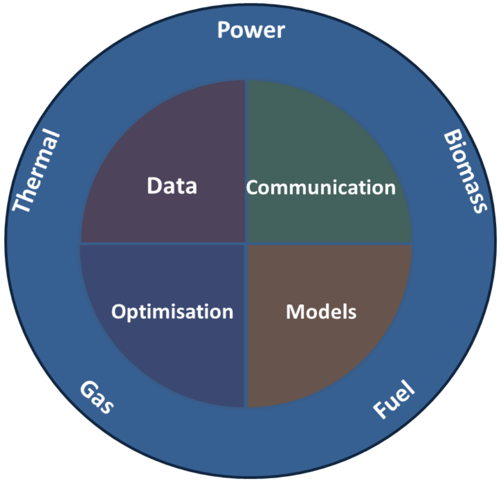
Enabling Efficiency in the Green Transition using Data-driven Methods and Energy Systems Integration



Henrik Madsen, Christian Thilker, Rune Junker, John B. Jørgensen

https://www.flexibleenergydenmark.dk/

http://www.smart-cities-centre.org

http://www.henrikmadsen.org

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Challenges

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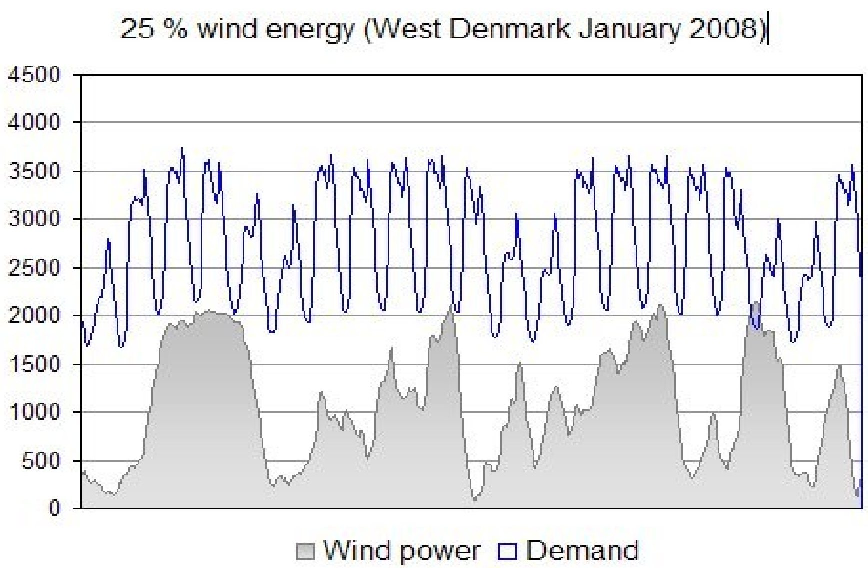
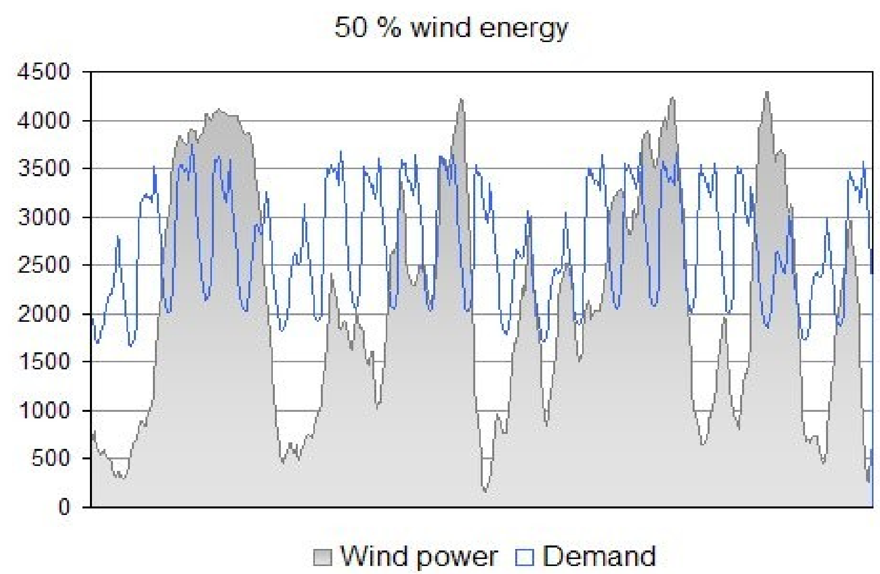
The Danish Wind Power Case

.... balancing of the power system





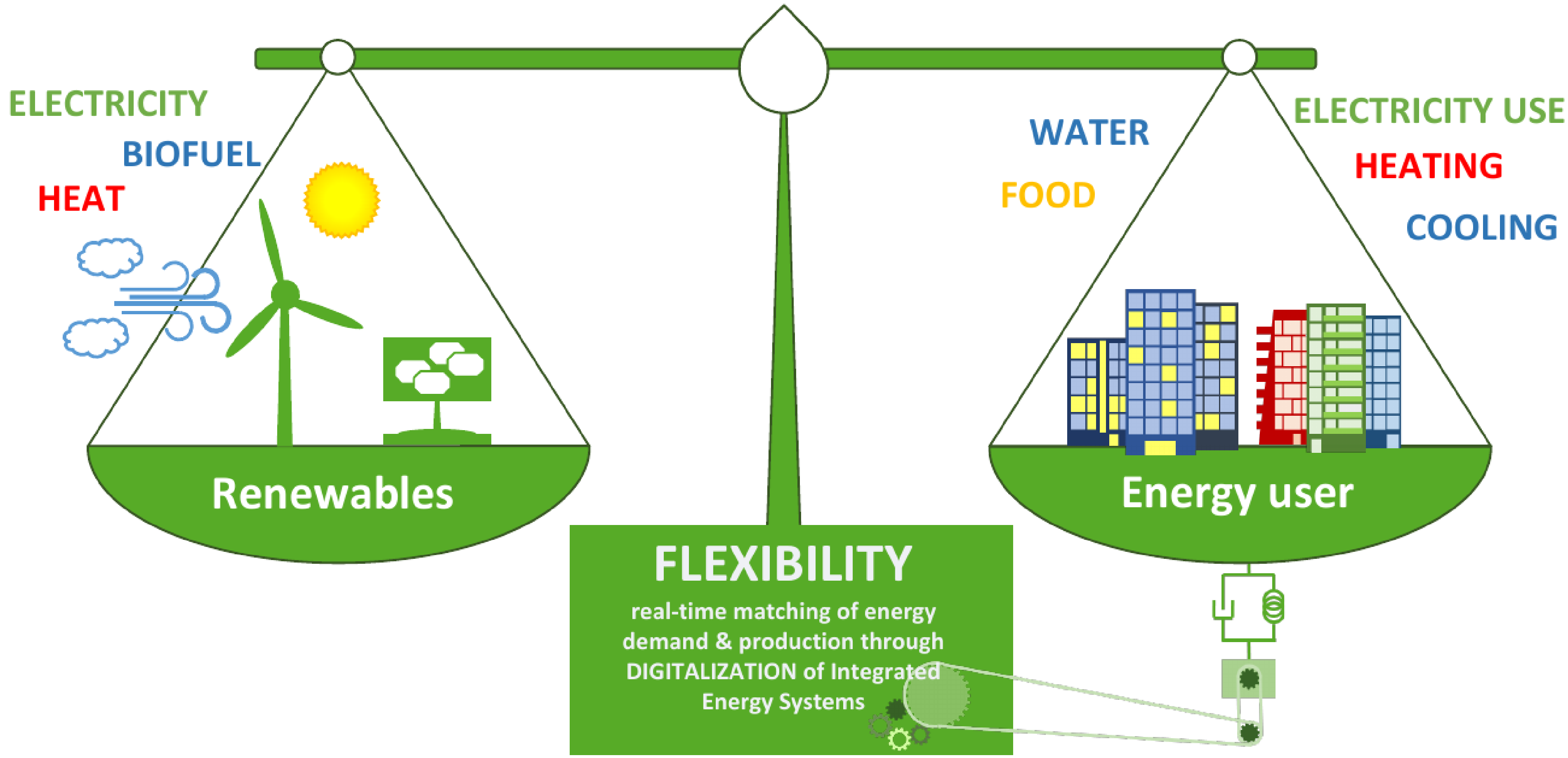
In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

In 2020 Flexibility and sector coupling are essential

That's the topic of 'Flexible Energy Denmark'

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

The Challenge: Denmark Fossil Free 2050



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Preparatory study on Smart Appliances

European Commission

Ecodesign Preparatory Study performed for the European Commission

Welcome | Project summary | Planning & Meetings | Documents | Register for website | Register for meeting | Contact & Consortium

Home > Project summary

Project Summary

The Ecodesign Preparatory Study on Smart Appliances (Lot 33) has analysed the technical, economic, market and societal aspects with a view to a broad introduction of smart appliances and to develop adequate policy approaches supporting such uptake.

The study deals with Task 1 to 7 of the Methodology for Energy related products (MEErP) as follows:

- Scope, standards and legislation (Task 1, Chapter 1);
- Market analysis (Task 2, Chapter 2);
- User analysis (Task 3, Chapter 3);
- Technical analysis (Task 4, Chapter 4);
- Definition of Base Cases (Task 5, Chapter 5);
- Design options (Task 6, Chapter 6);
- Policy and Scenario analysis (Task 7, Chapter 7).

An executive summary of the project results can be downloaded here.

Throughout the study, new relevant aspects have come up which will be covered in a second phase of the Preparatory Study:

- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.

Many projects have concluded:

Almost no Flexibility

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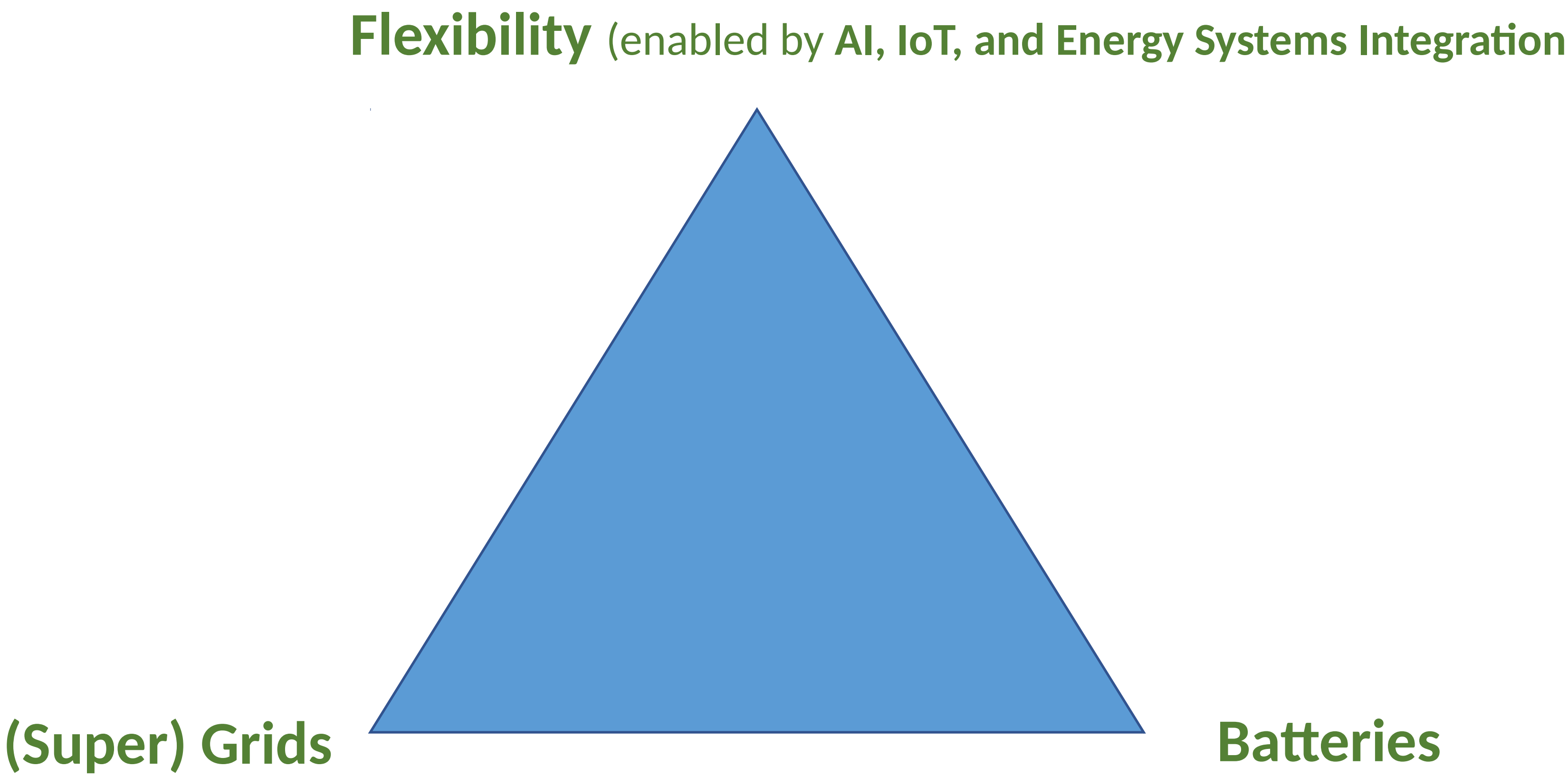
Markets – Needed changes

