Methodologies for Controlling the Electricity Load in Future Intelligent and Integrated Energy Systems

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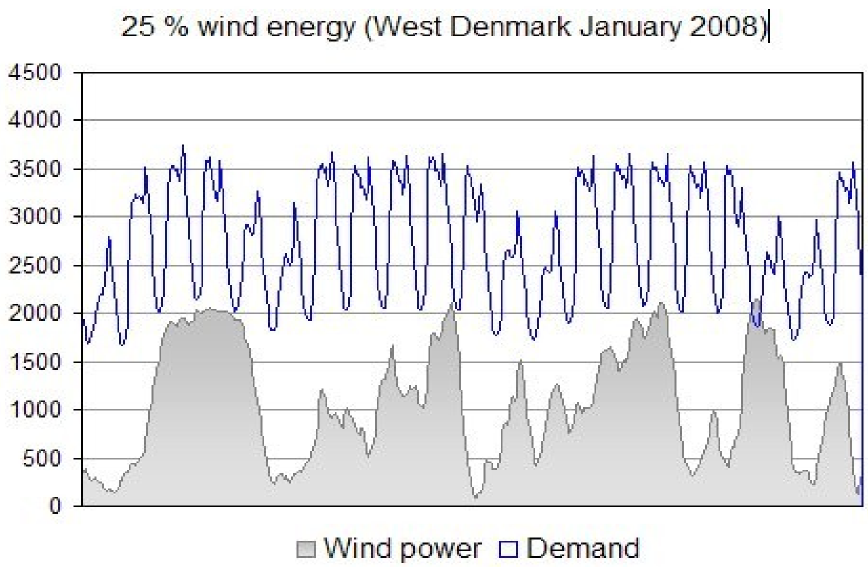
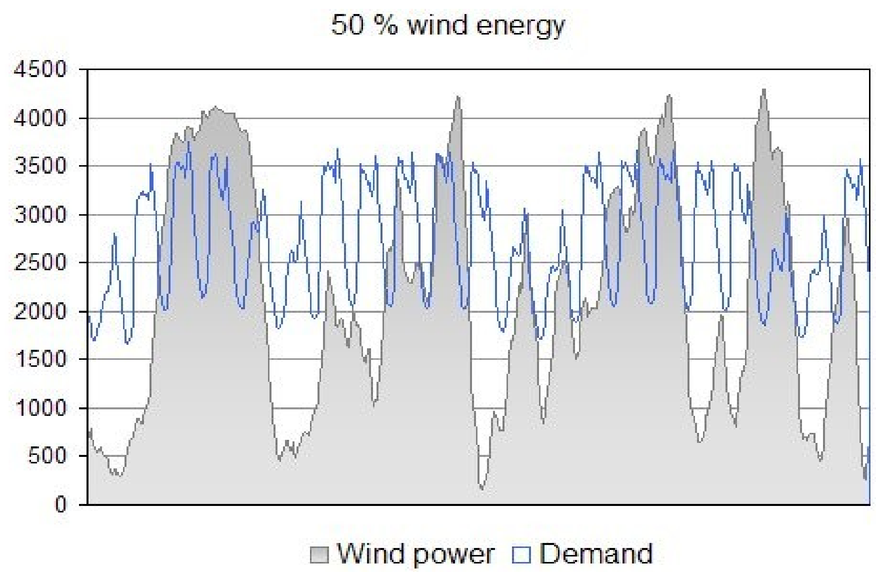
The Danish Wind Power Case

…. balancing of the power system



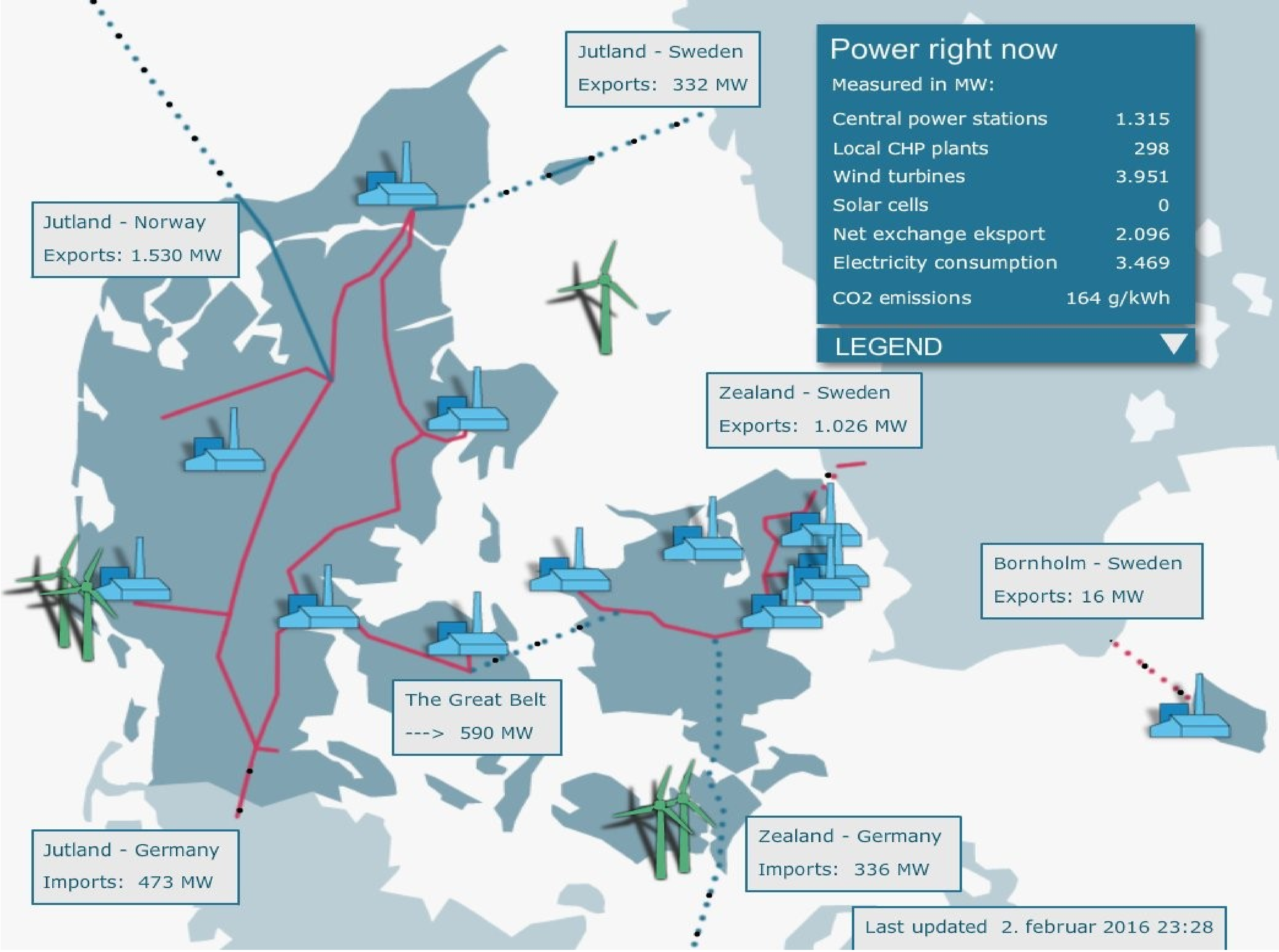


In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

In 2015 more than 42 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.

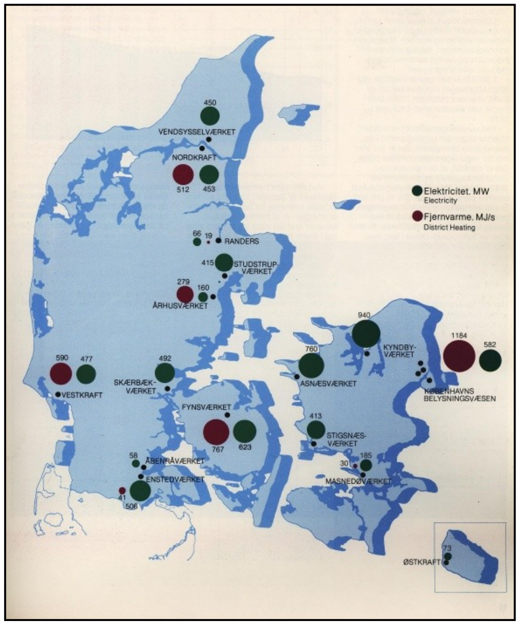
July 10th, 2015 more than 140 pct of the power load was covered by wind power

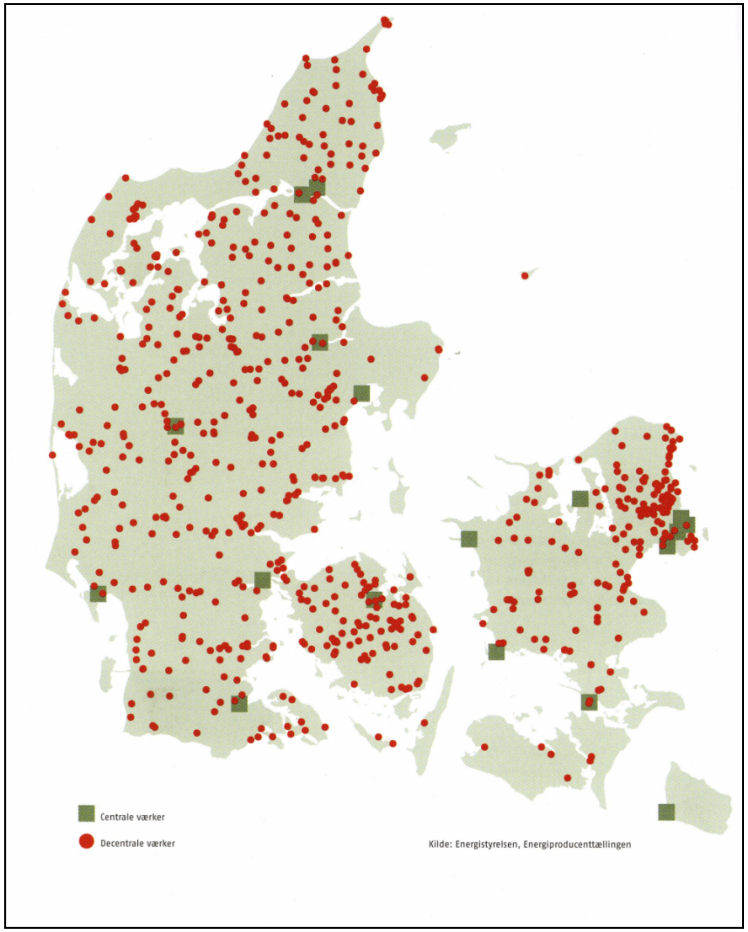

Jutland - Sweden
Exports: 332 MW
Power right now
Measured in MW:
Central power stations 1.315
Local CHP plants 298
Wind turbines 3.951
Solar cells 0
Net exchange eksport 2.096
Electricity consumption 3.469
CO2 emissions 164 g/kWh
LEGEND
Jutland - Norway
Exports: 1.530 MW
Zealand - Sweden
Exports: 1.026 MW
Bornholm - Sweden
Exports: 16 MW
The Great Belt
---> 590 MW
Jutland - Germany
Imports: 473 MW
Zealand - Germany
Imports: 336 MW
Last updated 2. februar 2016 23:28

From large central plants to Combined Heat and Power (CHP) production

1980

Today

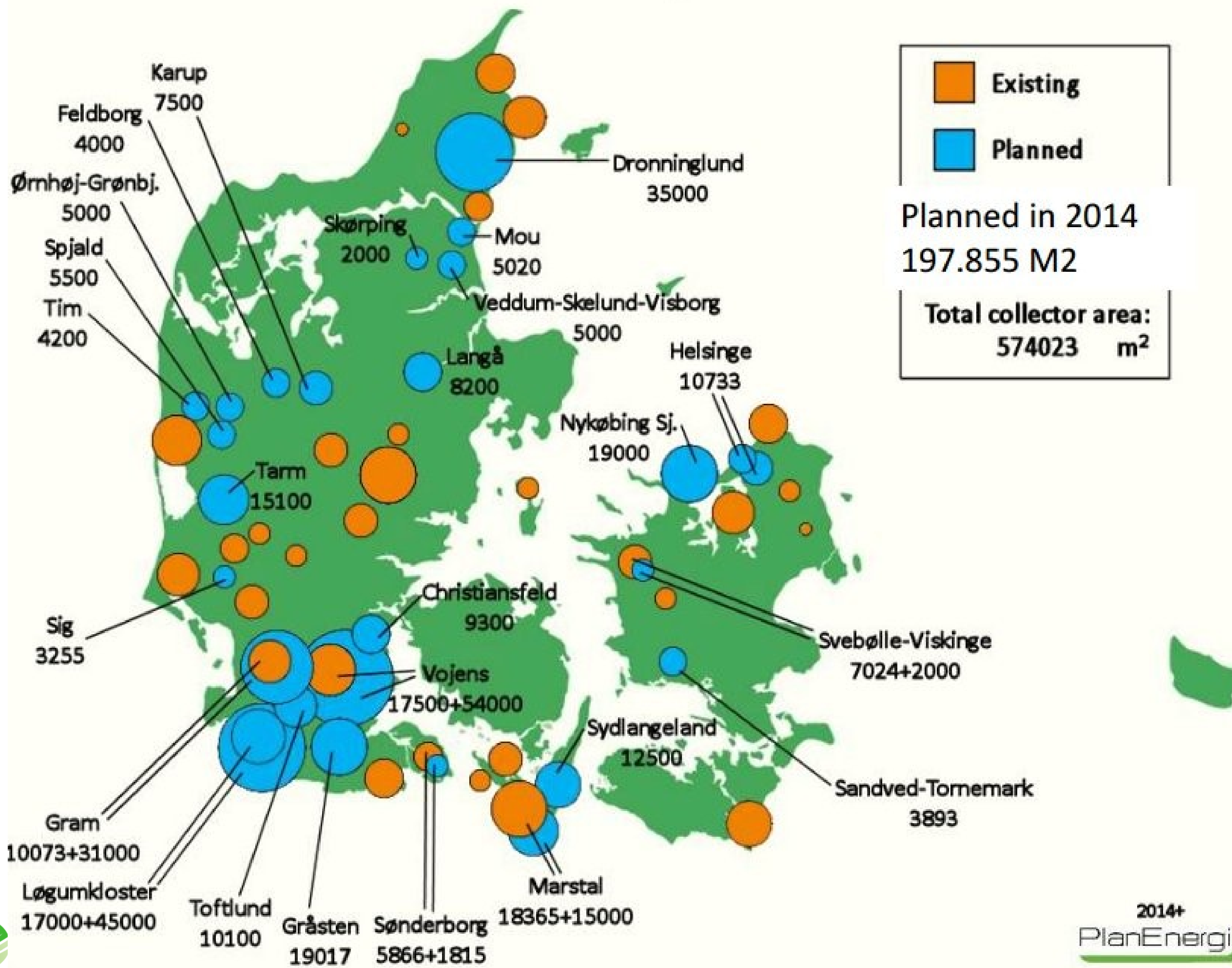




*From a few big power plants to many small **combined heat and power** plants – however most of them based on coal*

DK has enough excess heat to cover the entire need for heating .... but ...

