-response (indirect control)**
- **Methods for stochastic optimization and control**

Some examples are provided in case studies later on

Example: Probabilistic Wind Power Forecasting



Case study

Super Market Cooling

The physical system

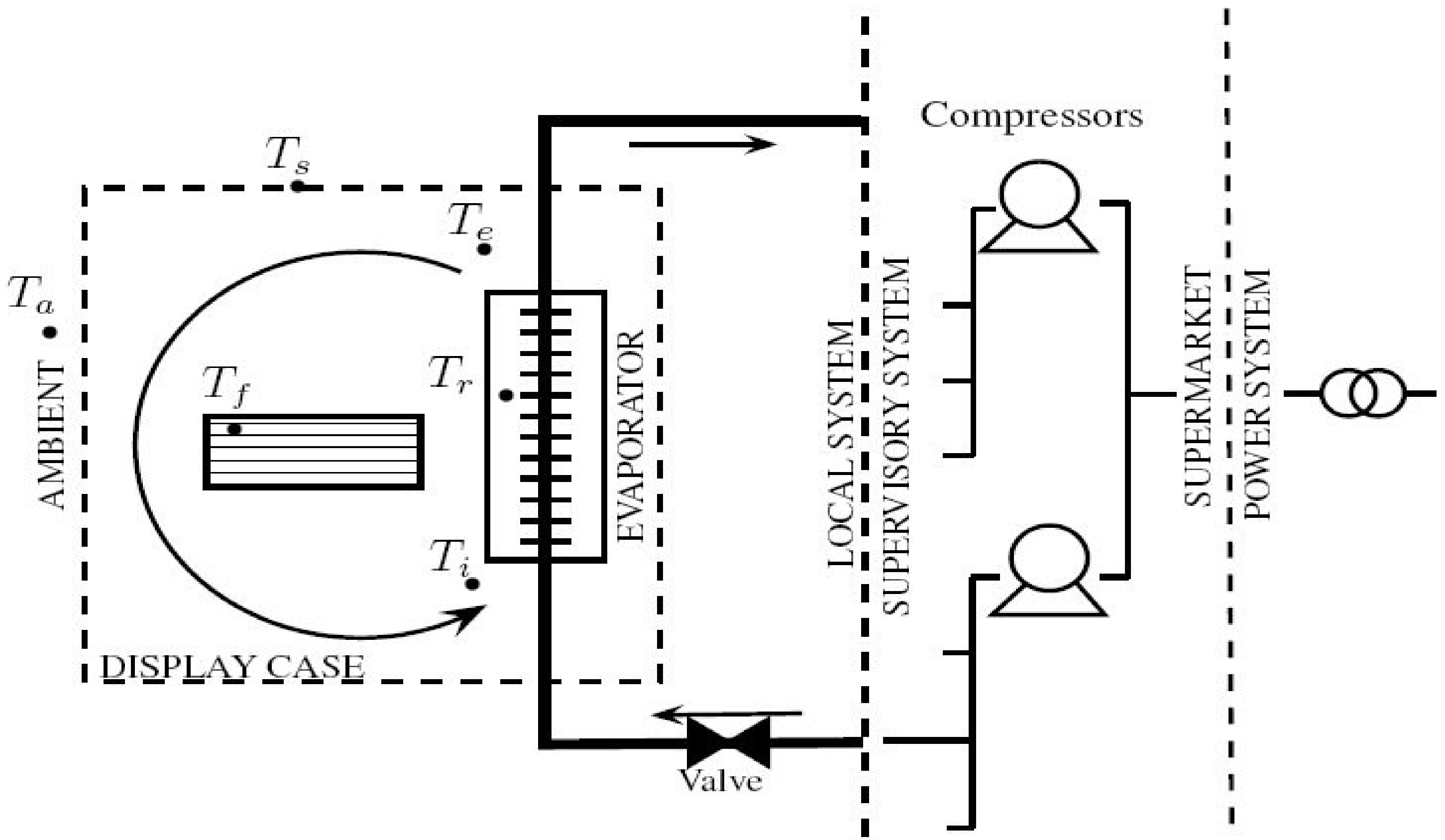


