



# How to characterize and label energy Flexible buildings and districts; For operating the future smart grids



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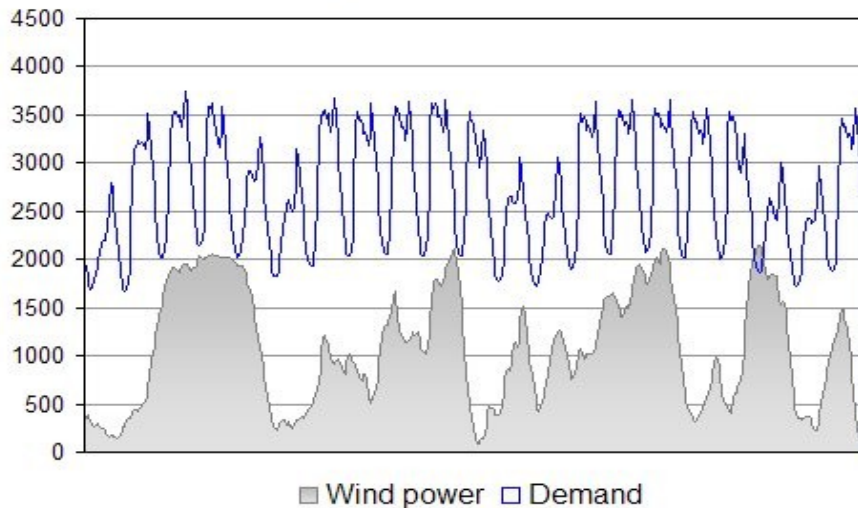
<http://www.henrikmadsen.org>



# The Danish Wind Power Case

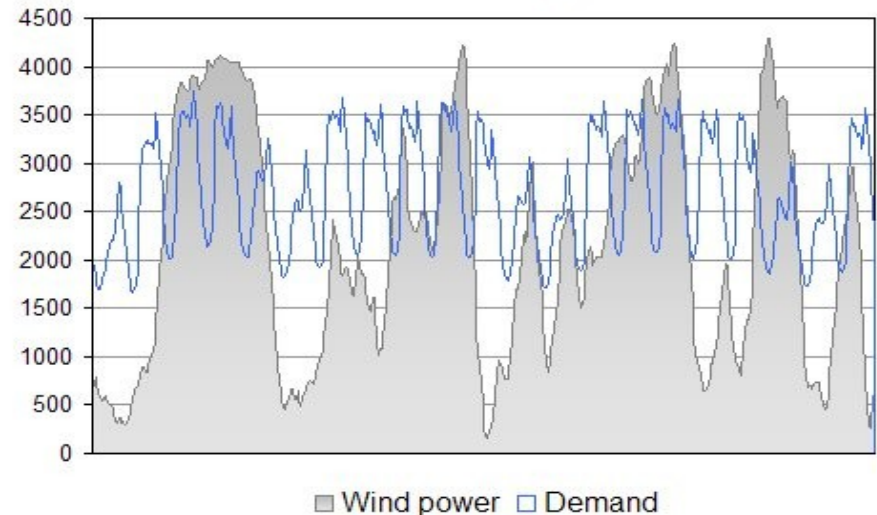
.... *balancing of the power system*

25 % wind energy (West Denmark January 2008)



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

50 % wind energy



**In the first half of 2017 more than 44 pct of electricity load was covered by wind power.**

For several days the wind power production was more than 100 pct of the power load.

July 10th, 2015 more than 140 pct of the power load was covered by wind power



# Energy Systems Integration

**Energy system integration (ESI)** = the process of optimizing energy systems across multiple pathways and scales

Single Building

Community, City

Region, Country



**Data Pathway:** Information and communication technologies allow a better understanding and control of systems by linking sensor data from multiple locations to control centers.



Electricity



Thermal



Fuel



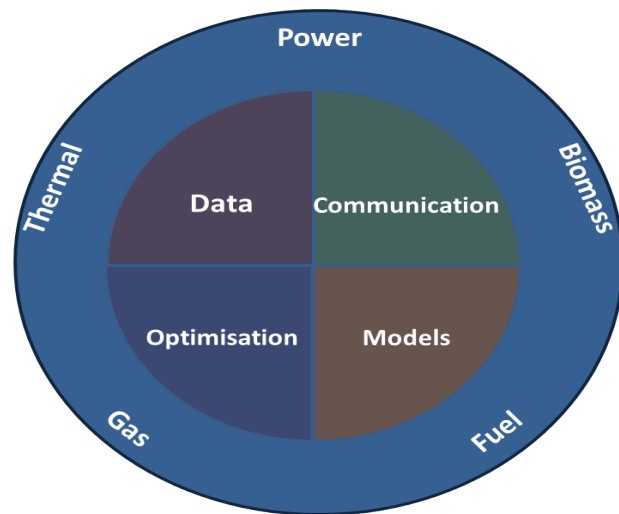
Data



# Flexible Solutions and CITIES

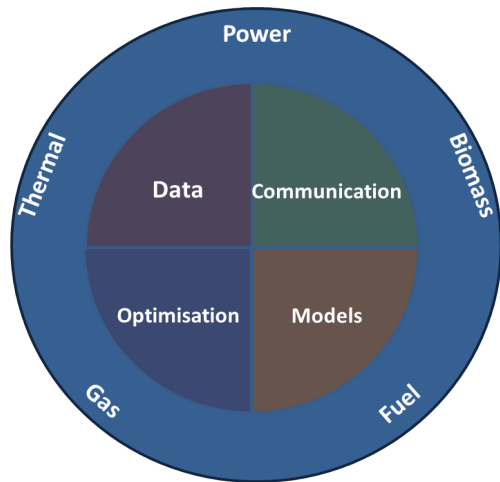
***Center for IT-Intelligent Energy Systems in Cities (CITIES)*** is aiming at establishing methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales.

CITIES is currently the largest Smart Cities and ESI research project in Denmark – see <http://www.smart-cities-centre.org> .





# Energy Systems Integration



The **central hypothesis** is that by **intelligently integrating** currently distinct energy flows (heat, power, gas and biomass) using grey-box models we can balance very large shares of renewables, and consequently obtain substantial reductions in CO<sub>2</sub> emissions.

**Intelligent integration** will (for instance) enable lossless 'virtual' storage on a number of different time scales.




# Existing Markets - Challenges

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






# Challenges (cont.)



## Preparatory study on Smart Appliances



Ecodesign Preparatory Study performed for the European Commission

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## 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](#).

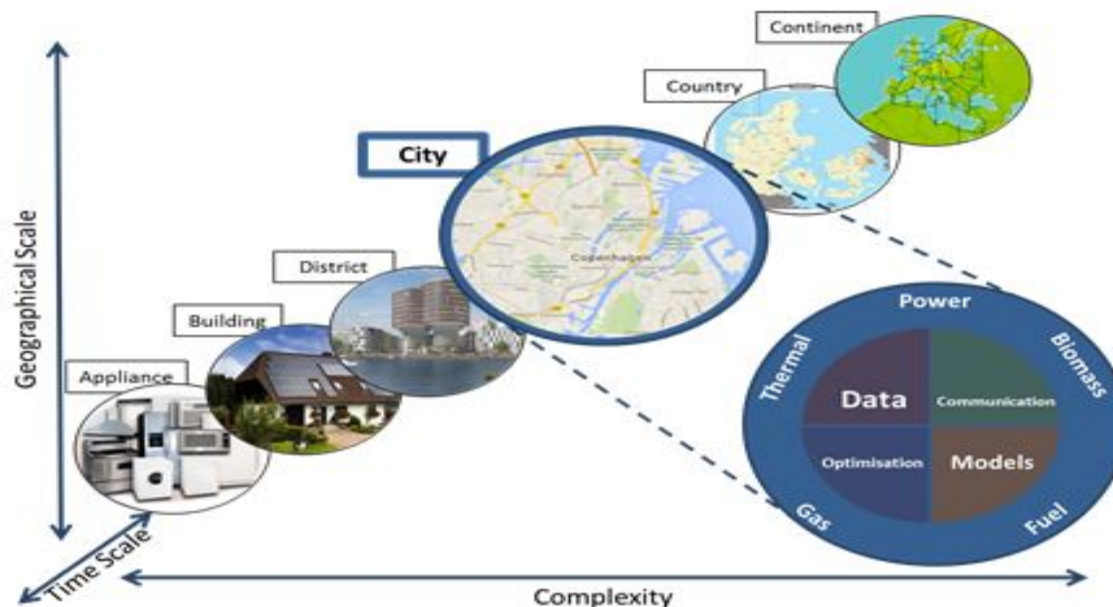
Throughout the study, new relevant aspects have come up which will be covered in a second phase of the Preparatory Study:

- 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.



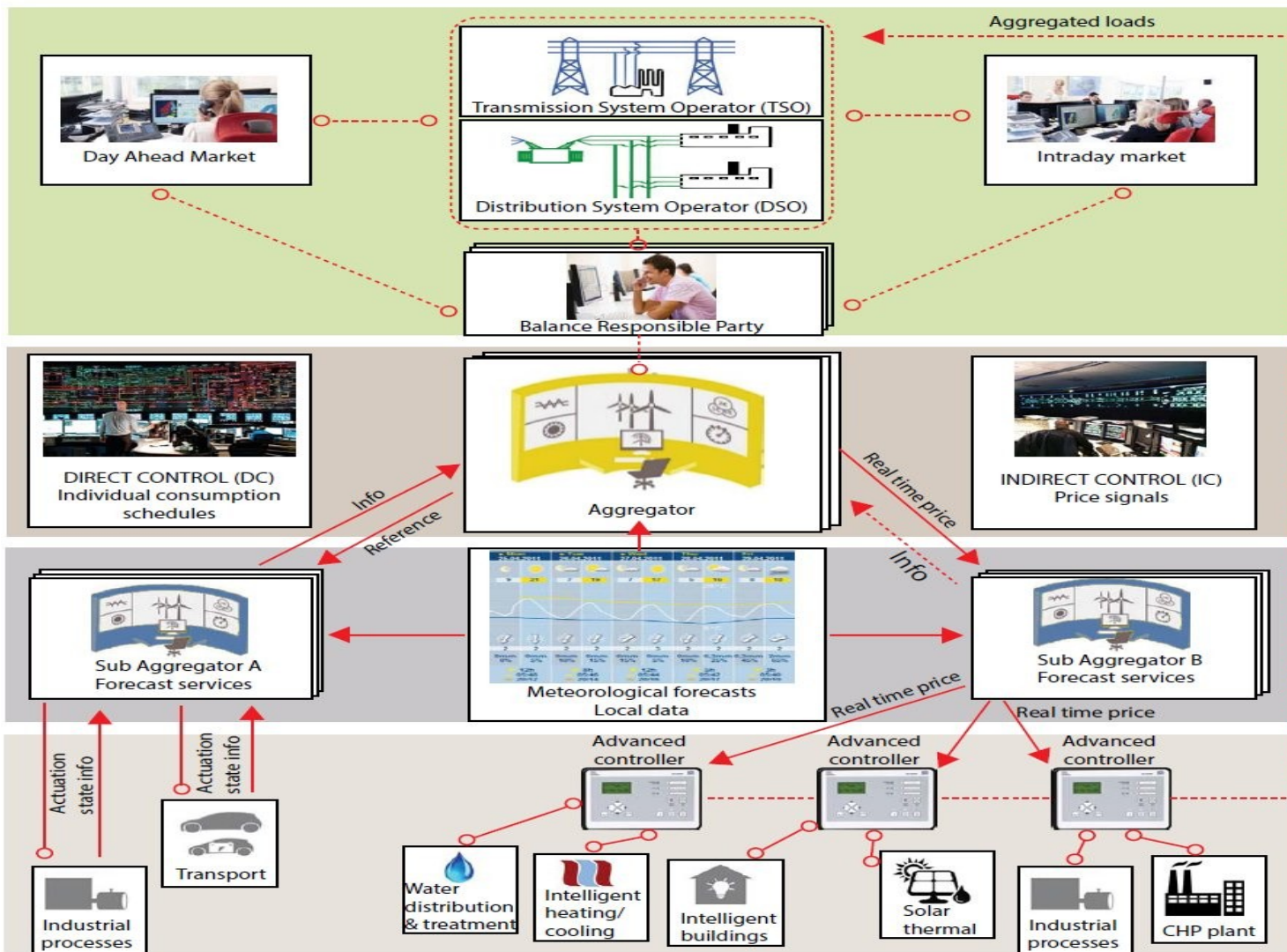
# Temporal and Spatial Scales

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**.