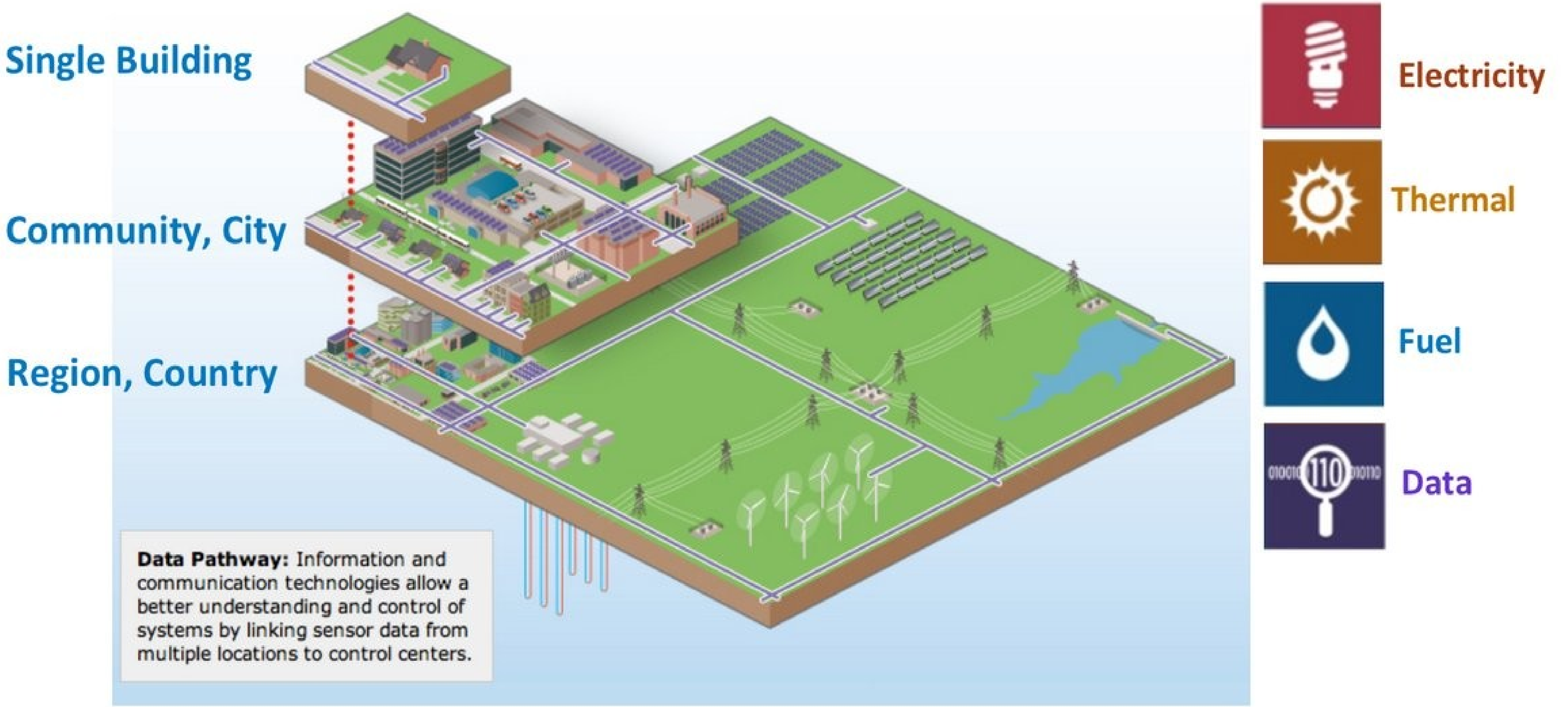
Solar district heating in Denmark



Planned in 2014
197.855 M2

Energy Systems Integration

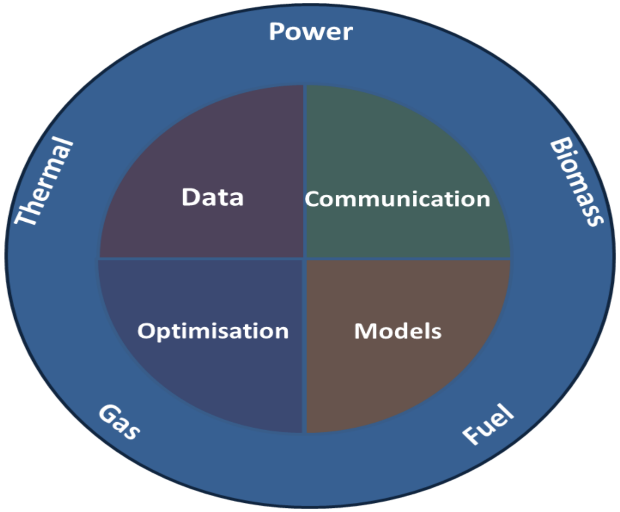
Energy system integration (ESI) = the process of optimizing energy systems across multiple pathways and scales



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 .



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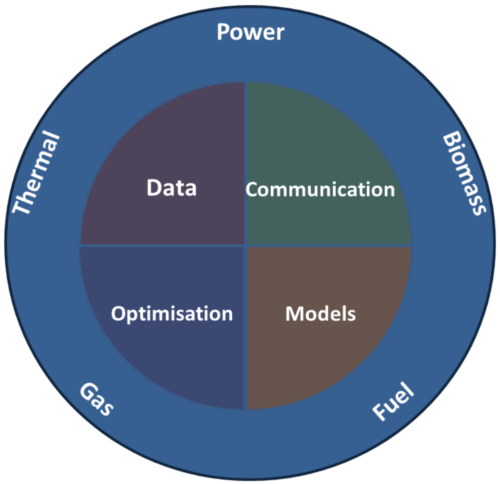
Energy Systems Integration



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 CO2 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.)

DTU

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:

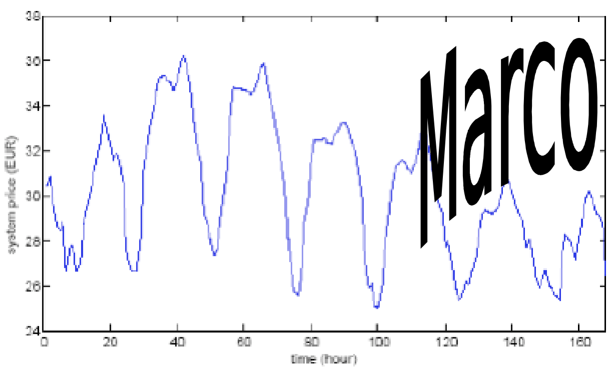
- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy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

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



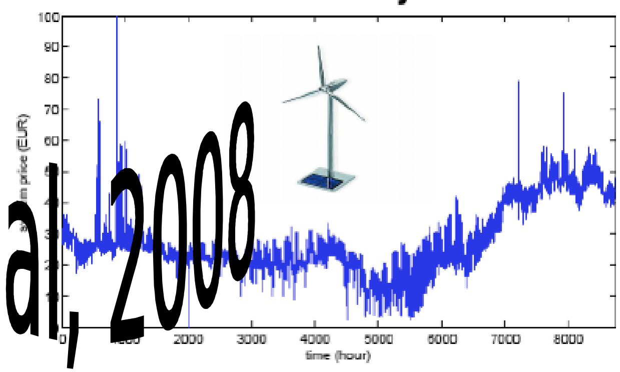
control theory provides ways of modeling the dynamics which is intrinsic in energy markets

↓

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

Marco Zugno et.al, 2008

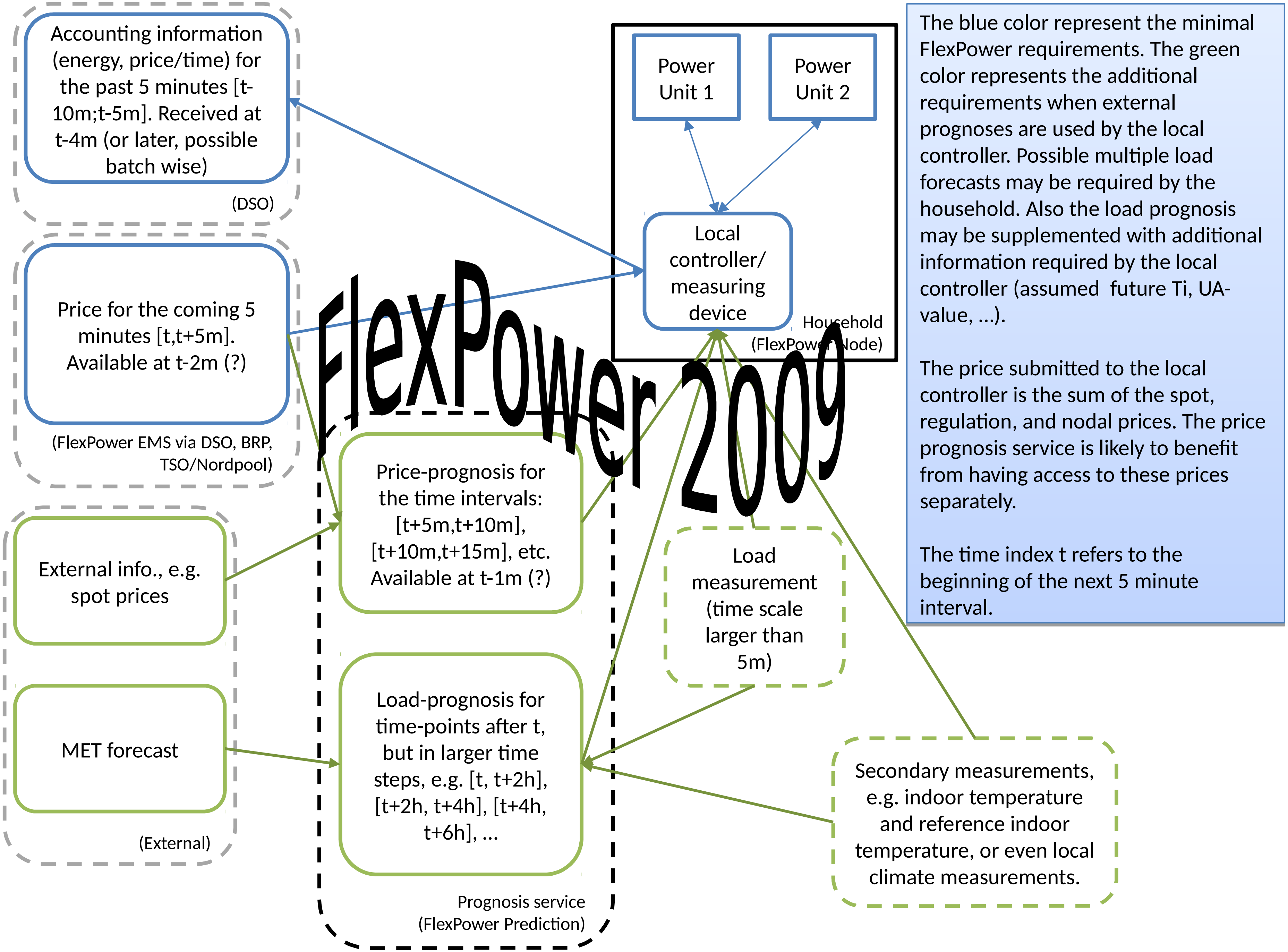
Uncertainty



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

↓

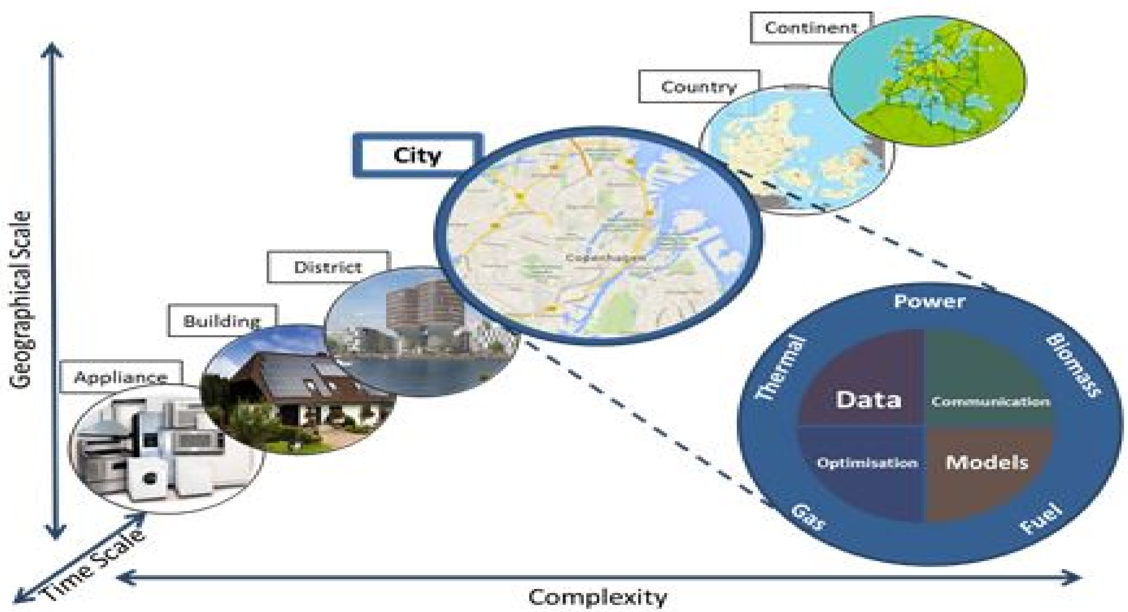
it is possible to develop bidding strategies which are optimal with respect to the stochastic characteristics of the market