- Static -> **Dynamic**
- Deterministic -> **Stochastic**
- Linear -> **Nonlinear**
- Silo oriented -> **Integrated Energy Systems**
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, ...) -> **Coordination + Hierarchy**
- Speed / problem size -> **Decomposition + Control Based Solutions**
- Characterization of flexibility (bids) -> **Flexibility Functions**
- Requirements on user installations -> **One-way communication**

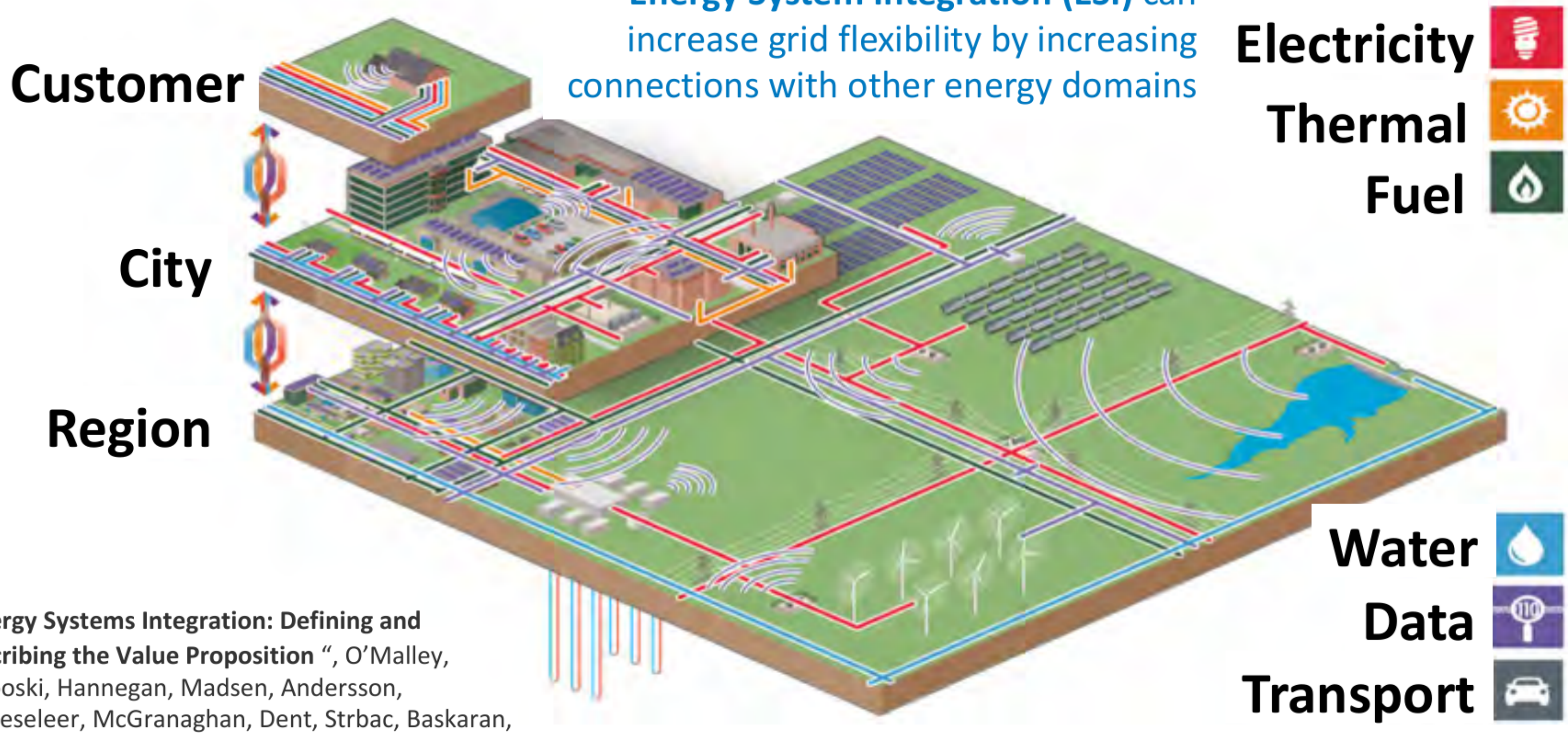
Data-Intelligent and Flexible Energy Systems

Space of Solutions



Energy Systems Integration

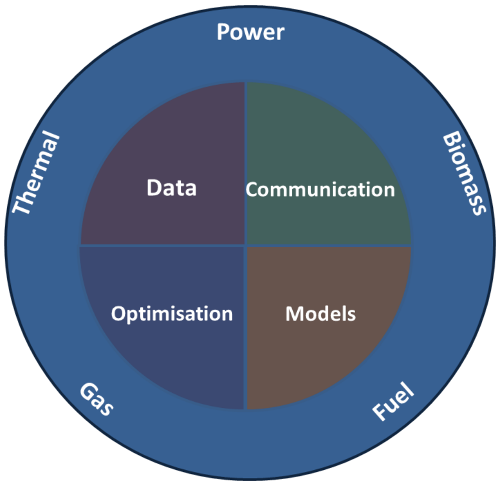
Energy System Integration (ESI) can increase grid flexibility by increasing connections with other energy domains



"Energy Systems Integration: Defining and Describing the Value Proposition ", O'Malley, Kroposki, Hannegan, Madsen, Andersson, D'haeseleer, McGranaghan, Dent, Strbac, Baskaran, Rinker., NREL/TP-5D00-66616. June 2016

NREL | 17

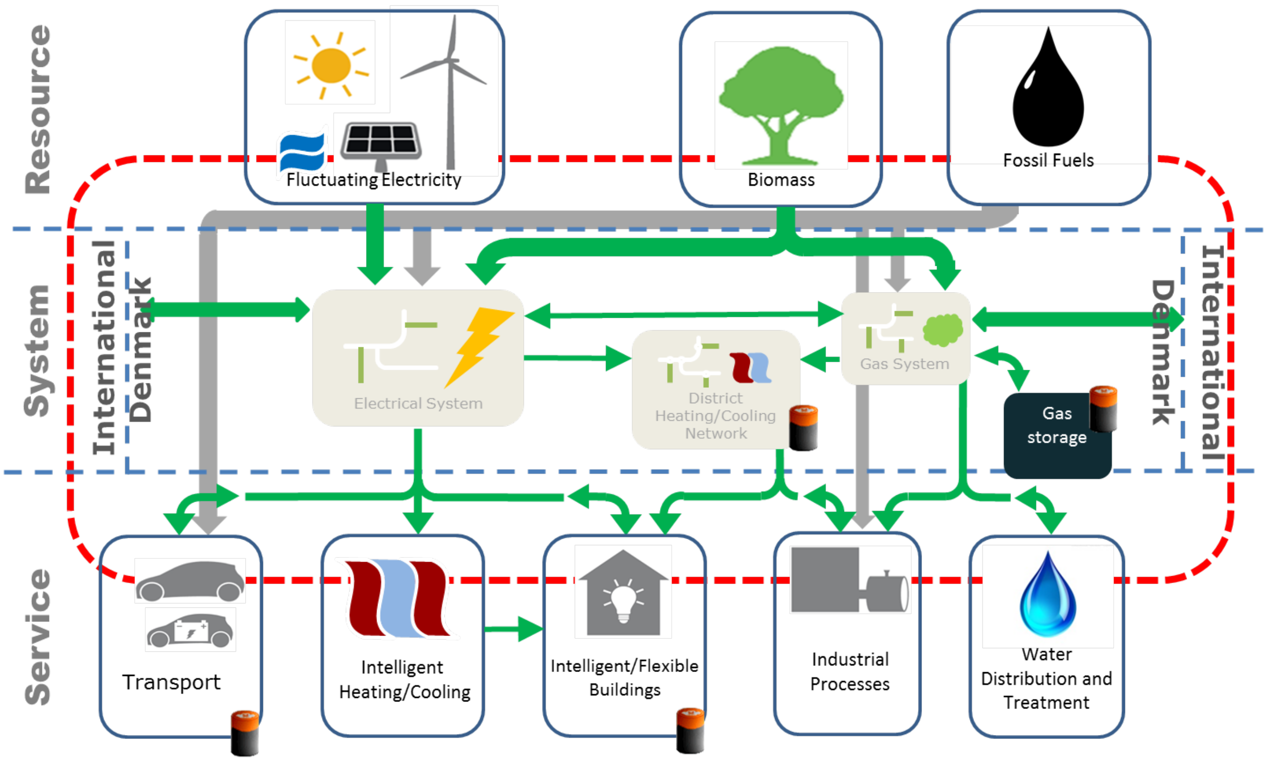
Use of AI and Energy Systems Integration



By **intelligently integrating** currently distinct **energy systems** (heat, power, gas and biomass) using **AI and ICT solutions** we can **unlock the flexibility** needed for integrating large shares of fluctuating renewable energy sources

Energy System Models for Real Time Applications and Data Assimilation

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



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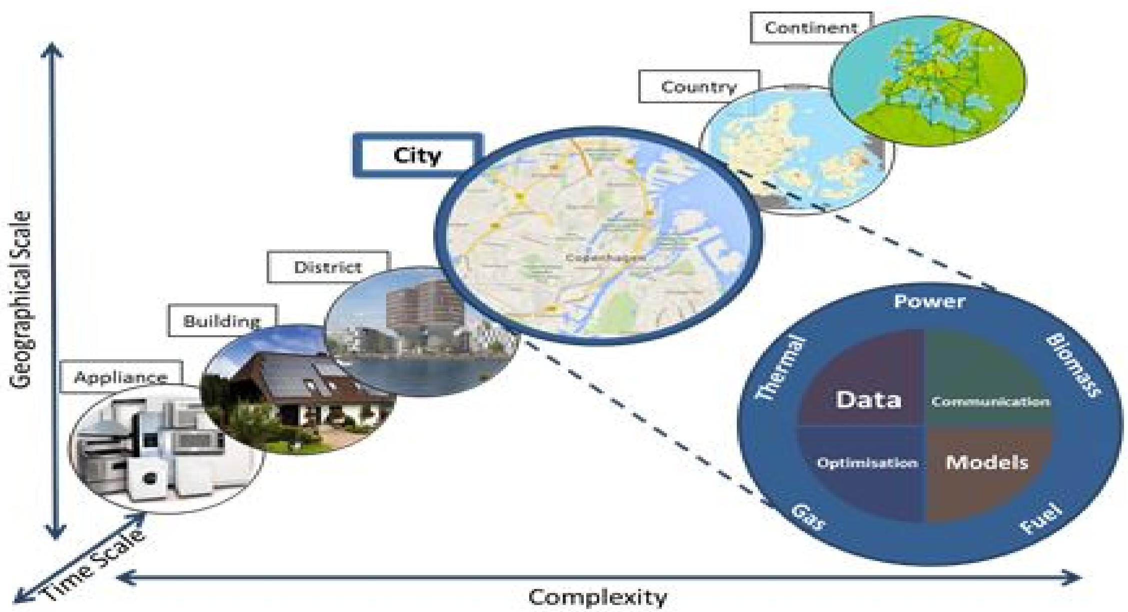
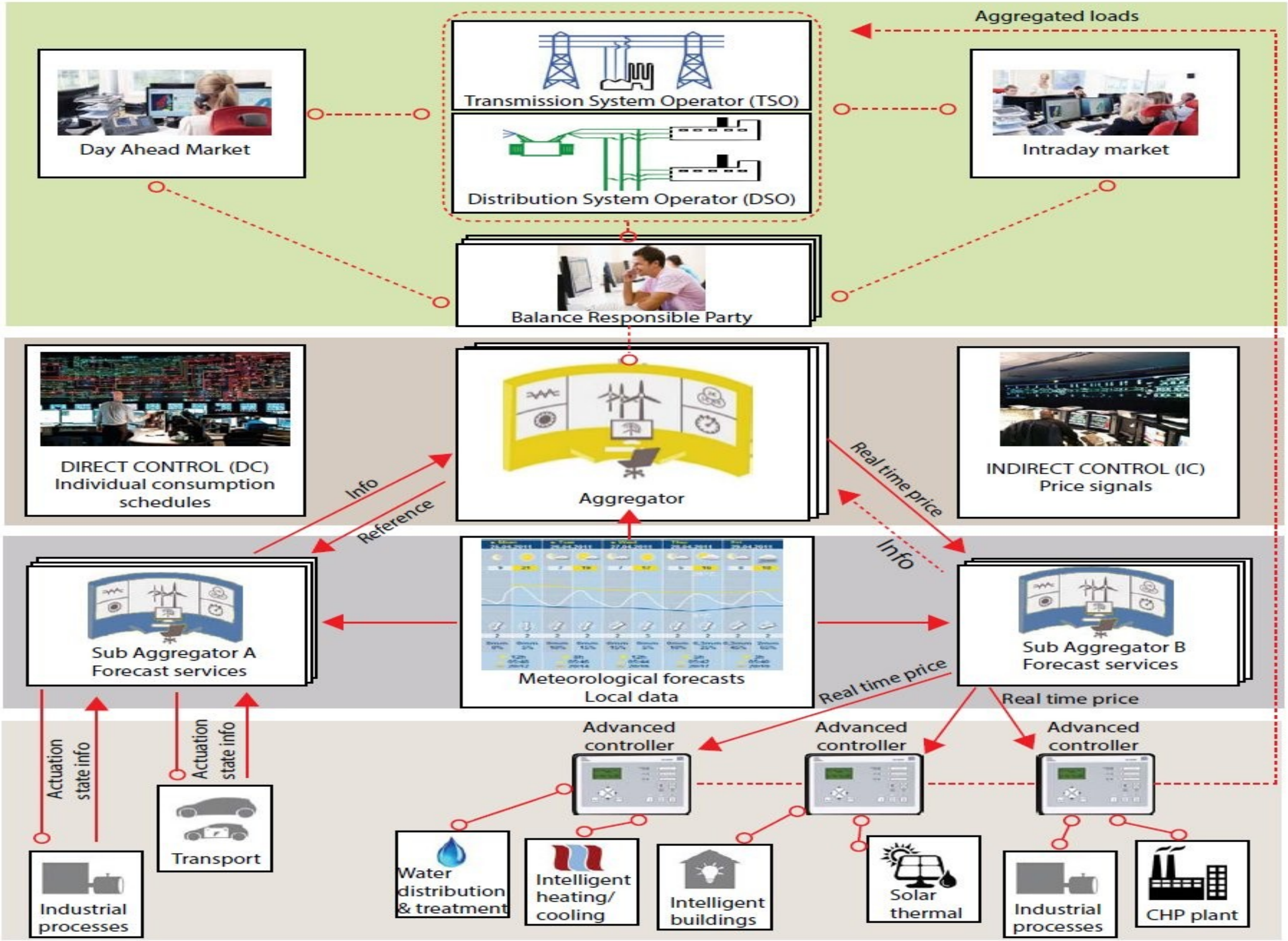
Temporal and Spatial Scales