Fig. 2: Simplified graphical representation of the display case system

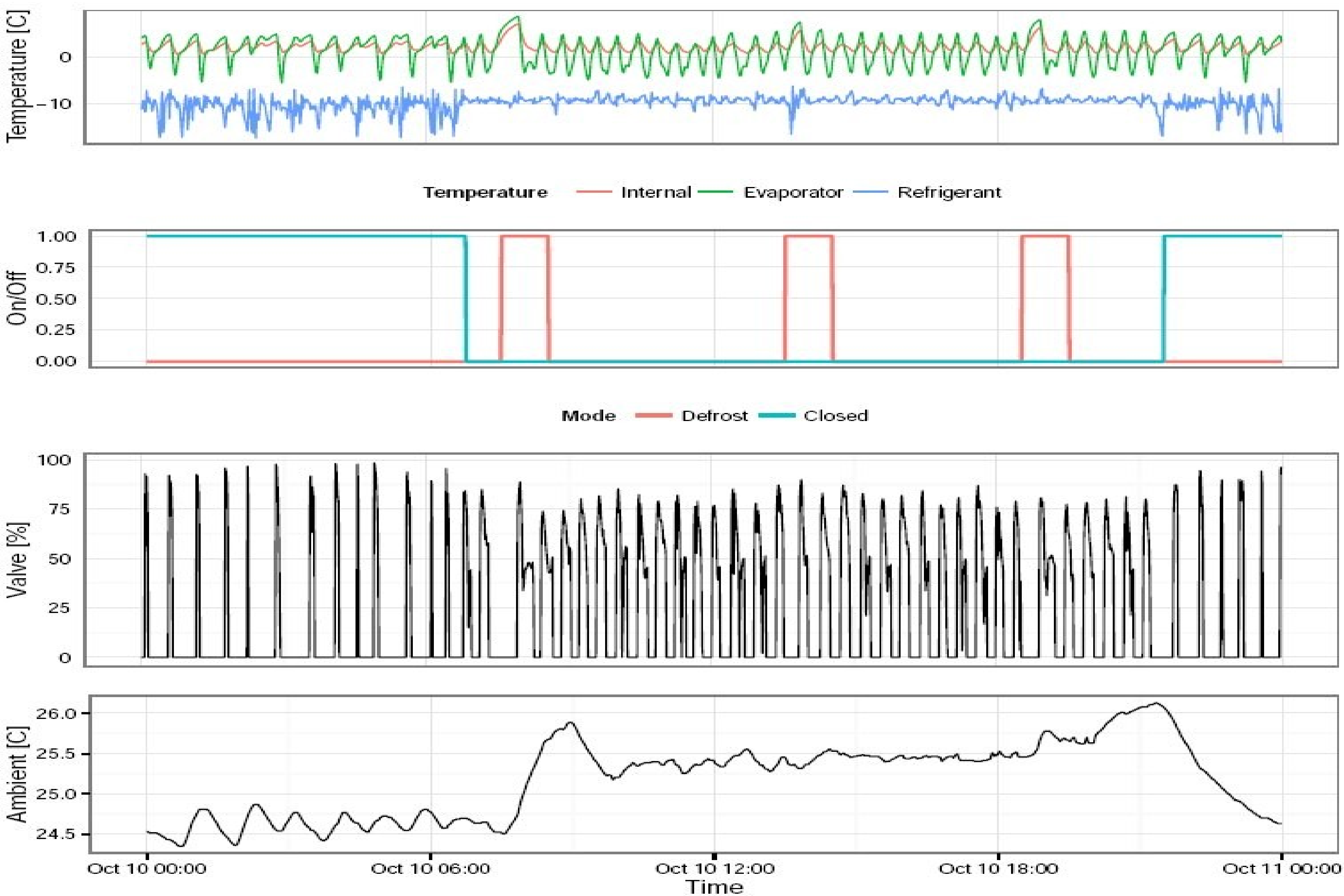


Fig. 3: Temperature, environmental (open/closed status, defrost status, ambient temperature) and control input (valve) data for an open medium temperature display case in a supermarket in Funen, Denmark

