Models and methods for facilitating energy flexibility in buildings and districts

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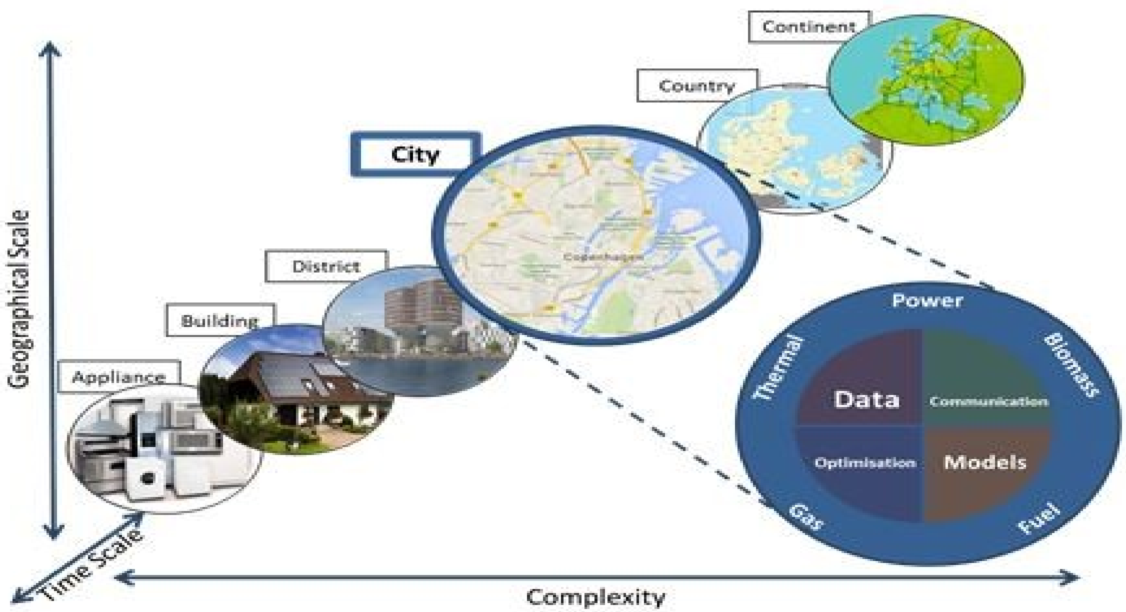
Flexible Solutions and CITIES

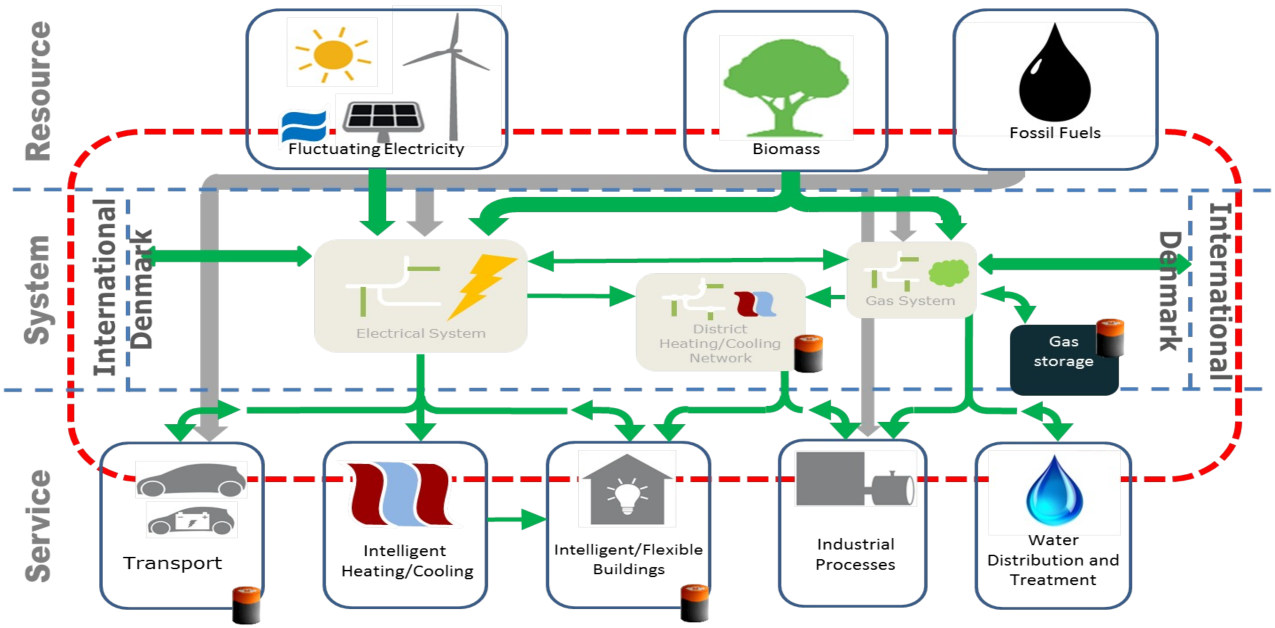
The ***Center for IT-Intelligent Energy Systems in Cities (CITIES)*** is aiming at establishing methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales.

CITIES is currently the largest Smart Cities and ESI research project in Denmark – see http://www.smart-cities-centre.org .

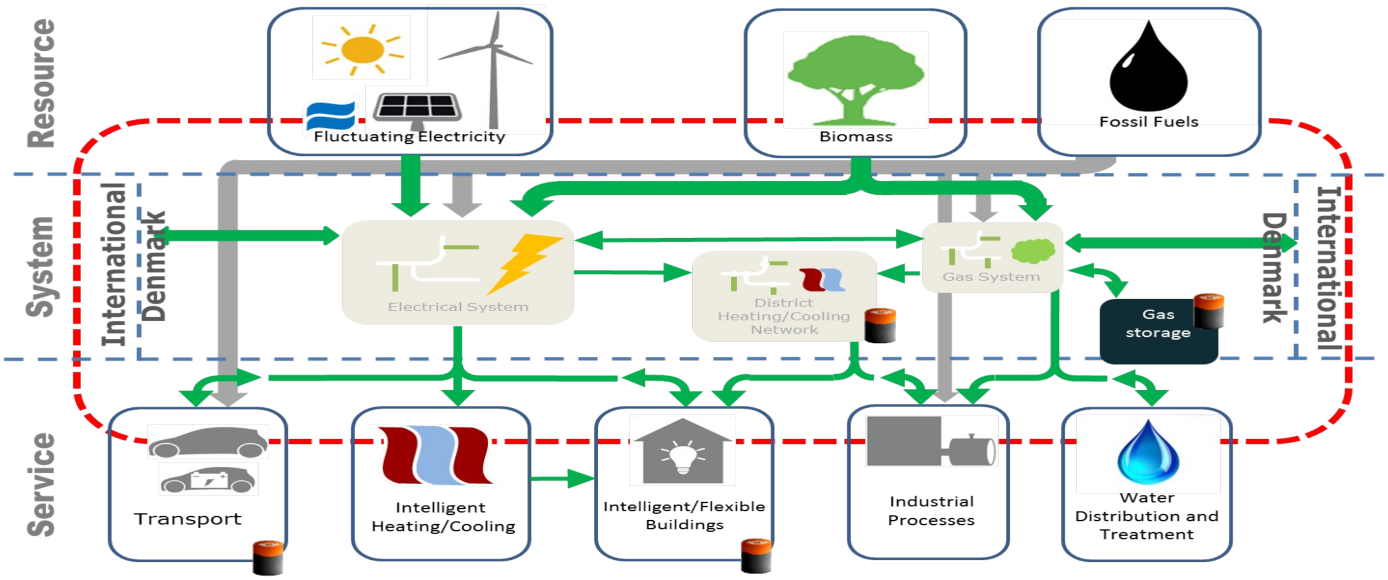


Models for integration and flexibility

Intelligent systems integration using **data and ICT solutions** are used to establish **grey-box models and methods for real-time operation of flexible energy systems**



Virtual Storage by Energy Systems Integration



- **Denmark (2014) : 48 pct of power load by renewables (> 100 pct for some days in January)**
- **(Virtual) storage principles:**
  - Buildings can provide storage up to, say, 5-12 hours ahead
  - District heating/cooling systems can provide storage up to 1-3 days ahead
  - Gas systems can provide seasonal storage