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

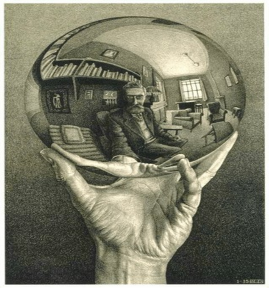


Smart-Energy OS



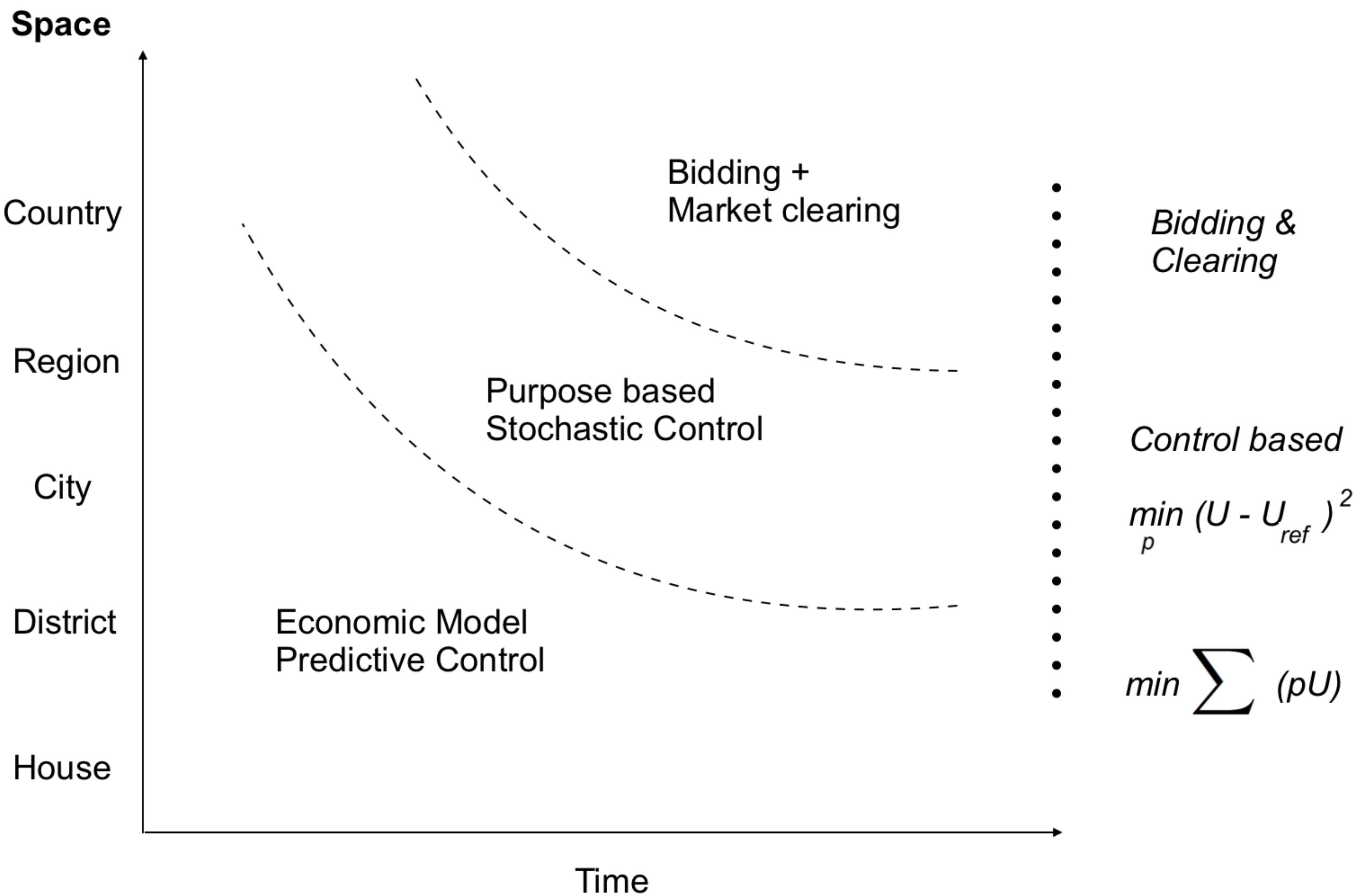
```r
# slow approach, but we are sure things get do
# Try to parallelize anyway
require(multicore)
numcores<-multicore:::detectCores()
mclapply(
  1:N,
  function(i,data) {
    print(paste(i, "/", N))

    # Find the indices of rows corresponding to
    j <- which(data$dt_agg %in% aggdata$dt[i])

    # Filter out those who are NA
    j <- j[!is.na(data$last_one_min_power[j])]

    # Count number of readings
    aggdata$num_readings[i] <- length(j)
```

SE-OS Characteristics



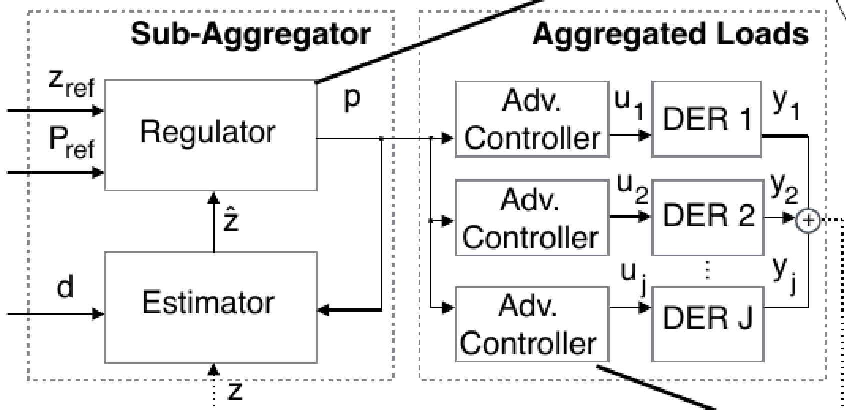
- AI and Grey-Box models for data-intelligence
- Nested sequence of systems – Systems of Systems
- Hierarchy of optimization (or control) problems
- Control principles at higher spatial/temporal resolutions
- Cloud, Fog, Edge based (IoT, IoS) solutions – eg. for forecasting and control
- Integrated modelling, forecasting, control and optimization
- Simple setup for the communication and contracts
- Facilitates **energy systems integration** (power, gas, thermal, …)

SE-OS: Hierarchy of Optimatization and Control Problems



Proposed methodology
Control-based methodology

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

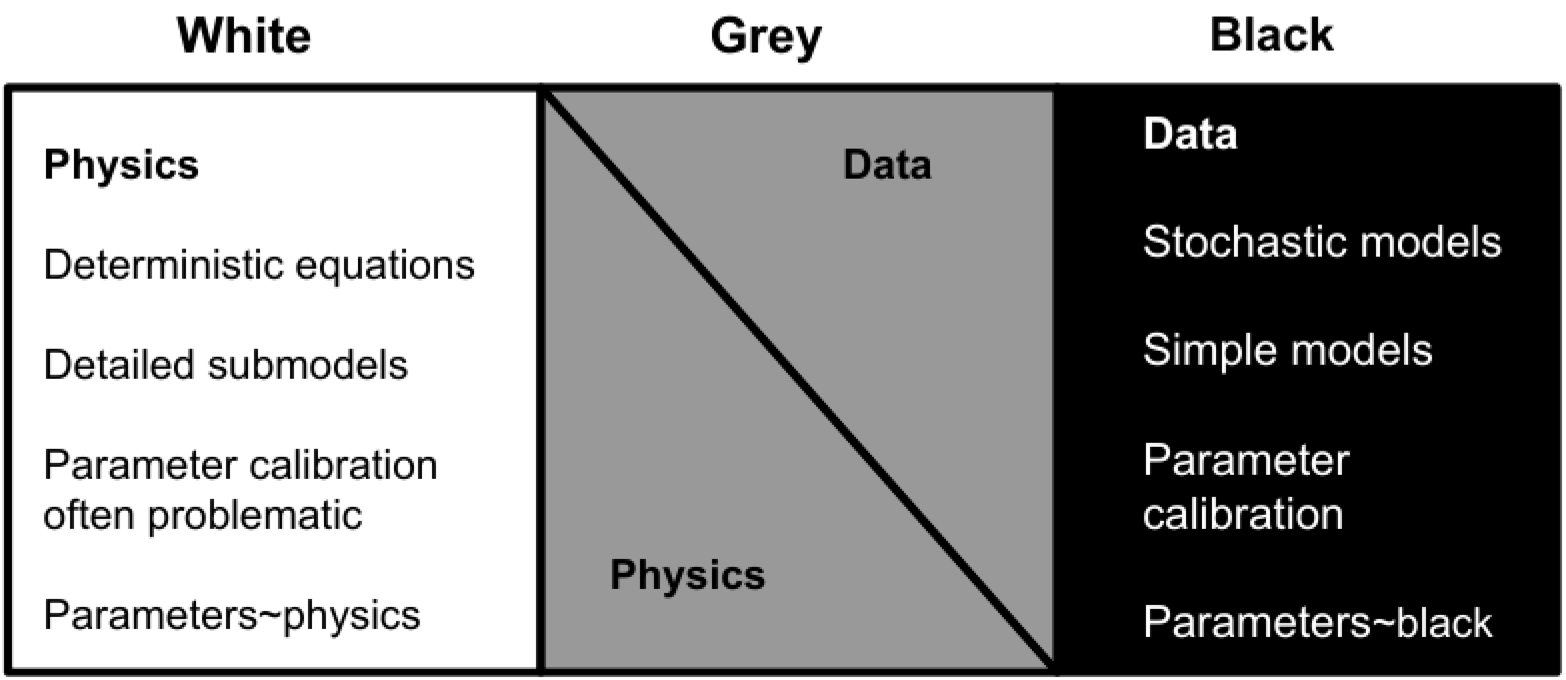


$$\min_{u} \quad E[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)]$$
$$\begin{aligned} \text{s.t.} \quad x_{k+1} &= Ax_k + Bu_k + Ed_k, \\ y_k &= Cx_k, \\ y_k^{min} \leq y_k &\leq y_k^{max}, \\ u_k^{min} \leq u_k &\leq u_k^{max} \end{aligned}$$

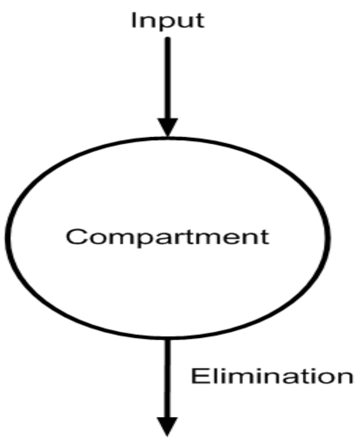
We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

