Characterizing the Energy Flexibility of Buildings and Districts

Henrik Madsen and Rune G. Junker

FME ZEN Centre, NTNU

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

http://www.henrikmadsen.org

Existing Markets - Challenges

- Dynamics
- Stochasticity
- Nonlinearities
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, ...)
- Speed / problem size
- Characterization and use of flexibility
- Requirements on user installations

Challenges (cont.)

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 [illegible]tal 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.

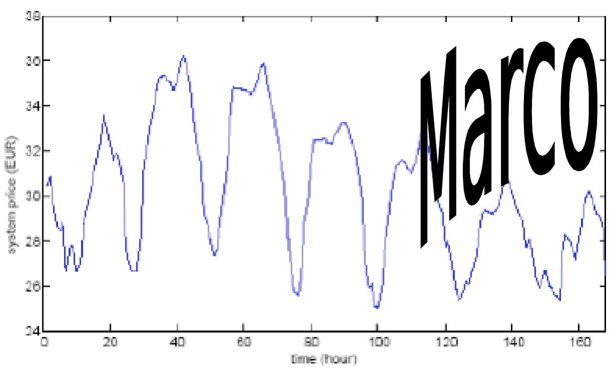
Almost no Flexibility

COMPETITIVE BIDDING AND STABILITY ANALYSIS IN ELECTRICITY MARKETS USING CONTROL THEORY

Main idea: **applying control theory to the study of power markets**

Advantages in handling effectively

Dynamics

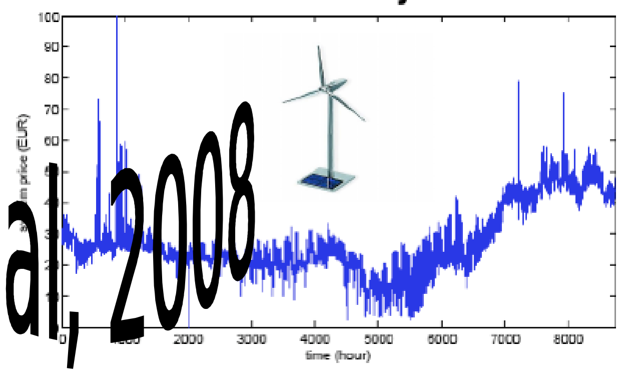


control theory provides ways of modeling the dynamics which is intrinsic in energy markets

↓

it is possible to develop advanced bidding strategies which exploit the inclusion of the dynamics in the model

Uncertainty



stochastic control theory allows for taking into account different sources of uncertainty (wind, ...)

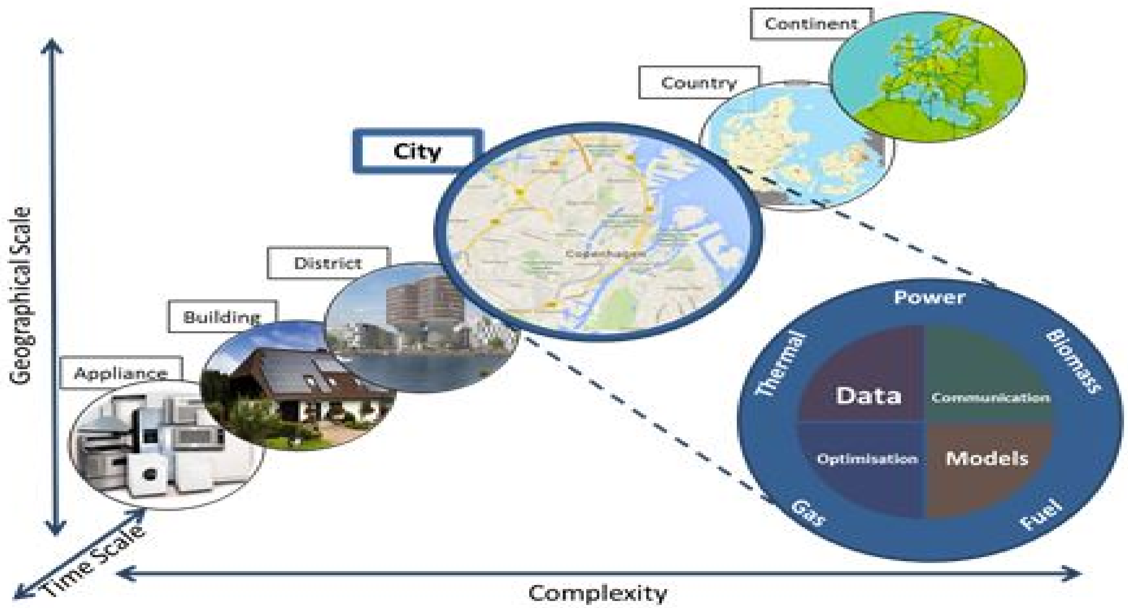
↓

it is possible to develop bidding strategies which are optimal with respect to the stochastic characteristics of the market

Marco Zugno et.al, 2008

Temporal and Spatial Scales

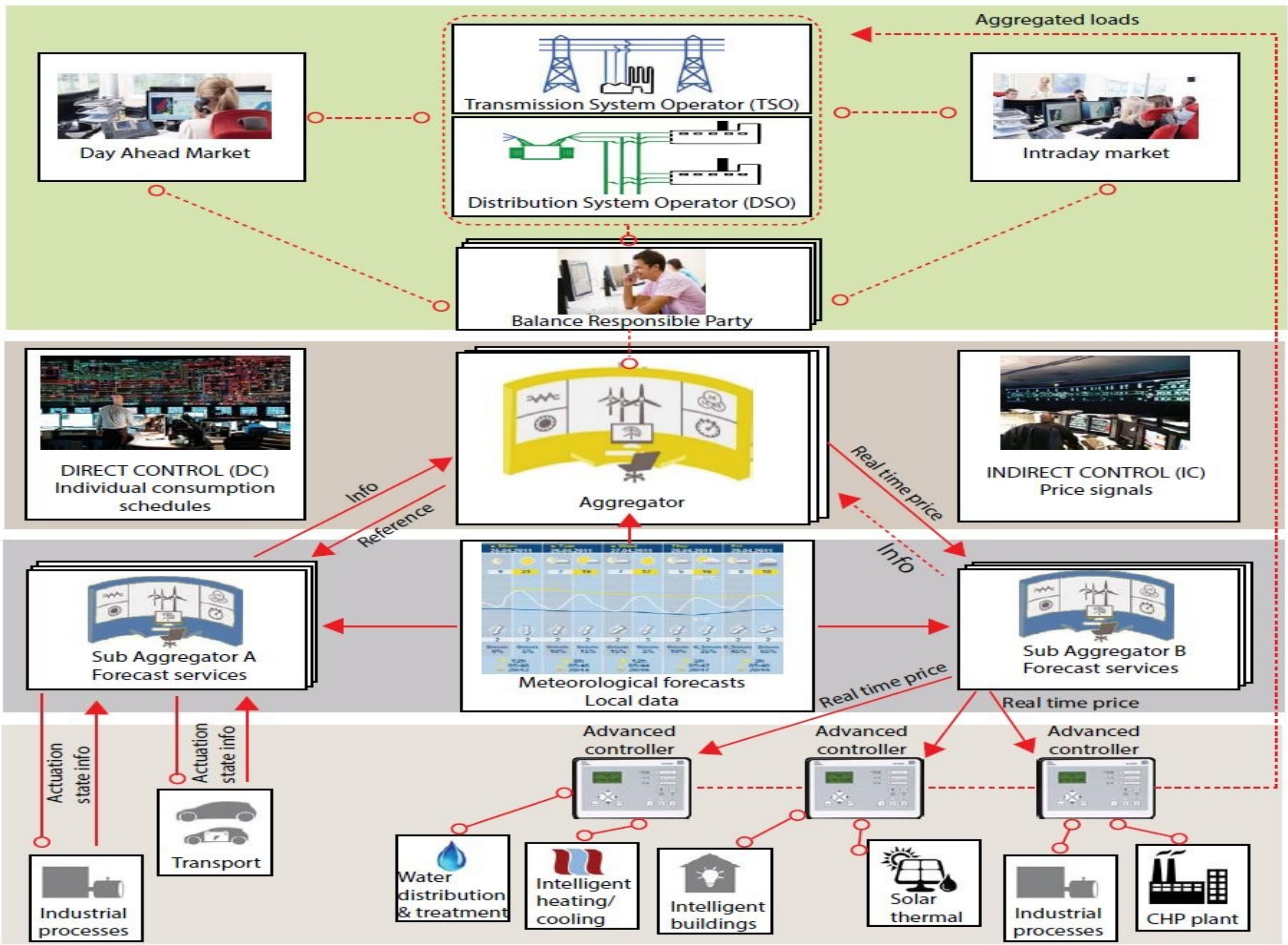
The ***Smart-Energy Operating-System (SE-OS)*** is used to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for ***operating flexible electrical energy systems*** at **all scales**.