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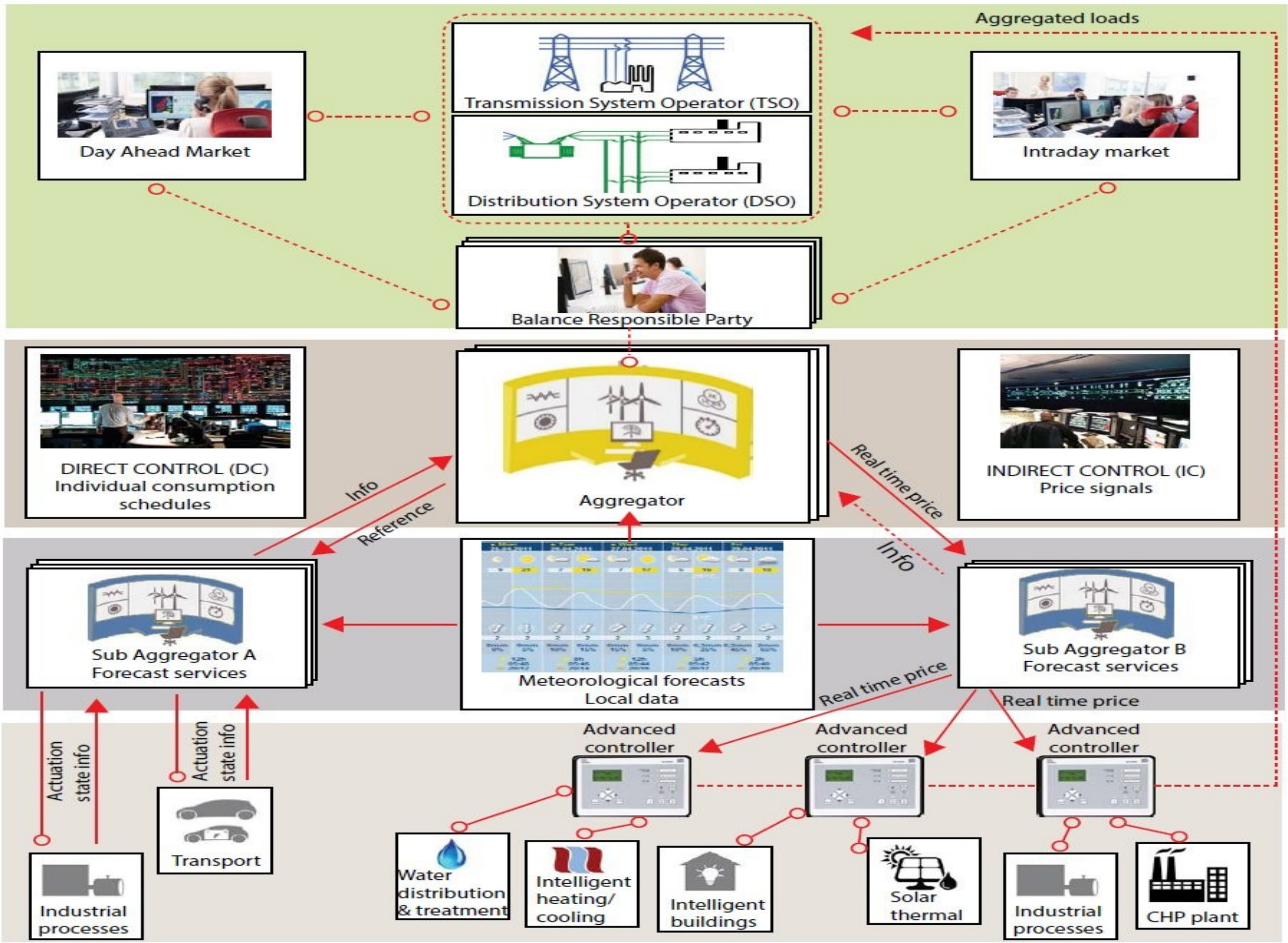
Smart-Energy OS



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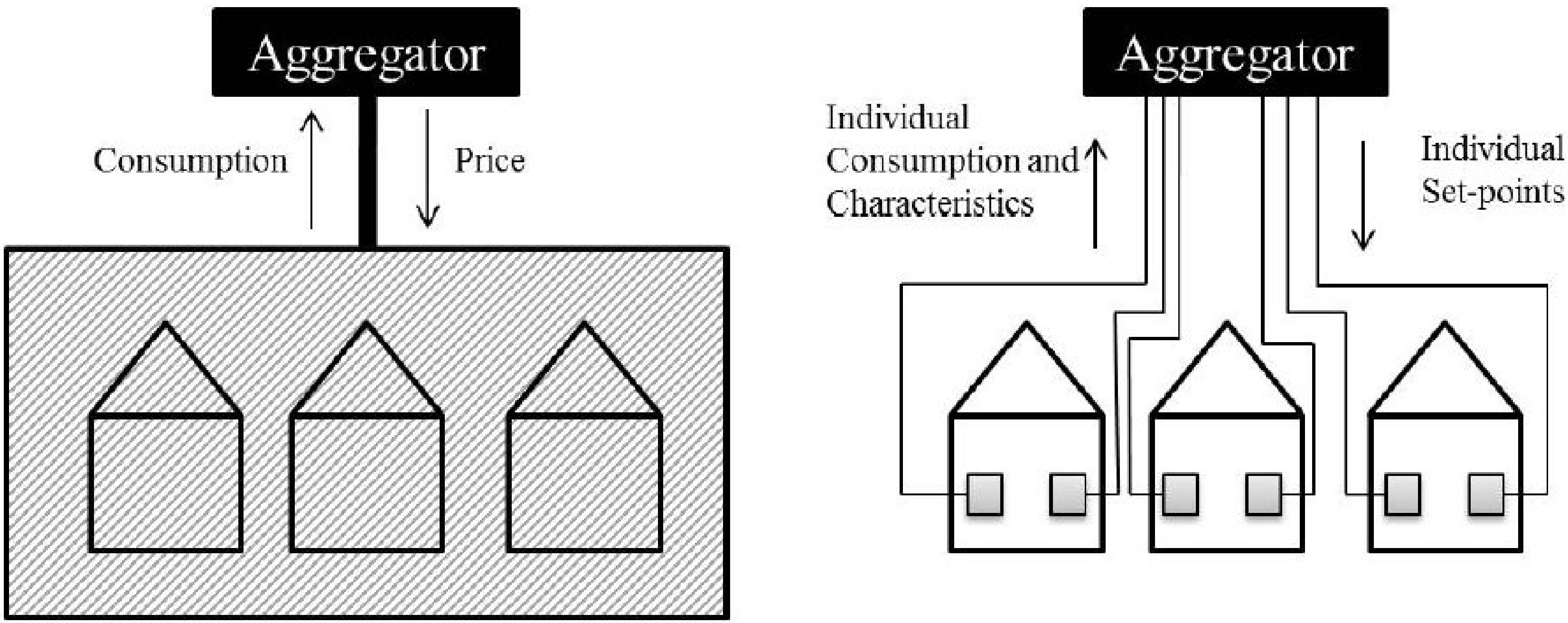
Direct and Indirect Control

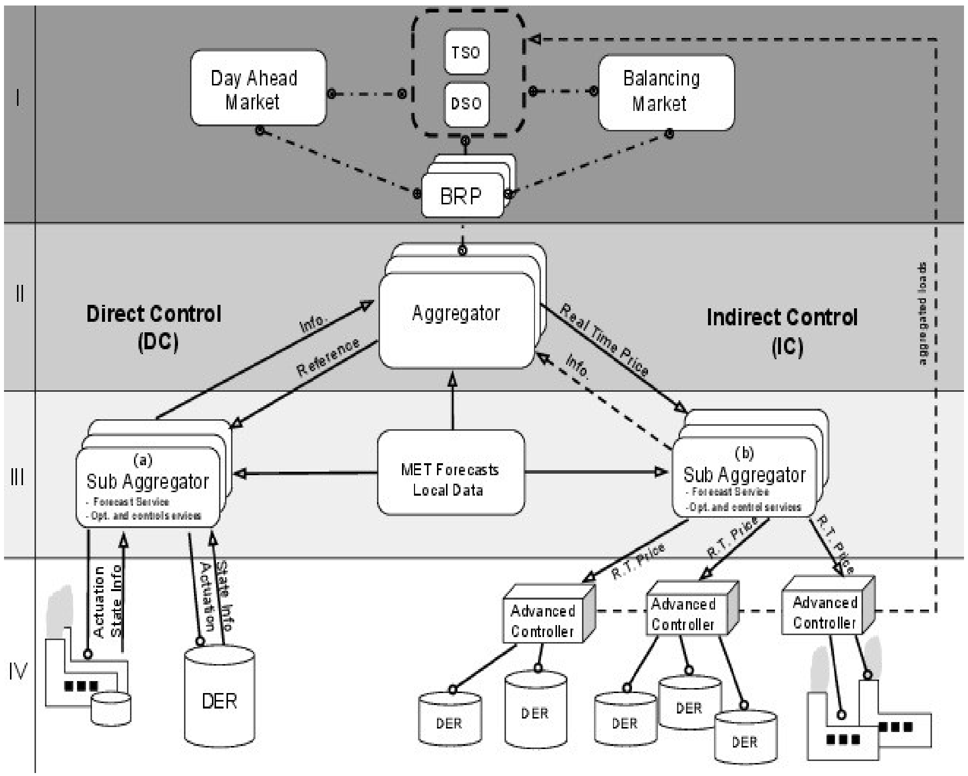
For DC info about individual states and constraints are needed



(a) Indirect control (b) Direct control

Control and Optimization

DTU



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: **<u>Power</u>**

Two-way communication

Models for DERs are needed

Constraints for the DERs (calls for state est.)