The grey-box model

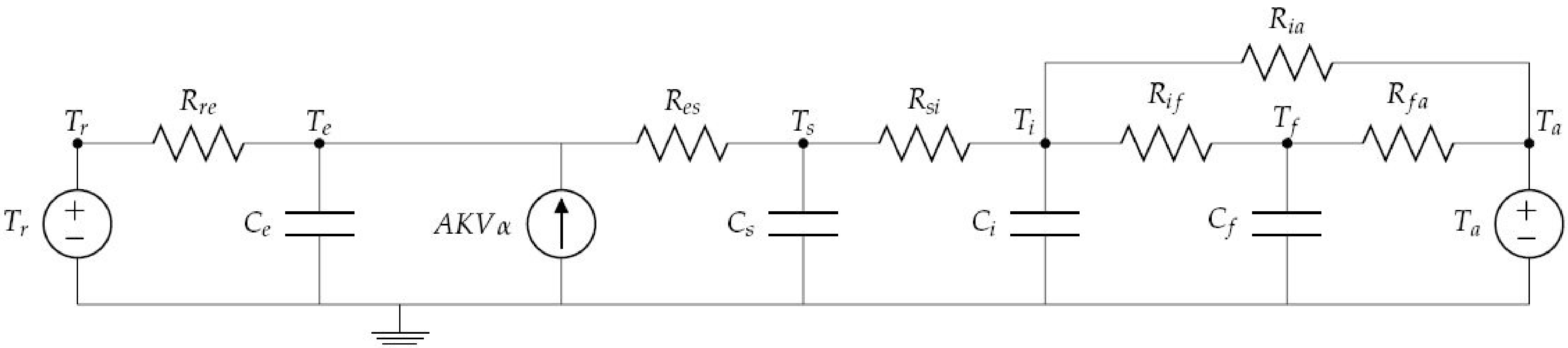


Fig. 6: RC-Representation of a four time constant model ($T_i T_e T_f T_s$)

Model validation

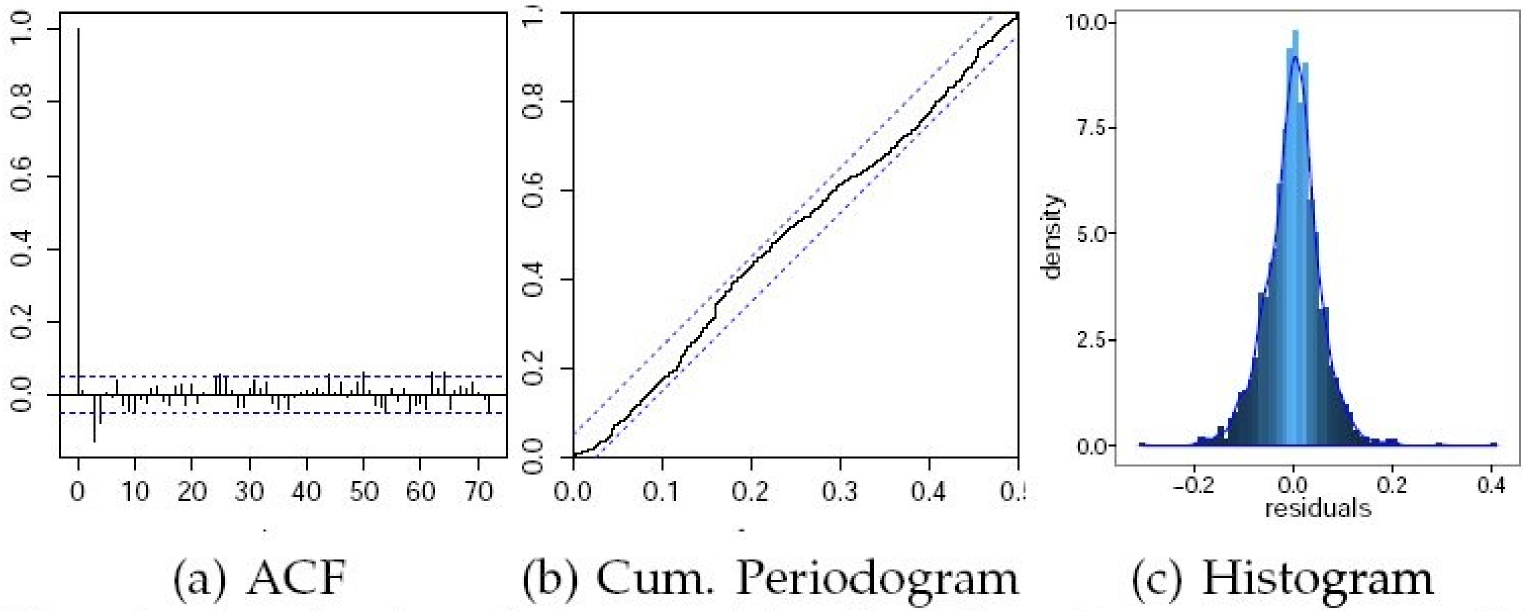


Fig. 8: Analysis of the residuals of a three state model ($T_iT_eT_f$)