Grey-box Modelling

Grey-box Modelling

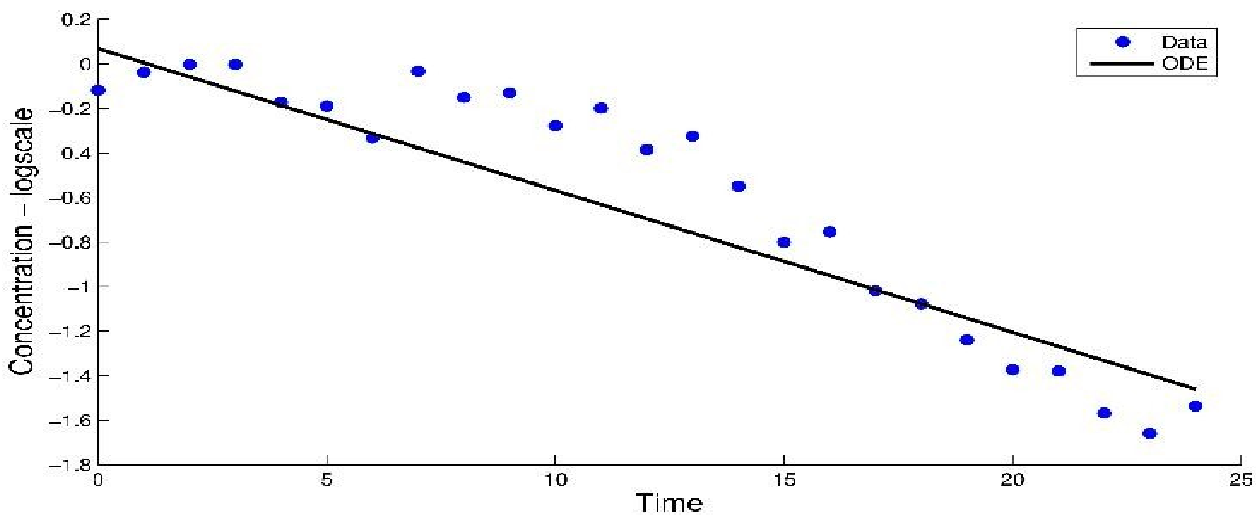


Traditional Dynamical Model

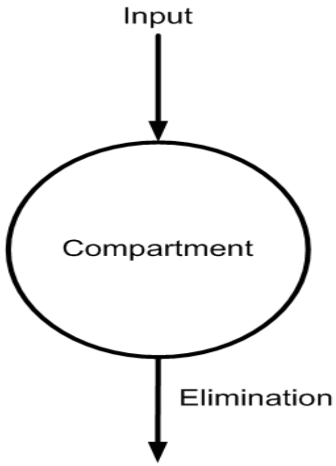


- Ordinary Differential Equation:

$$dA = -KAdt$$
$$Y = A + \epsilon$$

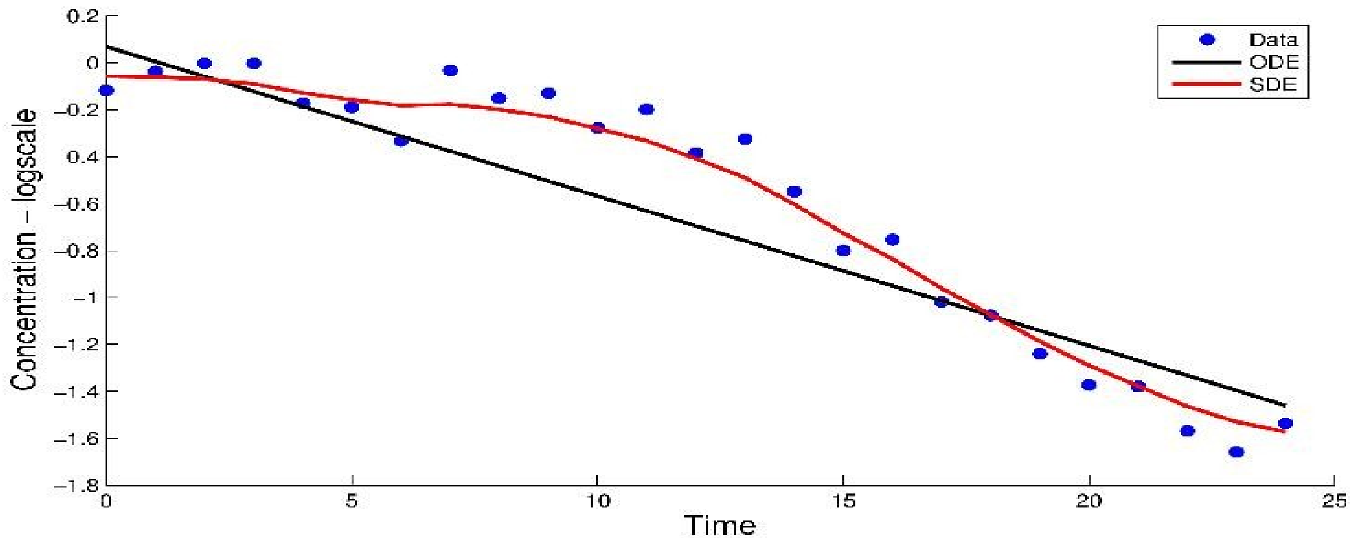


Stochastic Dynamical Model



- Stochastic Differential Equation:

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



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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 $N(0, S)$

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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**

For ODEs: **Forecasts are deterministic**

For SDEs: **Forecasts are probabilistic**

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Case study (Level III)

Price-based Control of Power Consumption (Peak Shaving)

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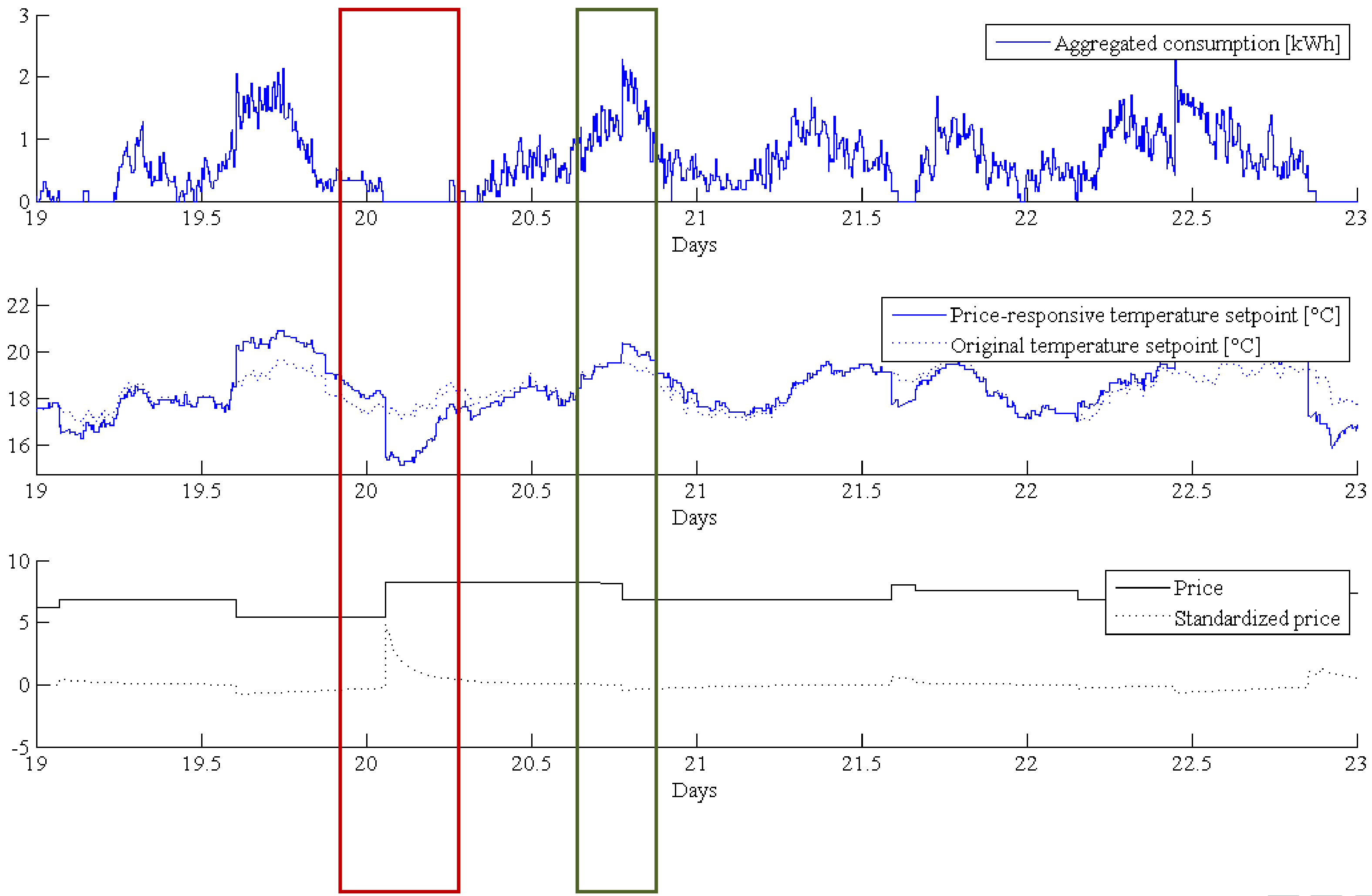
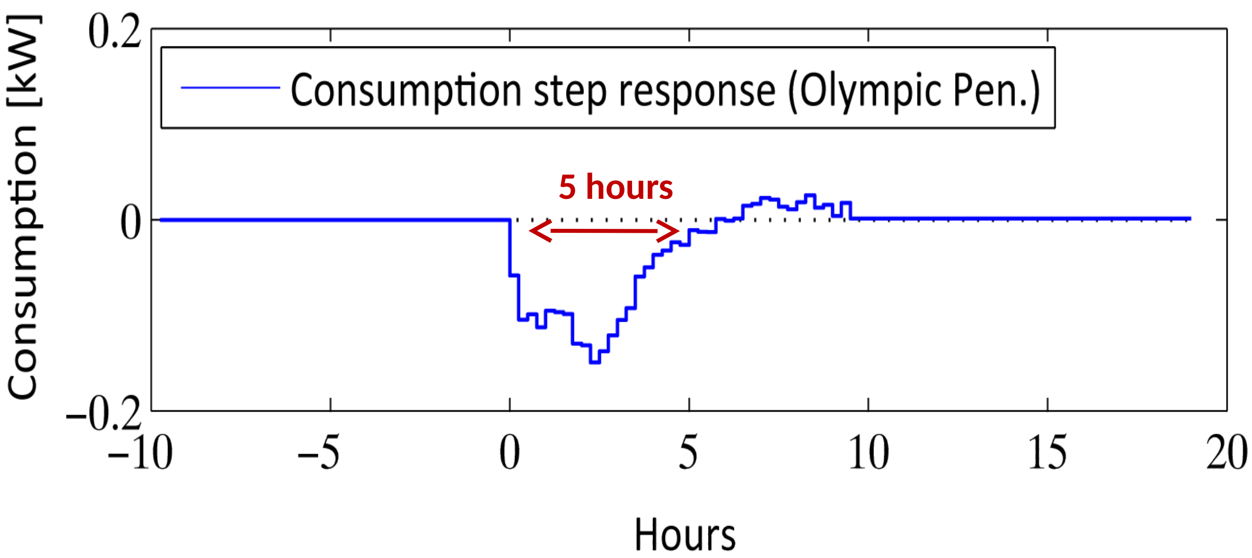
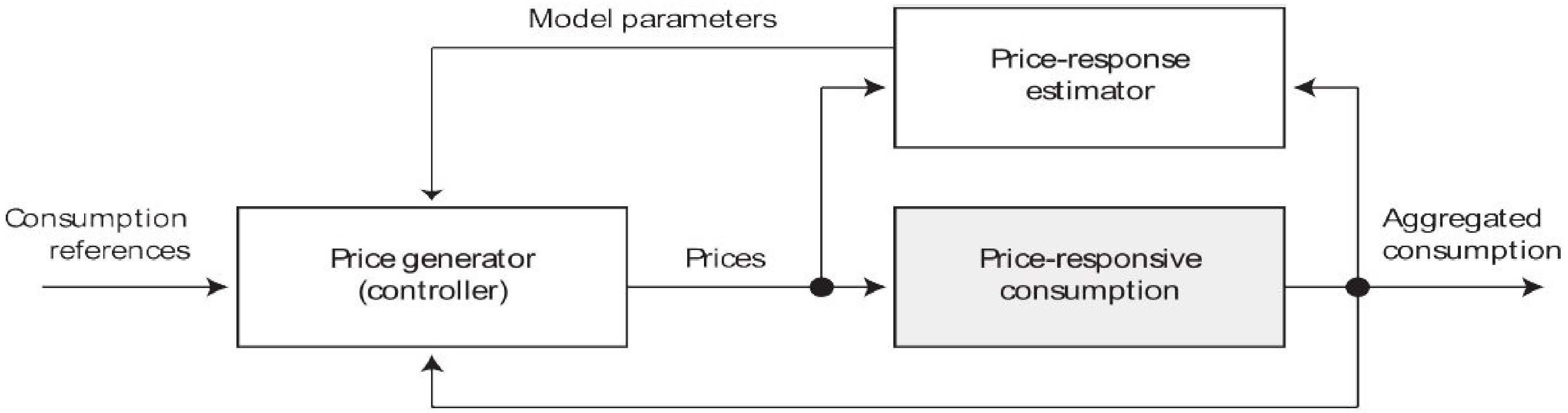
Aggregation (over 20 houses)

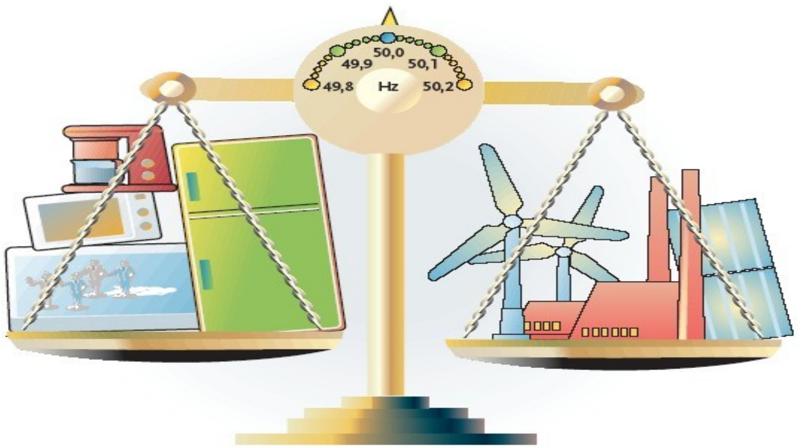


Response on Price Step Change



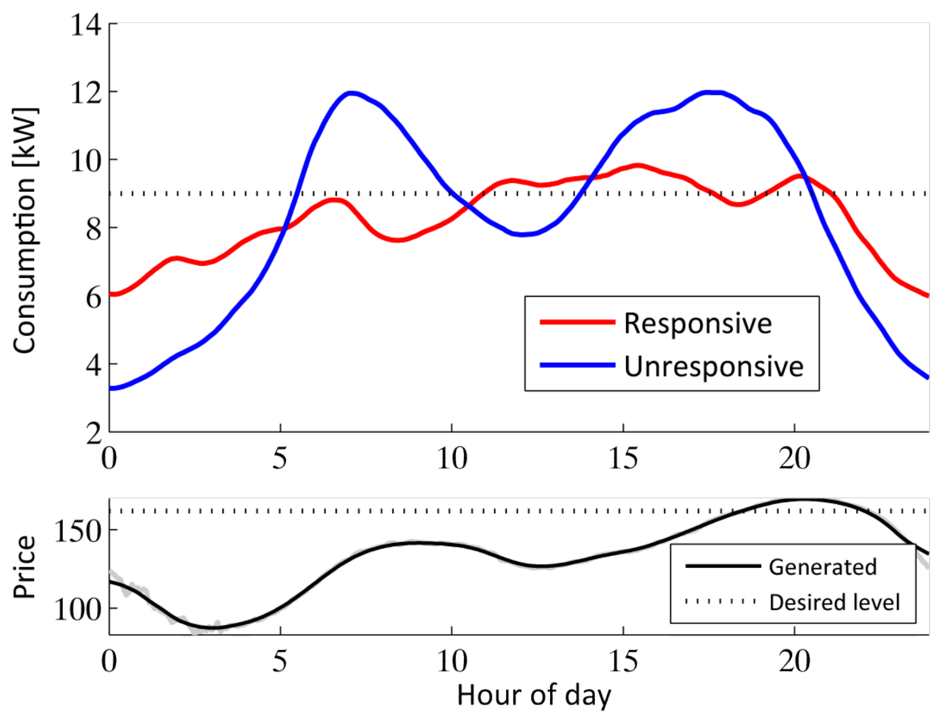
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**