Innovation Fund Denmark

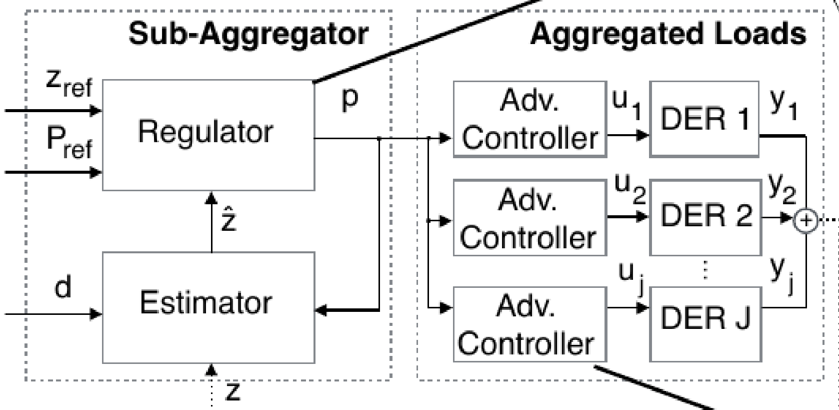
Smart-Energy OS

ZERO EMISSION NEIGHBOURHOODS IN SMART CITIES



CITIES
Centre for IT Intelligent Energy Systems

Proposed methodology
Control-based methodology



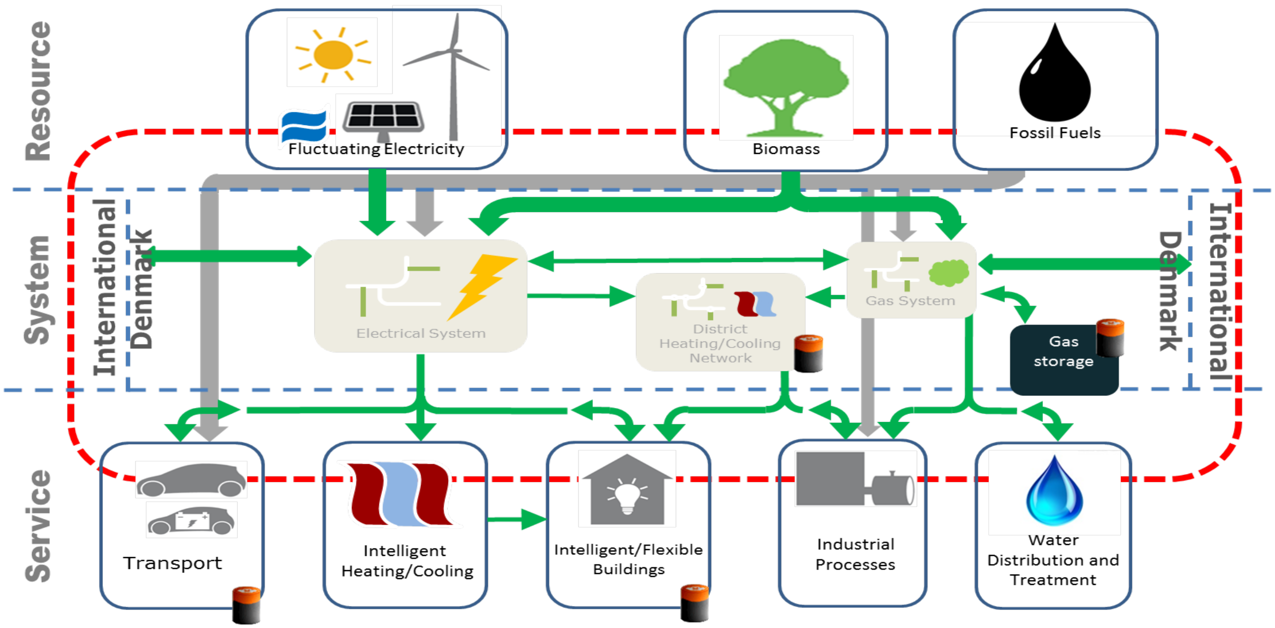
$$
\begin{aligned}
\min_{p} \quad & \mathrm{E}\Big[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||\Big] \\
\text{s.t.} \quad & \hat{z}_{k+1} = f(p_k)
\end{aligned}
$$

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

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

Models for systems of systems

Intelligent systems integration using **data and ICT solutions** are based on **<u>grey-box models</u>** **for real-time operation of flexible energy systems**

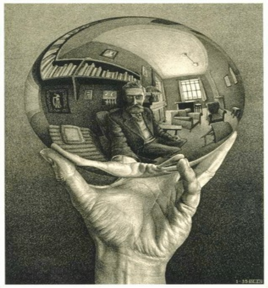


Innovation Fund Denmark

SE-OS Characteristics

ZERO EMISSION NEIGHBOURHOODS IN SMART CITIES

- ‘Bidding – clearing – activation’ at higher levels
- Nested sequence of systems – systems of systems
- Hierarchy of optimization (or control) problems
- Control principles at higher spatial/temporal resolutions
- Cloud or Fog (IoT, IoS) based solutions – eg. for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ...)
- Allow for new players (specialized aggregators)
- Simple setup for the communication and contracts
- Provides a solution for all ancillary services
- Harvest flexibility at all levels

