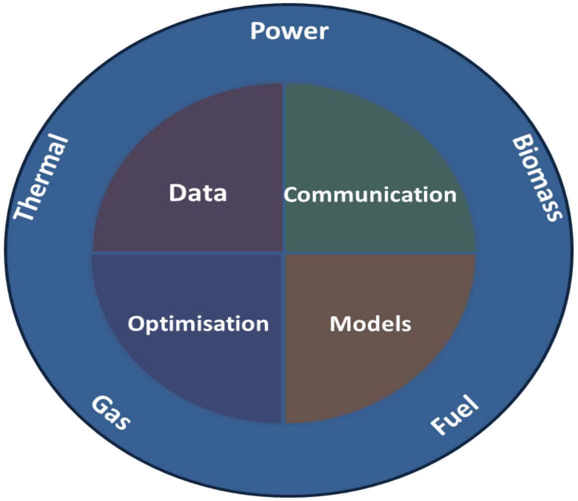
Methodologies for Operating Future Intelligent Energy Systems



Henrik Madsen, DTU Compute
http://www.henrikmadsen.org
http://www.smart-cities-centre.org

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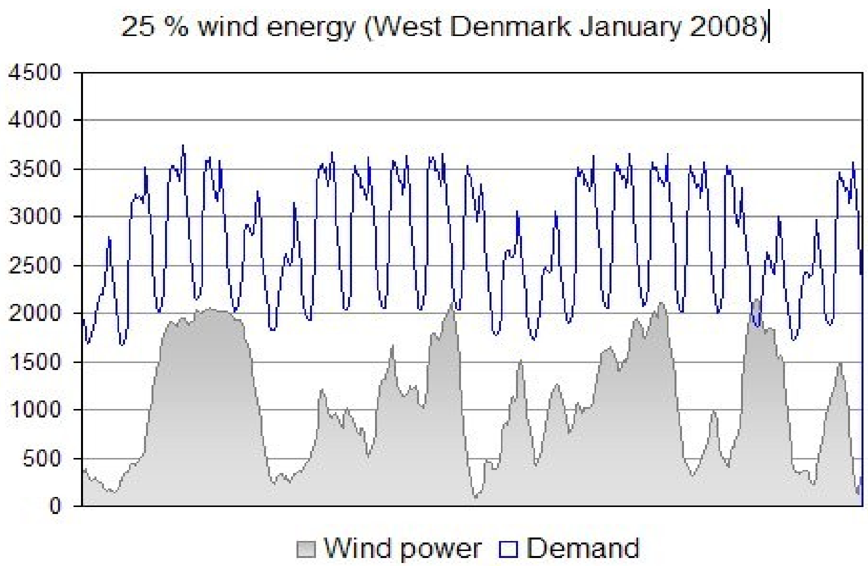
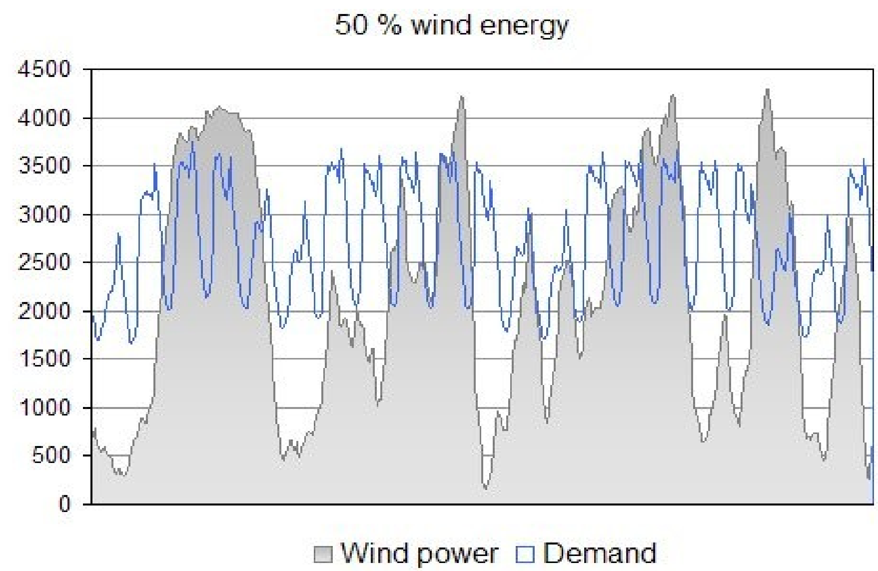
The Danish Wind Power Case

…. 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

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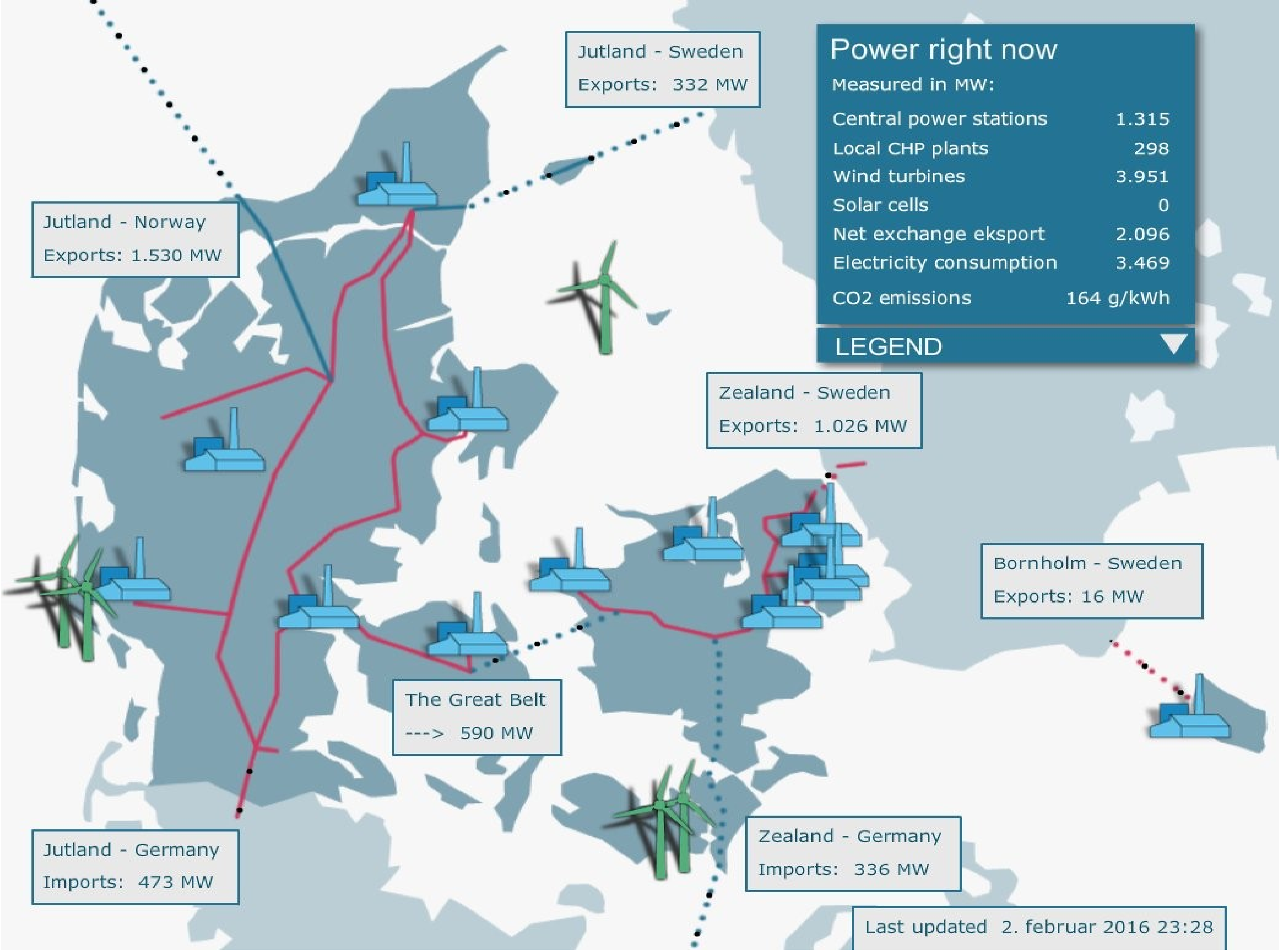
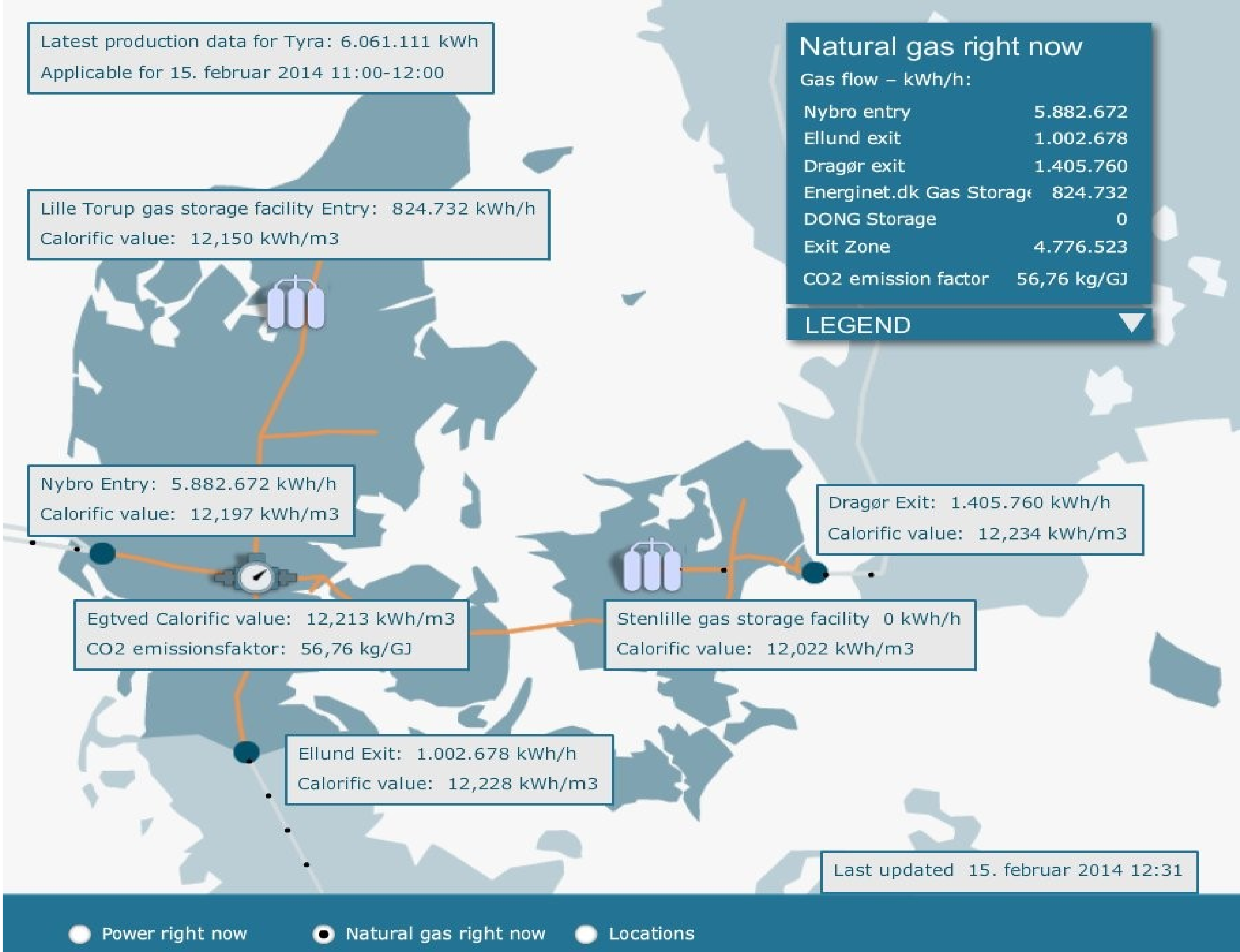
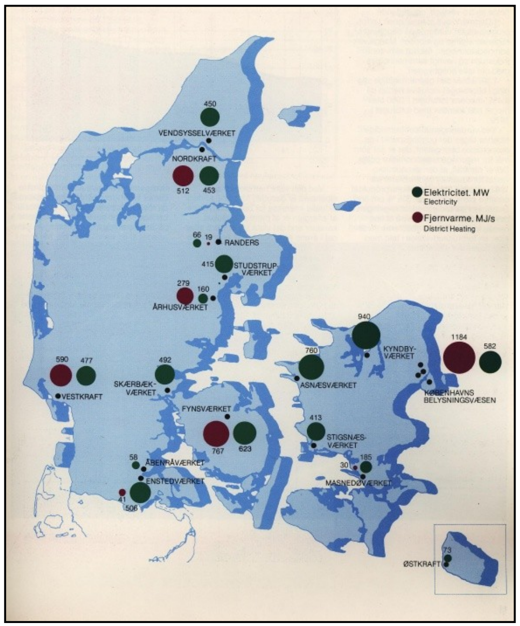

Jutland - Sweden
Exports: 332 MW
Power right now
Measured in MW:
Central power stations 1.315
Local CHP plants 298
Wind turbines 3.951
Solar cells 0
Net exchange eksport 2.096
Electricity consumption 3.469
CO2 emissions 164 g/kWh
LEGEND
Jutland - Norway
Exports: 1.530 MW
Zealand - Sweden
Exports: 1.026 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


Latest production data for Tyra: 6.061.111 kWh
Applicable for 15. februar 2014 11:00-12:00
Natural gas right now
Gas flow – kWh/h:
Nybro entry 5.882.672
Ellund exit 1.002.678
Dragør exit 1.405.760
Energinet.dk Gas Storage 824.732
DONG Storage 0
Exit Zone 4.776.523
CO2 emission factor 56,76 kg/GJ
LEGEND
Lille Torup gas storage facility Entry: 824.732 kWh/h
Calorific value: 12,150 kWh/m3
Nybro Entry: 5.882.672 kWh/h
Calorific value: 12,197 kWh/m3
Dragør Exit: 1.405.760 kWh/h
Calorific value: 12,234 kWh/m3
Egtved Calorific value: 12,213 kWh/m3
CO2 emissionsfaktor: 56,76 kg/GJ
Stenlille gas storage facility 0 kWh/h
Calorific value: 12,022 kWh/m3
Ellund Exit: 1.002.678 kWh/h
Calorific value: 12,228 kWh/m3
Last updated 15. februar 2014 12:31
Power right now
Natural gas right now
Locations

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 ...