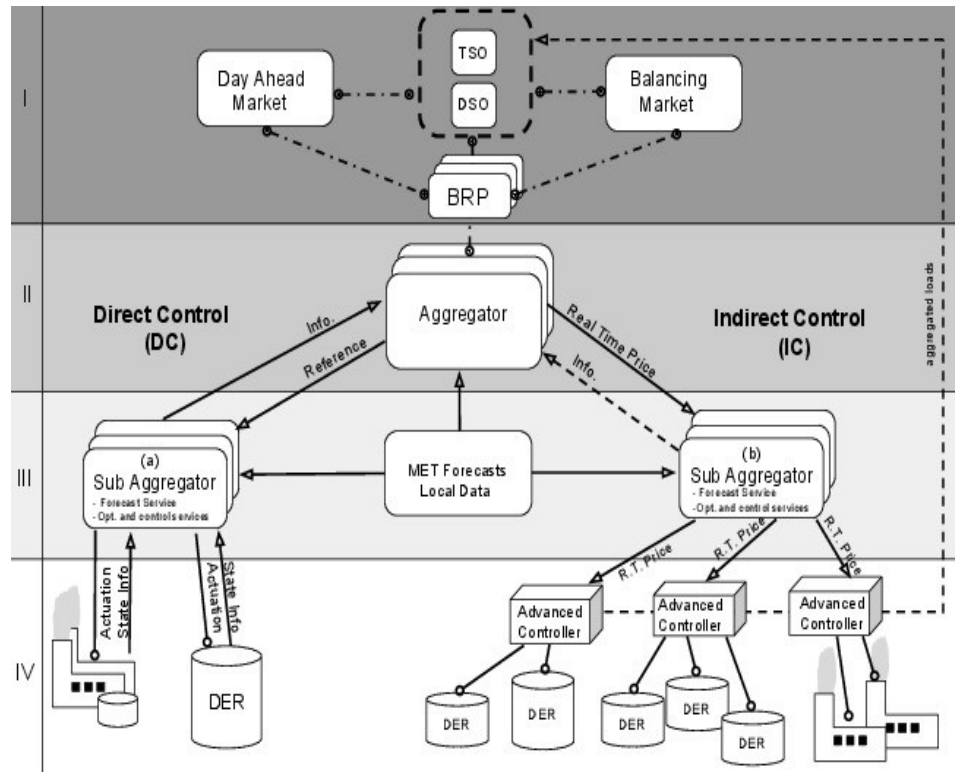




# Smart-Energy OS



# Control and Optimization



## Day Ahead:

Stoch. Programming based on eg. Scenarios

Cost: Related to the market (one or two levels)

## Direct Control:

Actuator: Power

Two-way communication

Models for DERs are needed

Constraints for the DERs (calls for state est.)

Contracts are complicated

## Indirect Control:

Actuator: Price

Cost: E-MPC at **low (DER) level**, One-way communication

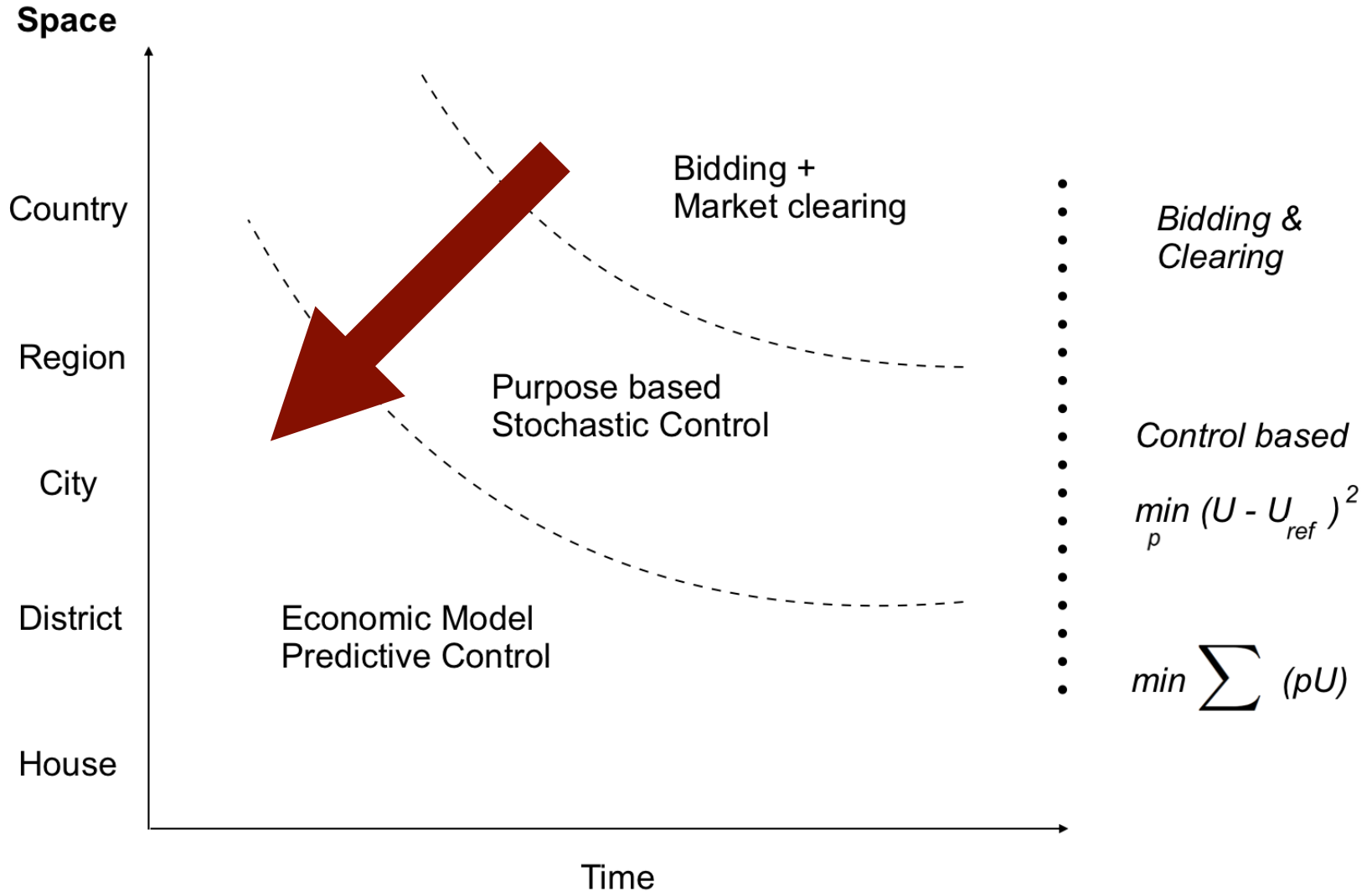
Models for DERs are not needed

Simple 'contracts'

**In New Wiley Book: Control of Electric Loads in Future Electric Energy Systems, 2015**

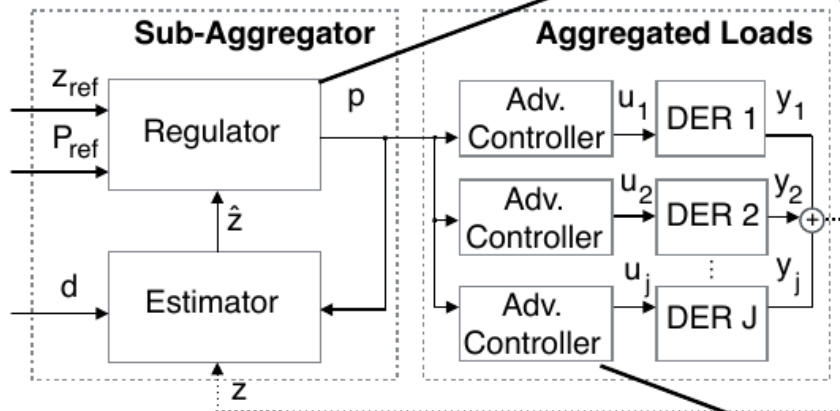


# The 'market' of tomorrow



# Proposed methodology

## Control-based methodology



$$\min_p \quad \mathbb{E} \left[ \sum_{k=0}^N w_{j,k} \|\hat{z}_k - z_{ref,k}\| + \mu \|p_k - p_{ref,k}\| \right]$$

$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$

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

$$\min_u \quad \mathbb{E} \left[ \sum_{k=0}^N \sum_{j=1}^J \phi_j(x_{j,k}, u_{j,k}, p_k) \right]$$

$$\text{s.t.} \quad x_{k+1} = Ax_k + Bu_k + Ed_k,$$

$$y_k = Cx_k,$$

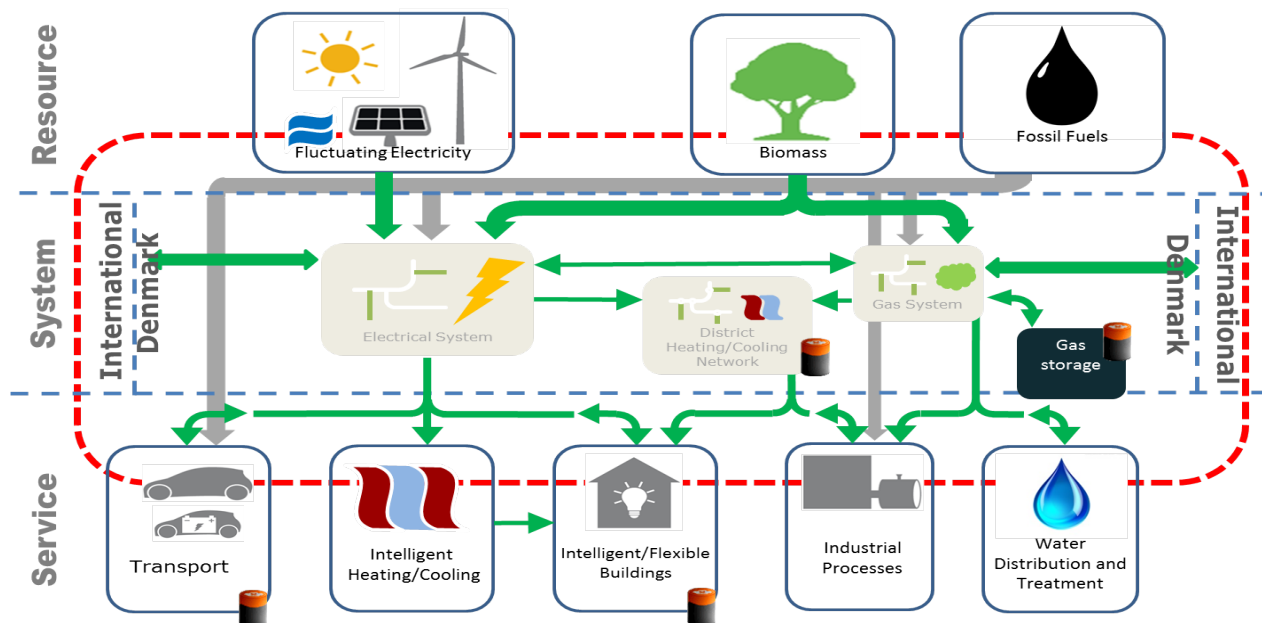
$$y_k^{\min} \leq y_k \leq y_k^{\max},$$