Flexibility Function

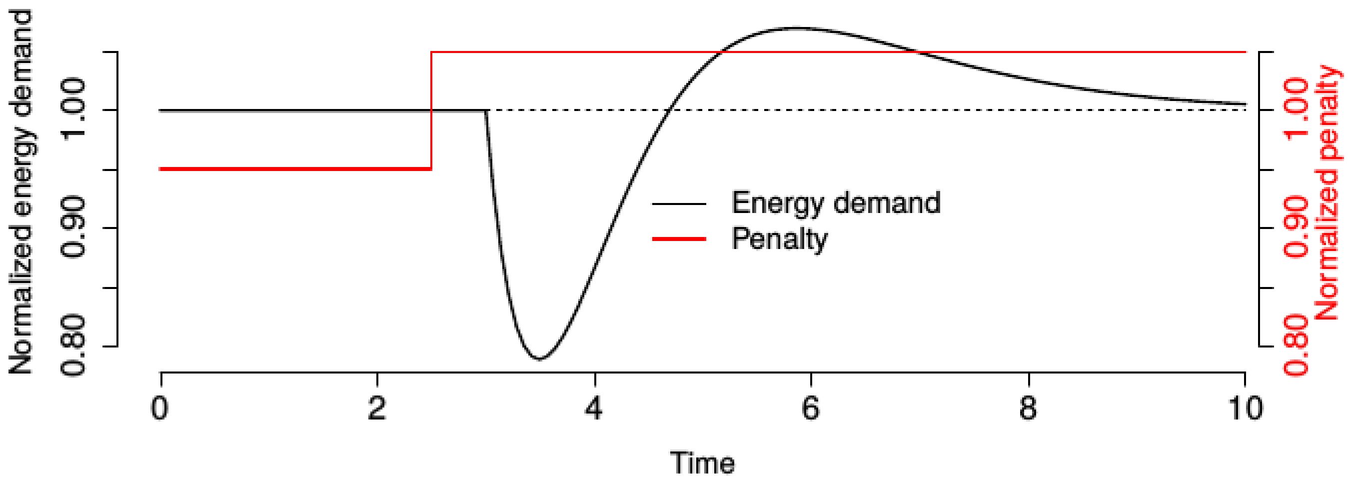
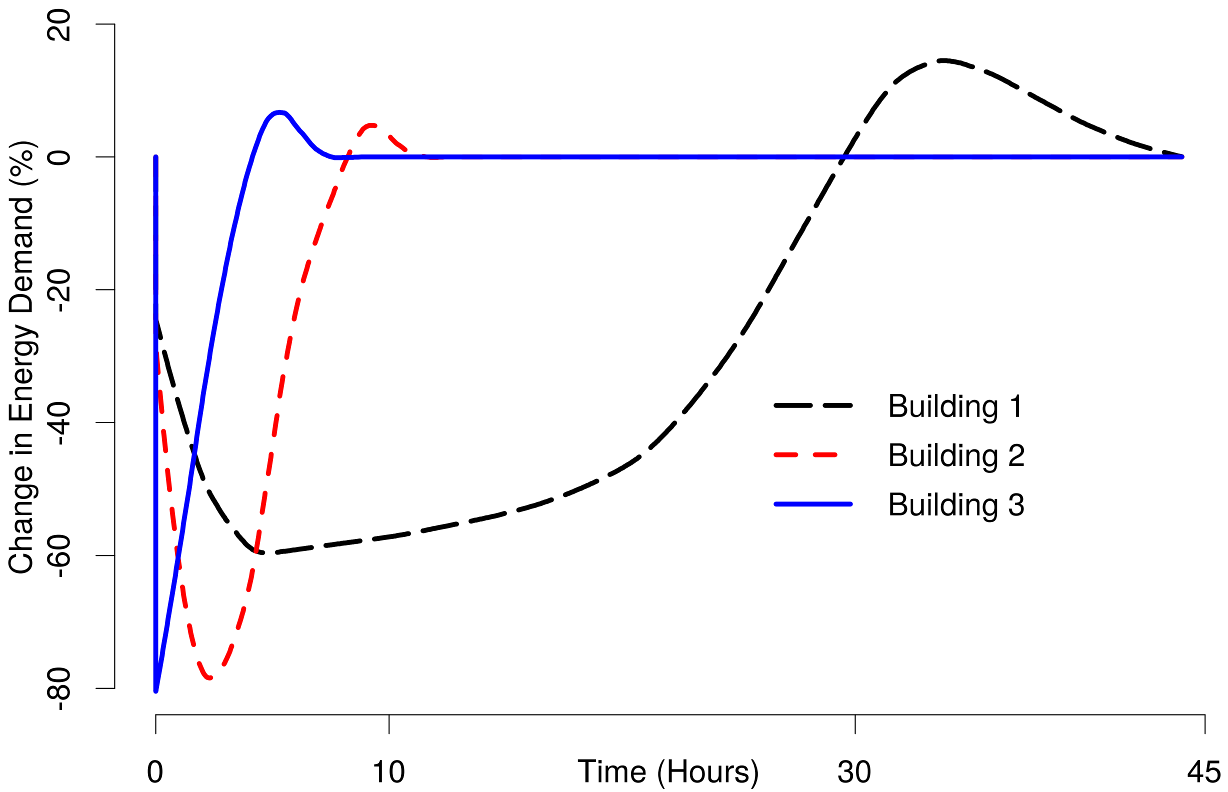


Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

Penalty Function (examples)

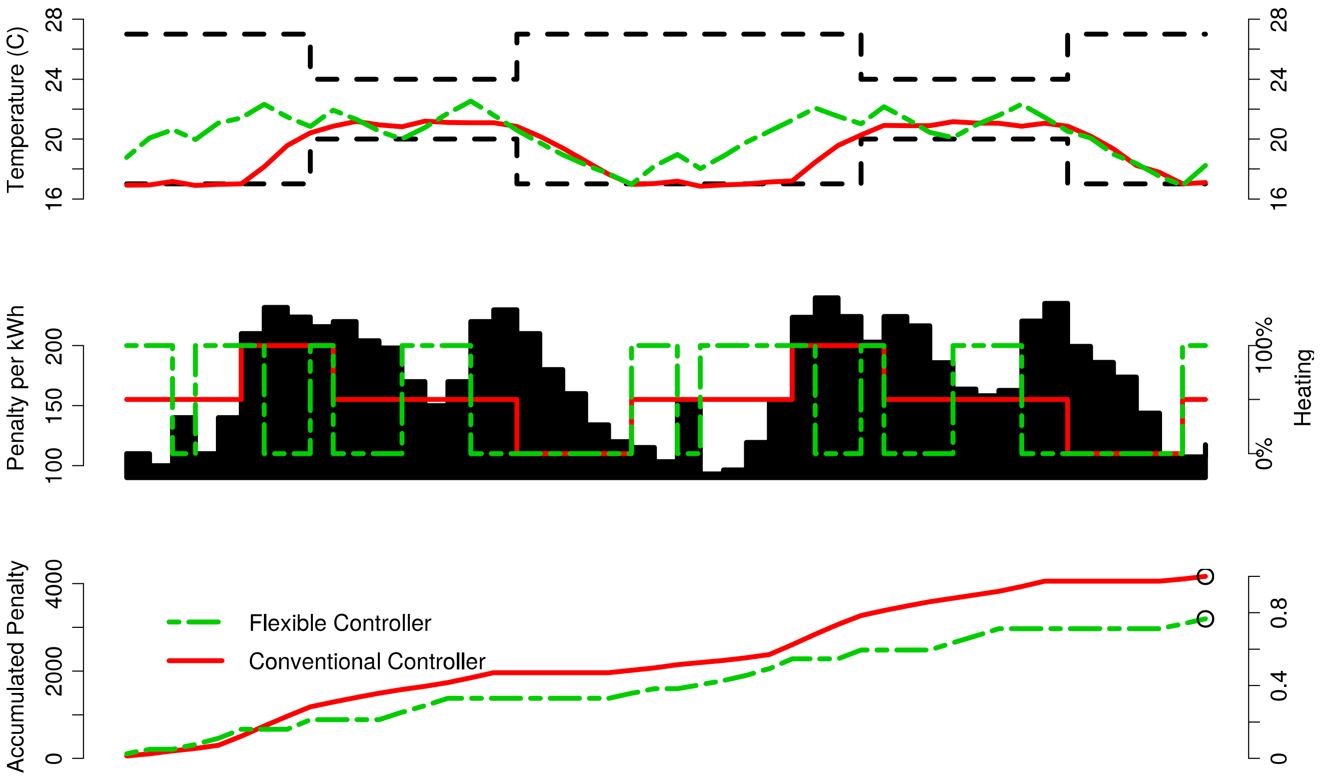
- **Real time CO_2.** If the real time (marginal) CO_2 emission related to the actual electricity production is used as penalty, then, a smart building will minimize the total carbon emission related to the power consumption. Hence, the building will be *emission efficient*.
- **Real time price.** If 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*.

Examples of Flexibility Functions



Flexibility Index

(Penalty based control setup)



Flexibility Index

Table 2: Flexibility Index for each of the buildings based reference penalty signals representing wind, solar and ramp problems.

	Wind (%)	Solar (%)	Ramp (%)
Building 1	36.9	10.9	5.2
Building 2	7.2	24.0	11.1
Building 3	17.9	35.6	67.5

Smart Grid Applications

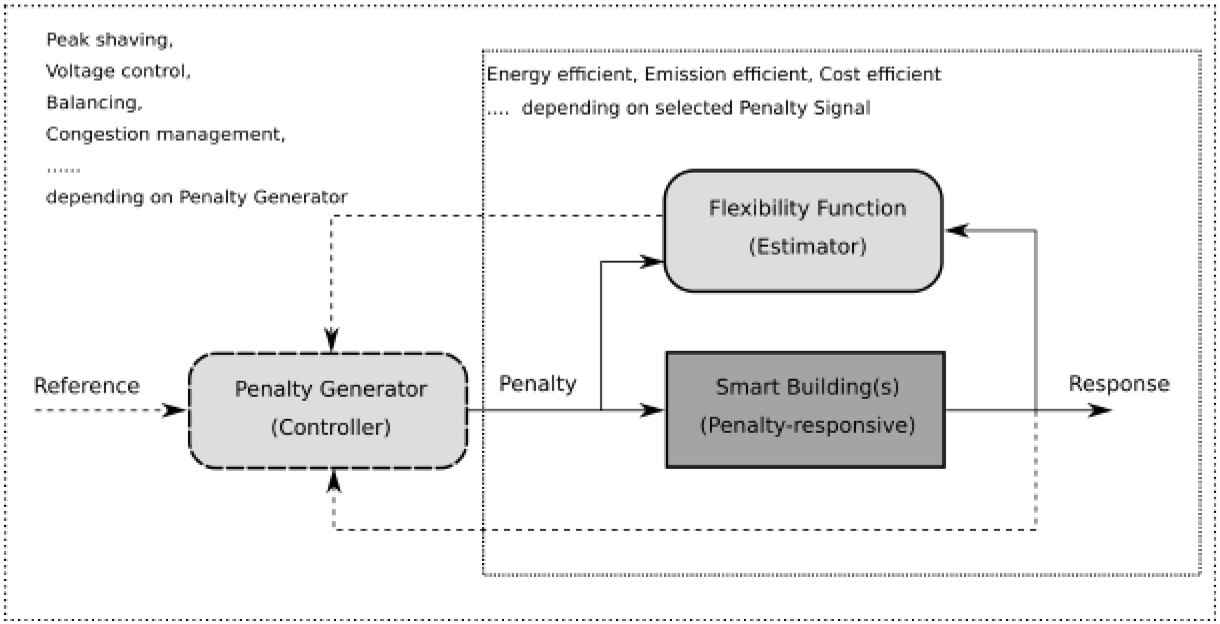


Figure 8: Smart buildings and penalty signals.

