Smart-Energy Operating-System

A system for controlling and operating flexibility in electric energy systems

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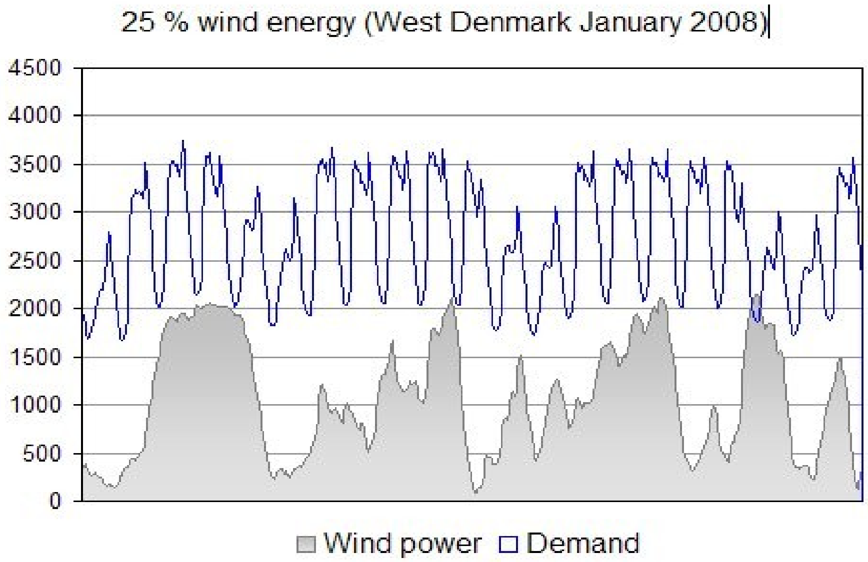
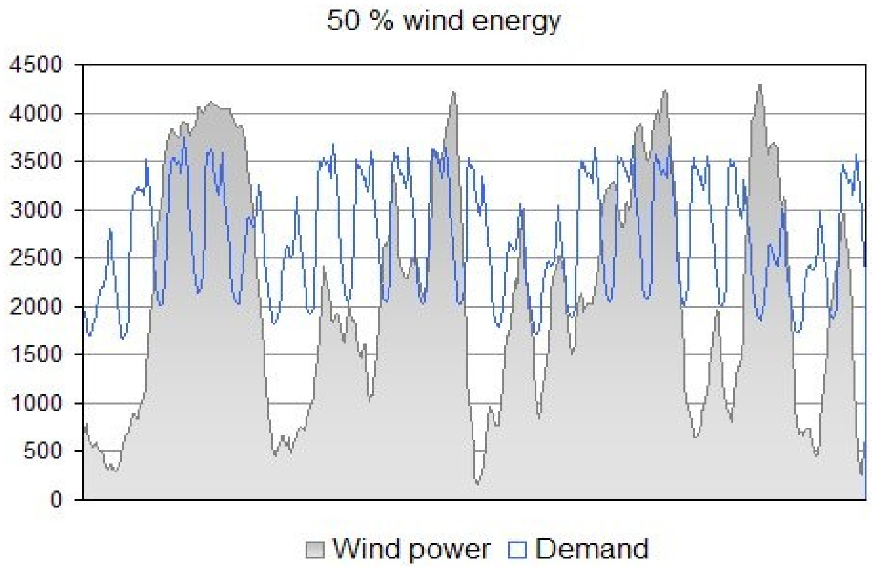
The Danish Wind Power Case

.... balancing of the power system





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

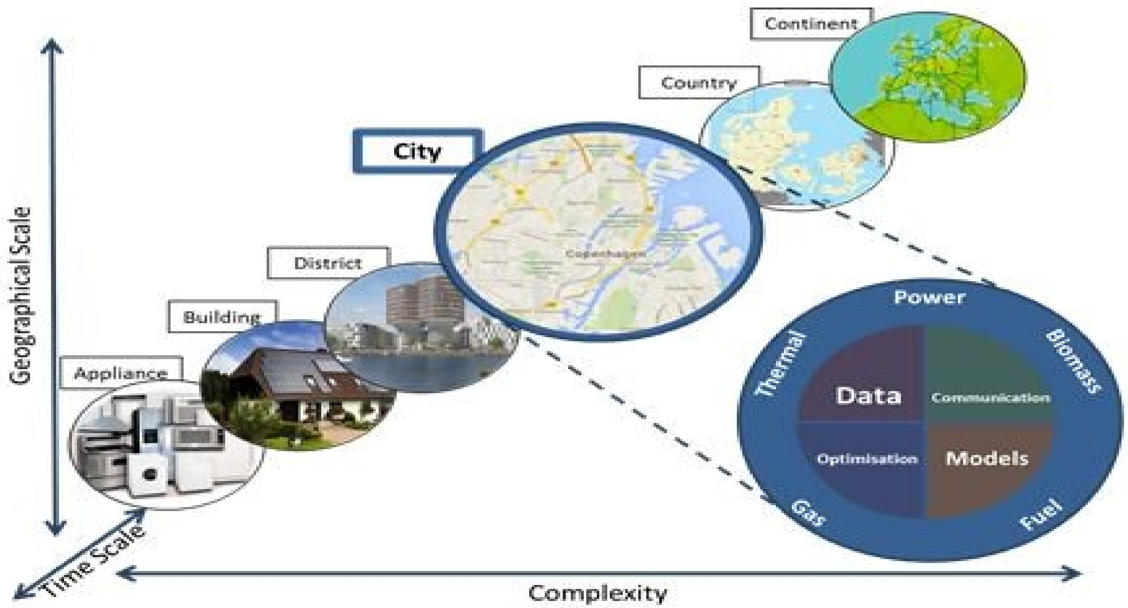
In 2015 more than 42 pct of electricity load was covered by wind power.

For several days the wind power production was more than 100 pct of the power load.

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

Temporal and Spatial Scales

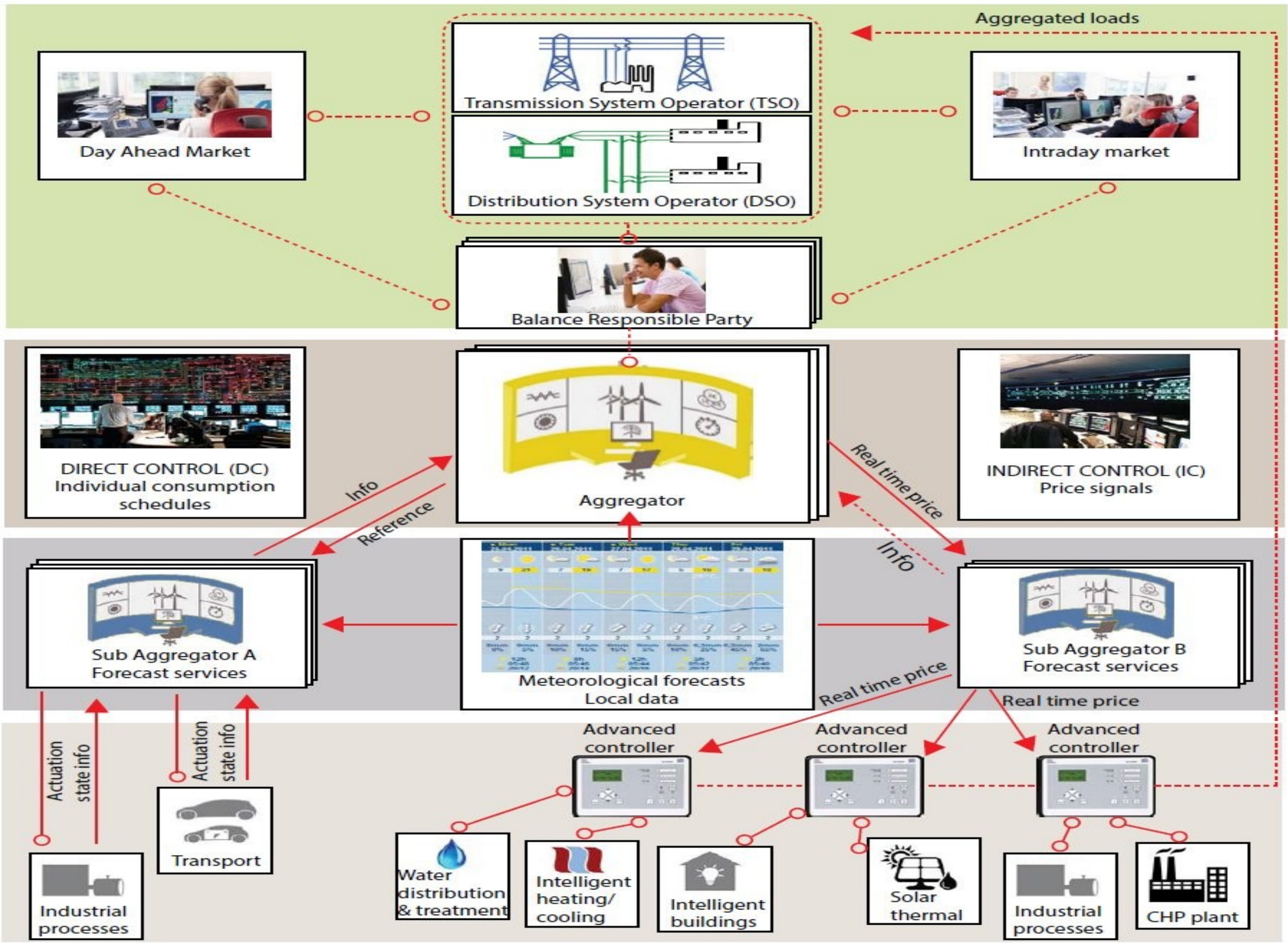
The ***Smart-Energy Operating-System (SE-OS)*** is used to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for ***operating flexible electrical energy systems*** at **all scales**.