$$u_k^{\min} \leq u_k \leq u_k^{\max}$$



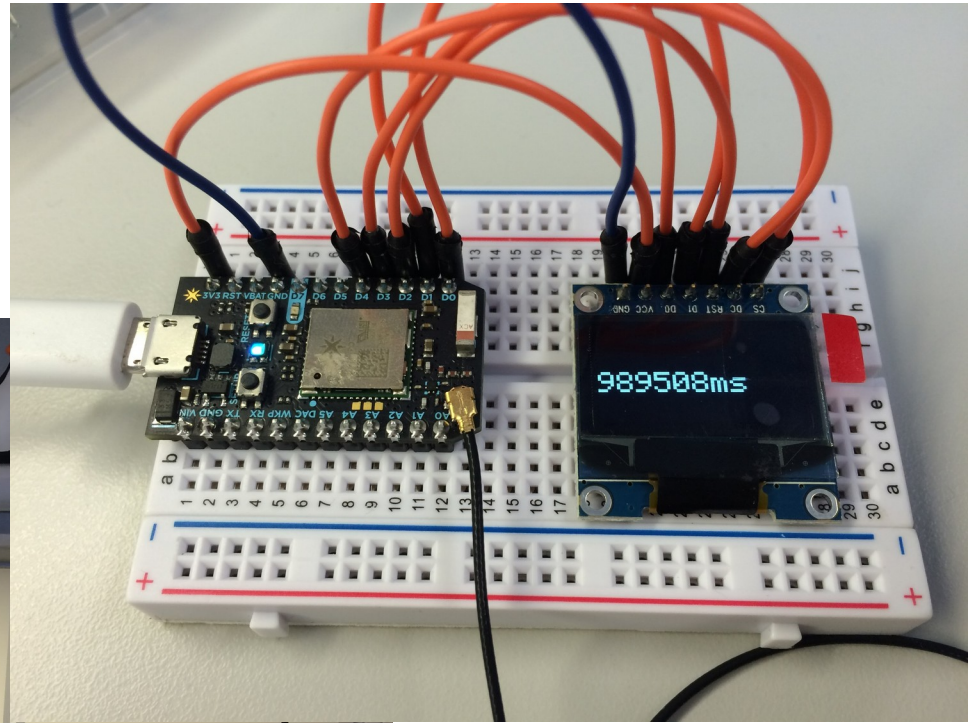
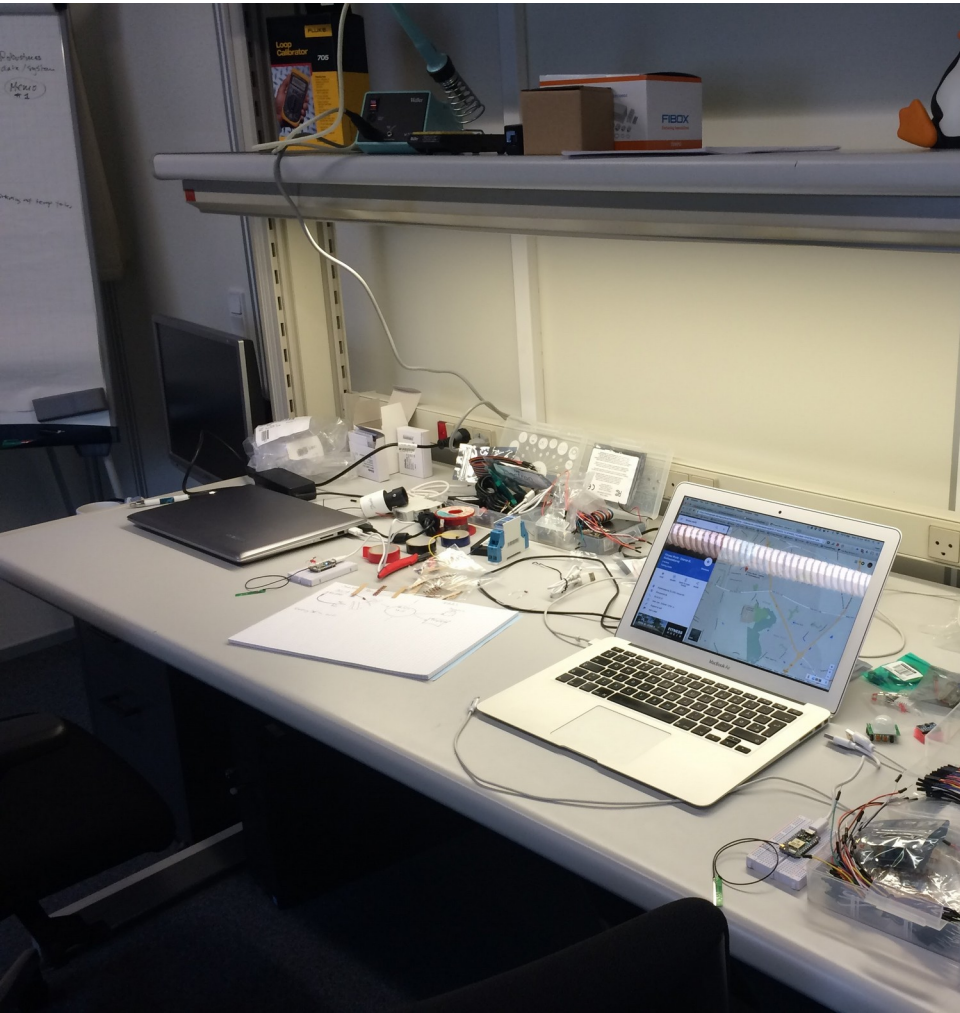
# Models for systems of systems

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





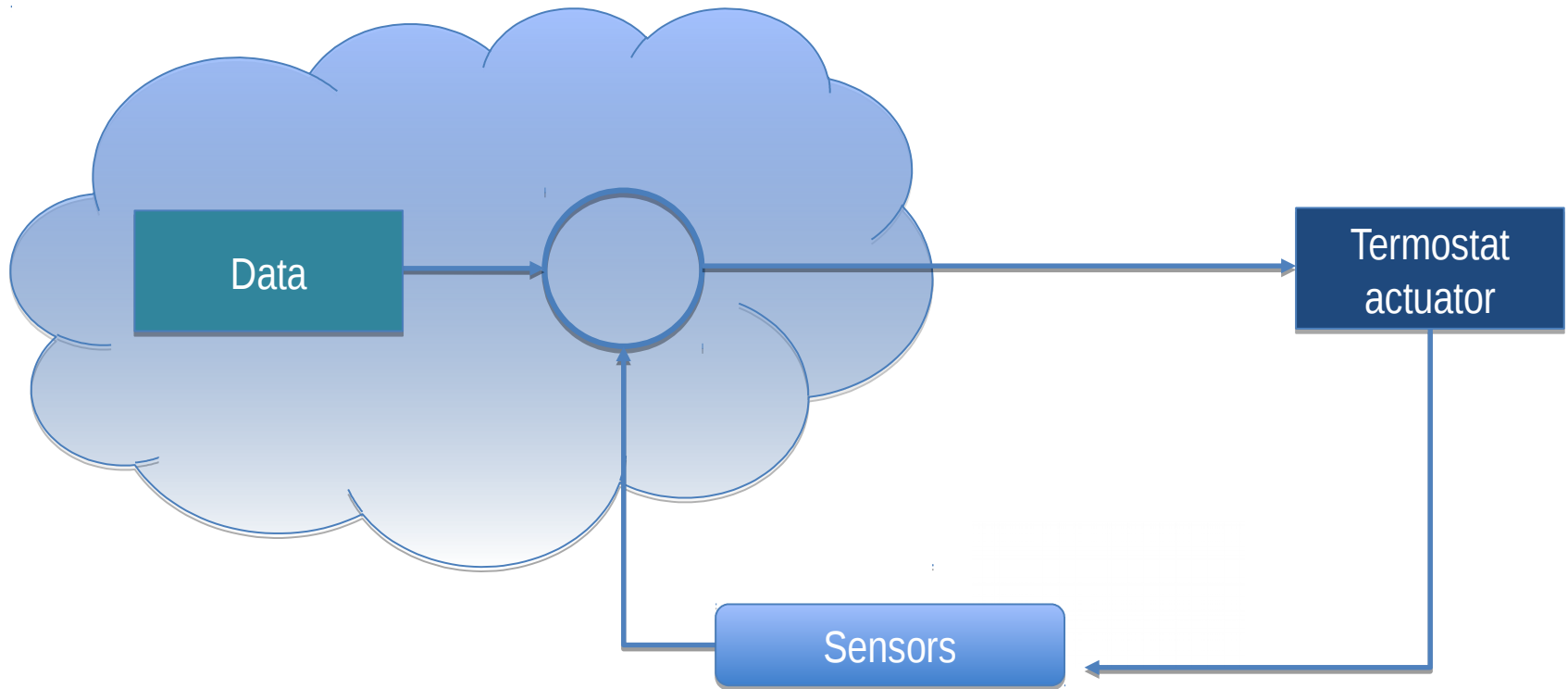
# Lab testing ....