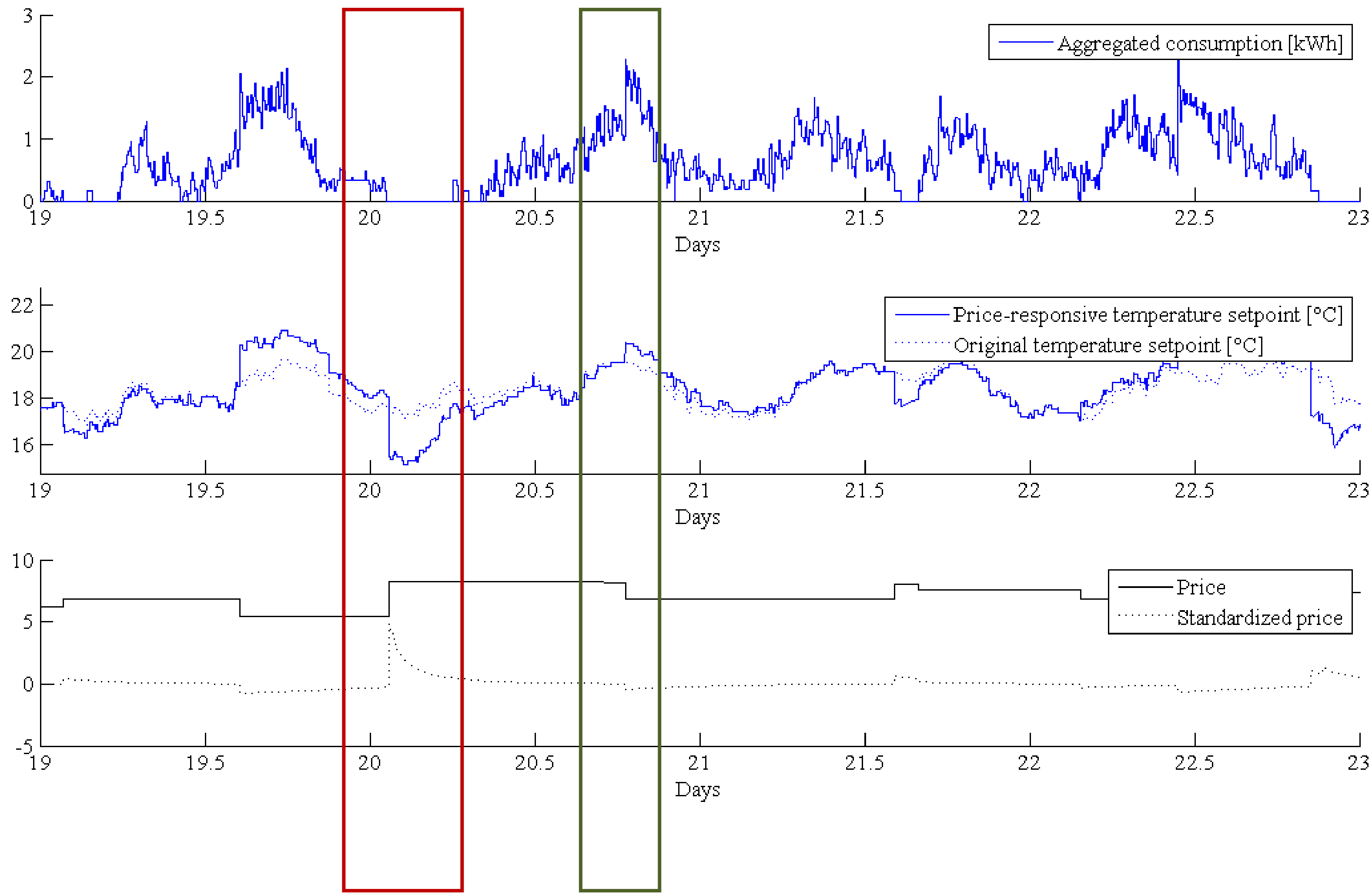


CITIES
Centre for IT Intelligent Energy Systems

Case study No. 1

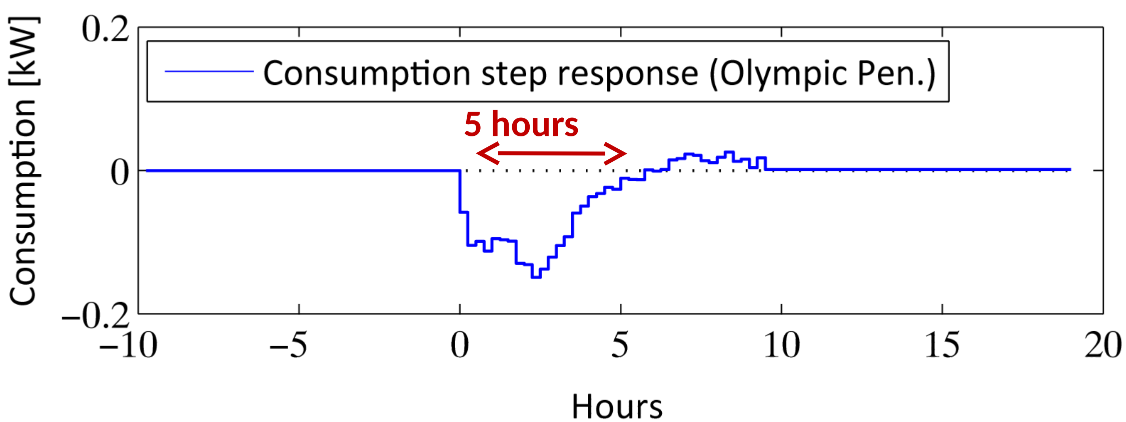
Control of Power Consumption using the Thermal Mass of Buildings (Peak shaving)

Aggregation (over 20 houses)

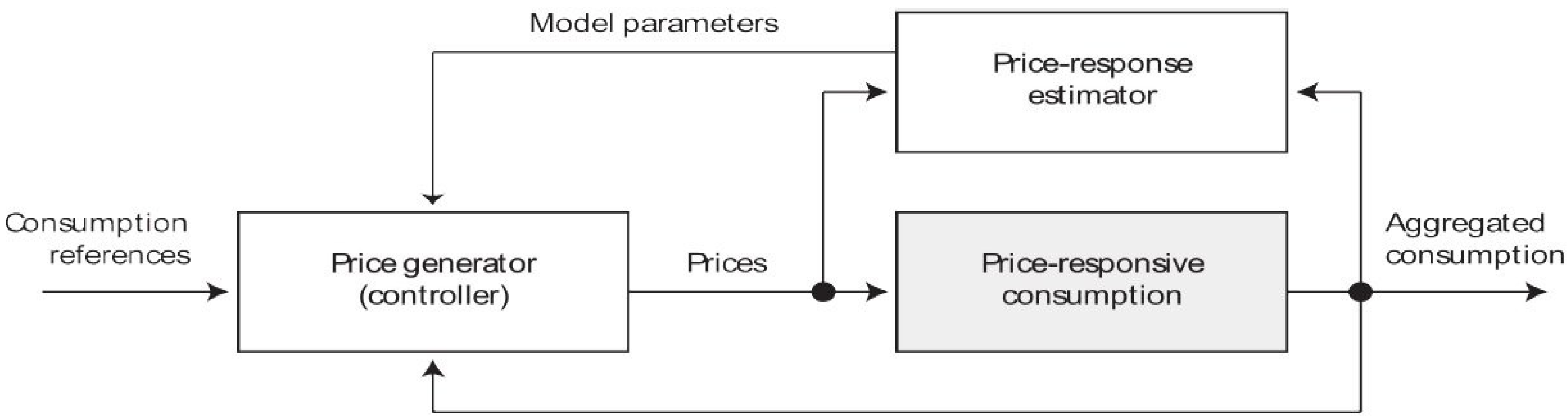


Non-parametric Response on Price Step Change

Olympic Peninsula



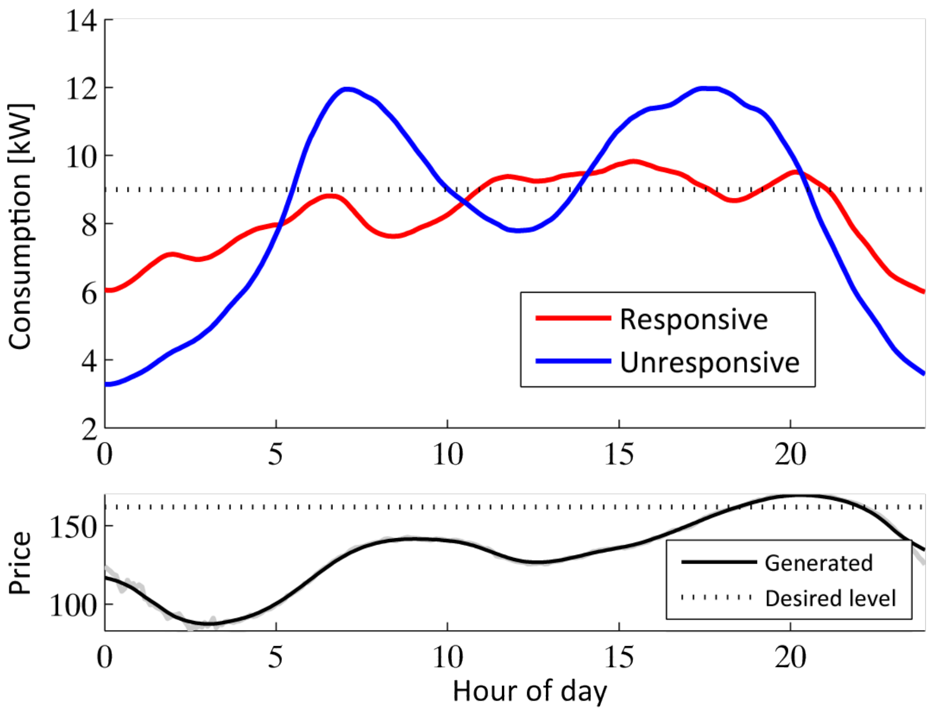
Control of Energy Consumption



Control performance

Considerable **reduction in peak consumption**

Mean daily consumption shift

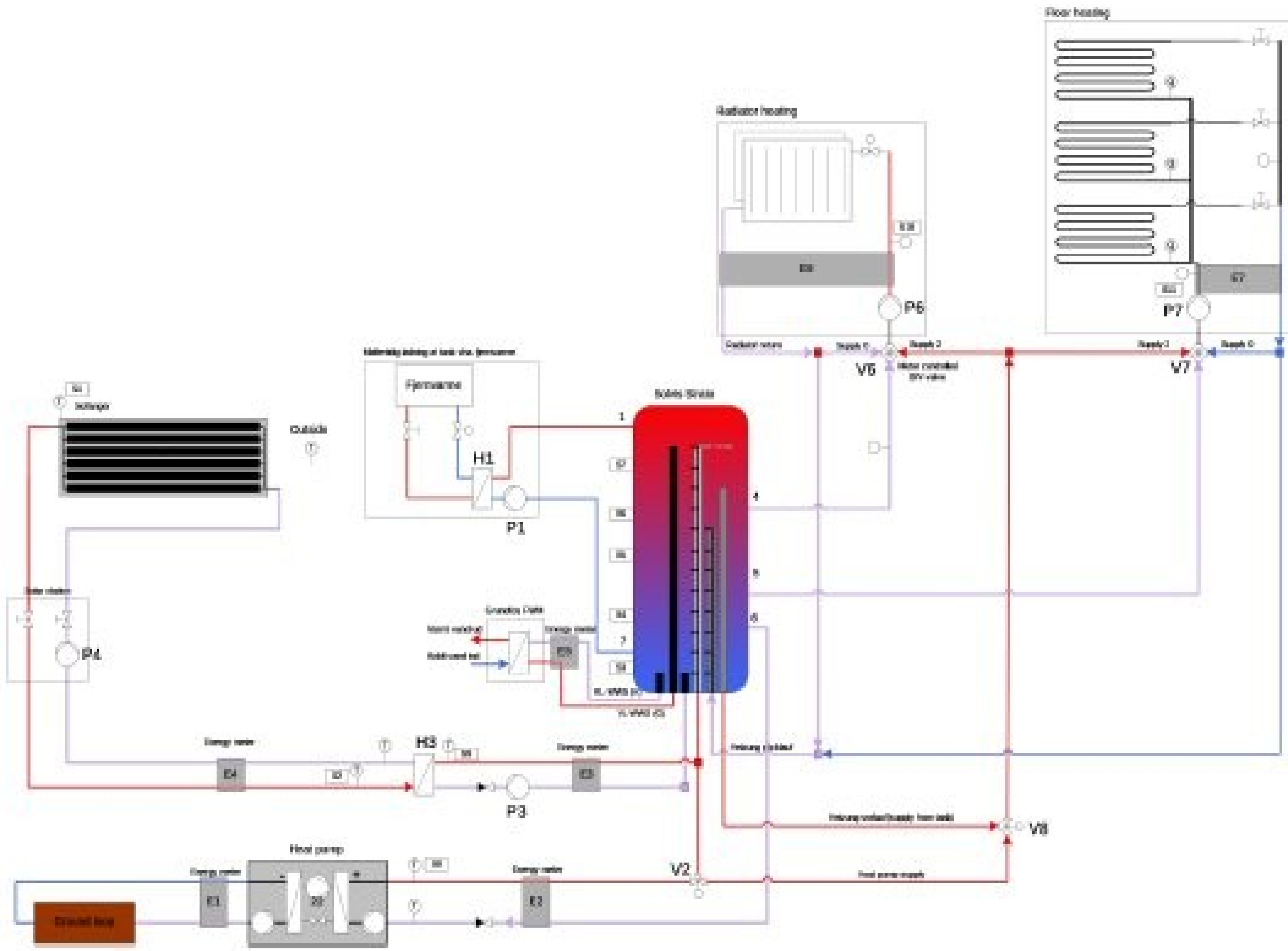


Case study No. 2

Control of Heat Pumps for buildings with a thermal solar collector (minimizing cost)