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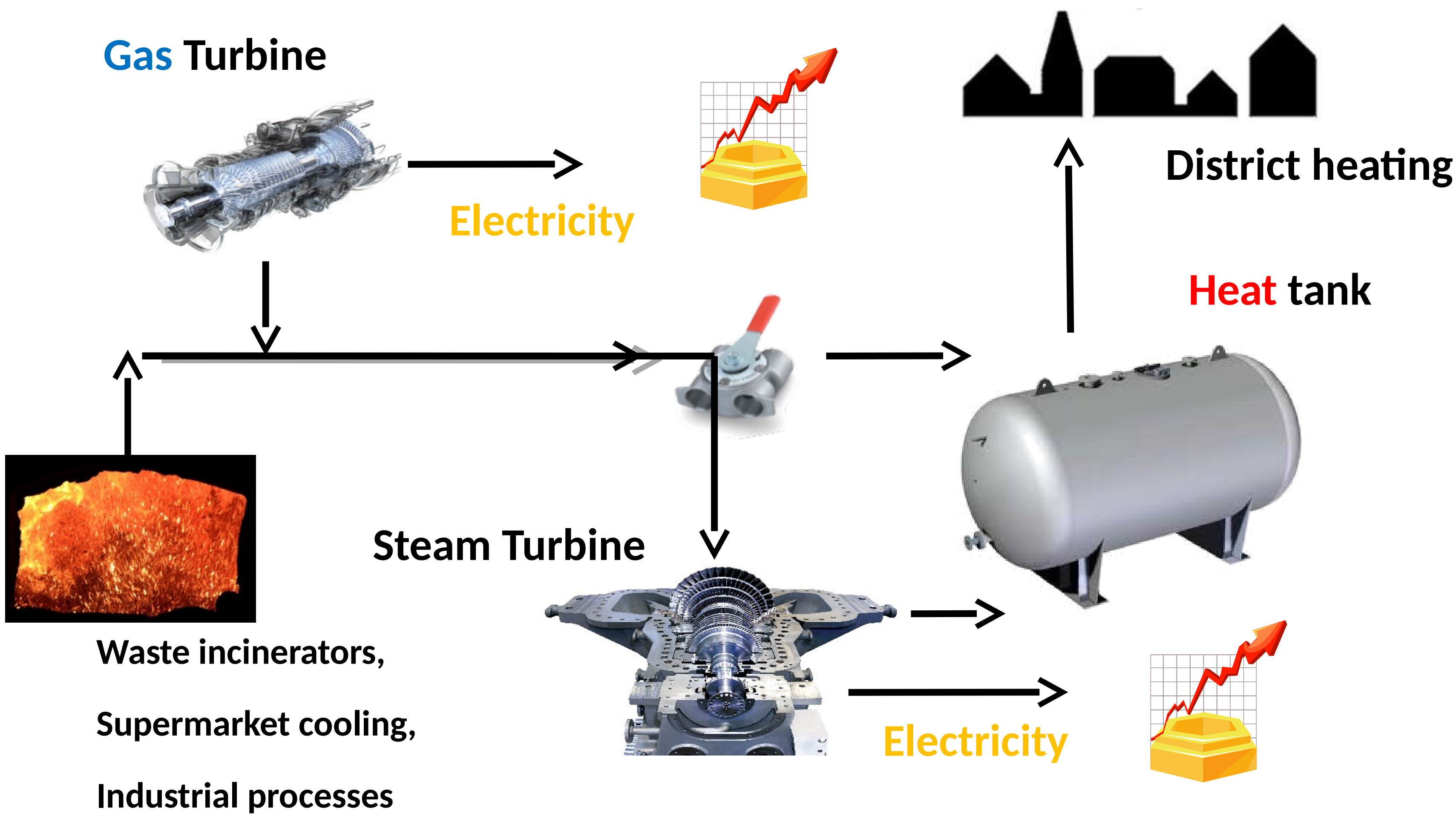
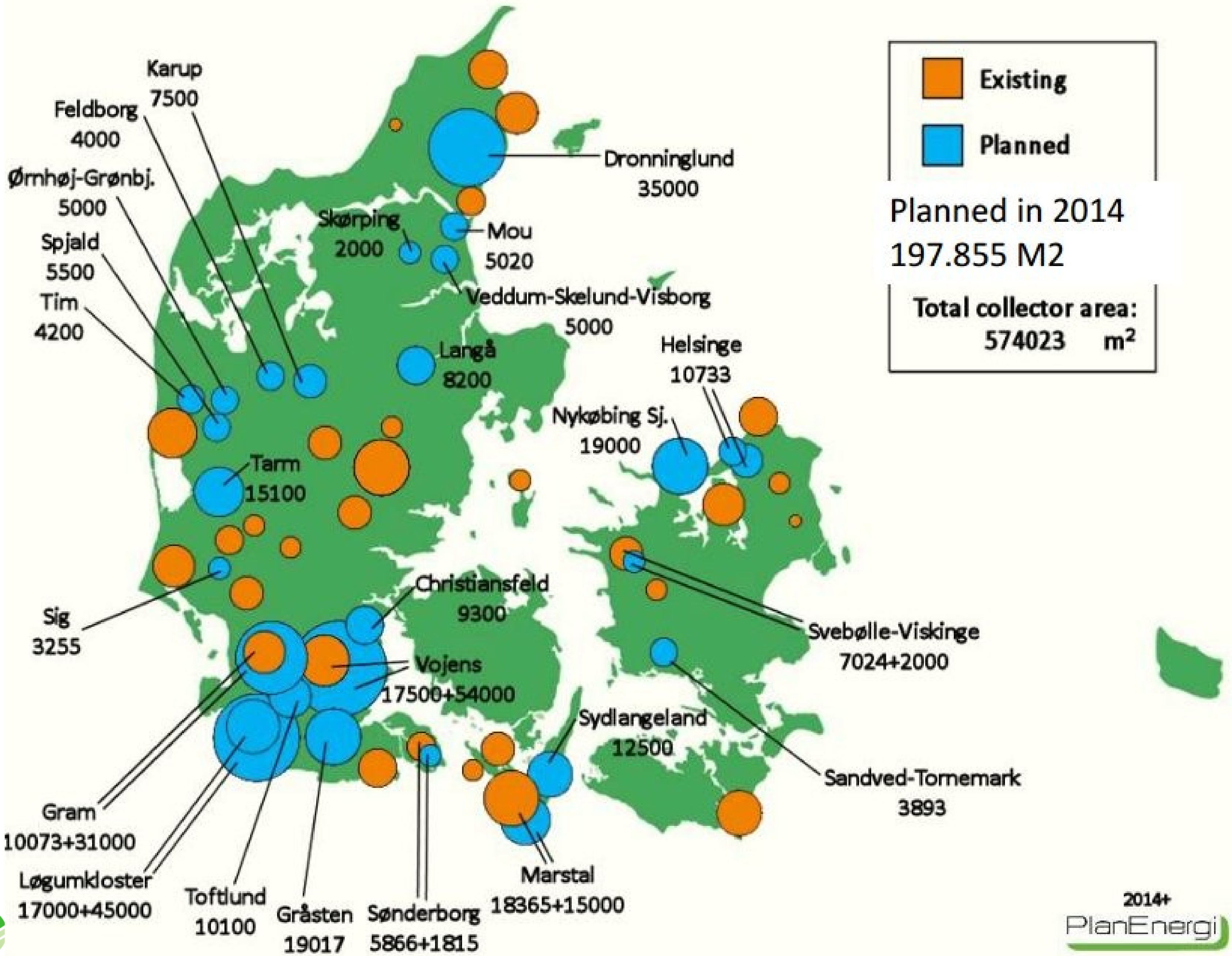
CHP and Integrated Energy Systems

(Paradigmatic example - Denmark)

