Data-driven Modelling, Forecasting and Control for Buildings in the Future Low Carbon Society

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https://www.flexibleenergydenmark.dk/

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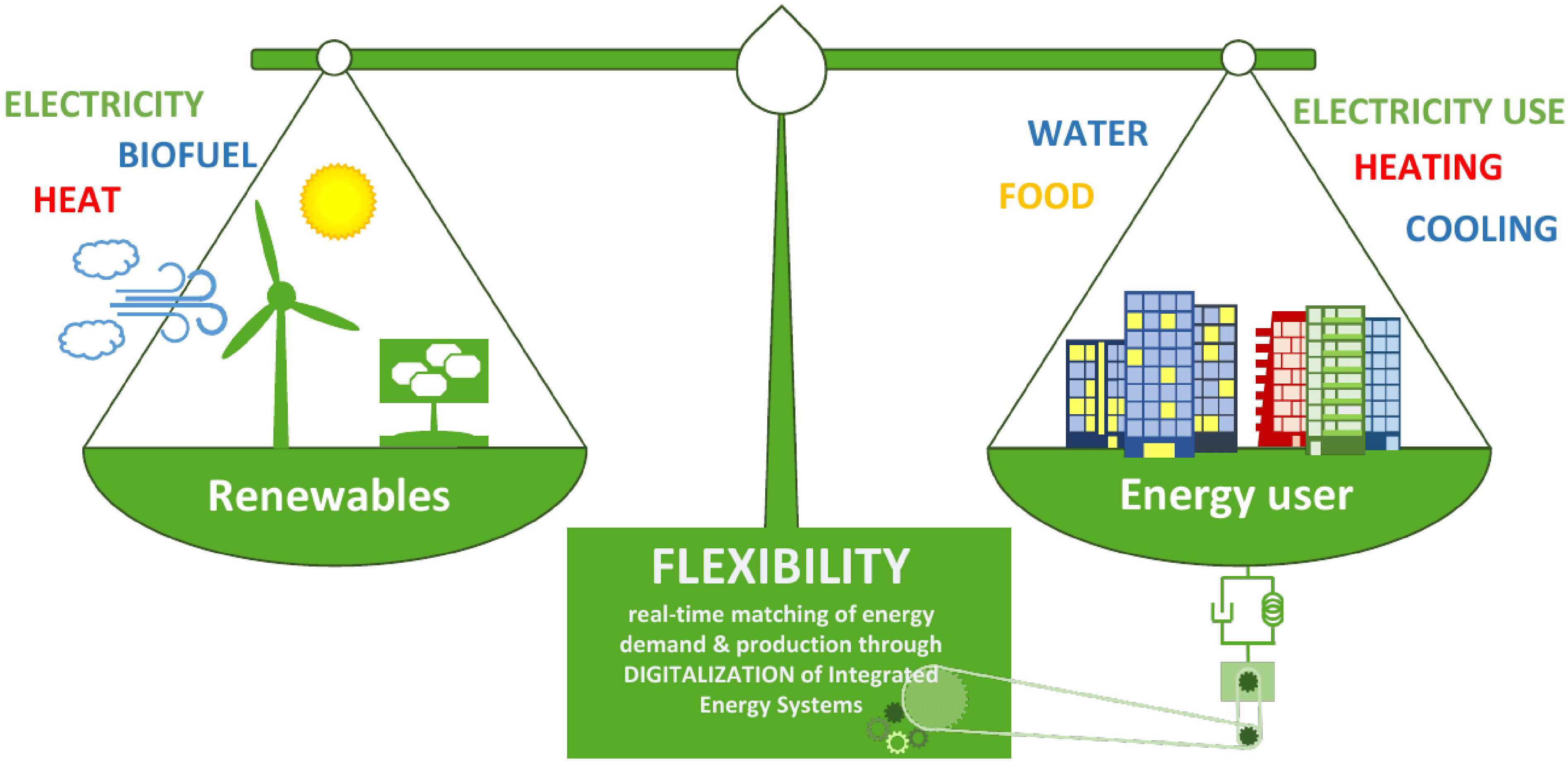
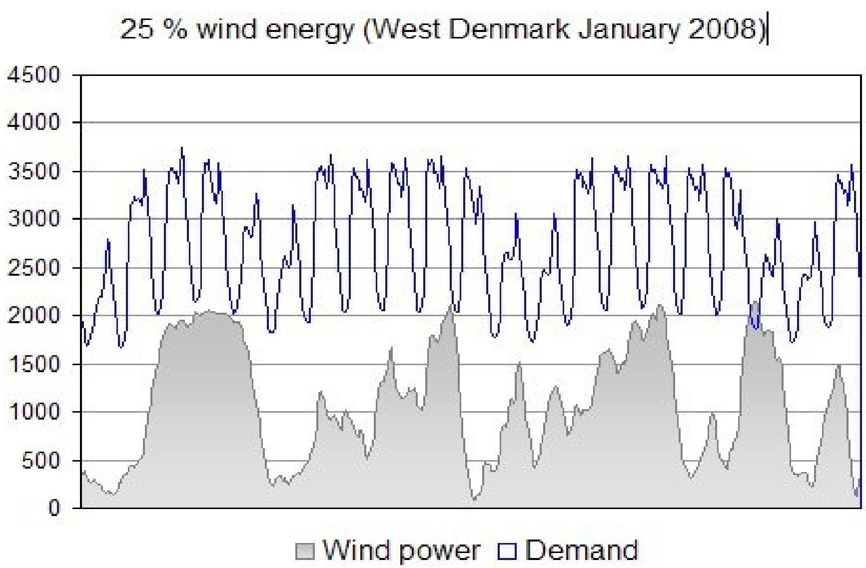
The Challenges

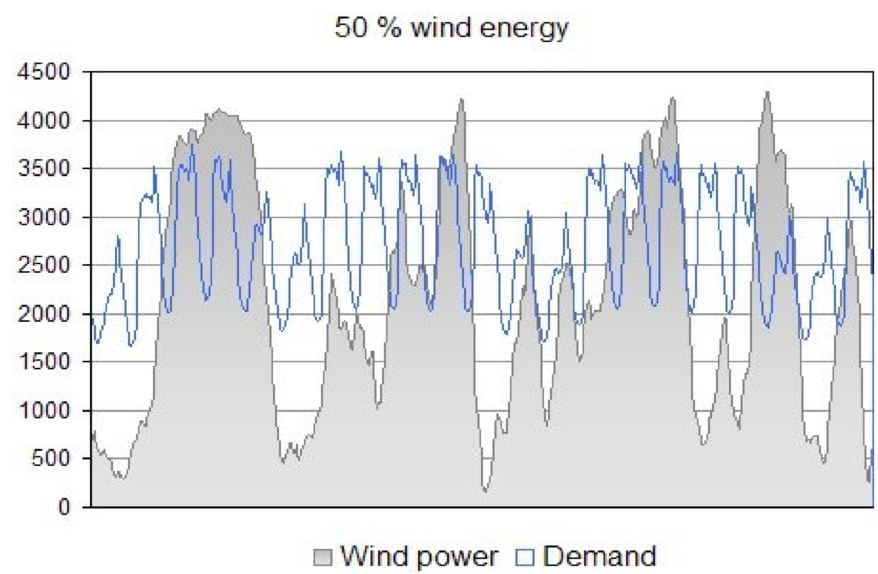
The Challenge: Denmark Fossil Free 2050



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 2020 Flexibility and End-user Engagement is Important (→ Need for Smart Buildings)

That's the topic of 'Flexible Energy Denmark'

(For several days the wind power production is more than 100 pct of the power load)

Combining grey-box modelling, forecasting and control (Smart-Energy OS)

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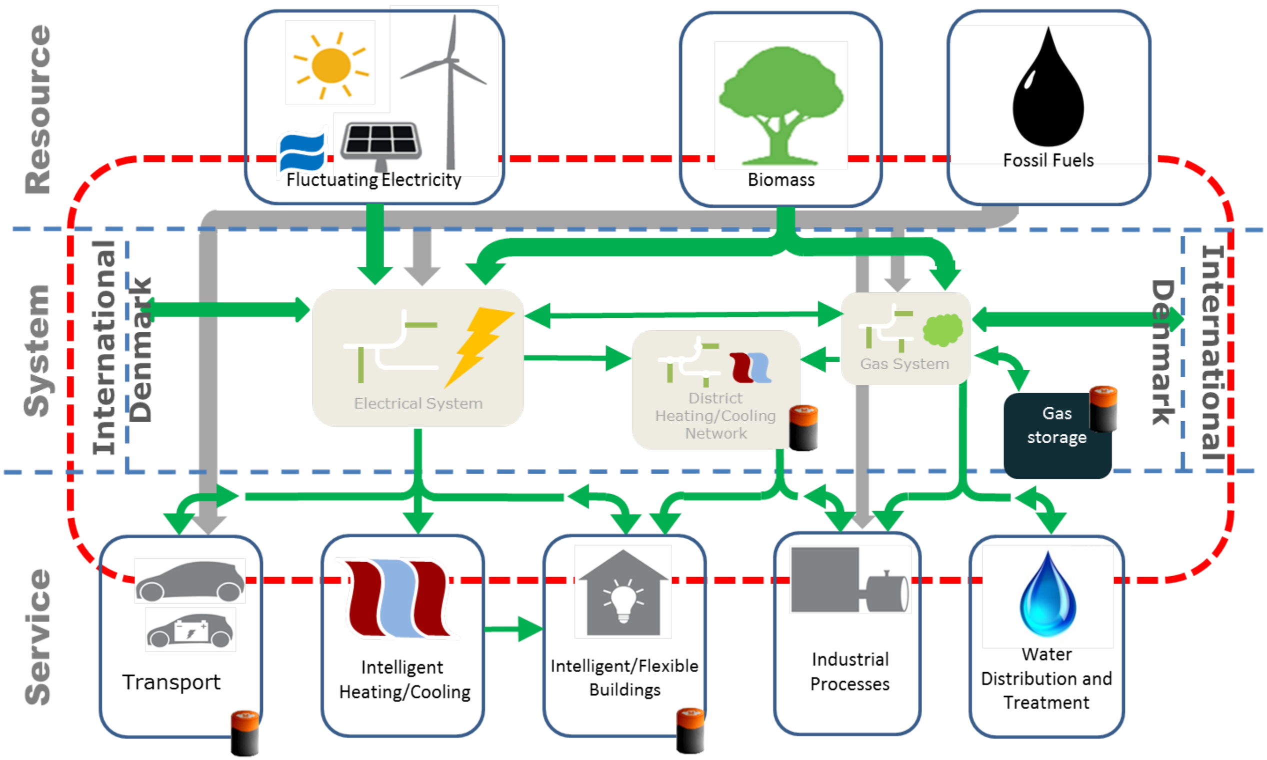
Energy System Models
for Real Time Applications and Data Assimilation

Grey-box models are simplified models for the individual components facilitating system integration and use of sensor data