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Case study
(Level IV – Indirect Control)

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

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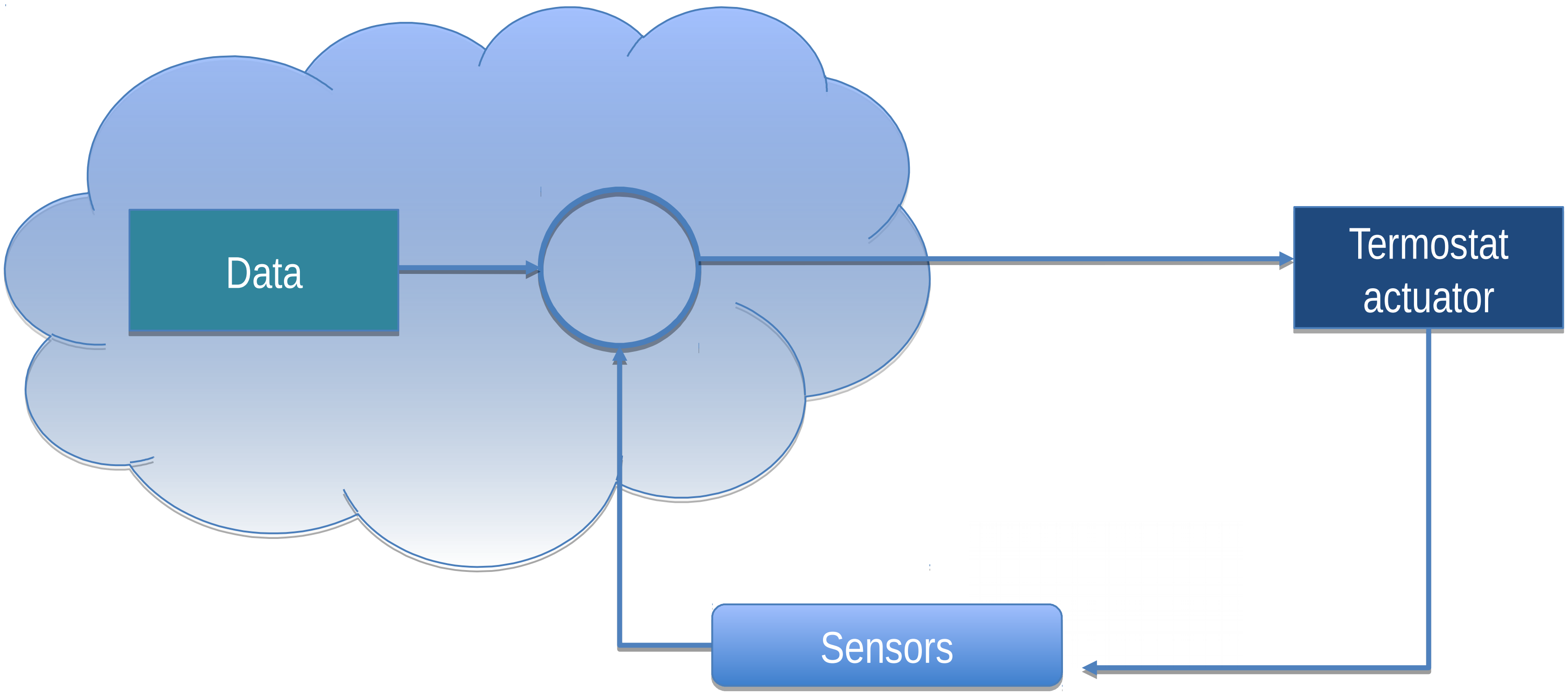
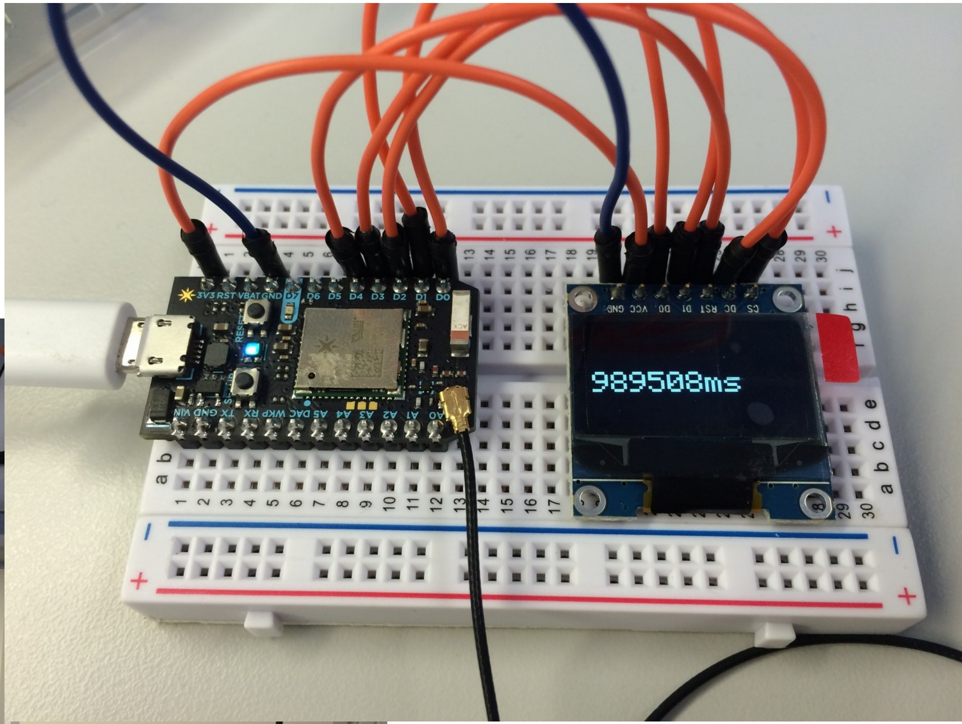
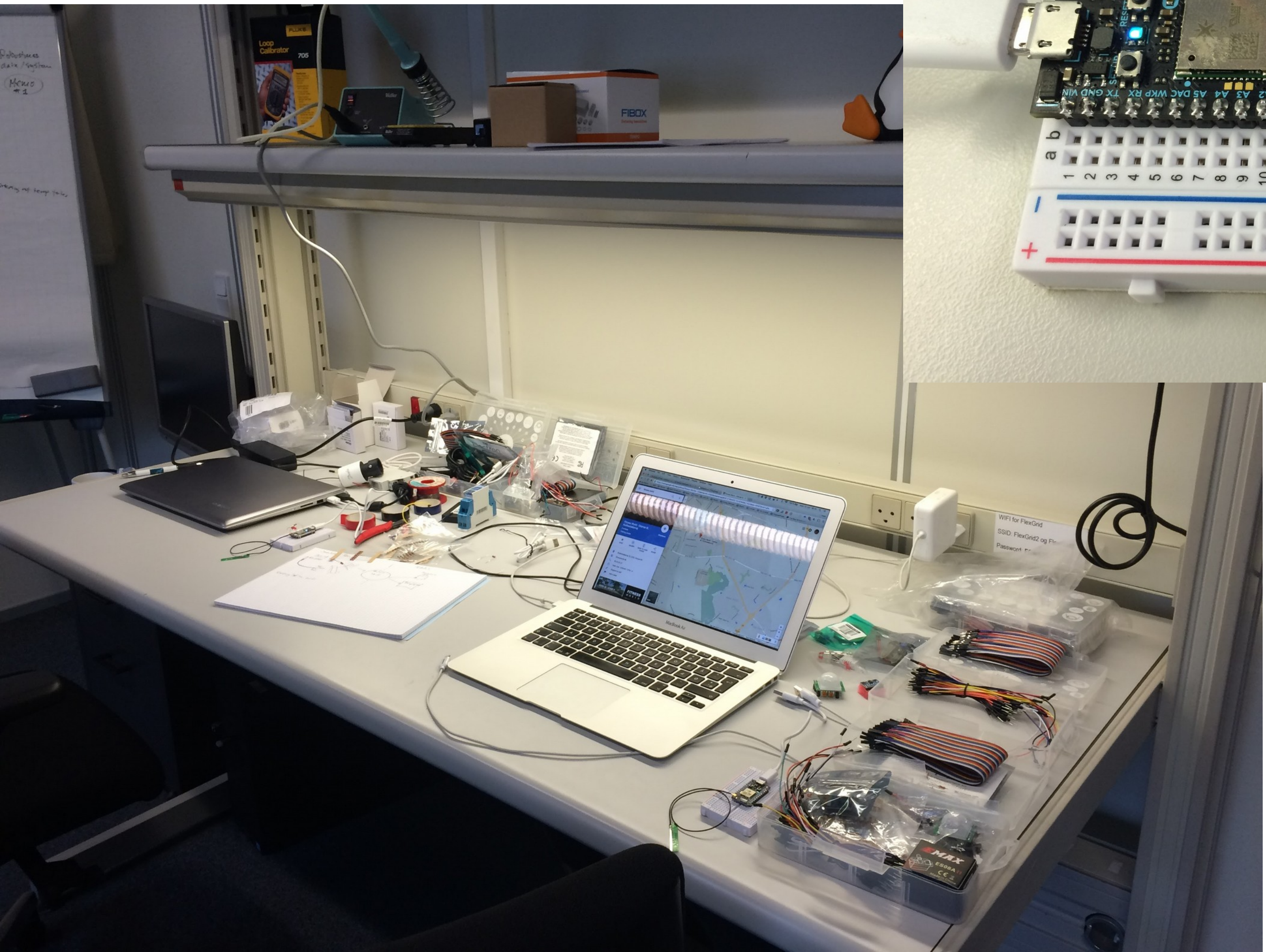
SE-OS – Low level controllers
Control loop design – **logical drawing**

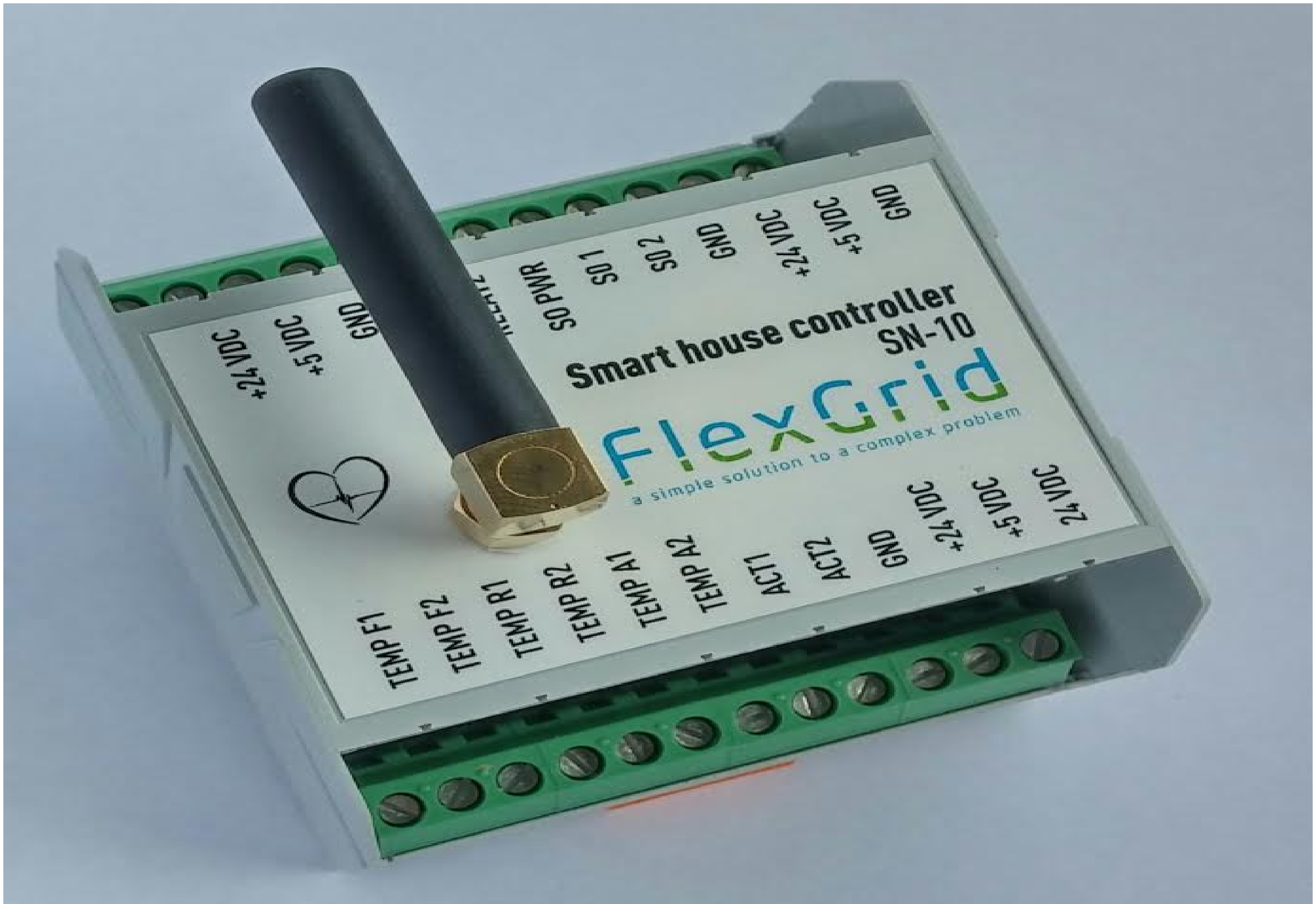


Lab testing ….