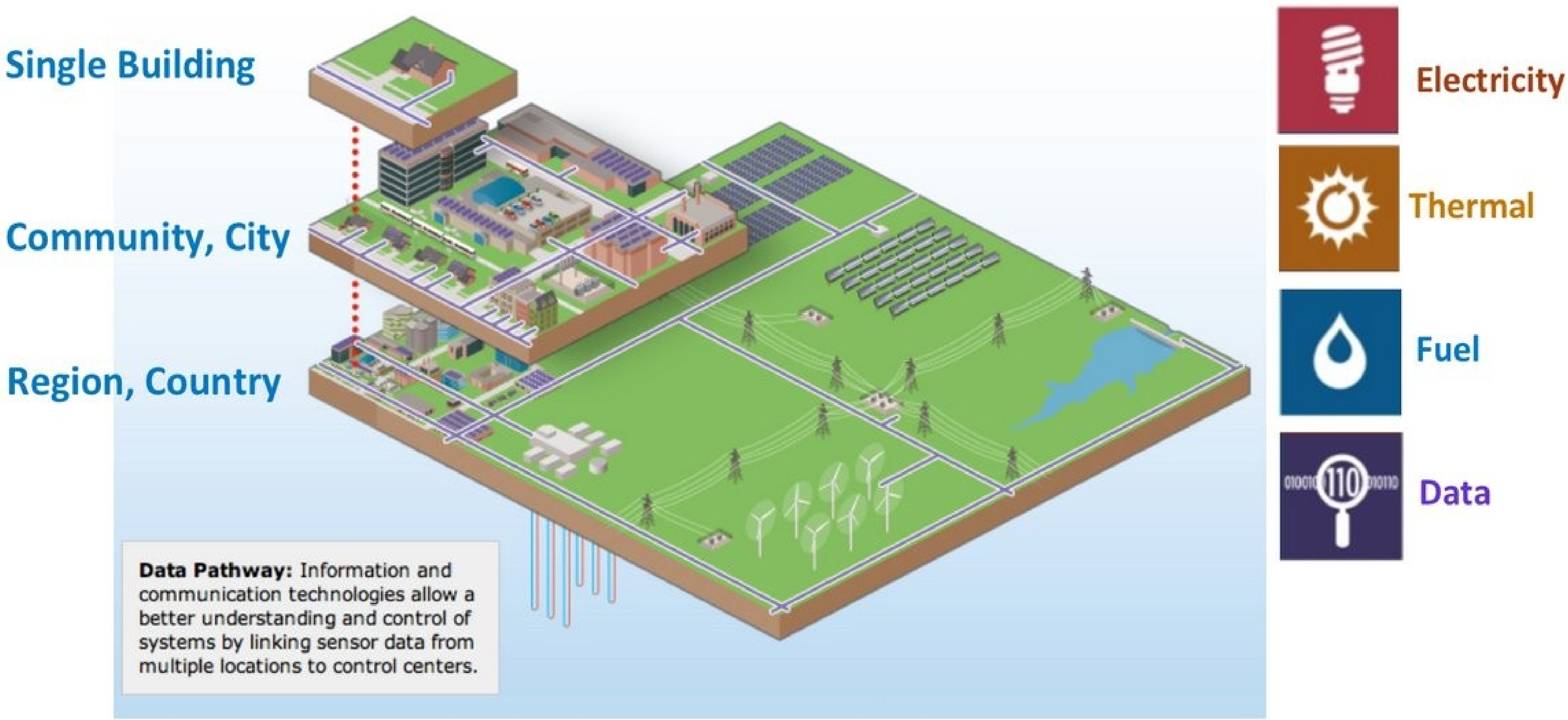


Solar district heating in Denmark



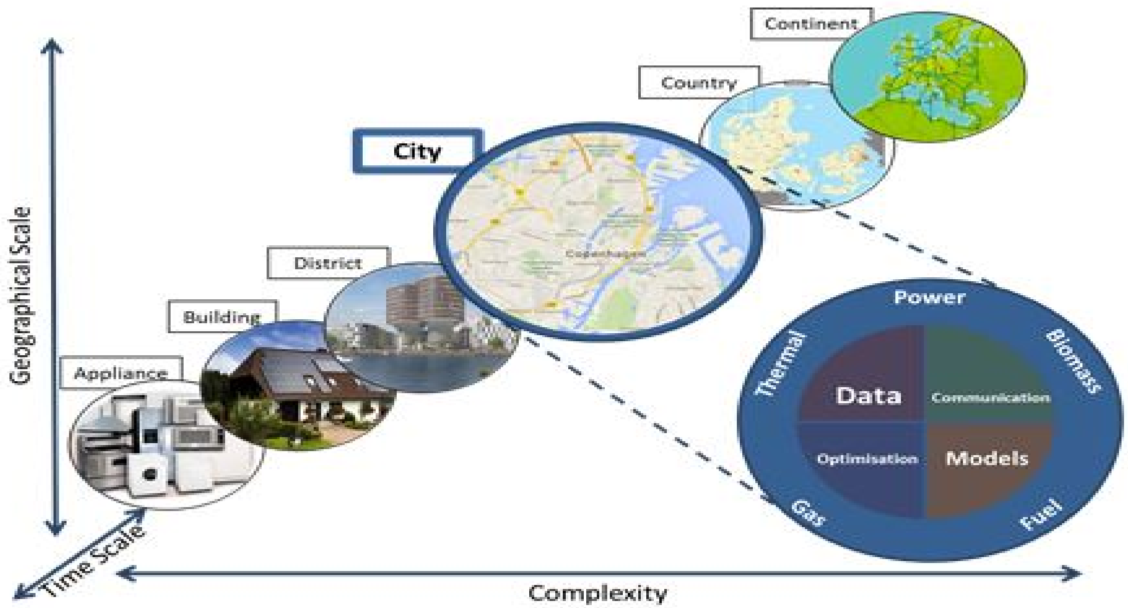
Energy Systems Integration

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

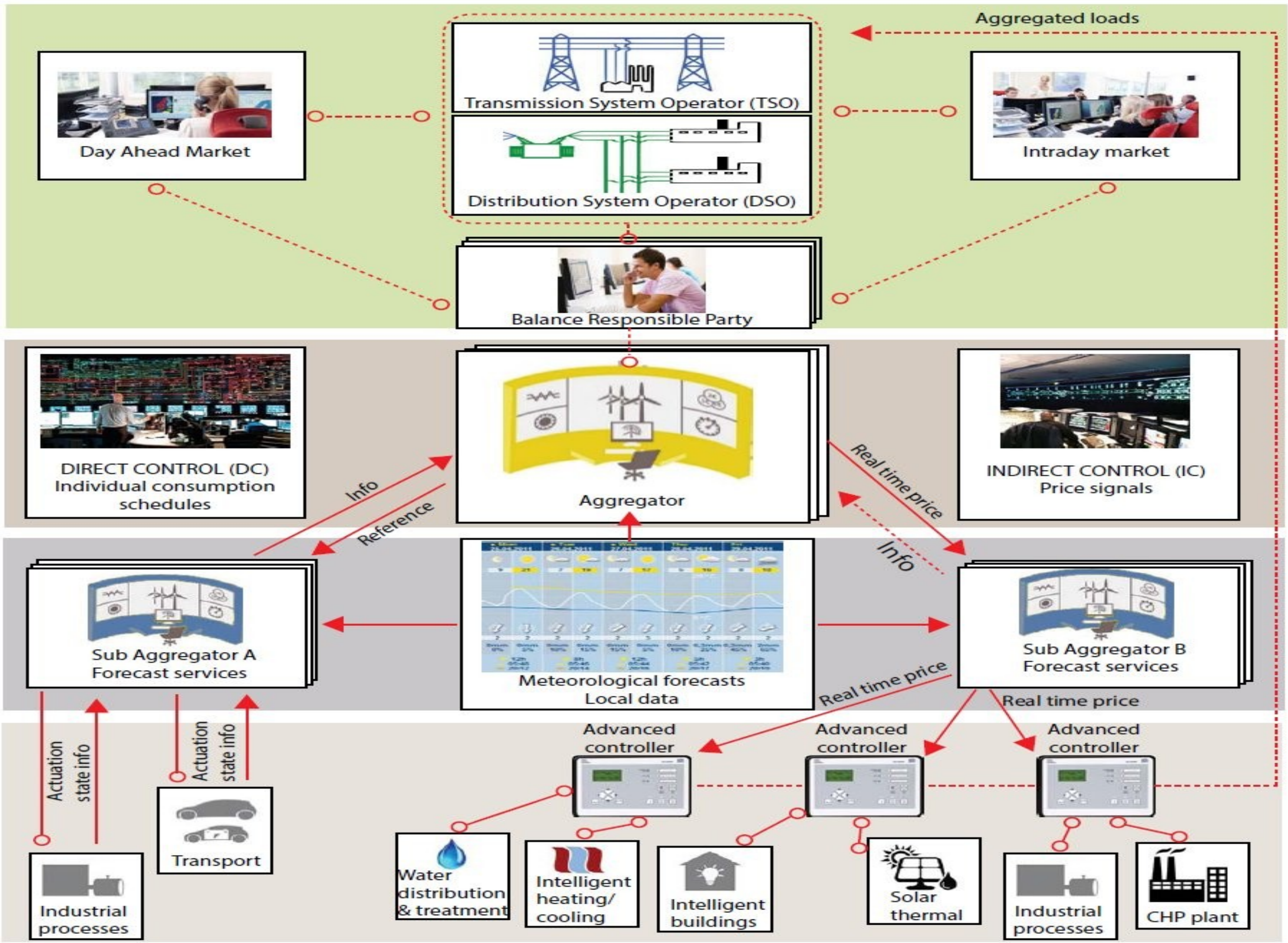


Flexible Solutions and CITIES

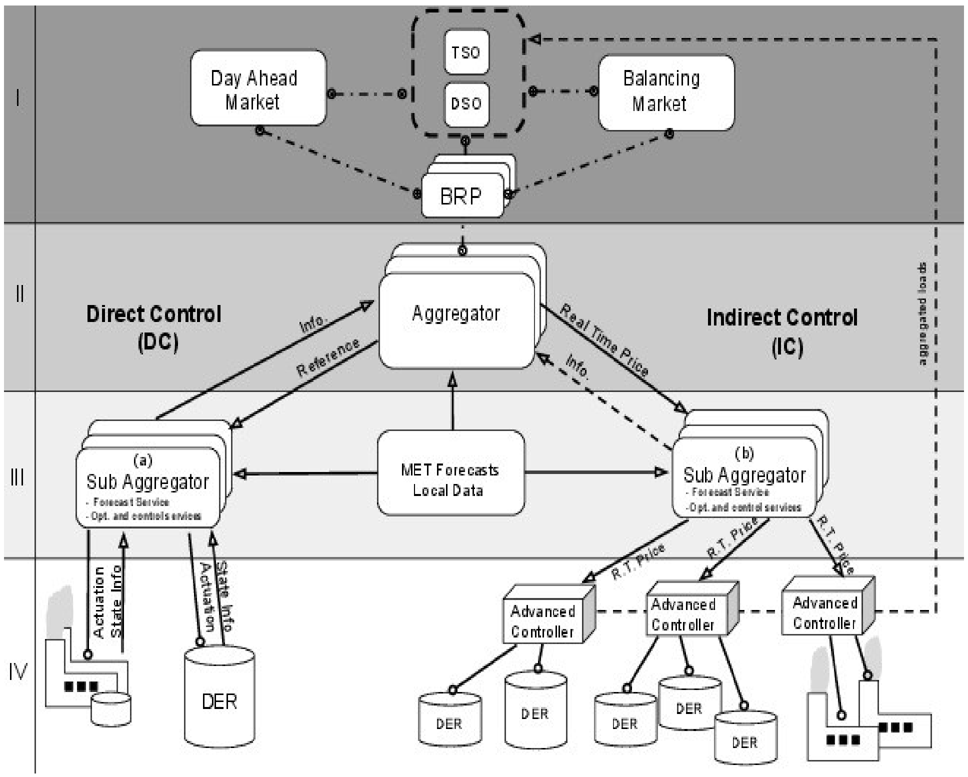
The ***Center for IT-Intelligent Energy Systems in Cities (CITIES)*** is aiming at establishing methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales.



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

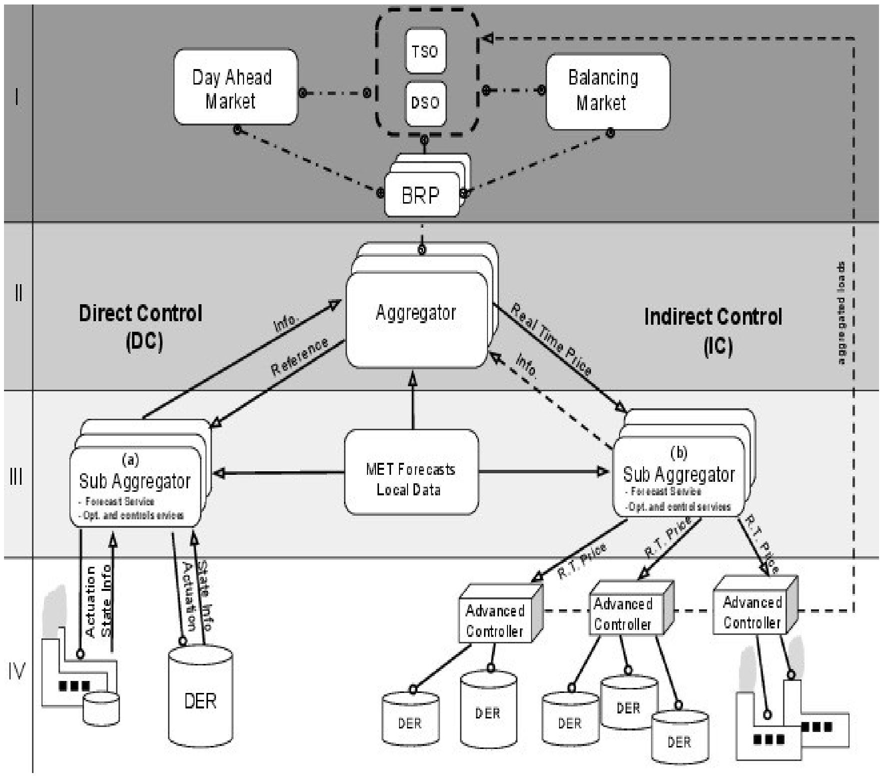
Simple 'contracts'

Direct vs Indirect Control

<table>
<tr><th>Level</th><th>Direct Control (DC)</th><th>Indirect Control (IC)</th></tr>
<tr><td>III</td><td rowspan="2">$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$
$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$
s.t. $\quad x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$</td><td>$\min_{\hat{z},p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$
s.t. $\quad \hat{z}_{k+1} = f(p_k)$</td></tr>
<tr><td>IV</td><td>$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$
s.t. $\quad x_{k+1} = f_j(x_k, u_k)$</td></tr>
</table>

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.

Forecast requirements



Day Ahead:

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

Direct Control: .

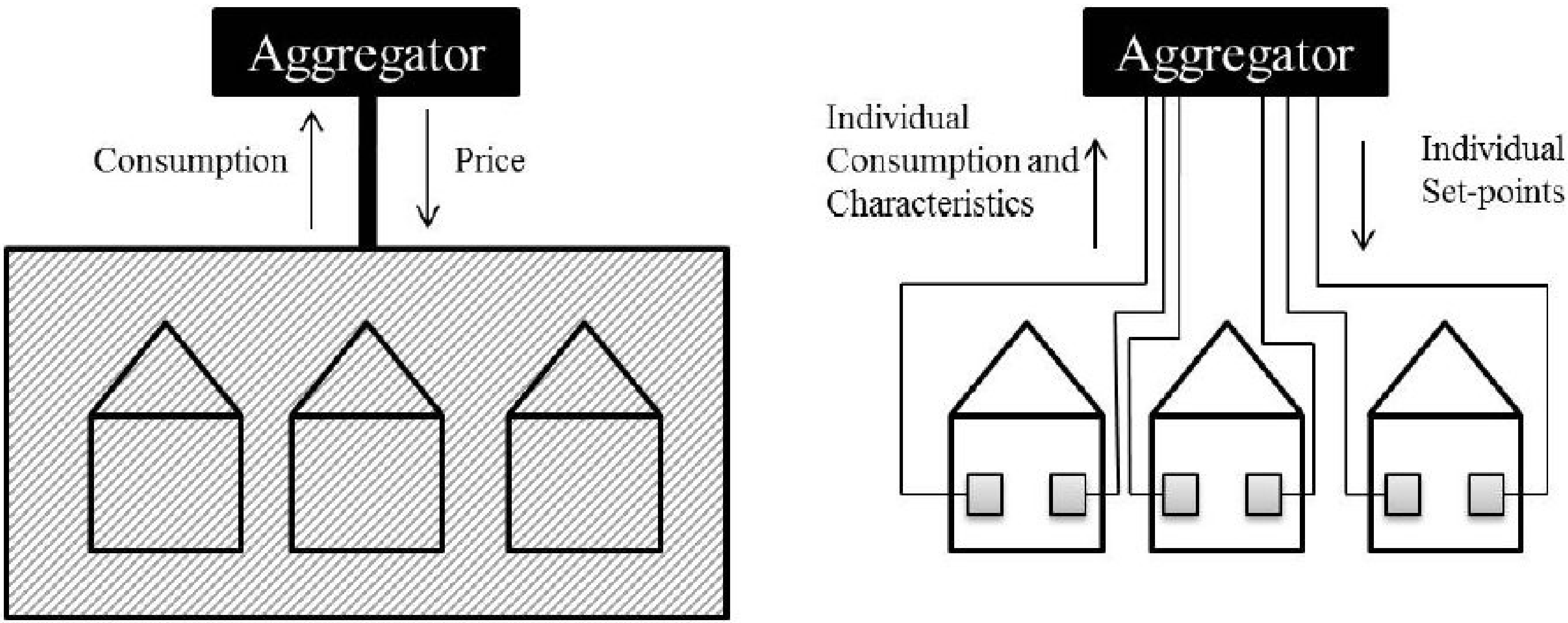
- Forecasts of states of DERs
- Forecasts of load

Indirect Control:

- Forecasts of prices
- Forecasts of load

Direct and Indirect Control

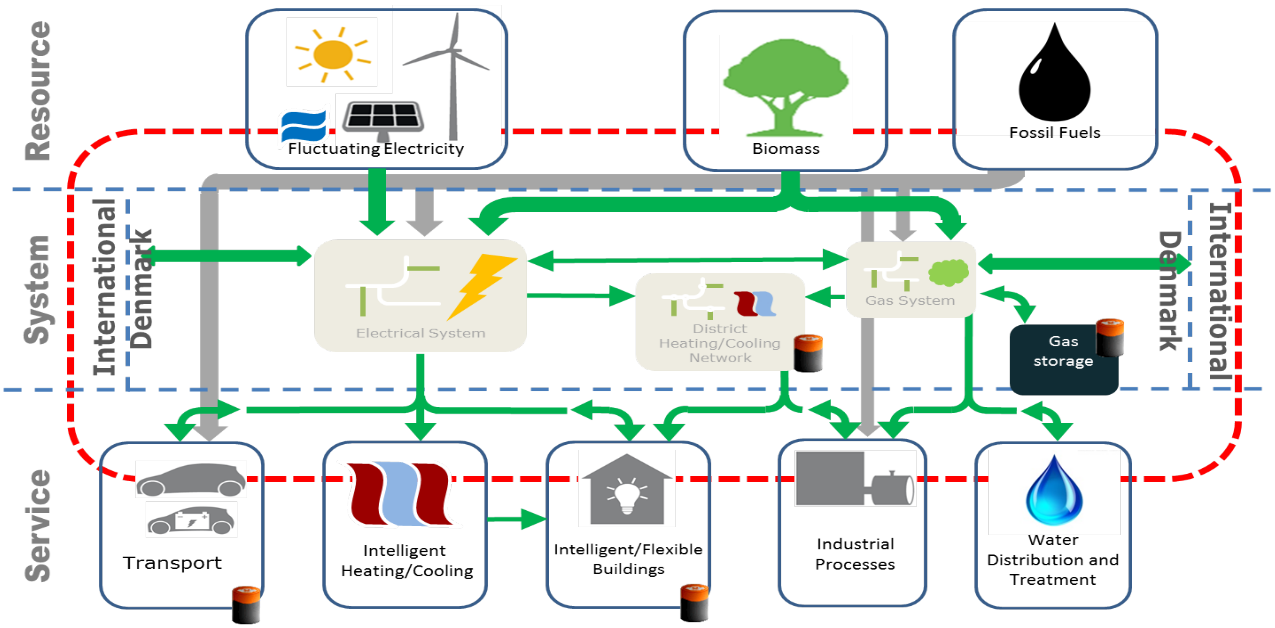
For DC info about individual states and constraints are needed