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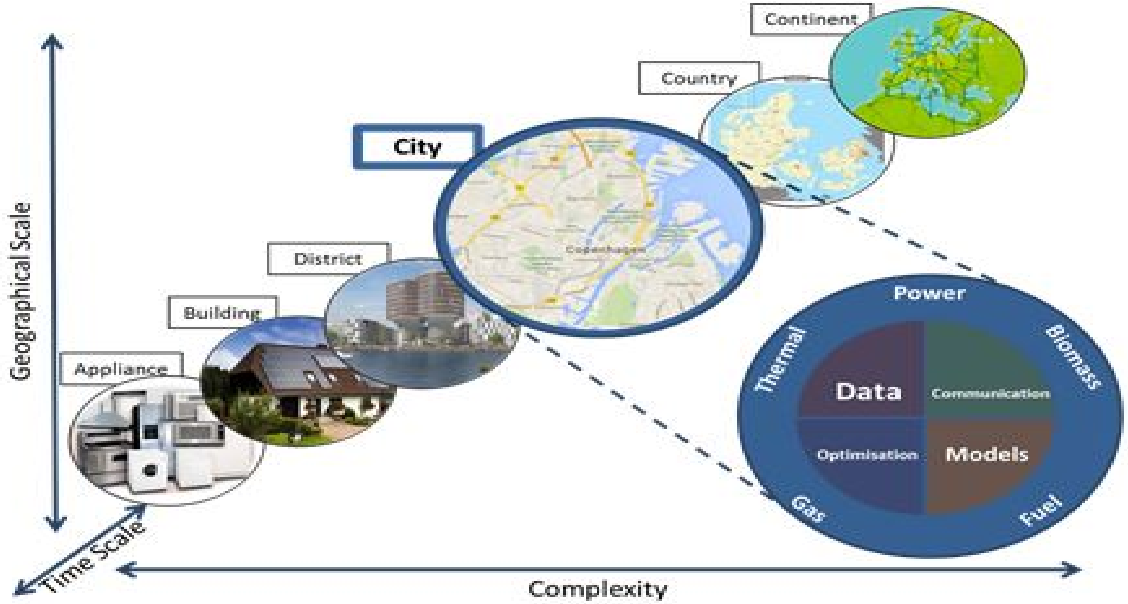
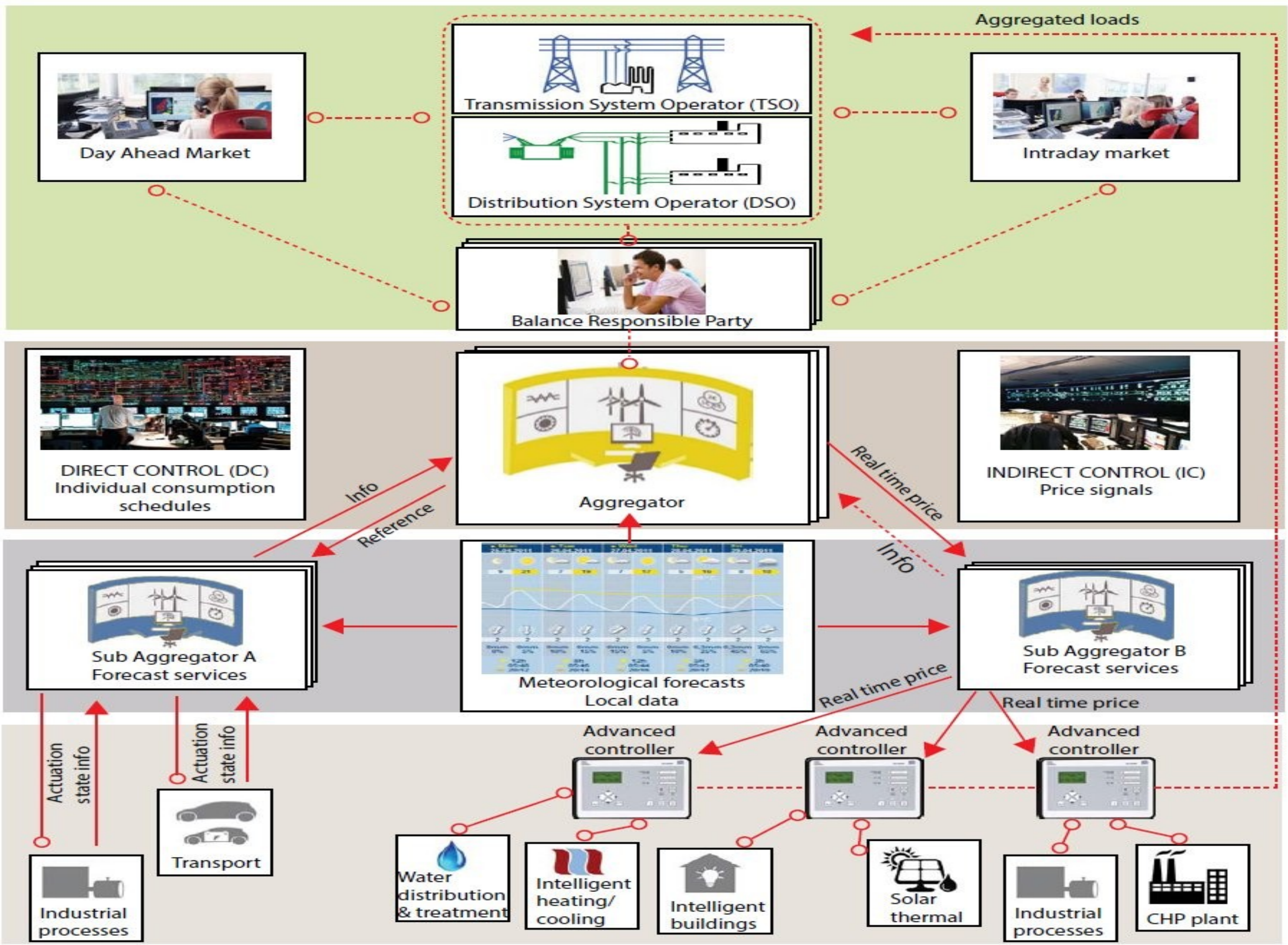
Temporal and Spatial Scales

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

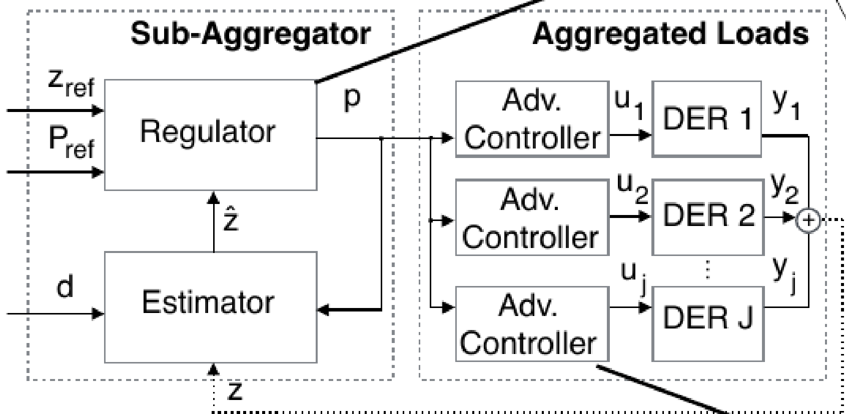


Smart-Energy OS



Proposed methodology
Control-based methodology

$$\min_{p} \quad \mathrm{E}[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||]$$
$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$

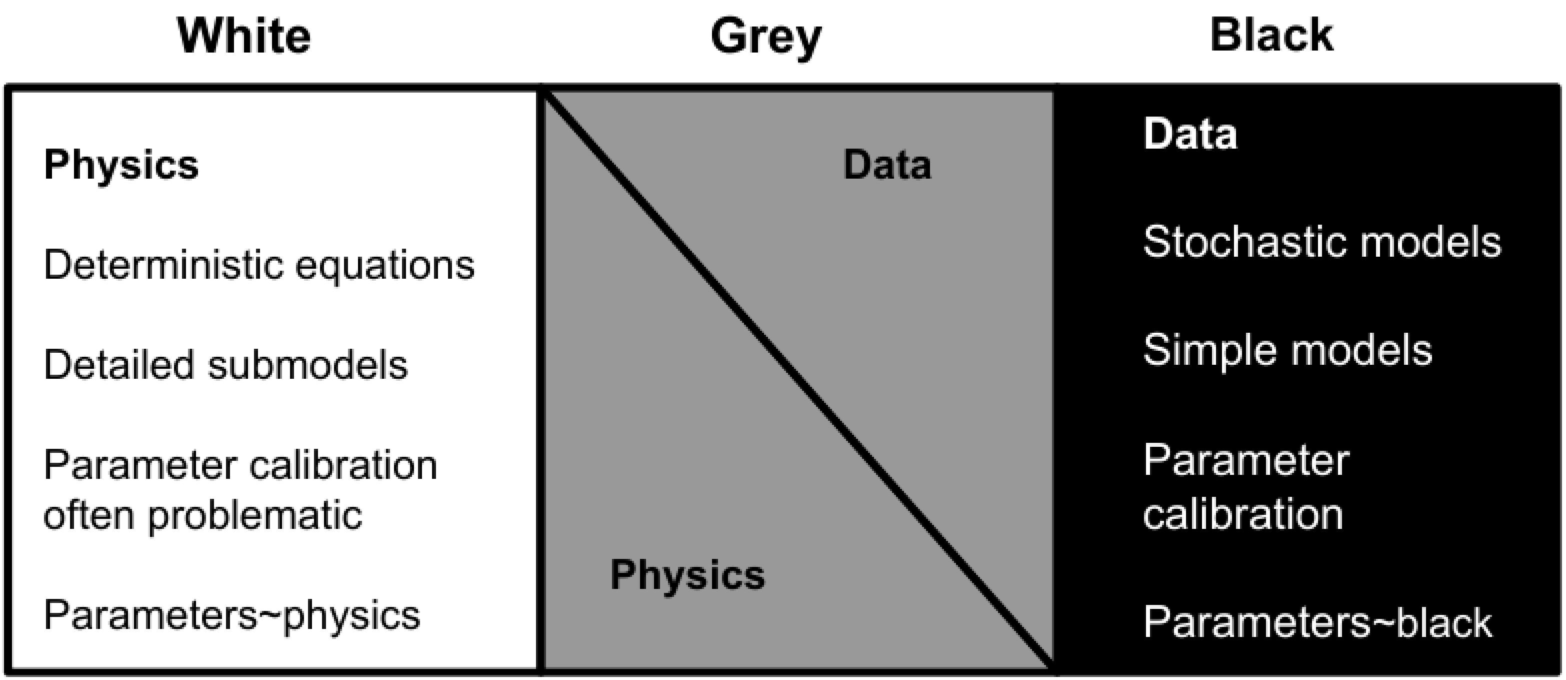


$$\min_{u} \quad \mathrm{E}[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)]$$
$$\begin{aligned} \text{s.t.} \quad x_{k+1} &= Ax_k + Bu_k + Ed_k, \\ y_k &= Cx_k, \\ y_k^{min} \leq y_k &\leq y_k^{max}, \\ u_k^{min} \leq u_k &\leq u_k^{max} \end{aligned}$$

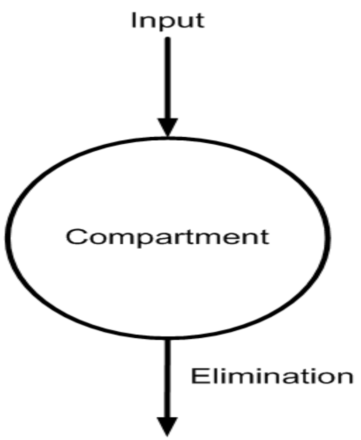
We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