SE-OS History

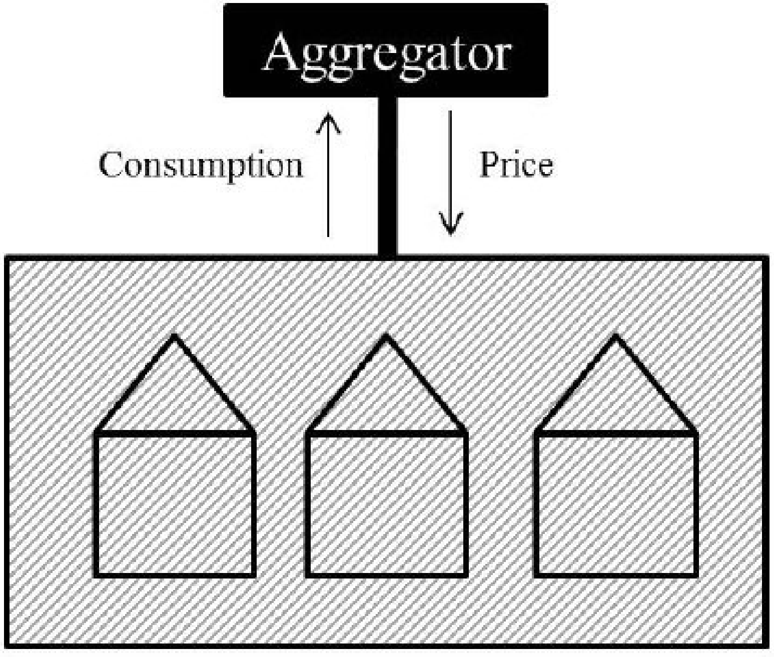
- 2008 - DTU Compute and IES part of FlexPower application
- 2010 - First complete simulation framework
- 2012 – Part of iPower (DTU Compute, Enfor and Grundfos)
- 2013/14 – Part of CITIES project (largest national project on intelligent and integrated energy systems)
- 2014/15 – Price-based control in EcoGrid EU, but oscilation due to sub-optimal control implementations
- 2015/16 – Pilot B in H2020 SmartNet

Smart-Energy OS

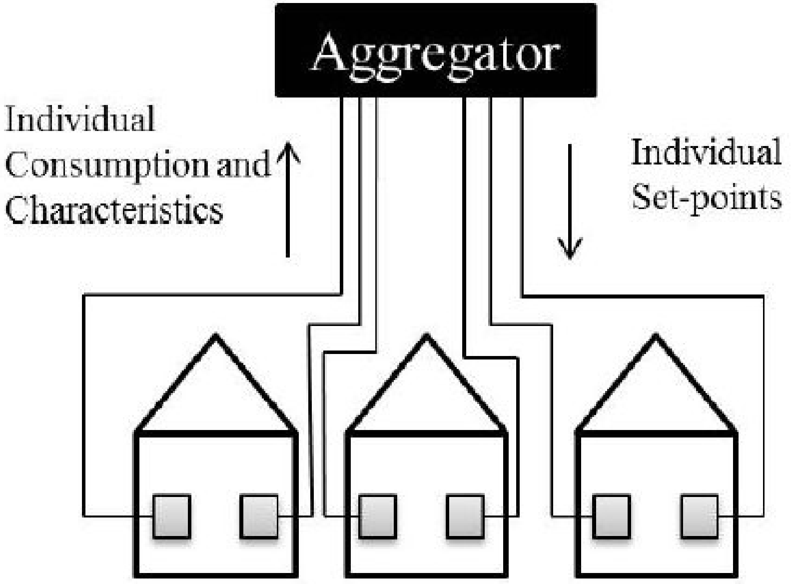


Direct and Indirect Control

For DC info about individual states and constraints are needed

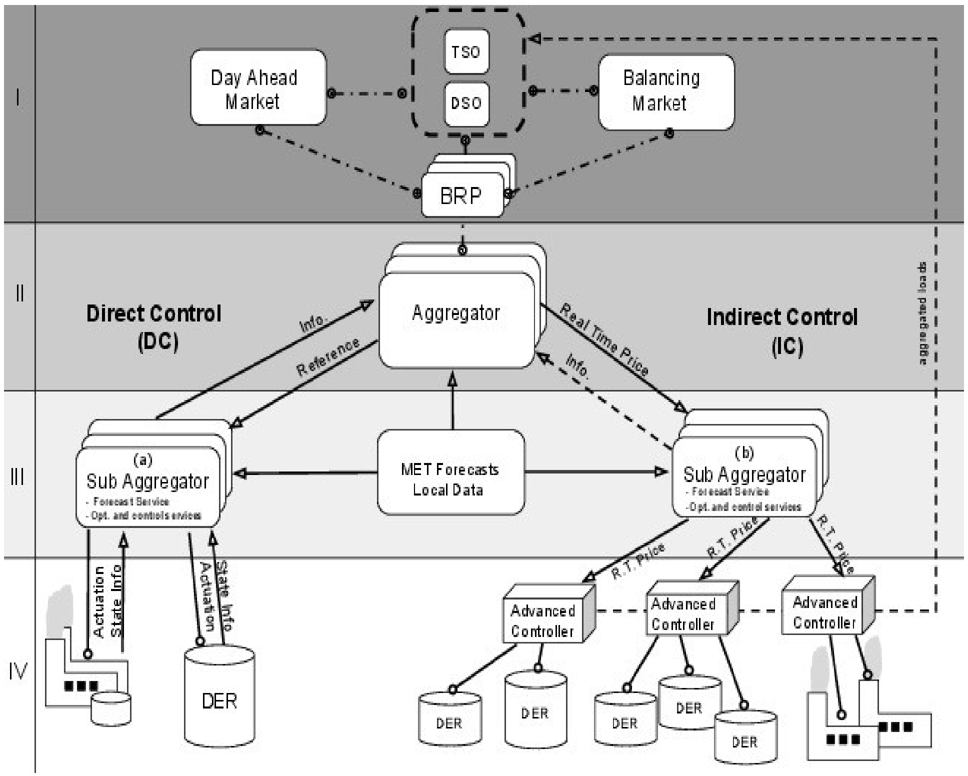


(a) Indirect control



(b) Direct control

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'