(a) Indirect control (b) Direct control

Models

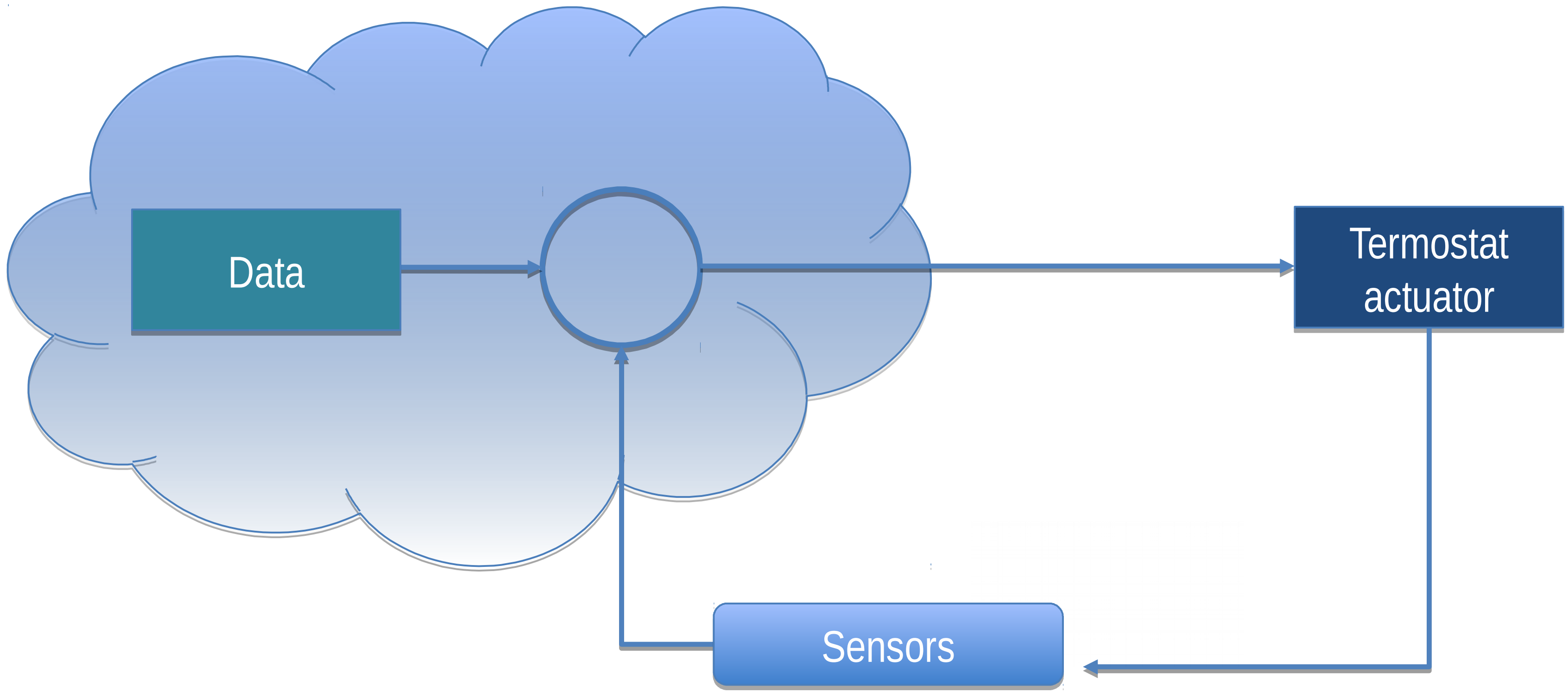
Grey-box modelling are used to establish **models and methods** **for real-time operation of future electric energy systems**



SE-OS Characteristics

- Bidding – clearing – activation at higher levels
- Control principles at lower levels
- Cloud based solution for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ...)
- Allow for new players (specialized aggregators)
- Simple setup for the communication
- Simple (or no) contracts
- Rather simple to implement
- Harvest flexibility at all levels

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



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Software solutions

Software for combined physical and statistical modelling

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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

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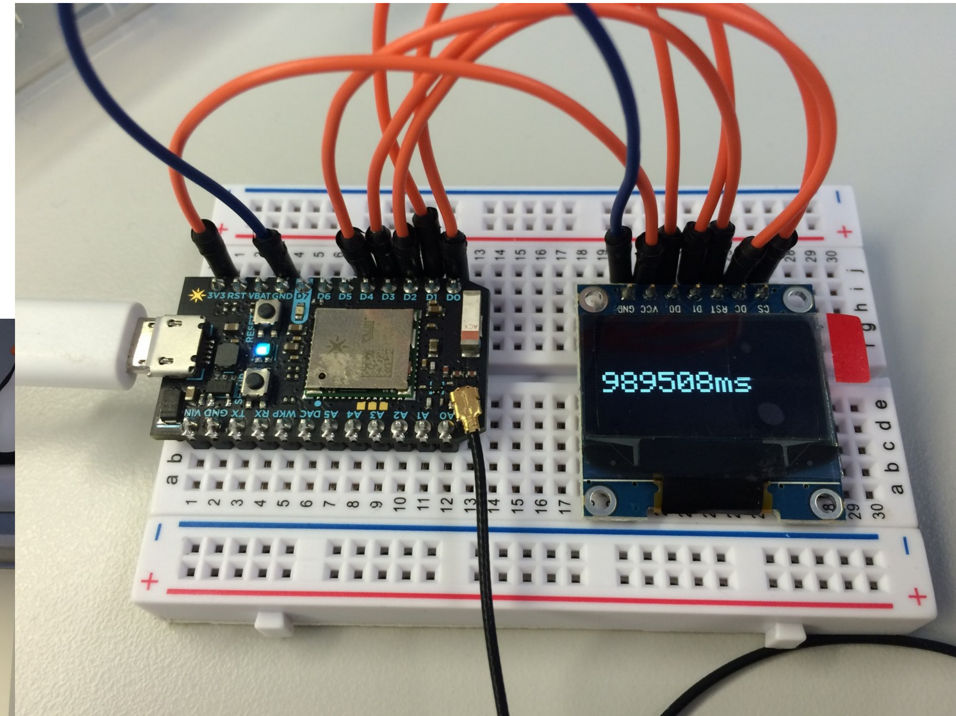
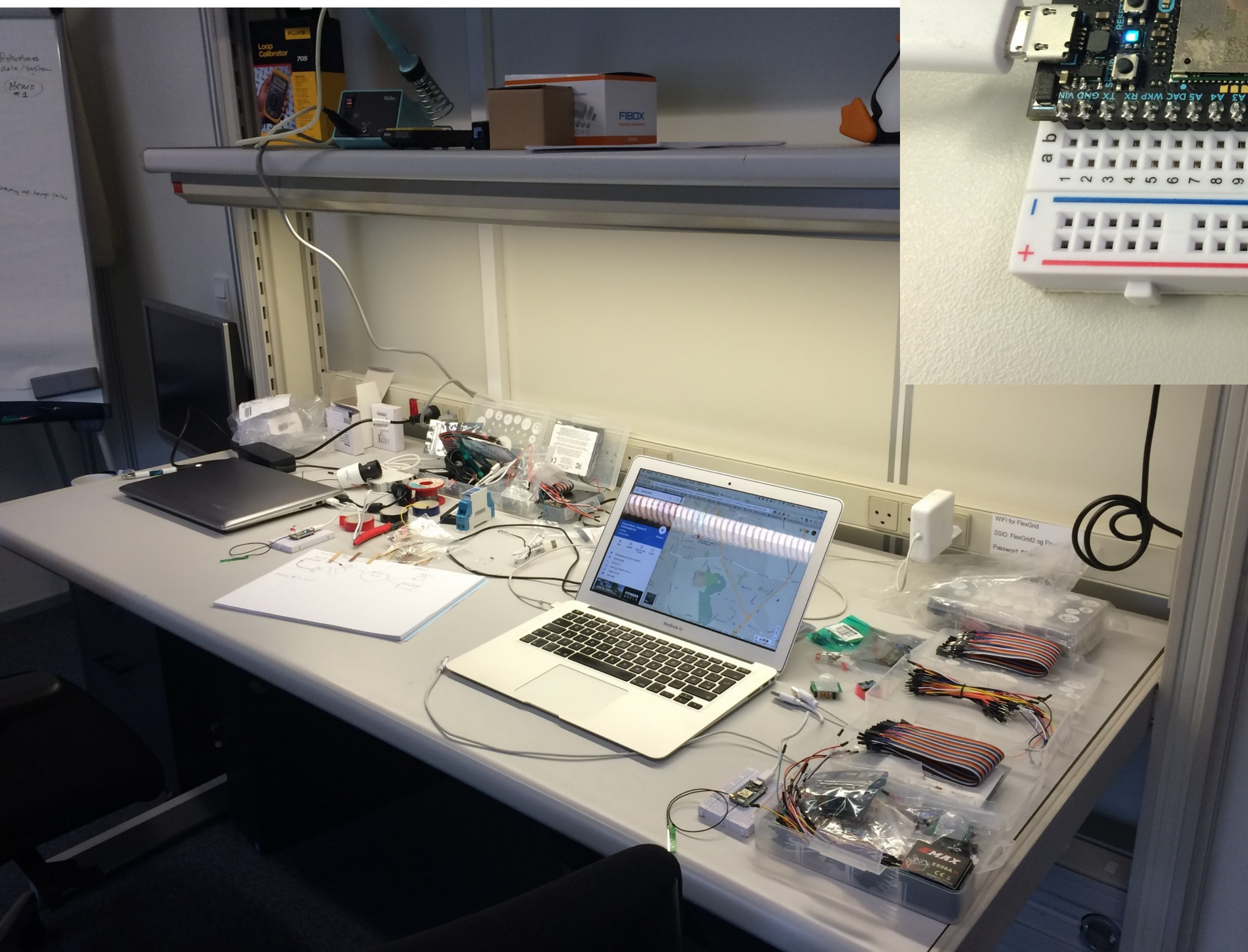
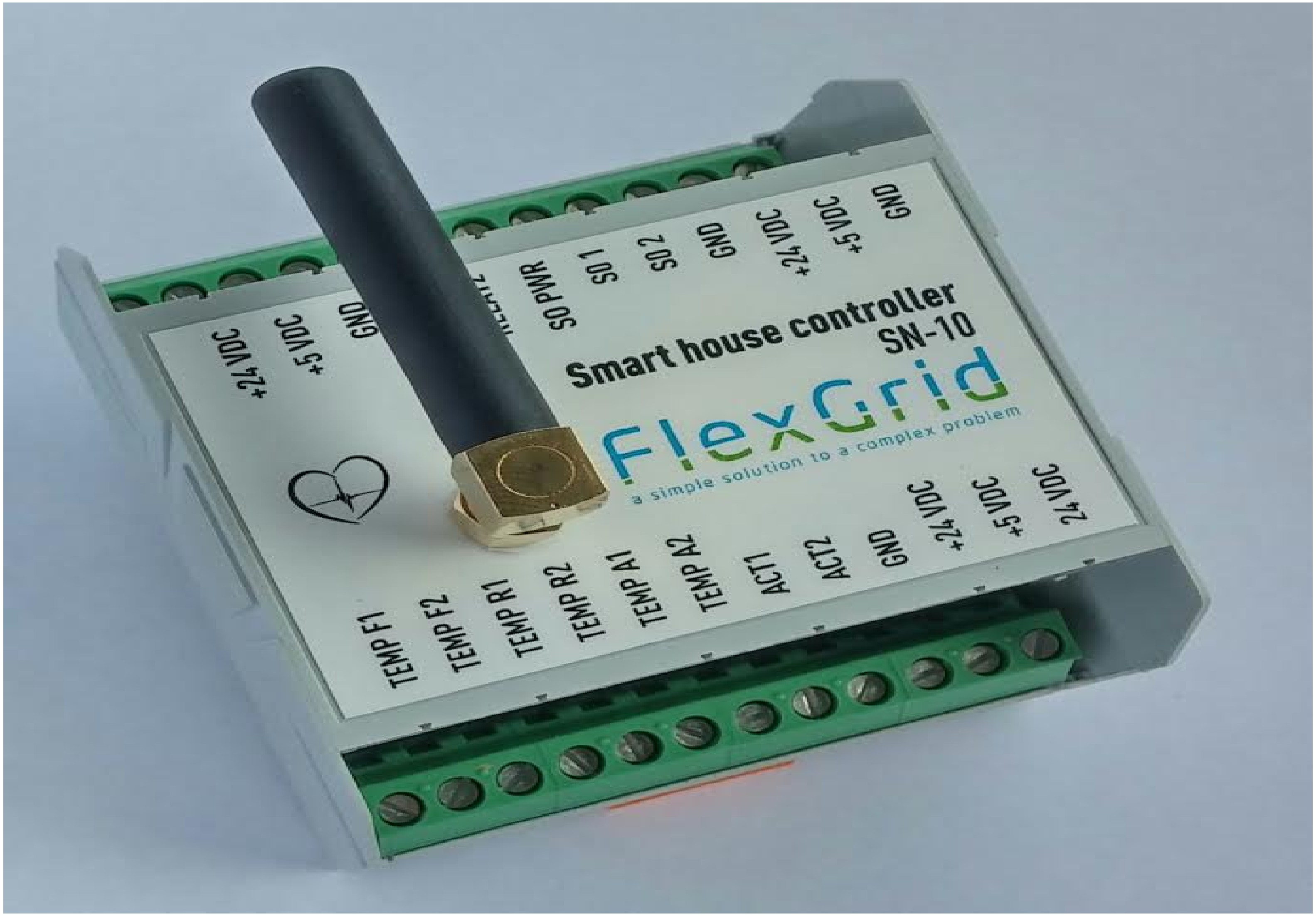
- Summer School – Granada, Spain, June 19th-24th 2016
- Third general consortium meeting – DTU, May 24th-25th 2016
- Smart City Challenge in Copenhagen – April 20th 2016
- Guest lecture by Pierluigi Mancarella at DTU, April 6th

Lab testing ….


