Data-driven Methods;

General introduction and specific examples

Henrik Madsen

DTU Compute

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

http://www.henrikmadsen.org

Innovation Fund Denmark

CITIES Centre for IT Intelligent Energy Systems

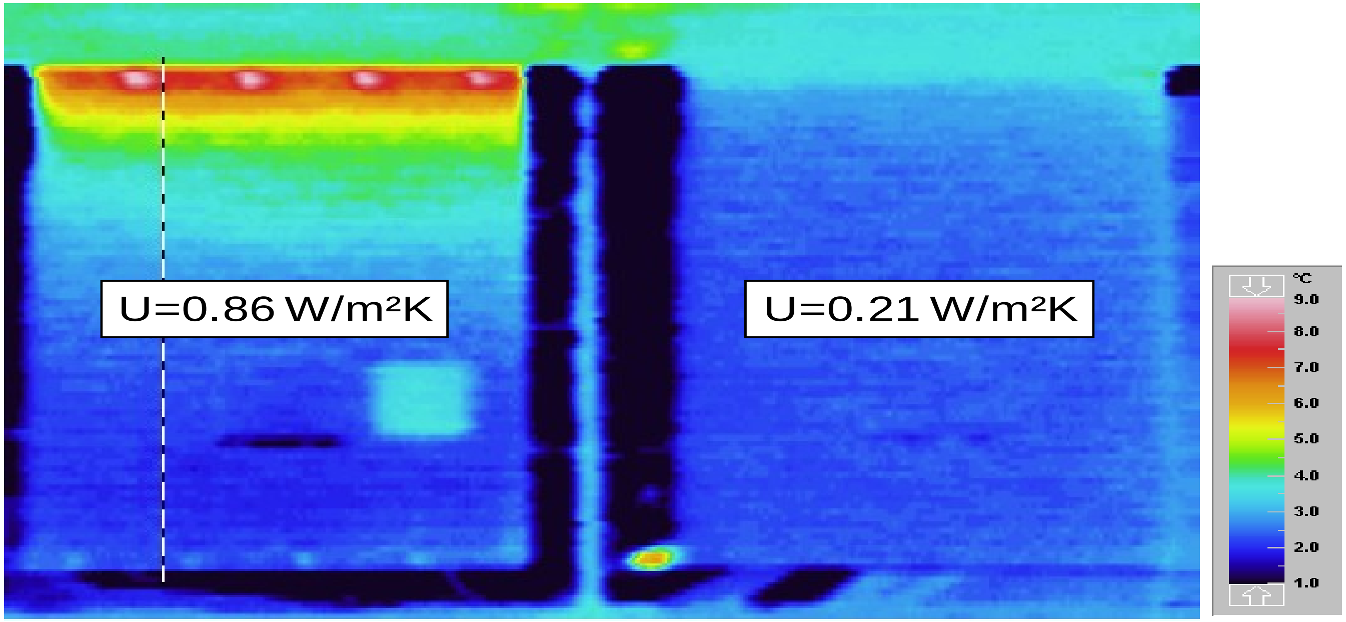
FED FLEXIBLE ENERGY DENMARK

General introduction

The Problem and a Generic Solution

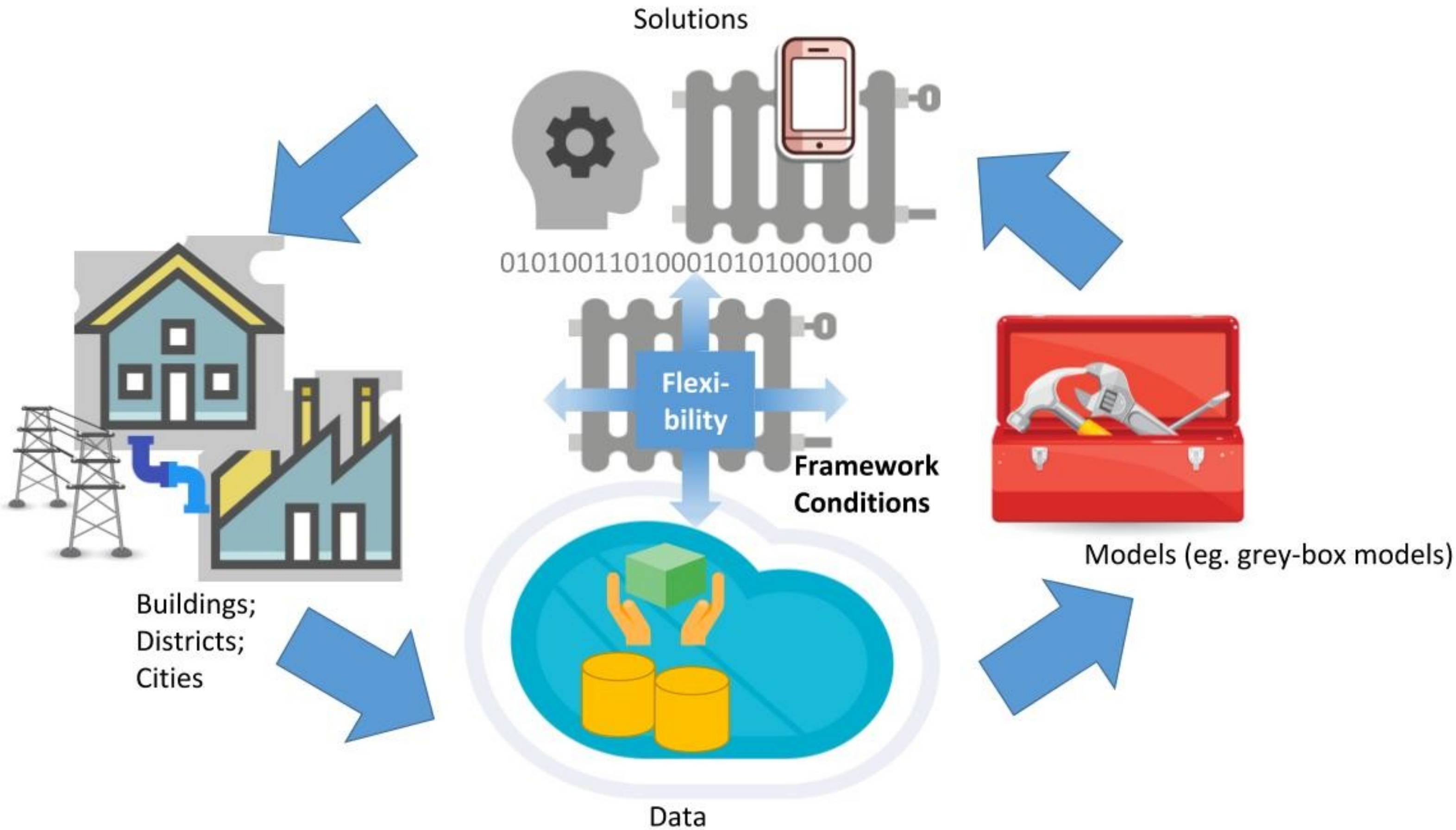
CITIES
Centre for IT Intelligent Energy Systems

