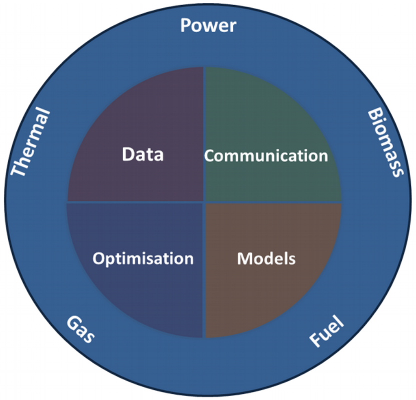
Smart and Flexible Buildings with a Focus on Data-Intelligent Control and Storage Options



Henrik Madsen

Results from the CITIES, SCA and REBUS projects

Technical University of Denmark

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

http://www.henrikmadsen.org

CITIES
Centre for IT Intelligent Energy Systems

Contents

- Flexibility enabled using our Smart-Energy OS
- Virtual storage options in smart buildings
- Flexibility Function and Index
- Optimized and evidence based methods for energy savings

Challenges

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.

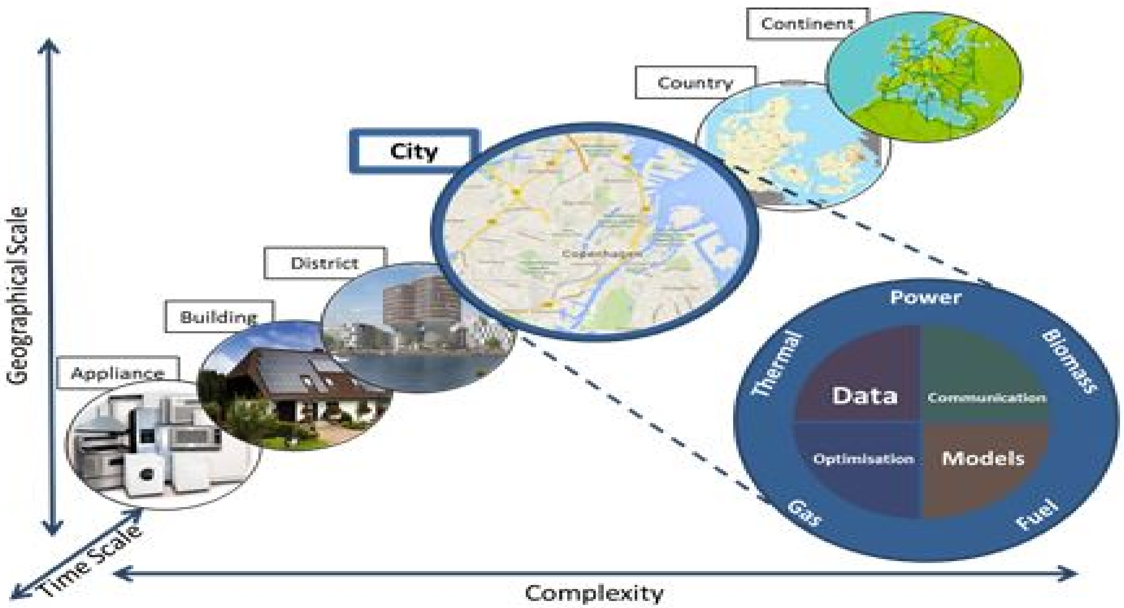
Almost no Flexibility

Data Intelligent Energy Systems
for a Smart Society

CITIES
Centre for IT Intelligent Energy Systems

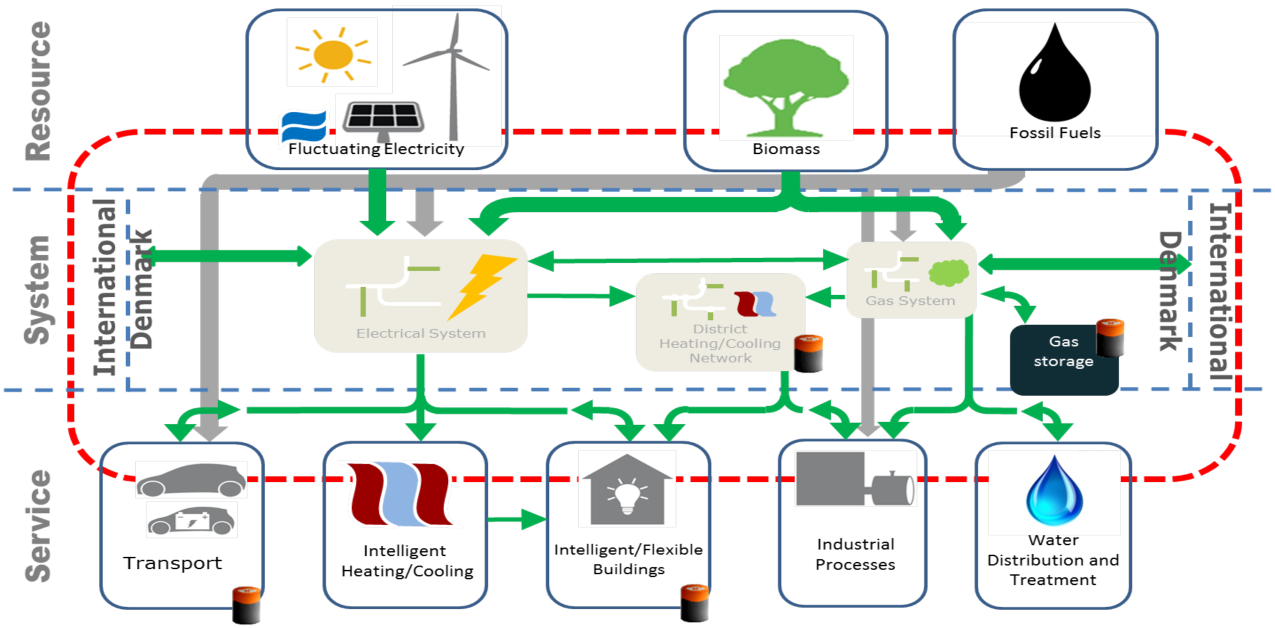
Temporal and Spatial Scales

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**.



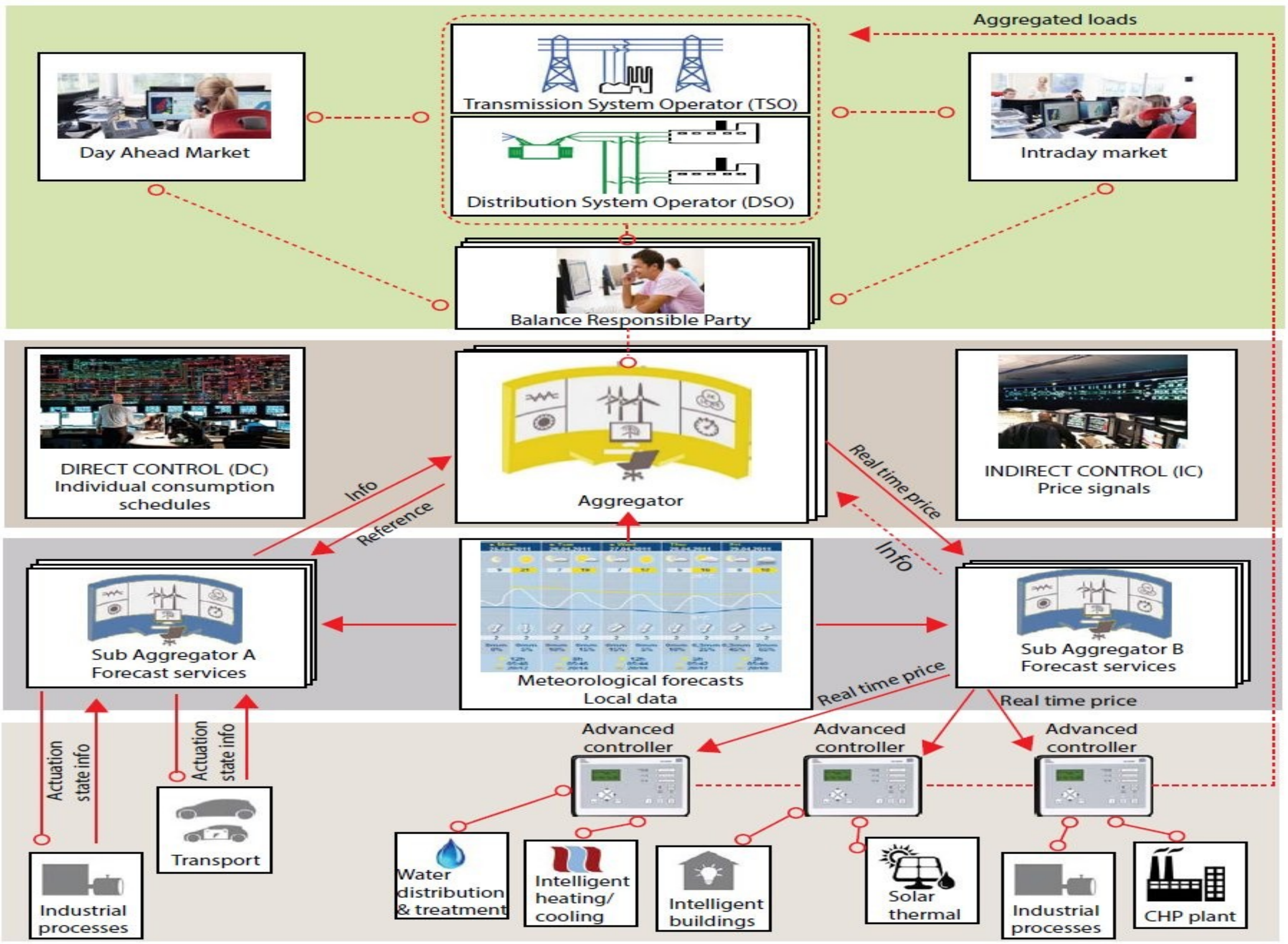
Models for Systems of Systems

Intelligent systems integration using **big data and ICT solutions** are based on **grey-box modelling for real-time operation of flexible energy systems**



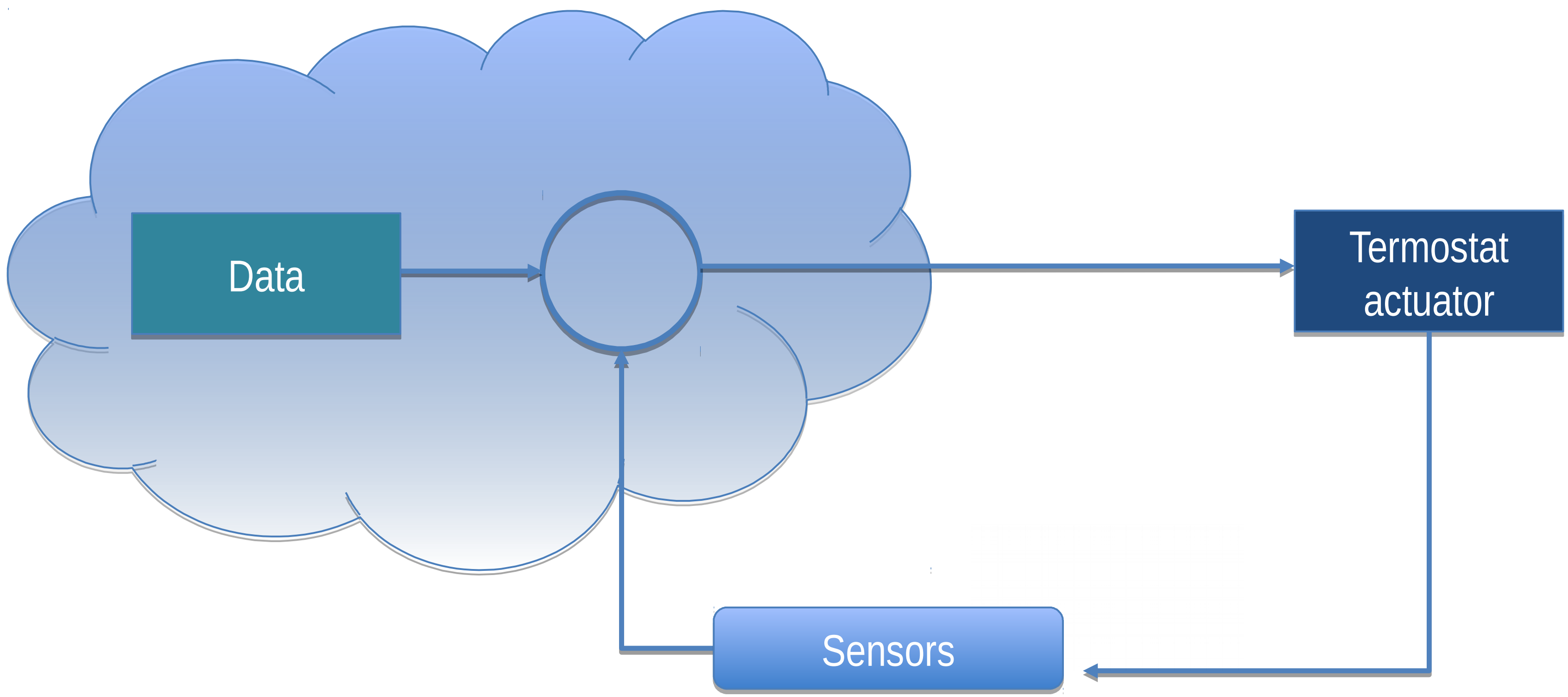
CITIES
Centre for IT Intelligent Energy Systems