Contracts are complicated

Indirect Control:

Actuator: **<u>Price</u>**

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.

Model Predictive Control

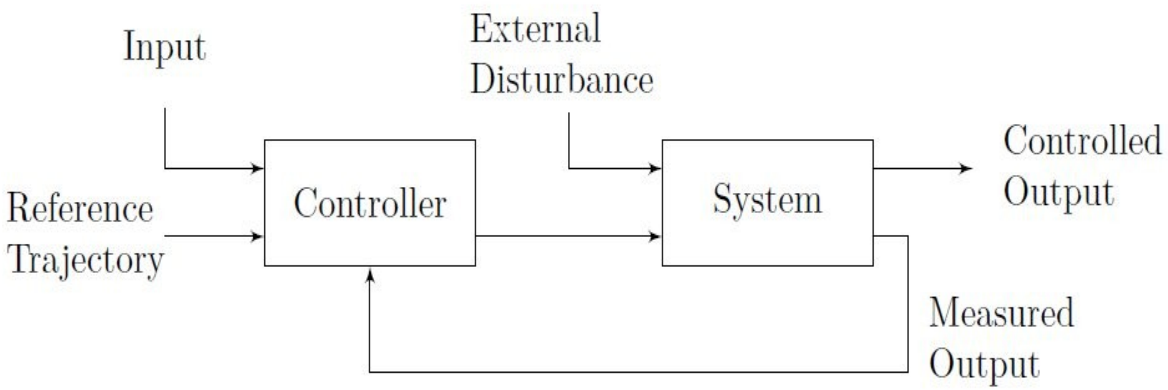


Figure A.1: Model Predictive Control Framework

Model Predictive Control

Simple example:

MPC for following a power reference with ARMAX model derived from a greybox model

$$\min_{\mathbf{P}} \sum_{t \in T_{opt}} (P_t - P_t^{ref})^2 + \nabla P_t \gamma \tag{A.1a}$$

subject to:

$$\phi(B) T_t = \omega(B) P_t \tag{A.1b}$$

$$\nabla P_t = P_t - P_{t-1} \tag{A.1c}$$

$$T^{min} \leq T_t \leq T^{max} \tag{A.1d}$$

$$P_t \leq P_{max} \tag{A.1e}$$

$$P_t \geq 0 \tag{A.1f}$$

The General Structure of Electricity Markets

Europe:
- Introduced new power exchanges (PXs)
- Emphasize markets and economics
- Include long-term contracts
- TSOs typically own transmission system
- VER as 'must take'

Market design elements:
- Day-ahead market (PX)
- Real-time balancing (TSO)
- Simple Bids
- Zonal pricing/market coupling
- Sequential reserve and energy markets

USA:
- Build into existing system operators (ISOs)
- Emphasize physics of power syst.
- Short-term system operation
- ISOs do not own transmission system
- 'Dispatchable VER

Market design elements:
- Day-ahead market (ISO-hourly)
- Real-time market (ISO- 5 min)
- Complex bids
- Locational marginal prices
- Co-optimization of energy and reserves

Case study (Level III)

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

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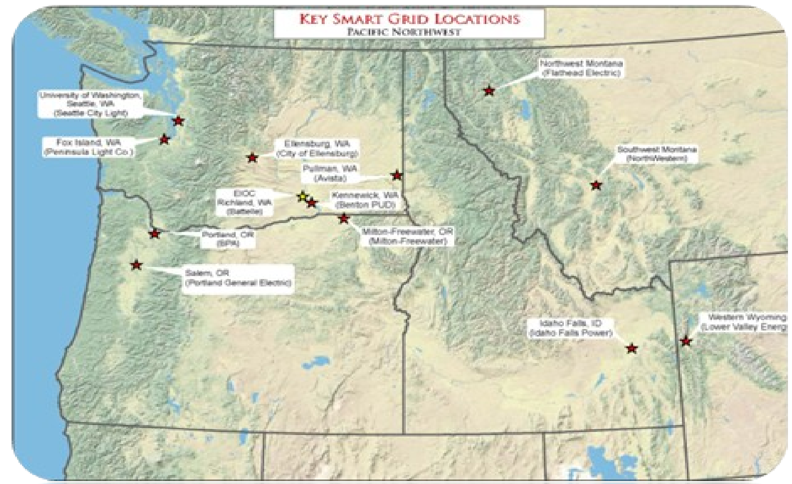
Data from BPA

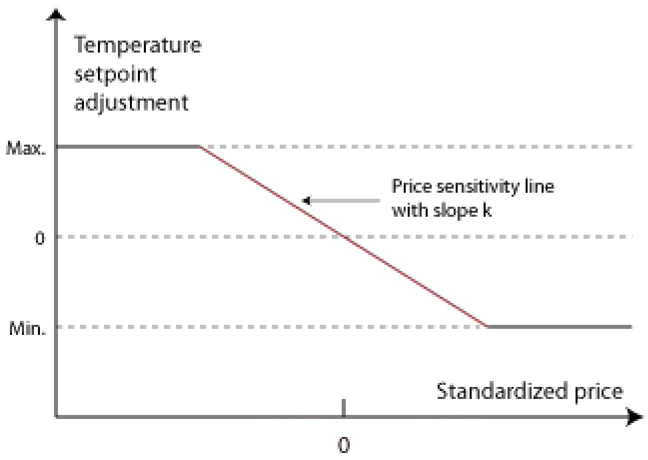
Olympic Pensinsula project

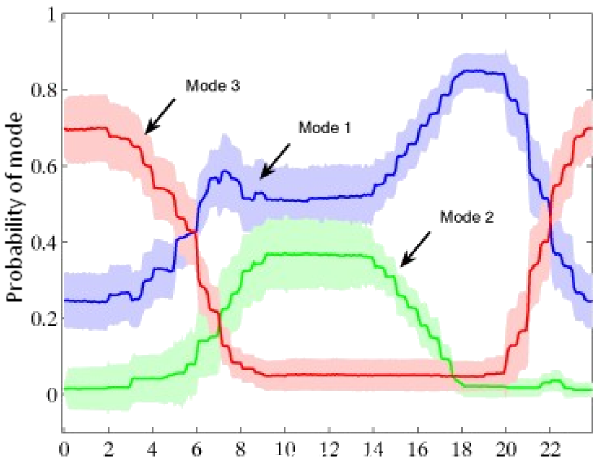
- 27 houses during one year
- Flexible appliances: HVAC, cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption



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).