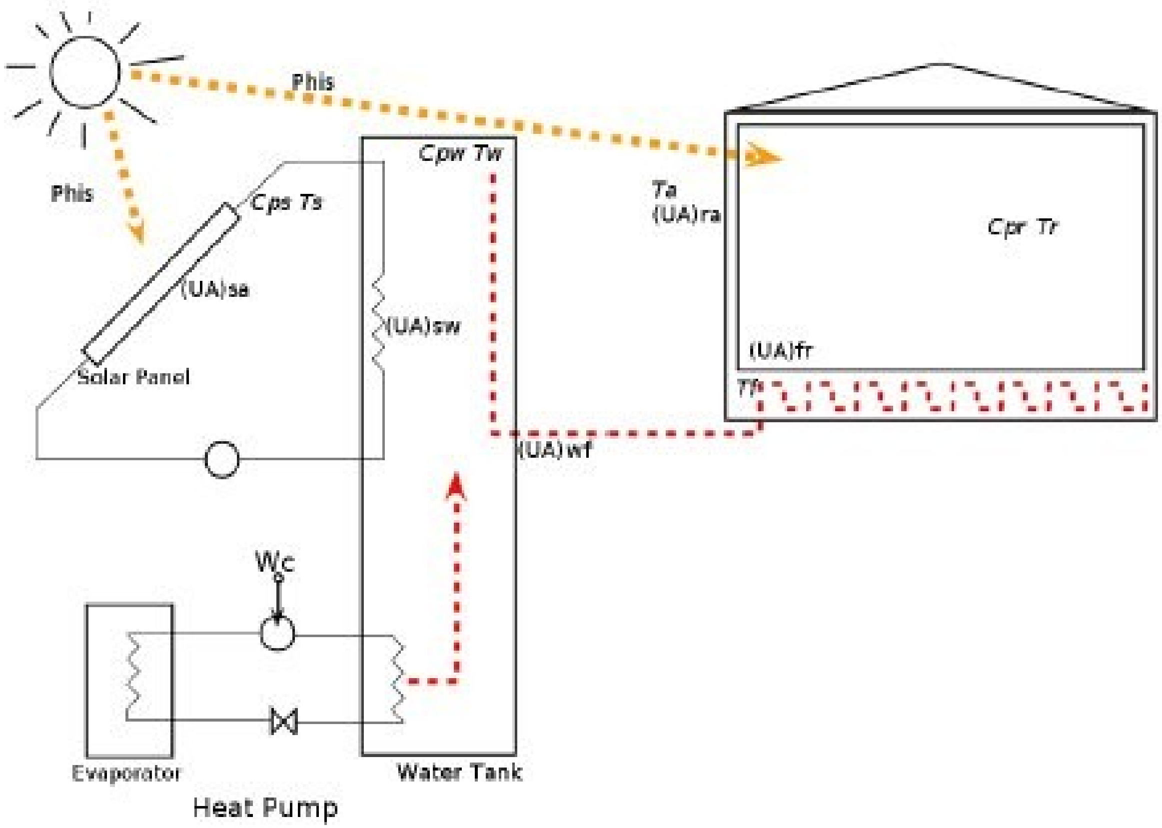
Grundfos Case Study

Schematic of the heating system



Modeling Heat Pump and Solar Collector

Simplified System



Formulation

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

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

$$\text{Subject to} \quad x_{k+1} = Ax_k + Bu_k + Ed_k \quad k = 0, 1, \ldots, N-1 \tag{4b}$$

$$y_k = Cx_k \quad k = 1, 2, \ldots, N \tag{4c}$$

$$u_{min} \leq u_k \leq u_{max} \quad k = 0, 1, \ldots, N-1 \tag{4d}$$

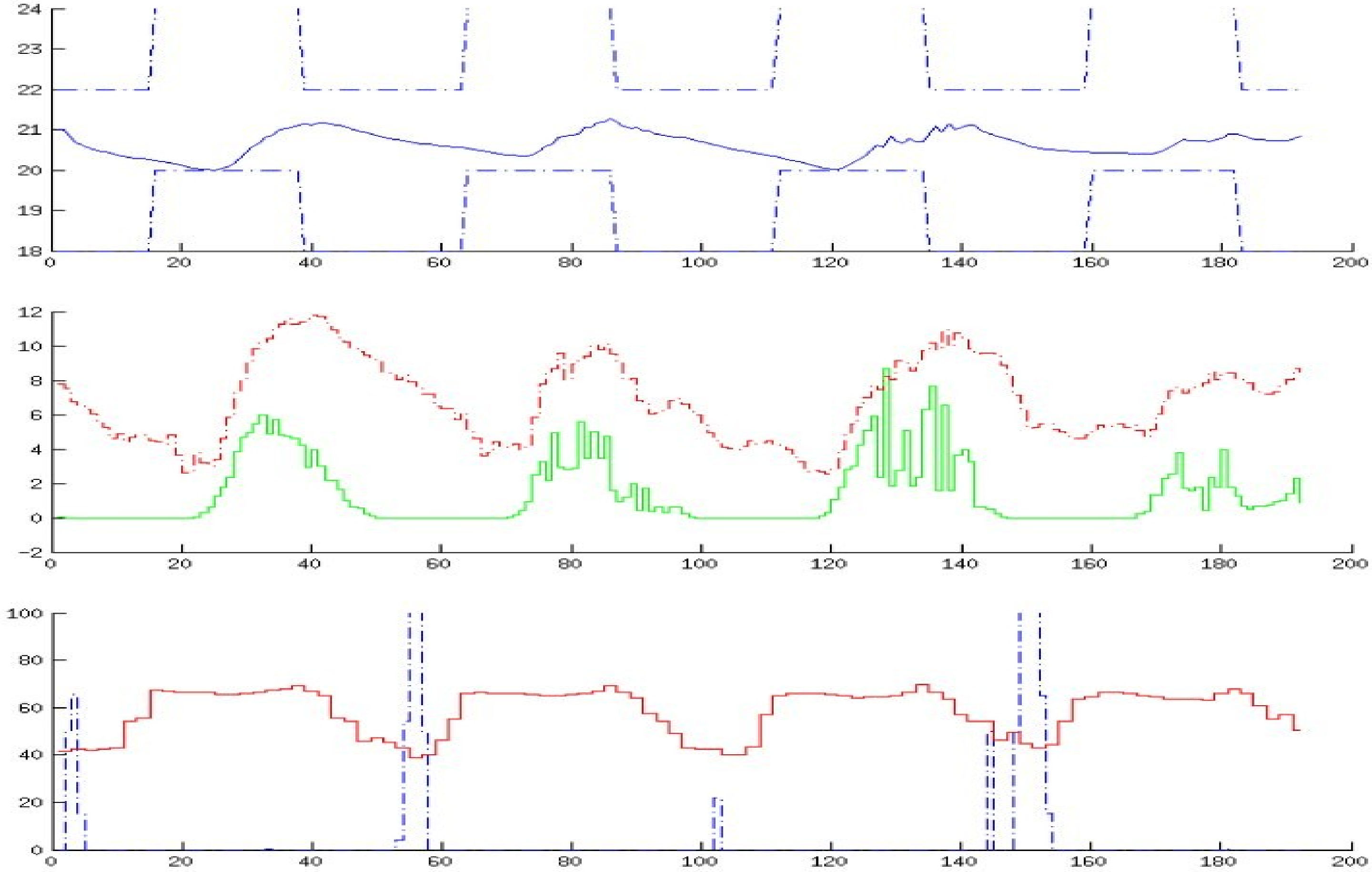
$$\Delta u_{min} \leq \Delta u_k \leq \Delta u_{max} \quad k = 0, 1, \ldots, N-1 \tag{4e}$$

$$y_{min} \leq y_k \leq y_{max} \quad k = 0, 1, \ldots, N \tag{4f}$$

Innovation Fund Denmark

EMPC for heat pump with solar collector (cost savings 25 pct)