Smart-Energy OS

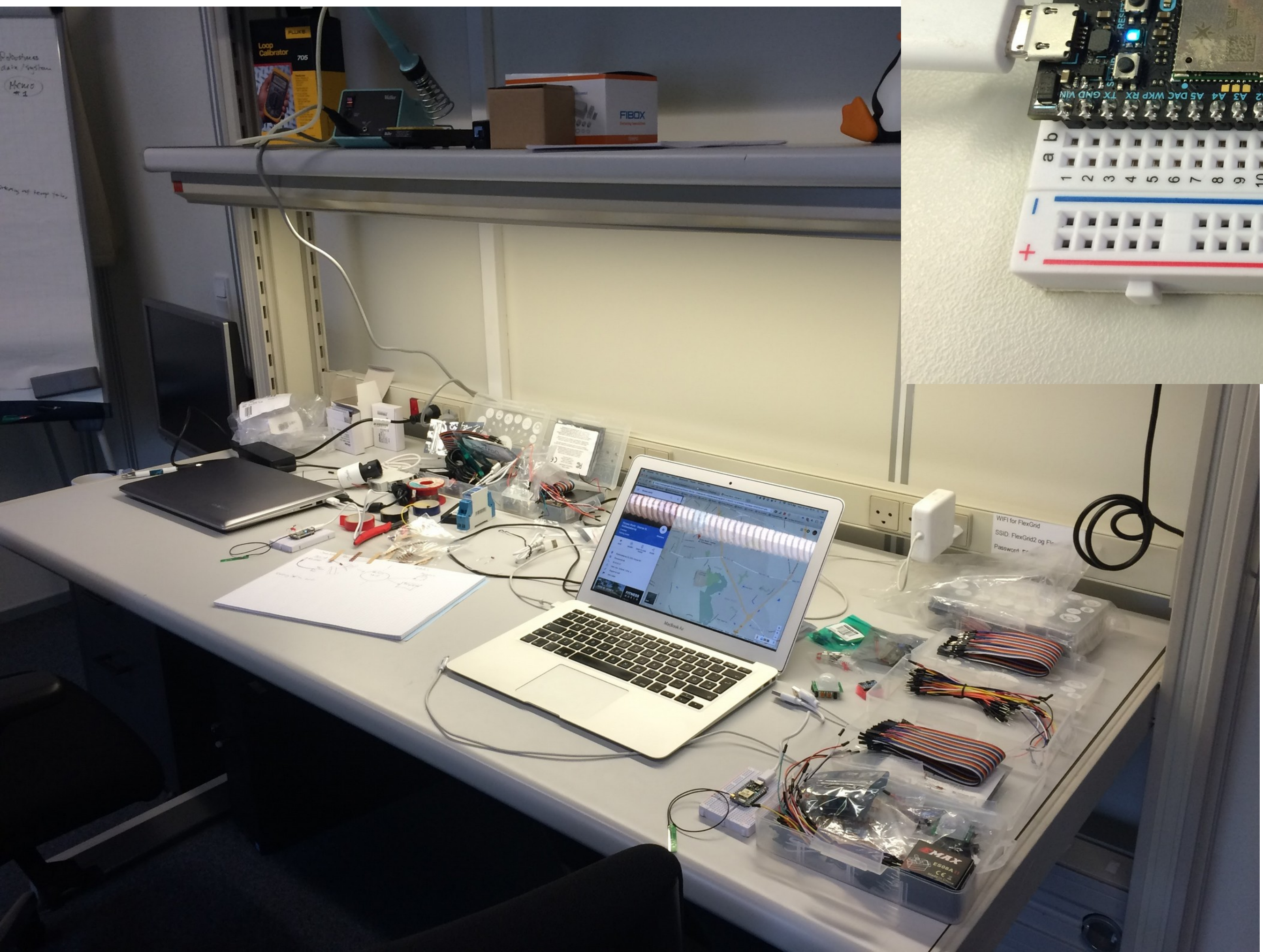


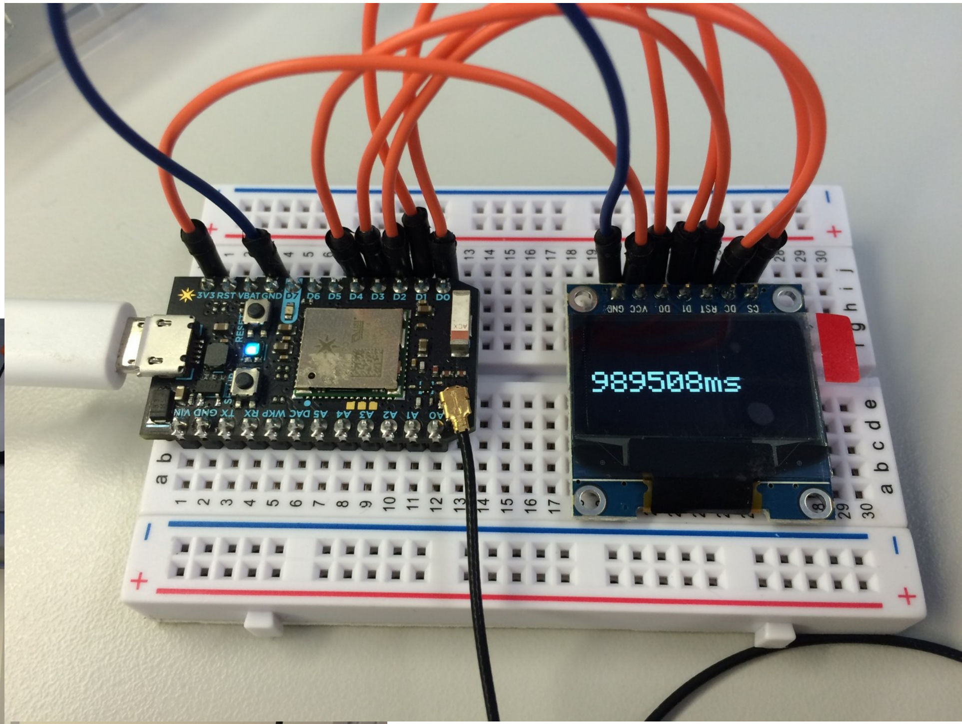
```
# Slow approach, but we are sure things get don
# Try to parallelize anyway
require(multicore)
numcores<-multicore:::detectCores()
mclapply(
  1:N, 
  function(i,data) {
    print(paste(i, "/", N))

    # 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
Control loop design – **logical drawing**

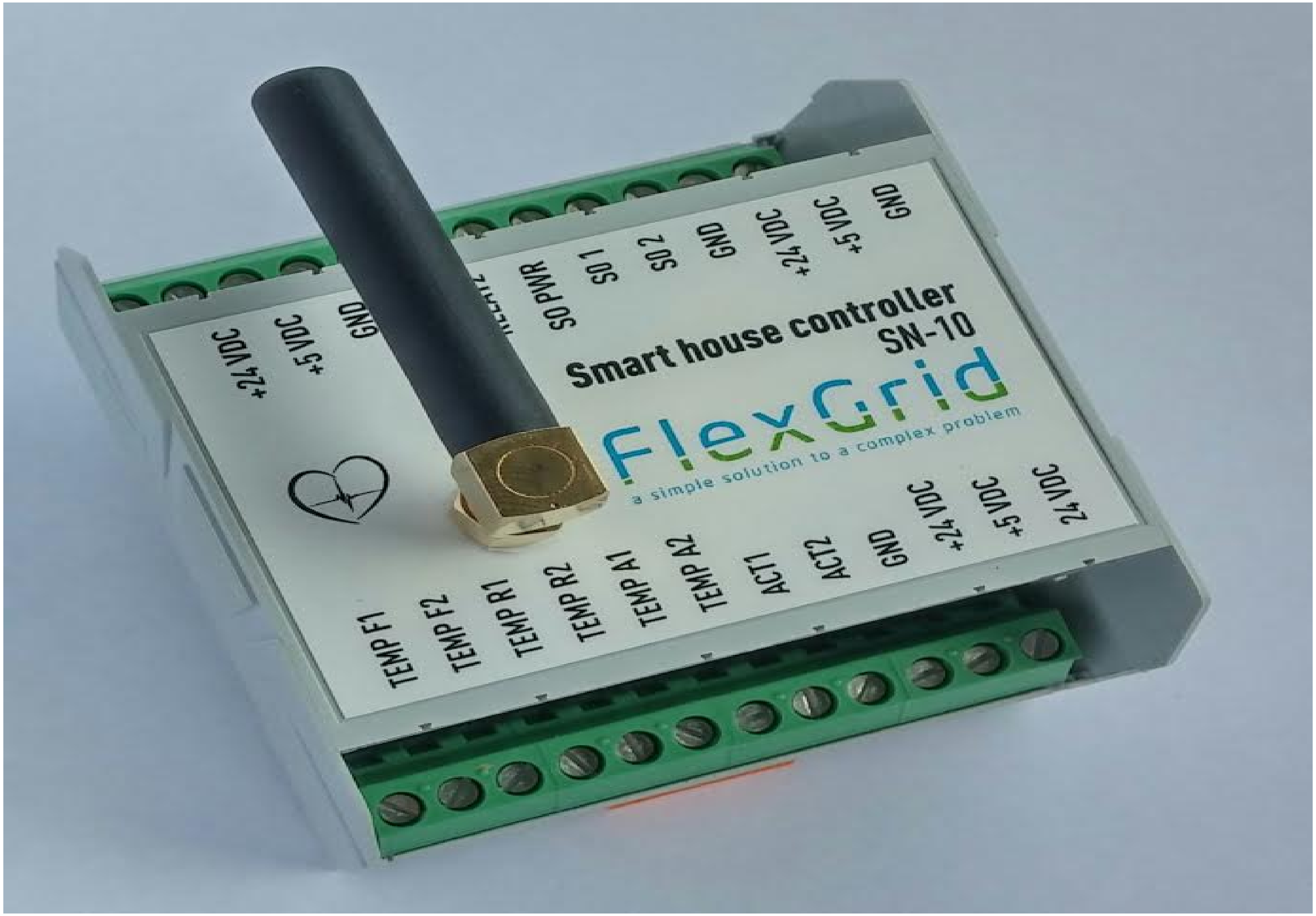


Lab testing ….





SN-10 Smart House Prototype

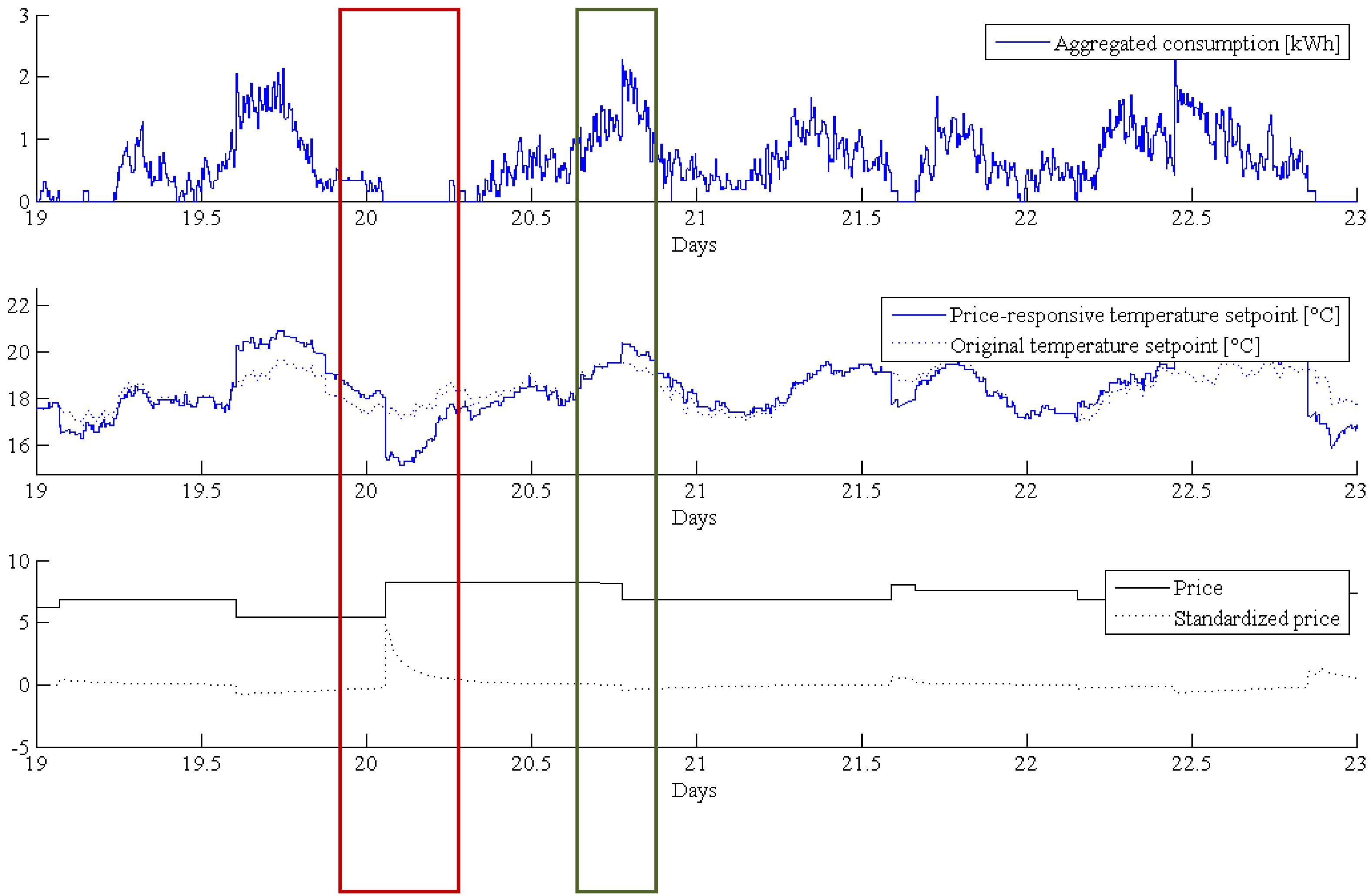


Some case studies ….

Case study

Control of Power Consumption; Storing Energy in the Thermal Mass of Buildings (Peak shaving)

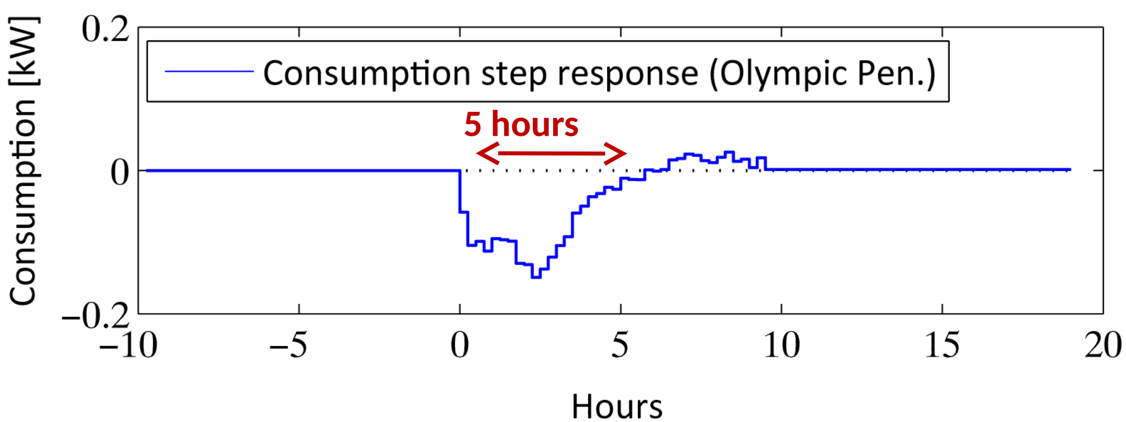
Aggregation (over 20 houses)



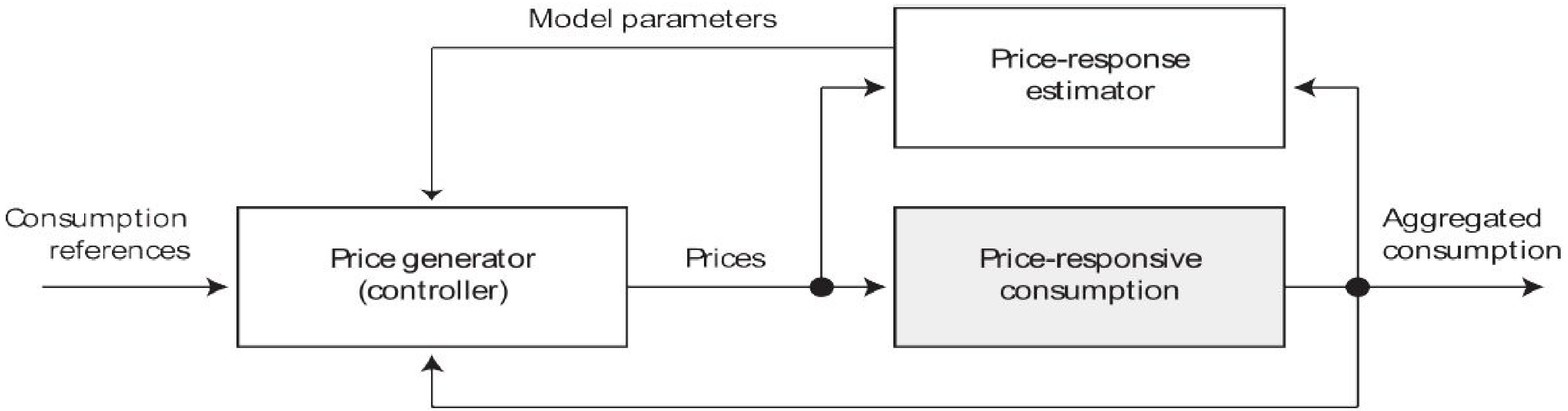
CITIES
Centre for IT Intelligent Energy Systems

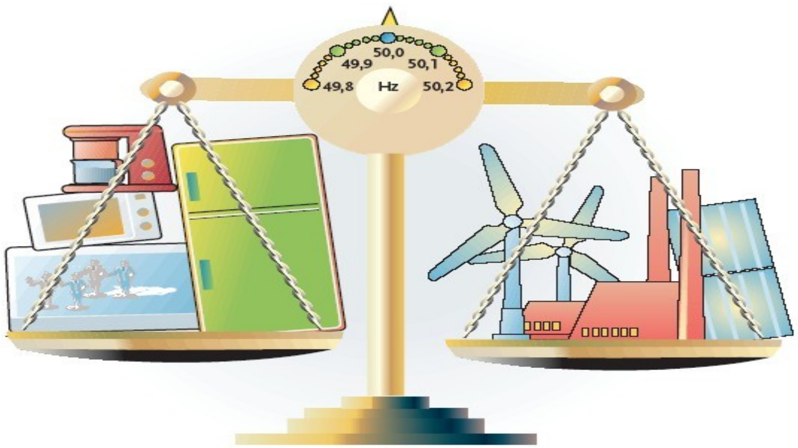
Non-parametric Response on Price Step Change