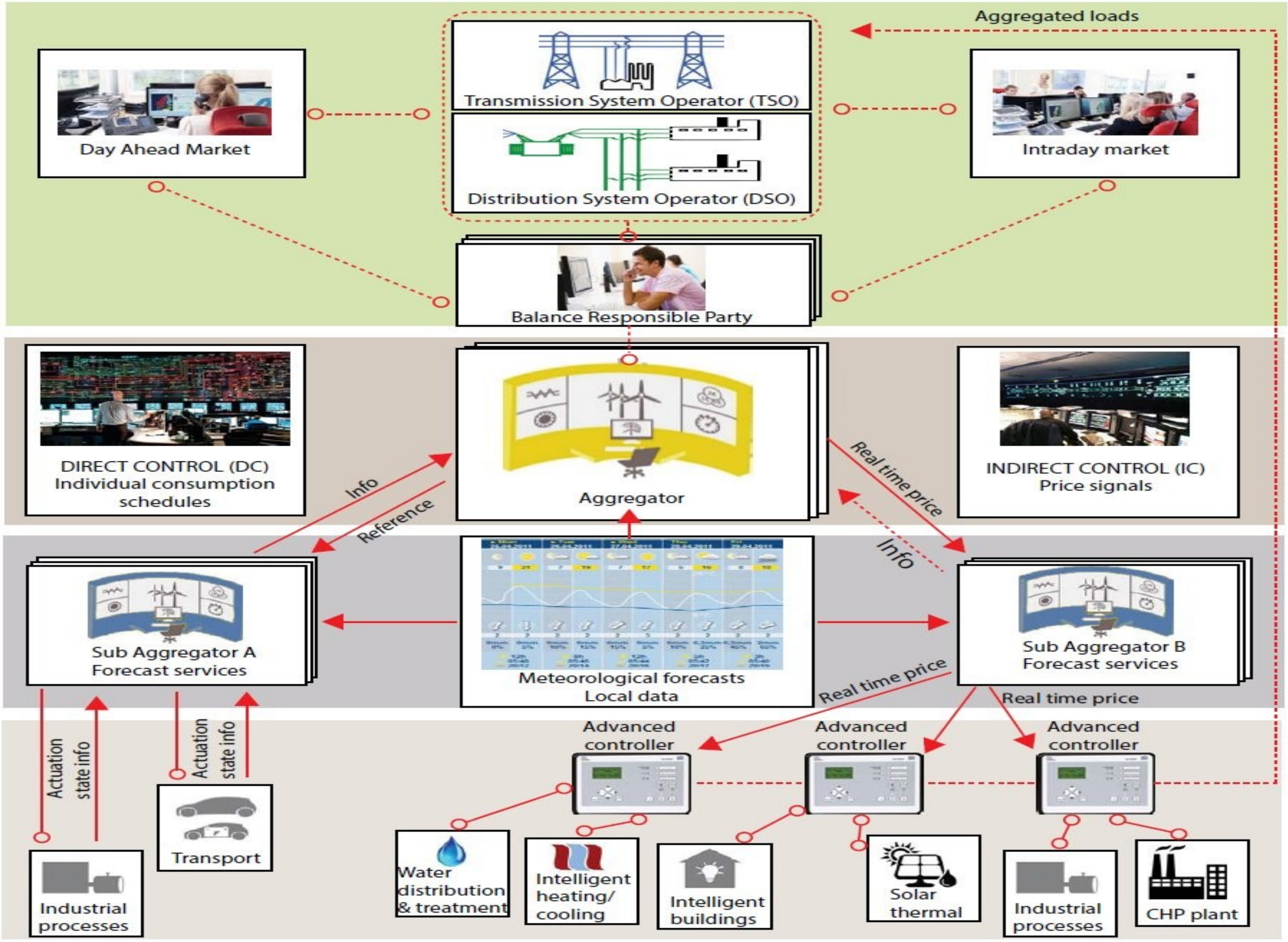
Accounting information (energy, price/time) for the past 5 minutes [t-10m;t-5m]. Received at t-4m (or later, possible batch wise)
(DSO)
Price for the coming 5 minutes [t,t+5m]. Available at t-2m (?)
(FlexPower EMS via DSO, BRP, TSO/Nordpool)
External info., e.g. spot prices
MET forecast
(External)
Price-prognosis for the time intervals: [t+5m,t+10m], [t+10m,t+15m], etc. Available at t-1m (?)
Load-prognosis for time-points after t, but in larger time steps, e.g. [t, t+2h], [t+2h, t+4h], [t+4h, t+6h], …
Prognosis service (FlexPower Prediction)
Power Unit 1
Power Unit 2
Local controller/ measuring device
Household (FlexPower Node)
Load measurement (time scale larger than 5m)
Secondary measurements, e.g. indoor temperature and reference indoor temperature, or even local climate measurements.
FlexPower 2009
The blue color represent the minimal FlexPower requirements. The green color represents the additional requirements when external prognoses are used by the local controller. Possible multiple load forecasts may be required by the household. Also the load prognosis may be supplemented with additional information required by the local controller (assumed future Ti, UA-value, …).
The price submitted to the local controller is the sum of the spot, regulation, and nodal prices. The price prognosis service is likely to benefit from having access to these prices separately.
The time index t refers to the beginning of the next 5 minute interval.

Temporal and Spatial Scales

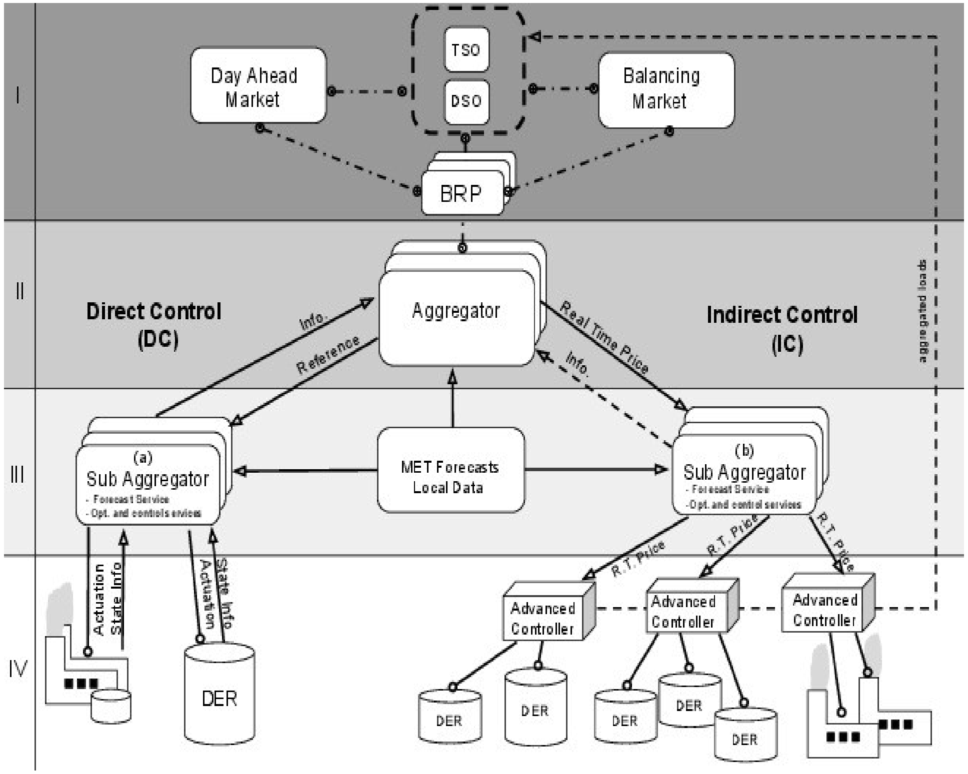
The ***Smart-Energy Operating-System (SE-OS)*** is used to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for ***operating flexible electrical energy systems*** at **all scales**.



Smart-Energy OS



Control and Optimization



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

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

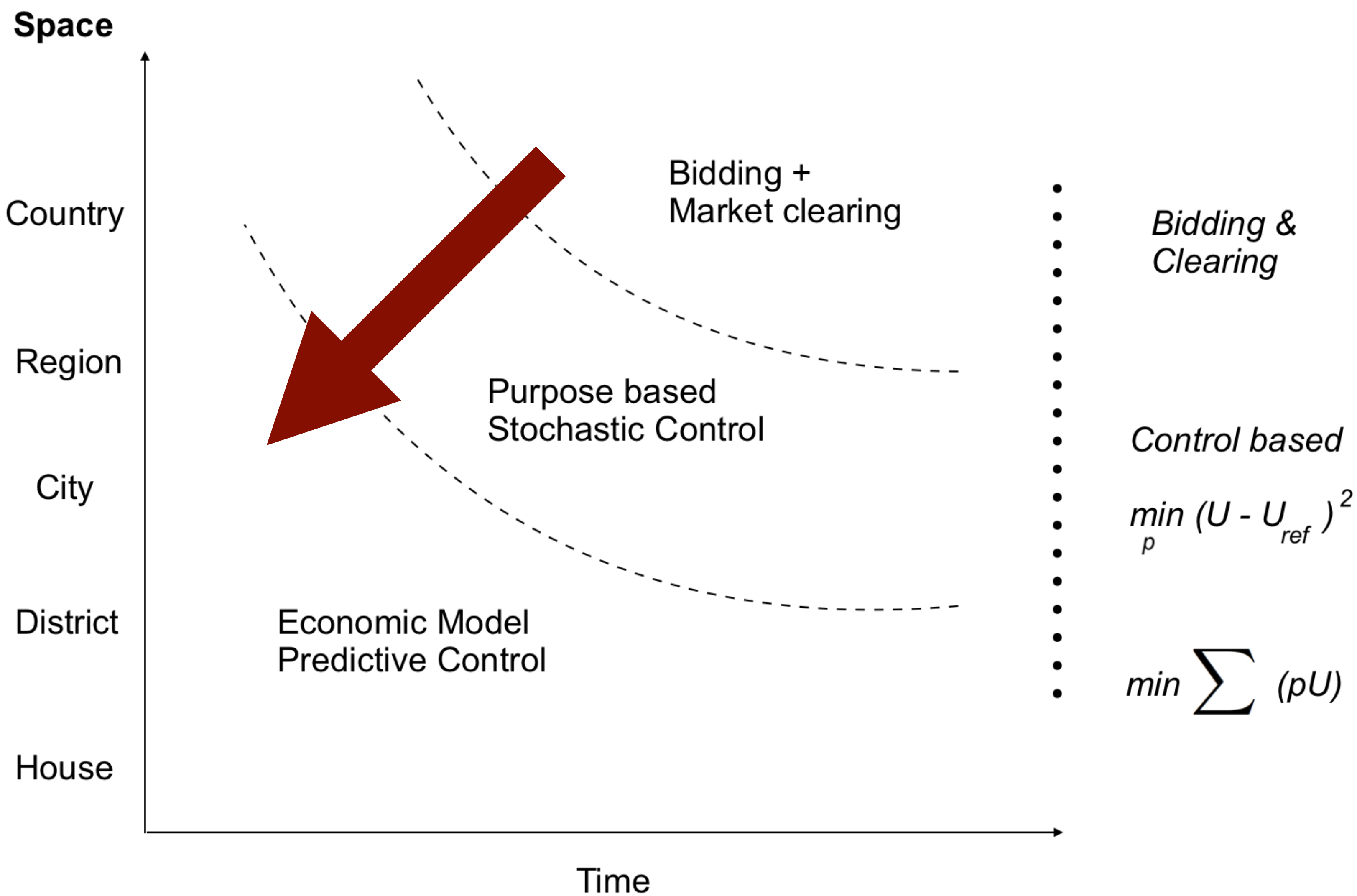
Simple 'contracts'

Direct vs Indirect Control

Level	Direct Control (DC)	Indirect Control (IC)
III	$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$ $\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$	$\min_{\hat{z},p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$ s.t. $\hat{z}_{k+1} = f(p_k)$
IV	s.t. $x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$	$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$ s.t. $x_{k+1} = f_j(x_k, u_k)$

Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals u_j are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes the optimal prices p which are sent to the J-units at level IV. Hence the J DERs optimize their own energy consumption taking into account p as the actual price of energy.