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**

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

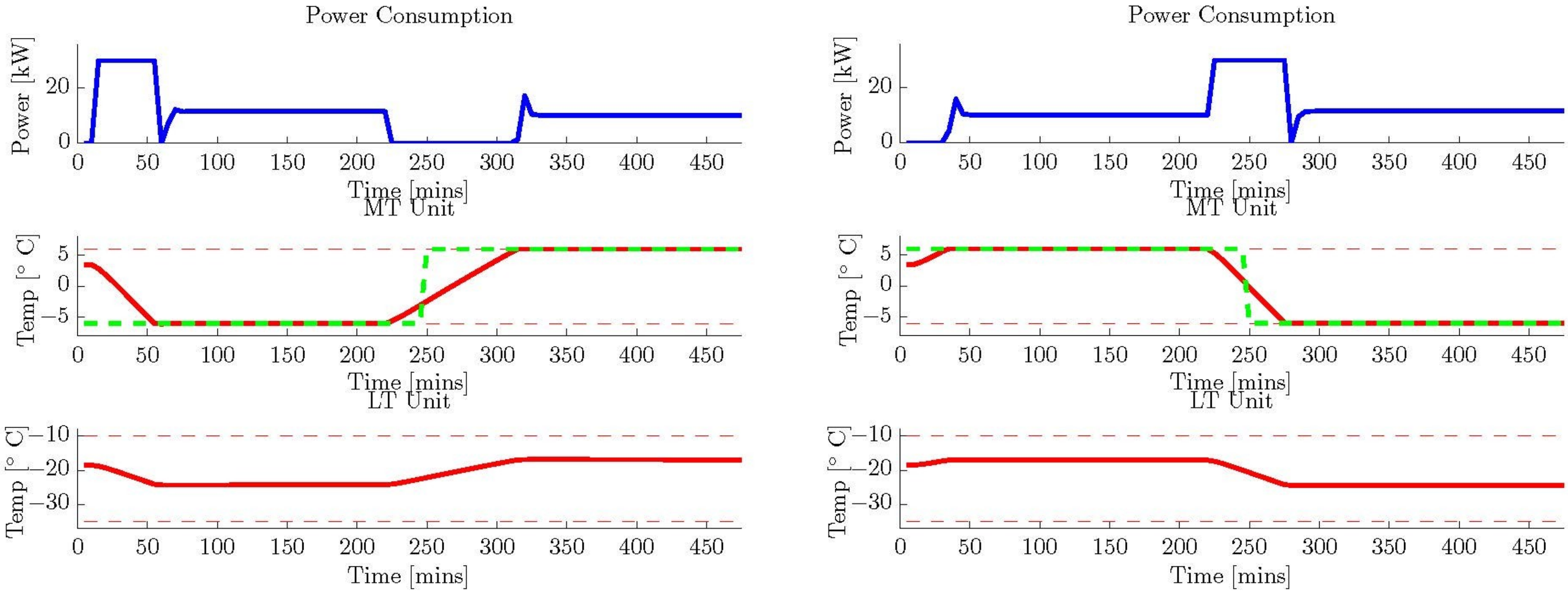
- Indirect Control
  - **Economic MPC**

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

- 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

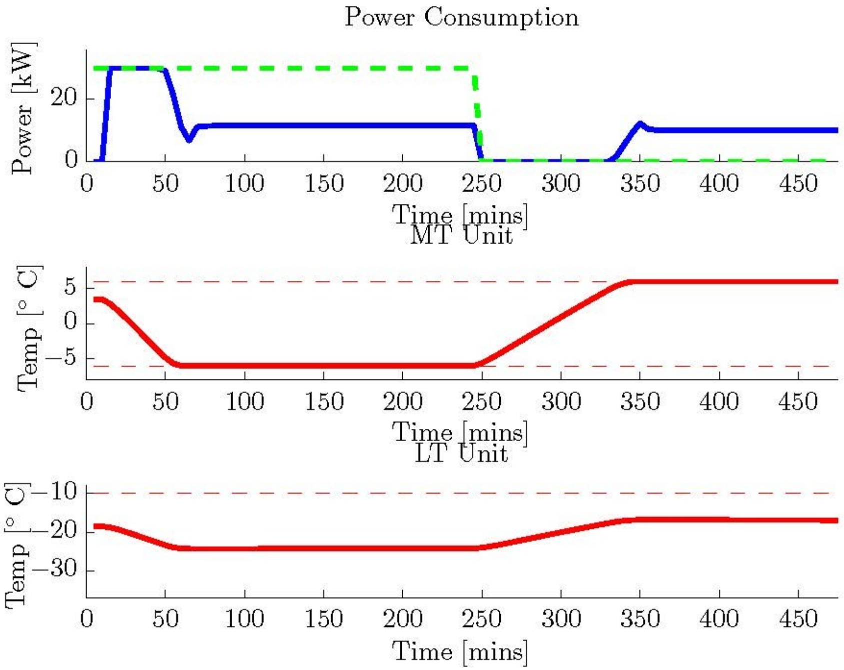