Example



Consequence of good or bad workmanship (theoretical value is U=0.16W/m2K)

Efficiency and Flexibility identified using AI and grey-box modelling

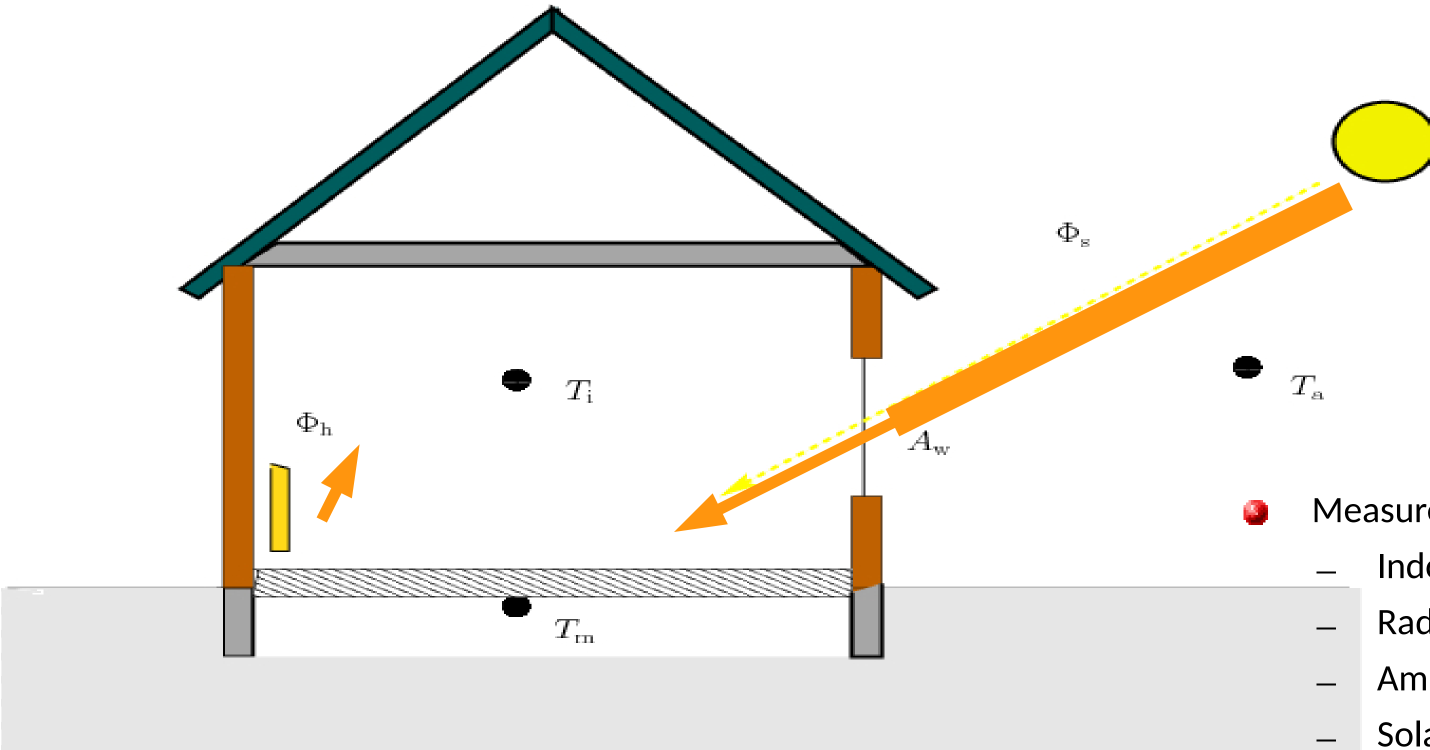


Case Study No. 1

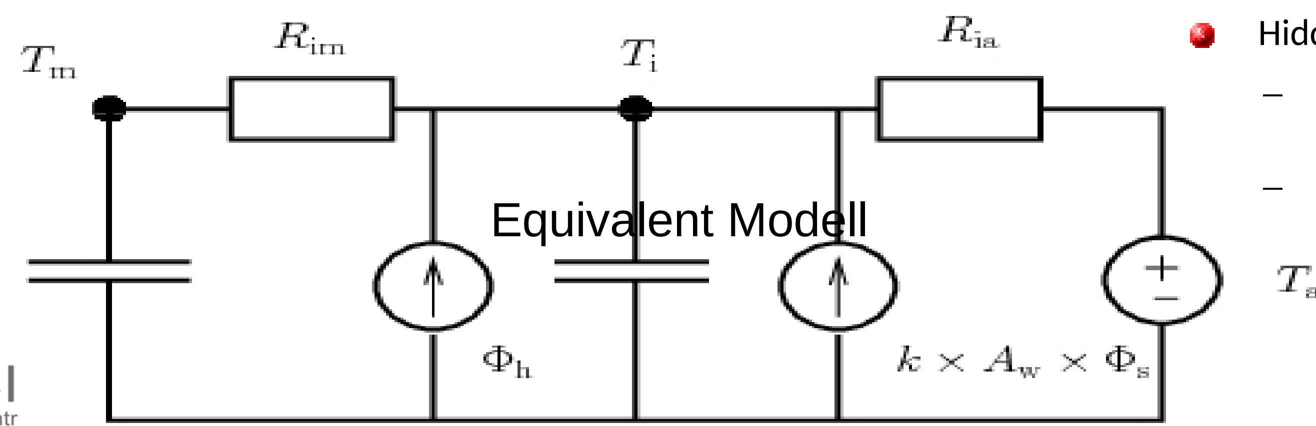
Characterization of Energy Efficiency of Buildings using (Smart) Meter Data