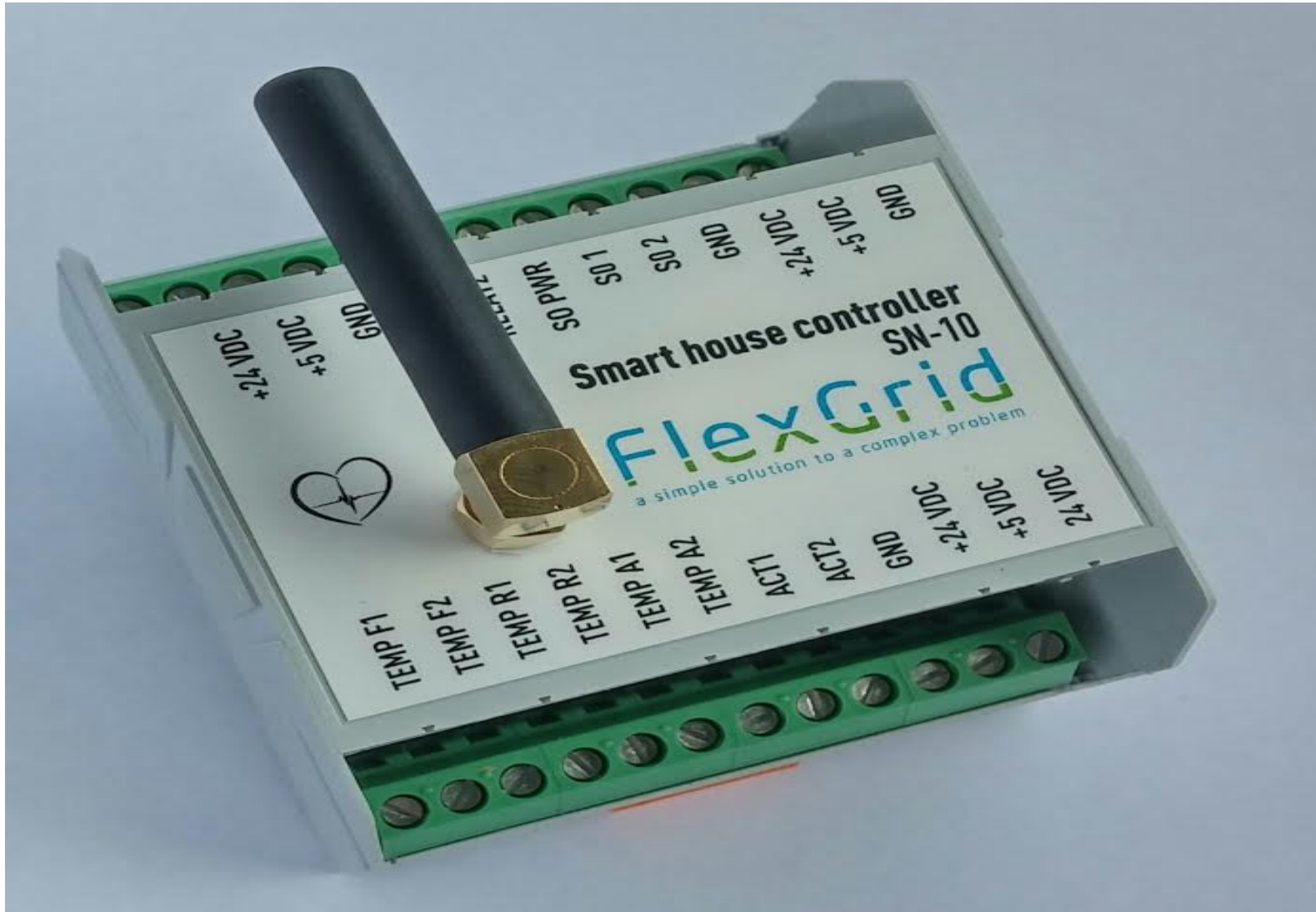


# SE-OS

## Control loop design – **logical drawing**



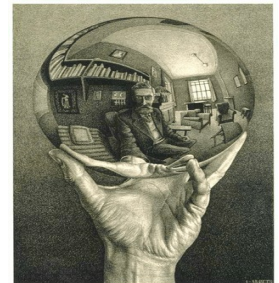
# SN-10 Smart House Prototype





# SE-OS Characteristics

- '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



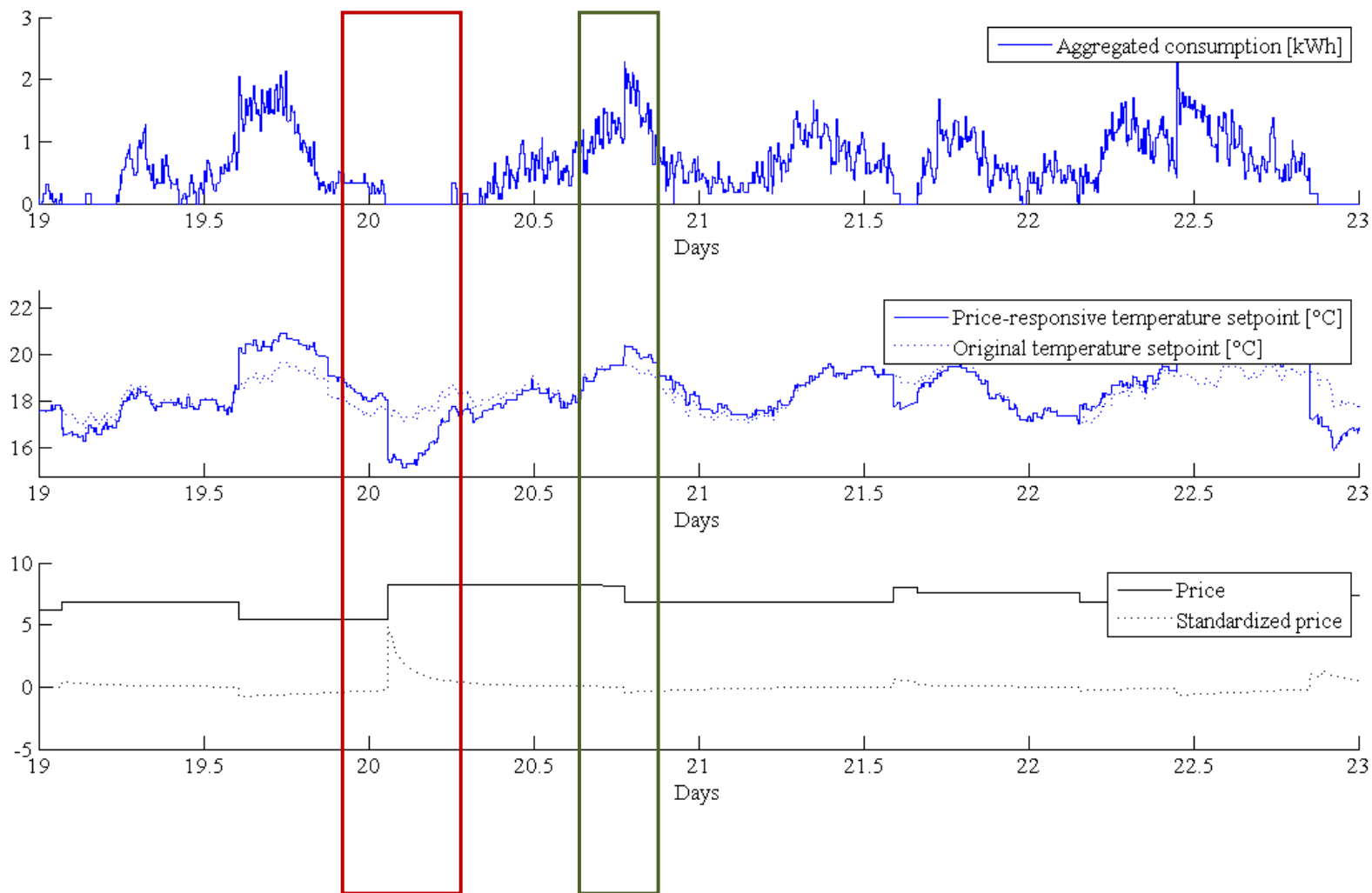
## Case study No. 1

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



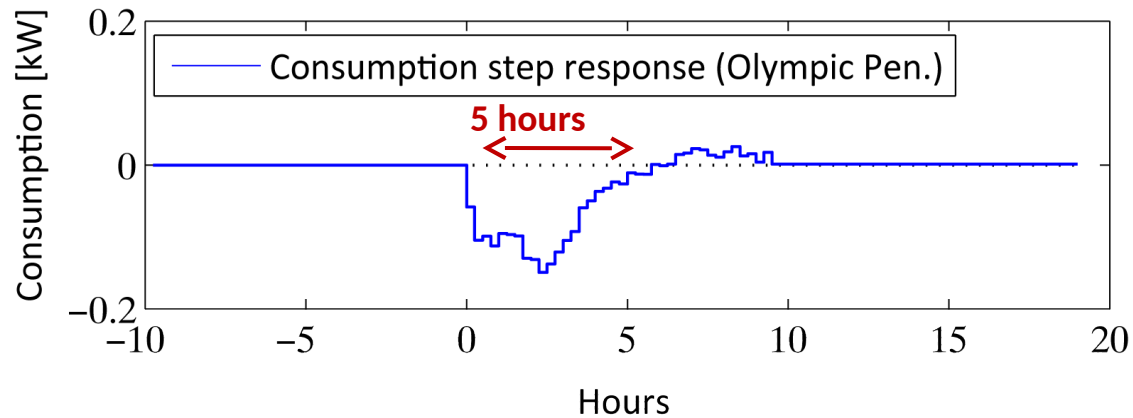


# Aggregation (over 20 houses)



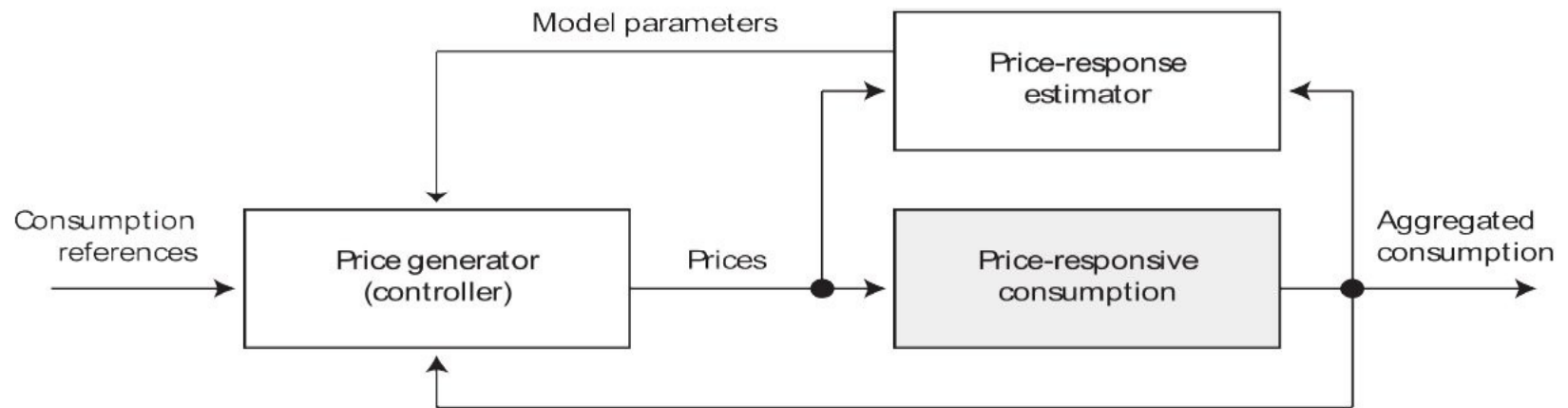
# Non-parametric Response on Price Step Change