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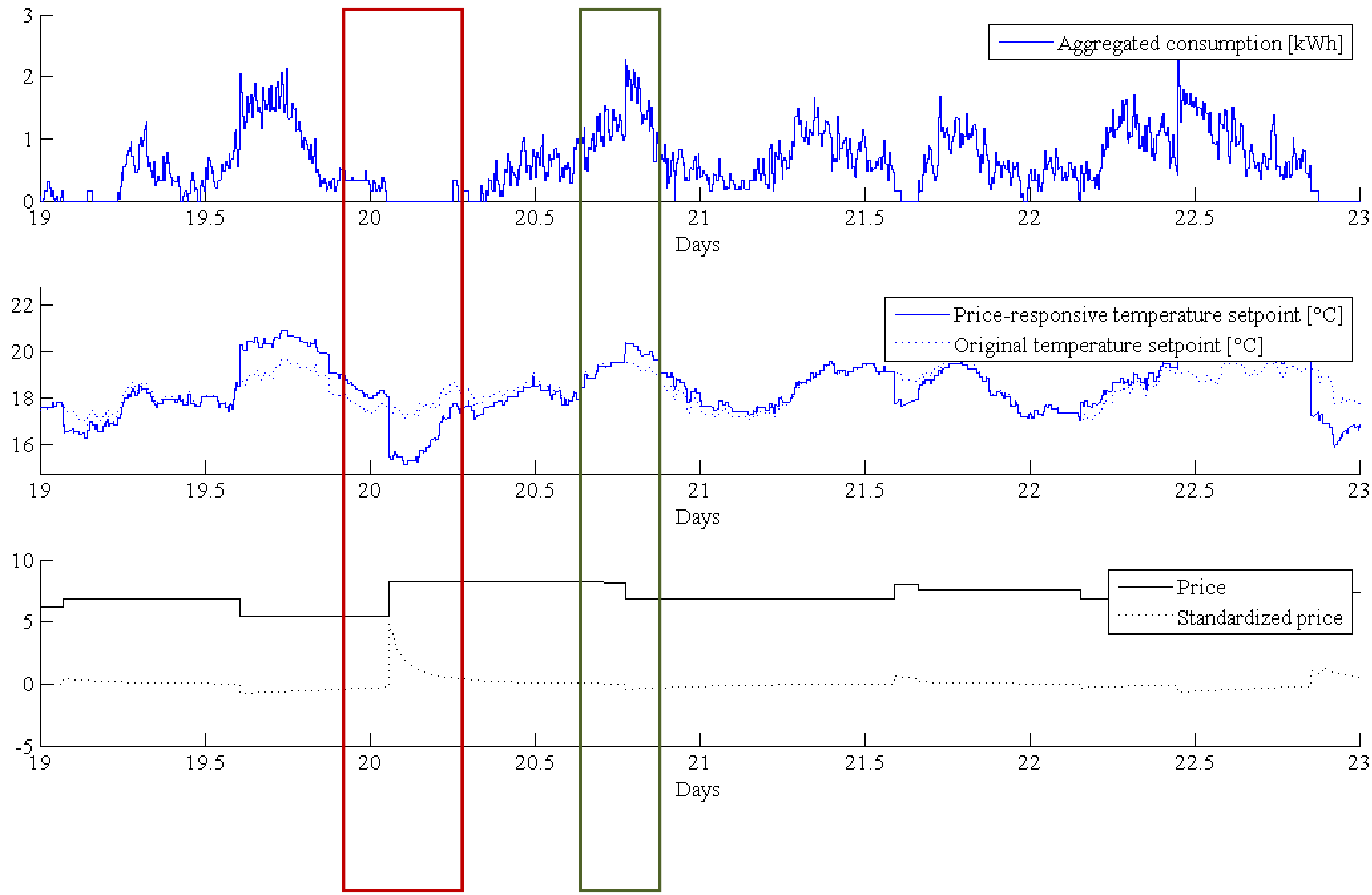
Aggregation (over 20 houses)



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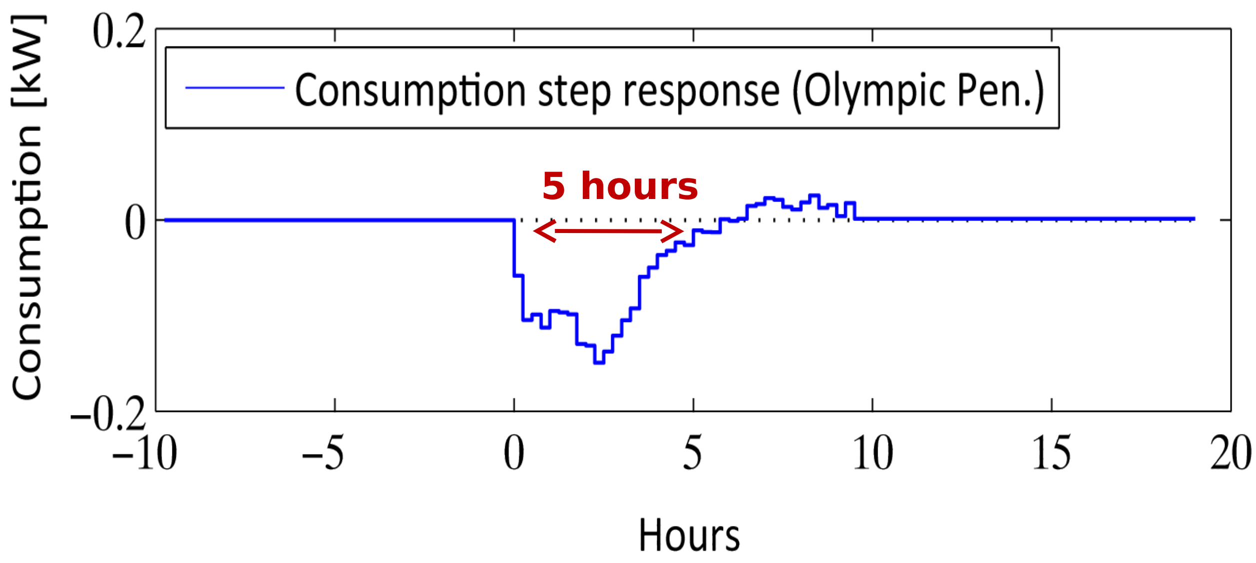
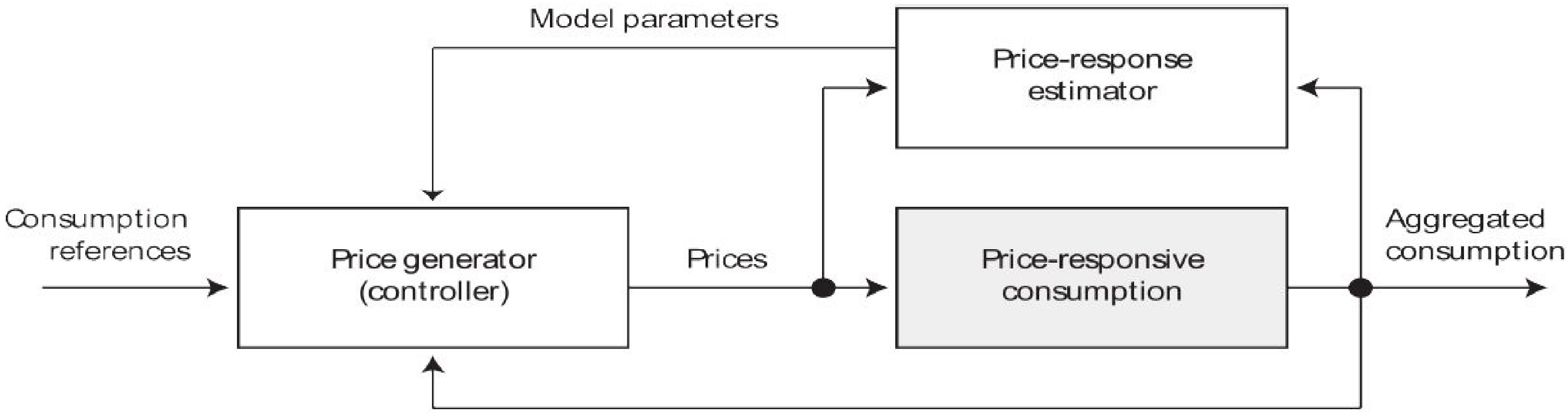
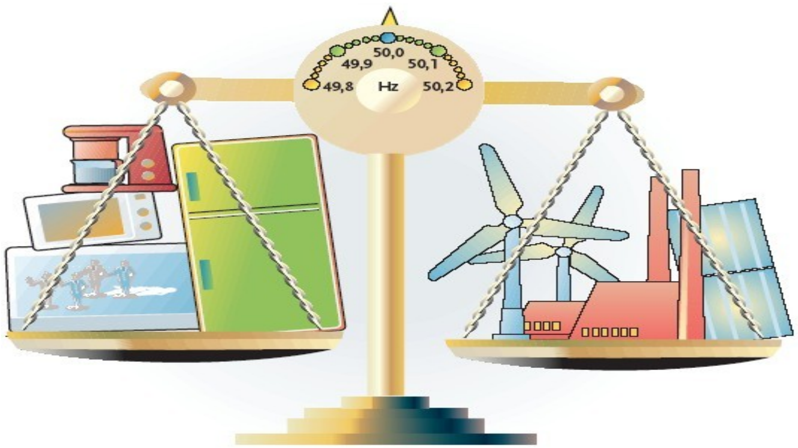
Response on Price Step Change