CITIES
Centre for IT Intelligent Energy Systems

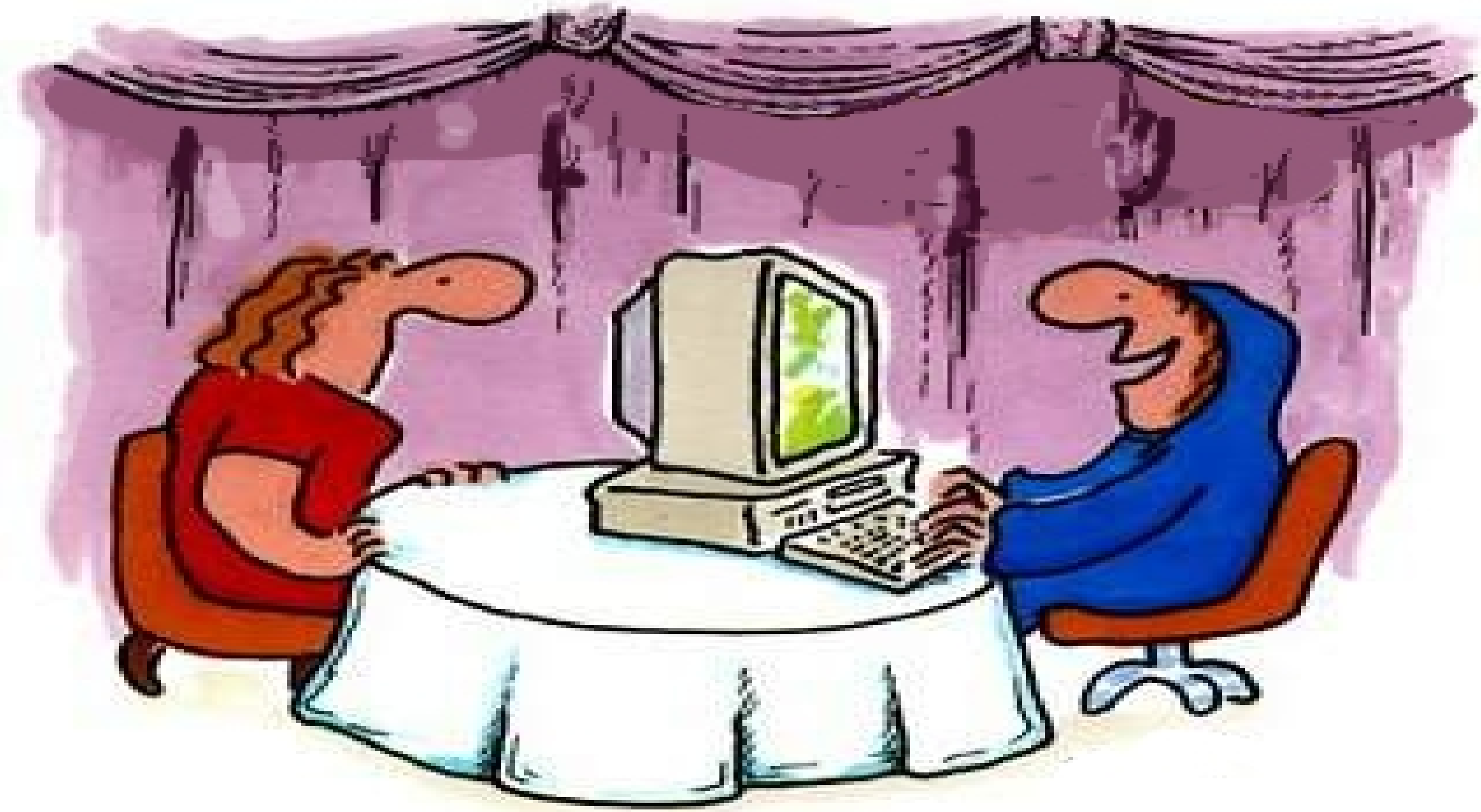
Model for the heat dynamics



- Measurements:
  - Indoor air temp
  - Radiator heat sup.
  - Ambient air temp
  - Solar radiations
- Hidden states are:
  - Heat accumulated in the building
  - *k*: Fraction of solar radiation entering the interior



Perspectives ...



"Skat, jeg kan se på k-værdierne, at vinduerne skal pudses"