Grey-box Modelling

Grey-box Modelling

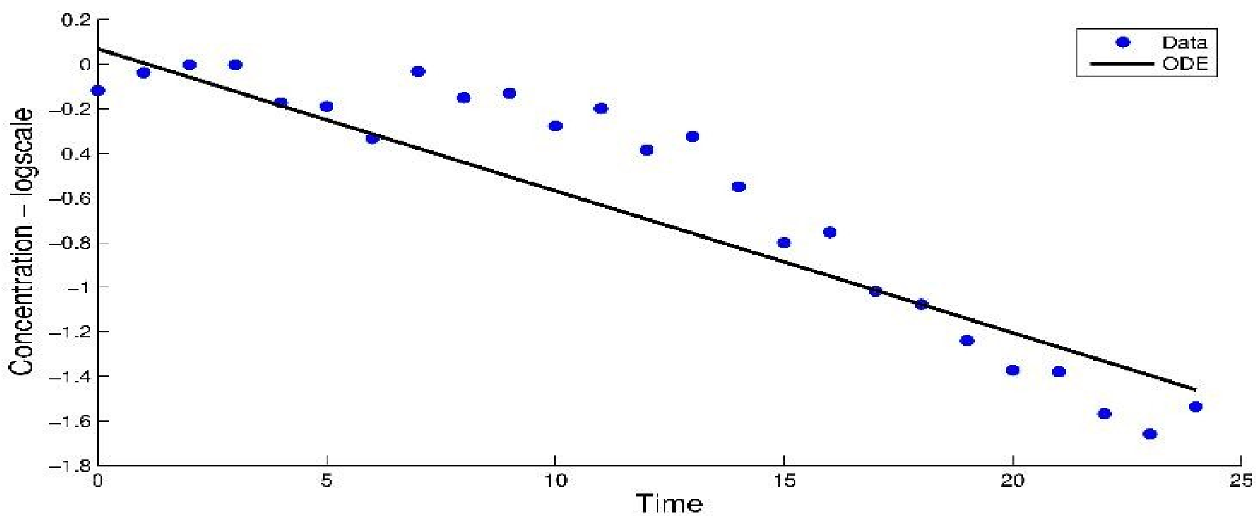


Traditional Dynamical Model

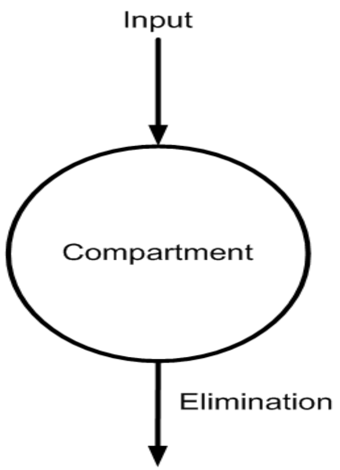


- Ordinary Differential Equation:

$$\begin{aligned} dA &= -KAdt \\ Y &= A + \epsilon \end{aligned}$$

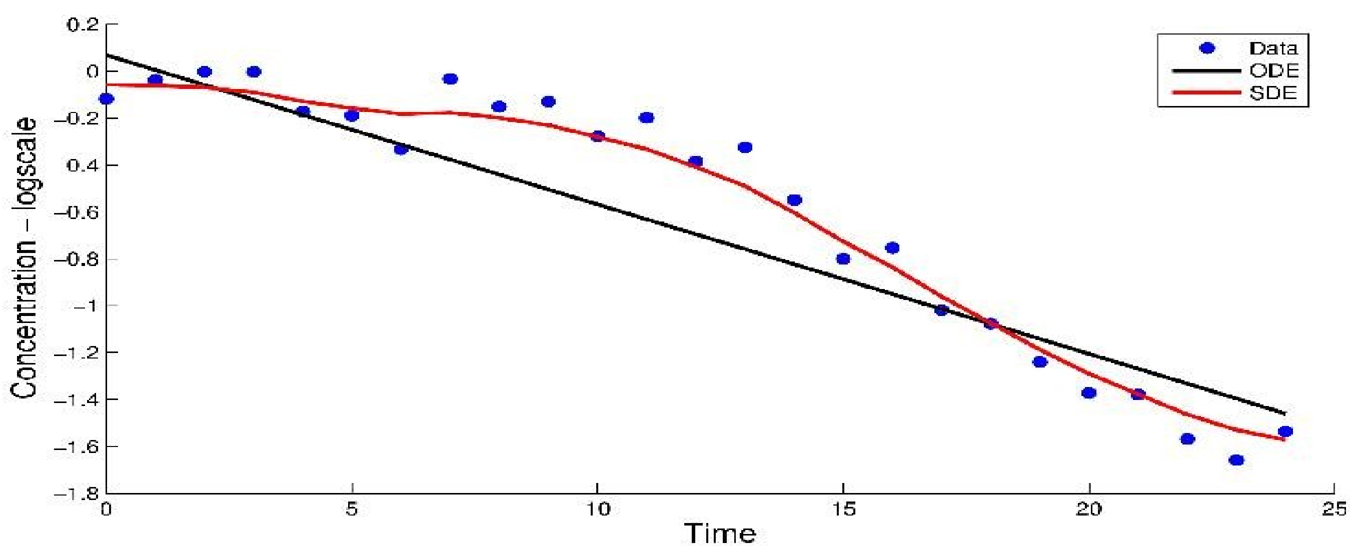


Stochastic Dynamical Model



- Stochastic Differential Equation:

$$
\begin{aligned}
dA &= -KA\,dt + \sigma\,dw \\
Y &= A + e
\end{aligned}
$$



The Grey-Box model

Drift term

Diffusion term

$$dX_t = f(X_t, u_t, t, \theta)dt + \sigma(X_t, u_t, t, \theta)d\omega_t$$ System equation

$$Y_k = h(X_k, u_k, t_k, \theta) + e_k,$$ Observation equation

Observation noise

Notation:

X_t: State variables
u_t: Input variables
θ: Parameters
Y_k: Output variables
t: Time
ω_t: Standard Wiener process
e_k: White noise process with $N(0, S)$

Grey-Box Modeling

- **Bridges the gap between physical and statistical modeling**
- Provides methods for **model identification**
- Provides methods for **model validation**
- Provides methods for **pinpointing model deficiencies**
- Enables methods for a reliable description of the uncertainties, which implies that the same model can be used for **k-step forecasting, simulation** and **control**

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Case study (Level III)

Price-based Control of Power Consumption (Peak Shaving)

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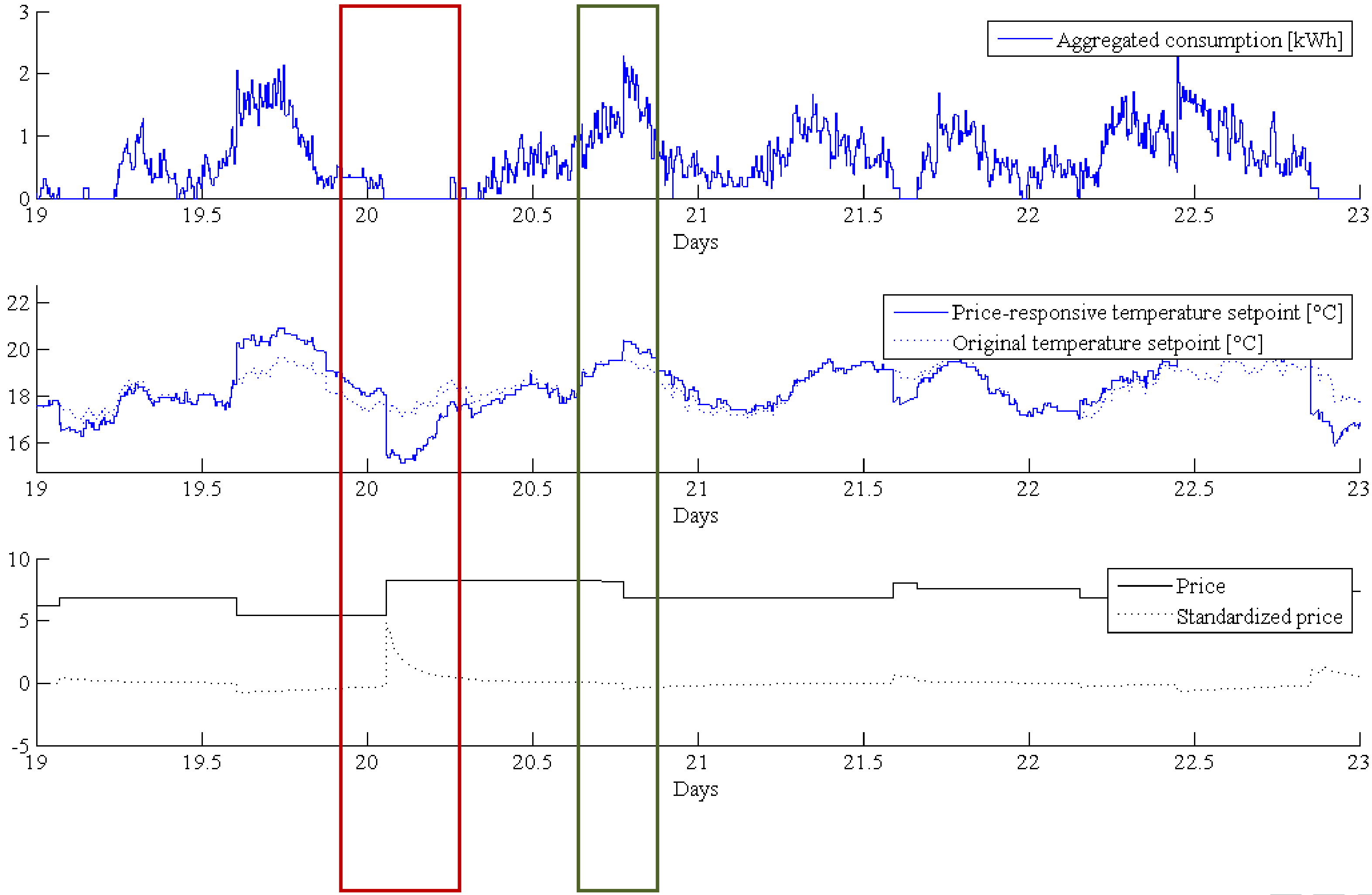
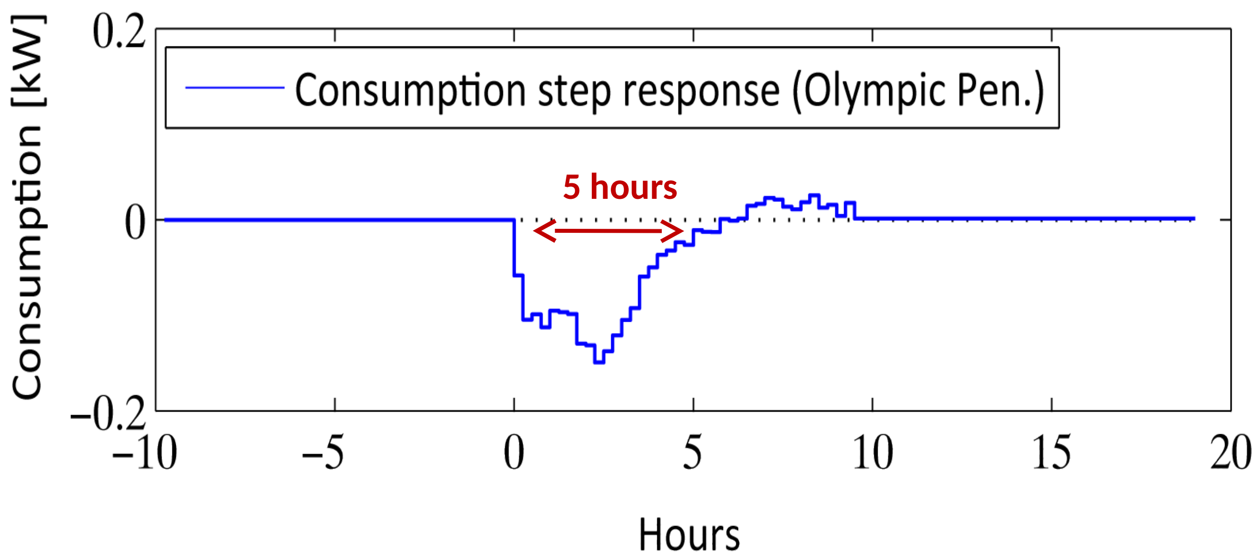
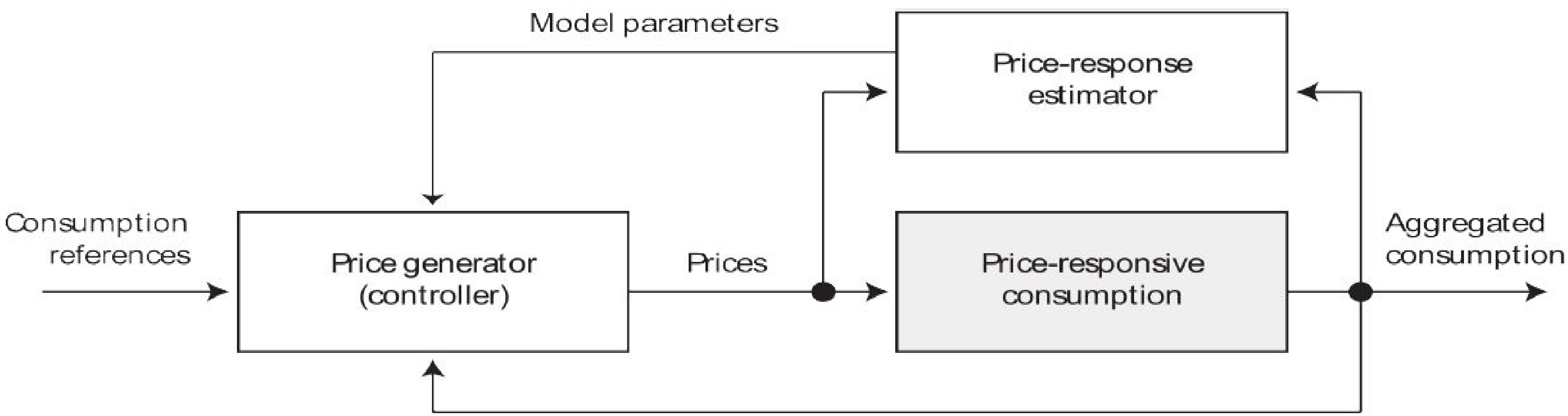
Aggregation (over 20 houses)