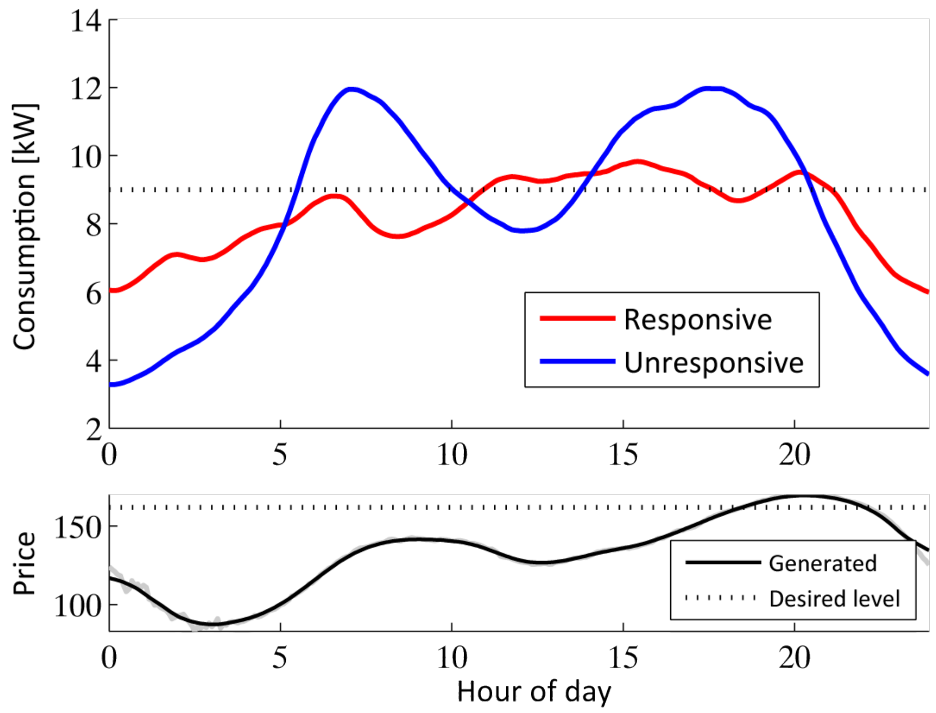
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**



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Case study (Level IV)

Control of Heat Pumps

(based on varying prices from Level III)

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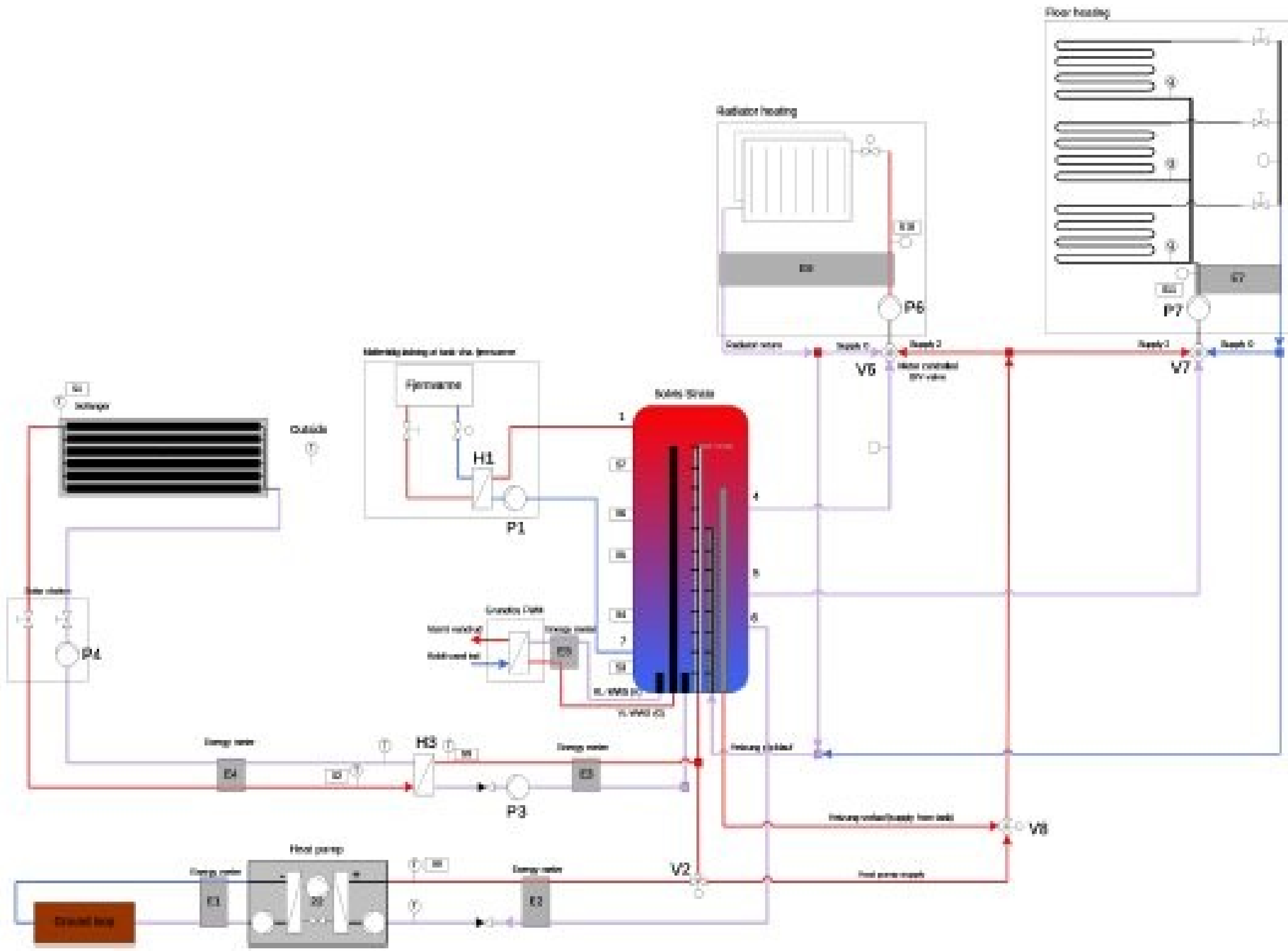
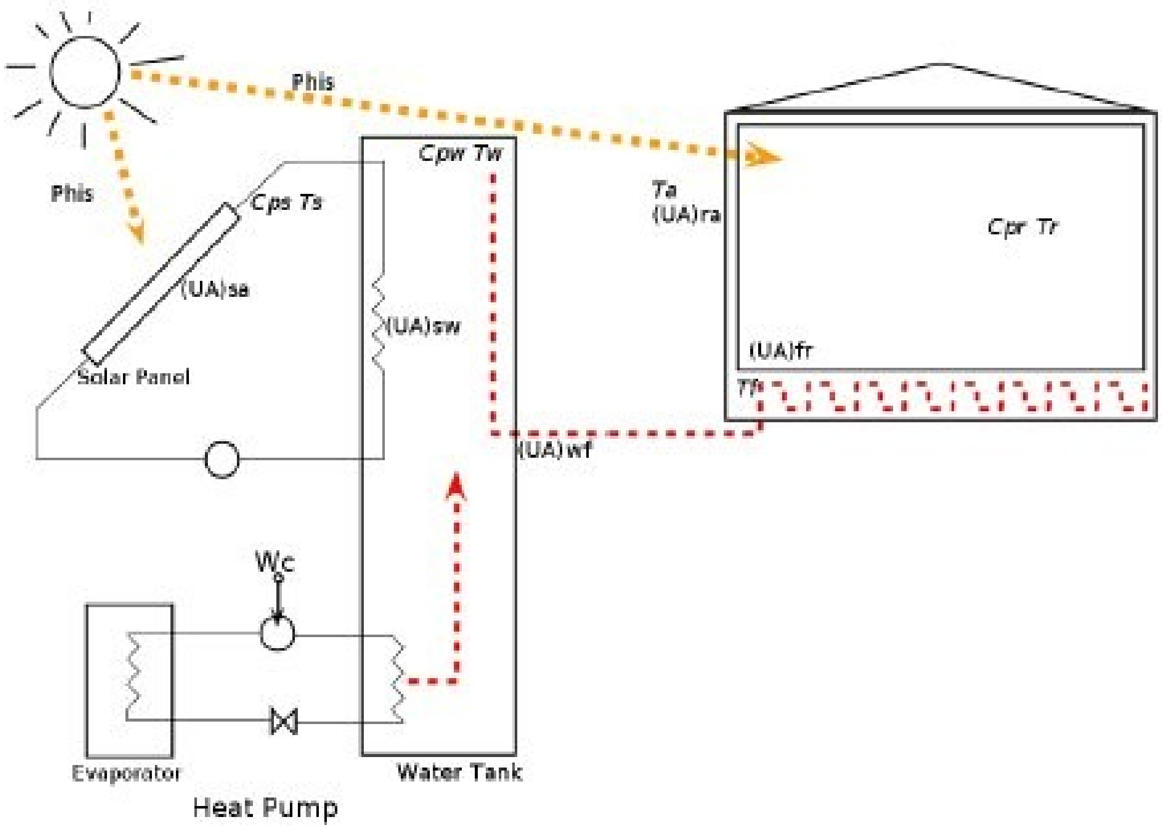
Grundfos Case Study