Olympic Peninsula



Control of Energy Consumption

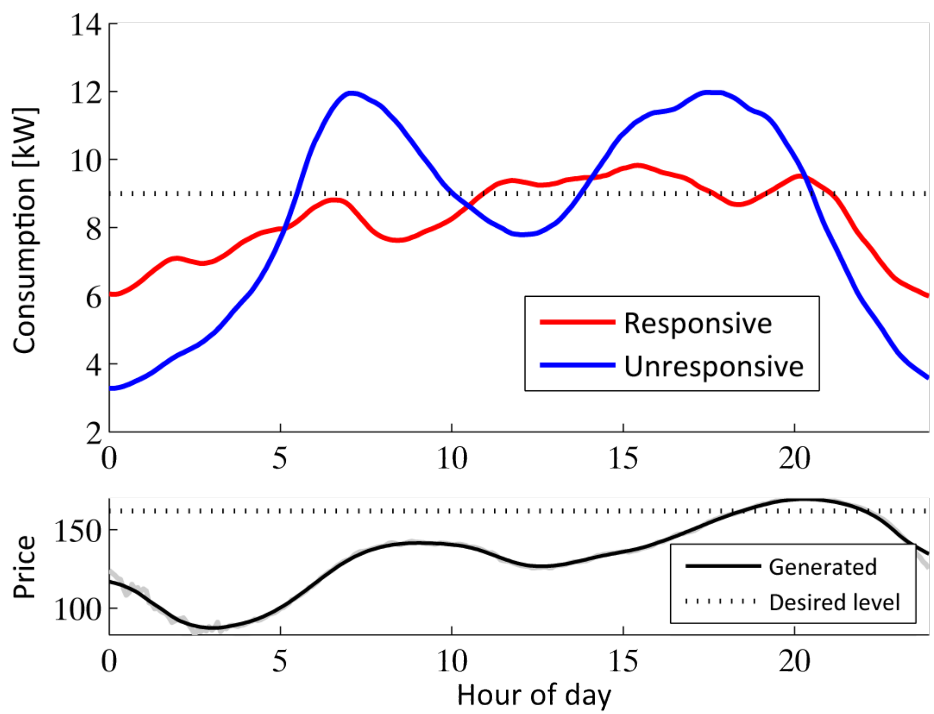




Control performance

Considerable **reduction in peak consumption**

Mean daily consumption shift



Flexibility Setup and Control

Characteristics

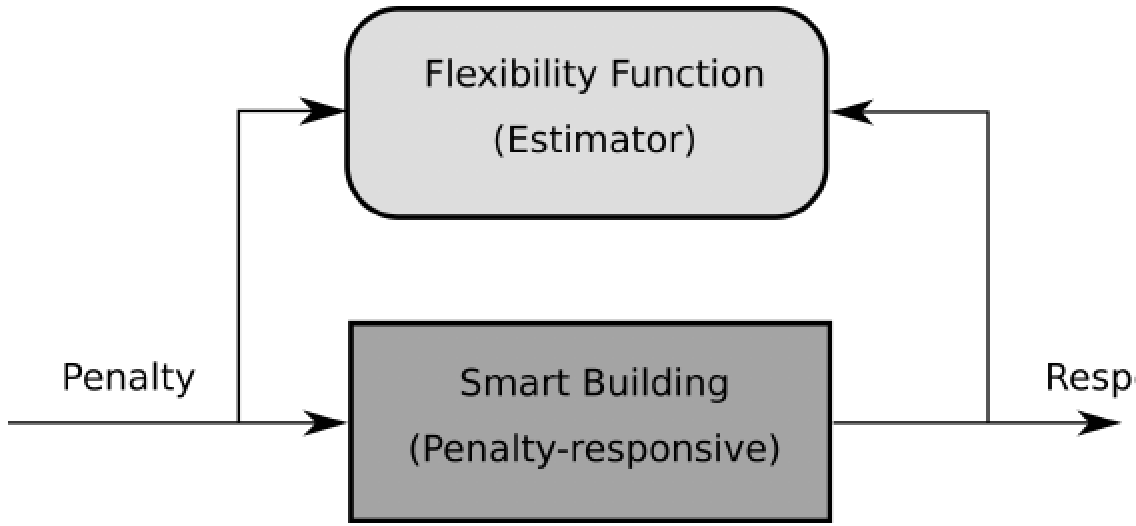


Figure 1: A smart building is able to respond to a penalty or external control signal.

Flexibility Function

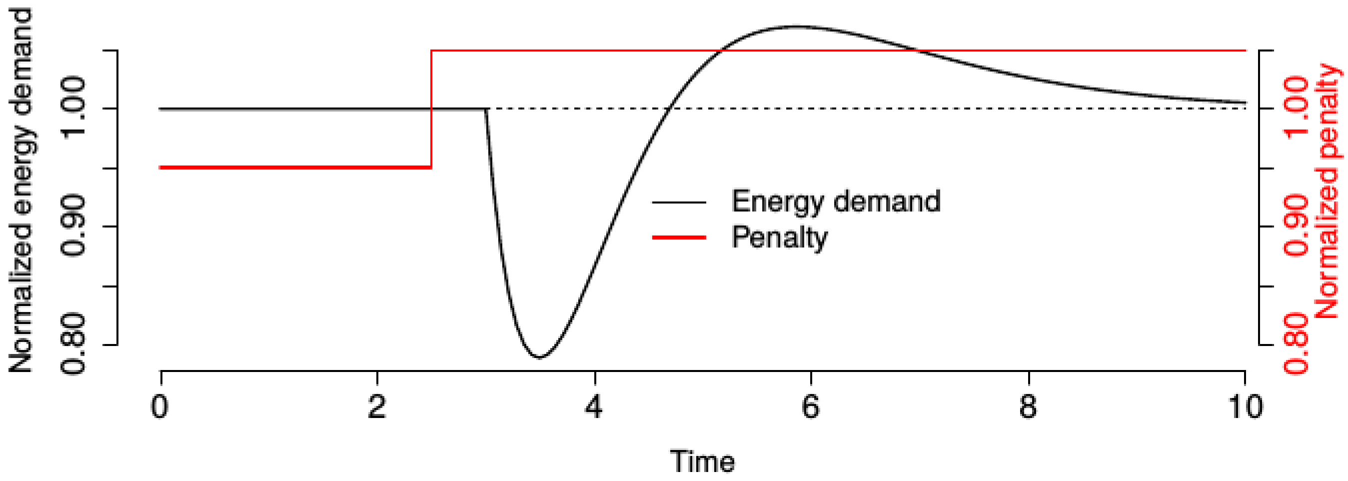


Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

Equivalent to: Impulse response, transfer function, and frequency response function

FF for three buildings

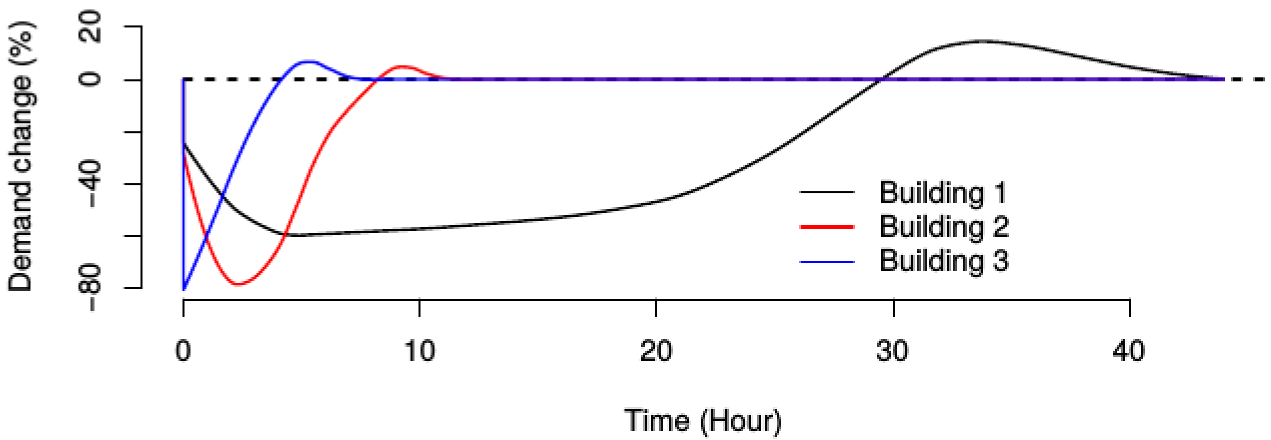


Figure 5: The Flexibility Function for three different buildings.

Penalty Function (examples)

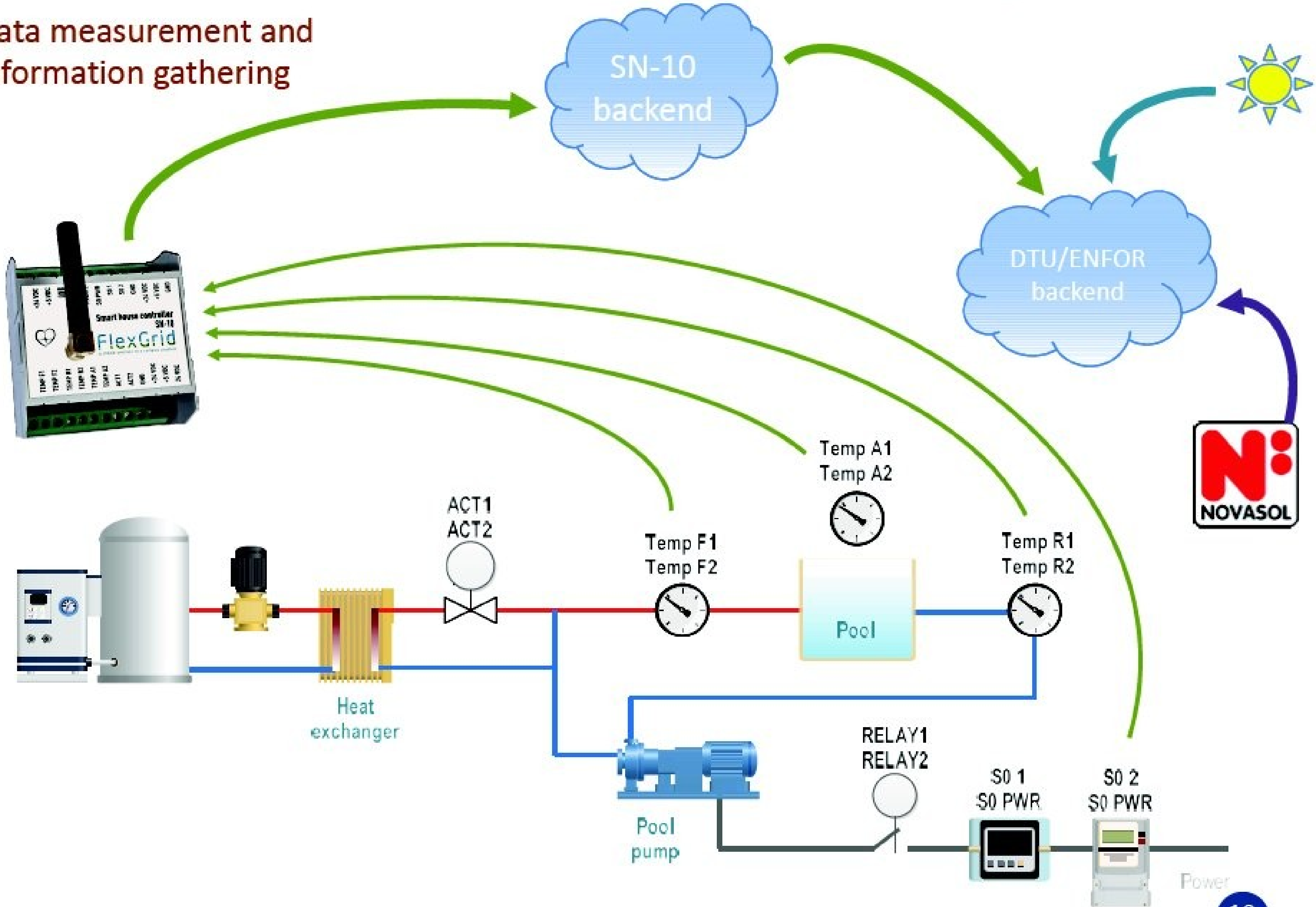