3V3 RST VBAT GND D7 D6 D5 D4 D3 D2 D1 D0
VIN GND TX RX WKP DAC A5 A4 A3 A2 A1 A0
GND VCC D0 D1 RST DC CS
989508ms

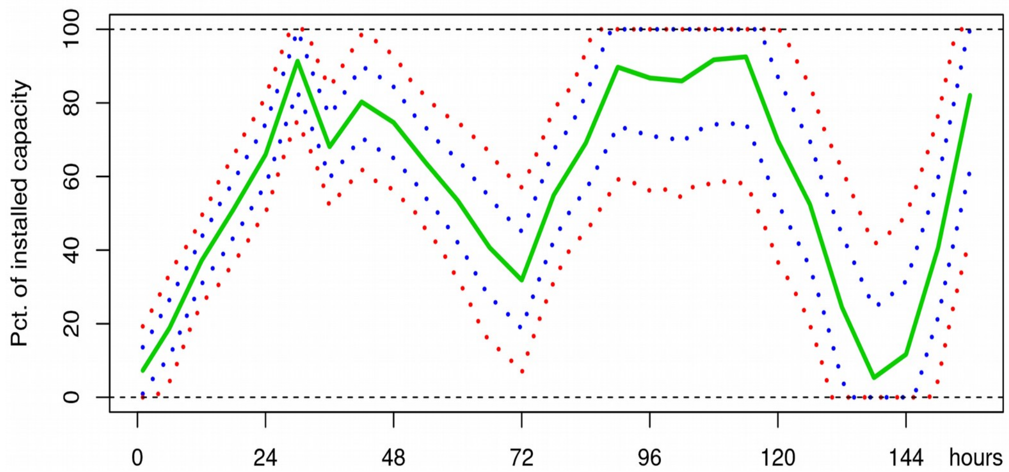


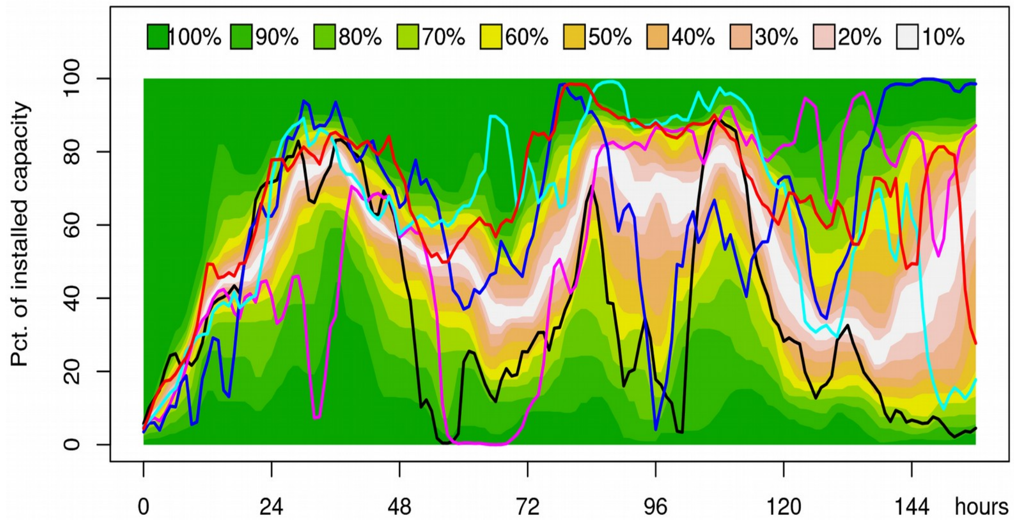
SN-10 Smart House Prototype



Which type of forecast?

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



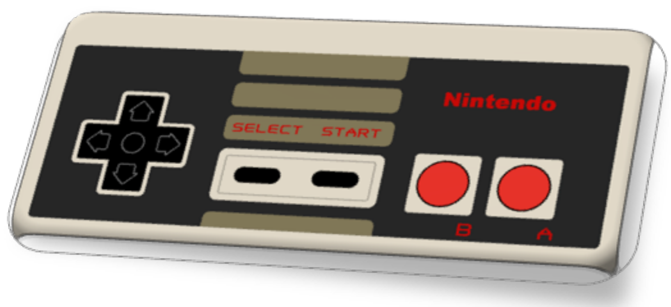


Wind and Solar Power Forecasting

- 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, ...)

Example

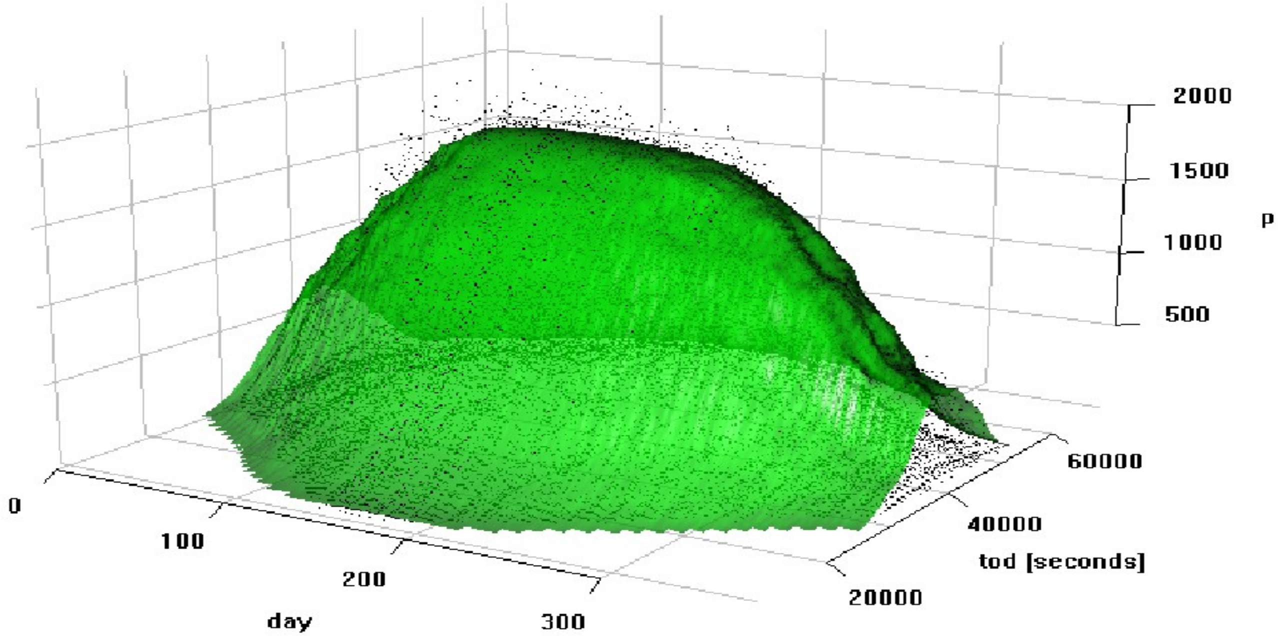
Solar Power Forecasting



Solar Power Forecasting

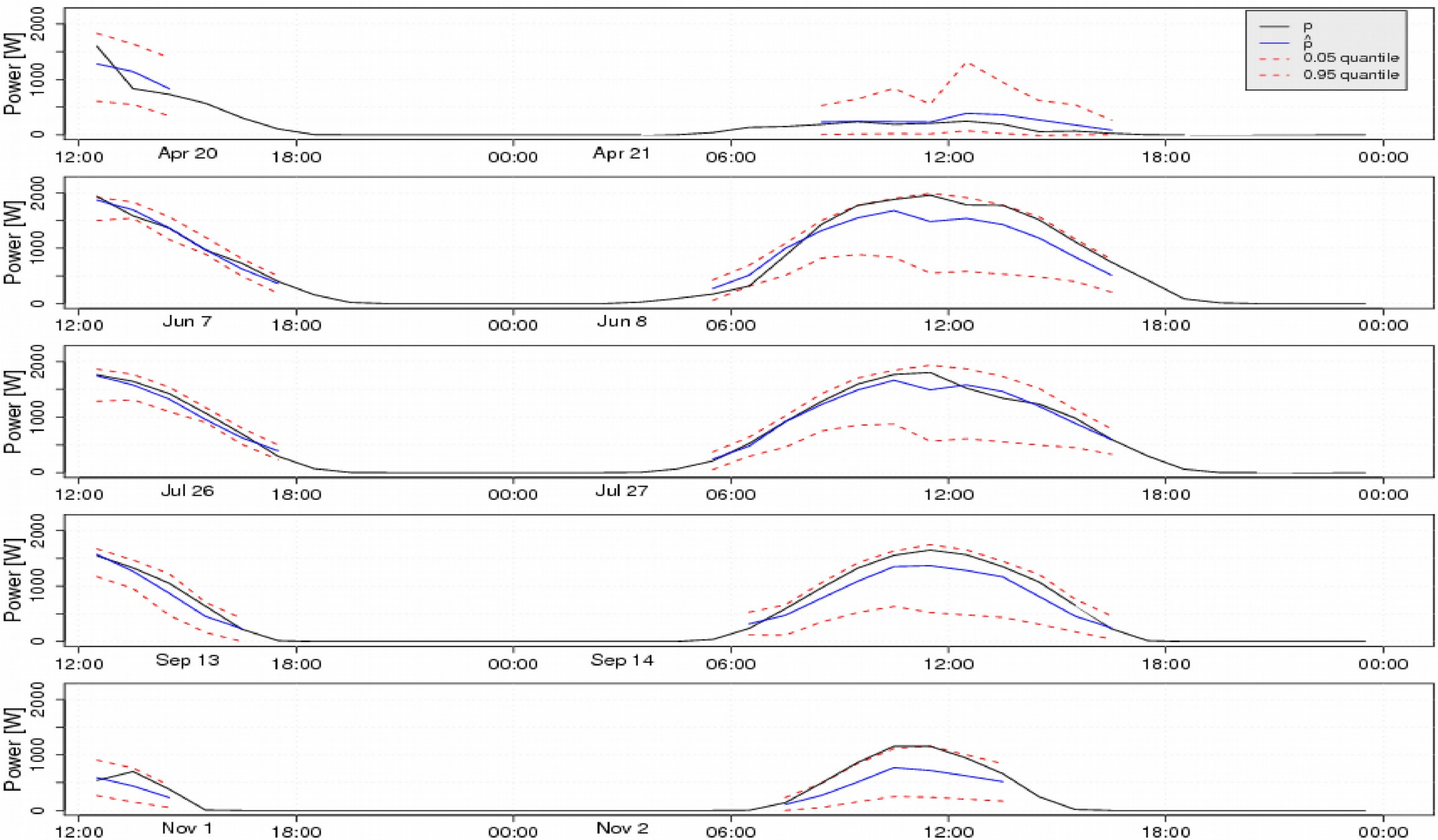
- Grid connected PV-systems mainly installed on rooftops
- Average of output from 21 PV systems in Brædstrup

Method

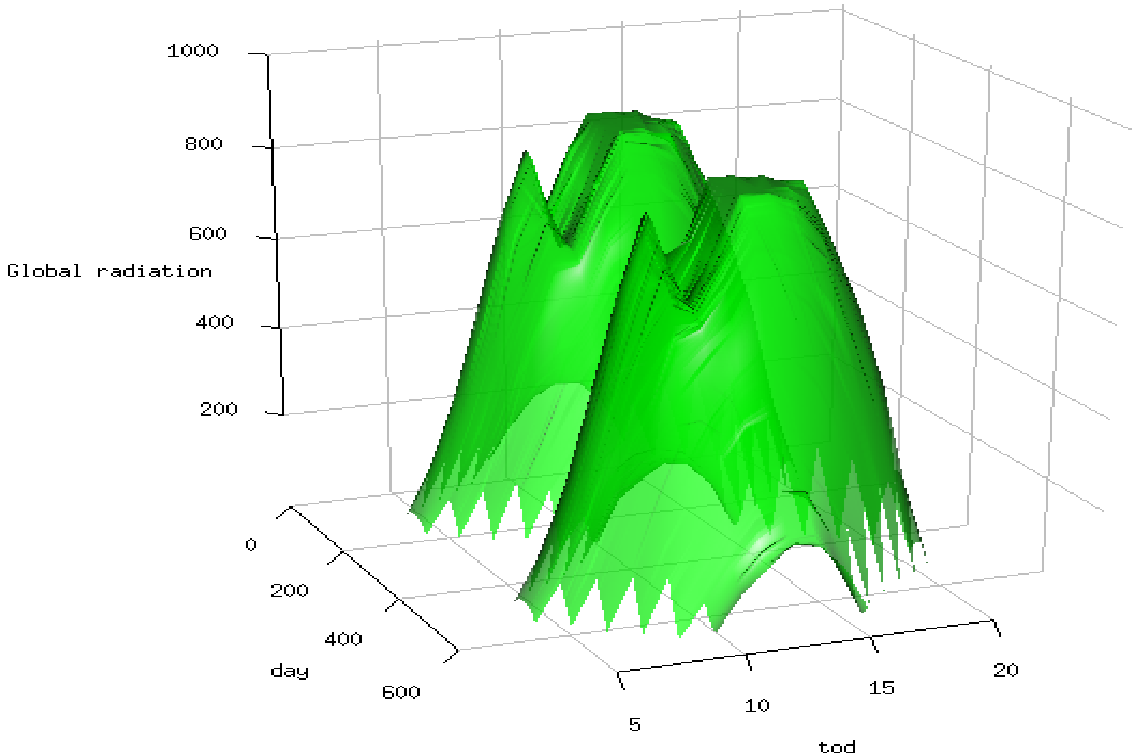


- **Based on MET forecasts and online readings of output**
- **Two-step method:**
  1) **Transformation to atmospheric transmittance with statistically clear sky (see above),**
  2) **A dynamic model + adaptive quantile regression.**

Example
(quantile forecasts – up to 36h ahead)