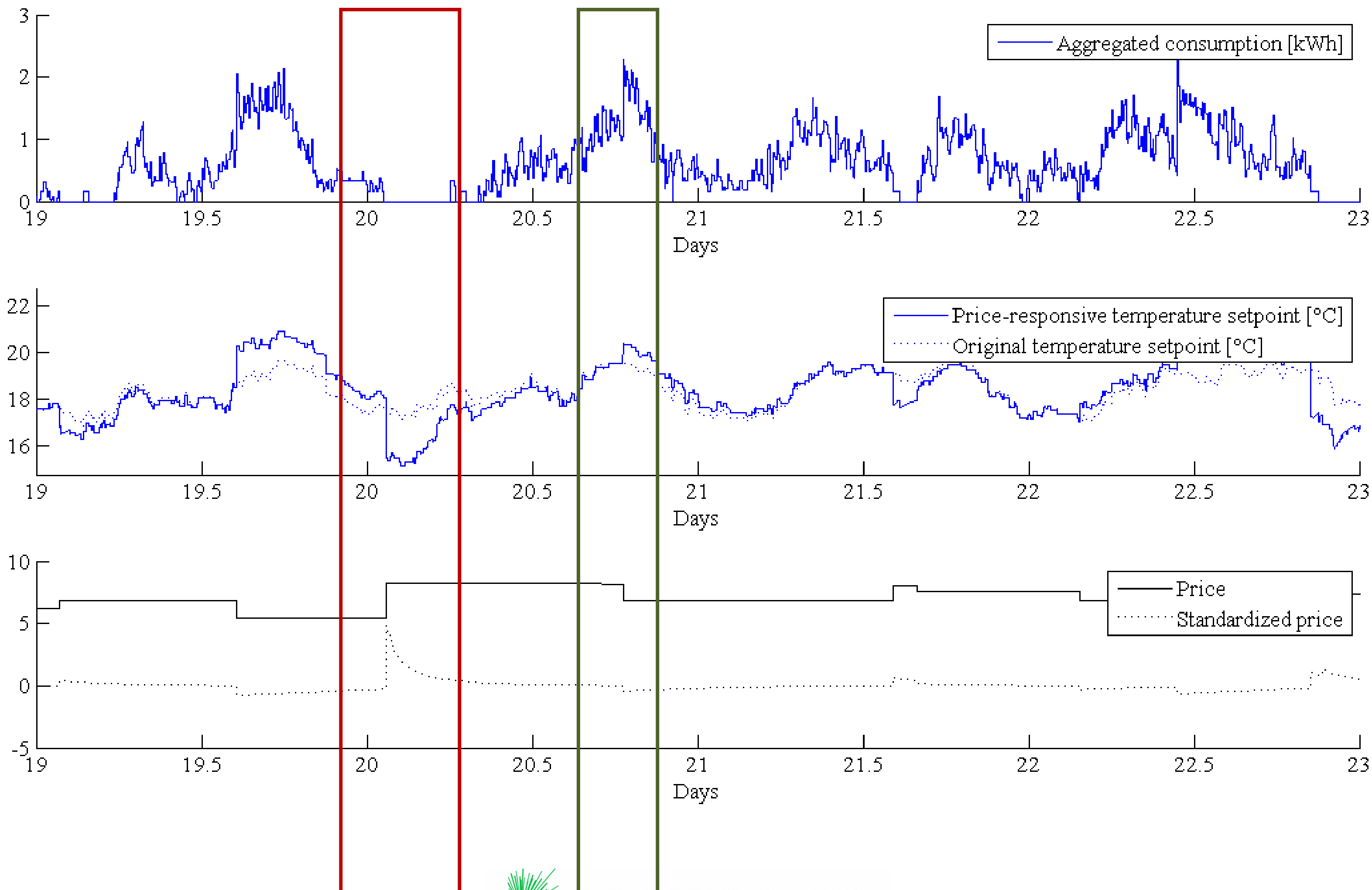
Perspectives

- Identification of most problematic buildings
- Automatic energy labelling
- Recommendations:
  - Should they replace the windows?
  - Or put more insulation on the roof?
  - Or tigthen the building?
  - Should the wall against north be further insulated?
  - ……
- Better control of the heat supply (using the flexibility)

Case study No. 2

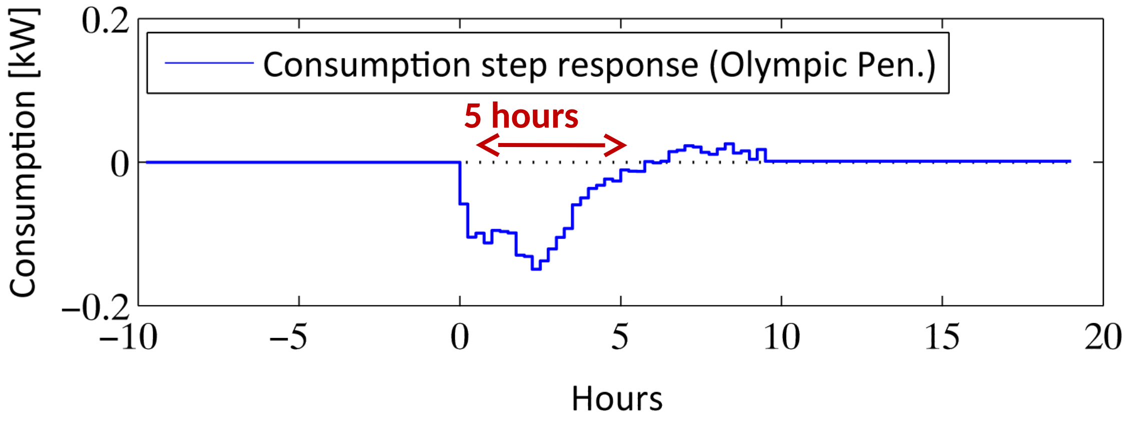
Control of Power Consumption using the Thermal Mass of Buildings (Peak shaving)

Aggregation (over 20 houses)