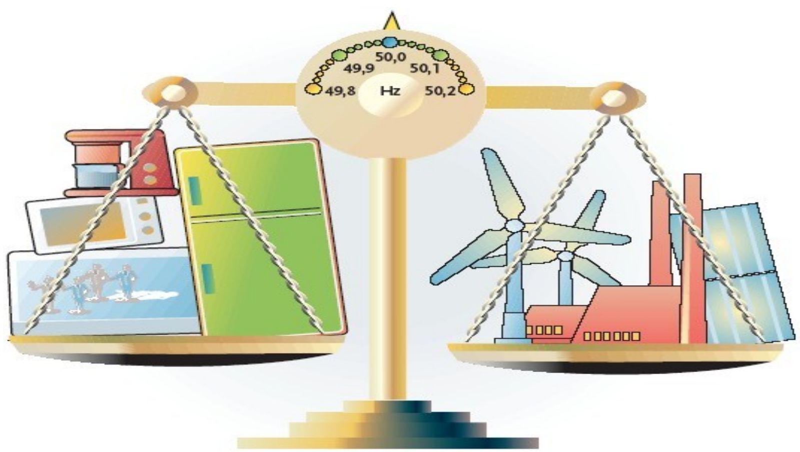


Response on Price Step Change



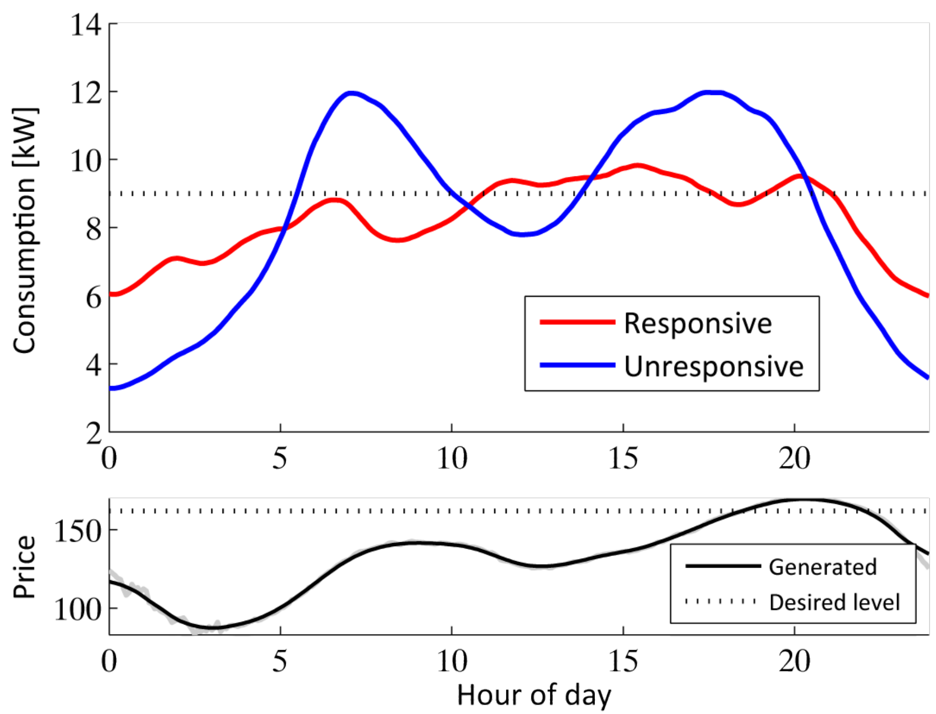
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**



Flexibility Function

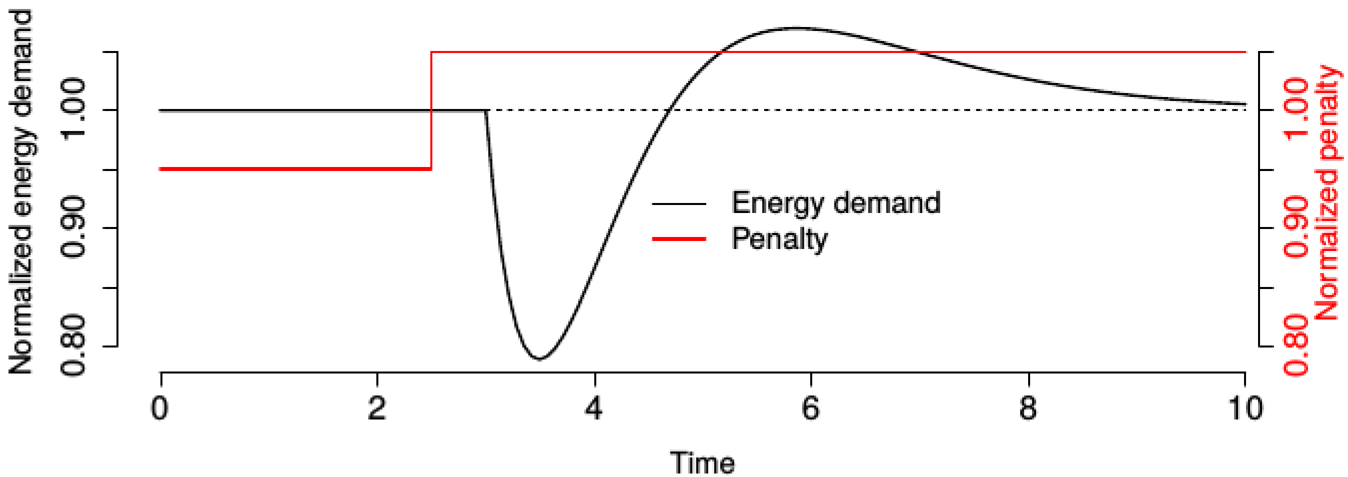
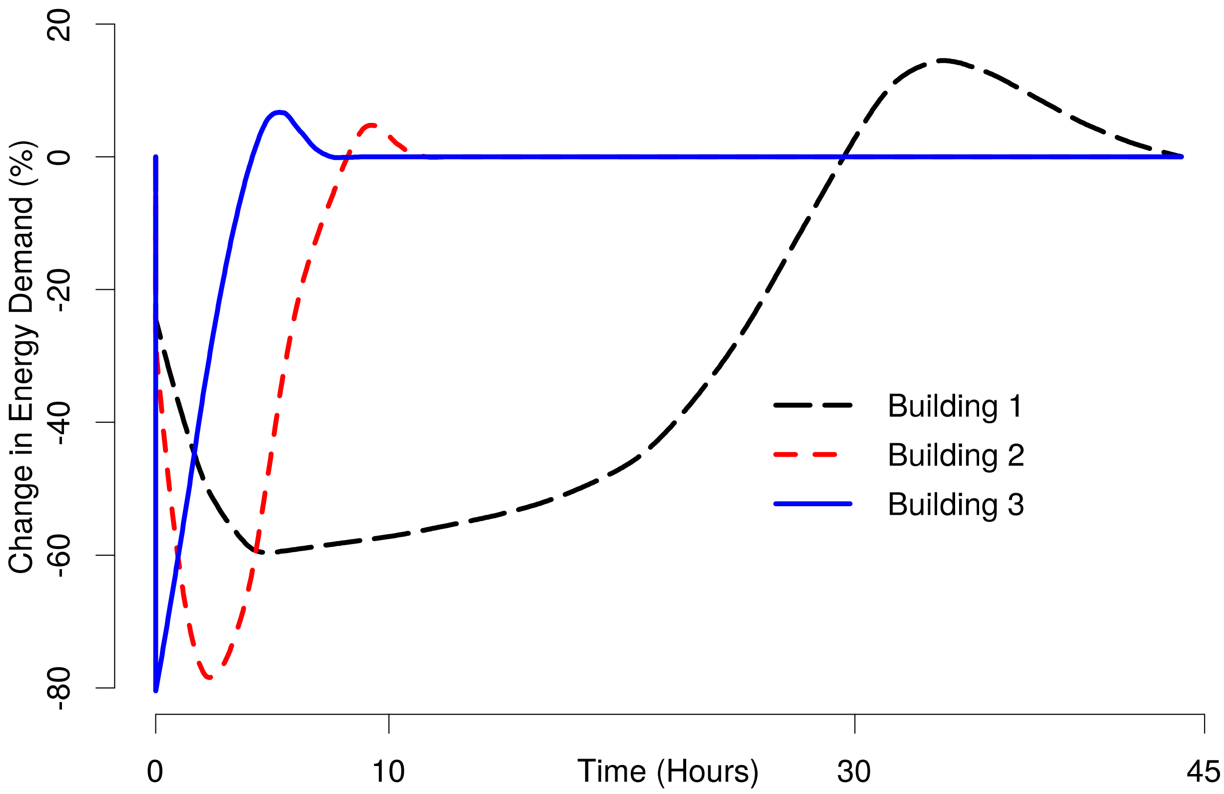