## Olympic Peninsula





# Control of Energy Consumption

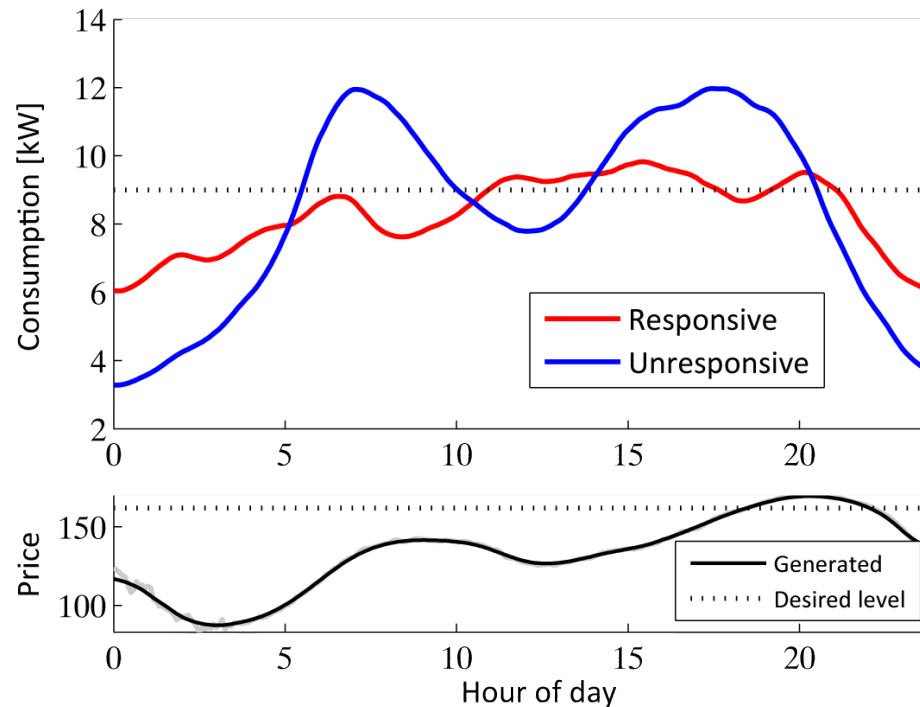




# Control performance

Considerable **reduction** in peak consumption

Mean daily consumption shift



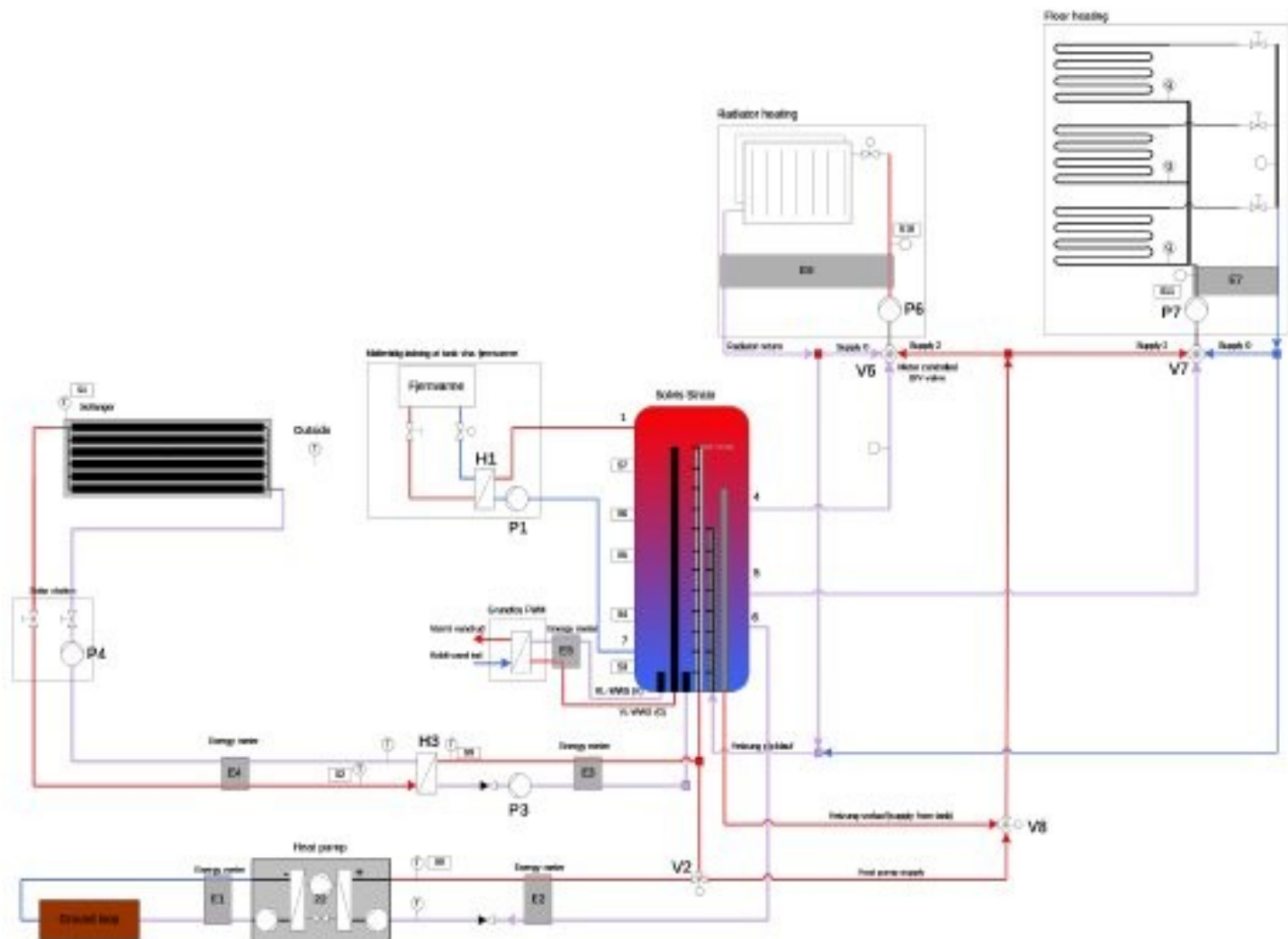
## Case study No. 2

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



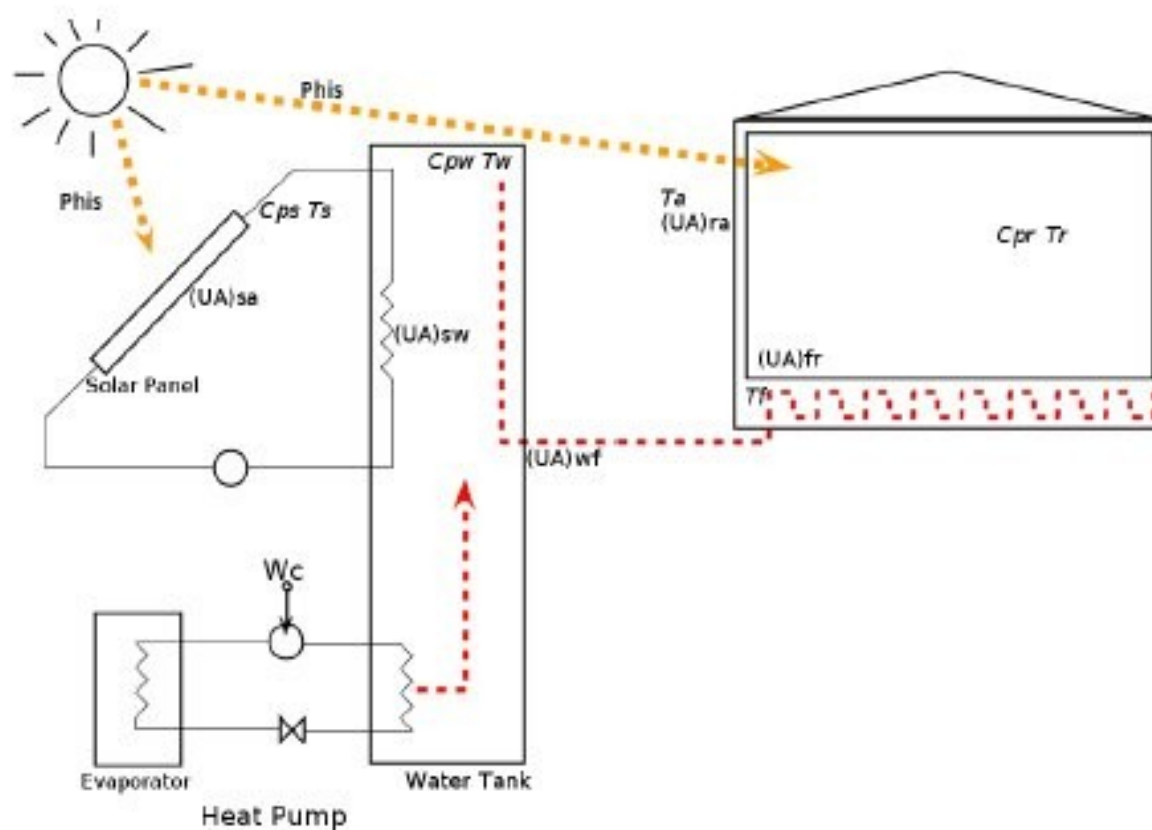
# Grundfos Case Study

## 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:

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

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

$$y_k = Cx_k \quad k = 1, 2, \dots, N \quad (4c)$$

$$u_{\min} \leq u_k \leq u_{\max} \quad k = 0, 1, \dots, N-1 \quad (4d)$$

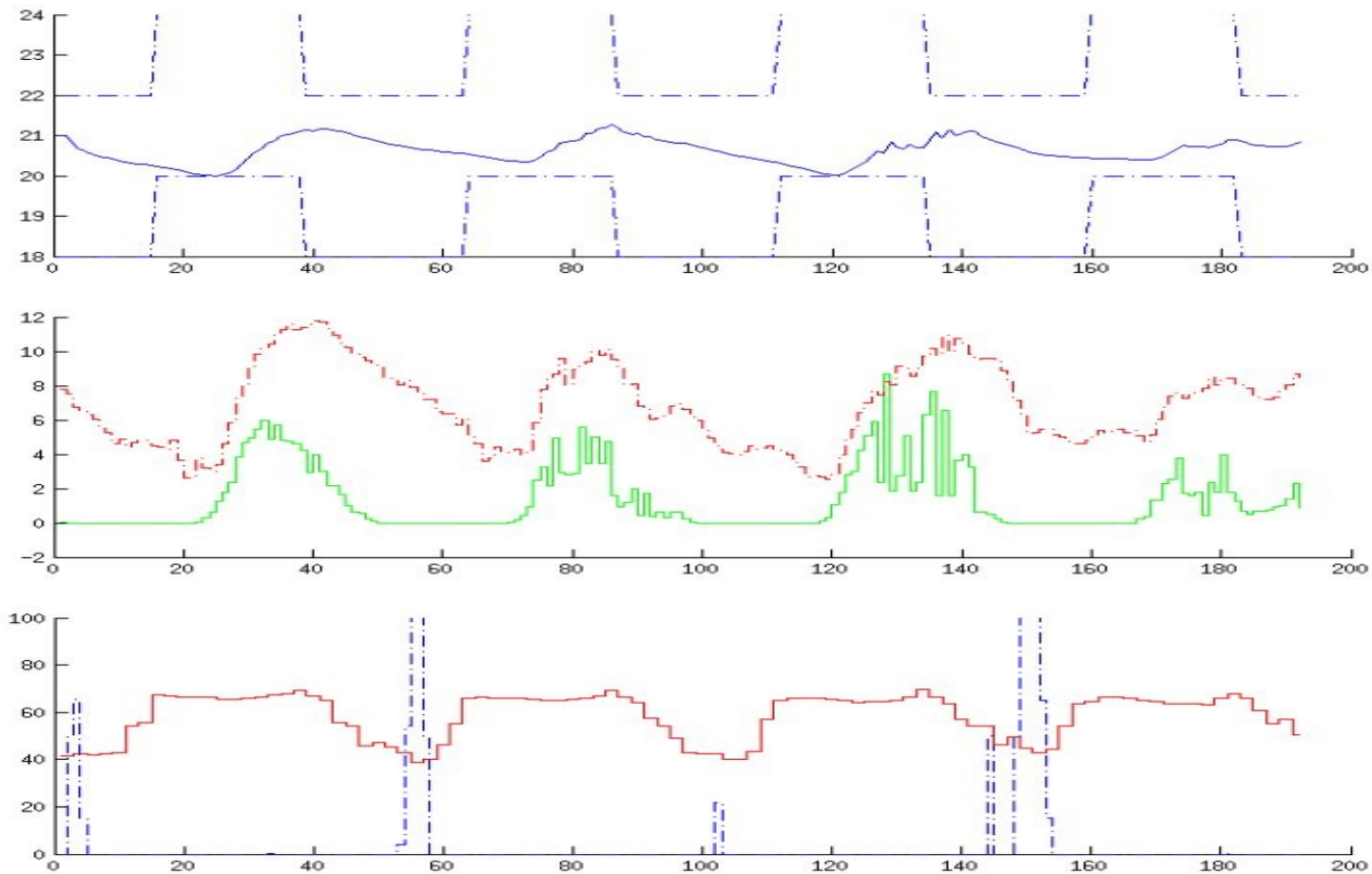
$$\Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max} \quad k = 0, 1, \dots, N-1 \quad (4e)$$

$$y_{\min} \leq y_k \leq y_{\max} \quad k = 0, 1, \dots, N \quad (4f)$$





# EMPC for heat pump with solar collector (savings 35 pct)




## Case study No. 3


# Control of heat pumps for swimming pools (CO<sub>2</sub> minimization)




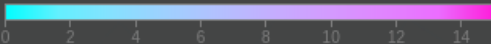
# Live CO2 emissions of the European electricity consumption

This shows in real-time where your electricity comes from and how much CO2 was emitted to produce it.



We take into account electricity imports and exports  between countries.