ZERO EMISSION NEIGHBOURHOODS IN SMART CITIES



CITIES
Centre for IT Intelligent Energy Systems

Innovation Fund Denmark

ZEN
ZERO EMISSION NEIGHBOURHOODS IN SMART CITIES

Flexibility Setup and Control

CITIES
Centre for IT Intelligent Energy Systems

Characteristics

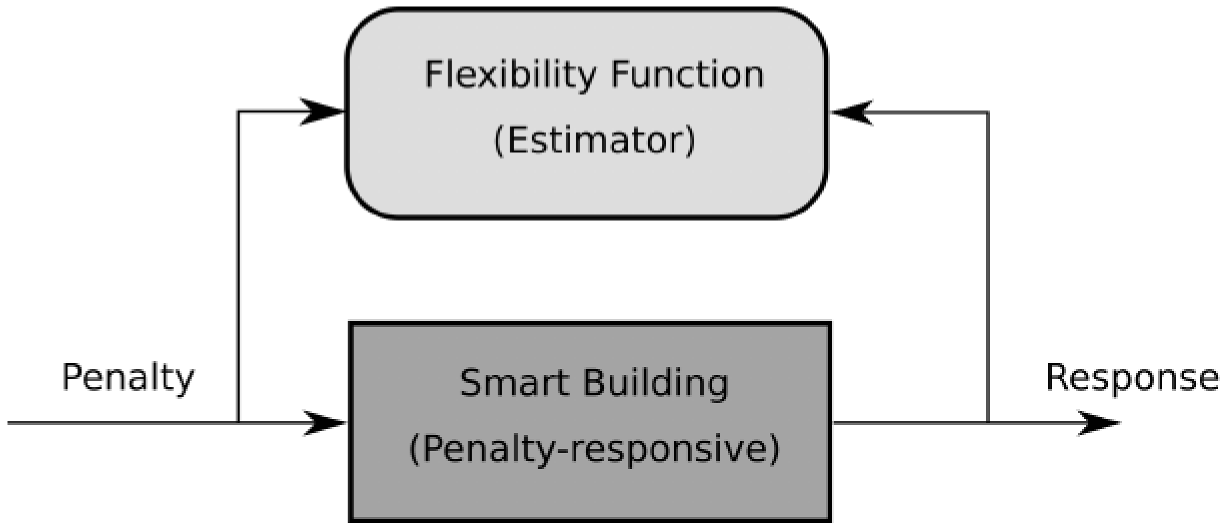


Figure 1: A smart building is able to respond to a penalty or external control signal.

Flexibility Function

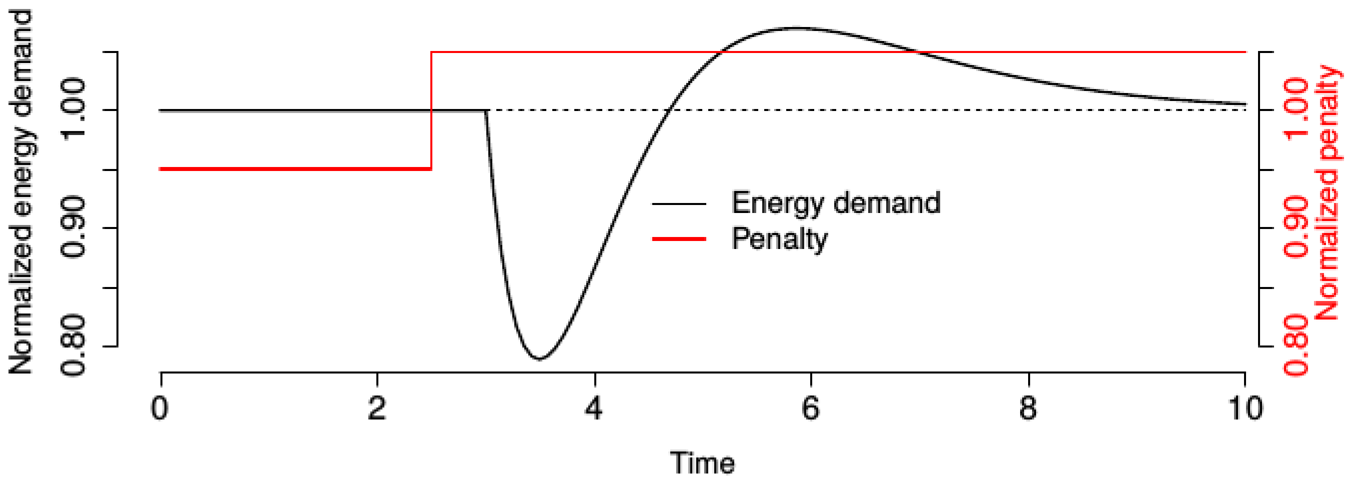


Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

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*.

Smart Grid Application

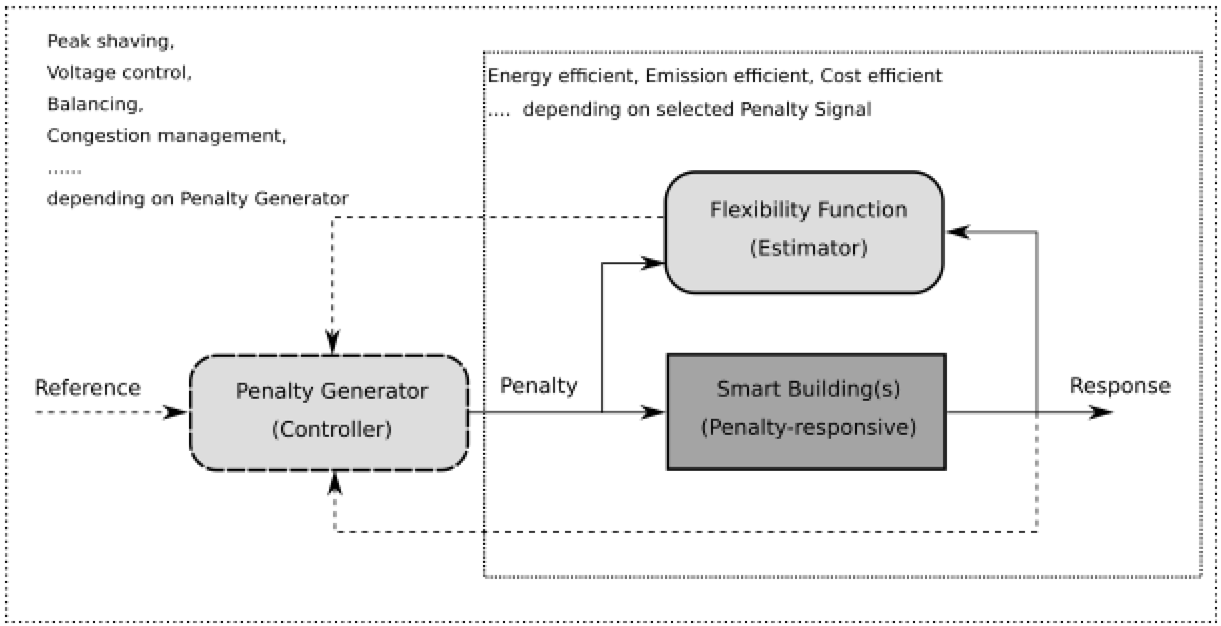


Figure 8: Smart buildings and penalty signals.