Schematic of the heating system



Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

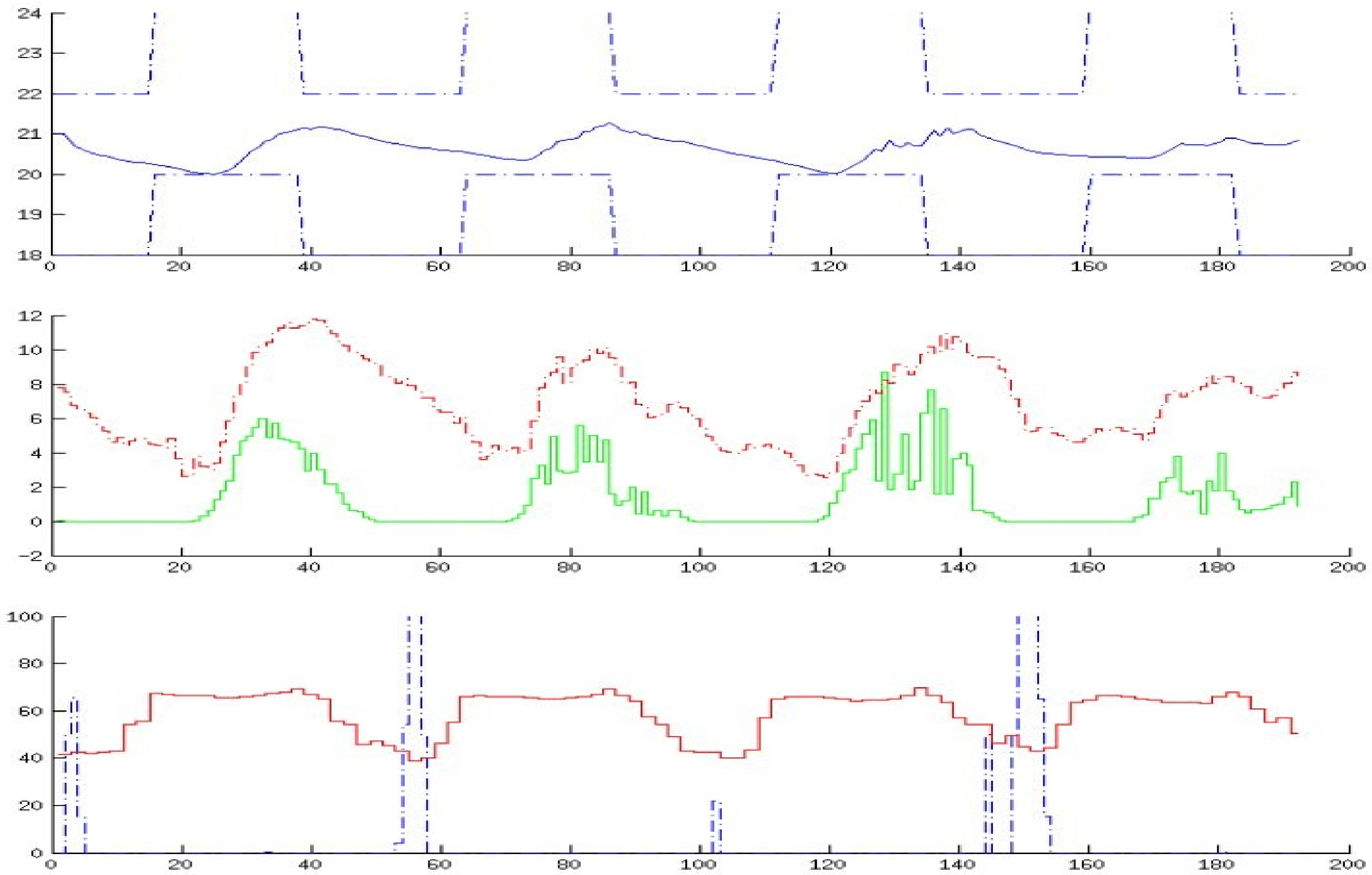
Formulation

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

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

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

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

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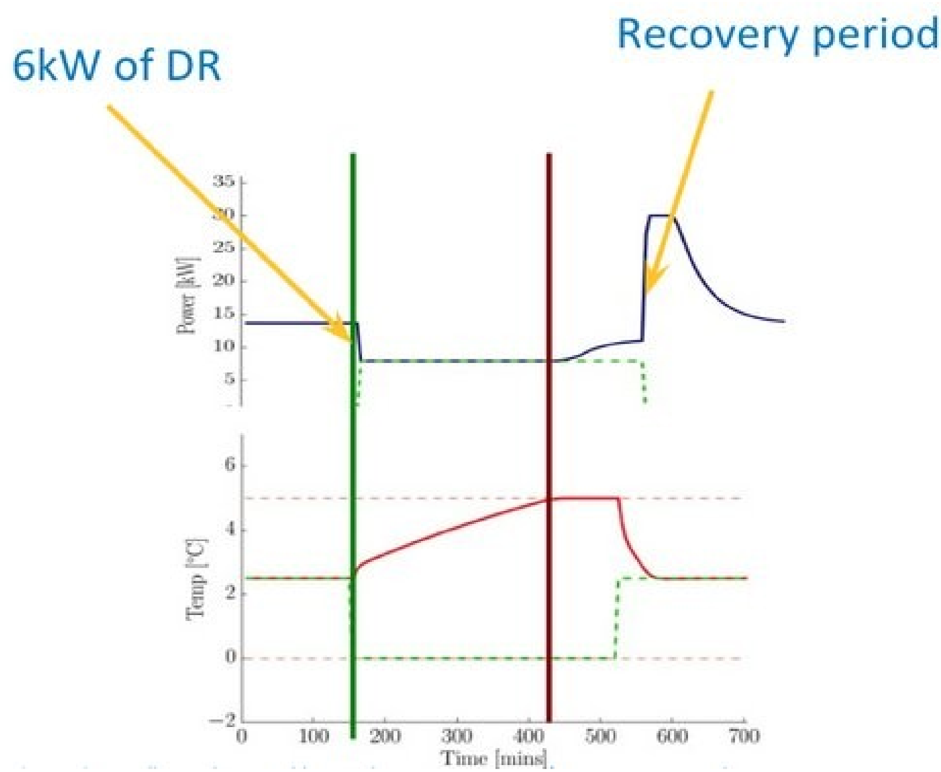
Synergize: Virtual Storage using Thermal Demand Response