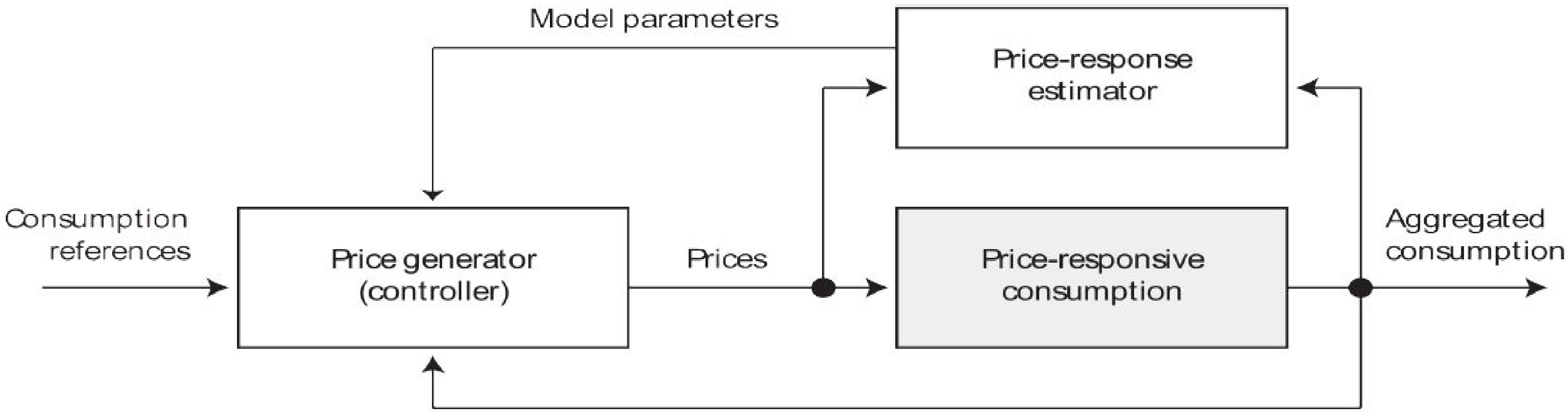


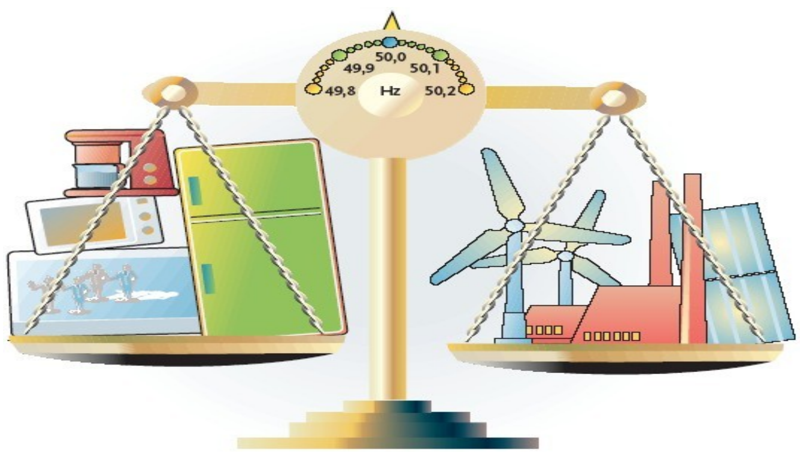
Response on Price Step Change

Olympic Peninsula



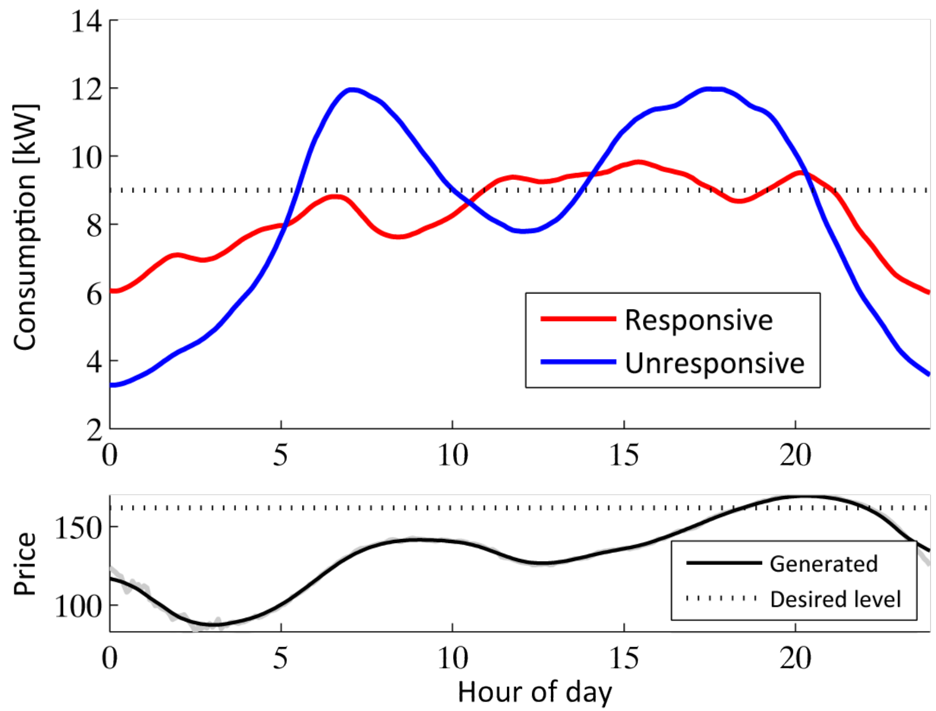
Control of Energy Consumption





Control performance

Considerable **reduction in peak consumption**
Mean daily consumption shift



General Introdution

Flexibility Function and Flexibility Index

Innovation Fund Denmark

CITIES
Centre for IT Intelligent Energy Systems

Data-driven methods for energy efficiency and flexibility

FED FLEXIBLE ENERGY DENMARK

Characteristics

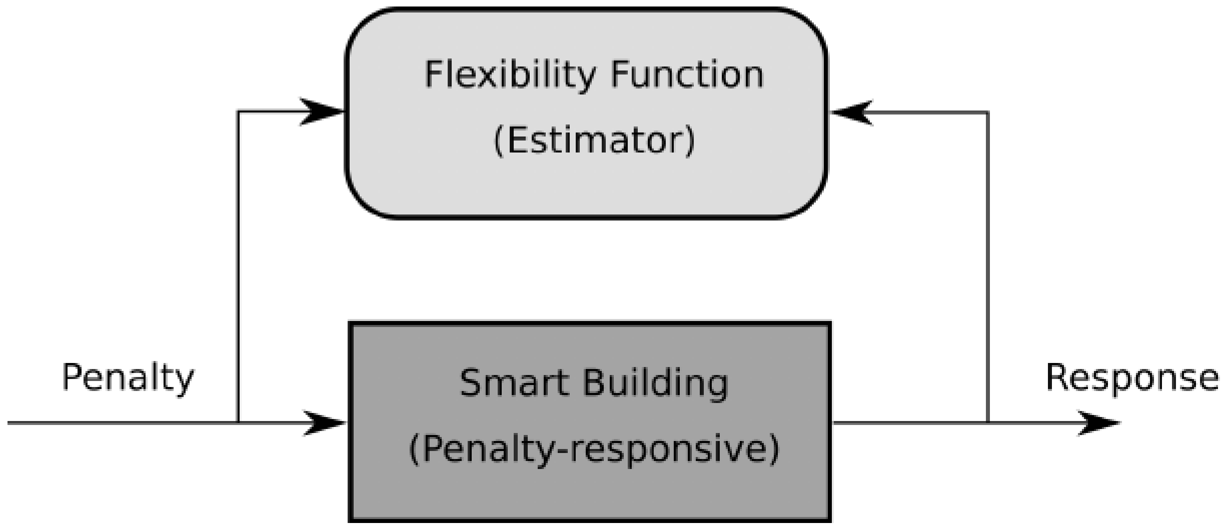


Figure 1: A smart building is able to respond to a penalty or external control signal.