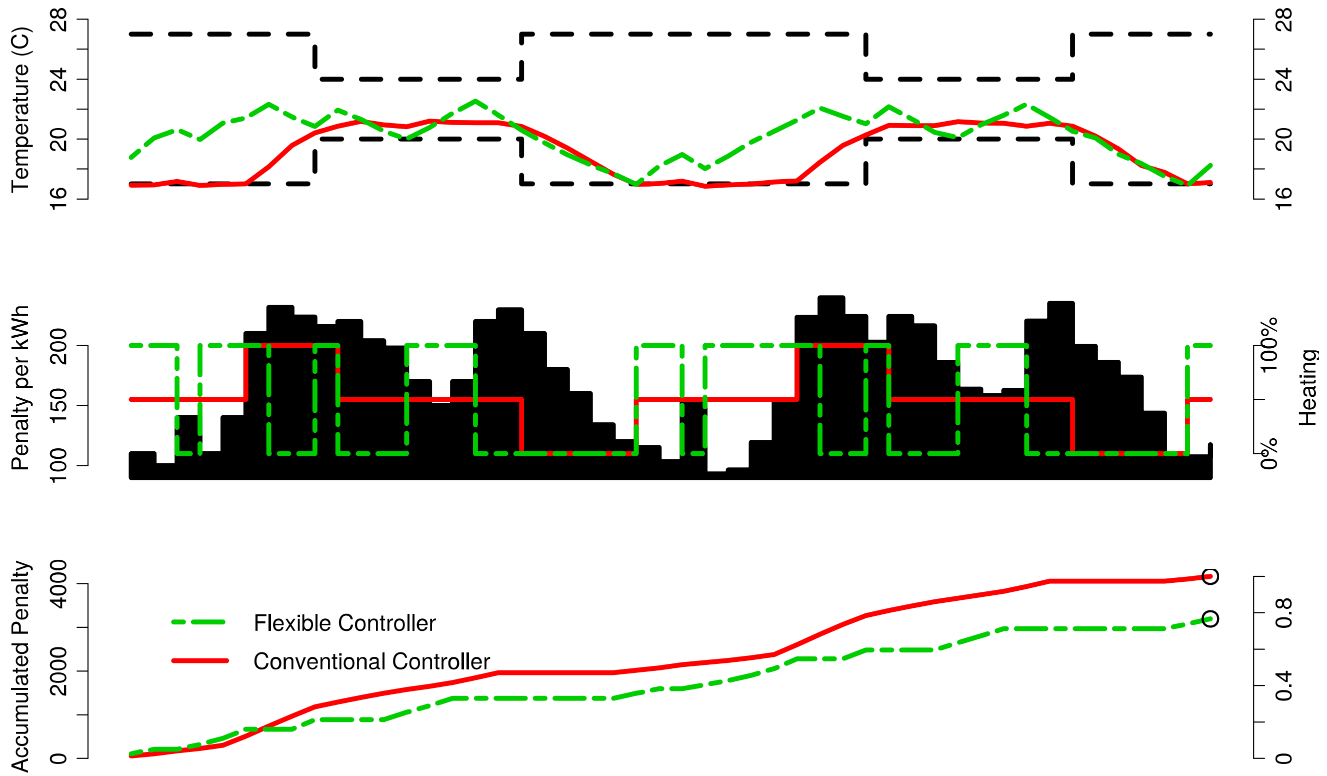
Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

Examples of Flexibility Functions



Flexibility Index

(Penalty based control setup)



Penalty Function (examples)

- **Real time CO_2**. If the real time (marginal) CO_2 emission related to the actual electricity production is used as penalty, then, a smart building will minimize the total carbon emission related to the power consumption. Hence, the building will be *emission efficient*.
- **Real time price**. If a real time price is used as penalty, the objective is obviously to minimize the total cost. Hence, the building is *cost efficient*.
- **Constant**. If a constant penalty is used, then, the controllers would simply minimize the total energy consumption. The smart building is, then, *energy efficient*.

Case study
(Level IV – Indirect Control)

Control of HVAC Systems
(based on varying prices from Level III)

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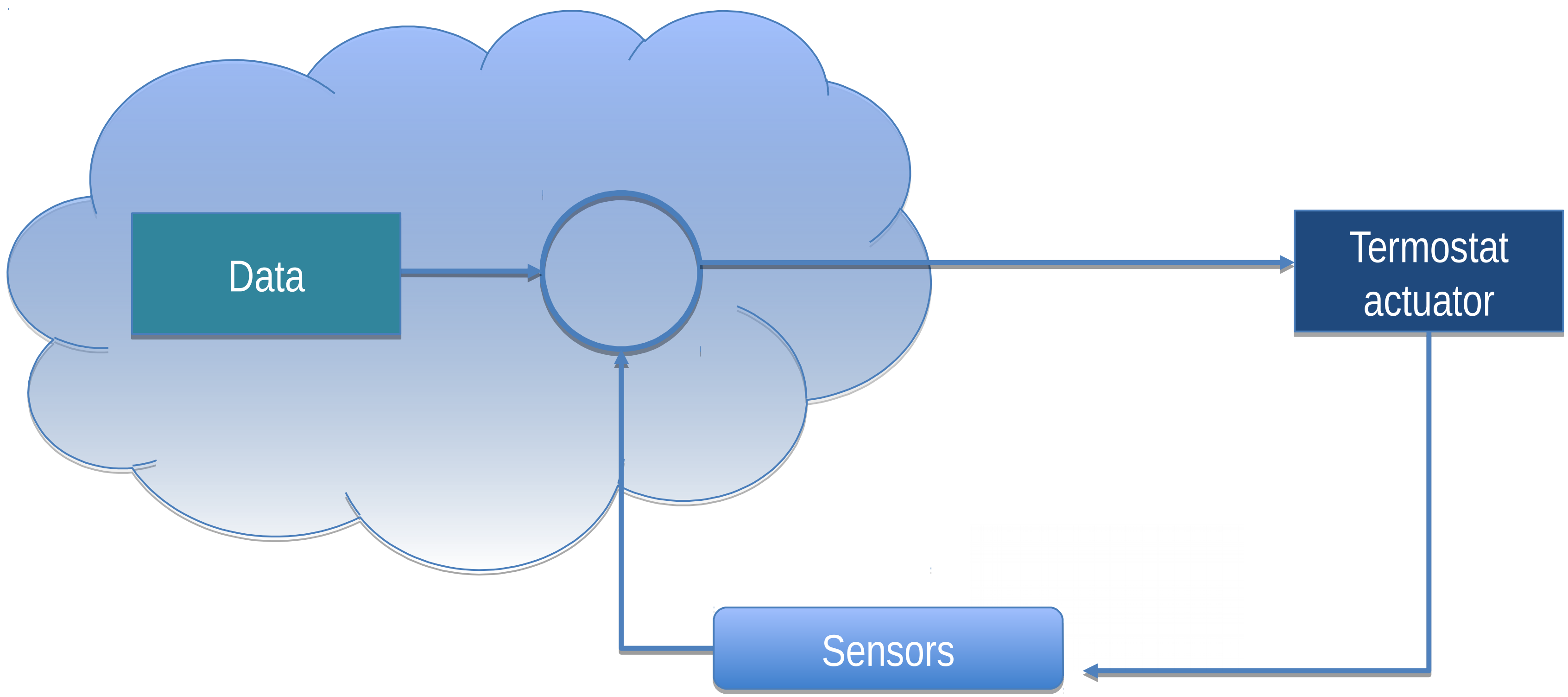
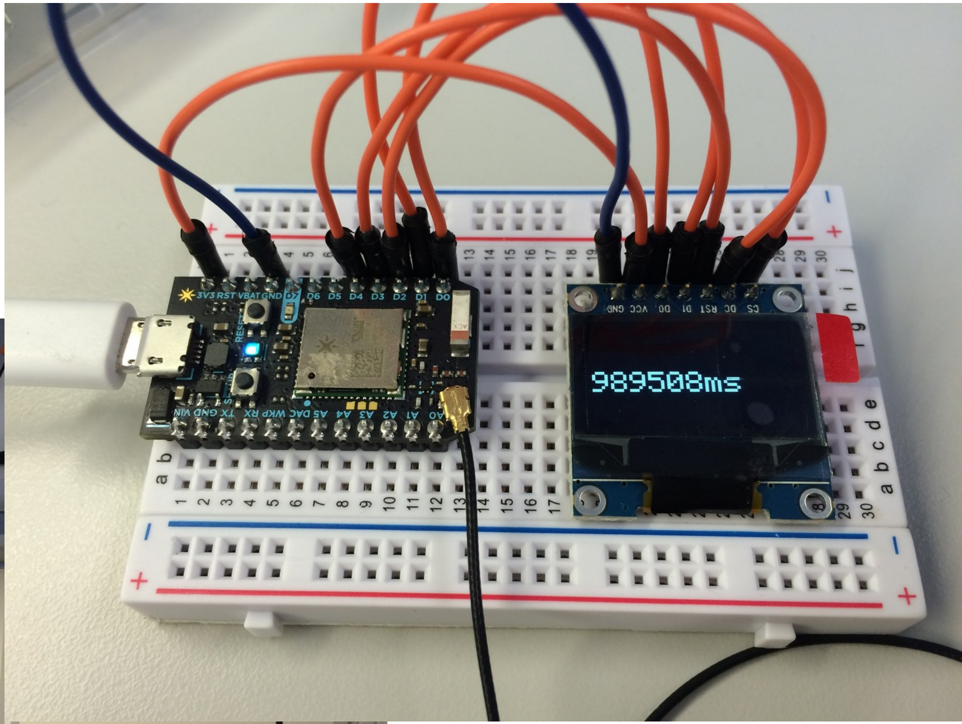
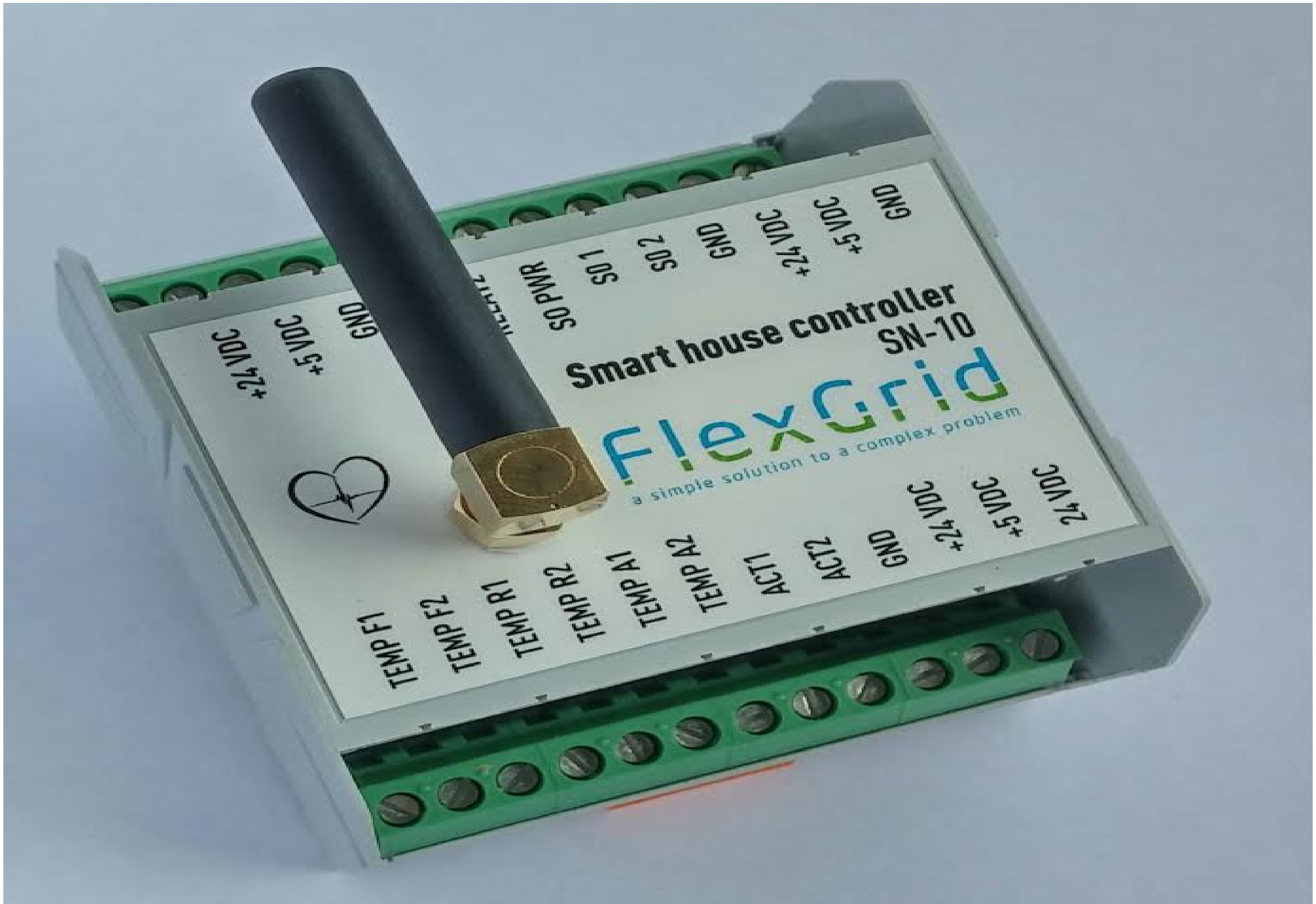
SE-OS – Low level controllers
Control loop design – **logical drawing**



Lab testing ....