CITIES
Centre for IT Intelligent Energy Systems

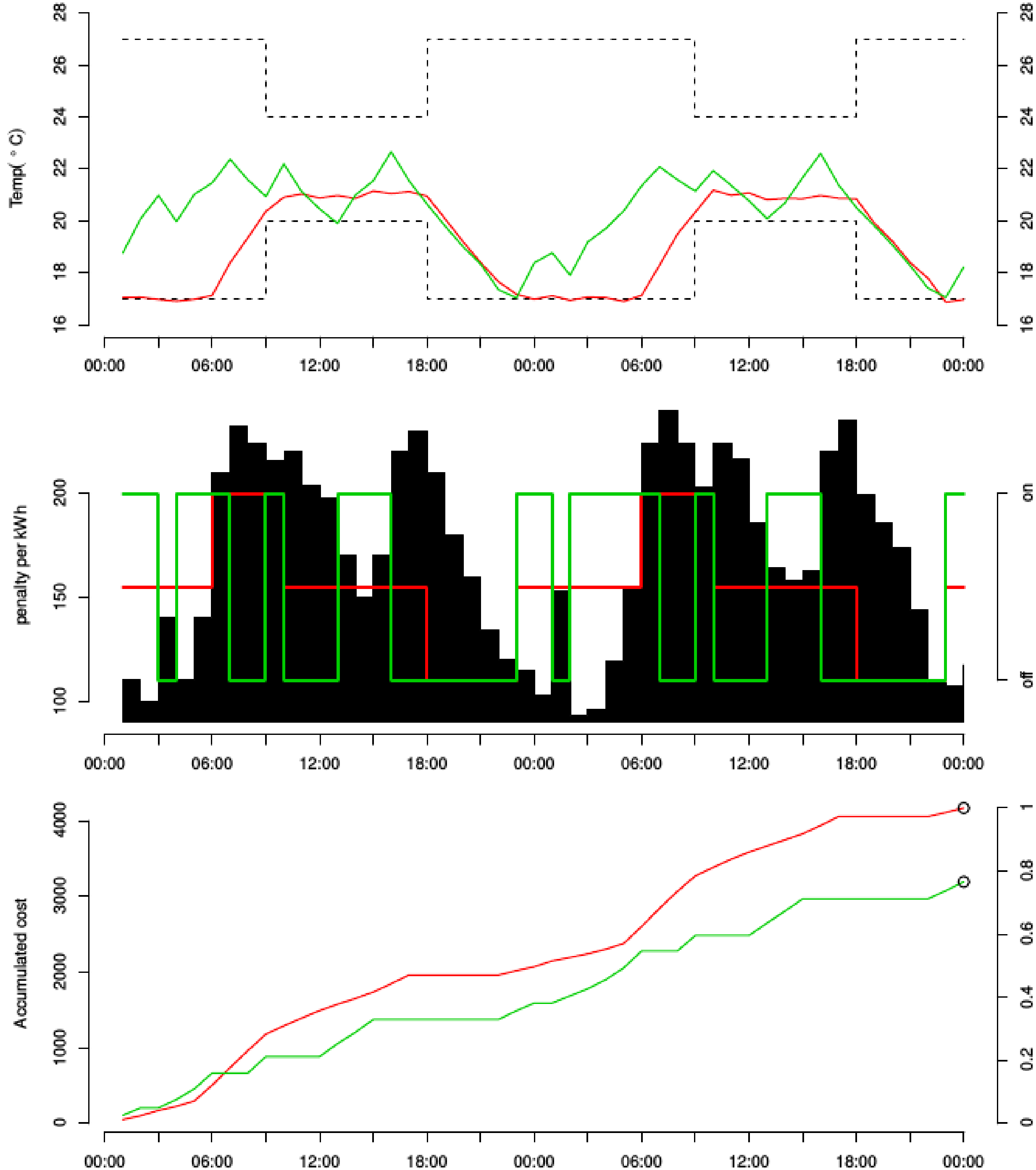
Procedure for calc. Flex. Index

for energy, price and emission based flexibility char.

The test consists of the following steps:

1. Let λ_t be the price of electricity at time t.
2. Simulate the control of the building *without considering* the price, and let u_t^0 be the electricity consumption at time t.
3. Simulate the control of the building *considering* the price, and let u_t^1 be the electricity consumption at time t.
4. The total operation cost of the price-ignorant control is given by $C^0 = \sum_{t=0}^{N} \lambda_t u_t^0$.
5. Similarly the operation cost of the price-aware control is given by $C^1 = \sum_{t=0}^{N} \lambda_t u_t^1$.
6. $1 - \frac{C^1}{C^0}$ is the result of the test, giving us the fractional amount of saved money.

This test is inspired by minimizing total costs for varying electricity prices, but in general λ_t could just represent ones desire to reduce electricity demand at time t.


Temp(° C)
penalty per kWh
on
off
Accumulated cost
00:00
06:00
12:00
18:00

Characteristics

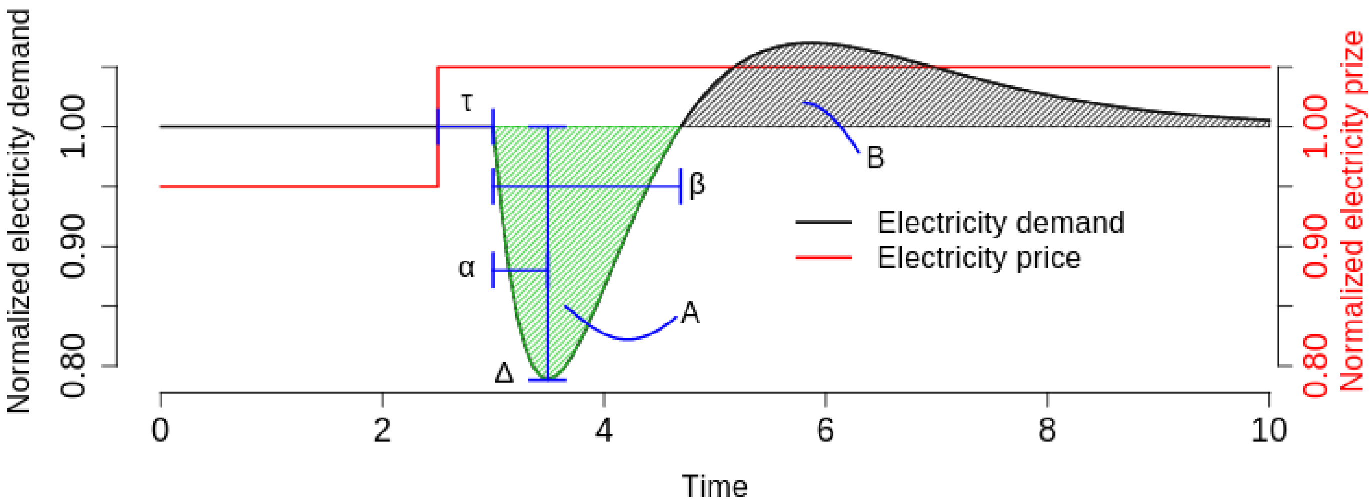


Figure 4: Six characteristics of the demand response to a step increase in electricity price. τ: The delay from adjusting the electricity prize and seeing an effect on the electricity demand, equal to approximately 0.5 here. Δ: The maximum change in demand following the price change, in this case close to 0.2. α: The time it takes from the change in demand starts until it reaches the lowest level, approximately equal to 0.5 here. β: The total time of decreased electricity demand, roughly equal to 2 here. A: The total amount of decreased energy demand, given by the green-shaded area. B: The total amount of increased energy demand, given by the grey-shaded area.

FF for three buildings

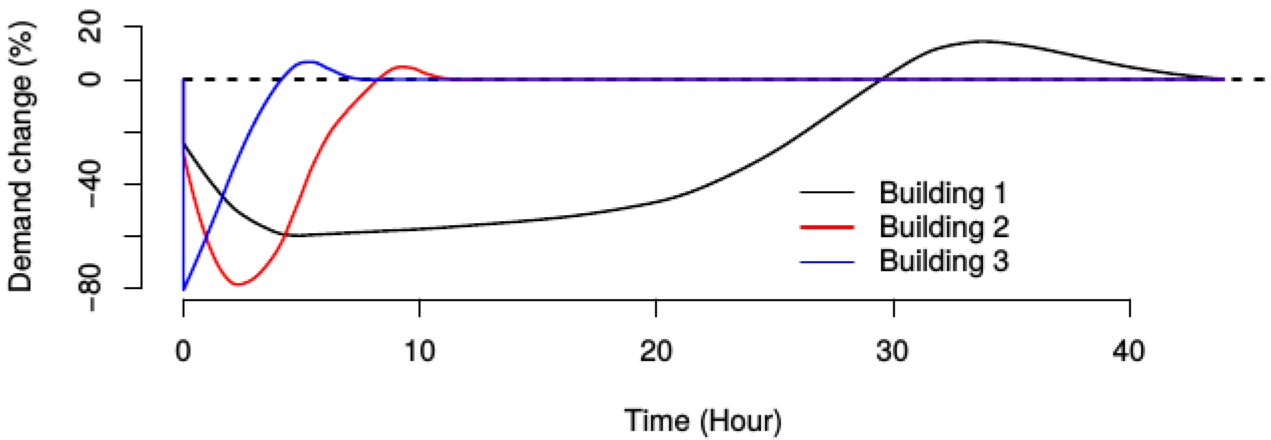
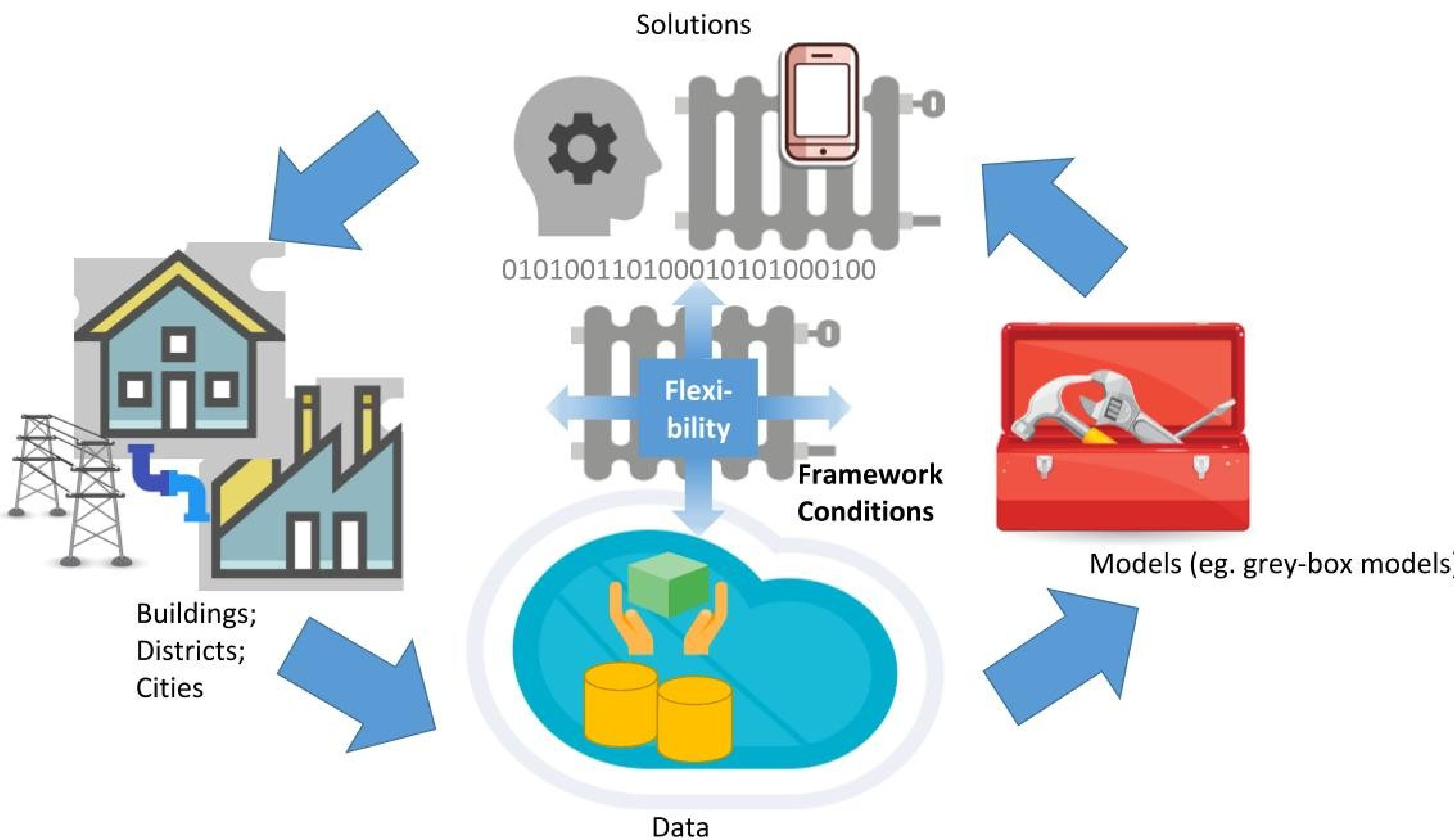