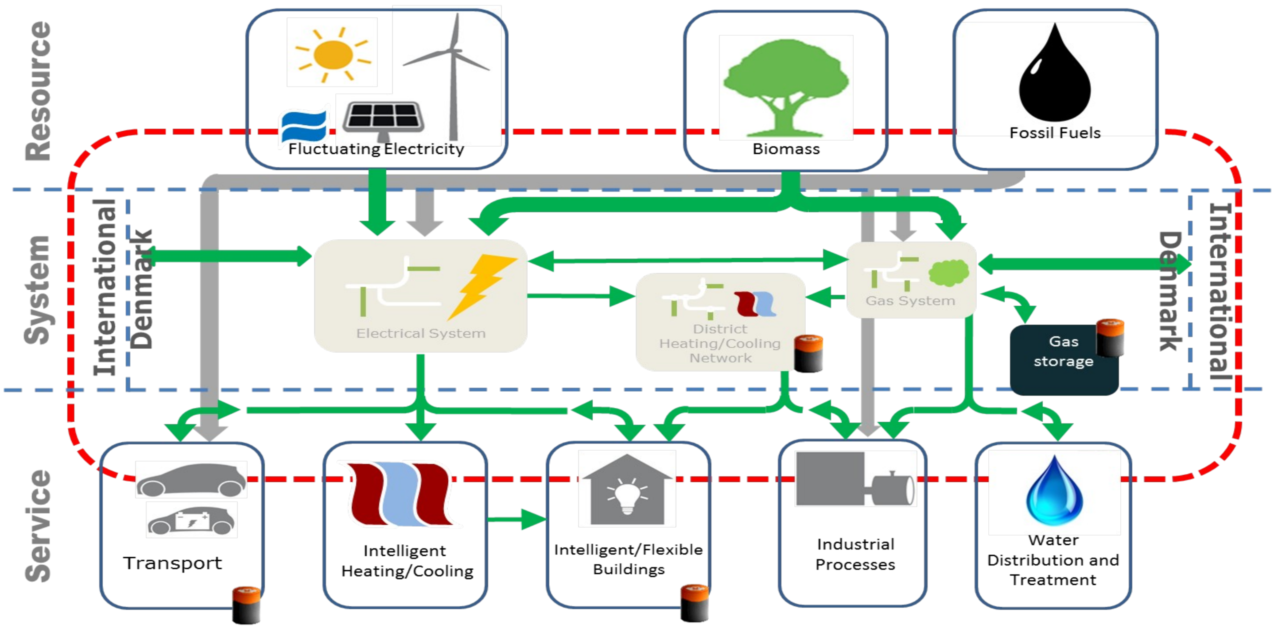
Direct vs Indirect Control

<table>
<tr><th>Level</th><th>Direct Control (DC)</th><th>Indirect Control (IC)</th></tr>
<tr><td>III</td><td rowspan="2">$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$
$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$
$\text{s.t.} \quad x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$</td><td>$\min_{\hat{z},p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$
$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$</td></tr>
<tr><td>IV</td><td>$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$
$\text{s.t.} \quad x_{k+1} = f_j(x_k, u_k)$</td></tr>
</table>

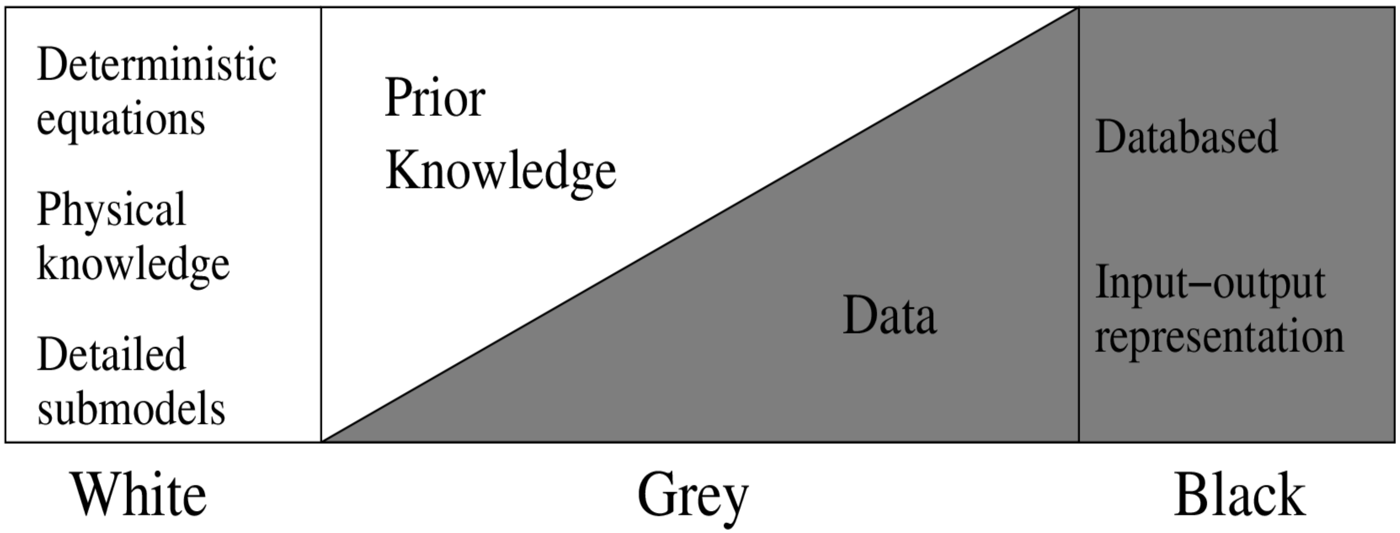
Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals u_j are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes 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.

Models

Grey-box modelling are used to establish **models and methods for real-time operation of future electric energy systems**

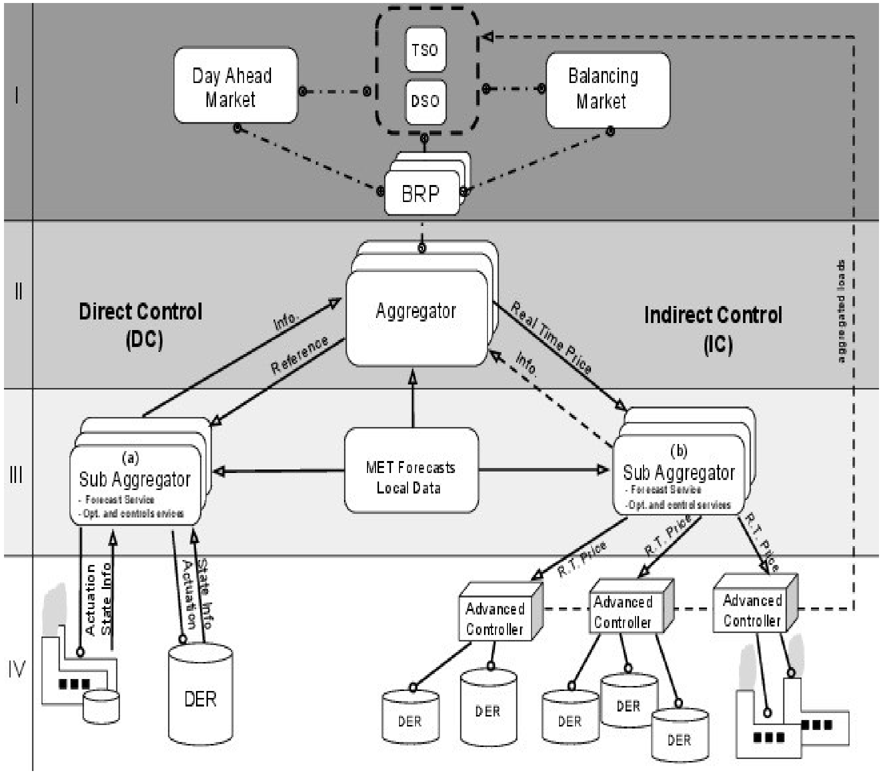


Grey-box modelling concept



- Combines prior physical knowledge with information in data
- Equations and parameters are physically interpretable
- Use of data from sensors, etc.

Forecast requirements



Day Ahead:

- Forecasts of loads
- Forecast of Grid Capacity (using eg. DLR)
- Forecasts of production (eg. Wind and Solar)

Direct Control: .