- **Real time CO_2.** If the real time (marginal) CO_2 emission related to the actual electricity production is used as penalty, then, a smart building will minimize the total carbon emission related to the power consumption. Hence, the building will be *emission efficient*.
- **Real time price**. If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

Control of heat pumps;
Storing wind power in pools / DH Systems
(Minimization of Cost / CO2)

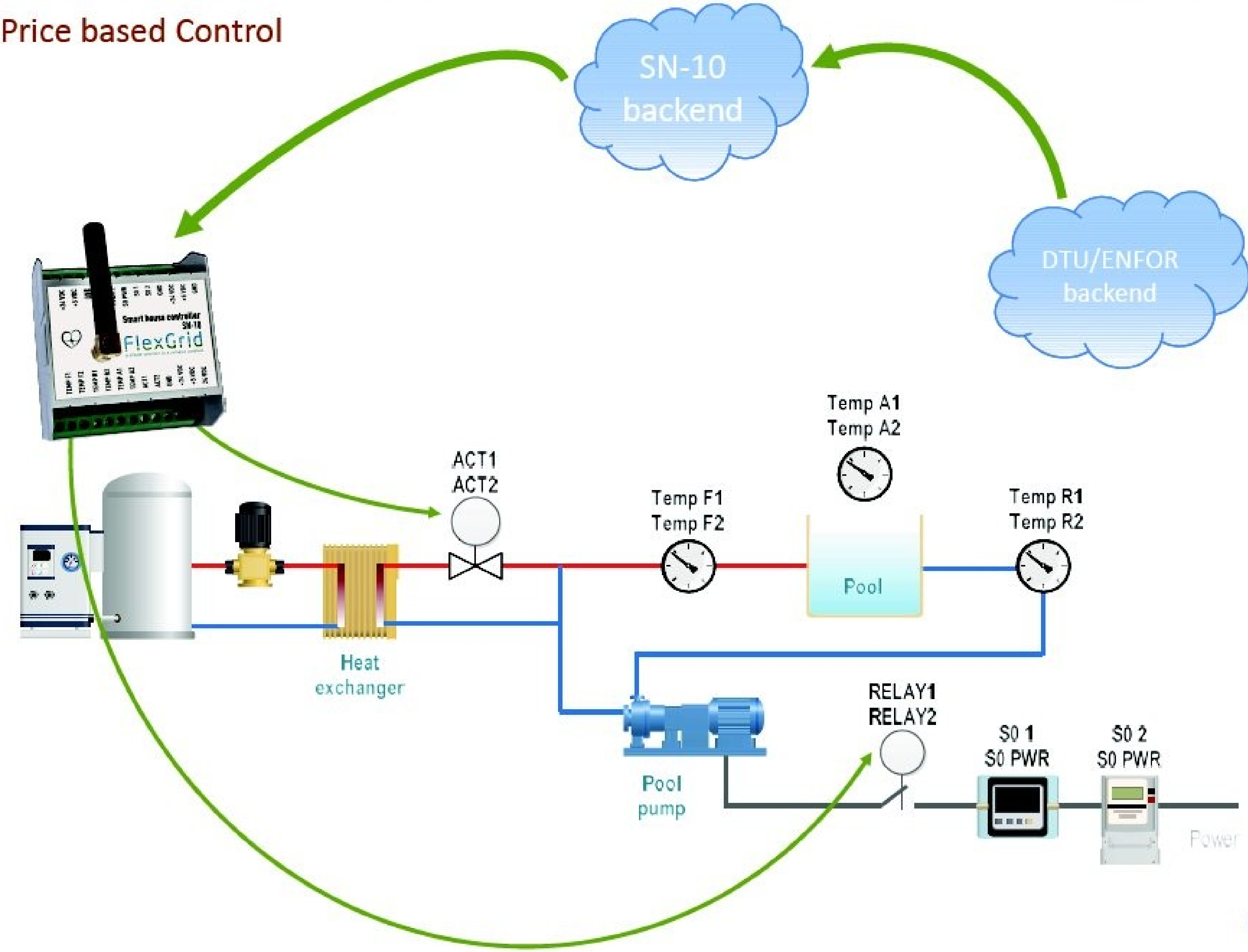
How does it work?

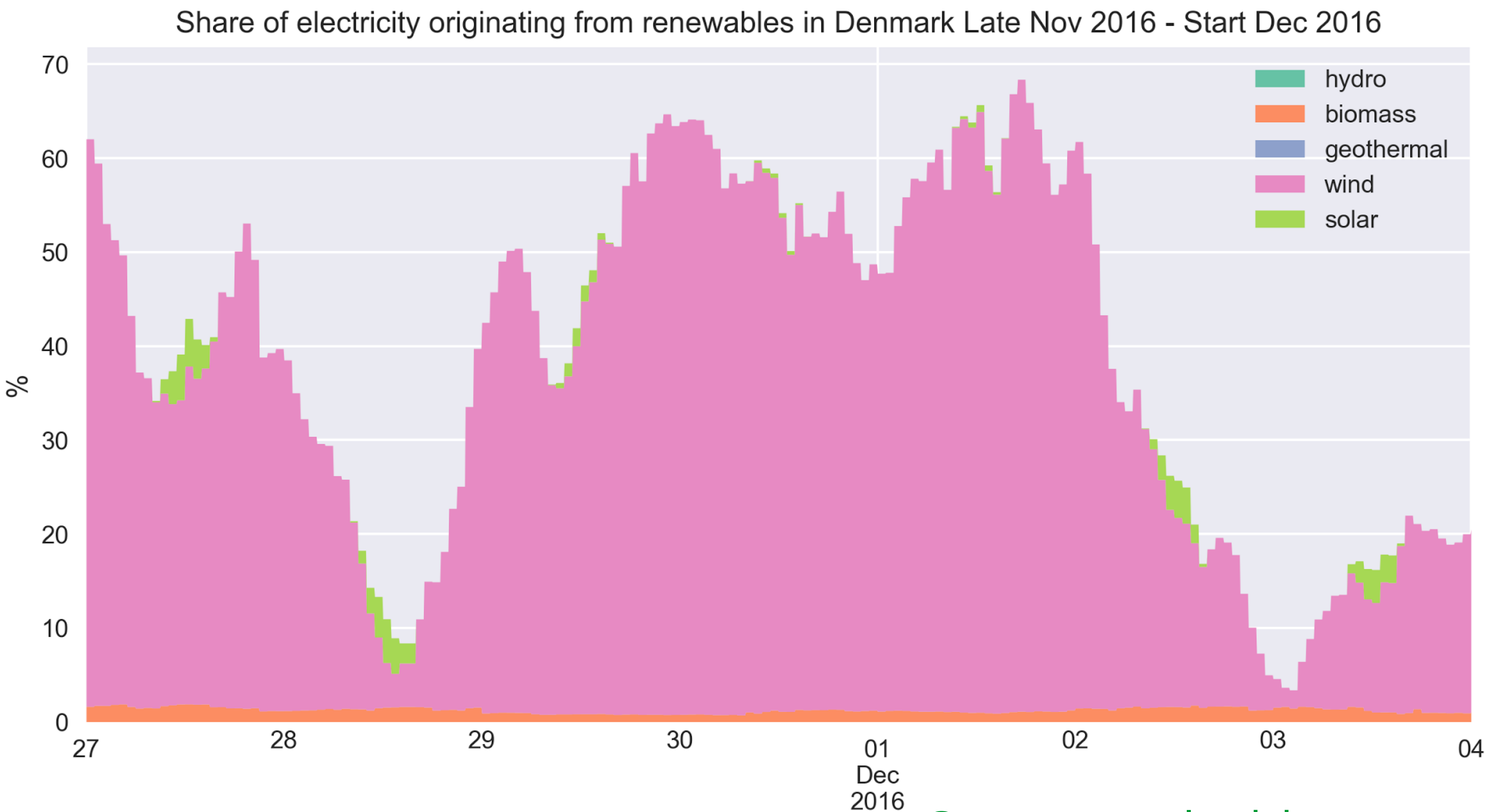
Data measurement and information gathering



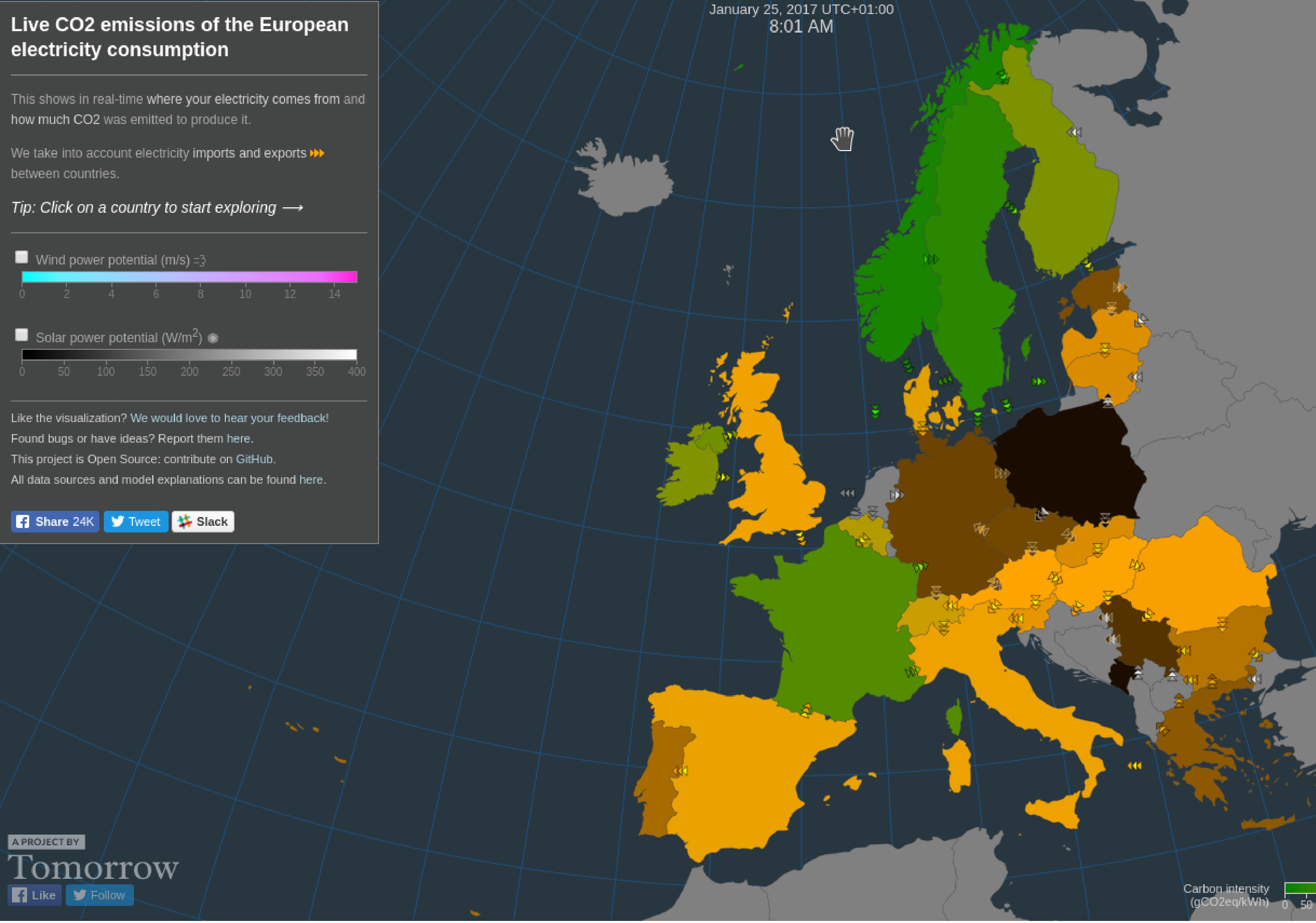
How does it work?

Price based Control



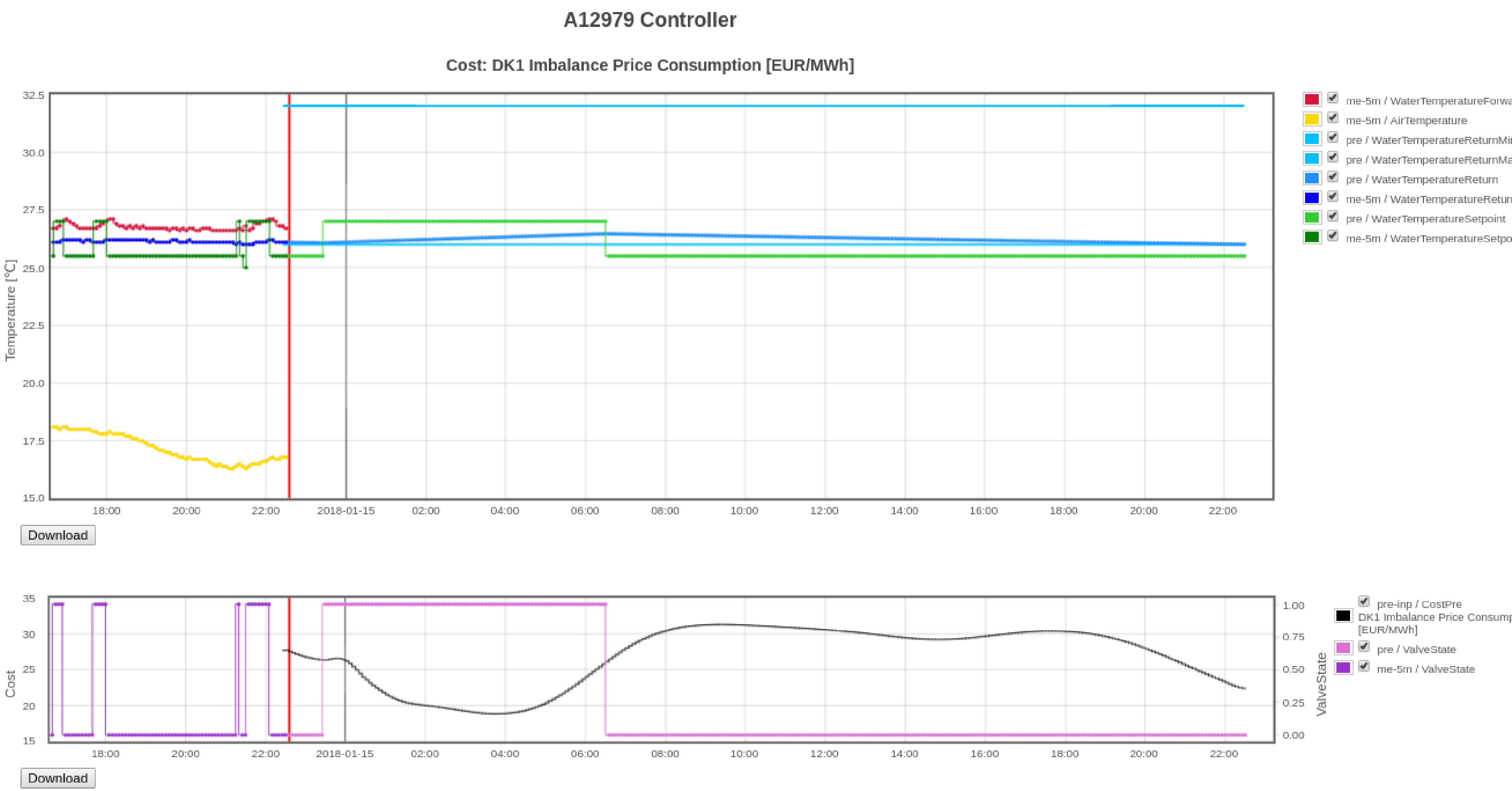


Source: pro.electicitymap.org



CITIES
Centre for IT Intelligent Energy Systems

Example: Price-based control



Example: CO2-based control

Flexibility, Smart Grids and Flexibility Index

CITIES
Centre for IT Intelligent Energy Systems

Smart Grid Application

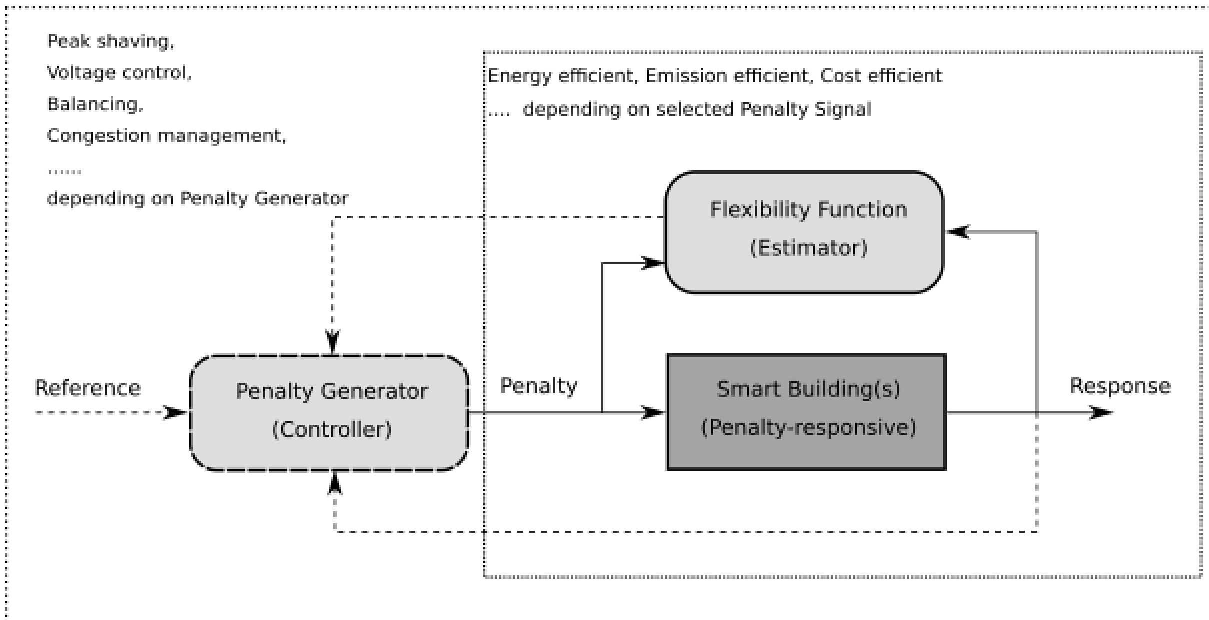
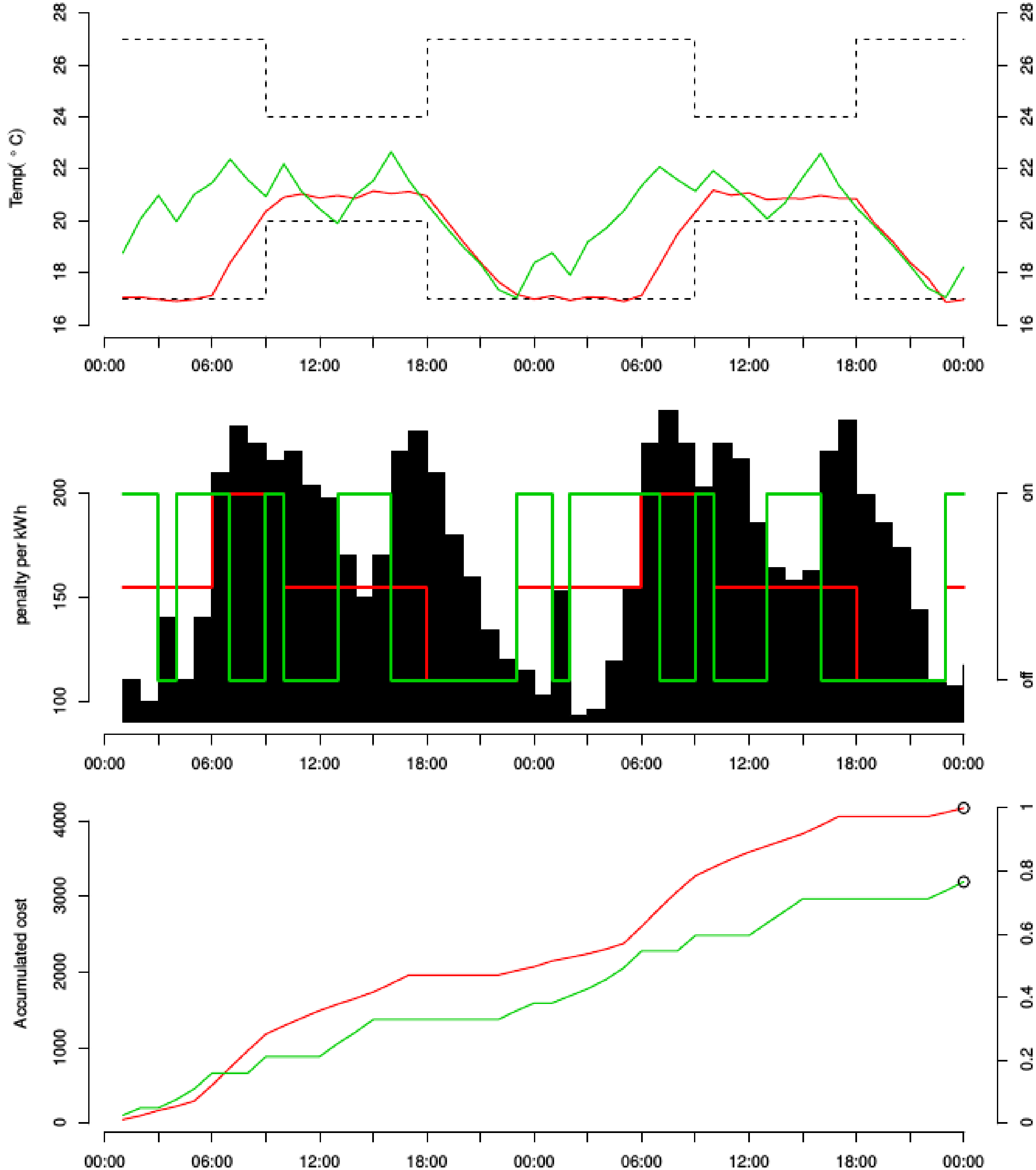