Figure 5: The Flexibility Function for three different buildings.

Flexibility given framework conditions



Realistic Penalties for DK

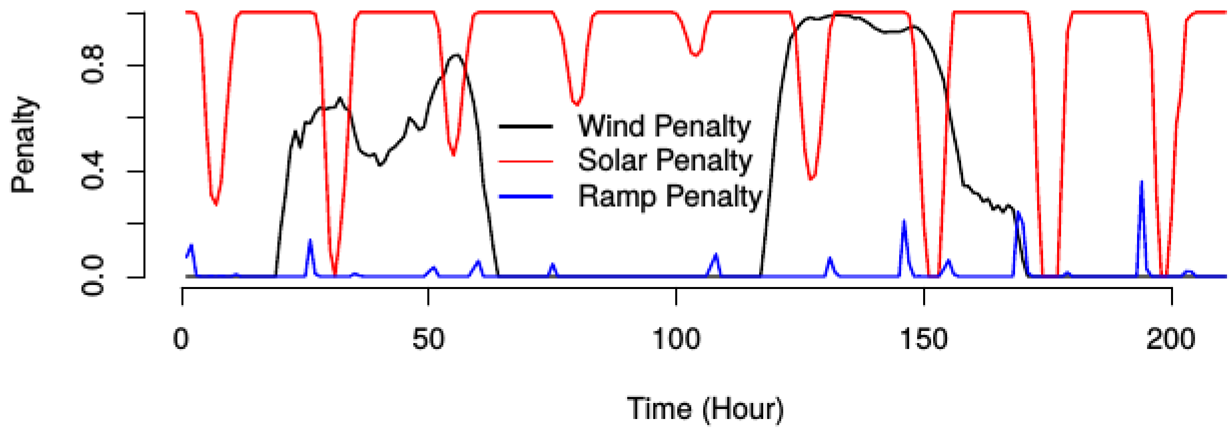


Figure 6: Penalty signals based on wind and solar power production in Denmark during some days in 2017.

Innovation Fund Denmark

Expected Flexibility Savings Index

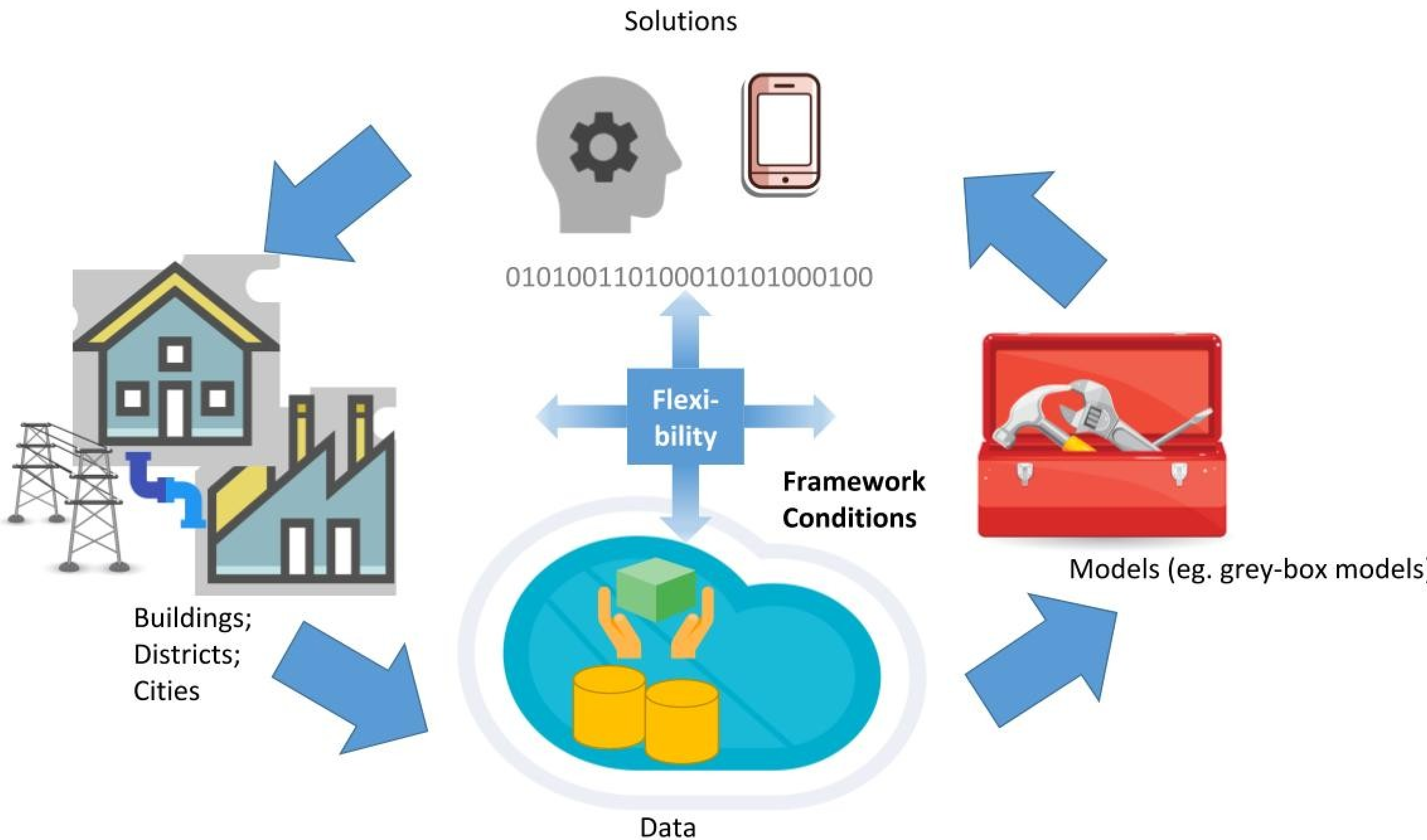
ZERO EMISSION NEIGHBOURHOODS IN SMART CITIES

Table 1: Expected Flexibility Savings Index (EFSI) for each of the buildings based on wind, solar and ramp penalty signals.