The ‘market’ of tomorrow



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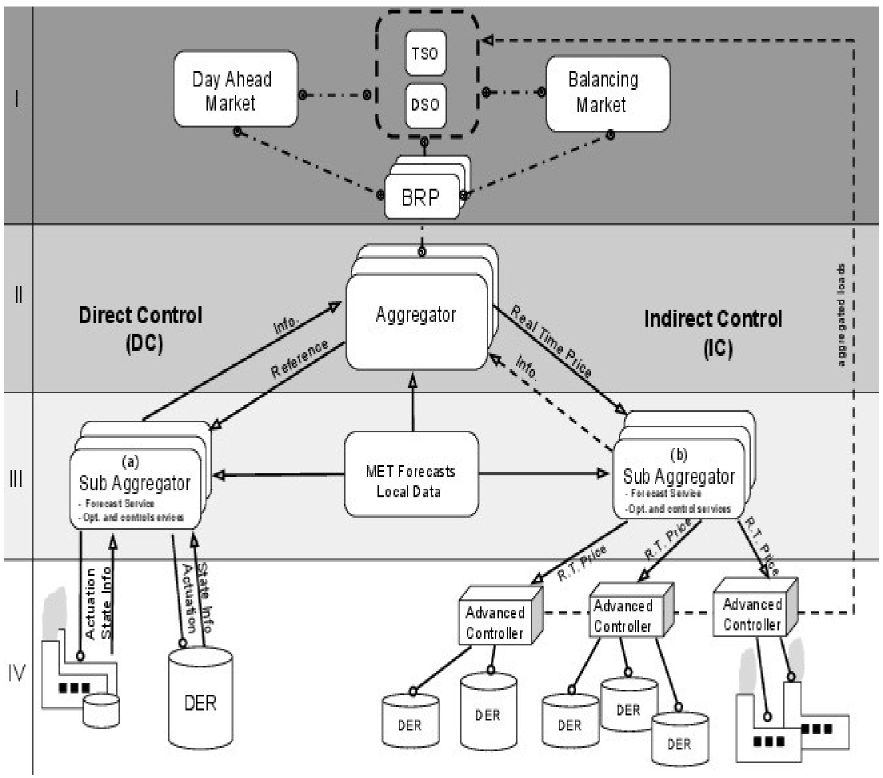
Forecast requirements



Day Ahead:

- Forecasts of loads
- Forecast of Grid Capacity (using eg. DLR)
- Forecasts of production (eg. Wind and Solar)

Direct Control: .

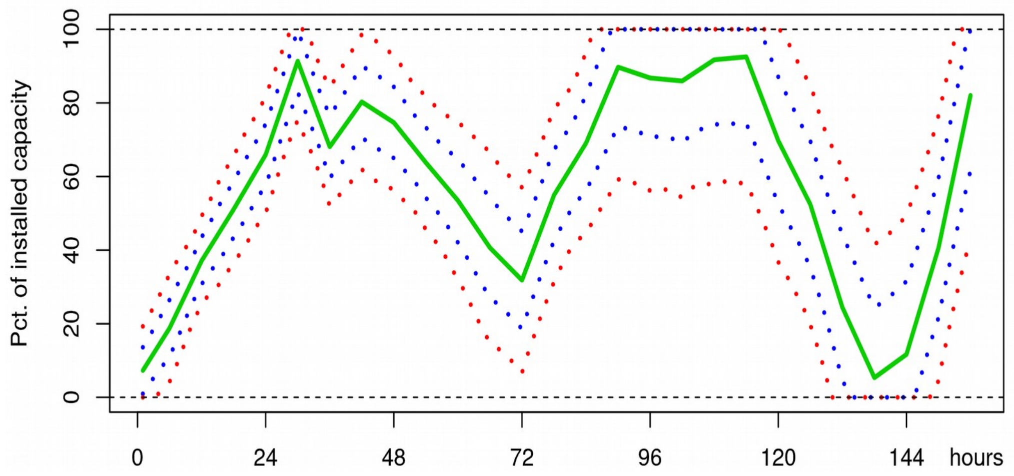
- Forecasts of states of DERs
- Forecasts of load

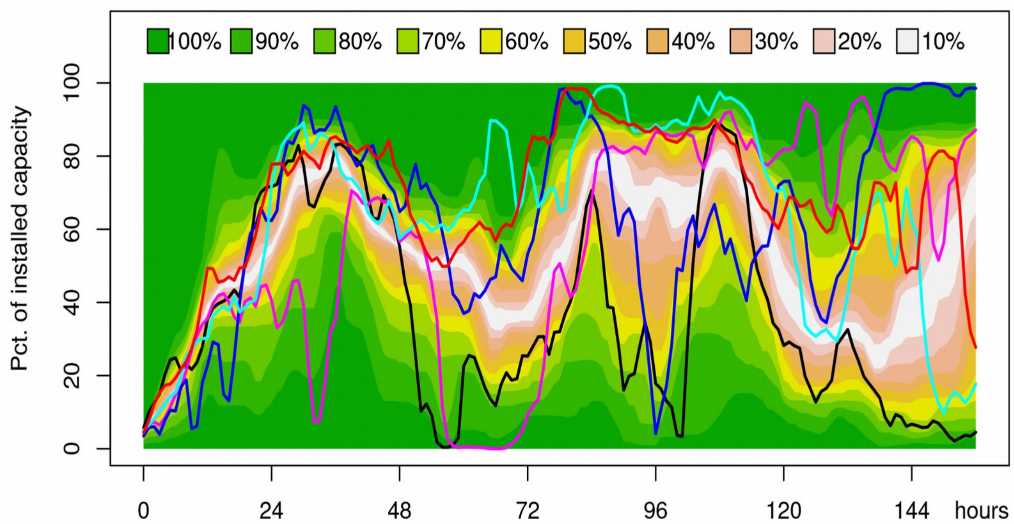
Indirect Control:

- Forecasts of prices
- Forecasts of load

Which type of forecast?

- Point forecasts
- Conditional mean and covariances
- Conditional quantiles (Prob. forecasts)
- Conditional scenarios
- Conditional densities
- Stochastic differential equations



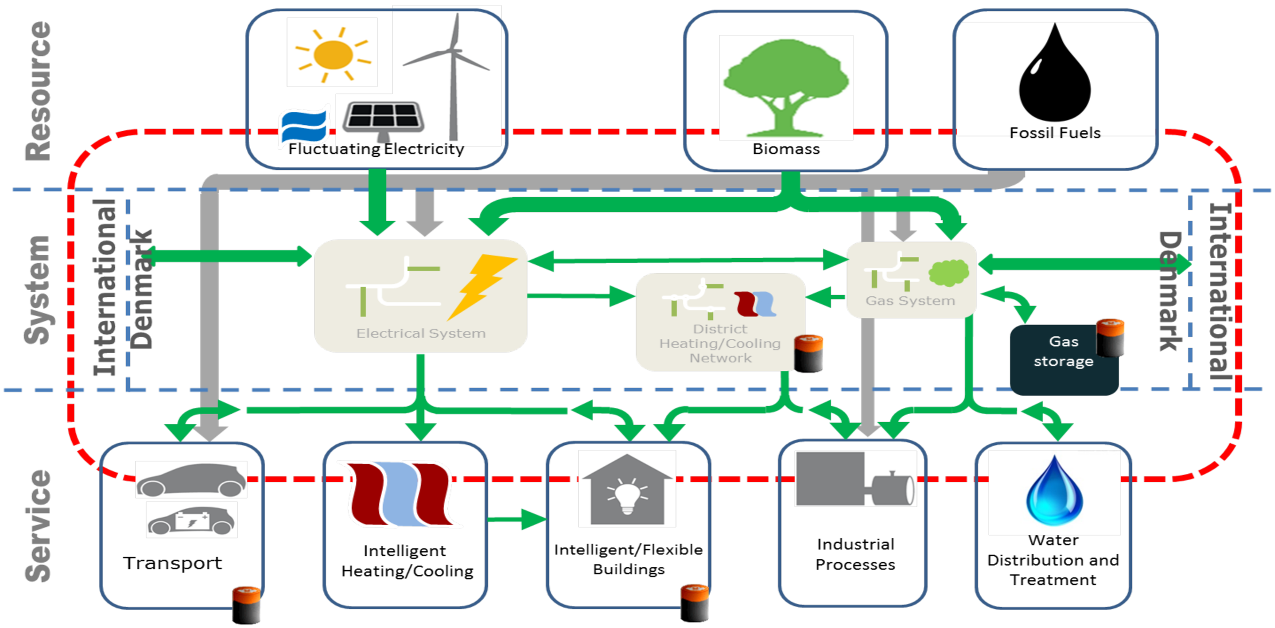


Wind and Solar Power Forecasting

- **Methods for wind power forecasting have been continuously developed and used operationally since 1995 (solar power since 2005).**
- **Implemented for instance in WPPT, Anemos WPS, AWEFS, ASEFS, ..**
- **Sold for instance in systems provided by ENFOR (Denmark) and Overspeed GmbH (Germany)**
- **Today our systems are used worldwide (North America, Europe, Africa, Japan, Middle East, Australia).**
- **Used by all major players in Denmark (TSO, DSOs, BRPs, ...)**

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**



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.

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 on GitHub.

MPCR is a toolbox for building Model Predictive Controllers written in R, the free statistical software. It contains several examples for different MPC problems and interfaces to opensource solvers in R . The software is available on GitHub.

Search ...

Latest news

Summer School at DTU, Lyngby, Denmark – July 4th-8th 2016

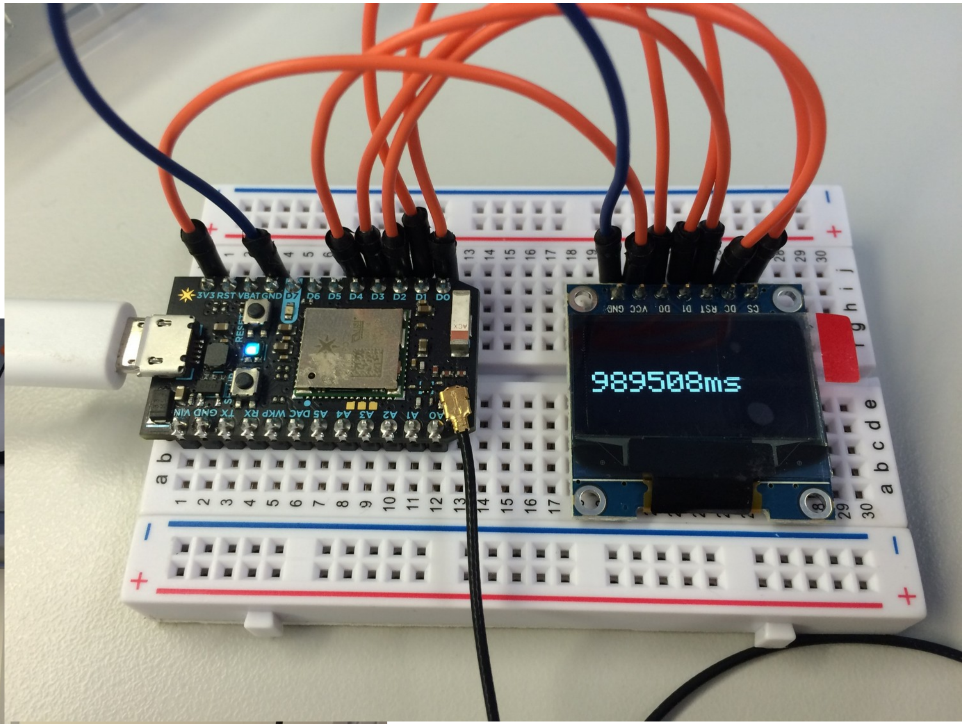
Summer School – Granada, Spain, June 19th-24th 2016

Third general consortium meeting – DTU, May 24th-25th 2016

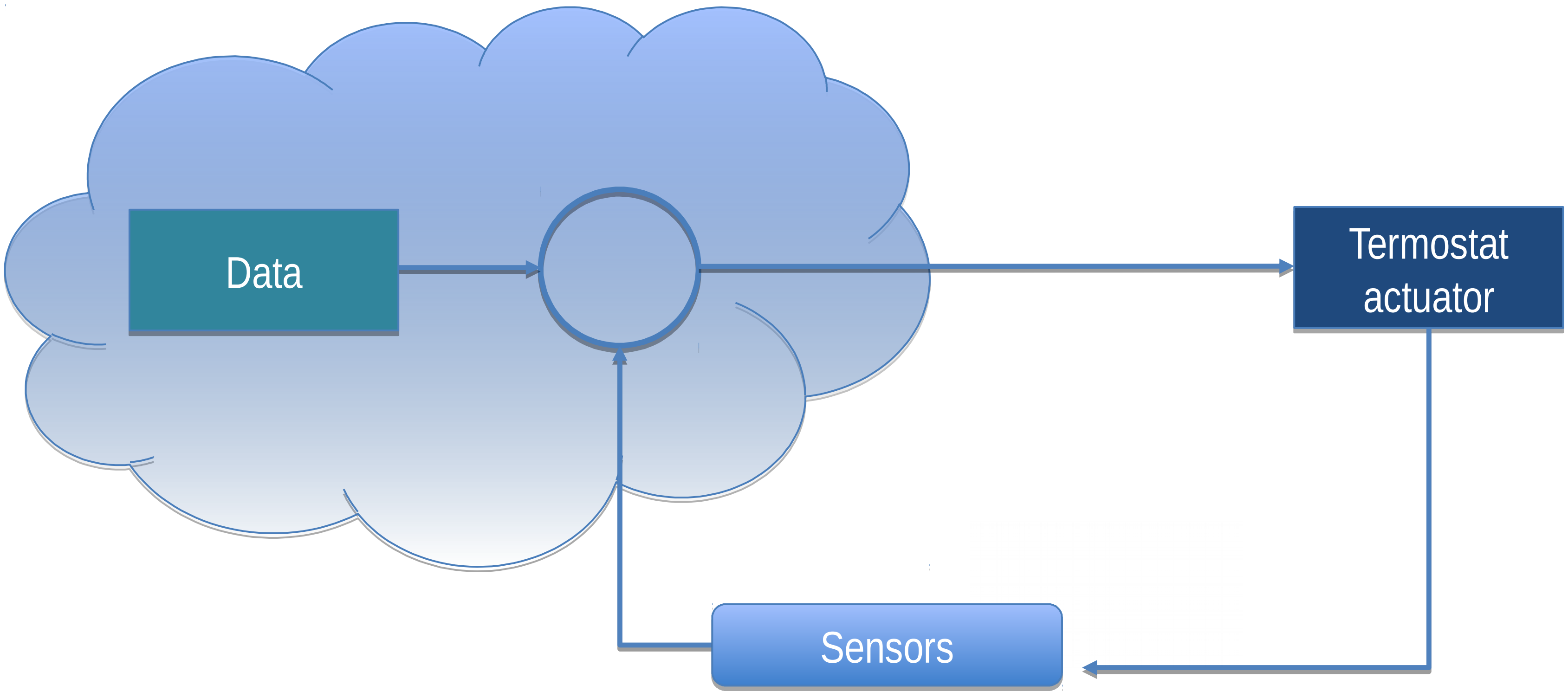
Smart City Challenge in Copenhagen – April 20th 2016