Flexibility Function

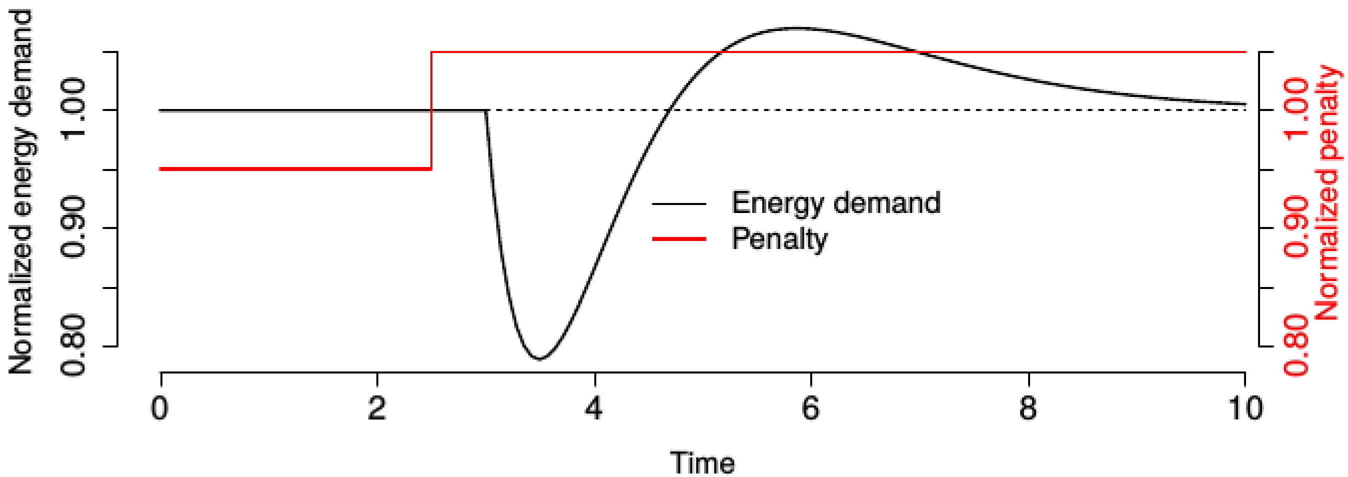


Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

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

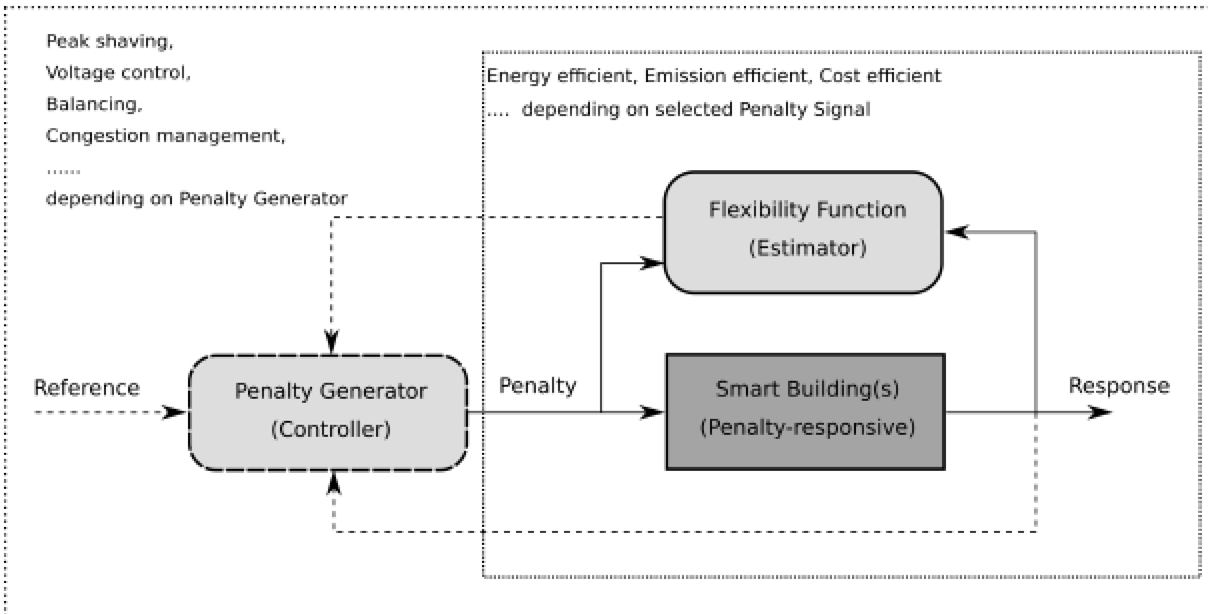
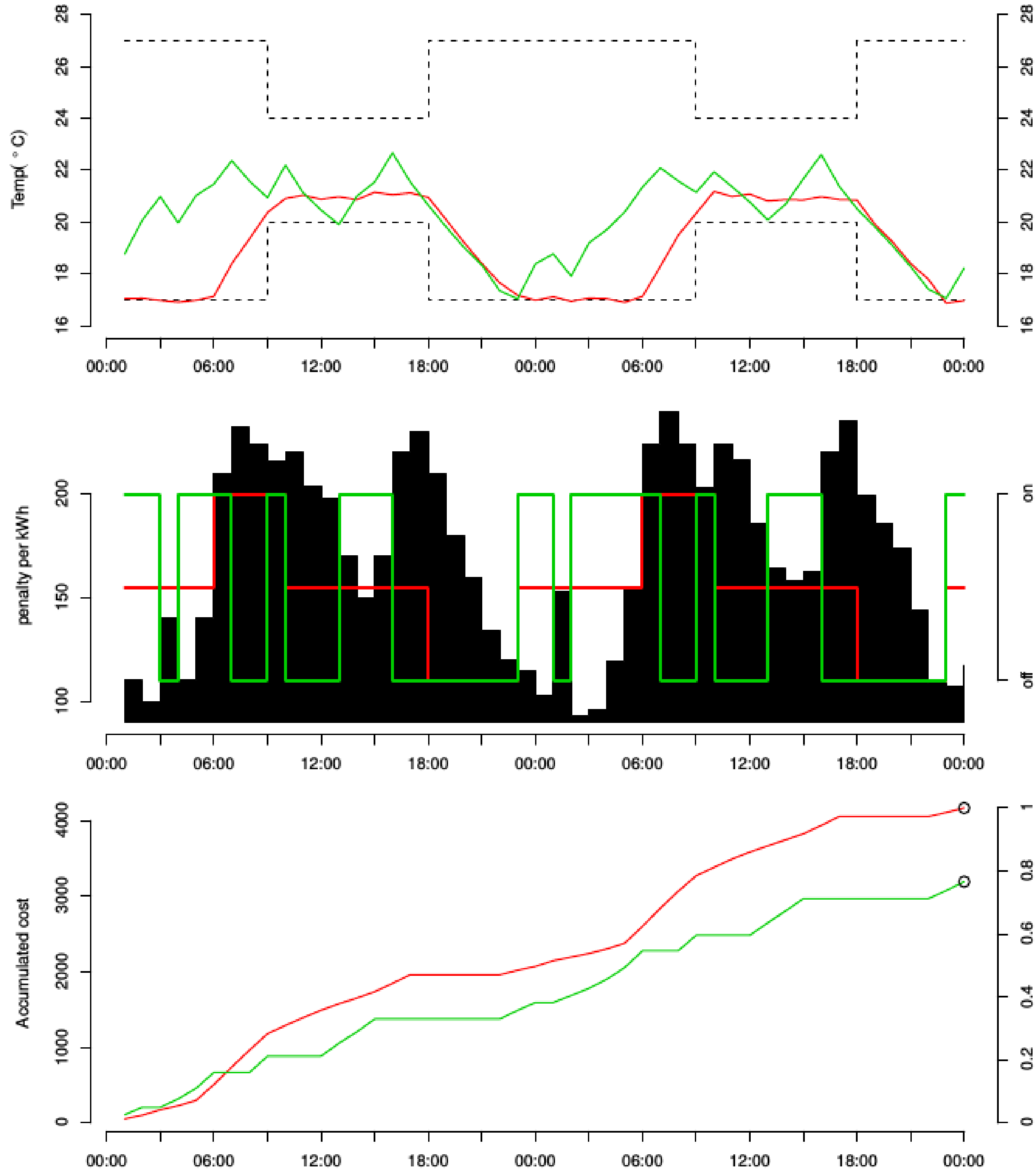


Figure 8: Smart buildings and penalty signals.