Simulations – Temperature Tracking

- Asymmetry

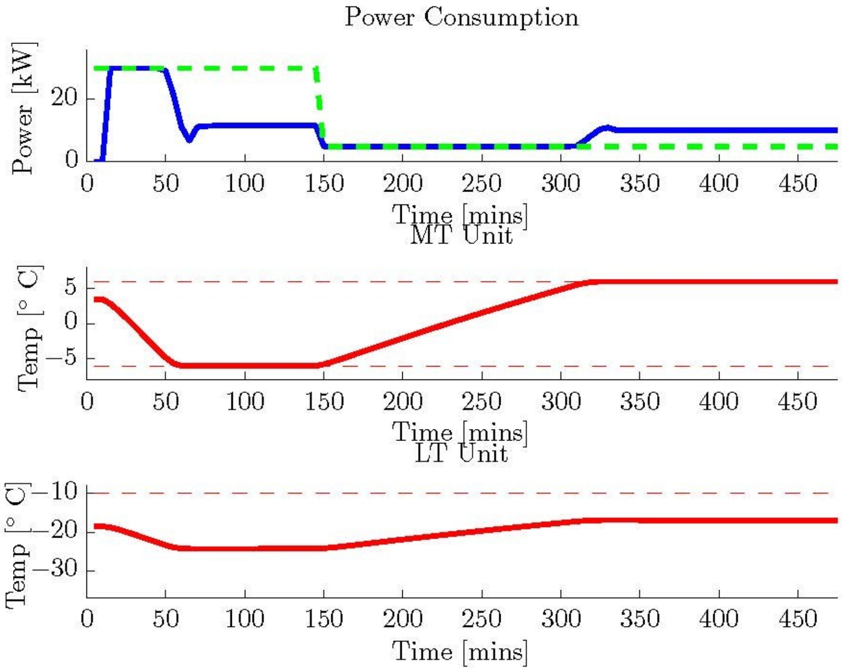


Simulations – Power Tracking

- Saturation Time

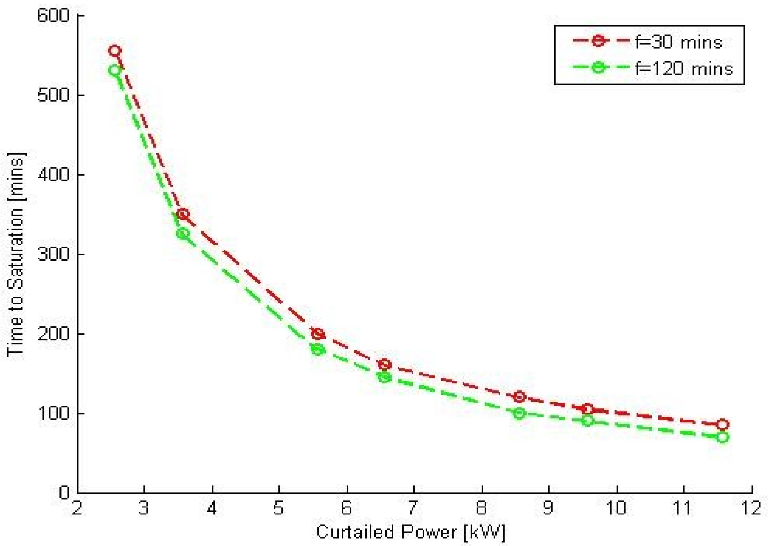


Pcurt: 0 kW



Pcurt: 5kW

Simulations - Power Tracking



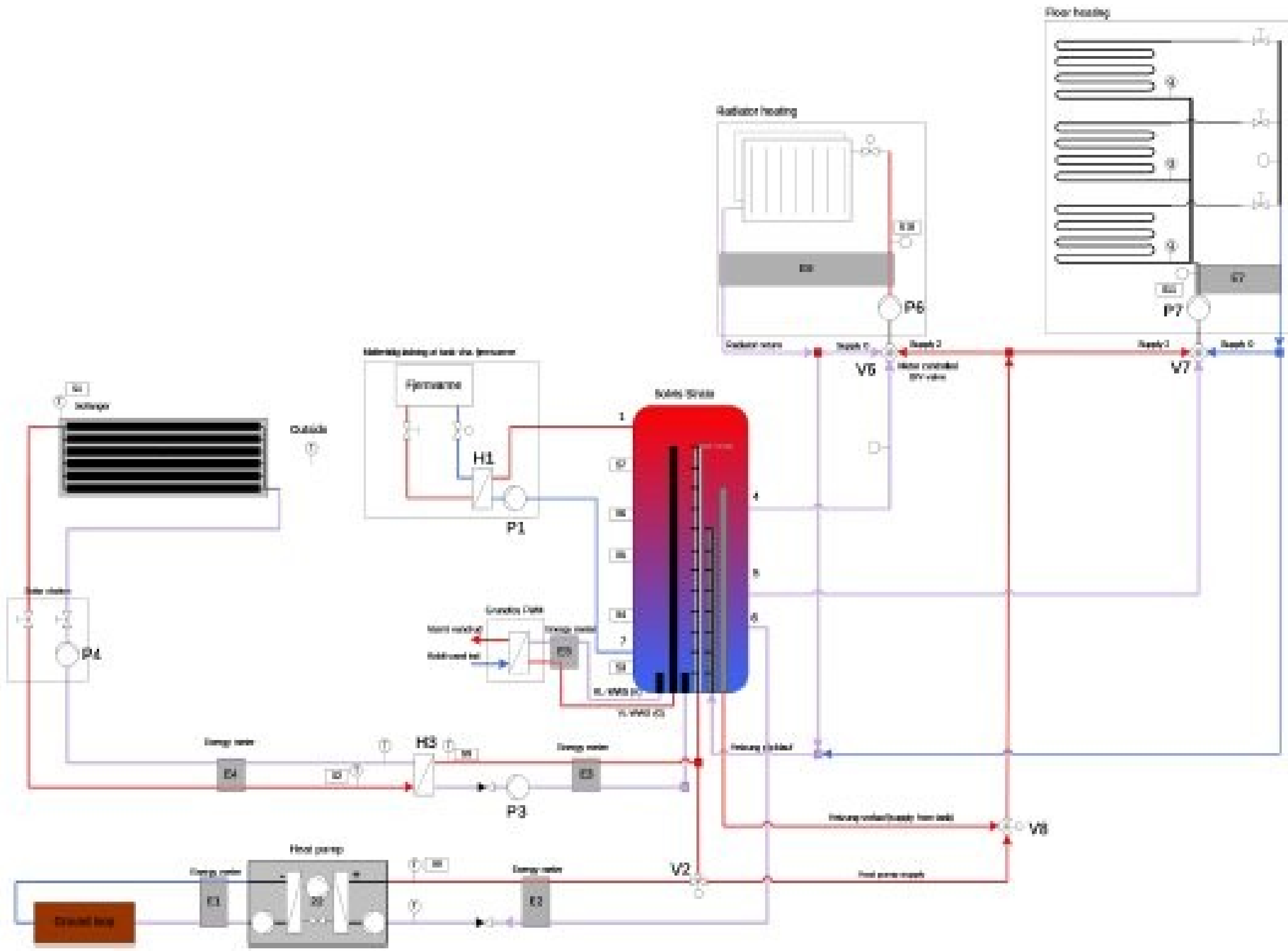
- Starting from maximum steady-state power consumption (to maintain **minimum** allowable temperature)
- Saturation defined as time until an increase in power consumption from the curtailed level (e.g. approximately time to reach **maximum** allowed temperature)
- Forecast of 30 minutes; initial work shows a longer forecasts decreases the time to saturation