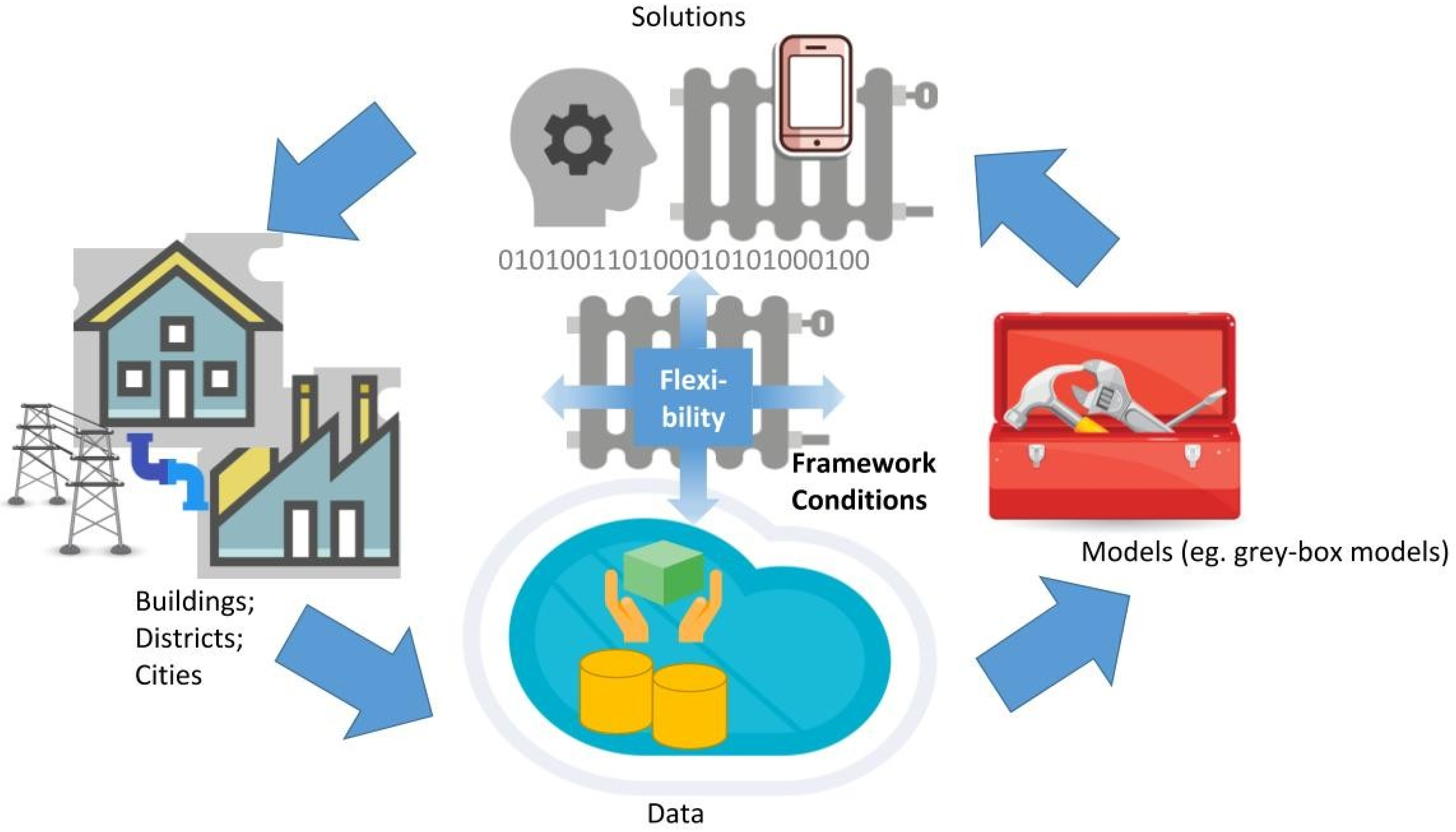


Figure 8: Smart buildings and penalty signals.


Temp(° C)
16
18
20
22
24
26
28
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
penalty per kWh
100
150
200
on
off
Accumulated cost
0
1000
2000
3000
4000
0
0.2
0.4
0.6
0.8
1

Flexibility given framework conditions



Realistic Penalties for DK

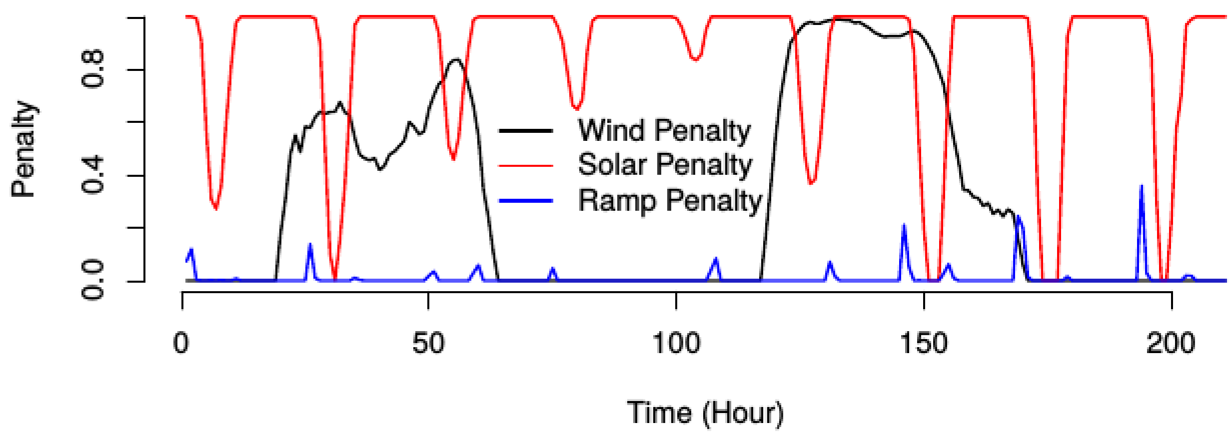


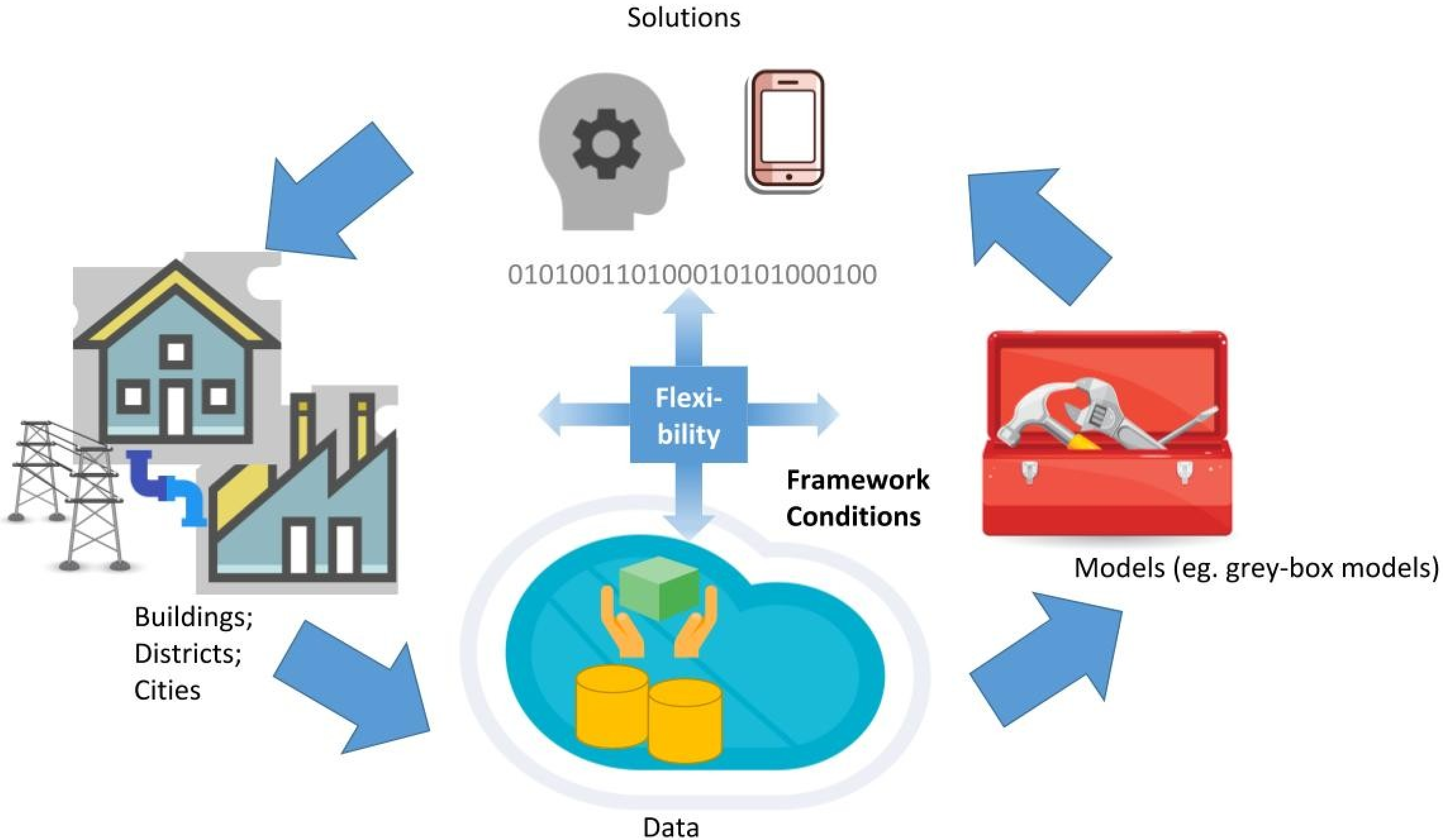
Figure 6: Penalty signals based on wind and solar power production in Denmark during some days in 2017.

Expected Flexibility Savings Index

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

Flexibility without framework conditions



Reference Penalties

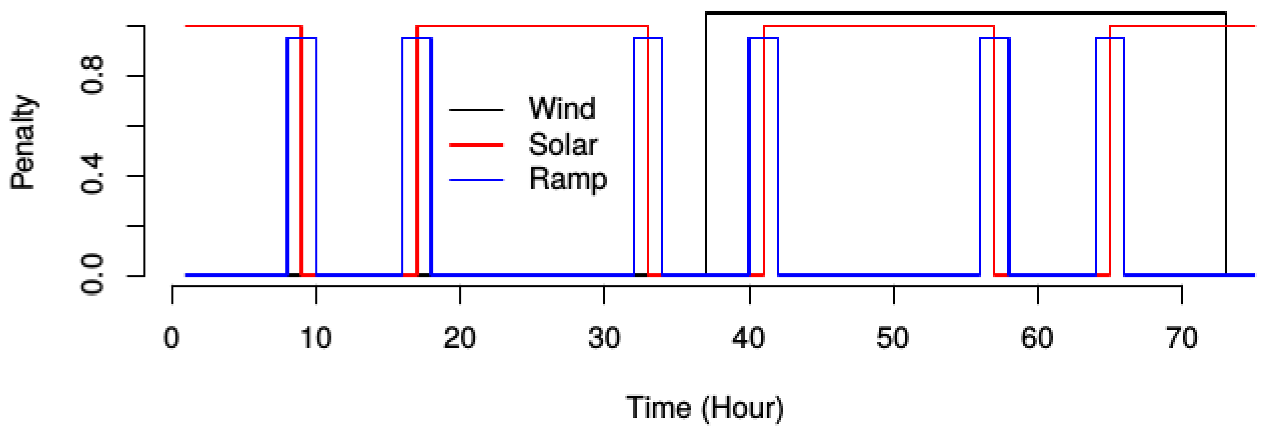


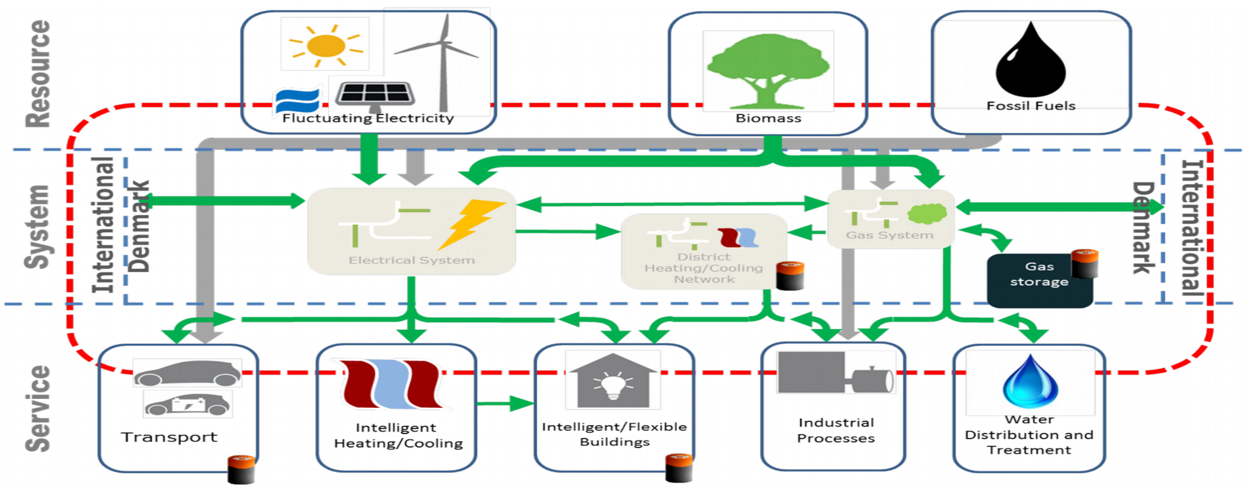
Figure 7: Reference scenarios of penalty signals related to ramping or peak issues as well as the integration of wind and solar power.