SN-10 Smart House Prototype

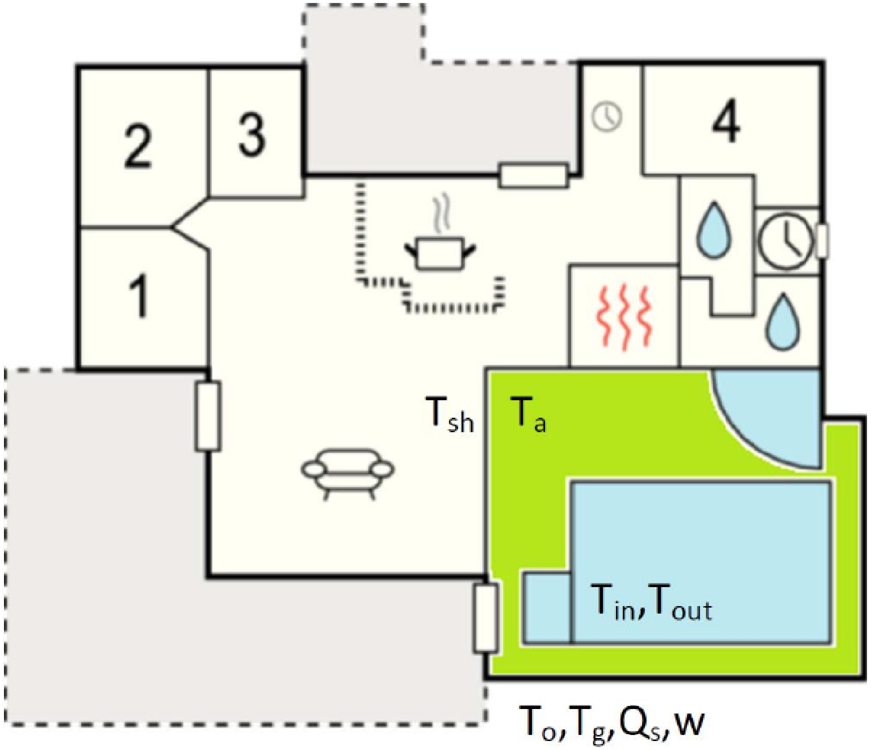


Case study

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

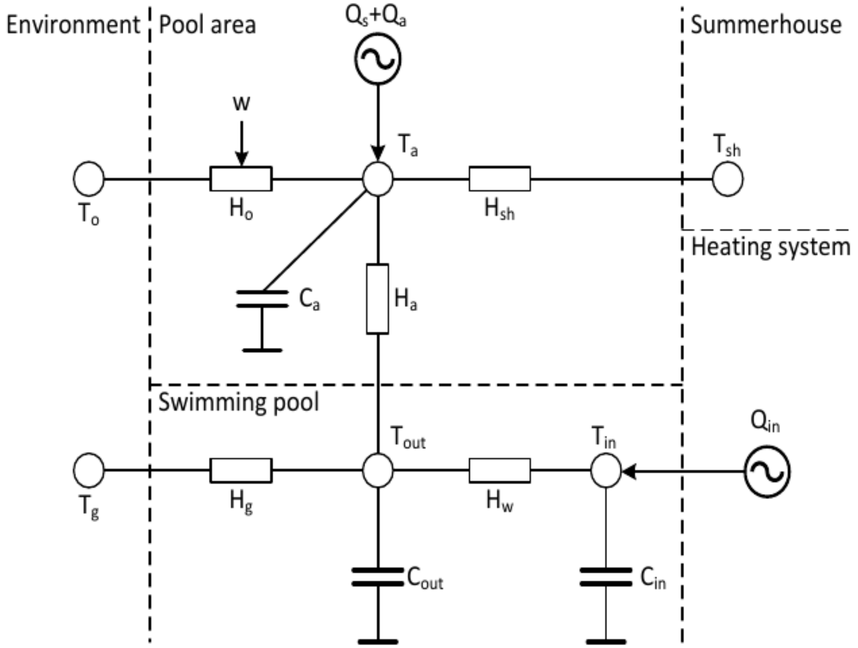
Berkeley Lab - BTUS Division, February 2021

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:

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

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

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

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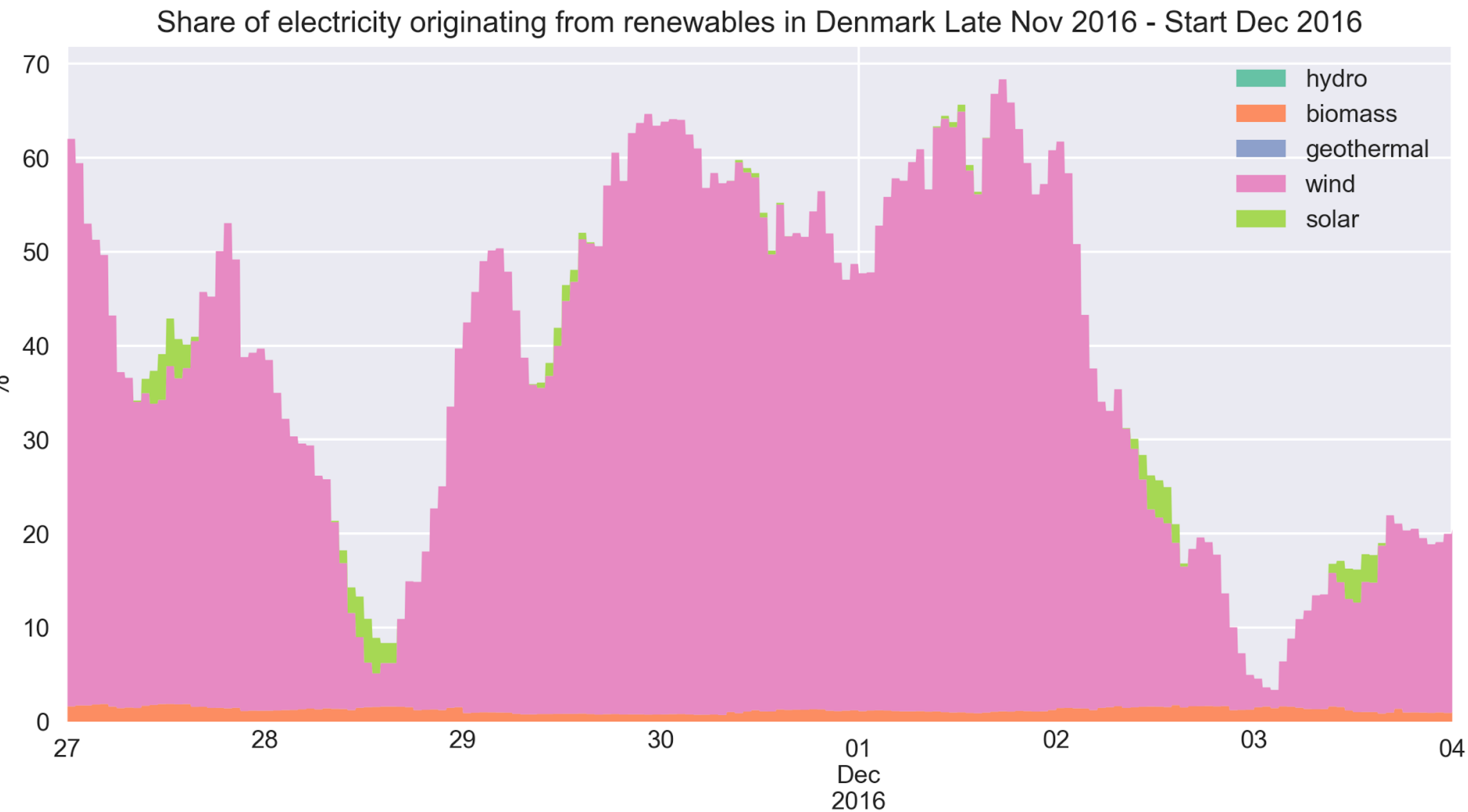

Source: pro.electicitymap.

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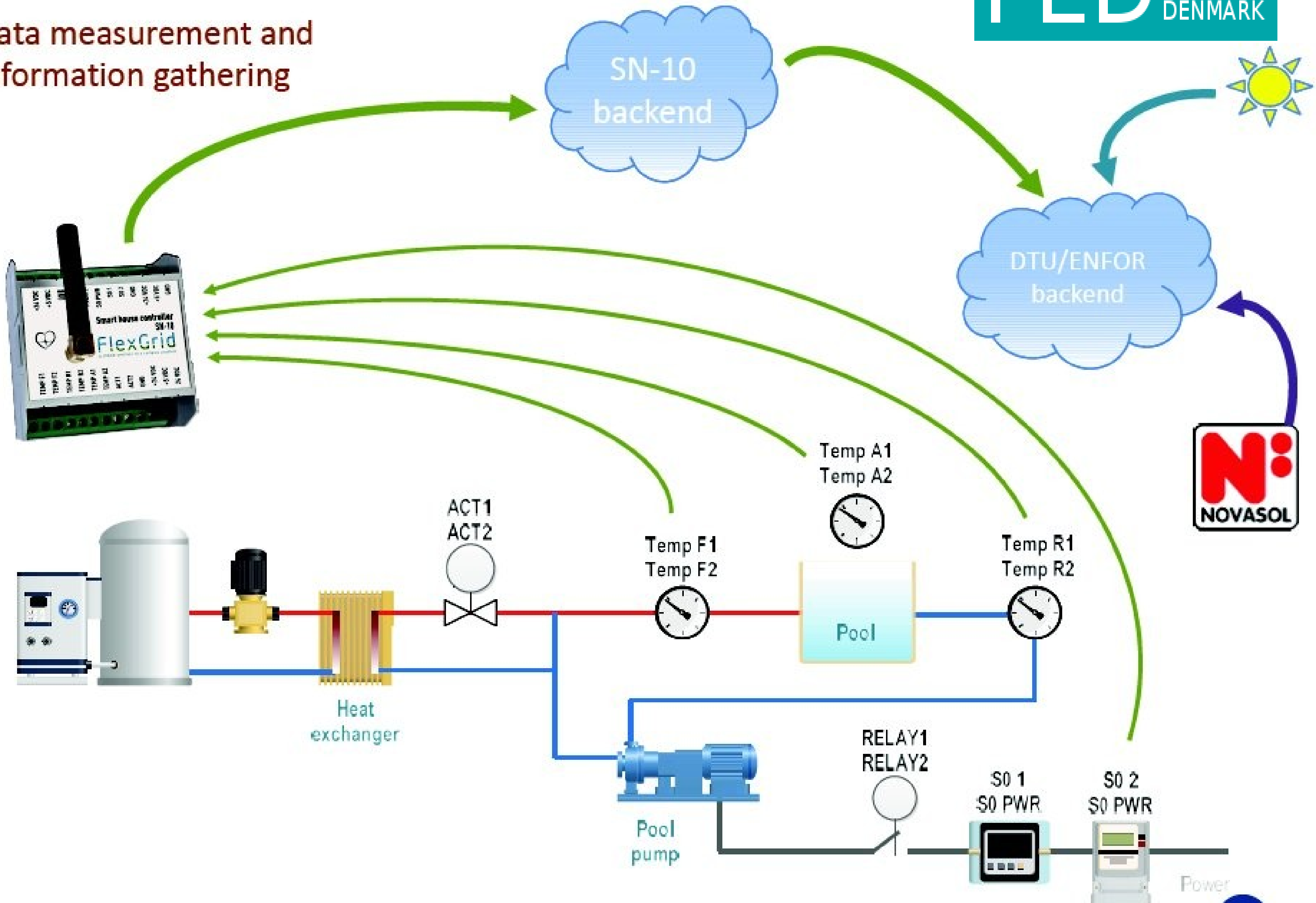
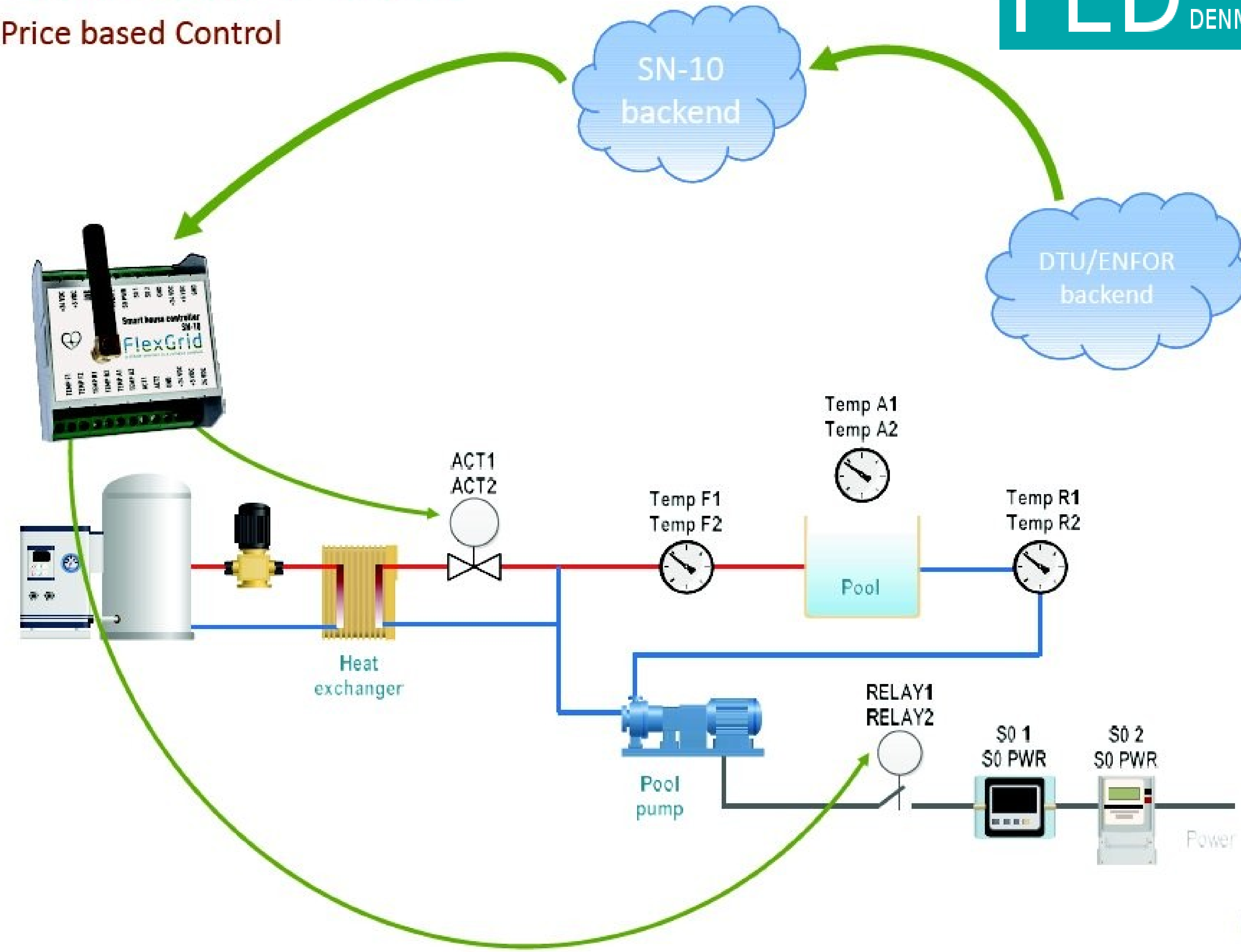
How does it work?