Centre for IT Intelligen

FF for three buildings

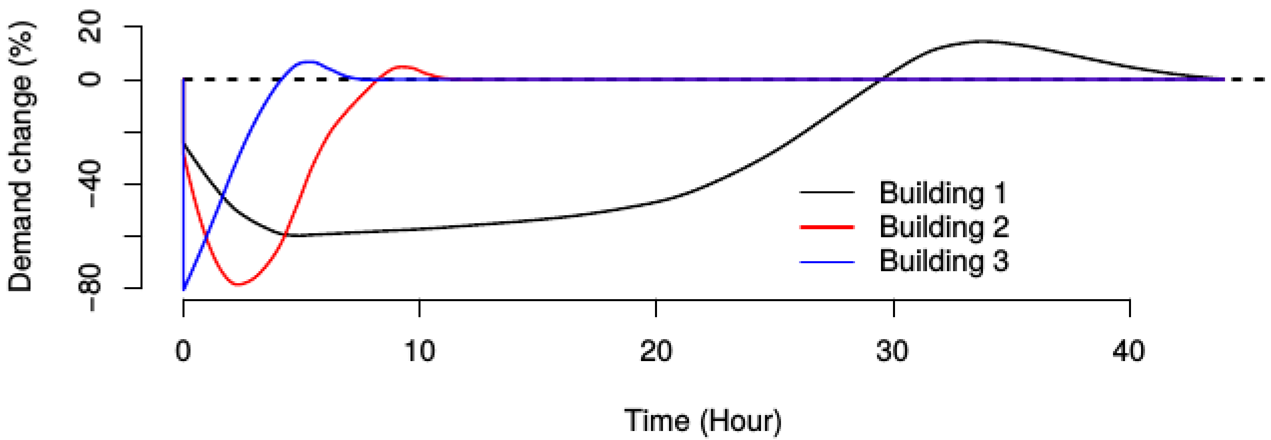


Figure 5: The Flexibility Function for three different buildings.

Reference Penalties

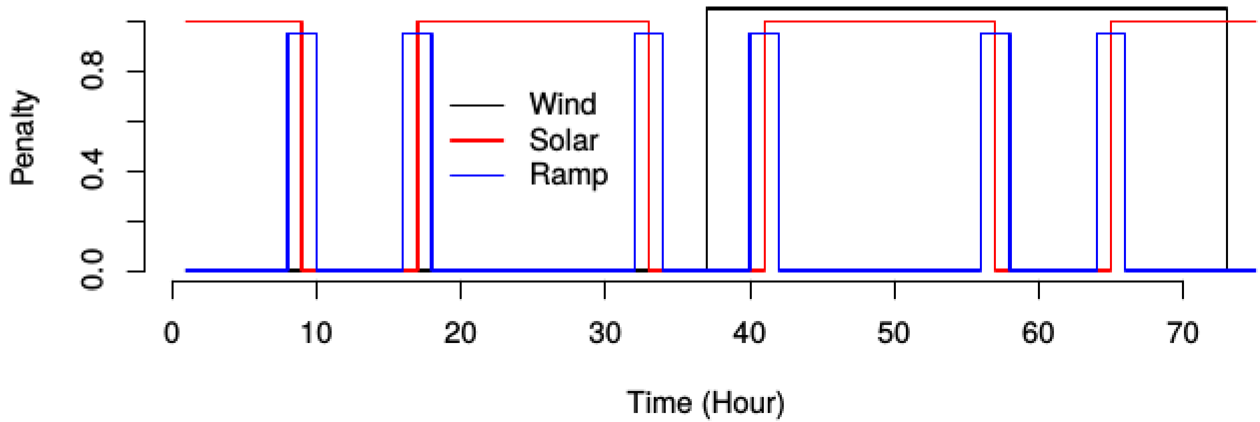


Figure 7: Reference scenarios of penalty signals related to ramping or peak issues as well as the integration of wind and solar power.

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

Center Denmark, Living Labs, Partnerships

UNILAB consortium

Cardiff University

Danmarks Tekniske Universitet (DTU), Denmark

Royal Institute of Technology (KTH), Sweden

German Technical and Scientific Association for Gas and Water (DVGW), Germany

Imperial College, United Kingdom

Tianjing University, P.R. China

TNO - Netherlands

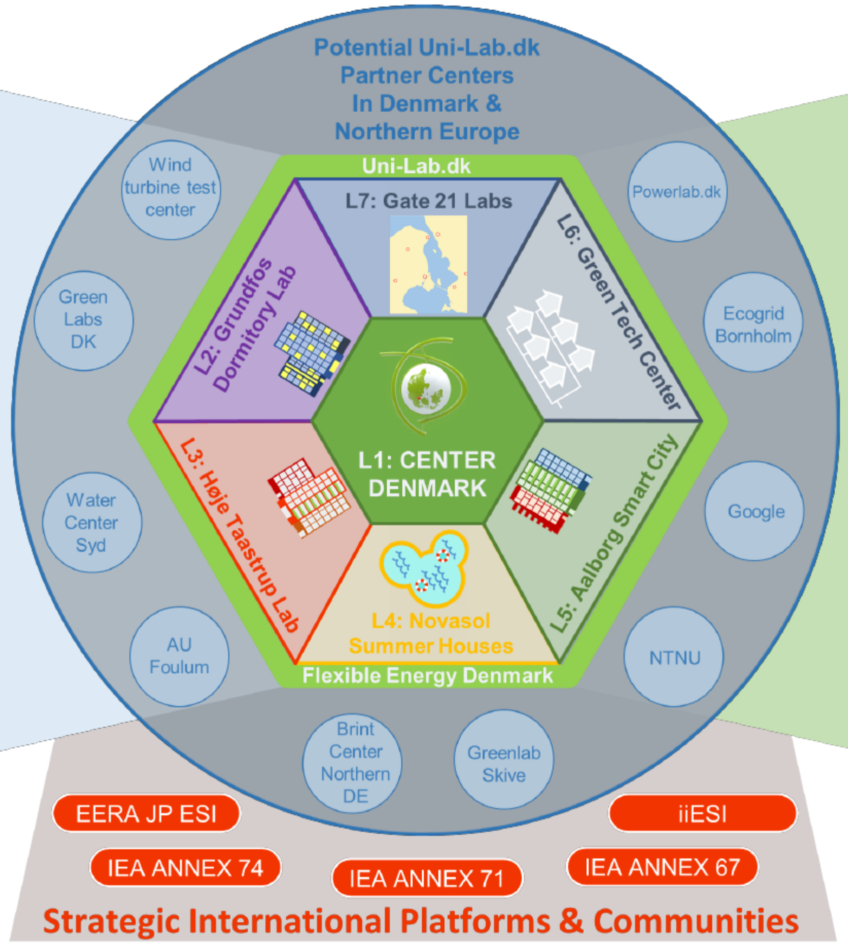
Toshiba Research Laboratory (TRL), UK

Tsinghua University - P.R. of China

Katholieke Universiteit Leuven (KUL), Belgium

Malardalen University, Sweden

University of Pisa (UP), Italy



International Cooperating labs

NREL (US)

CESI (UK)

ZEN (NORWAY)

Berkeley (US)

Argonne (US)

KIER (KOREA)

ESIPP (IRELAND

PSA (SPAIN)

KUBIK (SPAIN)

Summary

- We need more focus on data-driven technologies for energy efficiency and flexibility – simply by using frequent meter data
- Procedures for data intelligent control of power load using the flexibility are also suggested
- The controllers can provide
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
- We have demonstrated a large potential in Demand Response. Automatic solutions, and end-user focus are important
- We see large problems with the tax and tariff structures in many countries (eg. Denmark; we are working on a new design of taxes and tariffs.