Guest lecture by Pierluigi Mancarella at DTU, April 6th

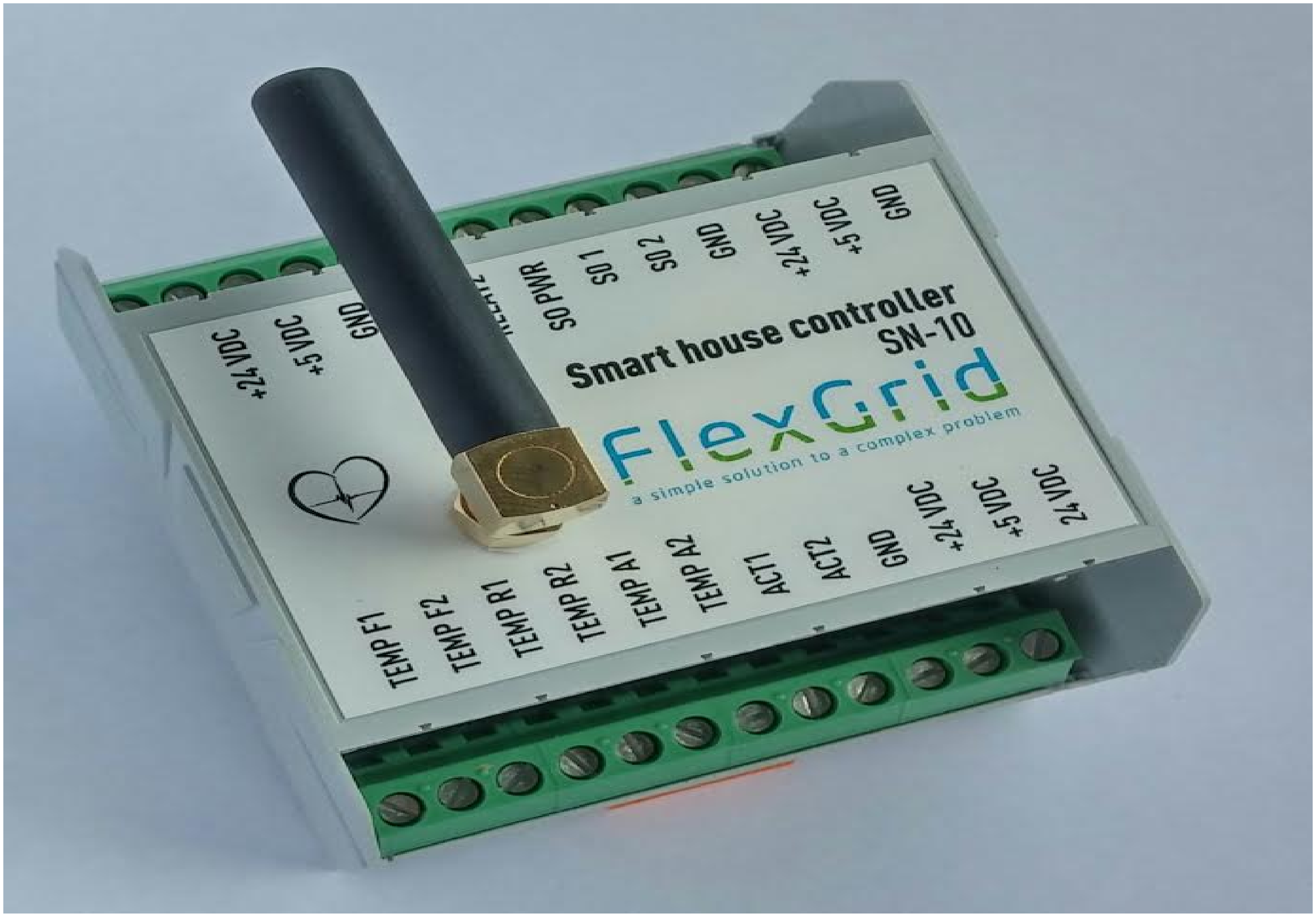
Lab testing ....



SE-OS
Control loop design – **logical drawing**



SN-10 Smart House Prototype

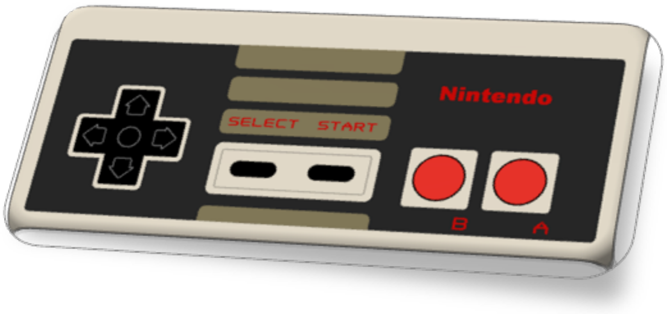


SE-OS Characteristics

- '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

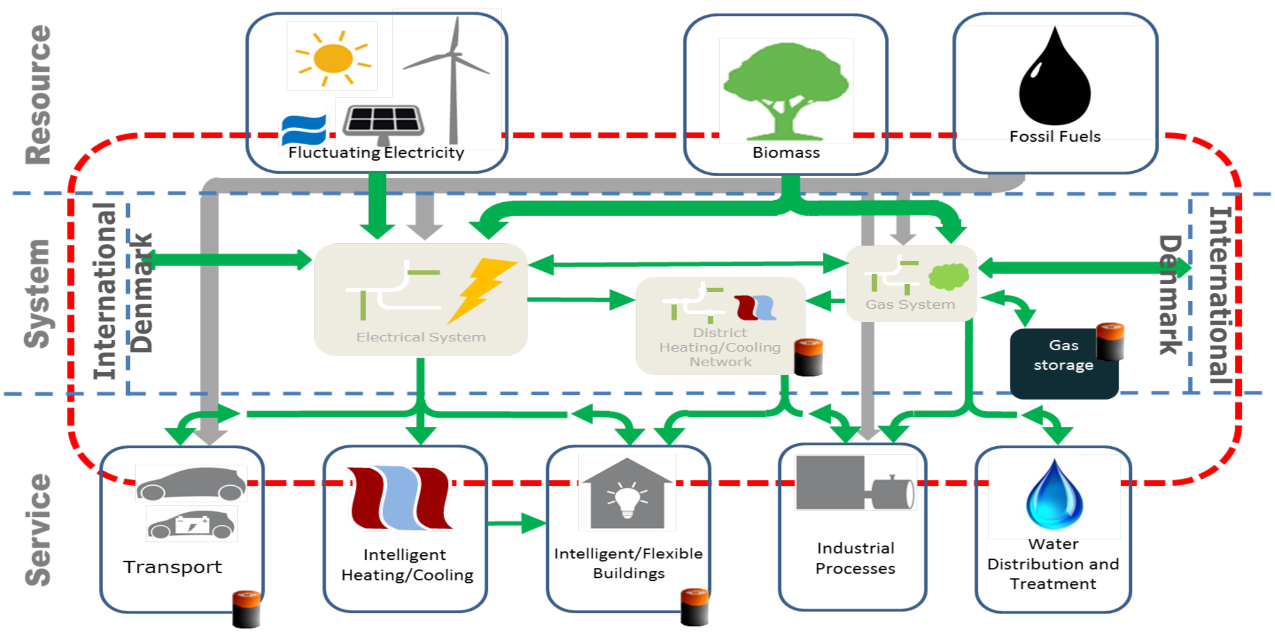
Example

Grey-box Modelling



Grey Box Models for Integration

Energy Systems Integration using **data** leading to **stochastic grey box models for real-time operation of future flexible energy systems.**



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

$$Y_k = h(X_k, u_k, t_k, \theta) + e_k,$$

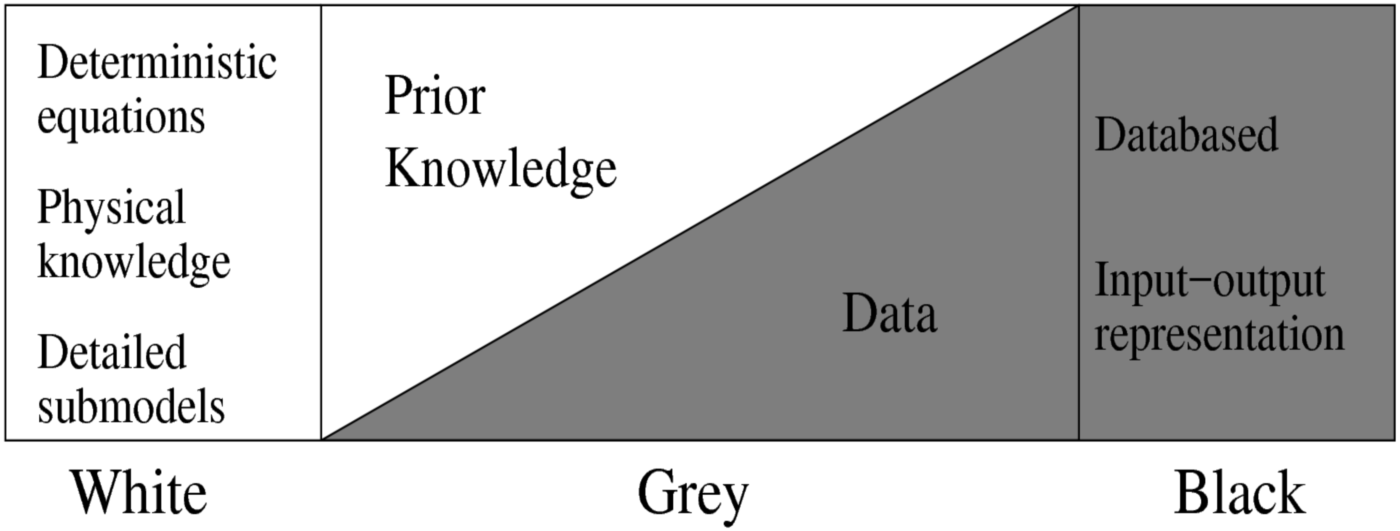
Observation equation

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 $N(0, S)$

Grey-box modelling concept



- Combines prior physical knowledge with information in data
- Equations and parameters are physically interpretable

Grey-Box Modelling

- Bridges the gap between physical and statistical modelling
- 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

Case study

Control of Power Consumption to Summer Houses with a Pool (H2020 SmartNet Project)

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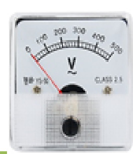
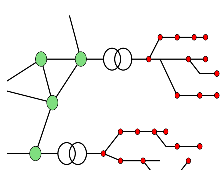
Services

Balancing

Voltage regulation (DSO)

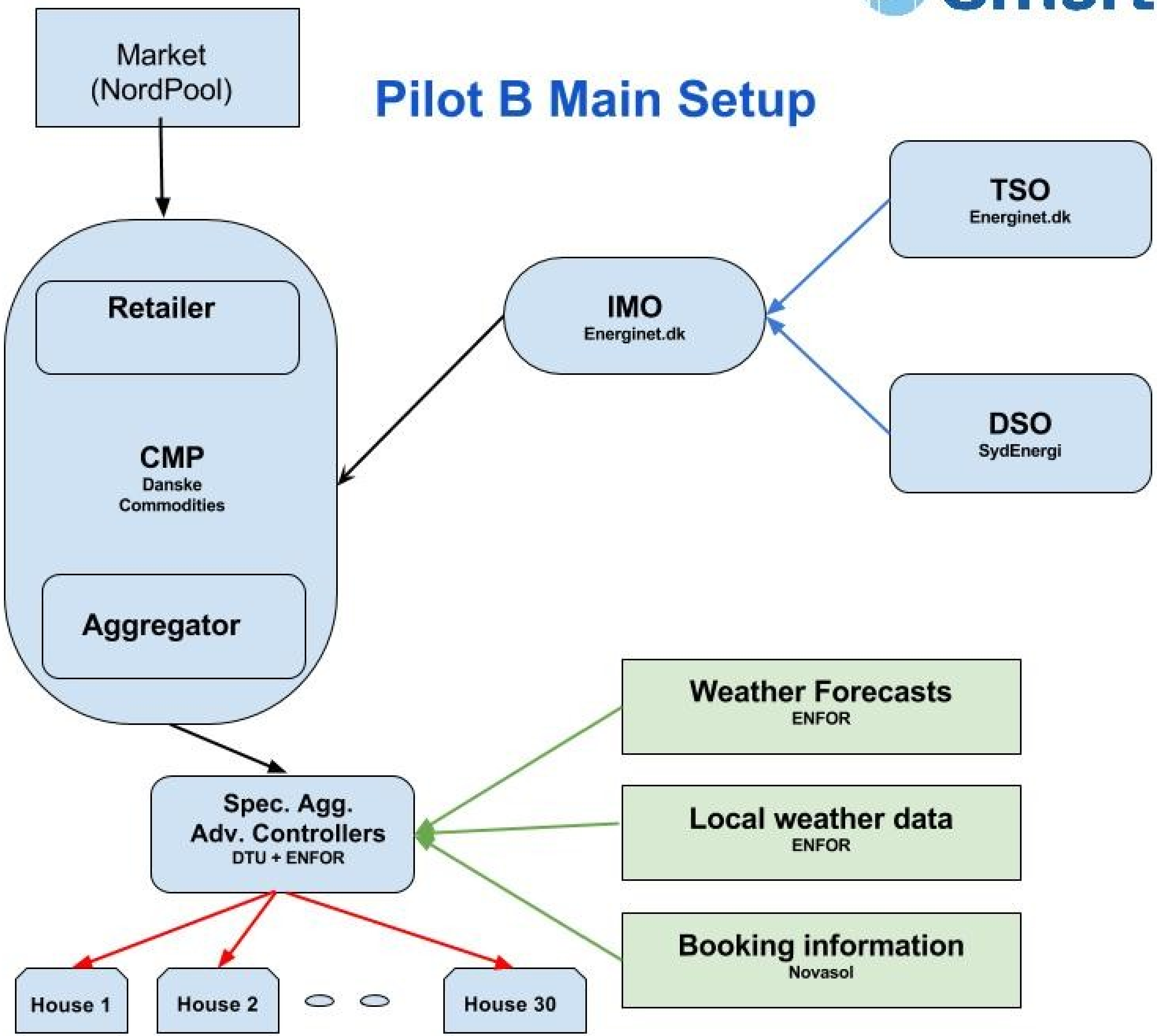


Congestion management



- The large inertia of pools allows for shift of electricity consumption by several hours.
- Via active coordination of the flexibility below a critical node on the DSO grid.
- Active load management to help finding an optimal routing of the power.