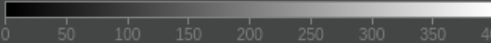
*Tip: Click on a country to start exploring *

 Wind power potential (m/s)  $\approx 3$






0 2 4 6 8 10 12 14

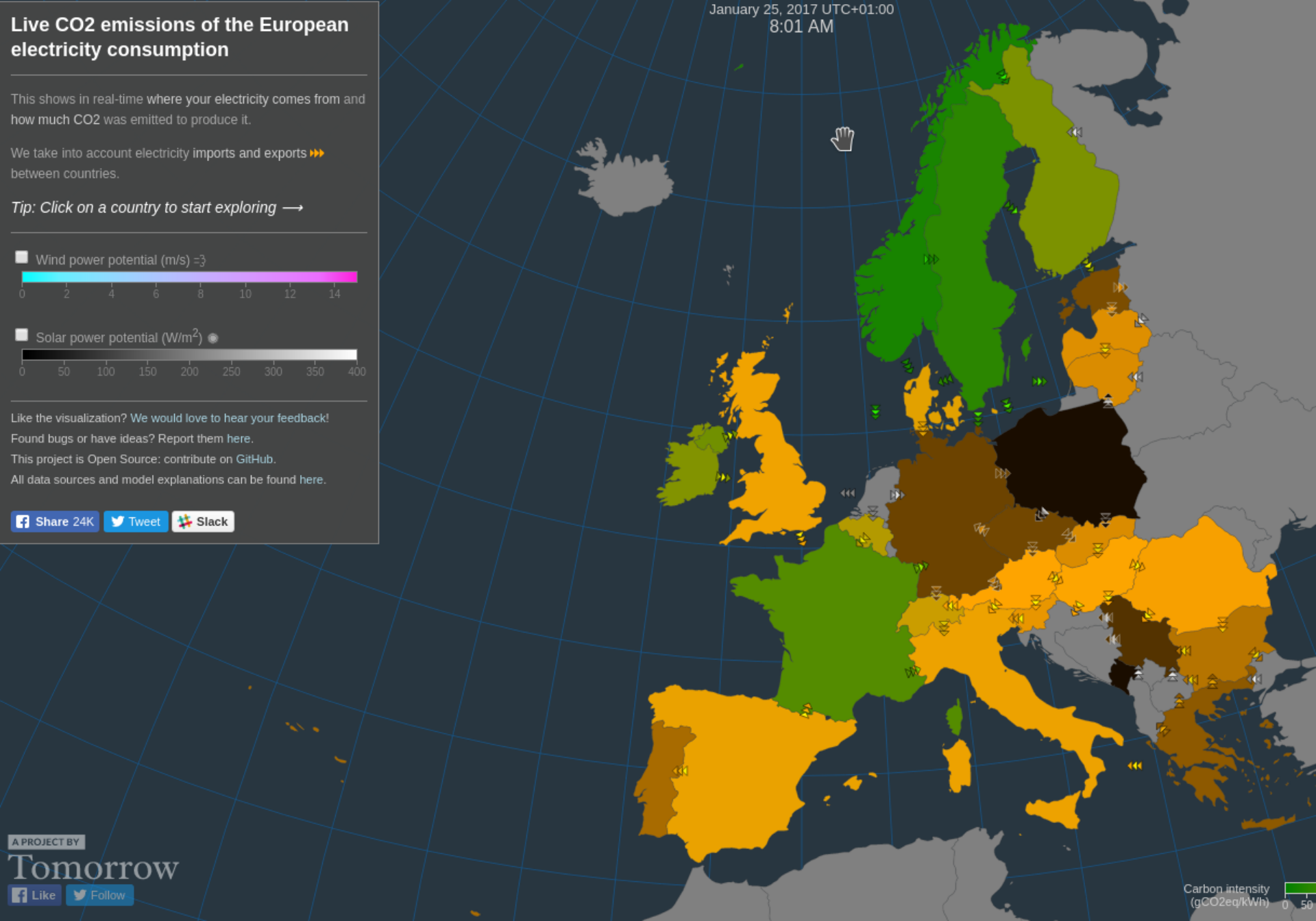
 Solar power potential (W/m<sup>2</sup>) 



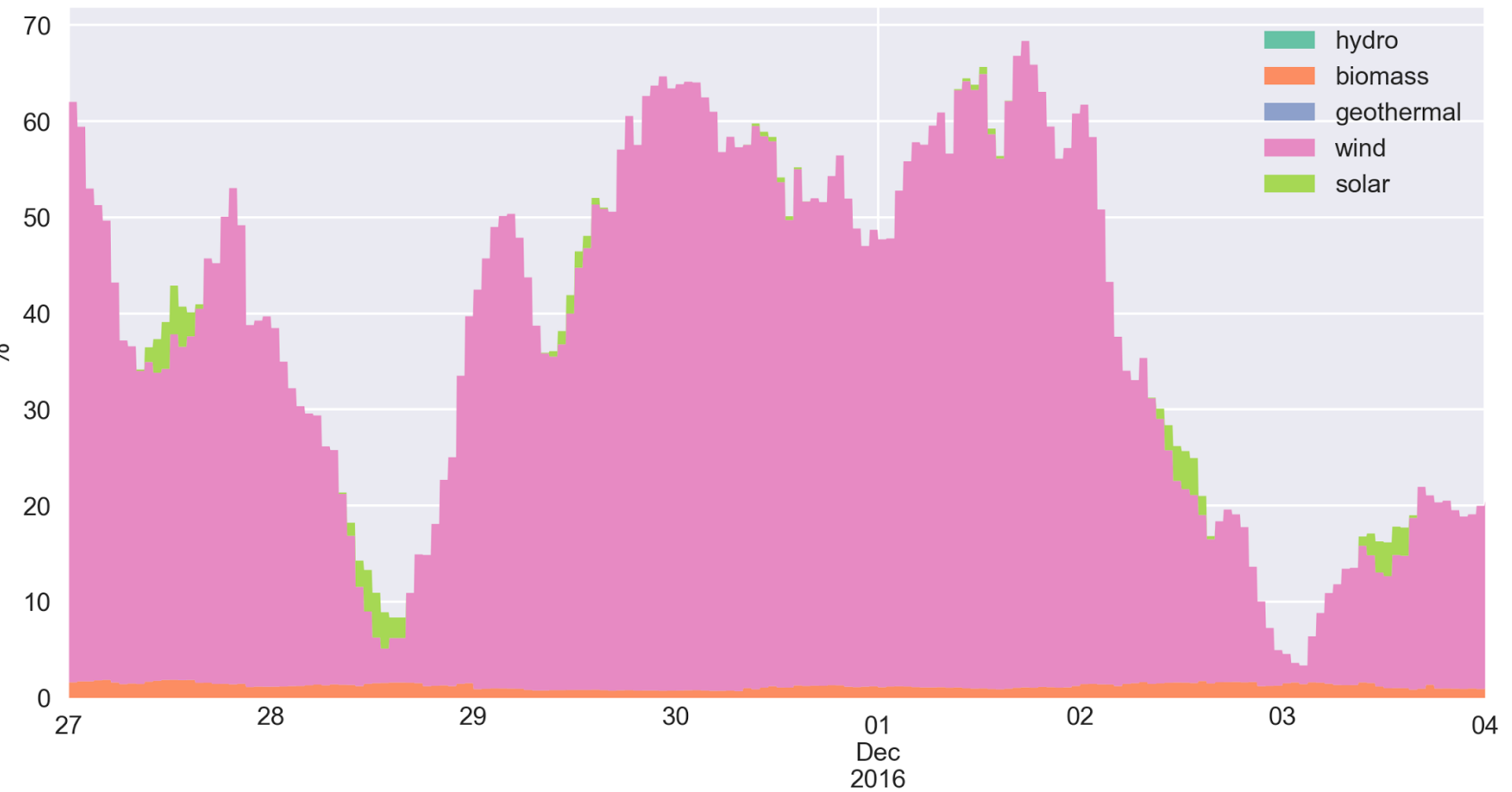
0 50 100 150 200 250 300 350 400

Like the visualization? We would love to hear your feedback!  
Found bugs or have ideas? Report them here.  
This project is Open Source: contribute on GitHub.  
All data sources and model explanations can be found here.

 Share 24K  Tweet  Slack



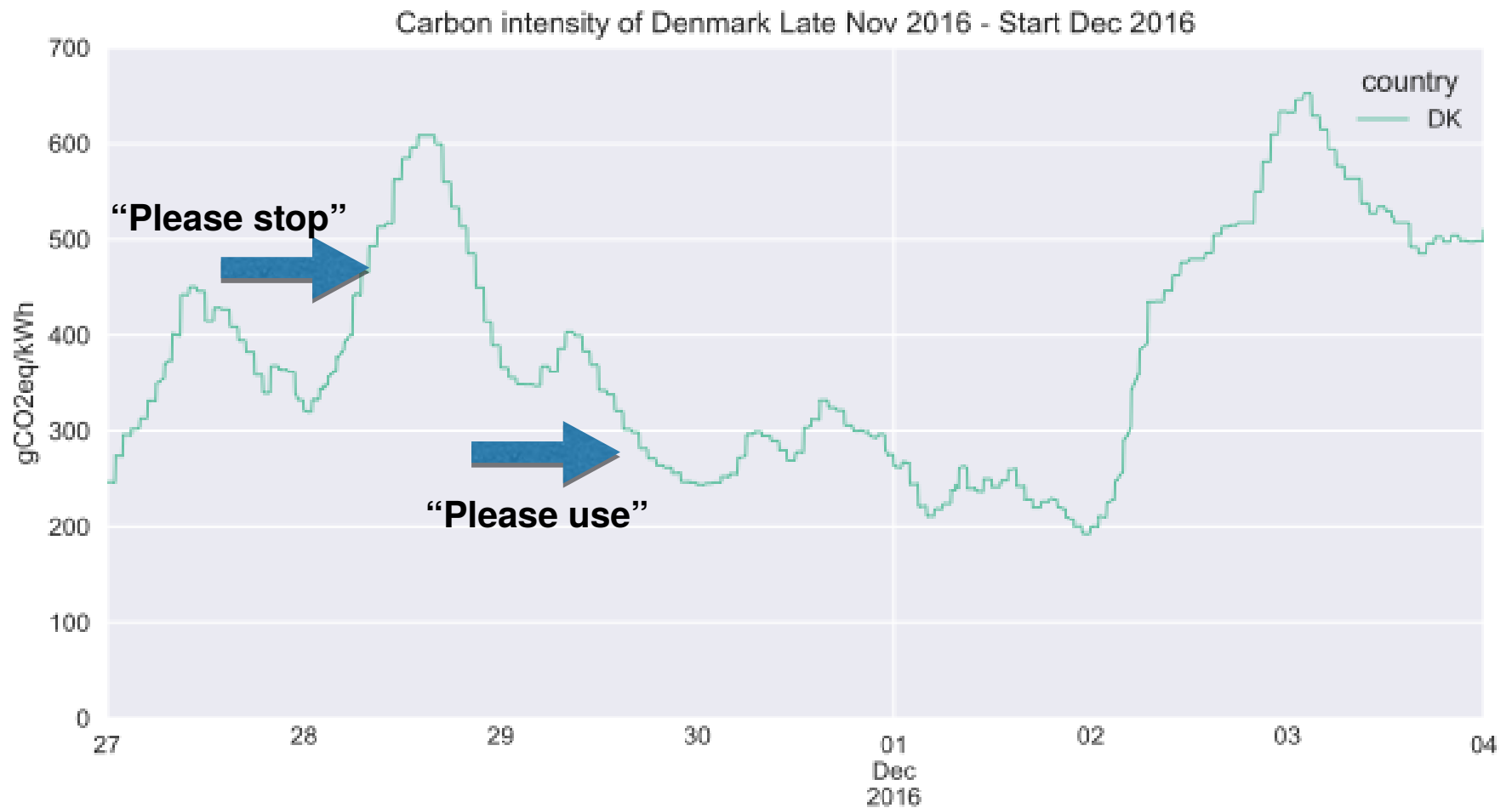
Share of electricity originating from renewables in Denmark Late Nov 2016 - Start Dec 2016



Source: [pro.electricitymap.org](http://pro.electricitymap.org)