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



The physical system

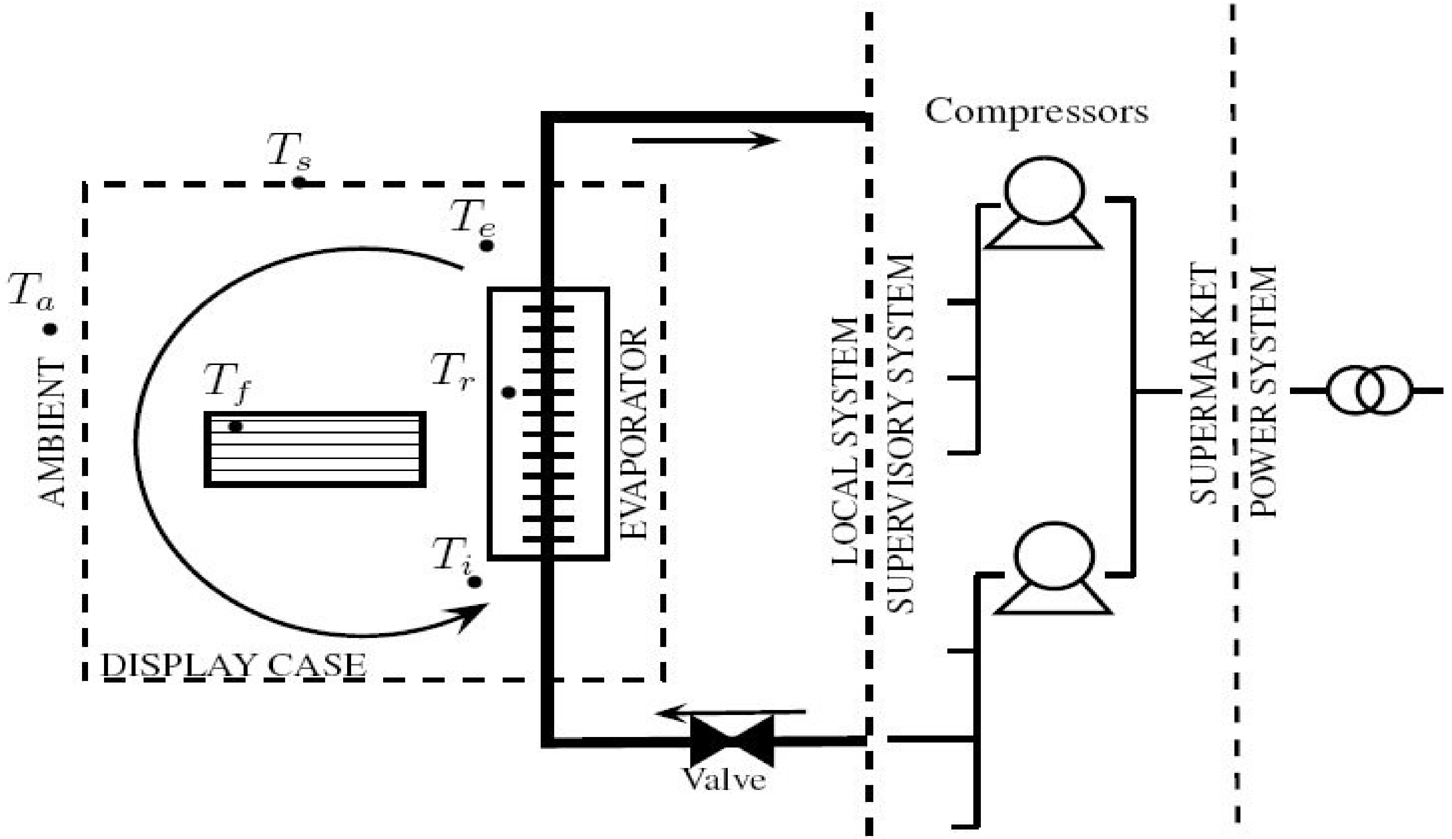


Fig. 2: Simplified graphical representation of the display case system

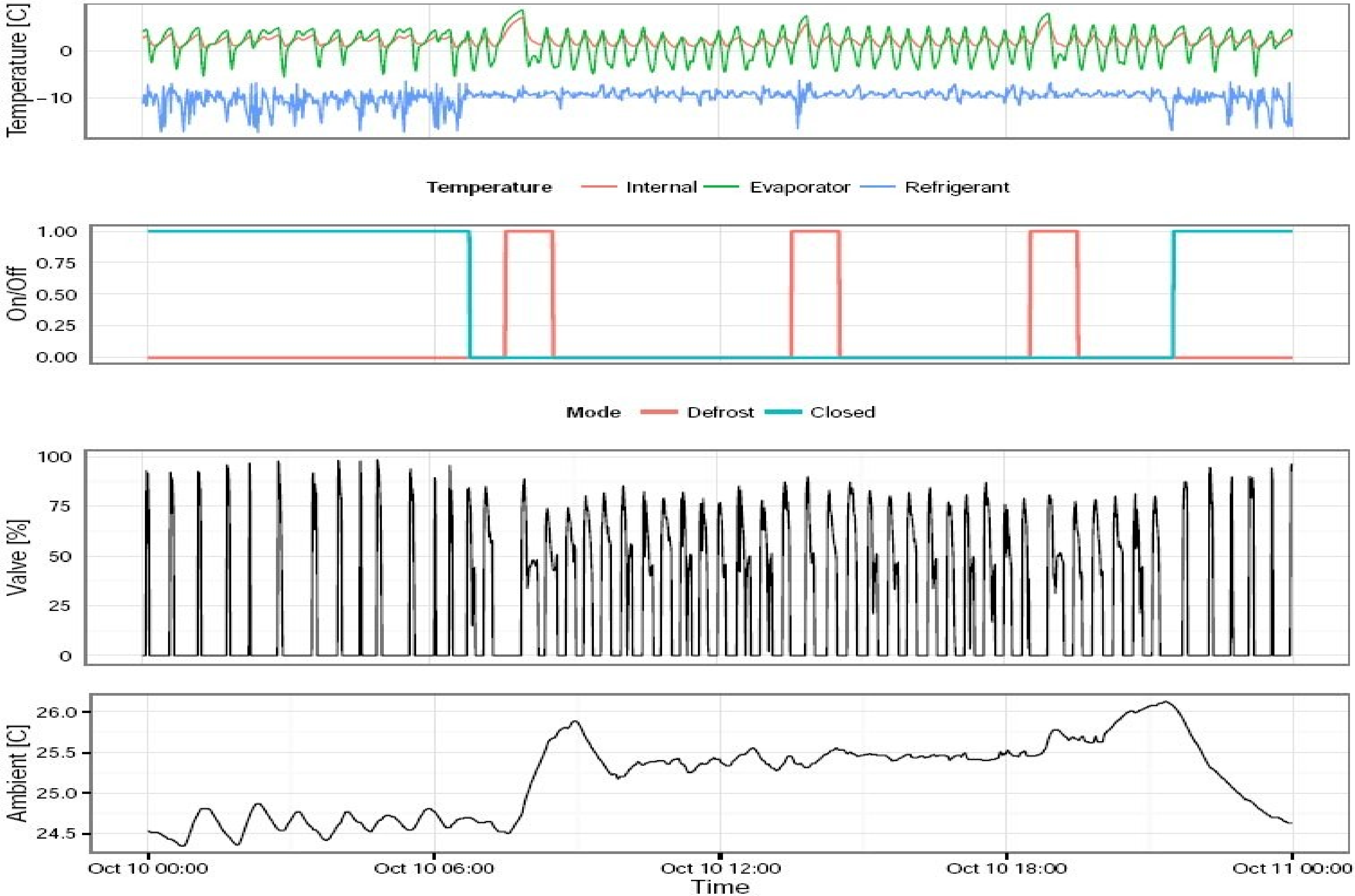


Fig. 3: Temperature, environmental (open/closed status, defrost status, ambient temperature) and control input (valve) data for an open medium temperature display case in a supermarket in Funen, Denmark