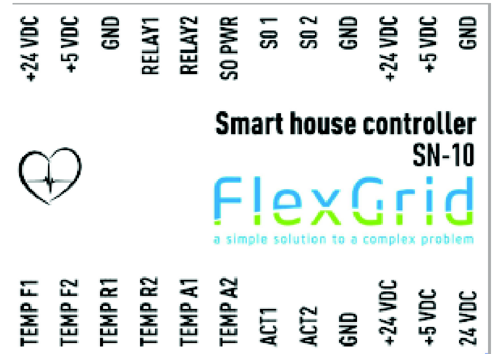
Pilot B Main Setup

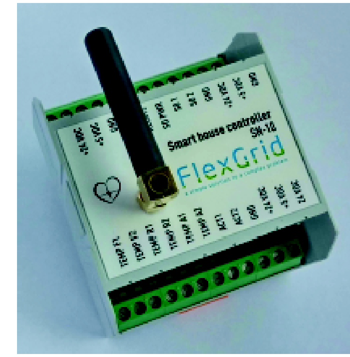


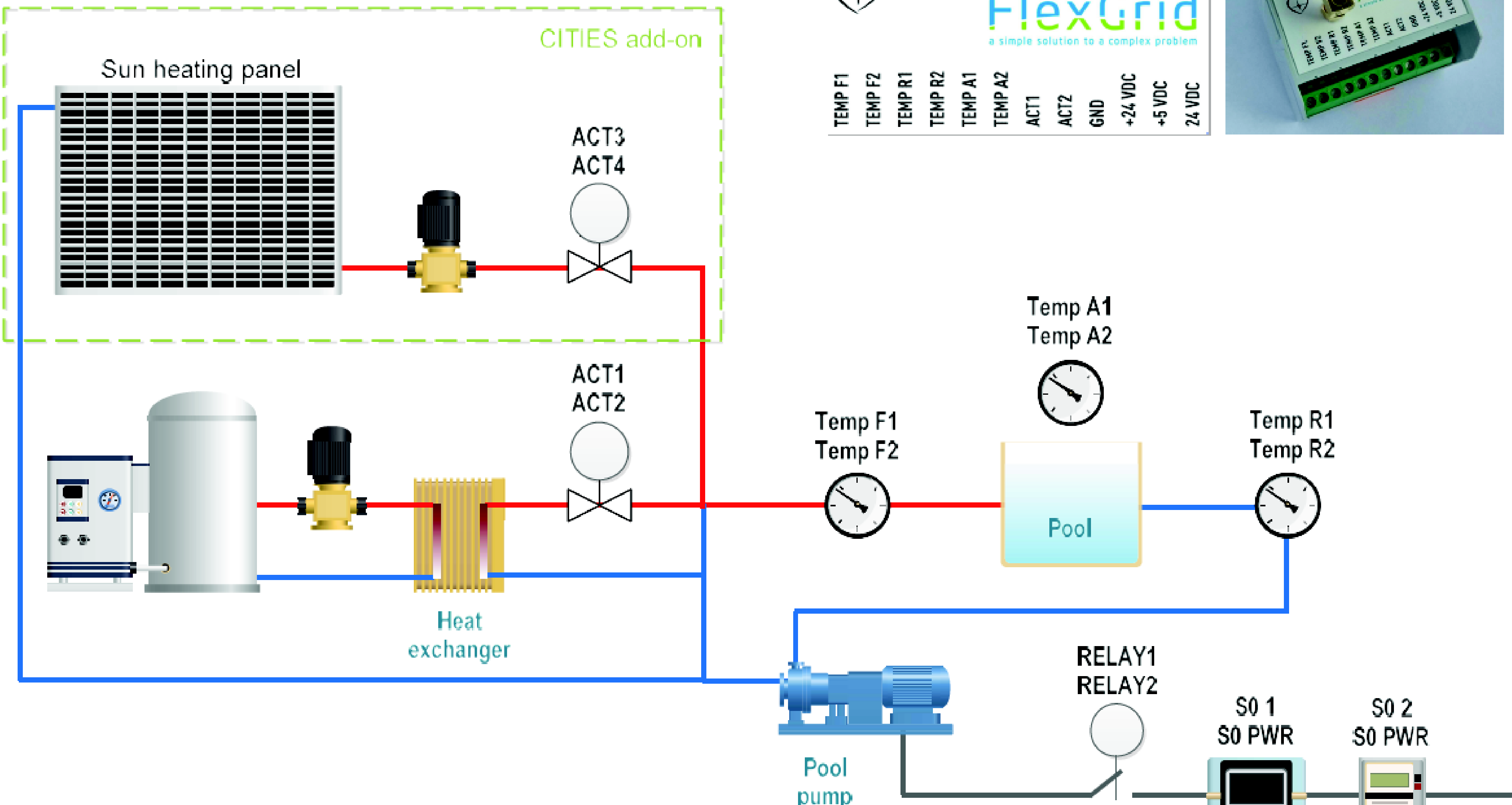
Smart Control of Houses with a Pool

PilotB SN-10 signal overview

revision 1.0 (CITIES add-on)







Case study (Level III)

Price-based Control of Power Consumption

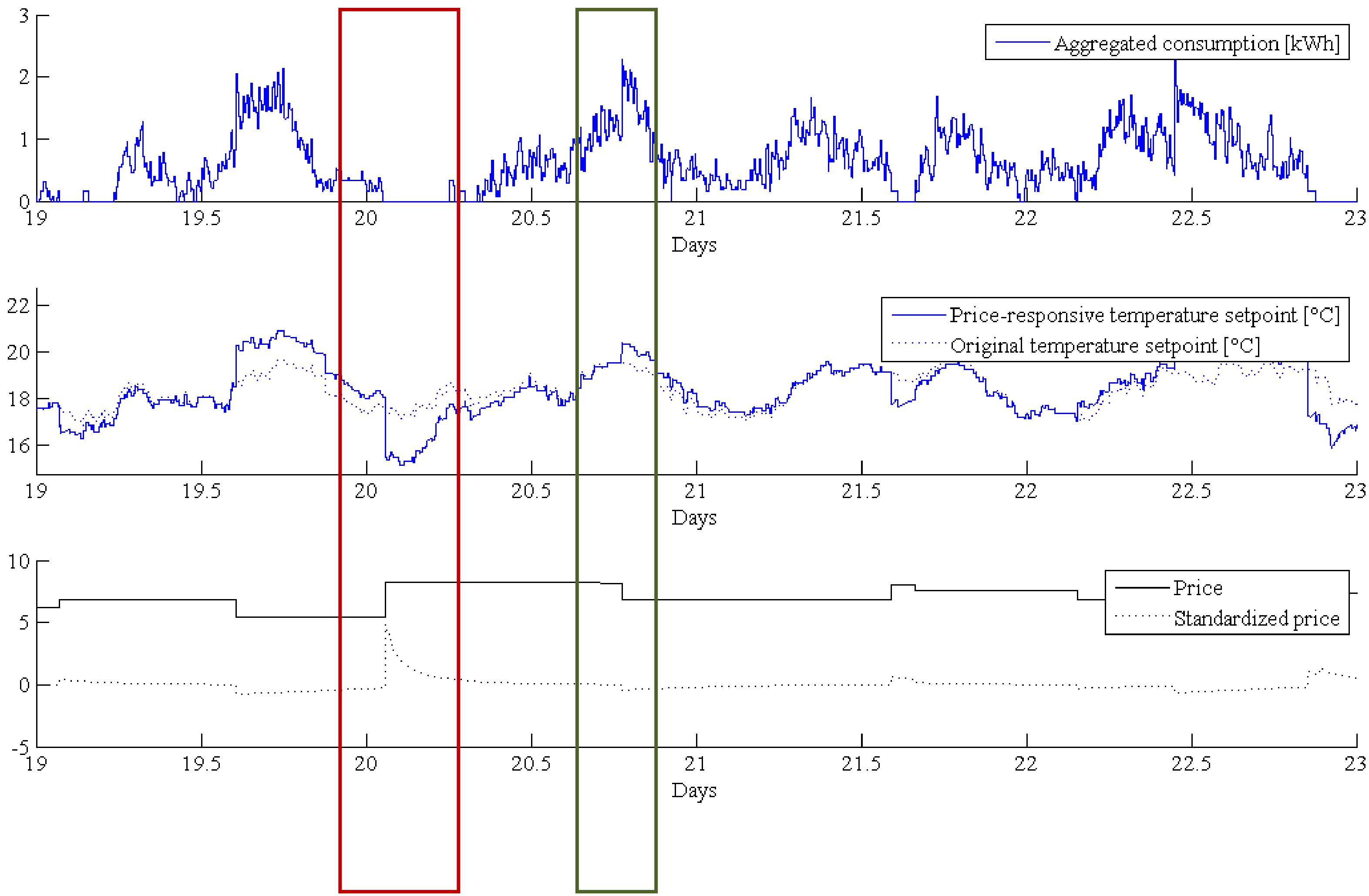
Centre for IT Intelligent Energy Systems

Data from BPA

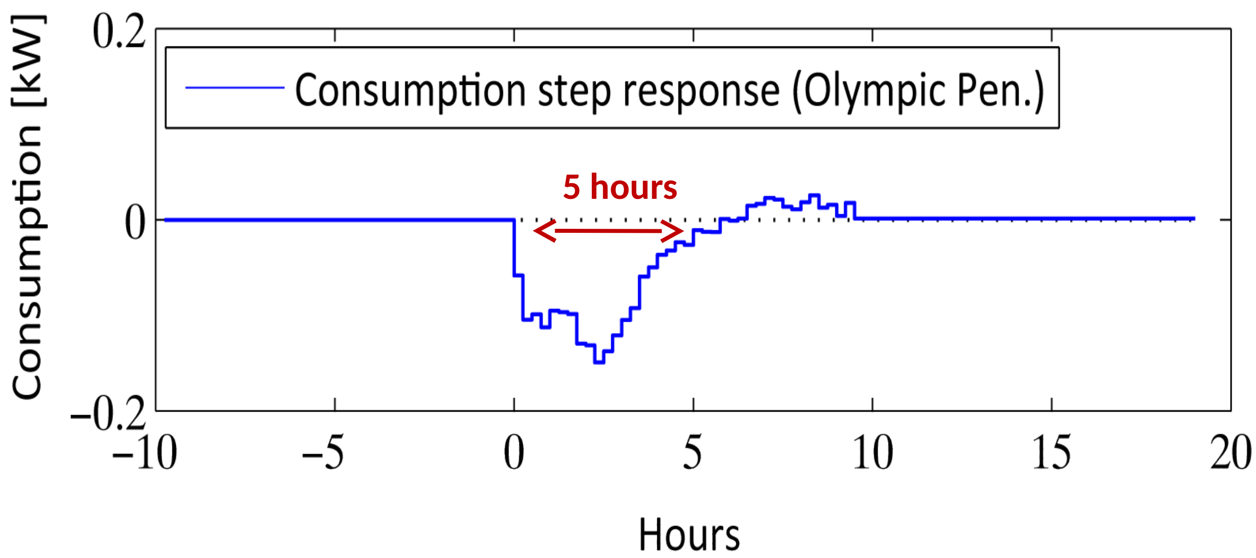
Olympic Pensinsula project

- 27 houses during one year
- Flexible appliances: HVAC,
  cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption

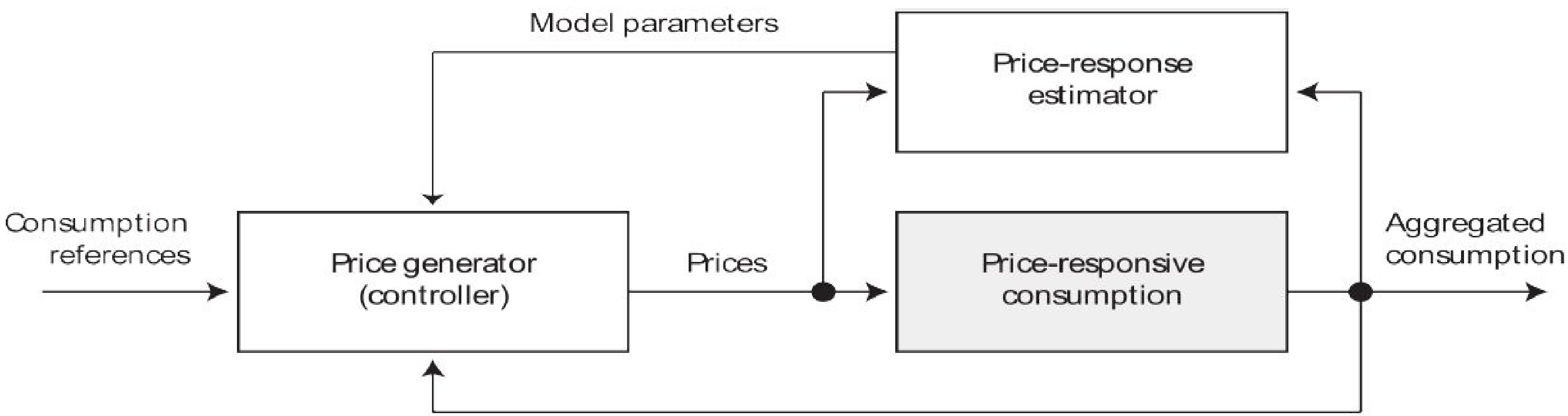
Aggregation (over 20 houses)