Case study

Control of Heat Pumps

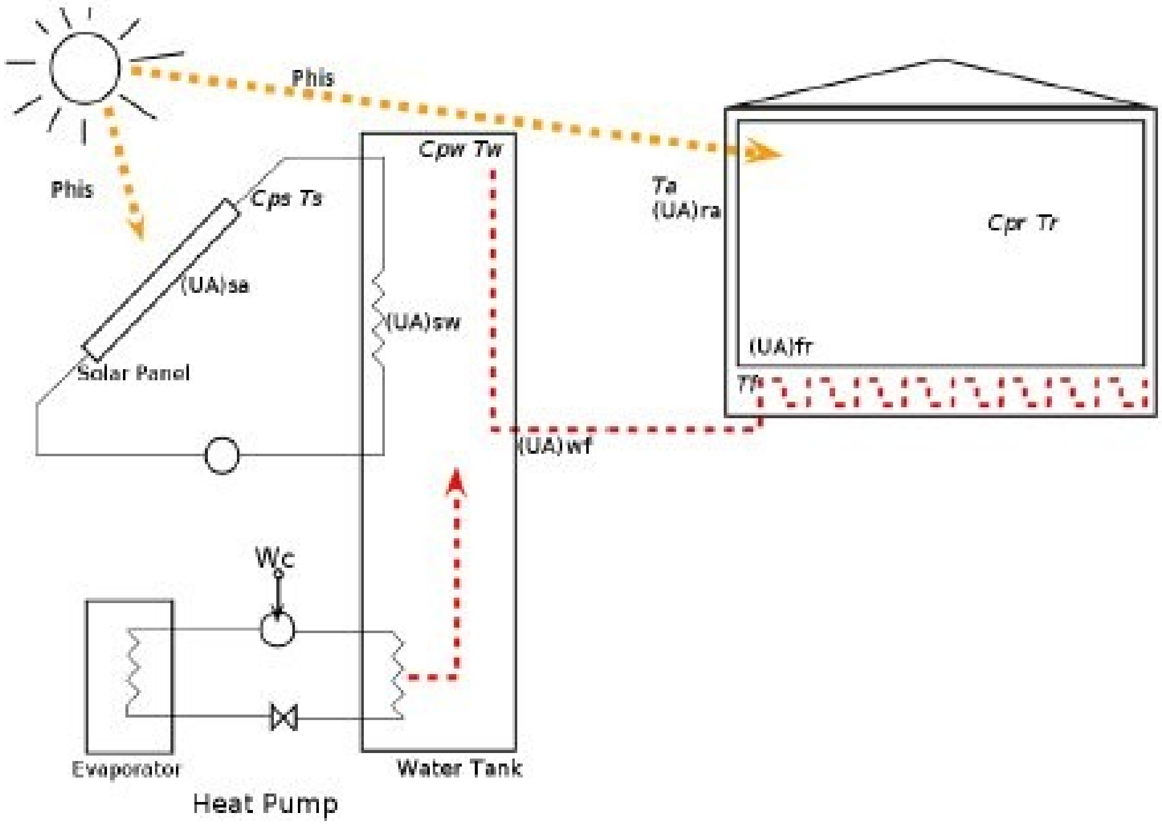
Grundfos Case Study

Schematic of the heating system



Modeling Heat Pump and Solar Collector

Simplified System



Modeling Heat Pump and Solar Collector

System Equations - Differential Equations

Equations

$$C_s \dot{T}_s = \eta\Phi_s - (UA)_{sw}(T_s - T_w) - (UA)_{sa}(T_s - T_a) \tag{2a}$$

$$C_w \dot{T}_w = \eta W_c + (UA)_{sw}(T_s - T_w) - (UA)_{wf}(T_w - T_f) \tag{2b}$$

$$C_f \dot{T}_f = (UA)_{wf}(T_w - T_f) - (UA)_{fr}(T_w - T_f) + p\Phi_s \tag{2c}$$

$$C_r \dot{T}_r = (UA)_{fr}(T_f - T_r) - (UA)_{ra}(T_r - T_a) + (1 - p)\Phi_s \tag{2d}$$