SN-10 Smart House Prototype



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Case study

Control of heat pumps
(Energy or/and CO2 efficient control)

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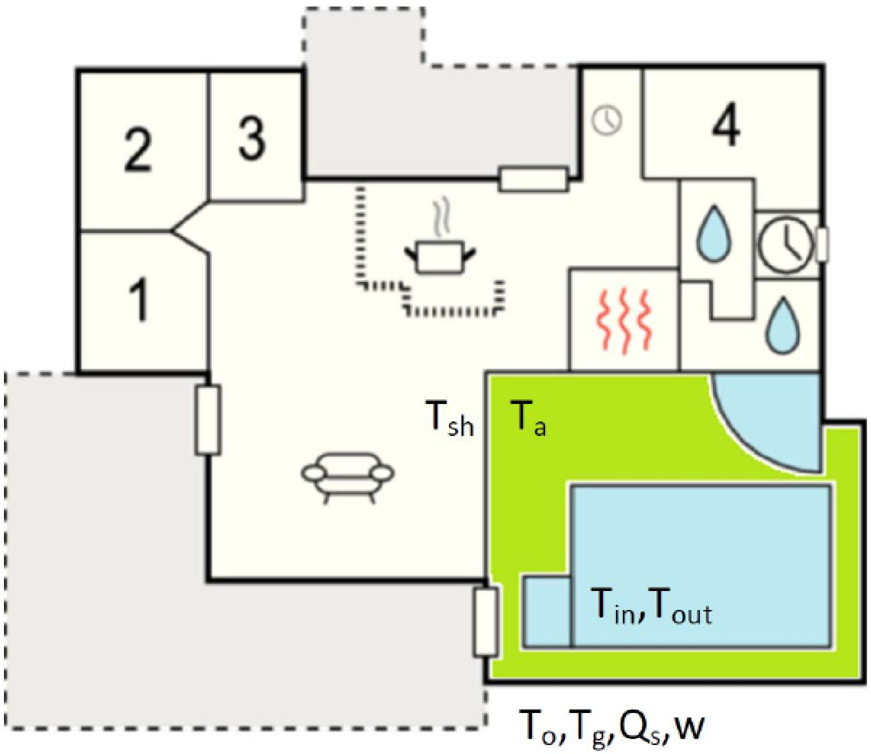
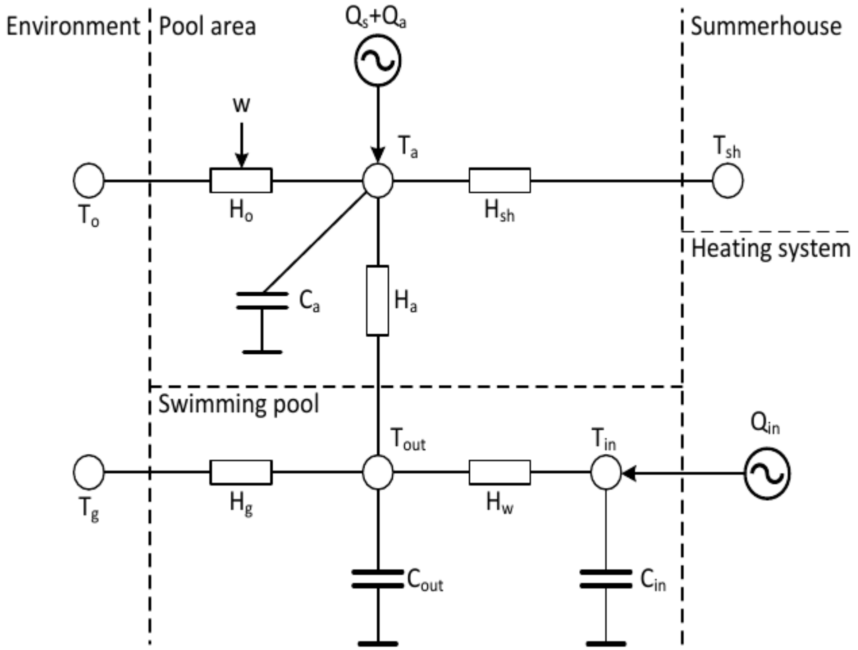
The considered house



- T_{sh} – summerhouse temperature
- T_a – temperature of air in the pool area
- T_{in} – water temperature into the swimming pool
- T_{out} – water temperature out of the swimming pool (controlled)
- T_o – outdoor temperature
- T_g – ground temperature
- Q_s – solar heat gain
- w – wind speed

Grey-box model
(lumped parameter model)



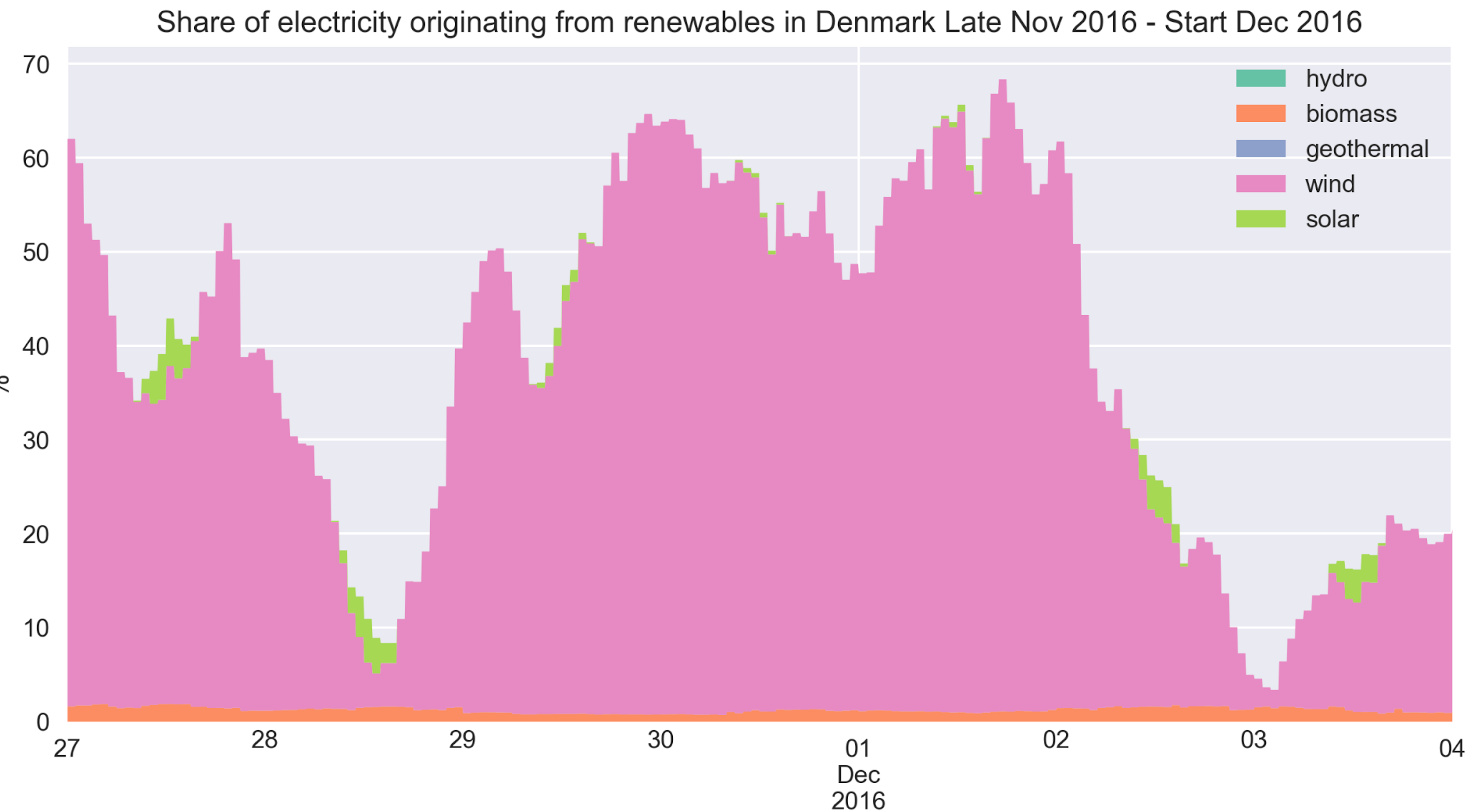
- Based on equivalent thermal parameters model

- Dynamics:

$$\frac{dT_{in}}{dt} = \frac{1}{C_{in}}[H_w(T_{out} - T_{in}) + Q_{in}]$$

$$\frac{dT_{out}}{dt} = \frac{1}{C_{out}}[H_w(T_{in} - T_{out}) + H_g(T_g - T_{out}) + H_a(T_a - T_{out})]$$

$$\frac{dT_a}{dt} = \frac{1}{C_a}[H_o(w)(T_o - T_a) + H_a(T_{out} - T_a) + H_{sh}(T_{sh} - T_a) + Q_s + Q_a]$$



Source: pro.electicitymap.

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How does it work?