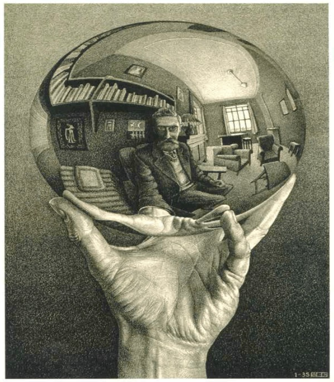
- Forecasts of states of DERs
- Forecasts of load

Indirect Control:

- Forecasts of prices
- Forecasts of load

SE-OS Characteristics

- Bidding – clearing – activation at higher levels
- Control principles at lower levels
- Cloud based solution for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ...)
- Allow for new players (specialized aggregators)
- Simple setup for the communication
- Simple (or no) contracts
- Rather simple to implement
- Harvest flexibility at all levels



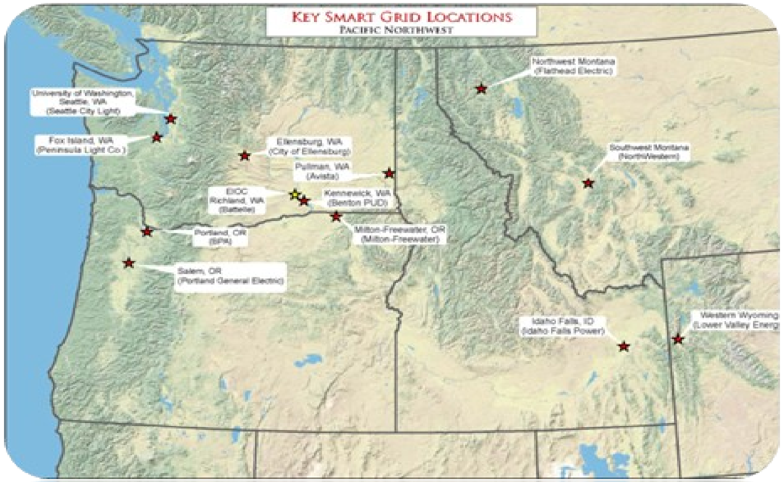
Case study (Level III)

Price-based Control of Power Consumption (Thermal flexible buildings)

Data from PNNL-BPA

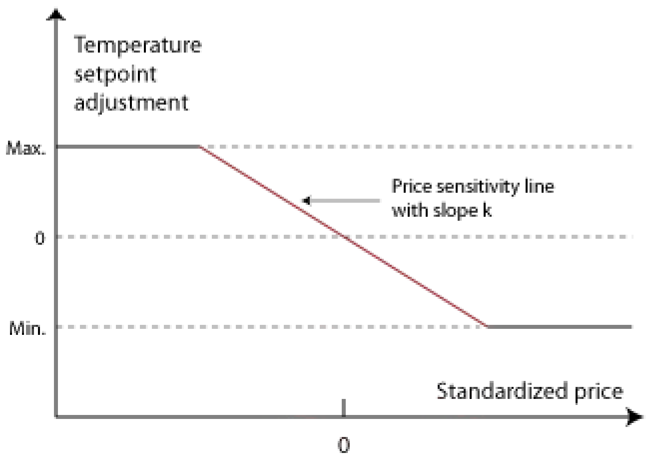
Olympic Pensinsula project

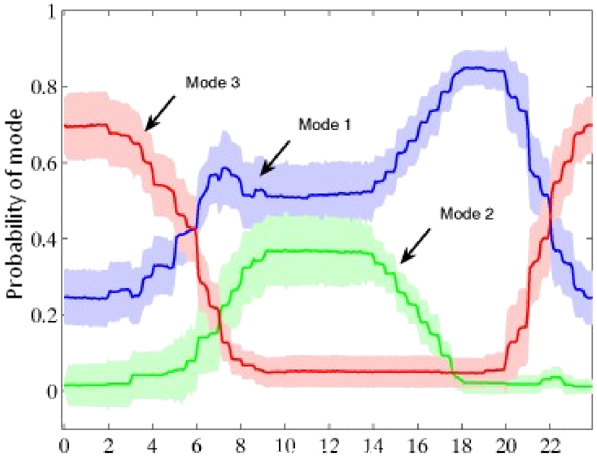
- 27 houses during one year
- Flexible appliances: HVAC, cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption



Price responsivity

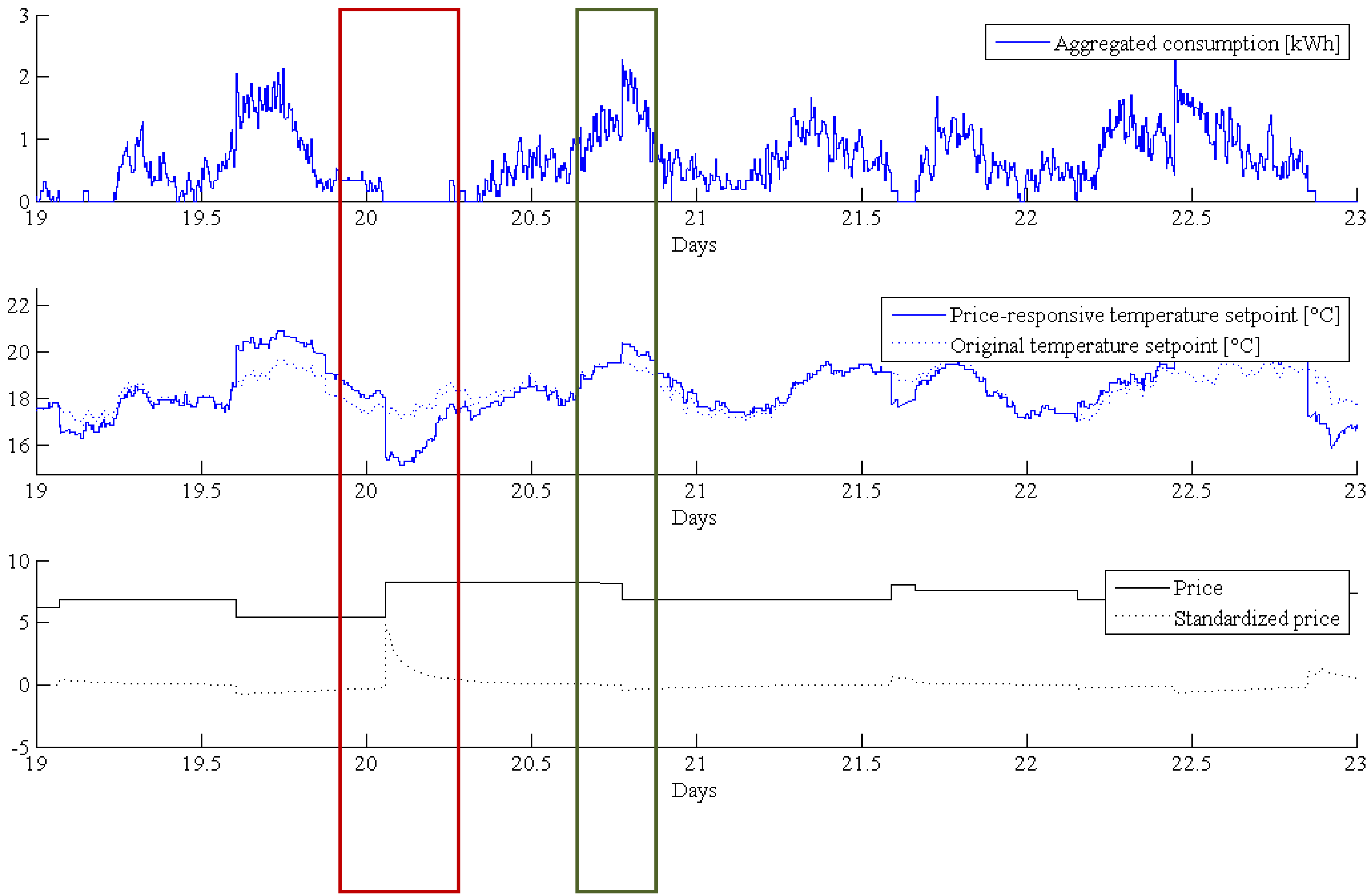
Flexibility is activated by adjusting the temperature reference (setpoint)



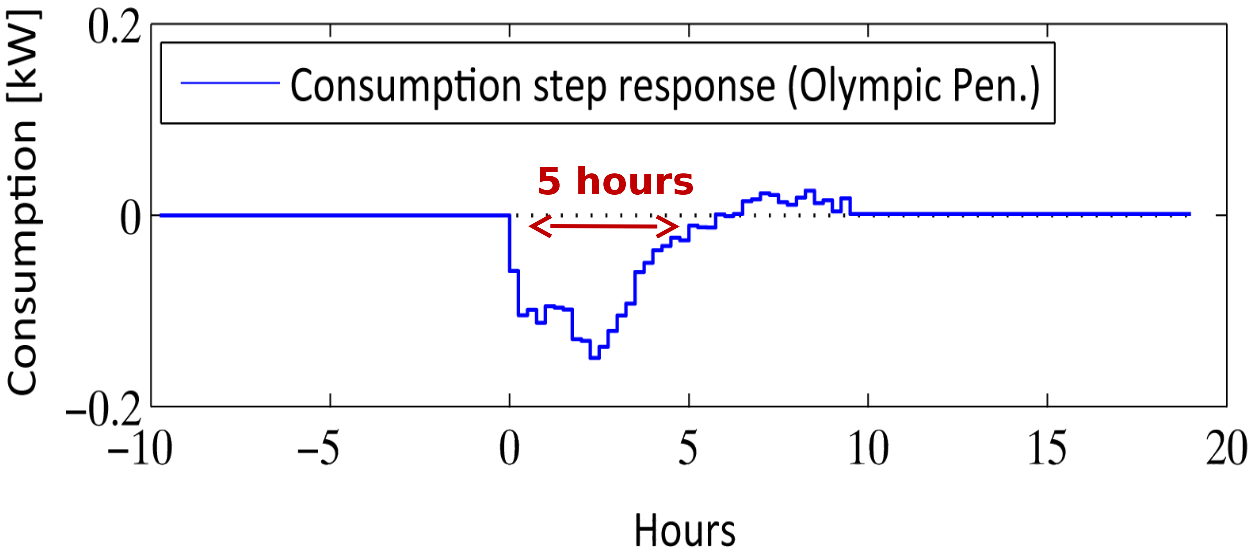


- **Standardized price** is the % of change from a price reference, computed as a mean of past prices with exponentially decaying weights.
- **Occupancy mode** contains a price sensitivity with its related comfort boundaries. 3 different modes of the household are identified (work, home, night).