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

Virtual Storage Solutions

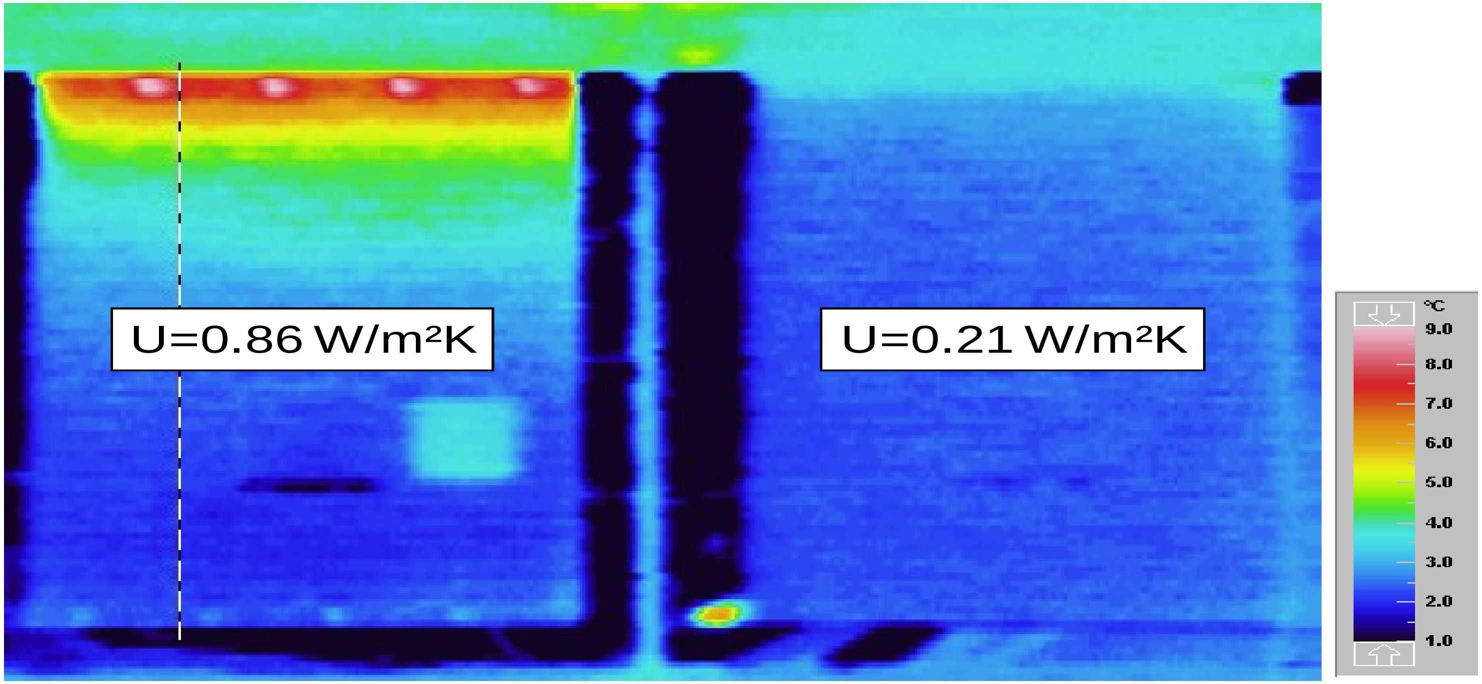


- **Flexibility (or virtual storage) characteristics:**
  - Supermarket refrigeration can provide storage 0.5-2 hours ahead
  - Buildings thermal capacity can provide storage up to, say, 1-10 hours ahead
  - Buildings with local water storage can provide storage up to, say, 3-18 hours ahead
  - District heating/cooling systems can provide storage up to 1-3 days ahead
  - DH systems with storage solutions can provide semi-seasonal storage
  - Gas systems can provide seasonal storage

Case study

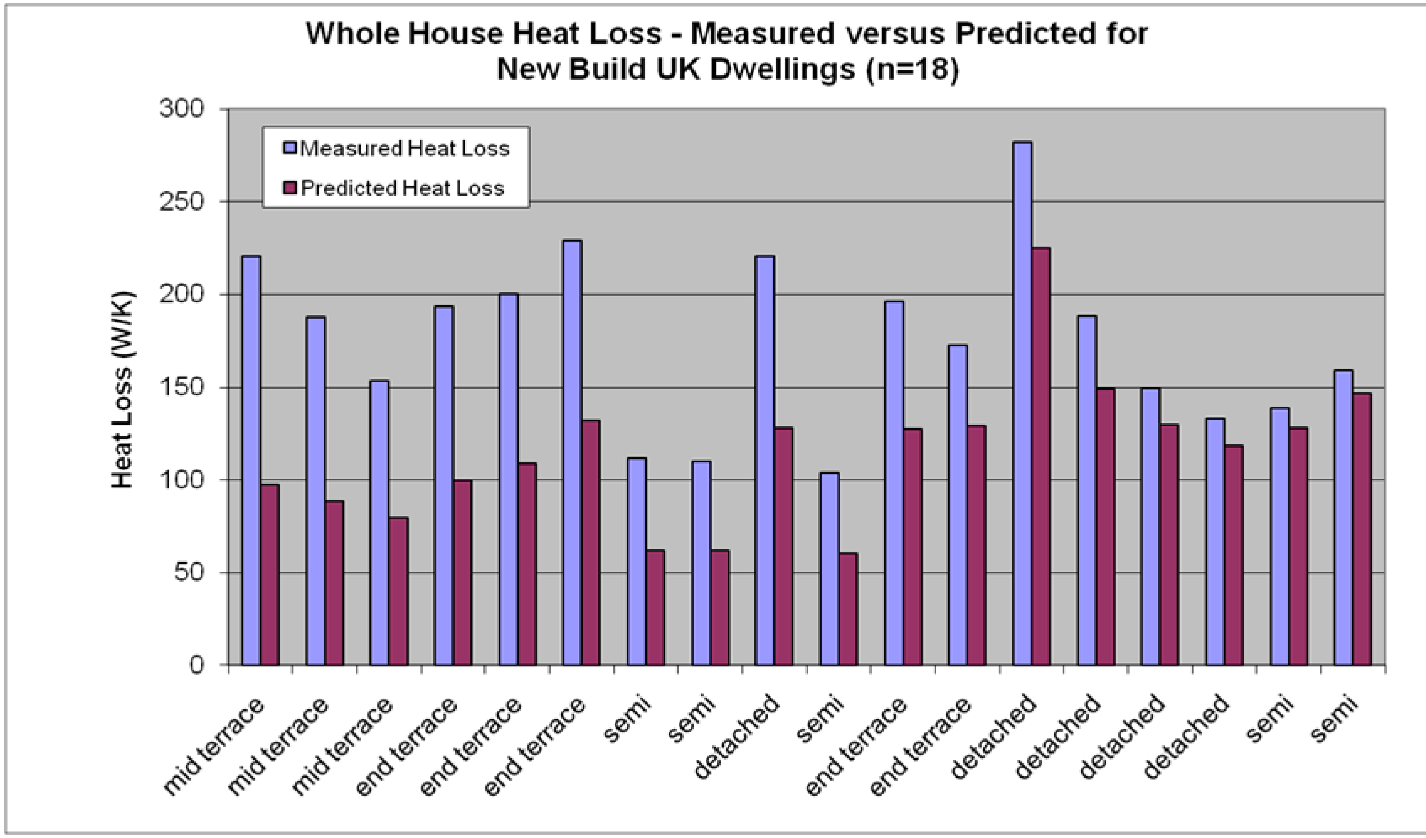
Identifying the Thermal Performance of Buildings using Meter Data

Example



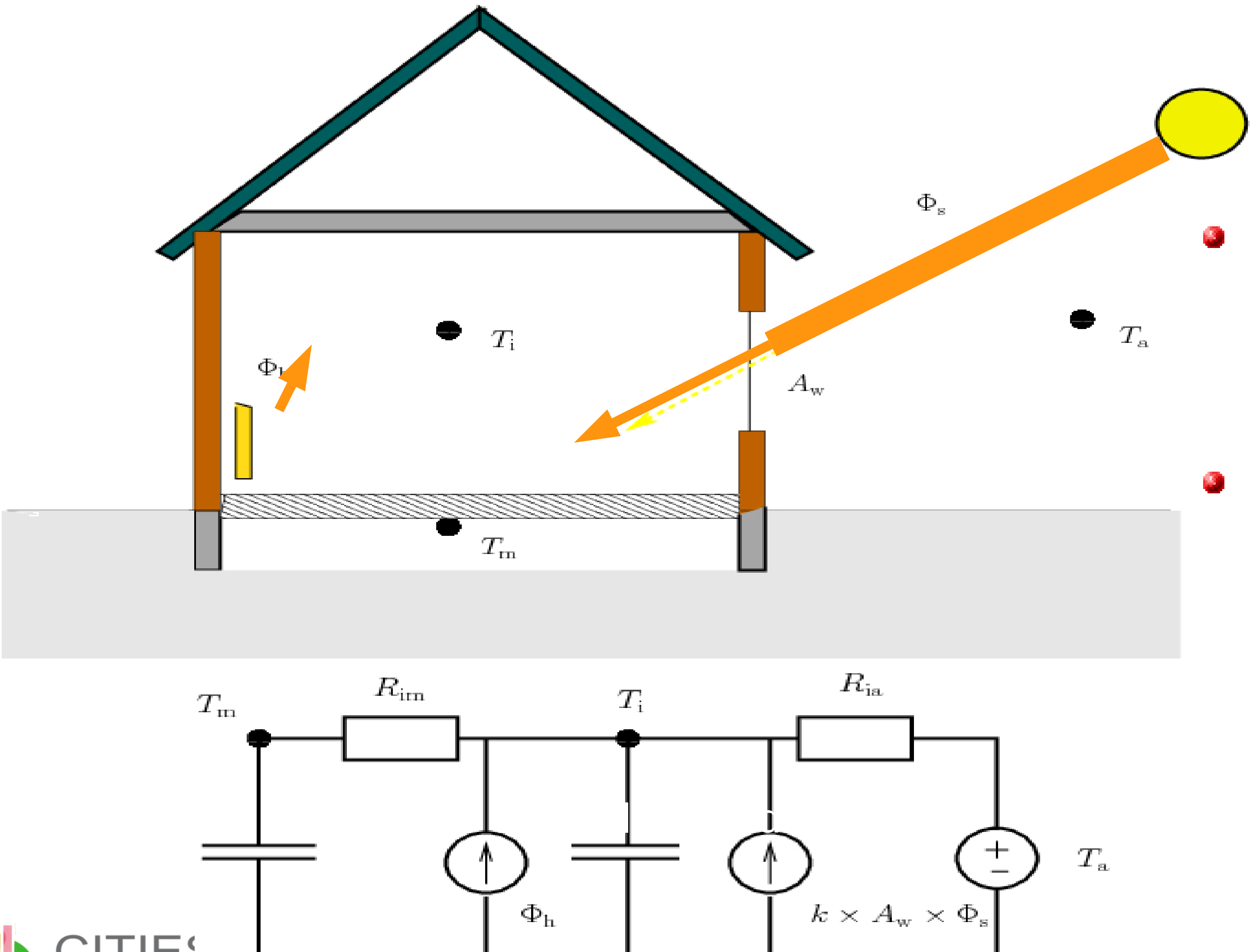
Consequence of good or bad workmanship (theoretical value is U=0.16W/m2K)

Examples (2)



Measured versus predicted energy consumption for different dwellings