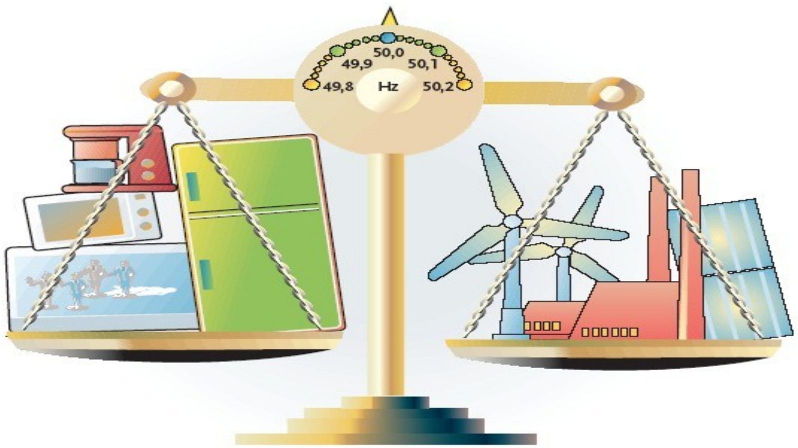


Response on Price Step Change



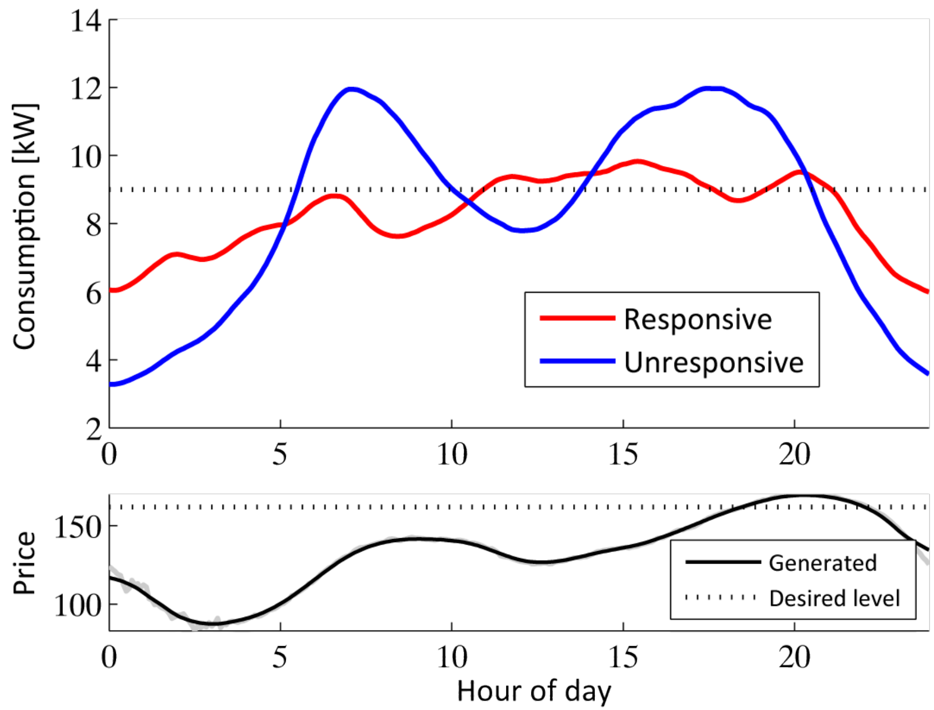
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**

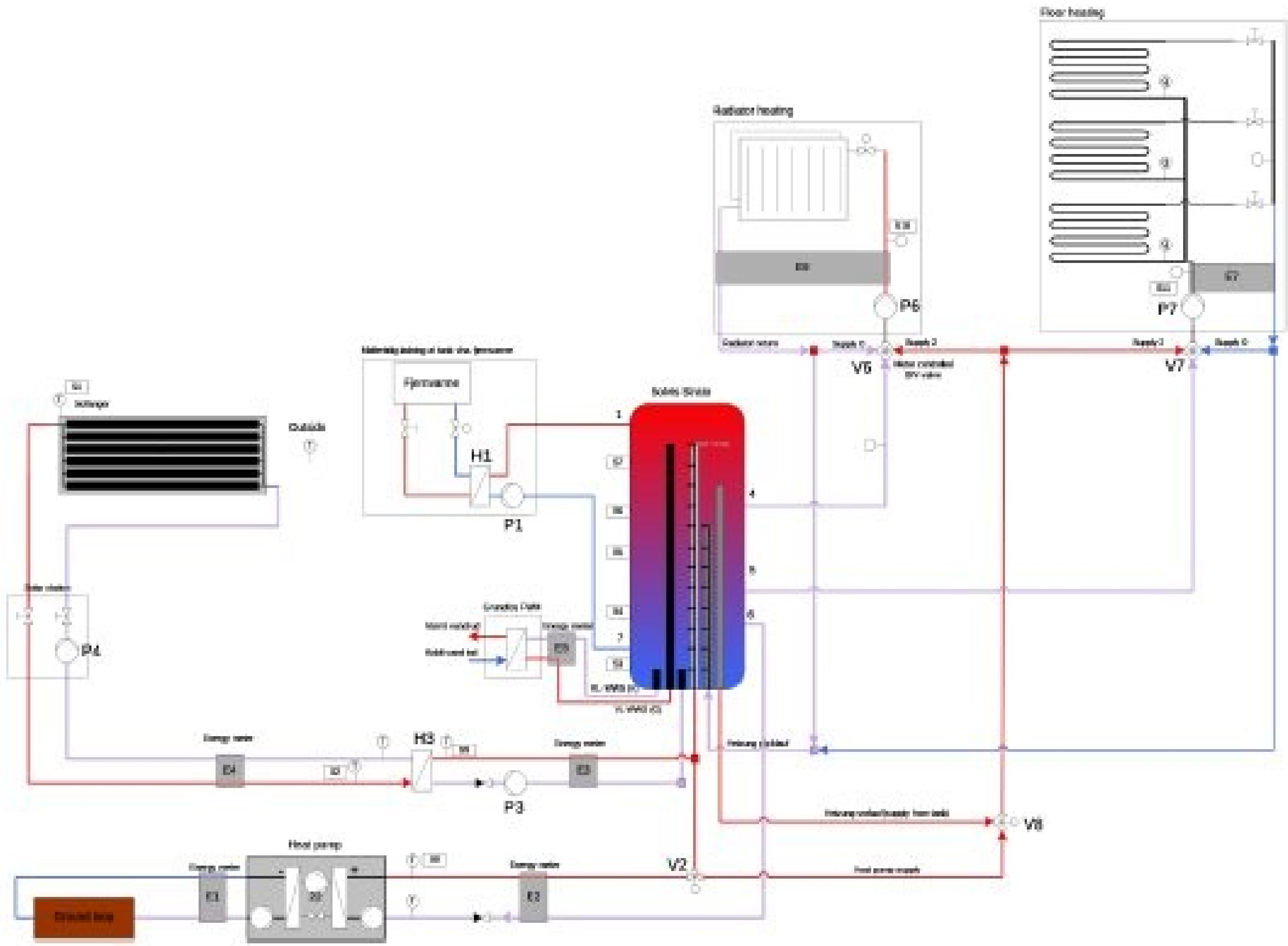


Case study
(Level IV – Indirect Control)

Control of Heat Pumps
(based on varying prices from Level III)

Grundfos Case Study

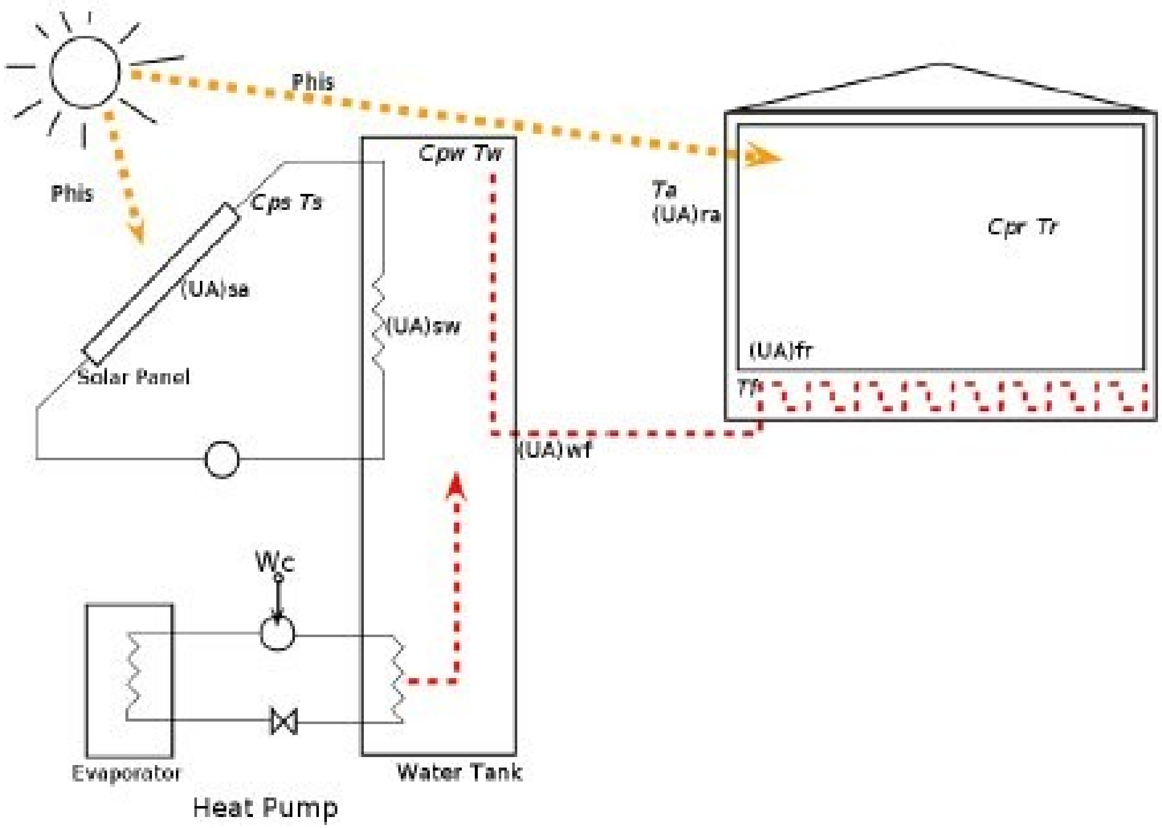
Schematic of the heating system



DTU

Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

Formulation

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

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

Subject to

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

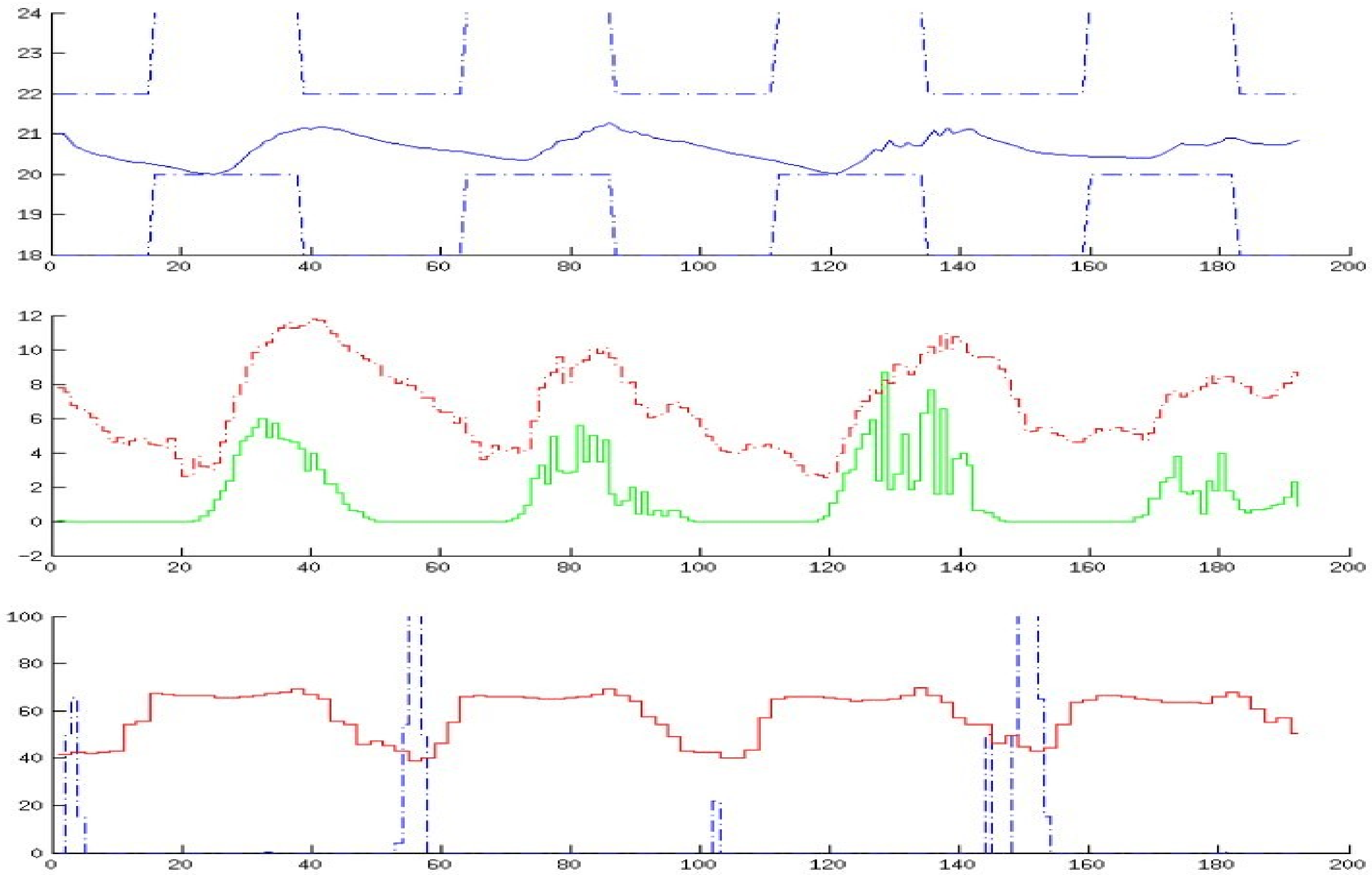
$$y_k = Cx_k \quad k = 1, 2, \ldots, N \quad (4c)$$