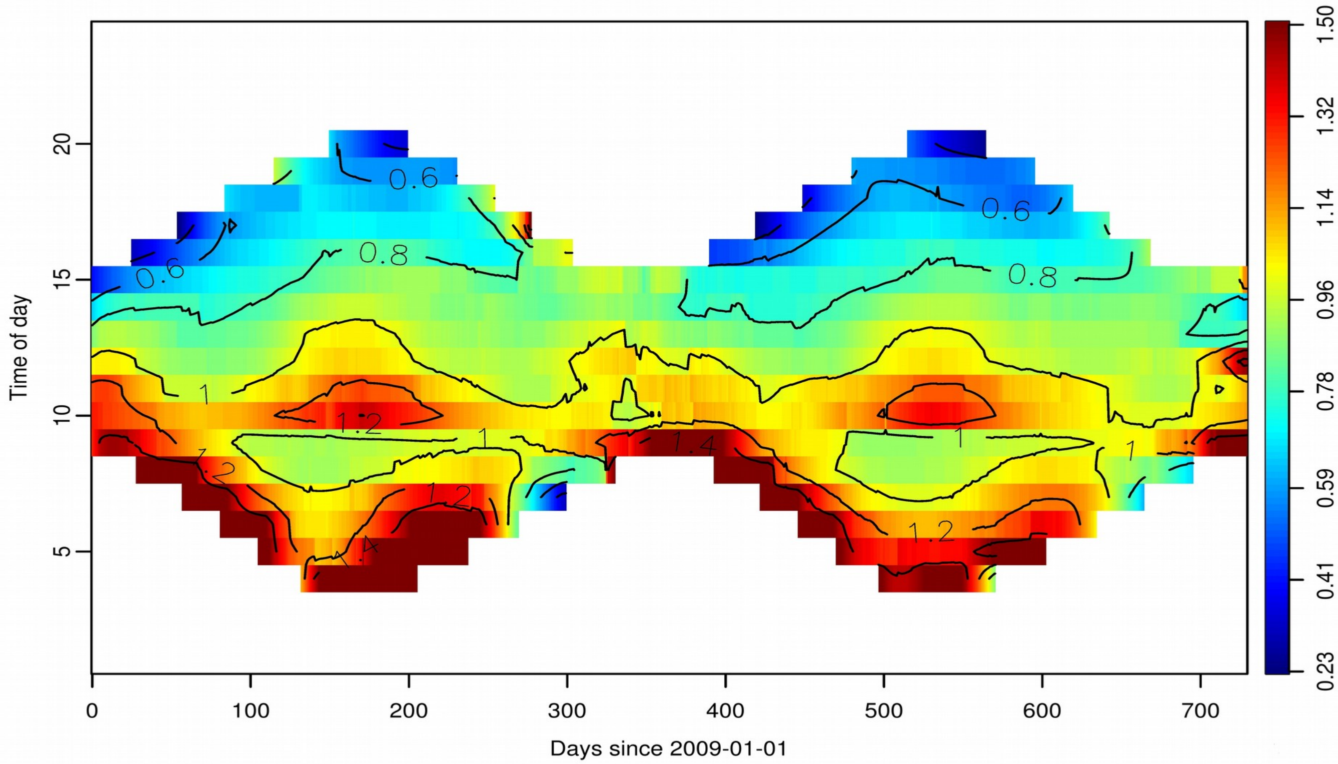


Adaptive correction method

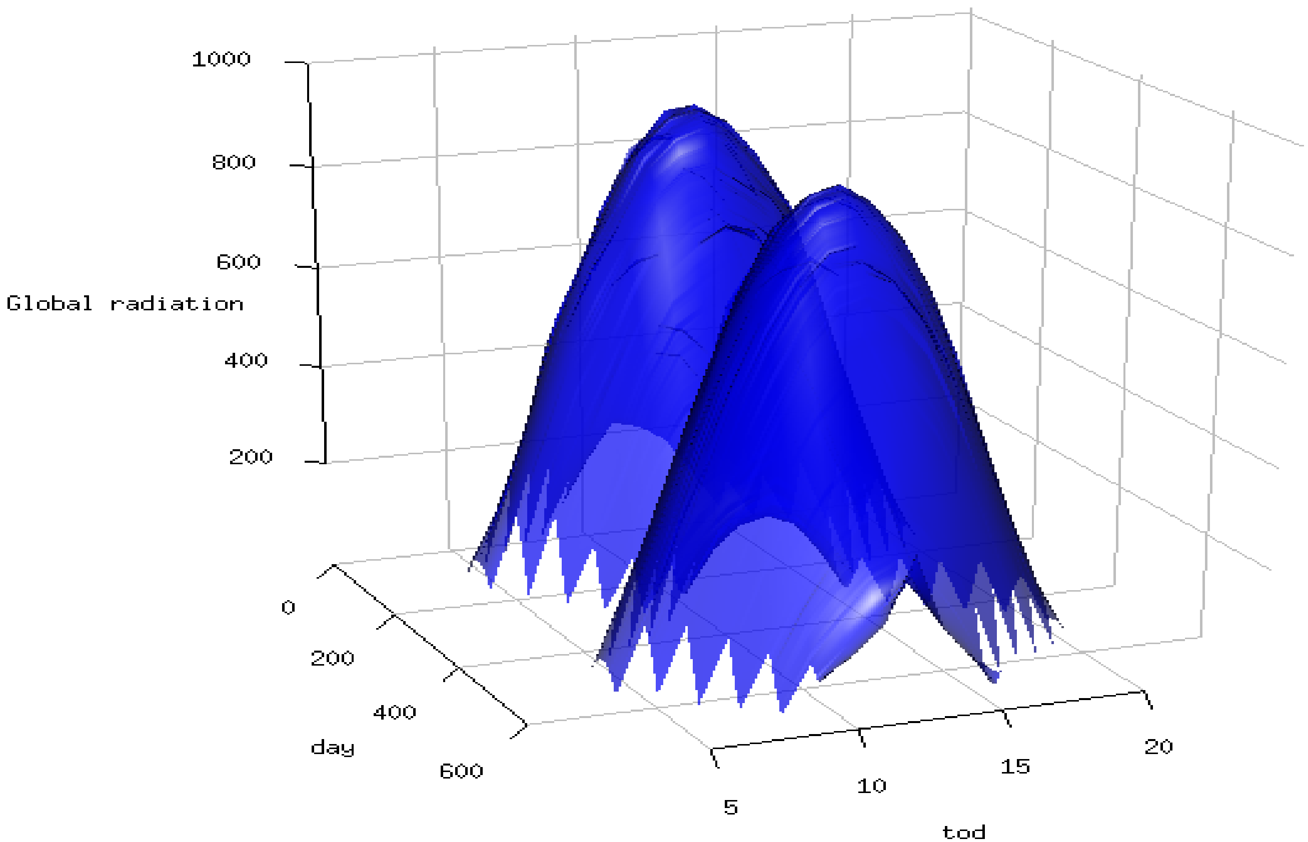


Adaptive correction method

Adaptive correction method (correction function)

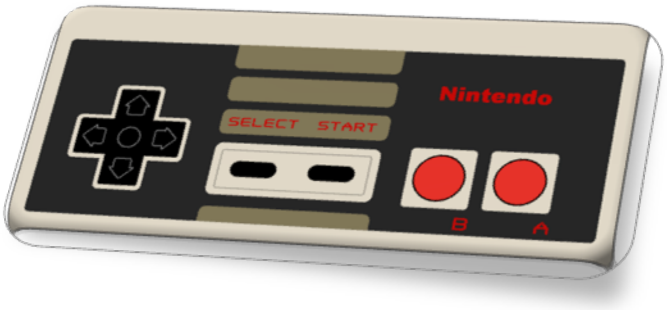


Adaptive correction method



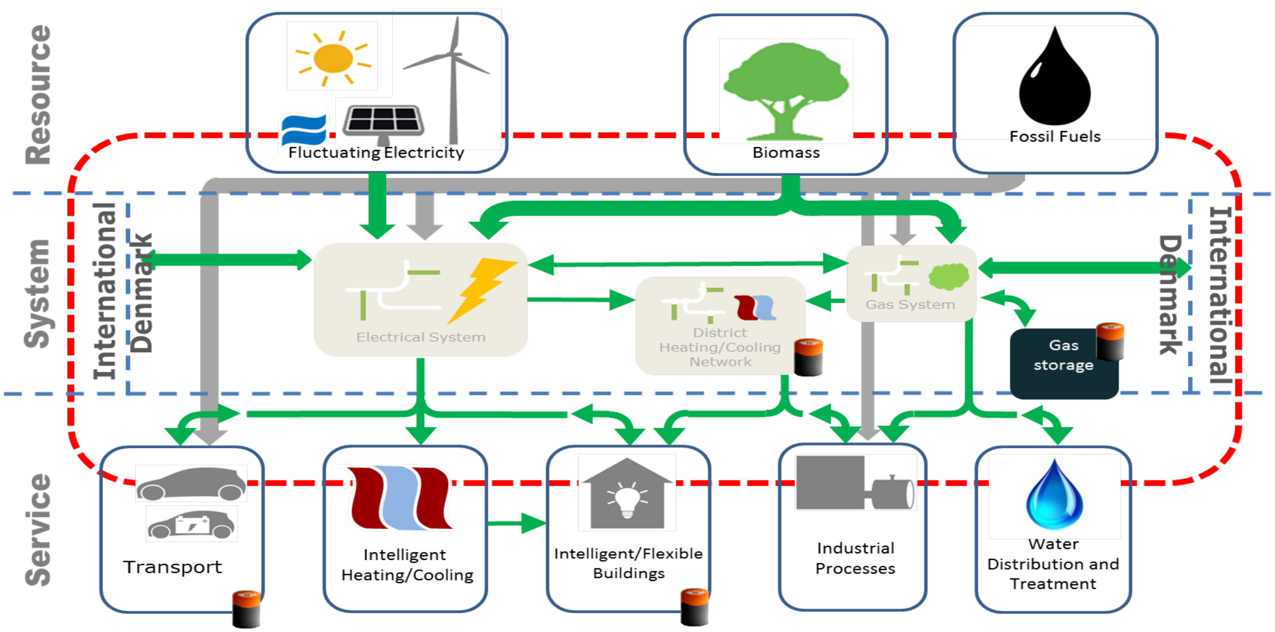
Example

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.**



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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

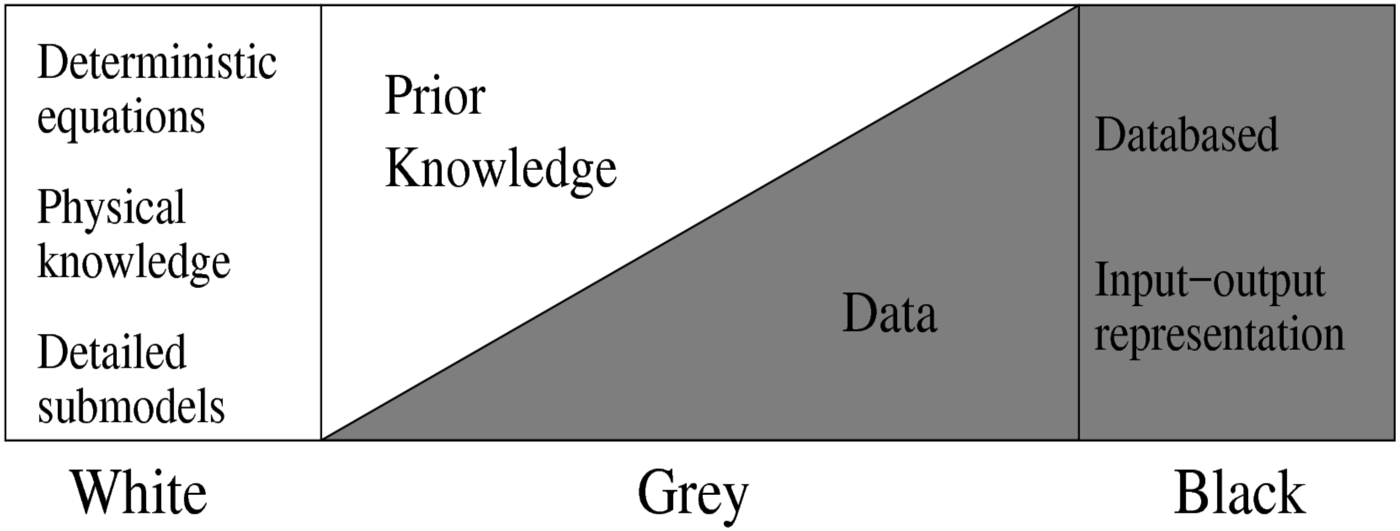
$$Y_k = h(X_k, u_k, t_k, \theta) + e_k,$$ Observation equation

Observation noise

Notation:

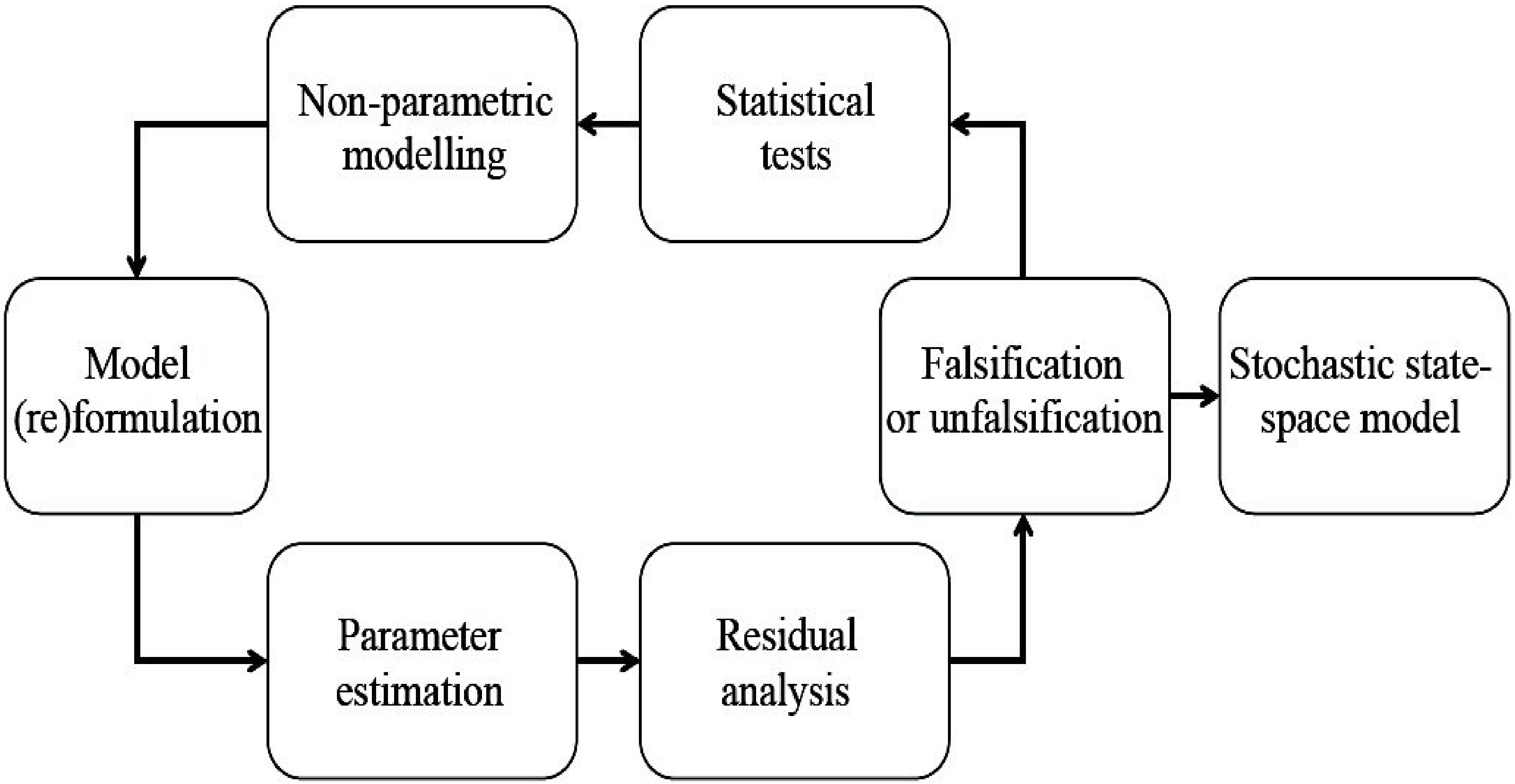
X_t:	State variables
u_t:	Input variables
θ:	Parameters
Y_k:	Output variables
t:	Time
ω_t:	Standard Wiener process
e_k:	White noise process with $N(0, S)$