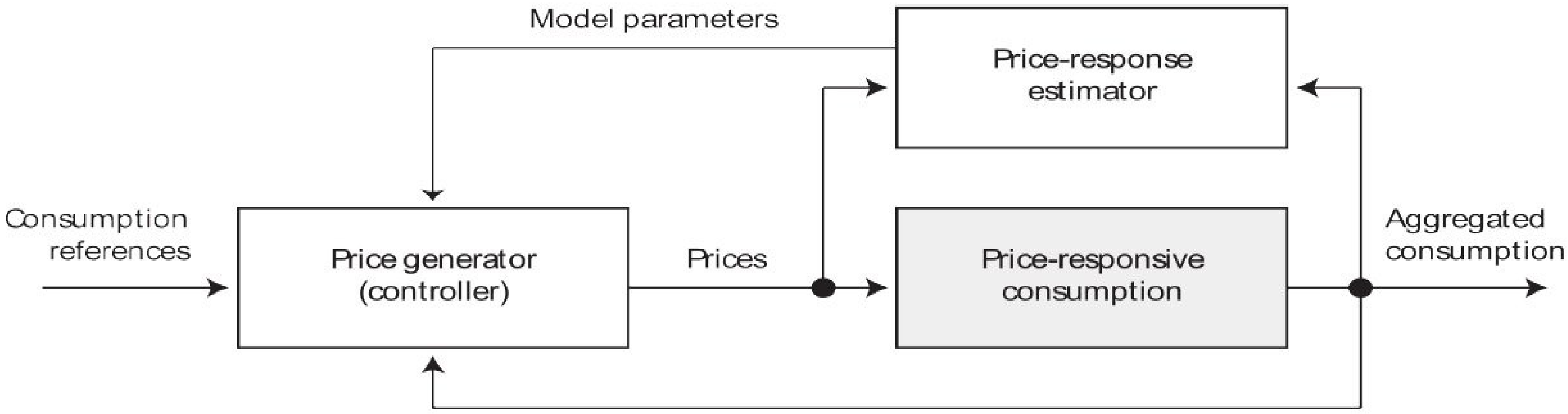
Aggregation (over 20 houses)

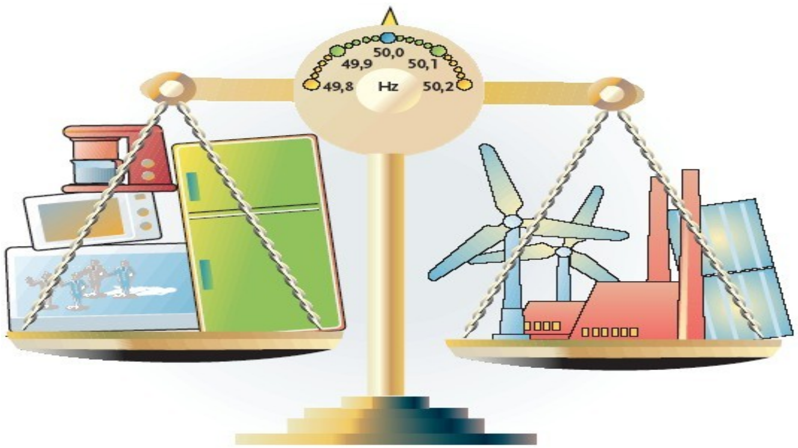


Response on Price Step Change



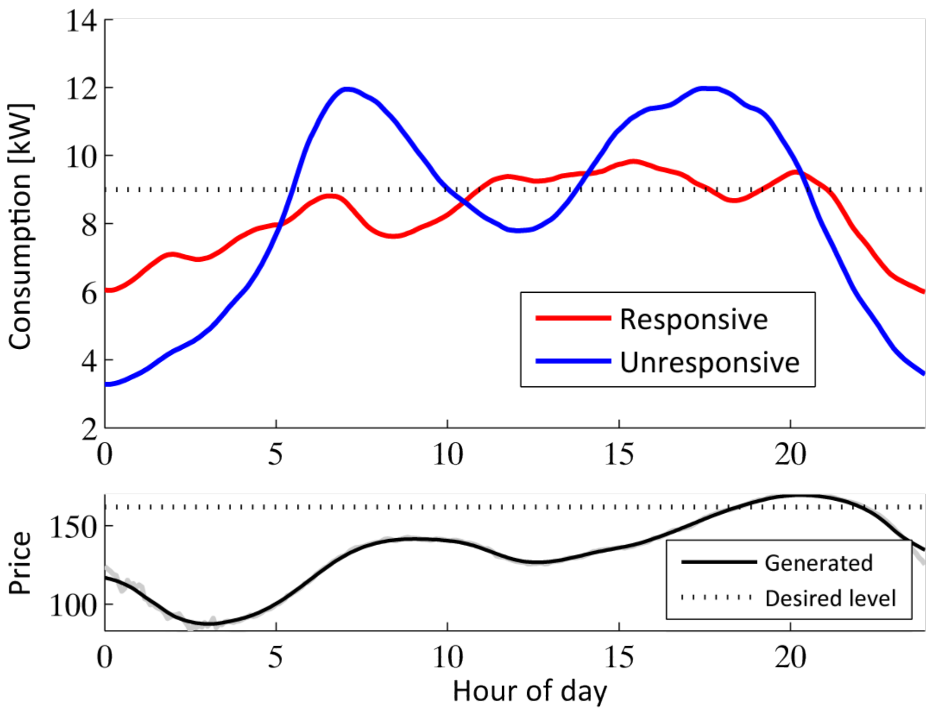
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**