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

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

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

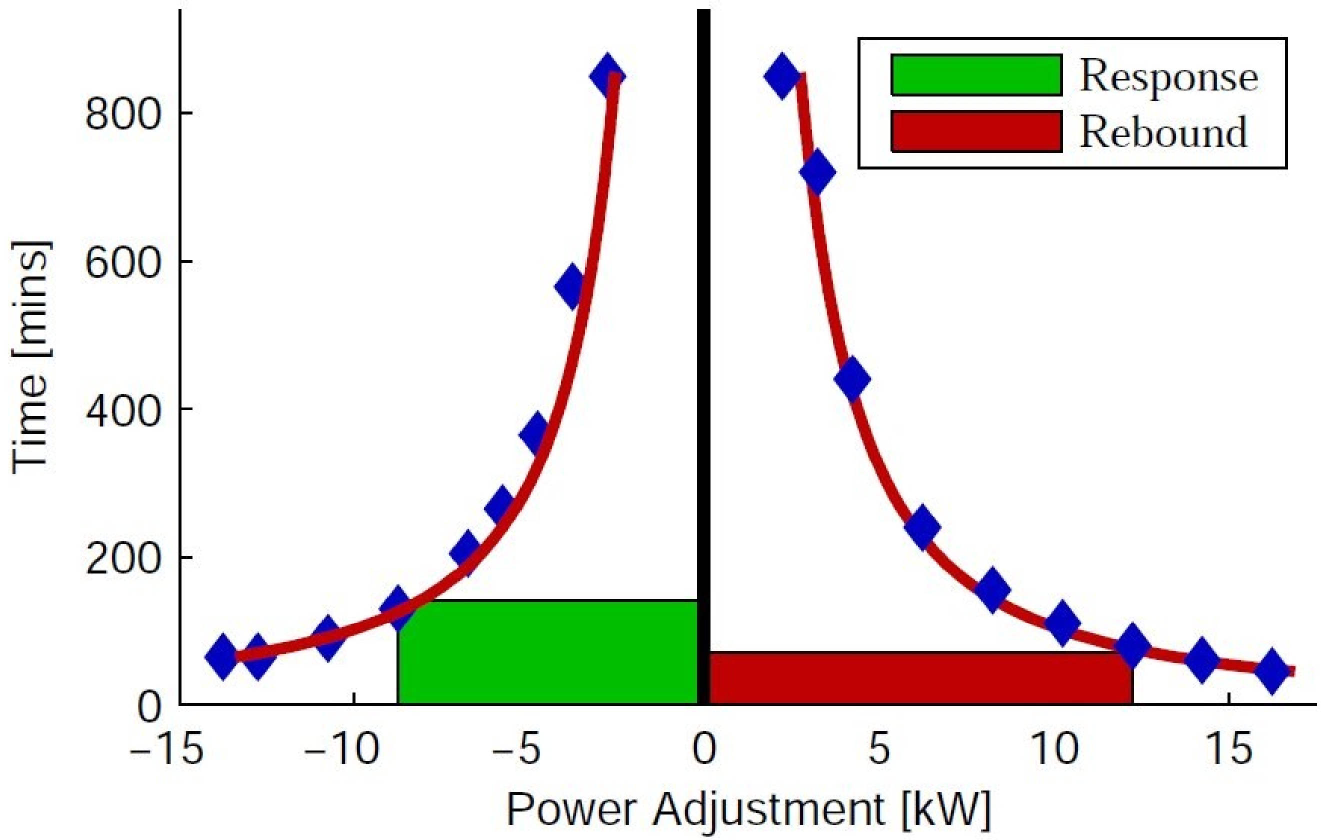
E-MPC for heat pump with solar collector (savings 35 pct)



Further Aspects

Flexibility Represented by Saturation Curves

(for market integration using block bids)



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)

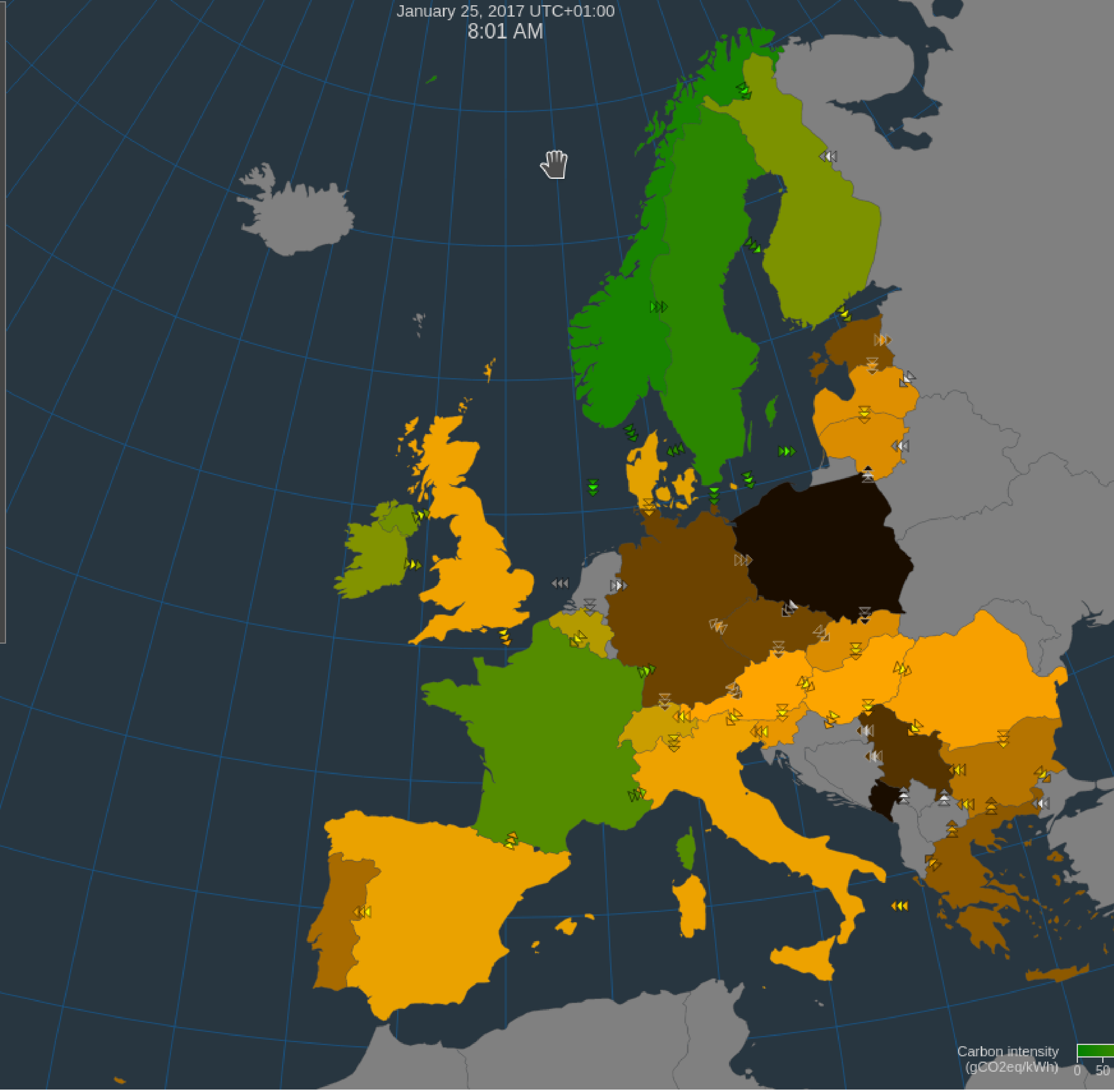
0 2 4 6 8 10 12 14

Solar power potential (W/m^2)

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



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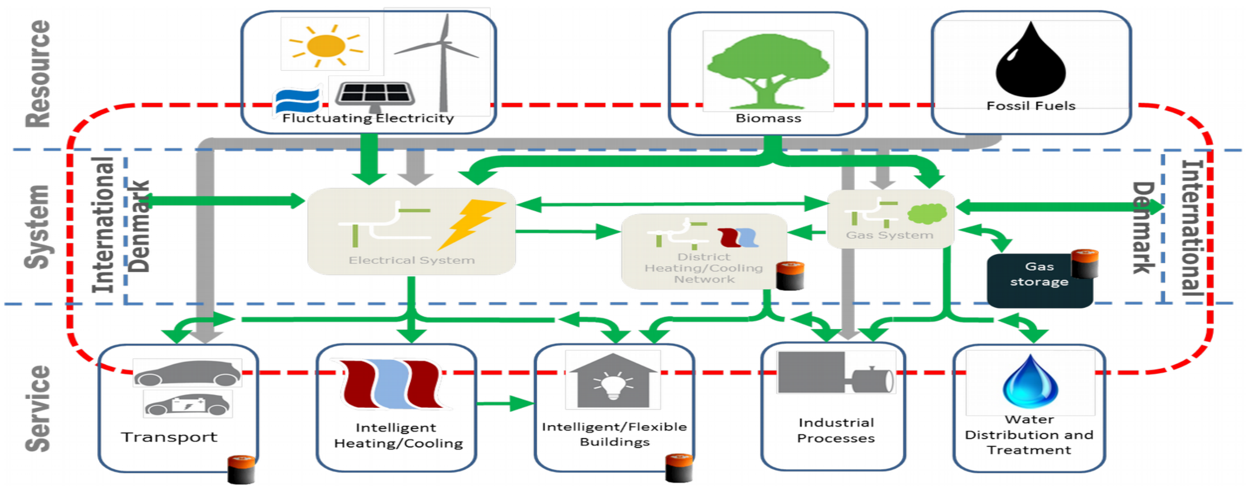
Understanding Power/Energy Flexibility
Some Demo Projects

- 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
- VE (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

Discussion

- IT-Intelligent Energy Systems Integration using grey-box models can provide virtual storage solutions (so maybe we should put less focus on electrical storage solutions)
- District heating (or cooling) systems can provide flexibility on the essential time scale (up to a few days)
- Gas systems can provide seasonal virtual storage solutions
- Smart Cities are just smart elements of a Smart Society
- We see a large potential in Demand Response. Automatic solutions, price based control, 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)

Summary

- A Smart-Energy OS for implementing future and flexible future electric energy systems has been described
- **Modelling:** Toolbox – CTSM-R - for combined physical and statistical modelling (**grey-box modelling**)
- **Control:** Toolbox – MPC-R - for Model Predictive Control
- Two models for ***characterizing the flexibility*** have been suggested and demonstrated:
  - **Dynamic models** (used for E-MPC based on prices / indirect control)
  - **Saturation curves** (used for market bidding / direct control)

For more information ...

See for instance

www.smart-cities-centre.org

...or contact

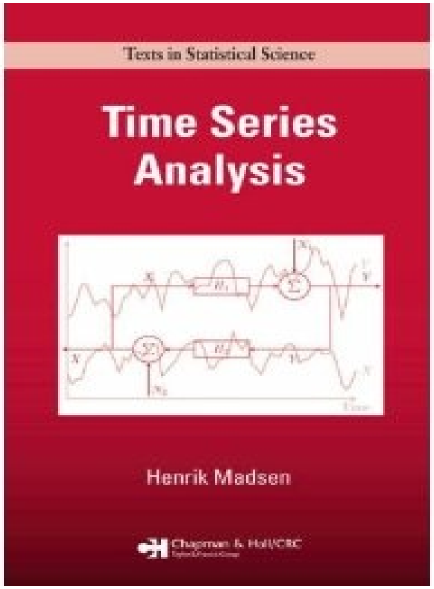
- Henrik Madsen (DTU Compute)

  hmad@dtu.dk

Acknowledgement - DSF 1305-00027B

CITIES
Centre for IT Intelligent Energy Systems

Some 'randomly picked' books on modelling ....



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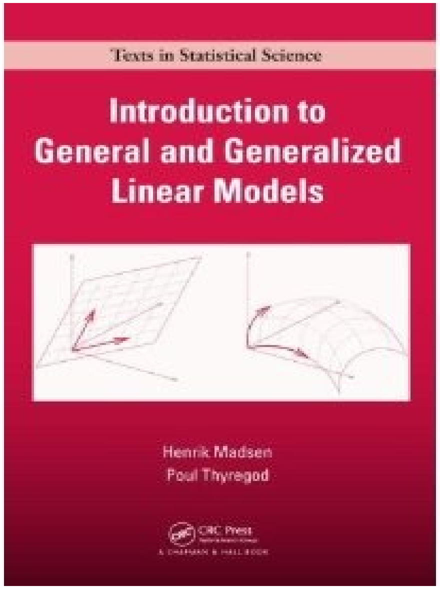

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