Grey-box modelling concept



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

Grey-box model building



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

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Case study

Control of Power Consumption to Summer Houses with a Pool

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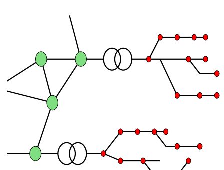
Services

Balancing

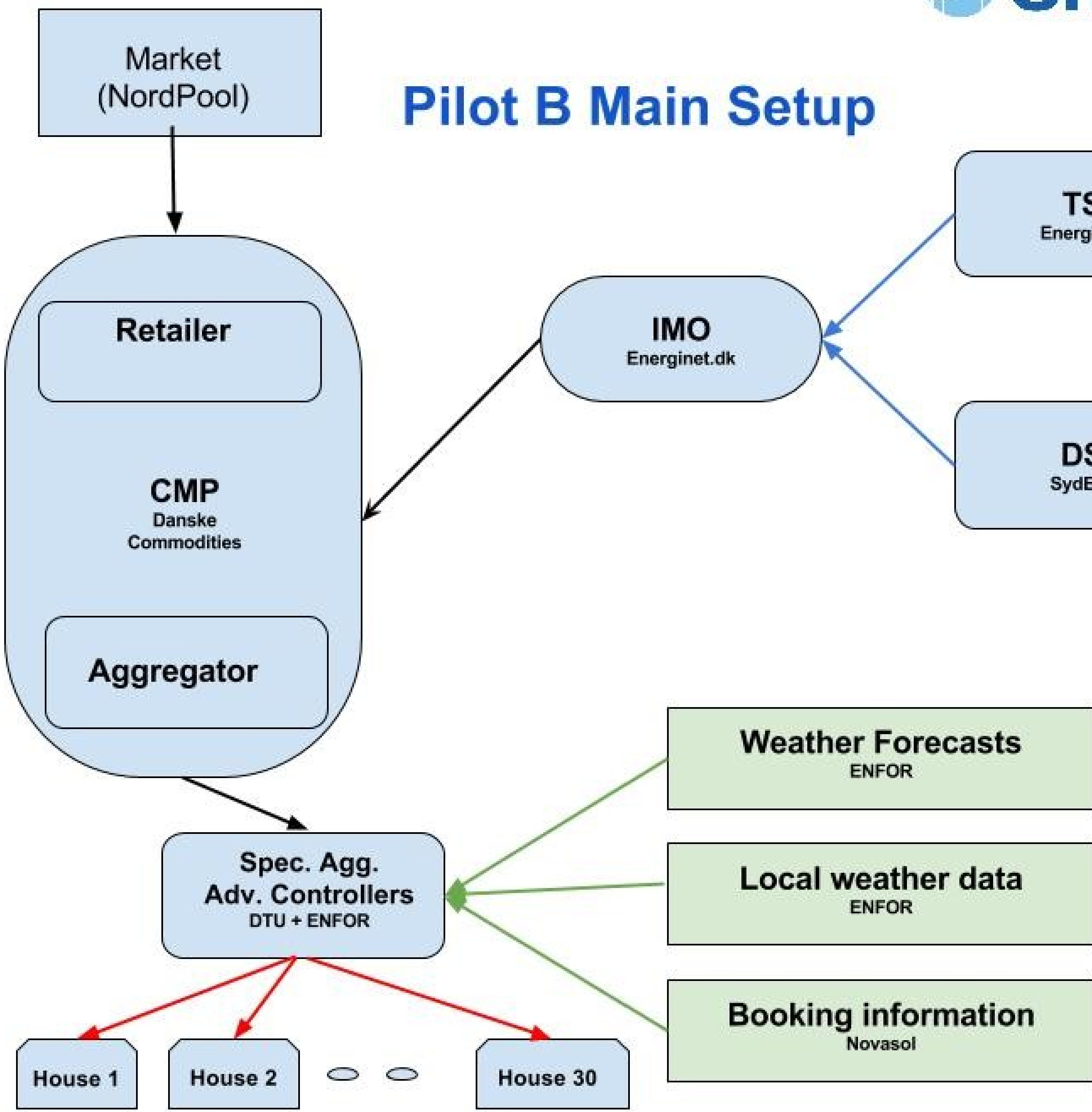
Voltage regulation (DSO)

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.

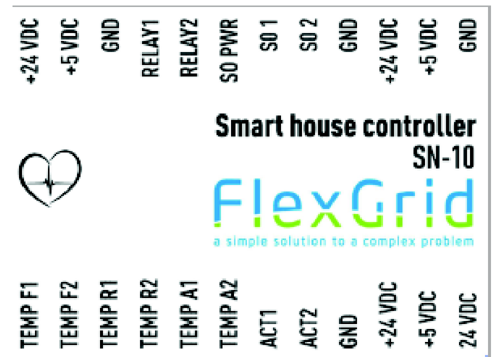
Pilot B Main Setup

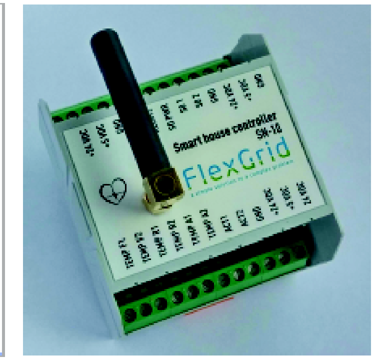


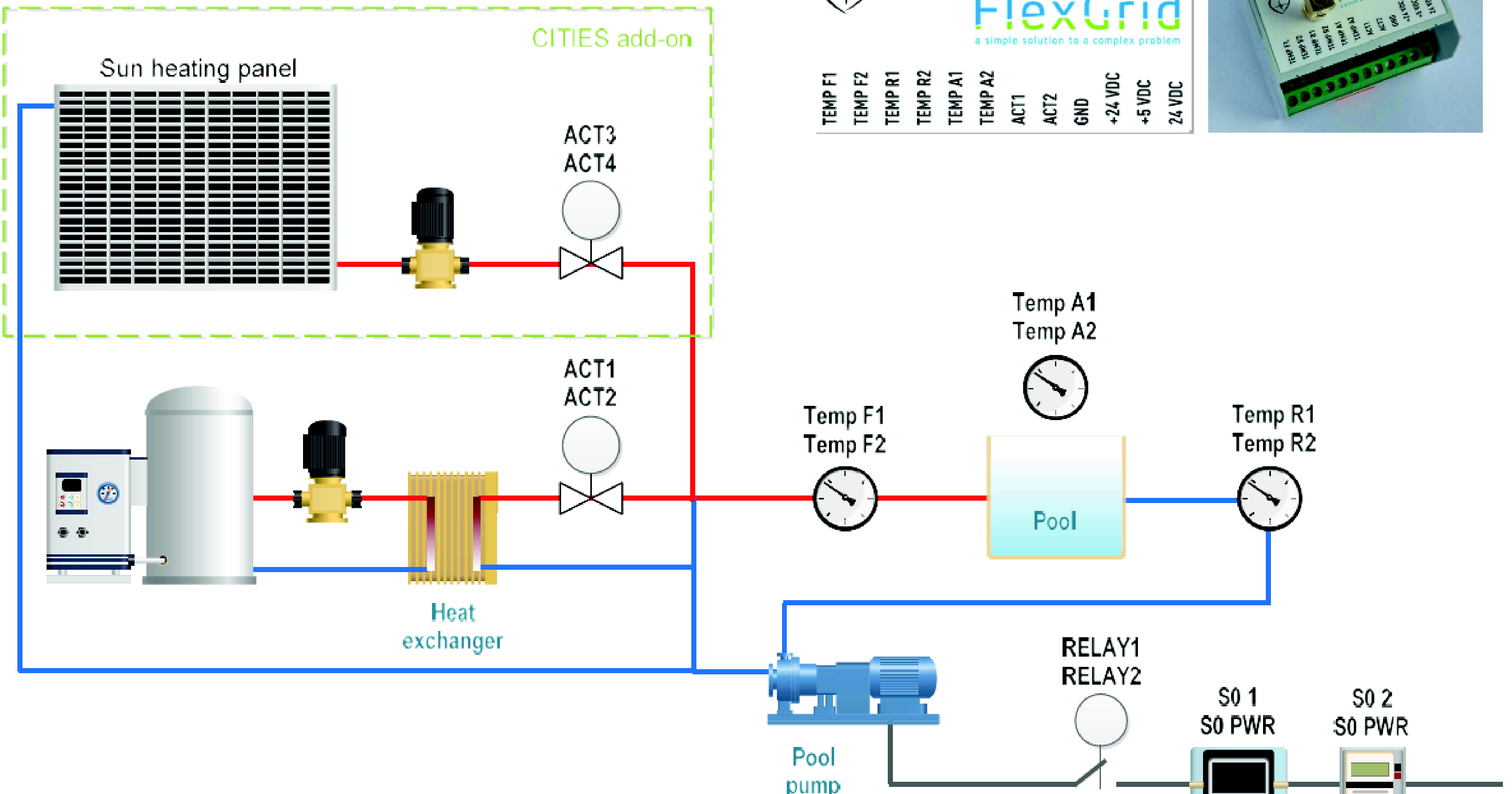
Smart Control of Houses with a Pool

PilotB SN-10 signal overview

revision 1.0 (CITIES add-on)







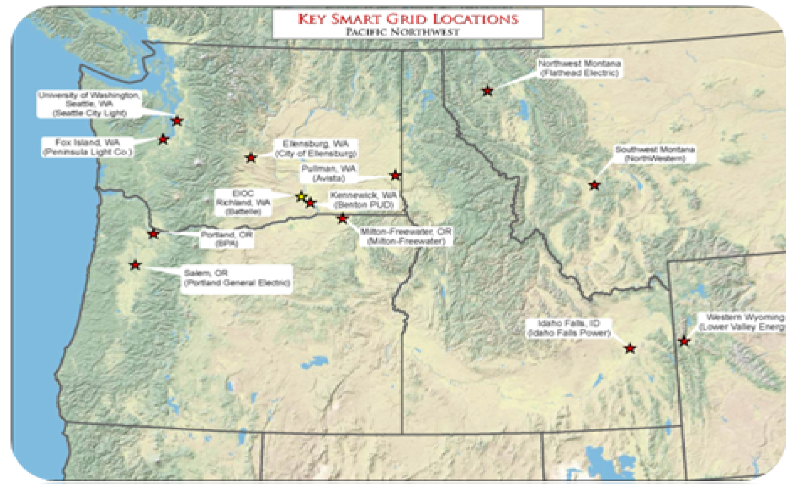
Case study

Control of Power Consumption (DSM) using the Thermal Mass of Buildings

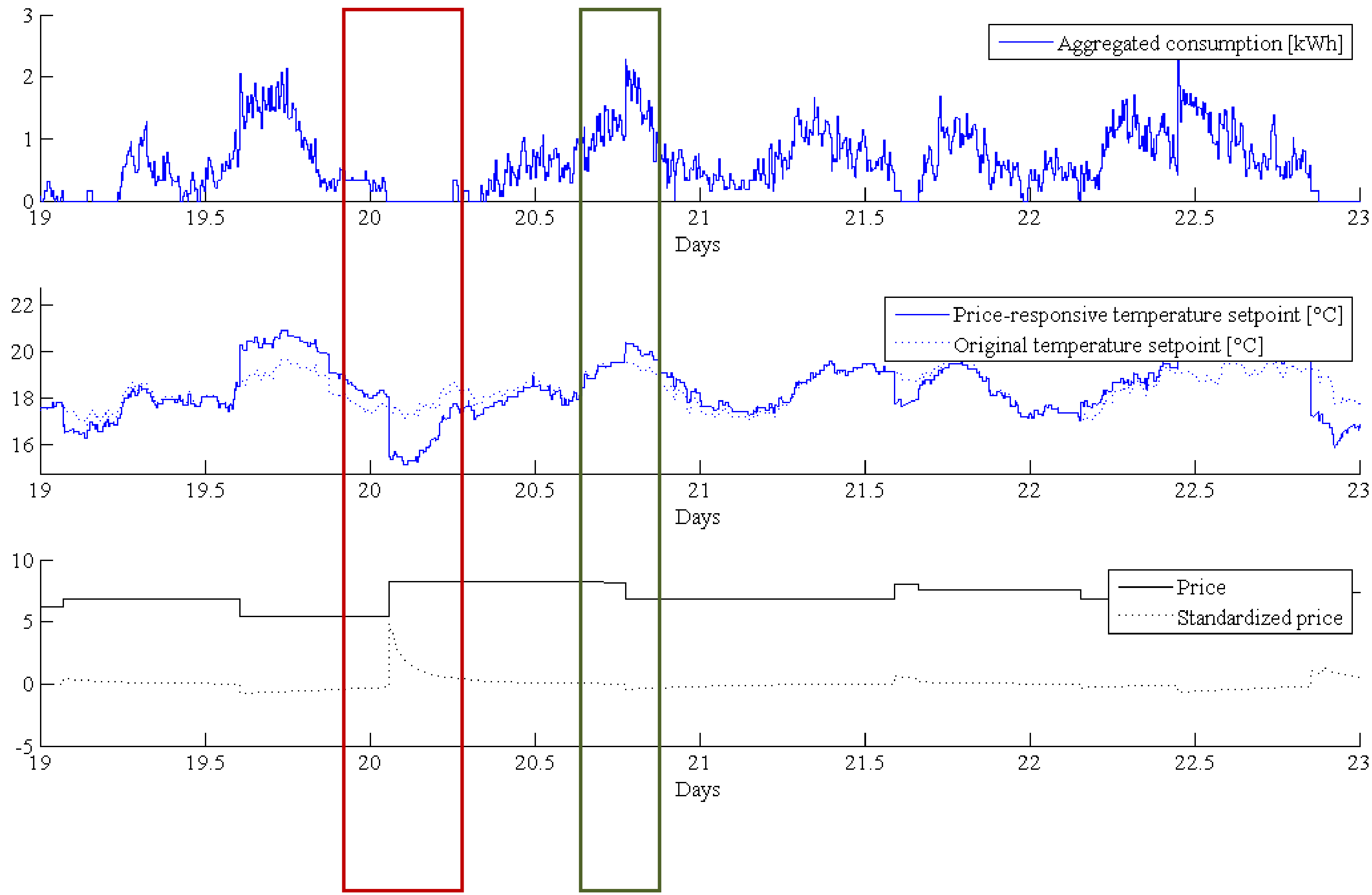
Data from BPA

Olympic Pensinsula project

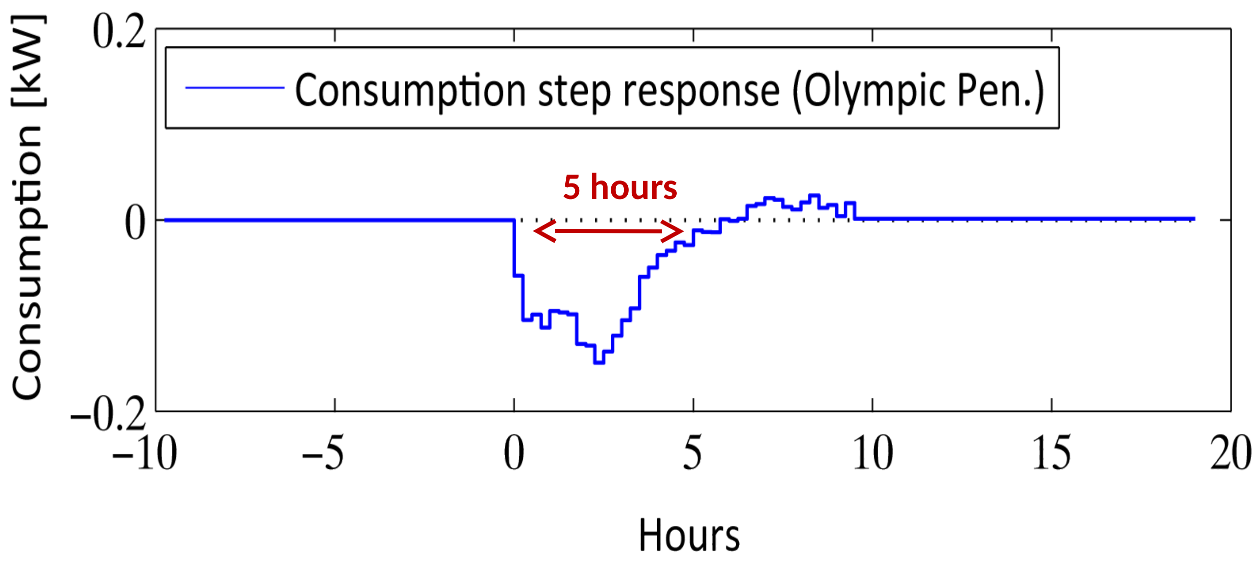
- 27 houses during one year
- Flexible appliances: HVAC,
  cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption