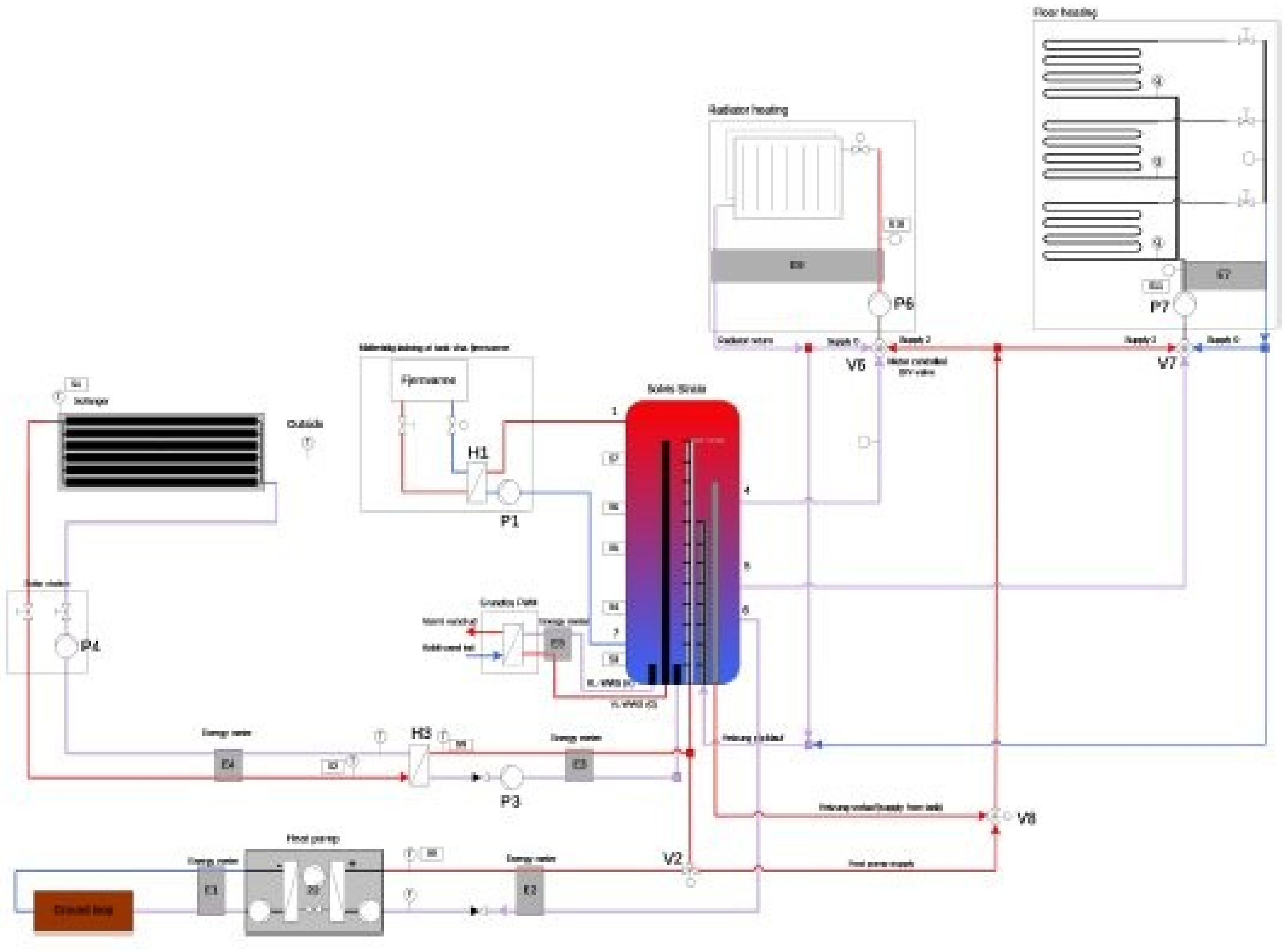


Case study (Level IV)

Control of Heat Pumps
(based on varying prices from Level III)

Grundfos Case Study

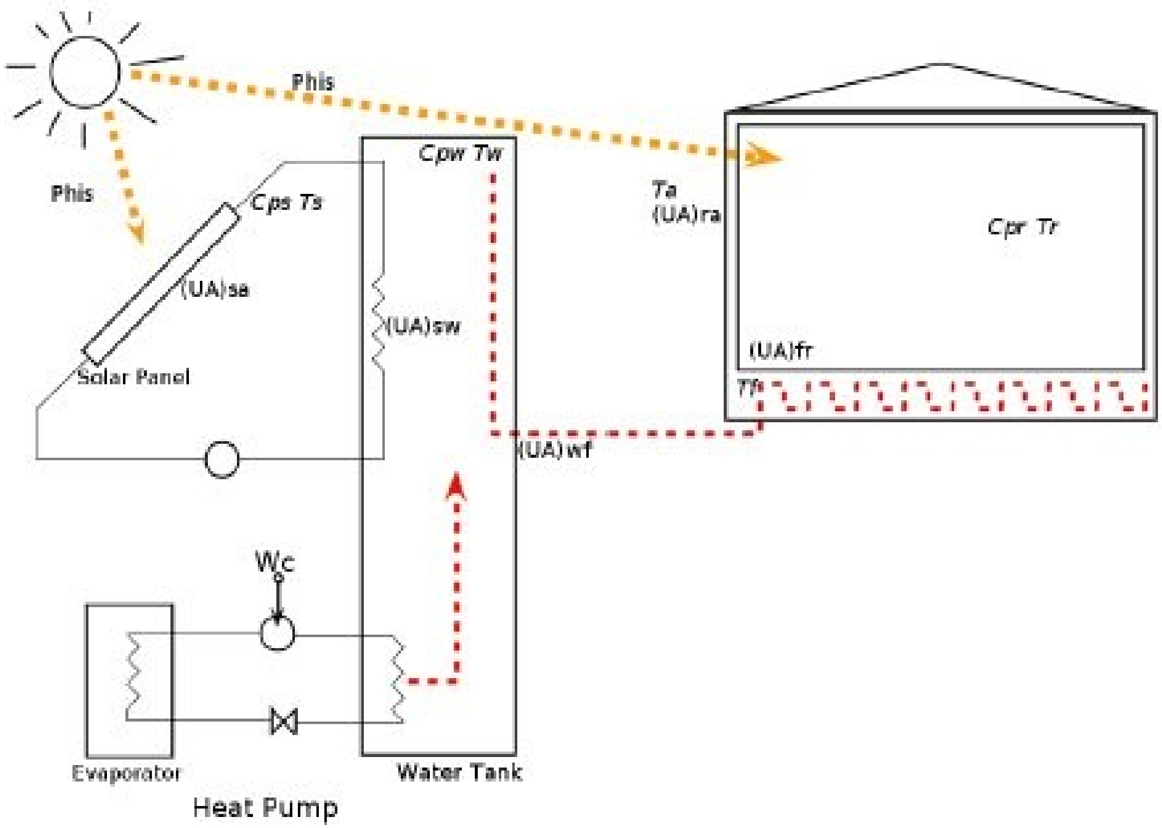
Schematic of the heating system



DTU

Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

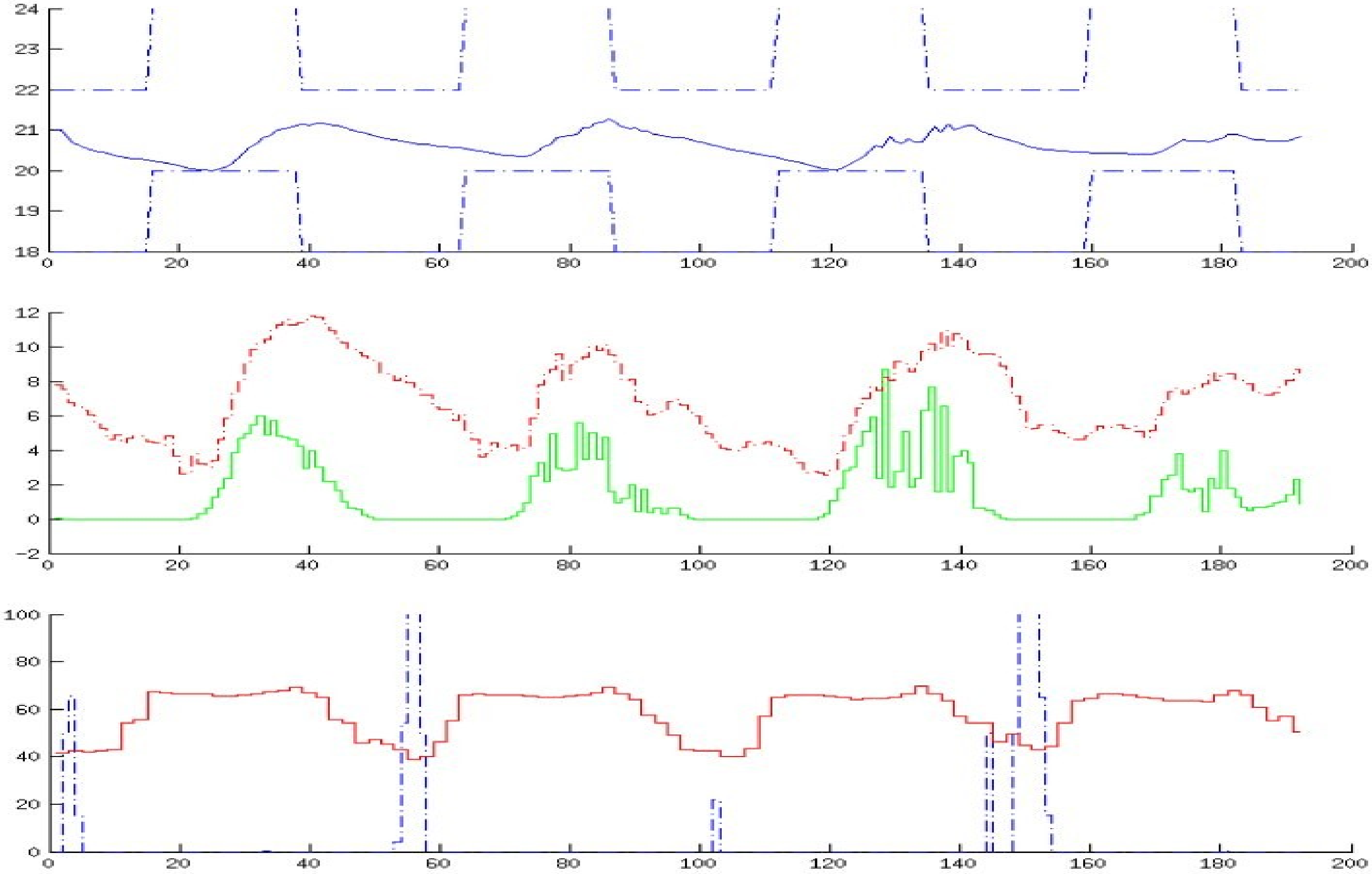
Formulation

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

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

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

E-MPC for heat pump with solar collector (savings 35 pct)