Some references

Grey-box models for buildings:

Madsen, H., & Holst, J. (1995). Estimation of Continuous-Time Models for the Heat Dynamics of a Building. Energy and Buildings, 22(1), 67–79.

Andersen, K. K., Madsen, H., & Hansen, L. H. (2000). Modelling the heat dynamics of a building using stochastic differential equations. Energy and Buildings, 31(1), 13–24.

Nielsen, H. A., & Madsen, H. (2006). Modelling the Heat Consumption in District Heating Systems using a Grey-box approach. Energy and Buildings, 38(1), 63–71.

Jiménez, M. J., Madsen, H., Bloem, J. J., & Dammann, B. (2008). Estimation of non-linear continuous time models for the heat exchange dynamics of building integrated photovoltaic modules. Energy and Buildings, 40(2), 157–167

Friling, N., Jimenez, M. J., Bloem, H., & Madsen, H. (2009). Modelling the heat dynamics of building integrated and ventilated photovoltaic modules. Energy and Buildings, 41(10), 1051–1057

Bacher, P., & Madsen, H. (2011). Identifying suitable models for the heat dynamics of buildings. Energy and Buildings, 43(7), 1511–1522

Lodi, C., Bacher, P., Cipriano, J., & Madsen, H. (2012). Modelling the heat dynamics of a monitored Test Reference Environment for Building Integrated Photovoltaic systems using stochastic differential equations. Energy and Buildings, 50, 273–281.

Naveros, I., Bacher, P., Ruiz, D. P., Jiménez, M. J., & Madsen, H. (2014). Setting up and validating a complex model for a simple homogeneous wall. Energy and Buildings, 70, 303–317.

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.

Madsen, H., Bacher, P., Bauwens, G., Deconinck, A.-H., Reynders, G., Roels, S., … Lethé, G. (2015). Thermal Performance Characterization using Time Series Data - IEA EBC Annex 58 Guidelines.

Rasmussen, C., Frölke, L., Bacher, P., Madsen, H., & Rode, C. (2020). Semi-parametric modelling of sun position dependent solar gain using Bsplines in grey-box models. Solar Energy, 195, 249–258.

Some references

Grey-box modelling techniques:

Holst, J., Lindström, E., Madsen, H., & Aalborg Nielsen, H. (2003). Model Validation in Non-Linear Continuous-Discrete Grey-Box Models. Ifac Proceedings Volumes (Ifac-Papersonline), 36(16), 1495–1500.

Sadegh, P., Melgaard, H., Madsen, H., & Holst, J. (1994). Optimal experiment design for identification of grey-box models. Proceedings of the American Control Conference, 1, 132–137.

Kristensen, N. R., Madsen, H., & Jørgensen, S. B. (2004). Parameter Estimation in Stochastic Grey-Box Models. Automatica, 40(2), 225–237.

Kristensen, N. R., Madsen, H., & Jørgensen, S. B. (2003). A unified framefowk for systematic model improvement. Process Systems Engineering, 15, 1292–1297.

Kristensen, N. R., Madsen, H., & Jørgensen, S. B. (2002). Using continuous time stochastic modelling and nonparametric statistics to improve the quality of first principles models. Computer Aided Chemical Engineering, 10(C), 901–906

Jorgensen, J. B., Thomsen, P. G., Madsen, H., & Kristensen, M. R. (2007). A computationally efficient and robust implementation of the continuous-discrete extended Kalman filter. 2007 American Control Conference, Vols 1-13, 2468

Boiroux, D., Juhl, R., Madsen, H., & Jørgensen, J. B. (2016). An Efficient UD-Based Algorithm for the Computation of Maximum Likelihood Sensitivity of Continuous-Discrete Systems. Lecture Notes in Computer Science, 3048–3053.

Juhl, R., Møller, J. K., & Madsen, H. (2016). CTSM-R - Continuous Time Stochastic Modeling in R, 11p https://arxiv.org/pdf/1606.00242.pdf.

Some references (cont.)

Forecasting, Flexibility and Control:

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.

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.

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.

Junker, R. G., Azar, A. G., Lopes, R. A., Lindberg, K. B., Reynders, G., Relan, R., & Madsen, H. (2018). Characterizing the energy flexibility of buildings and districts. Applied Energy, 225, 175–182.

Junker, R. G., Relan, R., & Madsen, H. (2019). Designing Individual Penalty Signals for Improved Energy Flexibility Utilisation. Ifac-Papersonline, 52(4), 123–128.

De Zotti, G., Pourmousavi, S. A., Madsen, H., & Poulsen, N. K. (2018). Ancillary Services 4.0: A Top-To-Bottom Control-Based Approach for Solving Ancillary Services Problems in Smart Grids. Ieee Access, 6, 11694–11706.

De Zotti, G., Pourmousavi Kani, S. A., Morales, J. M., Madsen, H., & Poulsen, N. K. (2019). A Control-based Method to Meet TSO and DSO Ancillary Services Needs by Flexible End-Users. IEEE Transactions on Power Systems

Some references (cont.)

Indoor climate and occupancy:

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.

Wolf, S., Calì Davide, Krogstie, J., & Madsen, H. (2019). Carbon dioxide-based occupancy estimation using stochastic differential equations. Applied Energy, 236, 32–41.

Wolf, S., Alonso, M. J., Cali, D., Krogstie, J., Mathisen, H. M., & Madsen, H. (2019). CO2-based grey-box model to estimate airflow rate and room occupancy. E3s Web of Conferences, 111,

Nienaber, F., Wolf, S., Wesseling, M., Calì, D., Müller, D., & Madsen, H. (2019). Validation, optimisation and comparison of carbon dioxide-based occupancy estimation algorithms. Indoor and Built Environment,

Wolf, S., Møller, J. K., Bitsch, M. A., Krogstie, J., & Madsen, H. (2019). A Markov-Switching model for building occupant activity estimation. Energy and Buildings, 183, 672–683

Wolf, S., Calì, D., Alonso, M. J., Li, R., Andersen, R. K., Krogstie, J., & Madsen, H. (2019). Room-level occupancy simulation model for private households. Journal of Physics.