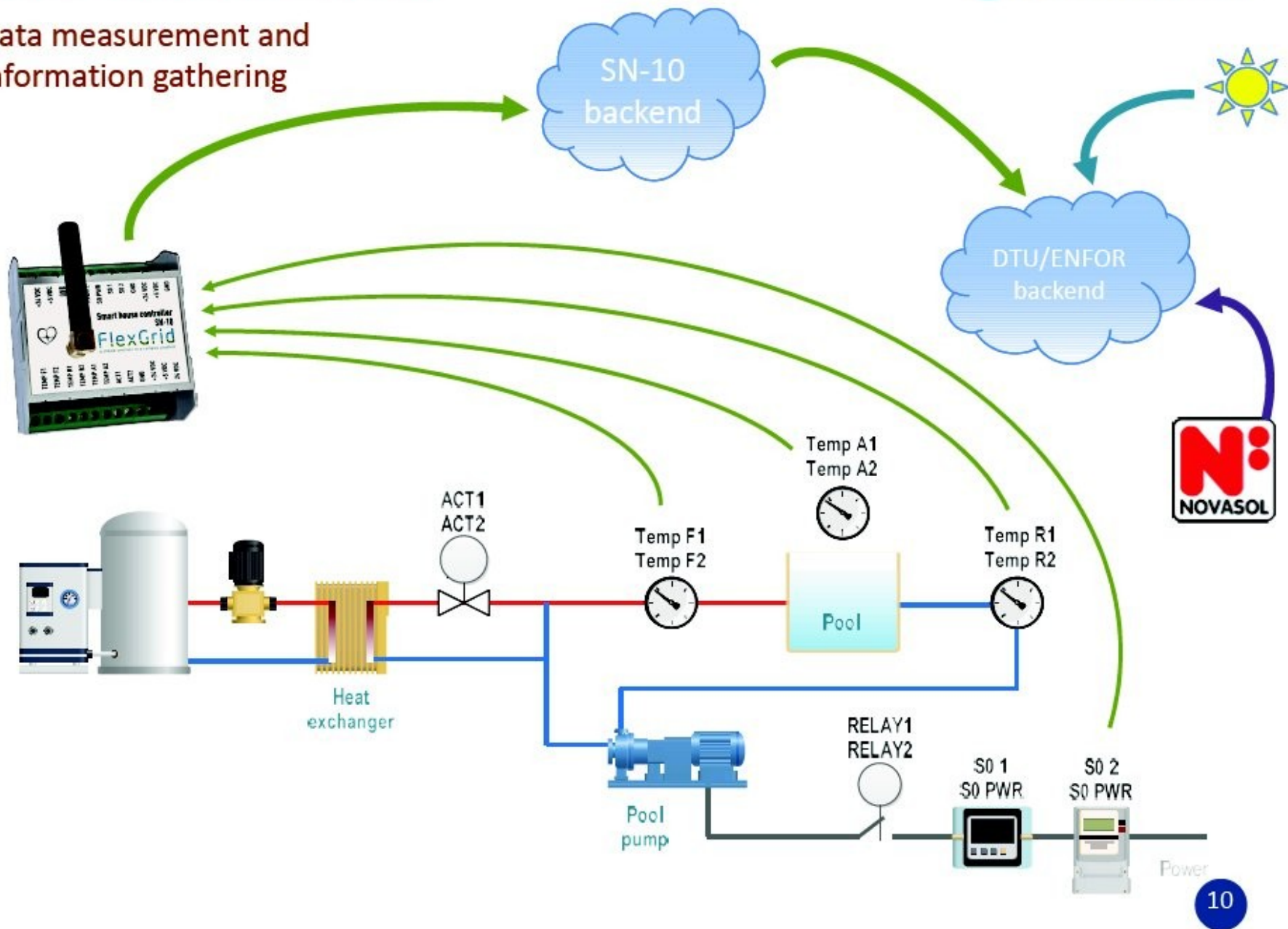


Source: [pro.electricitymap.org](http://pro.electricitymap.org)



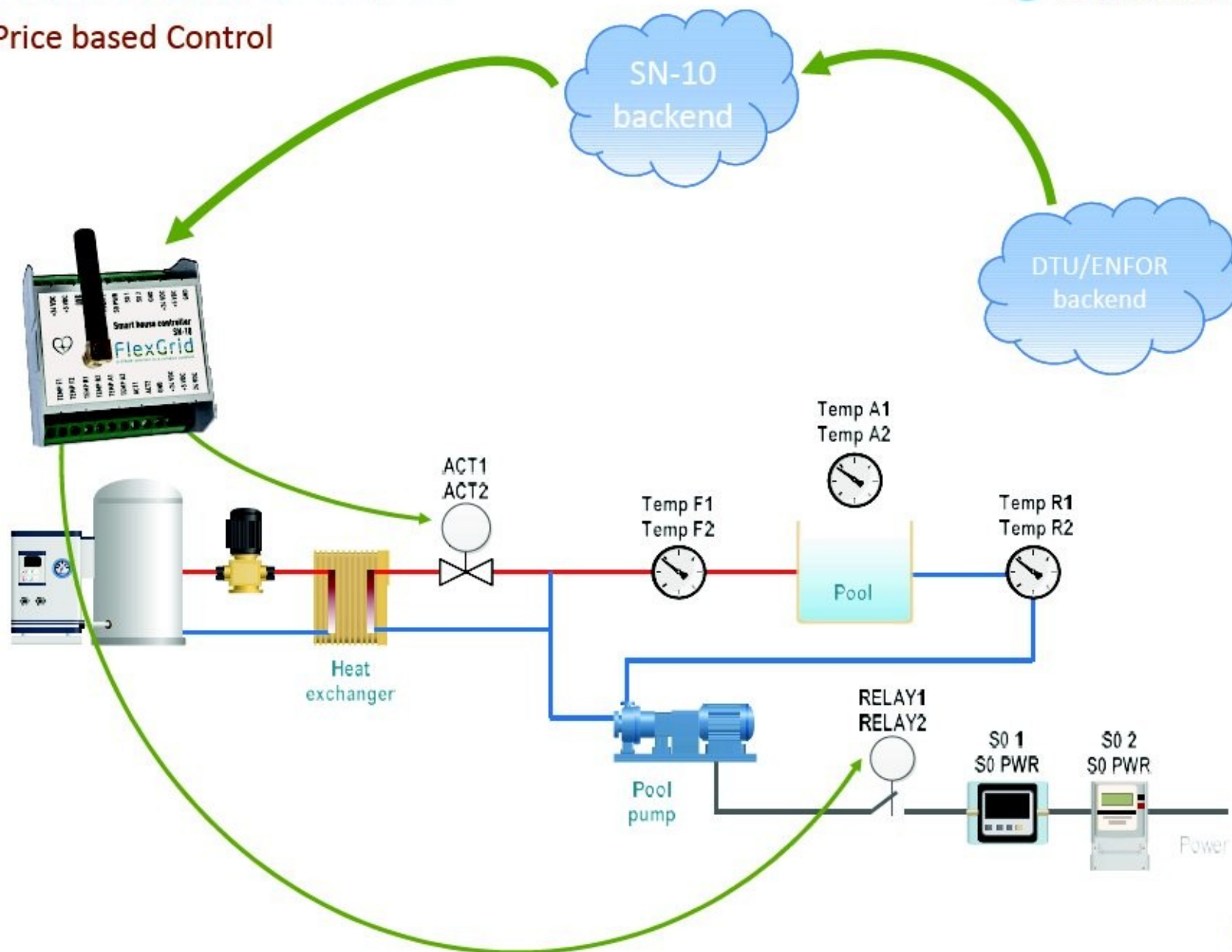
# How does it work?

Data measurement and  
information gathering




# How does it work?

## Price based Control



# Example: CO2-based control

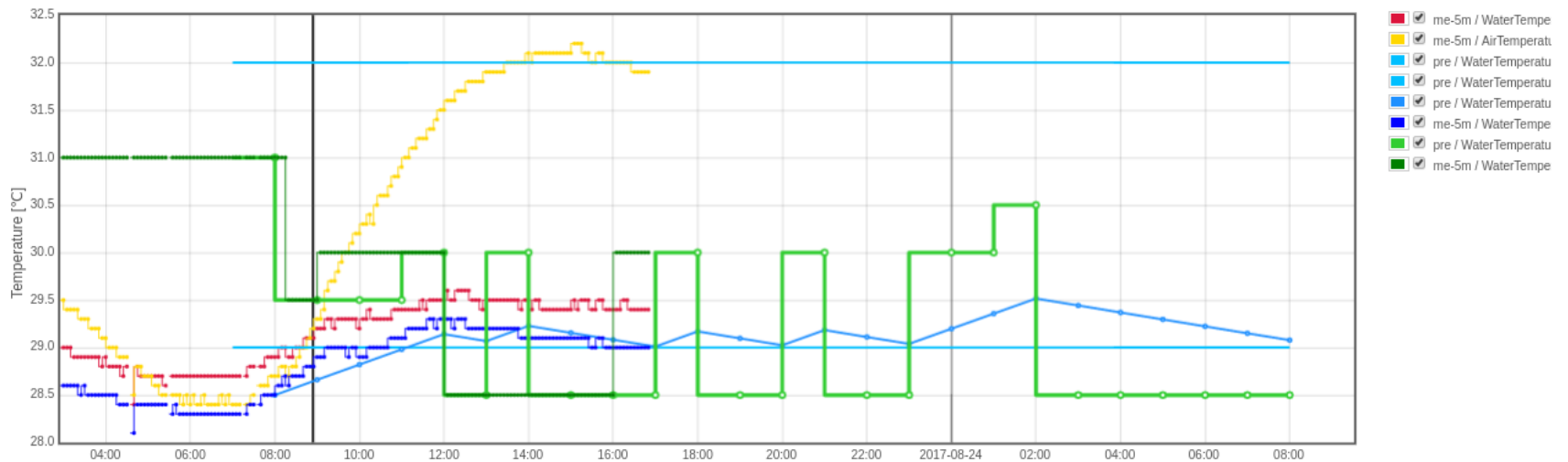
ENFOR  SmartNet

SmartNet > D7811

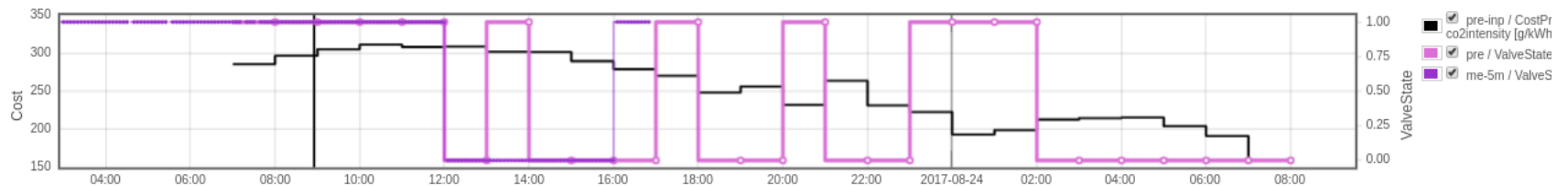
Measurements Weather forecast Booking plan **Controller** Temperature limits

## D7811 Controller

Cost: co2intensity [g/kWh]



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Demo projects

Software solutions

Work Packages

Partners

Events

Communications

Publications

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Contacts



## Software solutions

### Software for combined physical and statistical modelling

Continuous Time Stochastic Modelling (CTSM) is a software package for modelling and simulation of combined physical and statistical models. You find a technical description and the software at [CTSM.info](http://CTSM.info).

### Software for Model Predictive Control

HPMPC is a toolbox for High-Performance implementation of solvers for Model Predictive Control (MPC). It contains routines for fast solution of MPC and MHE (Moving Horizon Estimation) problems on embedded hardware. The software is available at [GitHub](https://github.com).