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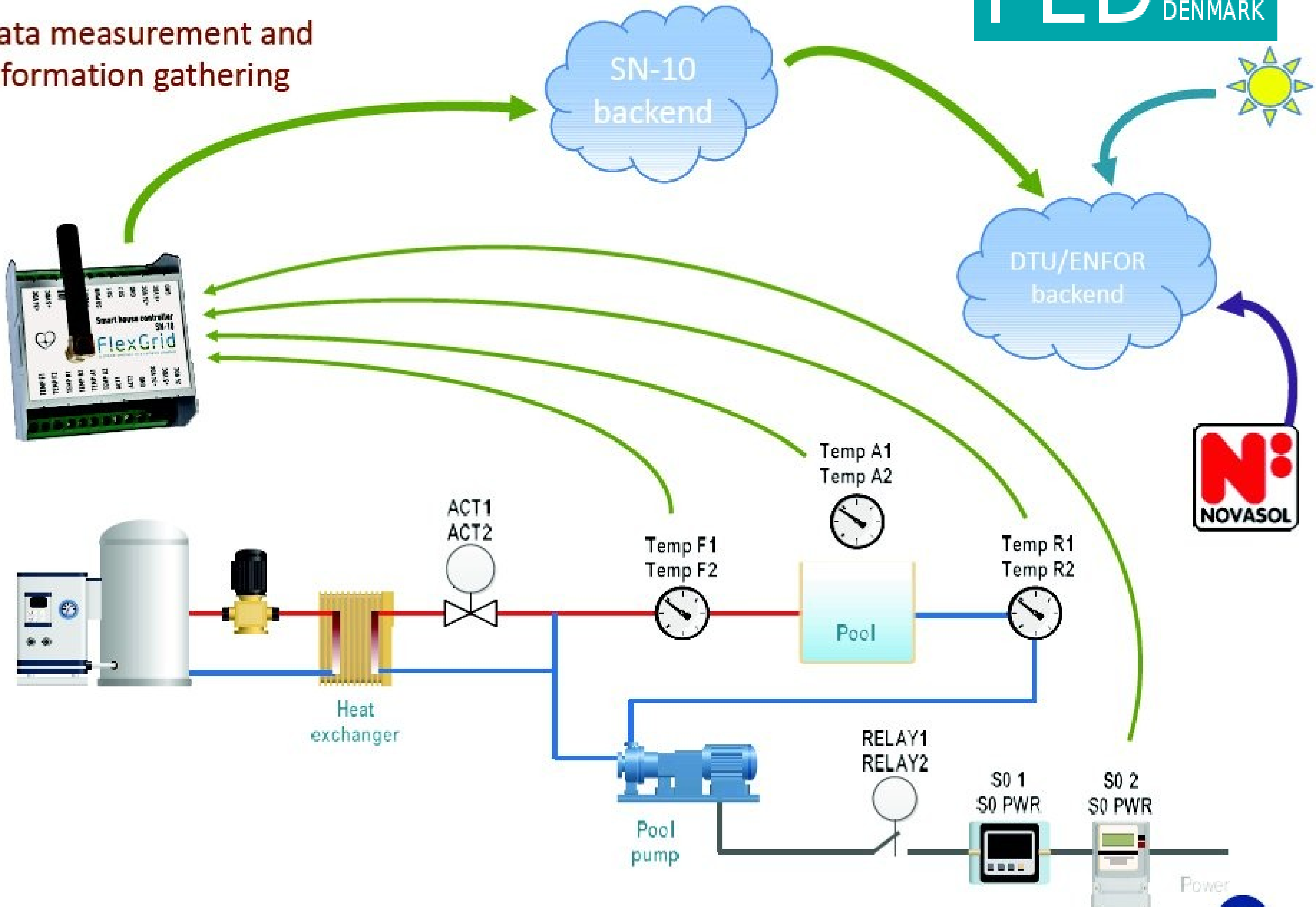
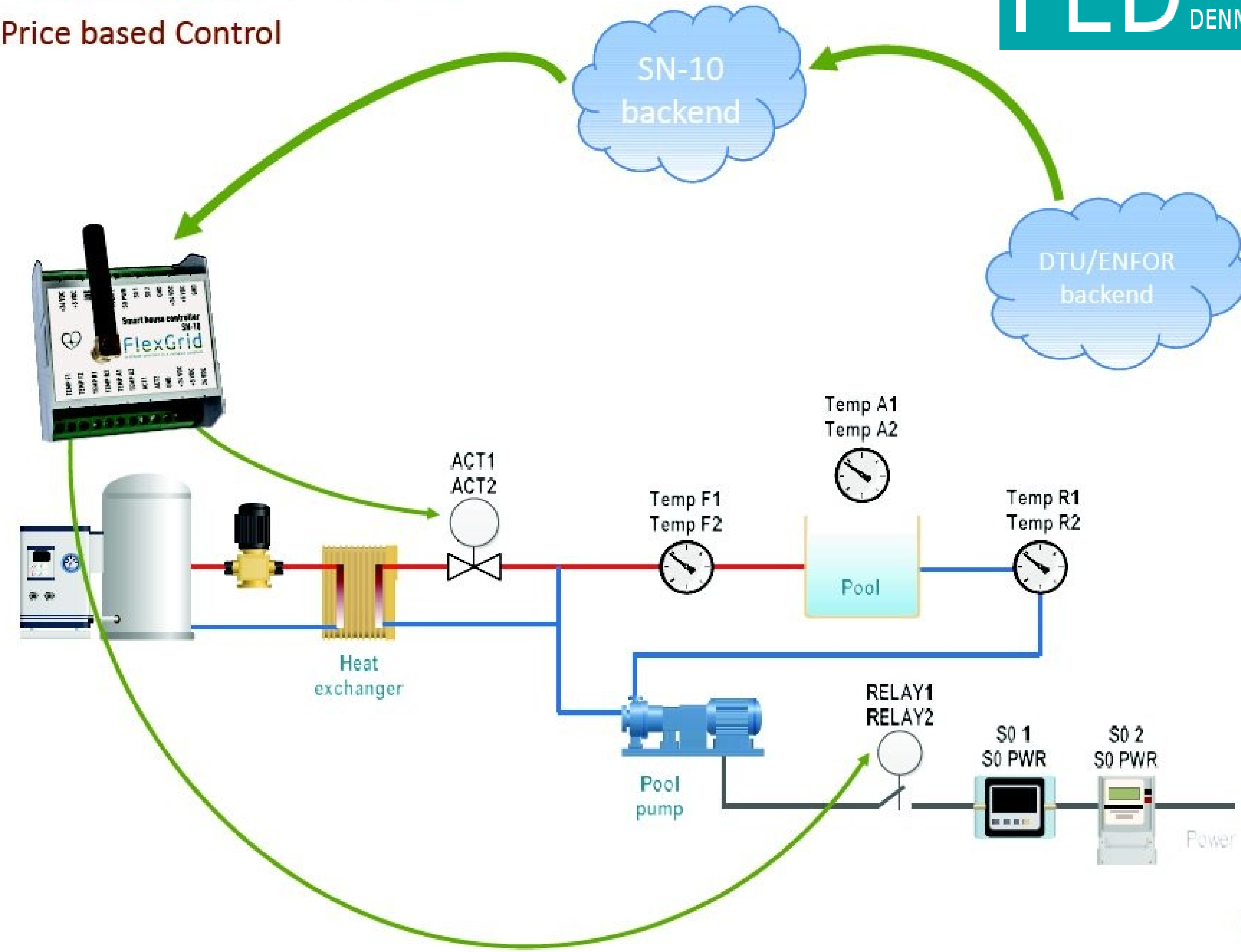
Data measurement and information gathering

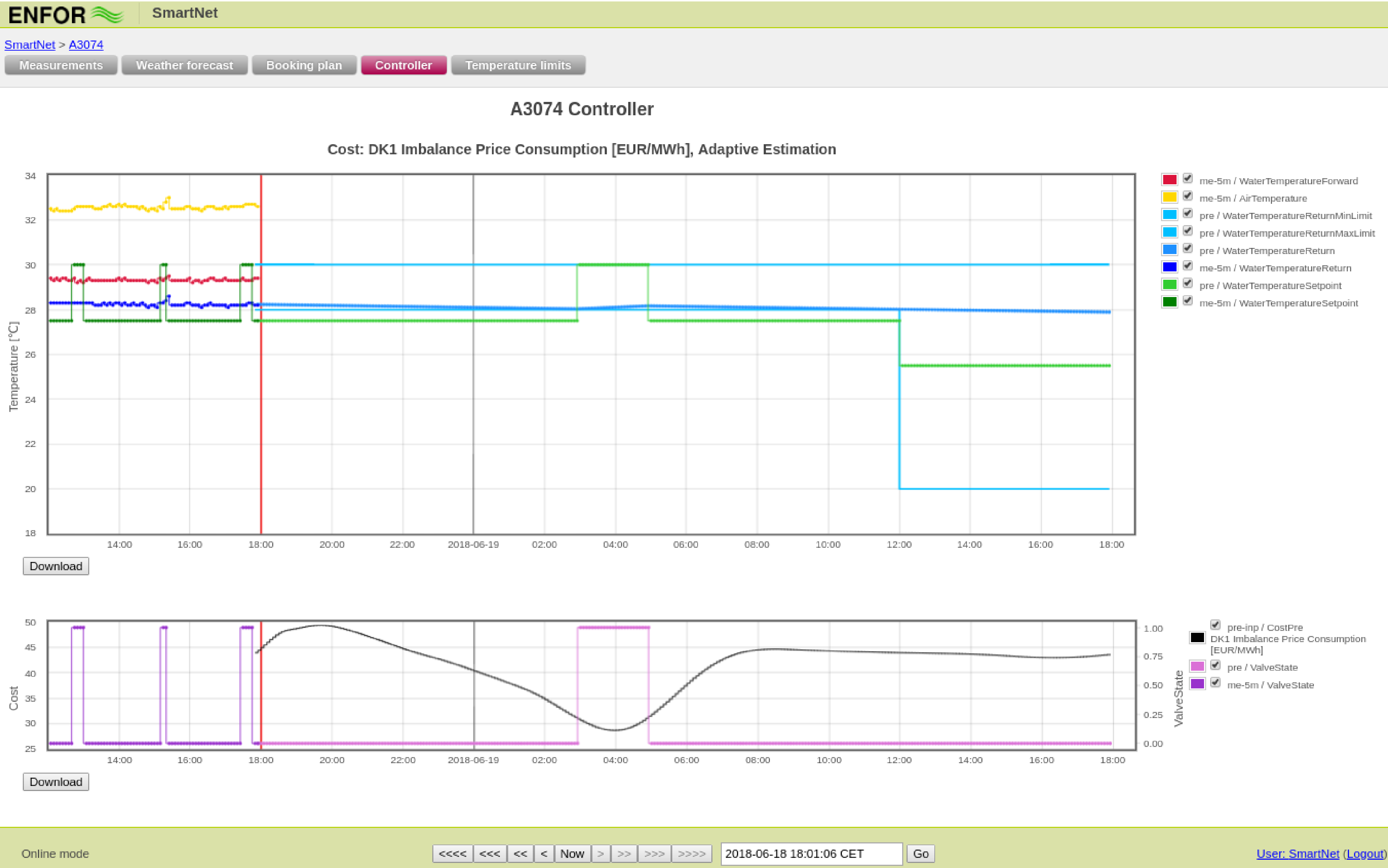


How does it work?