Case study

(Direct Control and Bids for Markets)

Virtual Storage Related to Super Market Cooling using Thermal Demand Response

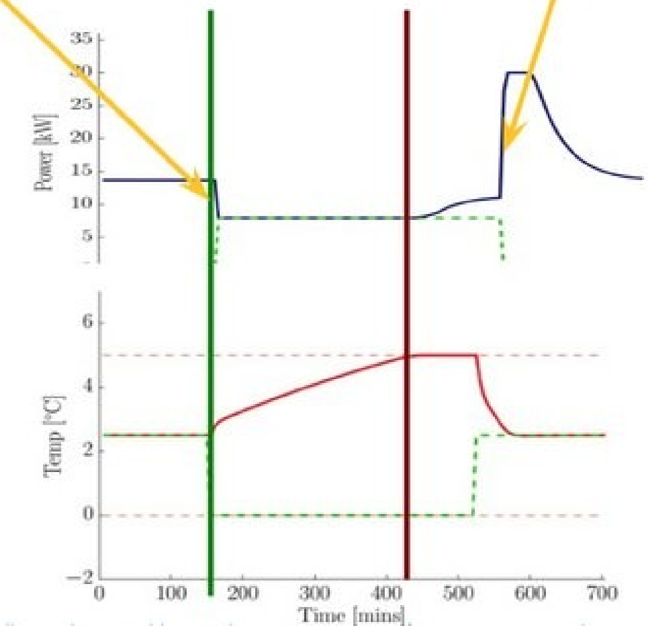
SmartNet

Synergize: Virtual Storage using Thermal Demand Response

Thermal mass in refrigeration display cases facilitates the adjustment of power consumption while maintaining acceptable temperatures for food.