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)

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Integrated Forecasting and Control for Smart Buildings

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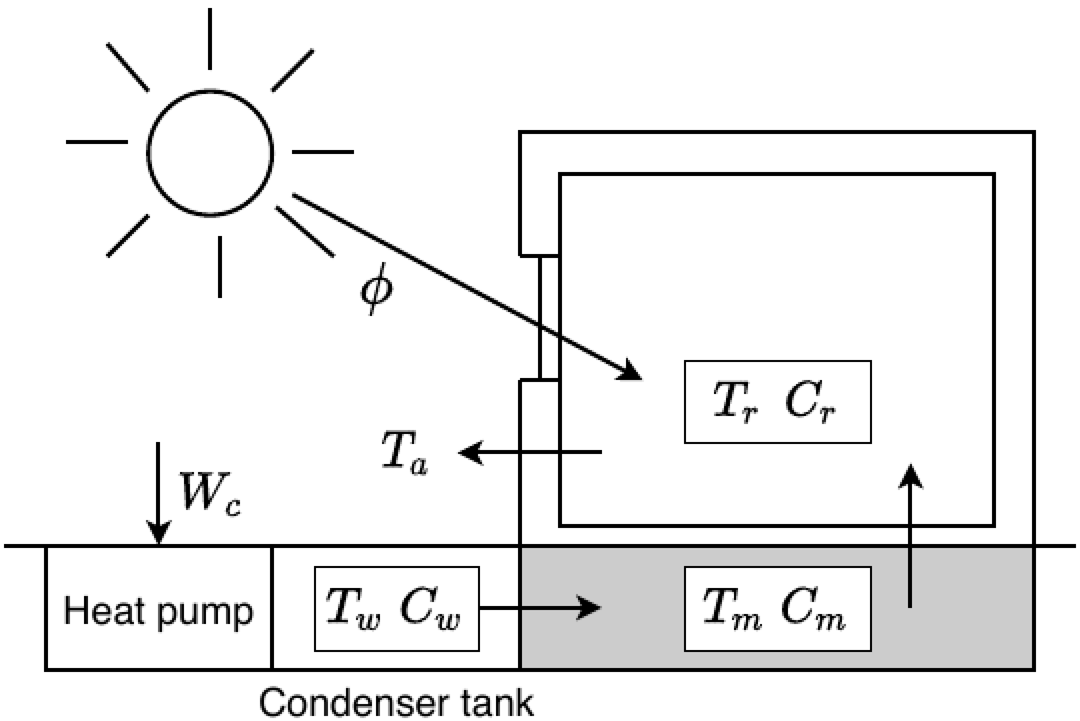
Grey-box Model for a Smart Building



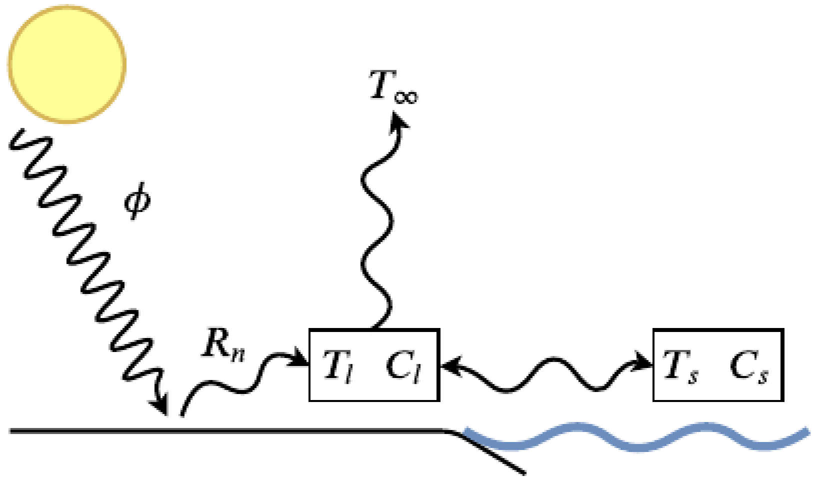
Grey-box Model for Forecasting

(Cloud cover, solar radiation, ambient air temperature)

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

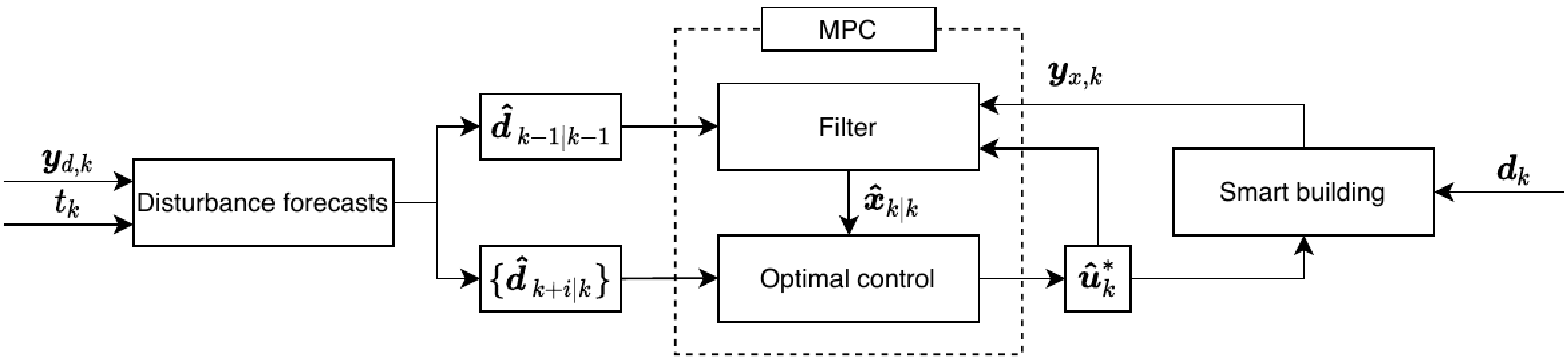
$$
\text{Observation equation} \begin{cases}
d_\phi = \phi + v_\phi, \quad v_\phi \sim N_{iid}(0, R_\phi) \\
d_{T_a} = T_l + v_{T_a}, \quad v_{T_a} \sim N_{iid}(0, R_{T_a}) \\
\boldsymbol{y}_d = [d_{T_a}, d_\phi]^T,
\end{cases} \tag{13}
$$

Grey-box model for Ambient Air Temperature



Integrated Forecasting and Control

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



$$\begin{aligned} \mathrm{d}\boldsymbol{x}(t) &= f_s(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t))\mathrm{d}t \\ &\quad + g_s(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t))\mathrm{d}\boldsymbol{\omega}_s(t) , \end{aligned} \tag{1a}$$

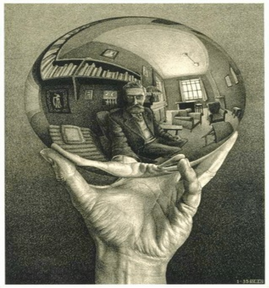
$$\mathrm{d}\boldsymbol{d}(t) = f_d(\boldsymbol{d}(t))\mathrm{d}t + g_d(\boldsymbol{d}(t))\mathrm{d}\boldsymbol{\omega}_d(t) , \tag{1b}$$

$$\boldsymbol{y}_s(t_k) = h_s(\boldsymbol{x}(t_k)) + \boldsymbol{v}_{s,k} , \tag{1c}$$

$$\boldsymbol{y}_d(t_k) = h_d(\boldsymbol{d}(t_k)) + \boldsymbol{v}_{d,k} , \tag{1d}$$

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

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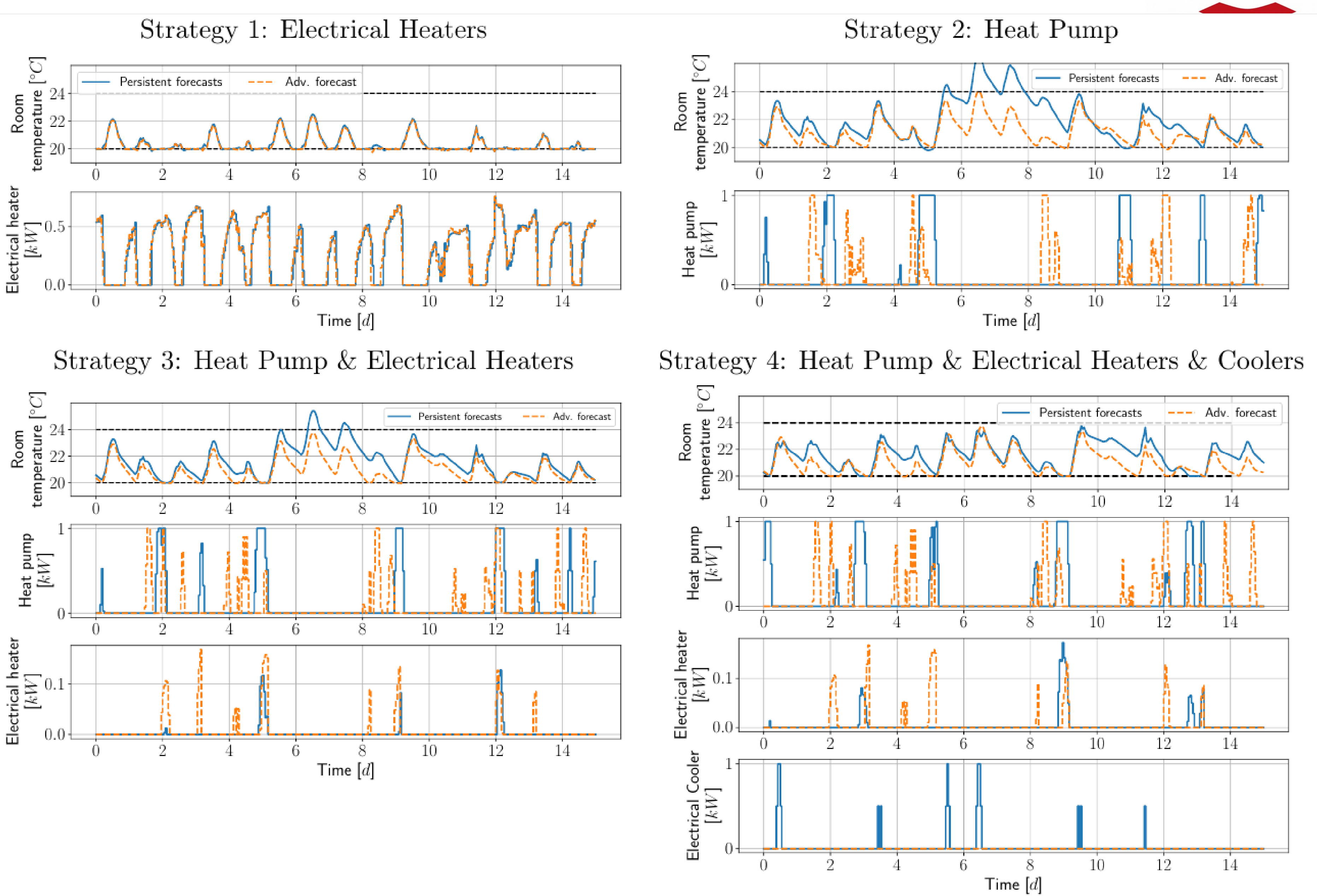

Electricity cost in EUR

Electricity cost of the simulations			
Heating strategy	Persistent	Advanced forecasts	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 forecasts	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

- Energy Systems Integration is important for unlocking the needed flexibility for an efficient large scale integration of wind and solar energy
- We have demonstrated how to use grey-box modelling for energy systems integration and control
- We have suggested the use of Flexibility Functions (and Flexibility Indeces)
- For Denmark buildings with district heating/cooling provide the needed flexibility (may include seasonal storage)
- FF and price-based control facilitates energy systems integration
- We have described the Smart-Energy OS, which is hierarchy of tools for aggregation, modelling, forecasting, optimization, and control
- The Smart-Energy OS can focus on
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency

For more information ...

See for instance

www.smart-cities-centre.org

...or contact

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