Price based Control



Example: Price-based control (using embedded forecasts)



Example: CO2-based control (using embedded forecasts)
(10-15 pct savings in CO2 emission)

Integrated Forecasting and Control for Smart Buildings

Grey-box model for Forecasting

(Cloud cover, solar radiation, ambient air temperature)

$$
\text{Disturbance model}
\begin{cases}
\mathrm{d}Z_\kappa = f_\psi(Z_\kappa)\mathrm{d}t + \sigma_\psi \mathrm{d}\omega_\kappa \\
\kappa = \psi^{-1}(Z_\kappa) \\
\phi = I_N(\kappa, t) + I_D(\kappa, t) \\
R_n = R_n(\kappa, \phi, t) \\
\mathrm{d}T_s = f_{T_s}(T_l, T_s)\mathrm{d}t + \sigma_s \mathrm{d}\omega_s \\
\mathrm{d}T_l = f_{T_l}(T_l, T_s, R_n)\mathrm{d}t + \sigma_l \mathrm{d}\omega_a \\
\boldsymbol{d} = [T_a, \phi]^T
\end{cases}
$$

$$
\text{Observation equation}
\begin{cases}
d_\phi = \phi + v_\phi, \quad v_\phi \sim N_{iid}(0, R_\phi) \\
d_{T_a} = T_l + v_{T_a}, \quad v_{T_a} \sim N_{iid}(0, R_{T_a}) \\
\boldsymbol{y}_d = [d_{T_a}, d_\phi]^T ,
\end{cases}
\tag{13}
$$

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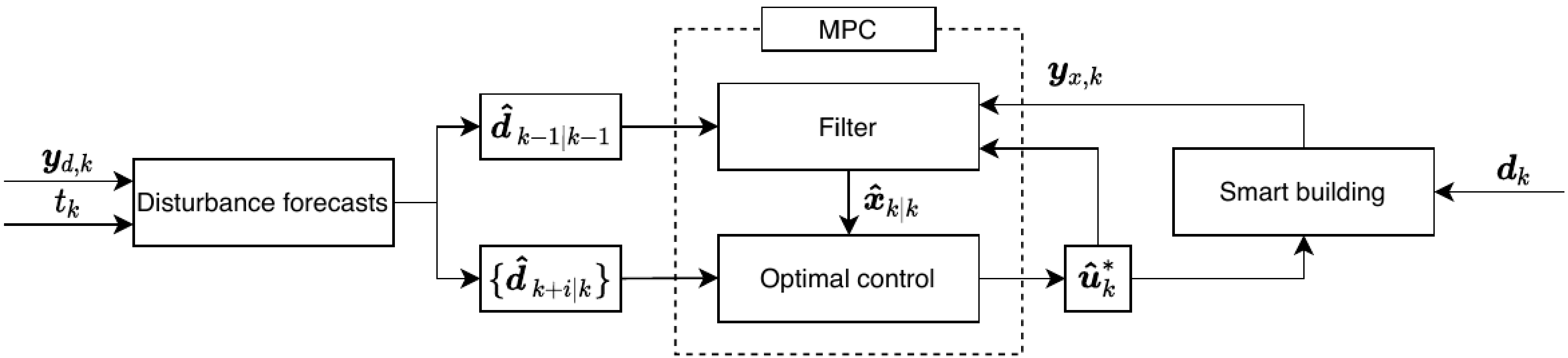
Integrated Forecasting and Control

The MPC framework for smart house control and how distrubance forecasts are incorporated



$$
\begin{aligned}
\mathrm{d}\boldsymbol{x}(t) &= f_s(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t))\mathrm{d}t \\
&\quad + g_s(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t))\mathrm{d}\boldsymbol{\omega}_s(t) \,, \qquad \text{(1a)} \\
\mathrm{d}\boldsymbol{d}(t) &= f_d(\boldsymbol{d}(t))\mathrm{d}t + g_d(\boldsymbol{d}(t))\mathrm{d}\boldsymbol{\omega}_d(t) \,, \qquad \text{(1b)} \\
\boldsymbol{y}_s(t_k) &= h_s(\boldsymbol{x}(t_k)) + \boldsymbol{v}_{s,k} \,, \qquad \text{(1c)} \\
\boldsymbol{y}_d(t_k) &= h_d(\boldsymbol{d}(t_k)) + \boldsymbol{v}_{d,k} \,, \qquad \text{(1d)}
\end{aligned}
$$

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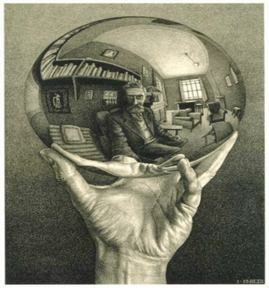
Heating strategies

- Strategy No. 1: Electrical heaters
- Strategy No. 2: Heat pump
- Strategy No. 3: Heat pump and electrical heaters
- Strategy No. 4: Heat pump plus electrical heaters and cooling



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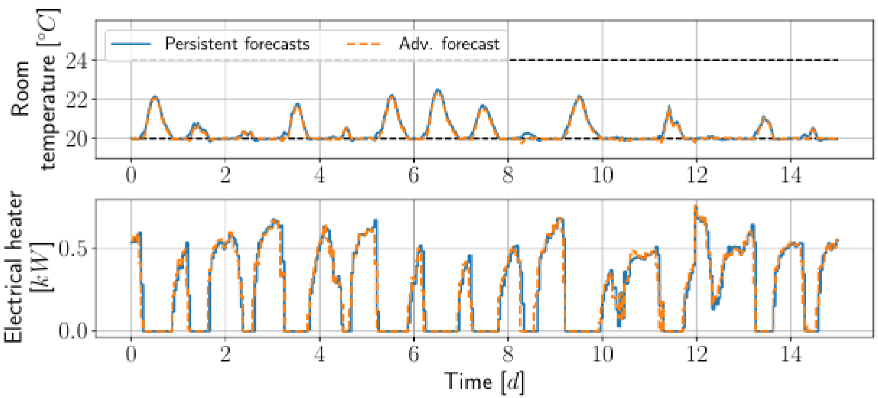
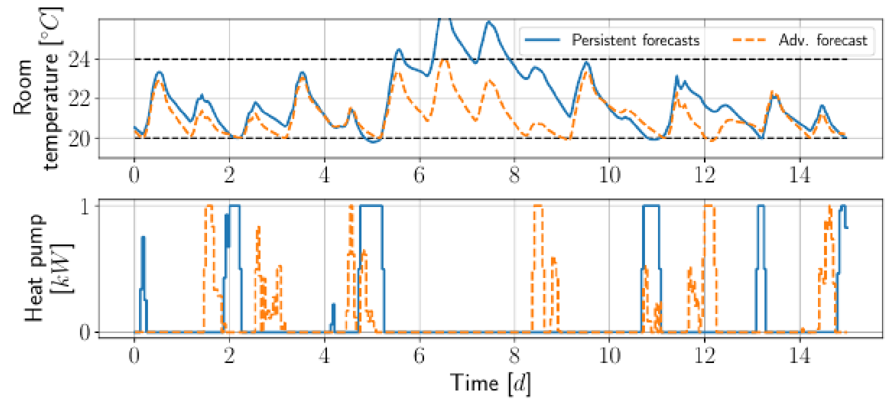
15 days out of 7 months simulation

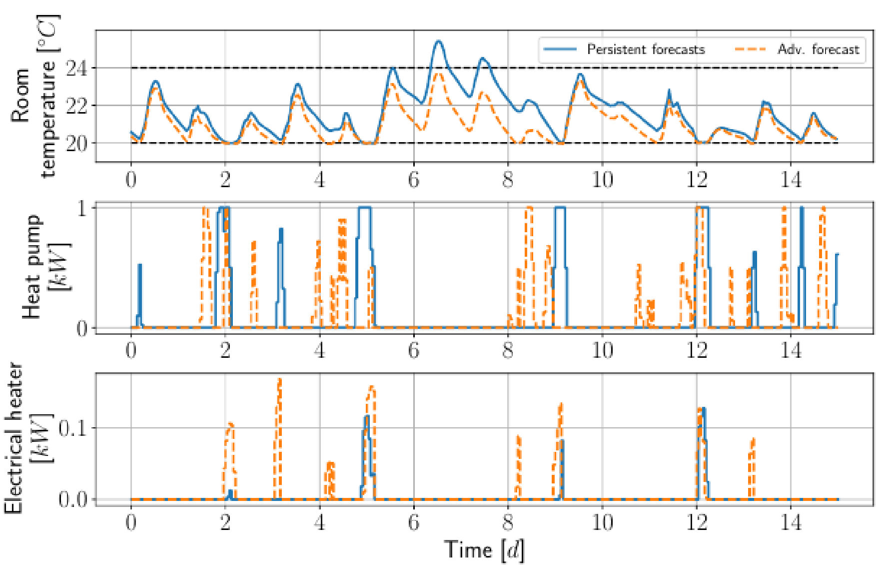
Strategy 1: Electrical Heaters



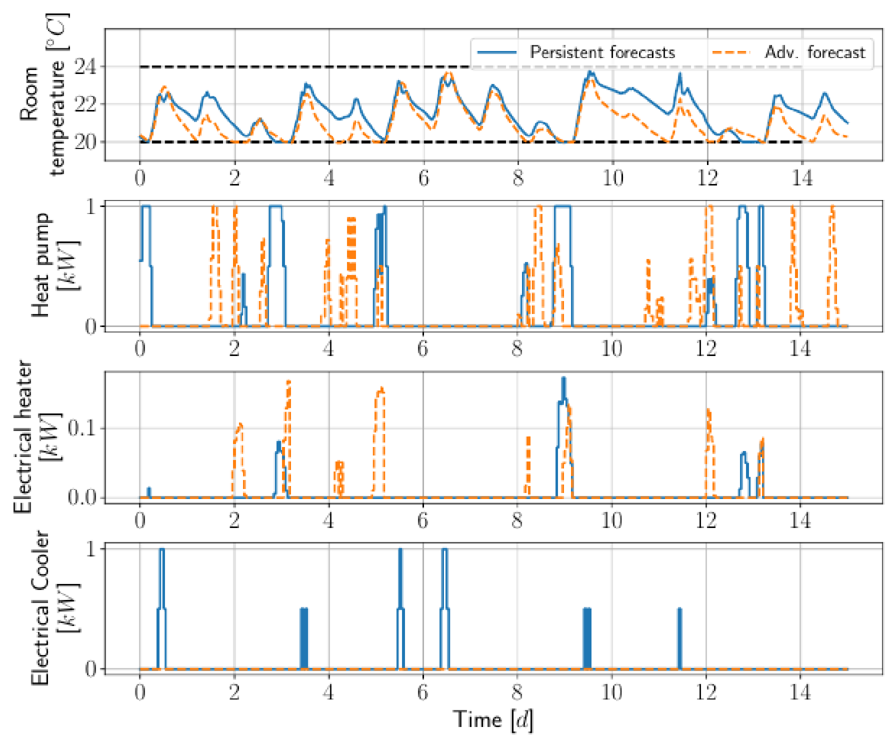
Strategy 2: Heat Pump



Strategy 3: Heat Pump & Electrical Heaters



Strategy 4: Heat Pump & Electrical Heaters & Coolers



Electricity cost in EUR

Electricity cost of the simulations			
Heating strategy	Persistent	Advanced disturbances	Perfect
Electrical heaters, u_1	303.2	302.2	302.0
Heat pump, u_2	117.3	110.4	107.7
Heat pump plus electrical heaters, $\boldsymbol{u}_3$	113.0	108.2	107.5
Heat pump plus electrical heaters and coolers, $\boldsymbol{u}_4$	117.9	108.3	107.5

Constraint violations

Constraint violation of the control simulations

Heating strategy	Persistent	Advanced disturbances	Perfect
Electrical heaters, u_1	48.5	39.6	25.1
Heat pump, u_2	157.9	12.3	1.7
Heat pump plus electrical heaters, $\boldsymbol{u}_3$	48.0	6.7	1.2
Heat pump plus electrical heaters and coolers, $\boldsymbol{u}_4$	4.4	2.4	0

Summary

- We have demonstrated how to use grey-box models for integrated forecasting and control for smart buildings
- We have suggested the use of Flexibility Functions (and Flexibility Indeces)
- We have described the hierarchy of Smart-Energy OS Controllers with embedded aggregation, modelling, and forecasting
- The Smart-Energy OS can focus eg. on
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency
- Center Denmark is established as a National Digitalization Hub for Smart Energy and related systems (eg. water). Main purpose is to unlock the flexibility needed for the green transition

For more information ...

See for instance

www.smart-cities-centre.org

...or contact

– Henrik Madsen (DTU Compute)
  hmad@dtu.dk

Acknowledgement:

Innovation Fund Denmark (DSF 1305-00027B) and EU H2020 (No. 691405)

Center Denmark – Control Room

Some 'randomly picked' books on modeling and renewable integration ....