6kW of DR

Recovery period



The physical system

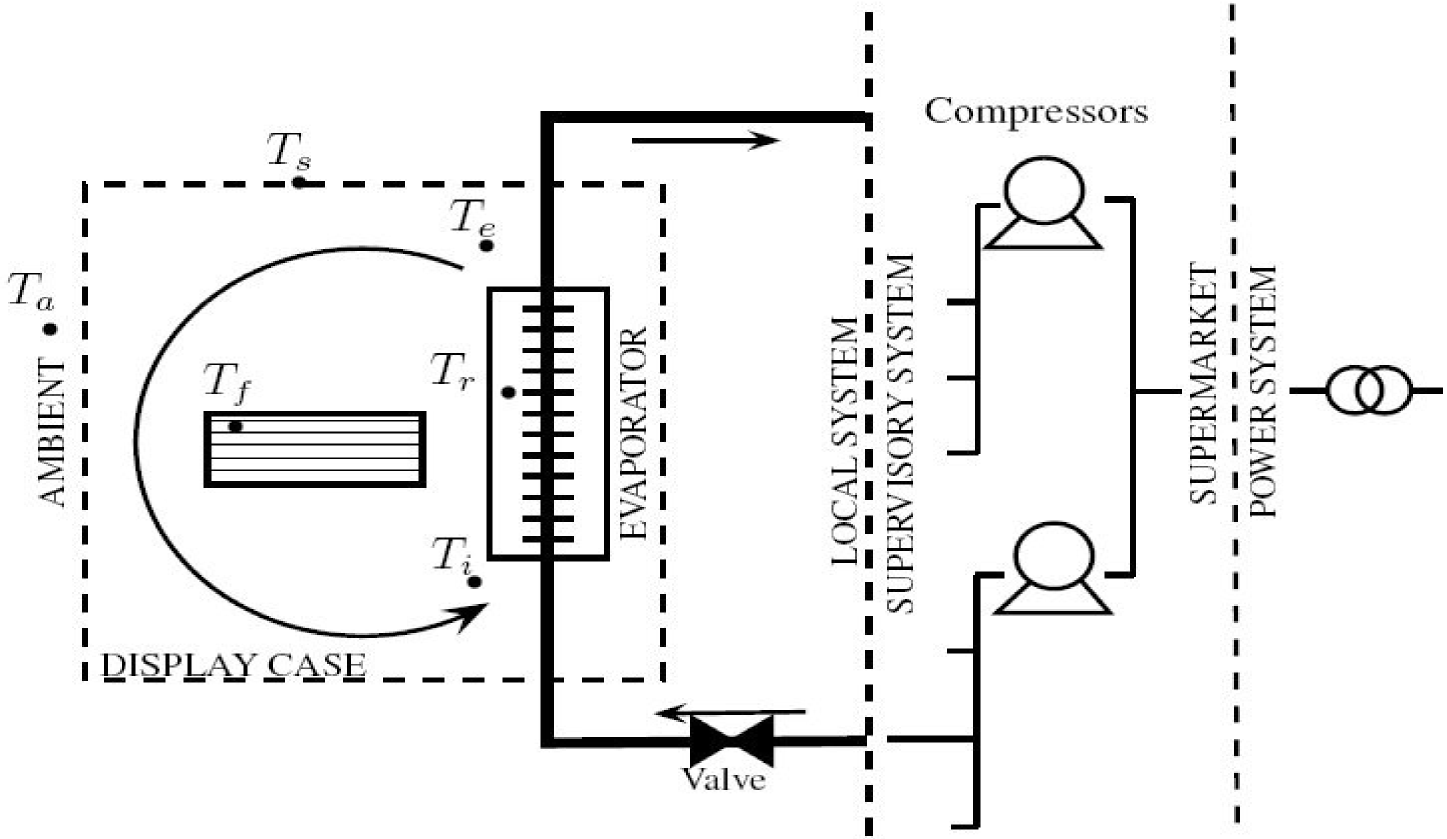


Fig. 2: Simplified graphical representation of the display case system

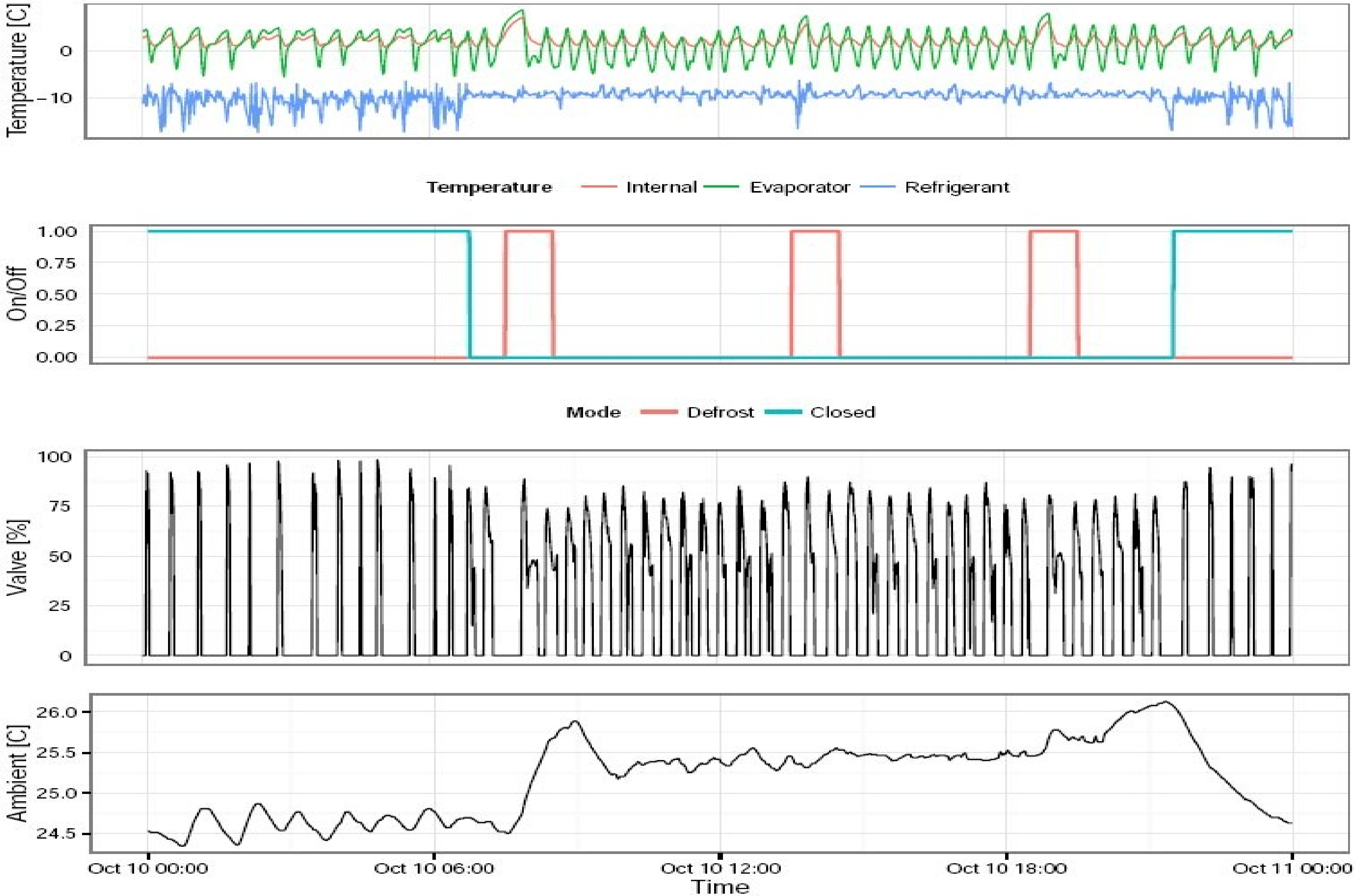


Fig. 3: Temperature, environmental (open/closed status, defrost status, ambient temperature) and control input (valve) data for an open medium temperature display case in a supermarket in Funen, Denmark

The grey-box model

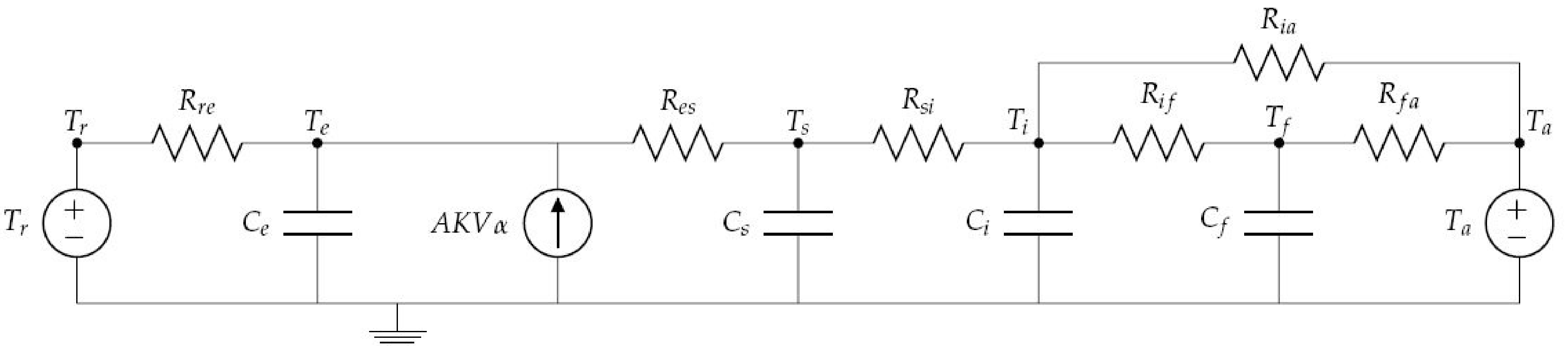


Fig. 6: RC-Representation of a four time constant model $(T_i T_e T_f T_s)$

Demand Response 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**

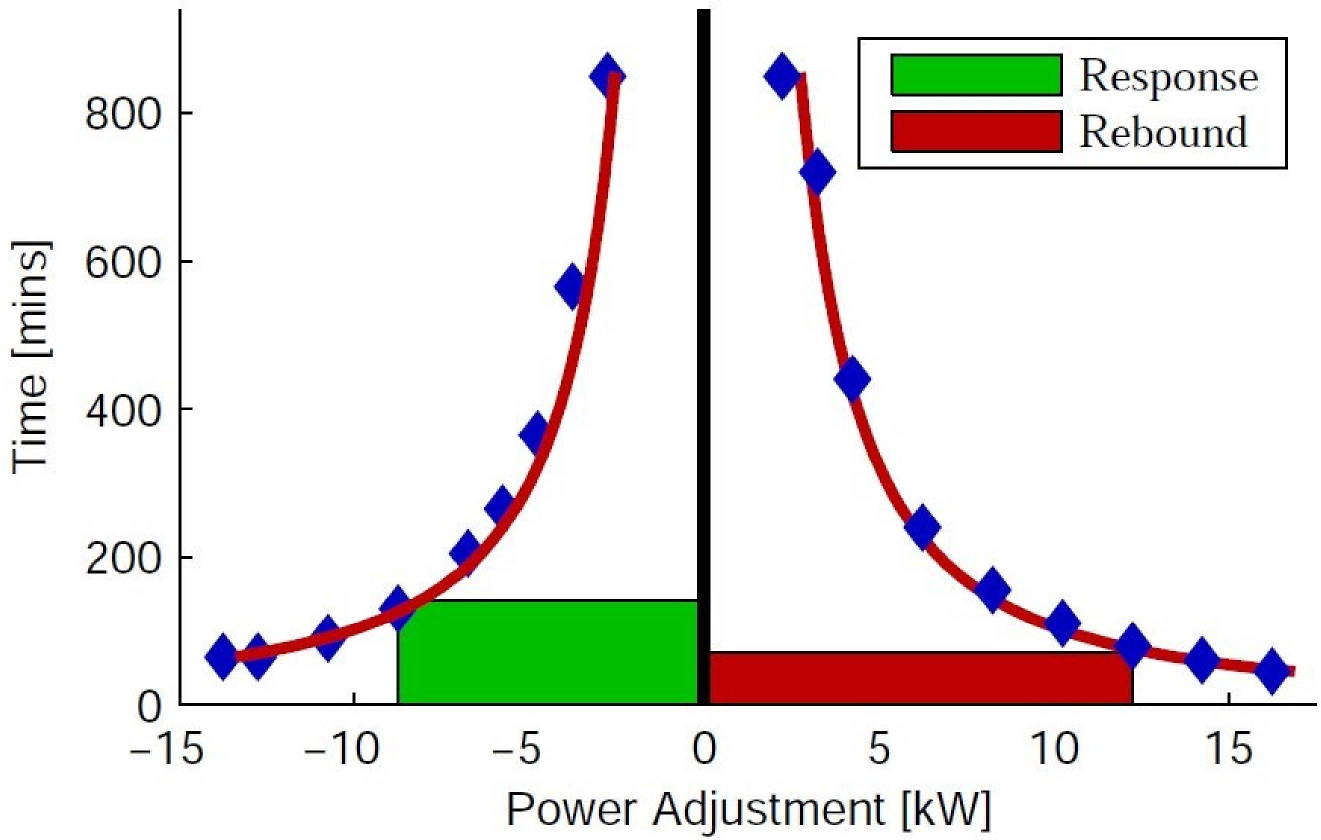
$$\min \sum_{n=1}^{N} \left(P_n - P_n^{ref}\right)^2$$

- 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

Flexibility Represented by Saturation Curves
(for market integration using block bids)



Energy Flexibility
Some Demo Projects

- Control of WWTP (Krüger, ED, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Green Houses (NeoGrid, Danfoss, Fj.Fyn, ...)
- CHP (Dong Energy, FjernvarmeFyn, HOFOR, NEAS, ...)
- Industrial production (DI, ...)
- EV (charging) (ED, Charge-ME, ...)
- ....

Summary

- A Smart-Energy OS for implementing flexibility in electric energy systems has been described
- Built on: Big Data Analytics, Cyber Physical systems, Stochastic opt./control, Forecasting, IoT, IoS, Cloud computing, ...
- **Modelling**: Toolbox – CTSM-R - for combined physical and statistical modelling (grey-box modelling)
- **Control:** Toolbox – MPC-R - for Model Predictive Control
- **Simulation:** Framework for simulating flexible power systems.
- Two models for ***operating flexibility*** have been suggested and demonstrated:
  - **Dynamic models** (used for E-MPC based on prices / indirect control)
  - **Saturation curves** (used for market bidding / direct control)

For more information ...

See for instance

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...or contact

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