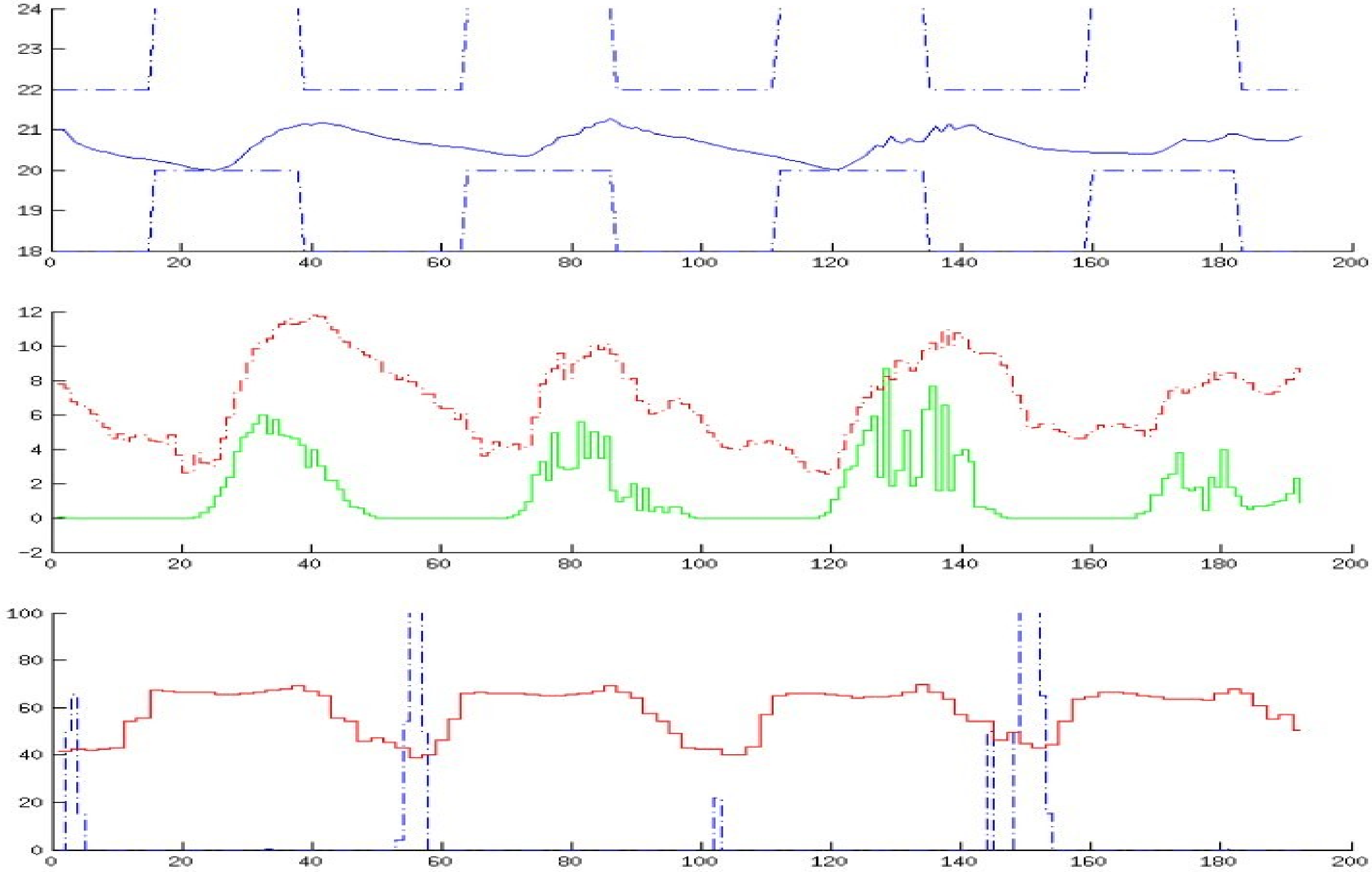
Formulation

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

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

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

EMPC for heat pump with solar collector



Conclusions

- A hierachi of optimization/control problems with integrated forecasting for both direct and indirect control have been described as the approach for integrating large fractions of wind/solar power in smart energy systems
- Two examples of smart grid applications are outlined:
  - Control of supermarket cooling (both direct and indirect control)
  - Control of heat pump and thermal solar collector system for a family house
- Both examples have illustrated the use of Grey-box models