#### Latest news

Ambassador Louise Bang Jespersen visited CITIES, October 29th 2015

CITIES Korean International Workshop – KIER, Daejeon, Korea, October 22nd 2015

Workshop on Mathematical Sciences Collaboration in Energy Systems Integration – DTU,

# Further Aspects





# Characteristics

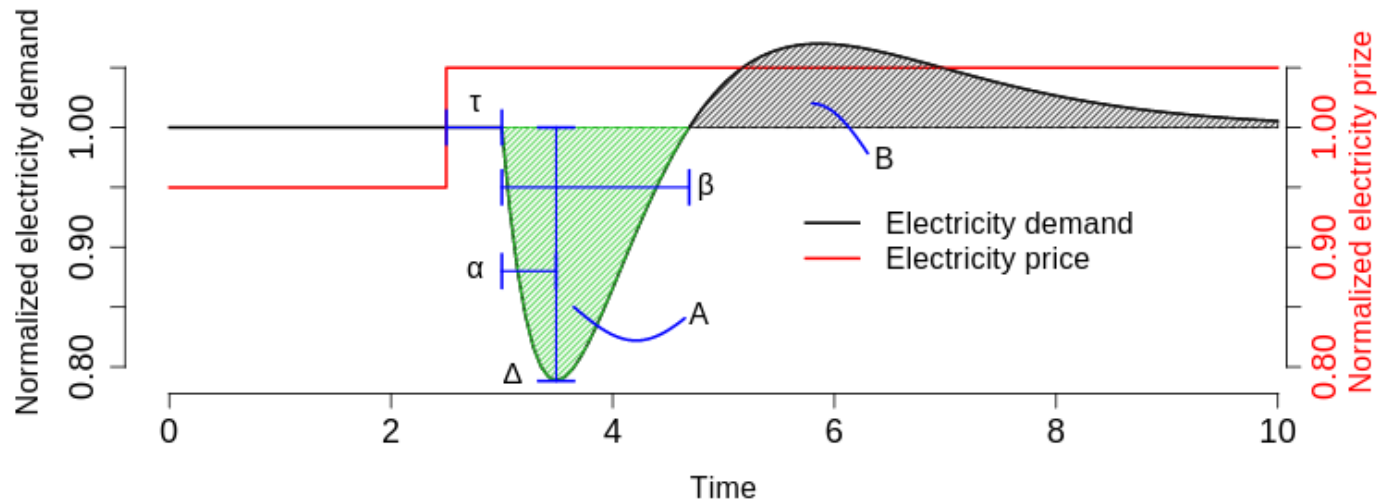


Figure 4: Six characteristics of the demand response to a step increase in electricity price.  $\tau$ : The delay from adjusting the electricity price and seeing an effect on the electricity demand, equal to approximately 0.5 here.  $\Delta$ : The maximum change in demand following the price change, in this case close to 0.2.  $\alpha$ : The time it takes from the change in demand starts until it reaches the lowest level, approximately equal to 0.5 here.  $\beta$ : 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.





# Labelling proposal

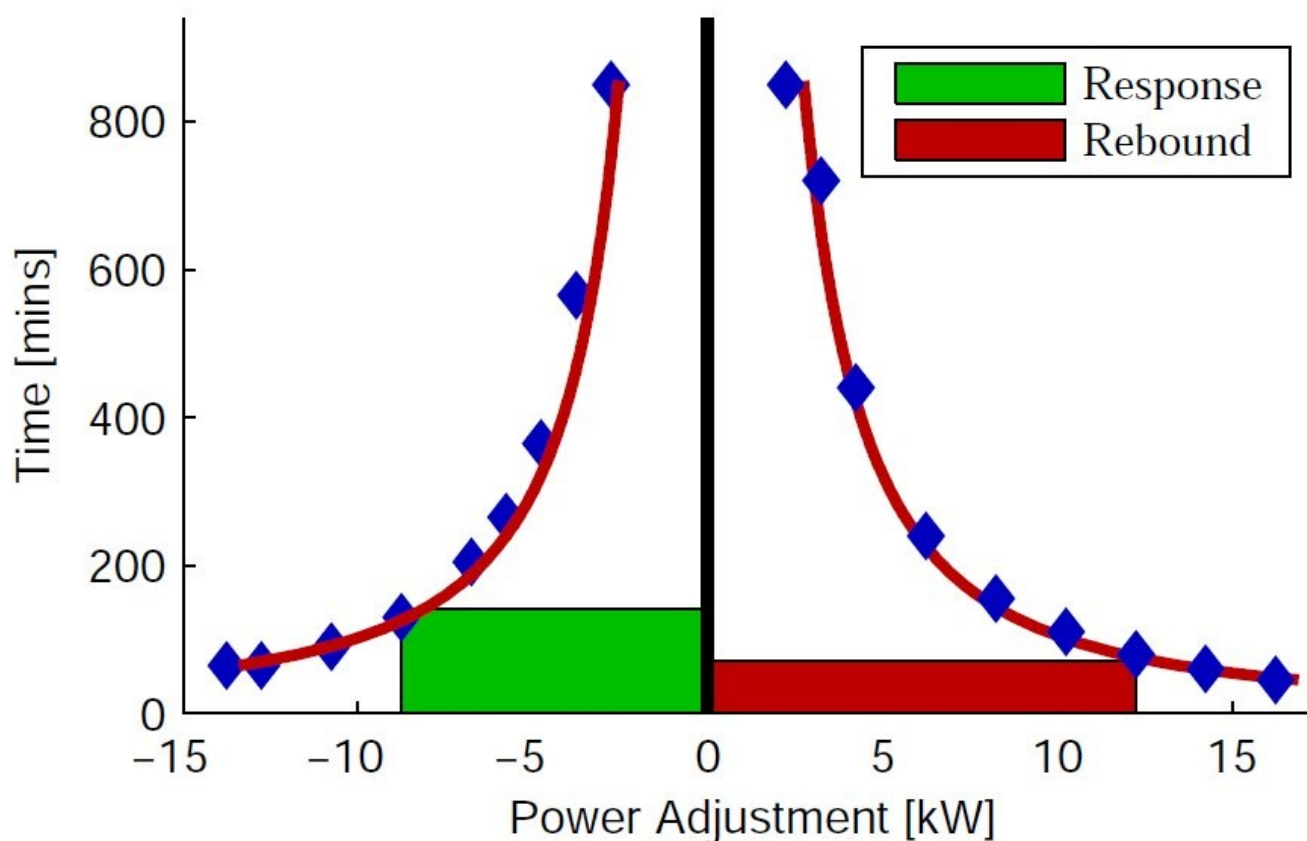
## for energy, price and emission based labelling

The test consists of the following steps:

1. Let  $\lambda_t$  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  $\lambda_t$  could just represent ones desire to reduce electricity demand at time  $t$ .

# Flexibility Represented by Saturation Curves (for market integration using block bids)

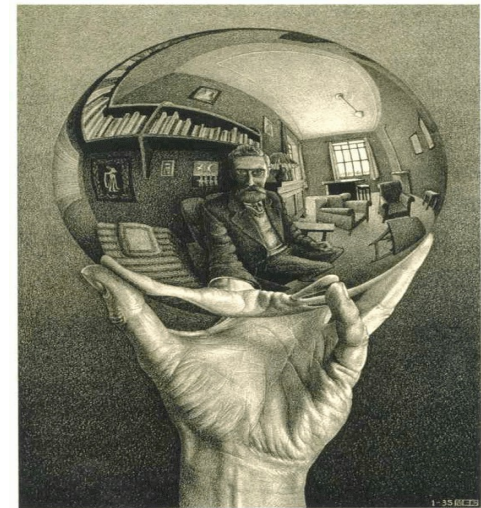




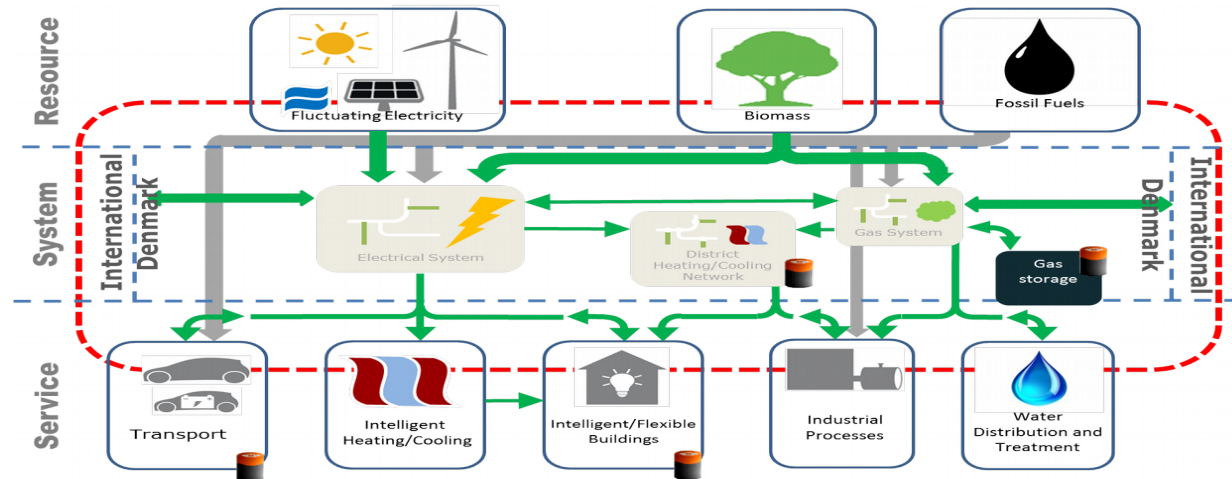
# Understanding Power/Energy Flexibility

## Some Demo Projects in CITIES:

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



# (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, 5-10 hours ahead
- Buildings with local water storage can provide storage up to, say, 2-12 hours ahead
- District heating/cooling systems can provide storage up to 1-3 days ahead
- DH systems with thermal solar collectors can often provide seasonal storage solutions
- Gas systems can provide seasonal/long term storage solutions



# Summary



- A procedure for data intelligent control of power load, 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 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).
- Markets and pricing principles need to be reconsidered; we see an advantage of having a physical link to the mechanism (eg. nodal pricing, capacity markets)





# 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 stochastic 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 framework 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.



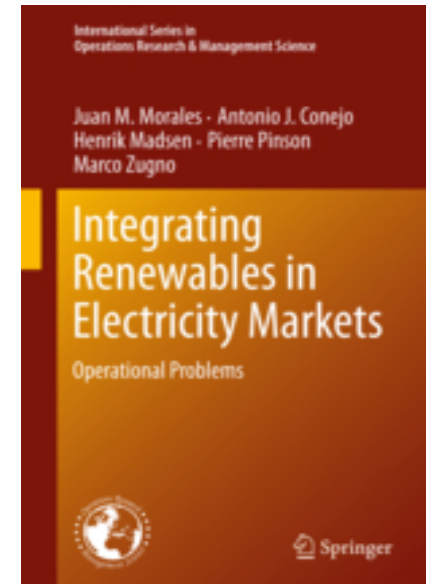
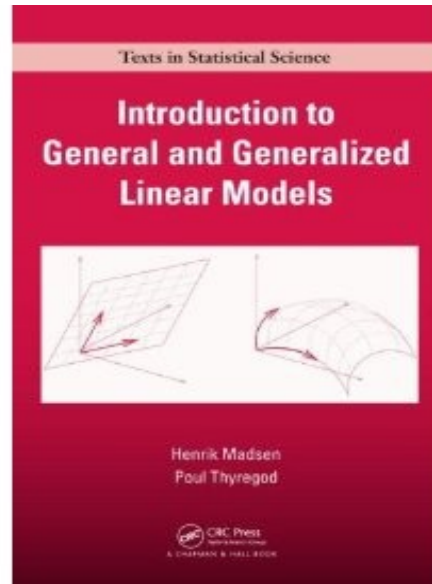
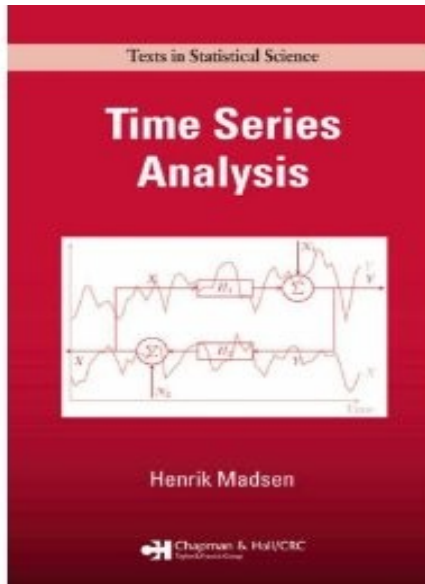


## Some references (cont.)



- 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.

## Some 'randomly picked' books on modeling ....



# For more information ...

See for instance

[www.smart-cities-centre.org](http://www.smart-cities-centre.org)

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