The grey-box model

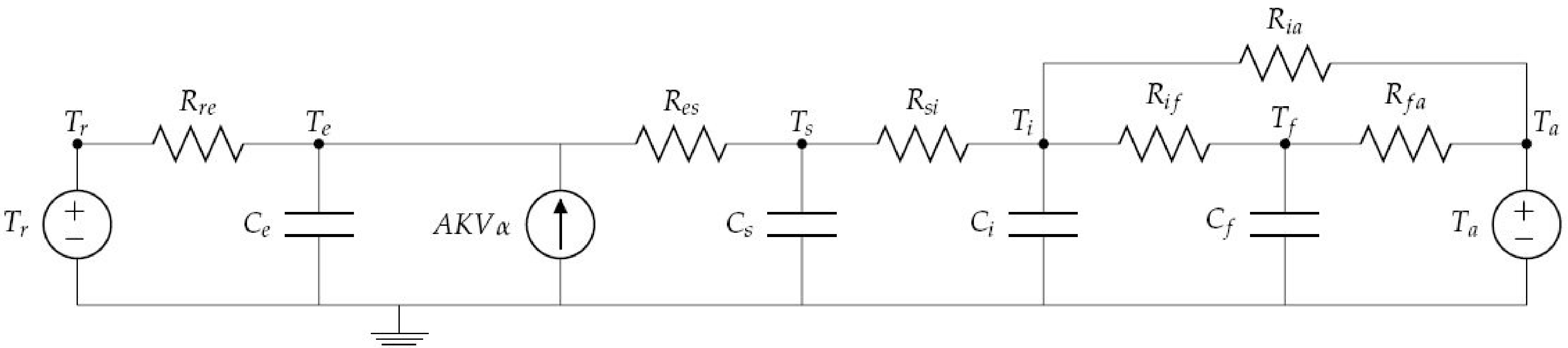


Fig. 6: RC-Representation of a four time constant model $(T_i T_e T_f T_s)$

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**

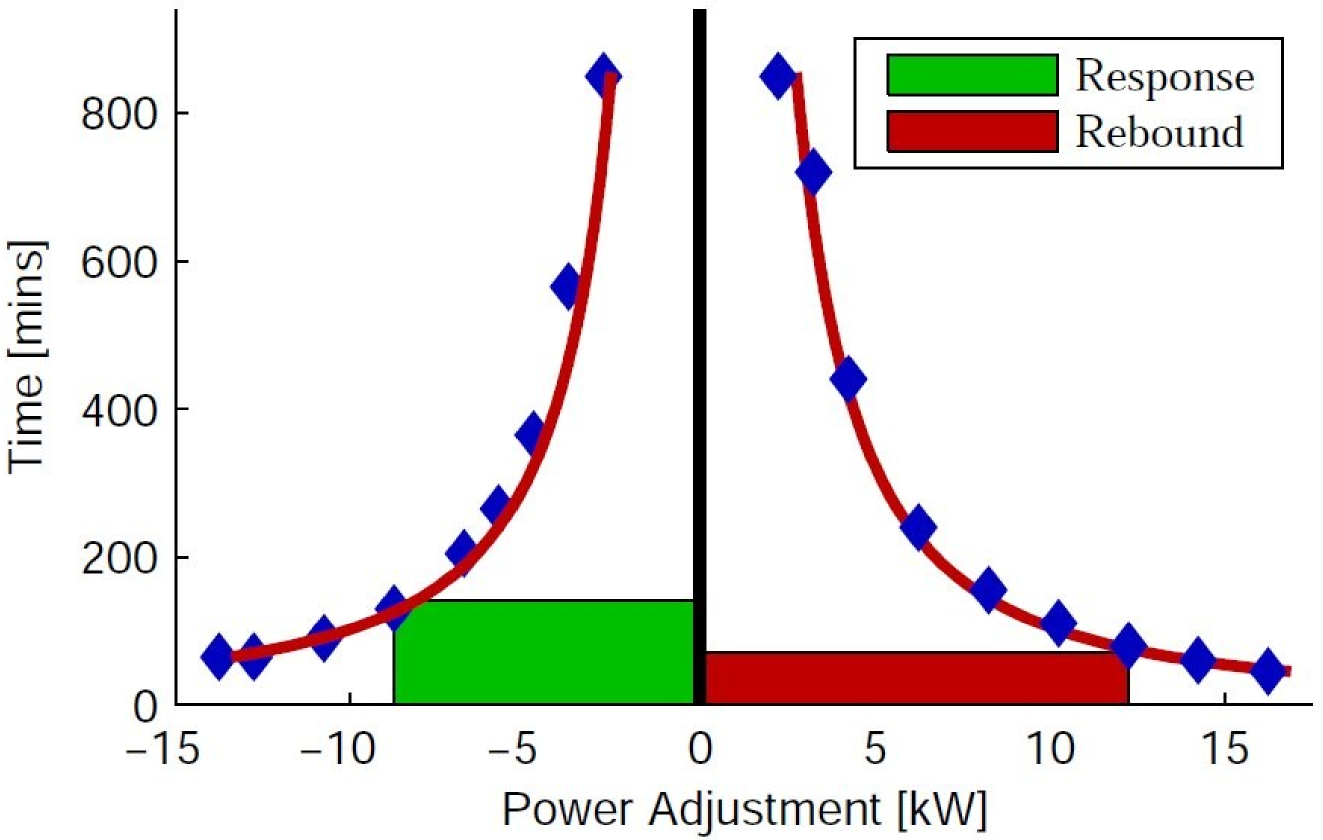
$$\min \sum_{n=1}^{N} \left(P_n - P_n^{ref}\right)^2$$

- Indirect Control
  - **Economic MPC**

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

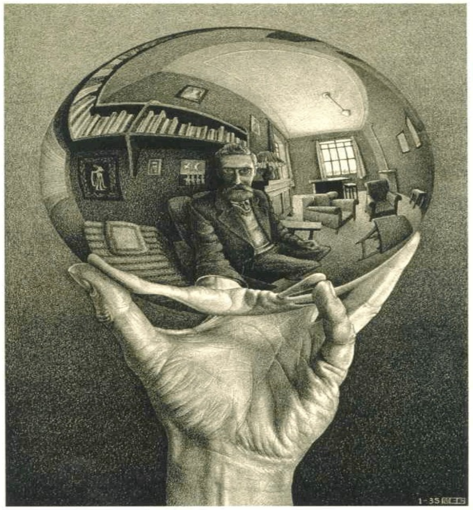
- Note all controller formulations are "MPC" – i.e. forecasts of price/references only available up to a fixed horizon – control consists of a sequence of receding horizon optimisations

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



Energy Flexibility
Some Demo Projects in CITIES

- Control of WWTP (ED, Kruger, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Summerhouses (DC, Nyfors, ..)
- Green Houses (NeoGrid, ENFOR, ...)
- CHP (Dong Energy, EnergiFyn, ...)
- Industrial production
- VE (charging)
- ....



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Software solutions

Software for combined physical and statistical modelling

Continuous Time Stochastic Modelling (CTSM) is a software package for modelling and simulation of combined physical and statistical models. You find a technical description and the software at CTSM.info.

Software for Model Predictive Control

HPMPC is a toolbox for High-Performance implementation of solvers for Model Predictive Control (MPC). It contains routines for fast solution of MPC and MHE (Moving Horizon Estimation) problems on embedded hardware. The software is available at GitHub.

Search ...

Latest news

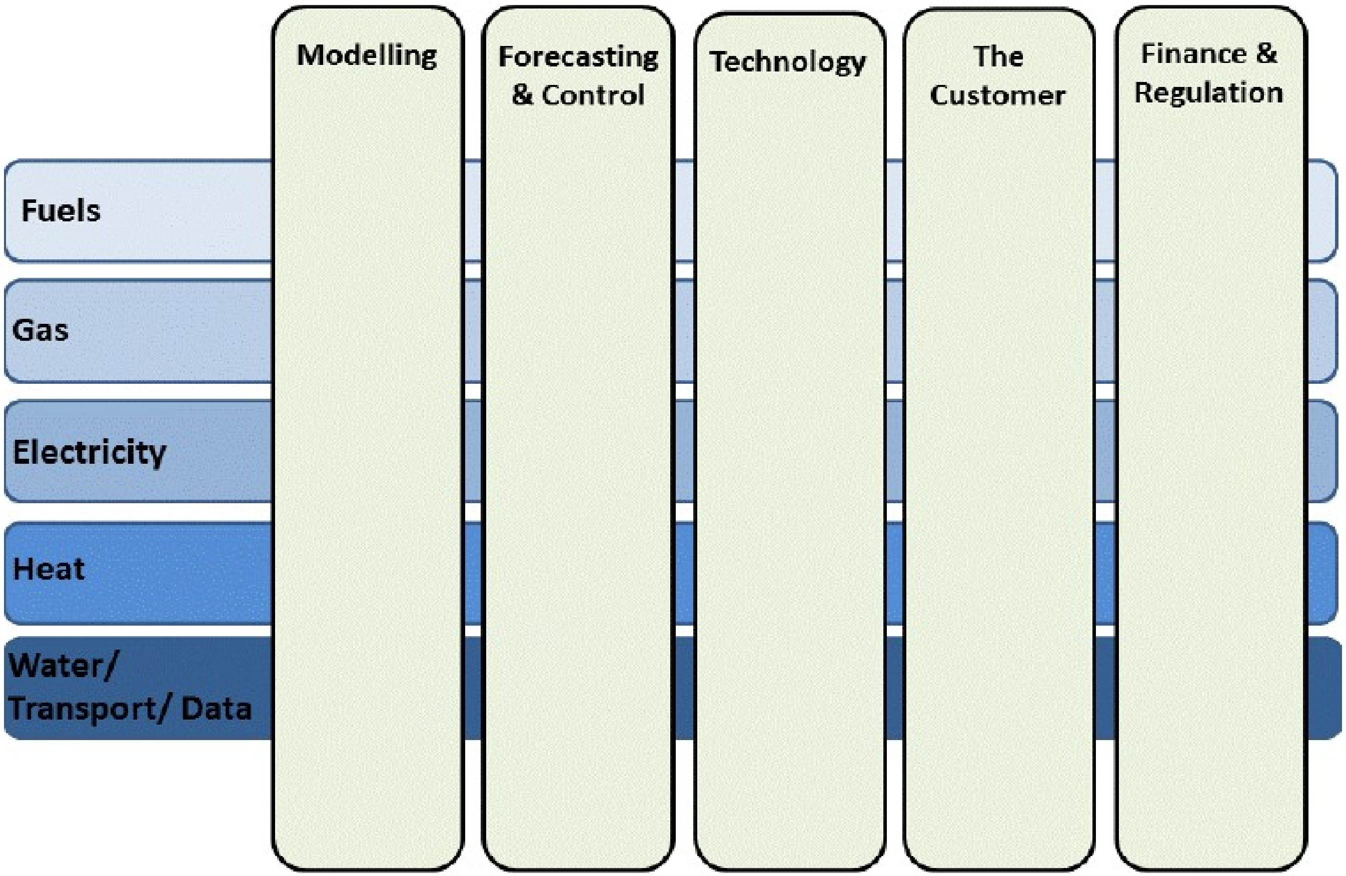
- Ambassador Louise Bang Jespersen visited CITIES, October 29th 2015
- CITIES Korean International Workshop – KIER, Daejeon, Korea, October 22nd 2015
- Workshop on Mathematical Sciences Collaboration in Energy Systems Integration – DTU,

Summary

- A Smart-Energy OS for implementing flexibility has been described
- **Modelling**: Toolbox – CTSM-R - for combined physical and statistical modelling (grey-box modelling)
- **Control:** Toolbox – MPC-R - for Model Predictive Control
- Toolboxes found on the homepage of our CITIES project
- Two models for ***characterizing the 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)

(Kick-off meeting 9-10 May 2016):

ESI Joint Program as a part of European Research (EERA)



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For more information ...

See for instance

www.henrikmadsen.org

www.smart-cities-centre.org

...or contact

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Acknowledgement all my PhD and Post Doc Students and CITIES (DSF 1305-00027B)

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