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

Results

	UA W/°C	σ_{UA}	gA^{max} W	wA_E^{max} W/°C	wA_S^{max} W/°C	wA_W^{max} W/°C	T_i °C	σ_{T_i}
4218598	211.8	10.4	597.0	11.0	3.3	8.9	23.6	1.1
4381449	228.2	12.6	1012.3	29.8	42.8	39.7	19.4	1.0
4711160	155.4	6.3	518.8	14.5	4.4	9.1	22.5	0.9
4836681	155.3	8.1	591.0	39.5	28.0	21.4	23.5	1.1
4836722	236.0	17.7	1578.3	4.3	3.3	18.9	23.5	1.6
4986050	159.6	10.7	715.7	10.2	7.5	7.2	20.8	1.4
5069878	144.8	10.4	87.6	3.7	1.6	17.3	21.8	1.5
5069913	207.8	9.0	962.5	3.7	8.6	10.6	22.6	0.9
5107720	189.4	15.4	657.7	41.4	29.4	16.5	21.0	1.6
.	.	.	.	.	.	.	.	.

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

Perspectives (2)

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

Summary

- A framework called Smart-Energy OS based on grey-box modelling is described for implementing smart energy systems in cognitive buildings with storage options
- A number of case studies related to smart buildings is outlined
- The intelligence setup for the smart buildings can focus on
  - Energy Efficiency
  - Cost Efficiency (Minimization)
  - Emission Efficiency (-> accelerating the transition to a low-carbon energy system)
  - Smart Grid demand (like ancillary services needs, ...)
- We have demonstrated a large potential for unlocking the flexibility and for demand response using grey-box modelling and AI
- We have suggested a method for characterizing the energy flexibility which facilitates smart grid applications
- We have demonstrated AI methods for optimizing the energy savings

For more information ...

See for instance

www.smart-cities-centre.org

...or contact

– Henrik Madsen (DTU Compute)

hmad@dtu.dk

Acknowledgements - IFD 1305-00027B (CITIES), REBUS project, and EU Interreg V (SCA project)

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.