	Wind (%)	Solar (%)	Ramp (%)
Building 1	11.8	3.6	1.0
Building 2	4.4	14.5	5.0
Building 3	6.0	10.0	18.4

CITIES Centre for IT Intelligent Energy Systems

Flexibility without framework conditions



Reference Penalties

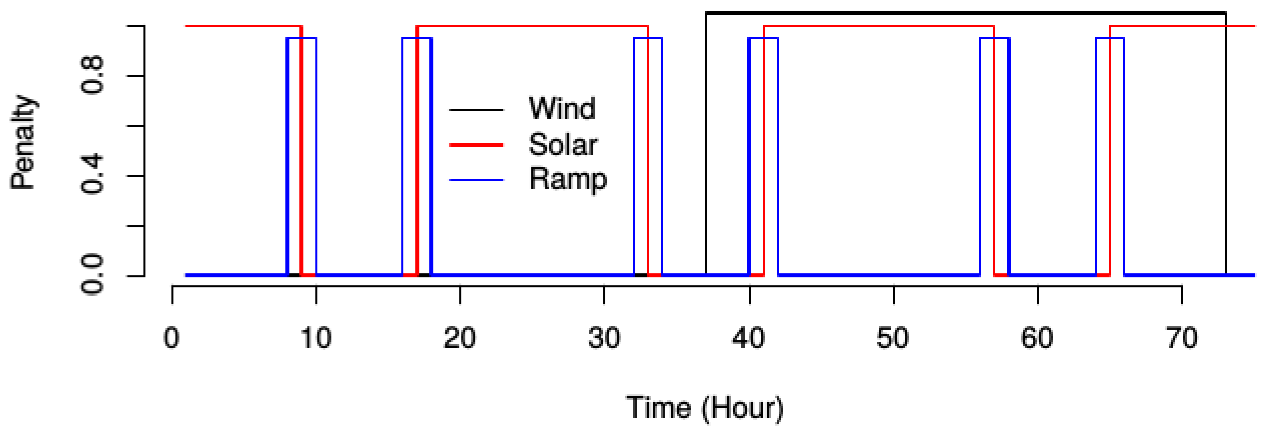


Figure 7: Reference scenarios of penalty signals related to ramping or peak issues as well as the integration of wind and solar power.

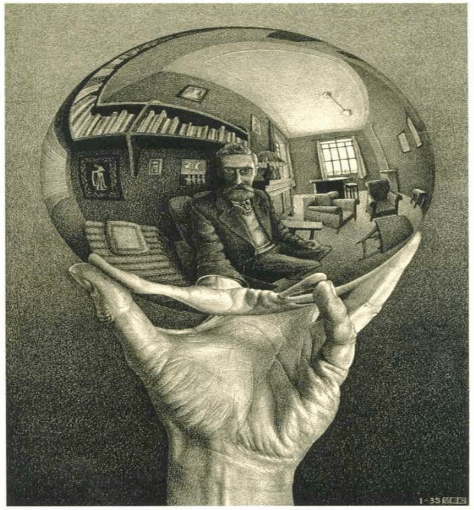
Flexibility Index

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

Energy Flexibility
Some Demo Projects

- Control of WWTP (ED, Kruger, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Summerhouses (DC, ENDK, SE, ..)
- Green Houses (NeoGrid, ENFOR, ...)
- CHP (Dong Energy, EnergiFyn, ...)
- Industrial production
- EV (Eurisco, Enfor, ...)
- ....



Summary

- A procedure for data intelligent control of flexible loads, using the Smart-Energy OS (SE-OS) setup, is suggested.
- The SE-OS controllers can focus on
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency
- We have defined two concepts :

  1) Flexibility Function

  2) Flexibility Index
- We have demonstrated a large potential in Demand Response using the Flexibility Function. Automatic solutions are important

Some references

Madsen, Henrik; Holst, Jan. Estimation of Continuous-Time Models for the Heat Dynamics of a Building. In: Energy and Buildings, Vol. 22, 1995

Andersen, Klaus Kaae; Madsen, Henrik; Hansen, Lars Henrik. Modelling the heat dynamics of a building using stochastic differential equations. In: Energy and Buildings, Vol. 31, No. 1, 2000, p. 13-24.

Kristensen, Niels Rode; Madsen, Henrik; Jørgensen, Sten Bay. Using continuous time stochstic modelling and nonparametric statistics to improve the quality of first principles models. In: Computer – Aided Chemical Engineering, Vol. 10, 2002, p. 901-906

Kristensen, N.R.; Madsen, Henrik; Jørgensen, Sten Bay. A unified framefork for systematic model improvement. In: Process Systems Engineering, Vol. 15, 2003, p. 1292-1297.

Kristensen, Niels Rode; Madsen, Henrik; Jørgensen, Sten Bay. Parameter Estimation in Stochastic Grey-Box Models. In: Automatica, Vol. 40, No. 2, 2004, p. 225-237.

Nielsen, Henrik Aalborg; Madsen, Henrik. Modelling the Heat Consumption in District Heating Systems using a Grey-box approach. In: Energy and Buildings, Vol. 38, No. 1, 2006, p. 63-71.

Friling, N.; Jimenez, M.J.; Bloem, H.; Madsen, Henrik. Modelling the heat dynamics of building integrated and ventilated photovoltaic modules. In: Energy and Buildings, Vol. 41, No. 10, 2009, p. 1051-1057.

Bacher, Peder; Madsen, Henrik. Identifying suitable models for the heat dynamics of buildings. In: Energy and Buildings, Vol. 43, No. 7, 2011, p. 1511-1522.

Lodi, C.; Bacher, Peder; Cipriano, J.; Madsen, Henrik. Modelling the heat dynamics of a monitored Test Reference Environment for Building Integrated Photovoltaic systems using stochastic differential equations. In: Energy and Buildings, Vol. 50, 2012, p. 273-281.

Morales González, Juan Miguel; Pinson, Pierre; Madsen, Henrik. A Transmission-Cost-Based Model to Estimate the Amount of Market-Integrable Wind Resources. In: IEEE Transactions on Power Systems, Vol. 27, No. 2, 2012, p. 1060-1069 .

Halvgaard, Rasmus; Bacher, Peder; Perers, Bengt; Andersen, Elsa; Furbo, Simon; Jørgensen, John Bagterp; Poulsen, Niels Kjølstad; Madsen, Henrik. Model predictive control for a smart solar tank based on weather and consumption forecasts. In: Energy Procedia, Vol. 30, 2012, p. 270-278.

Some references (cont.)

Morales González, Juan Miguel; Pinson, Pierre; Madsen, Henrik. A Transmission-Cost-Based Model to Estimate the Amount of Market-Integrable Wind Resources. In: IEEE Transactions on Power Systems, Vol. 27, No. 2, 2012, p. 1060-1069

Dorini, Gianluca Fabio ; Pinson, Pierre; Madsen, Henrik. Chance-constrained optimization of demand response to price signals. In: IEEE Transactions on Smart Grid, Vol. 4, No. 4, 2013, p. 2072-2080.

Bacher, Peder; Madsen, Henrik; Nielsen, Henrik Aalborg; Perers, Bengt. Short-term heat load forecasting for single family houses. In: Energy and Buildings, Vol. 65, 2013, p. 101-112.

Corradi, Olivier; Ochsenfeld, Henning Peter; Madsen, Henrik; Pinson, Pierre. Controlling Electricity Consumption by Forecasting its Response to Varying Prices. In: IEEE Transactions on Power Systems, Vol. 28, No. 1, 2013, p. 421-430.

Zugno, Marco; Morales González, Juan Miguel; Pinson, Pierre; Madsen, Henrik. A bilevel model for electricity retailers' participation in a demand response market environment. In: Energy Economics, Vol. 36, 2013, p. 182-197.

Meibom, Peter; Hilger, Klaus Baggesen; Madsen, Henrik; Vinther, Dorthe. Energy Comes Together in Denmark: The Key to a Future Fossil-Free Danish Power System. In: IEEE Power & Energy Magazine, Vol. 11, No. 5, 2013, p. 46-55.

Andersen, Philip Hvidthøft Delff ; Jiménez, María José ; Madsen, Henrik ; Rode, Carsten. Characterization of heat dynamics of an arctic low-energy house with floor heating. In: Building Simulation, Vol. 7, No. 6, 2014, p. 595-614.

Andersen, Philip Hvidthøft Delff; Iversen, Anne; Madsen, Henrik; Rode, Carsten. Dynamic modeling of presence of occupants using inhomogeneous Markov chains. In: Energy and Buildings, Vol. 69, 2014, p. 213-223.

Madsen, H, Parvizi, J, Halvgaard, RF, Sokoler, LE, Jørgensen, JB, Hansen, LH & Hilger, KB 2015, 'Control of Electricity Loads in Future Electric Energy Systems'. in AJ Conejo, E Dahlquist & J Yan (eds), Handbook of Clean Energy Systems: Intelligent Energy Systems. vol. 4, Wiley.

Halvgaard, RF, Vandenberghe, L, Poulsen, NK, Madsen, H & Jørgensen, JB 2016, Distributed Model Predictive Control for Smart Energy Systems IEEE Transactions on Smart Grid, vol 7, no. 3, pp. 1675-1682.

Bacher, P, de Saint-Aubain, PA, Christiansen, LE & Madsen, H 2016, Non-parametric method for separating domestic hot water heating spikes and space heating Energy and Buildings, vol 130, pp. 107-112.

For more information ...

See for instance

http://fmezen.no

...or contact

- Henrik Madsen

  hmad@dtu.dk

Acknowledgement - FME ZEN project and the CITIES project