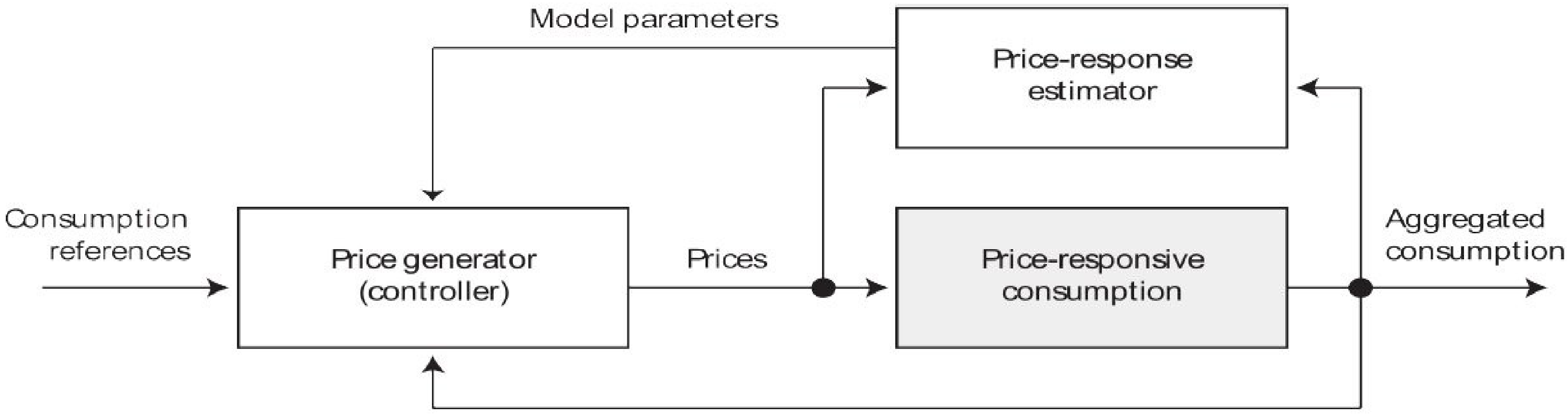
Aggregation (over 20 houses)

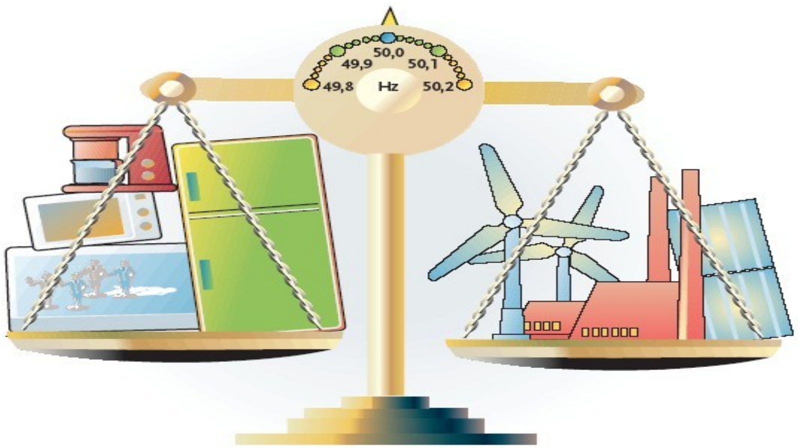


Response on Price Step Change



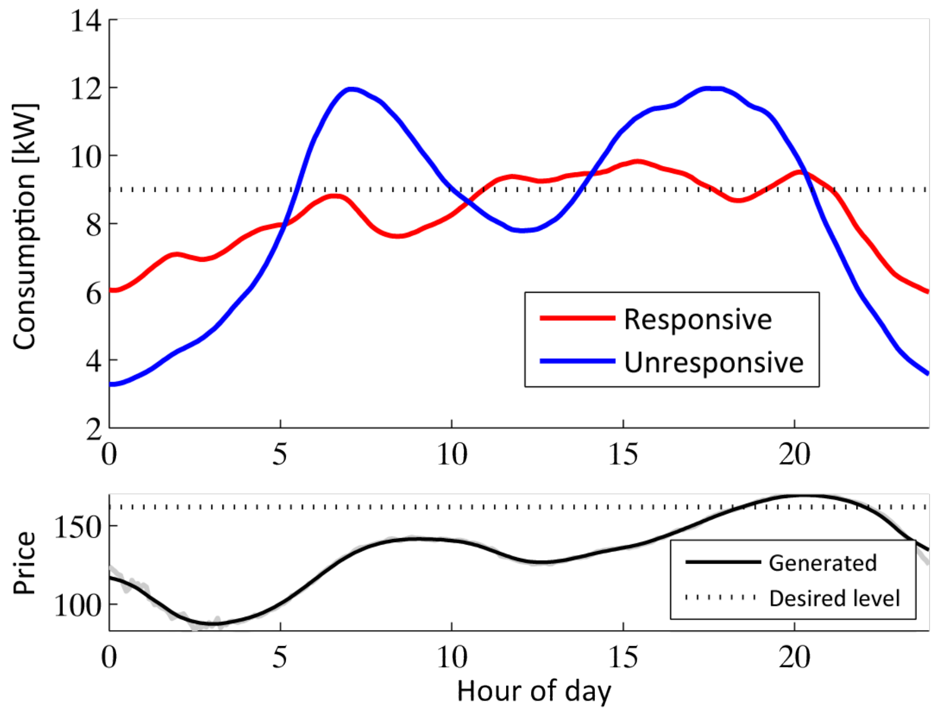
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**



DTU

Case study

Heat Pumps and Local Storage

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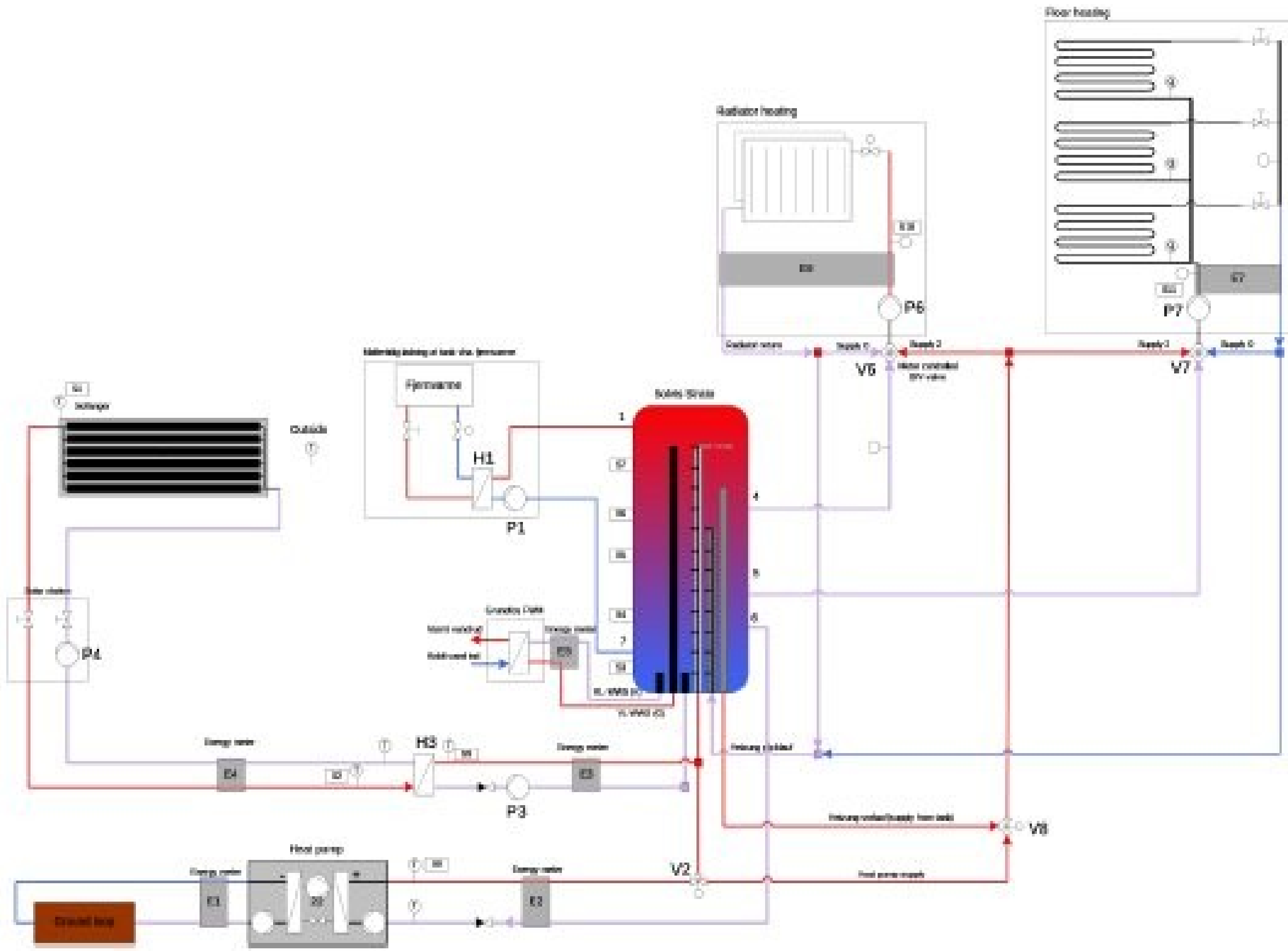
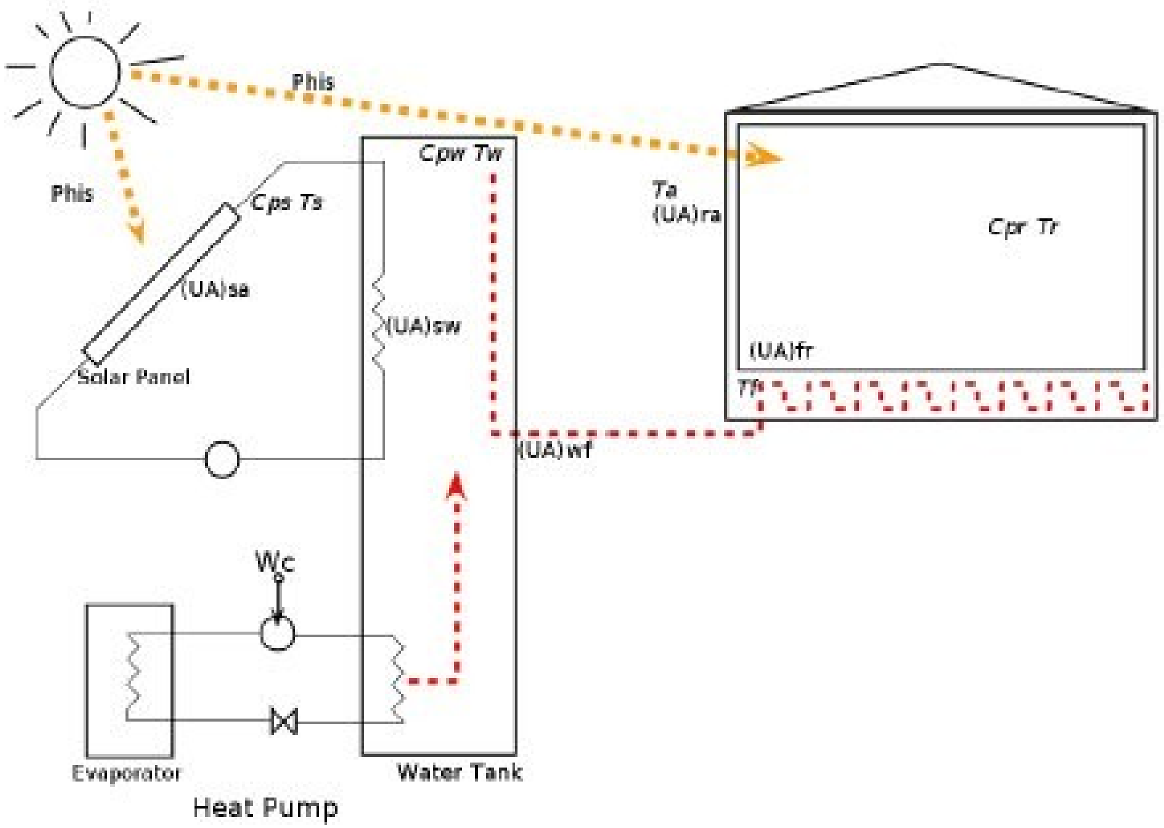
Grundfos Case Study

Schematic of the heating system



Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

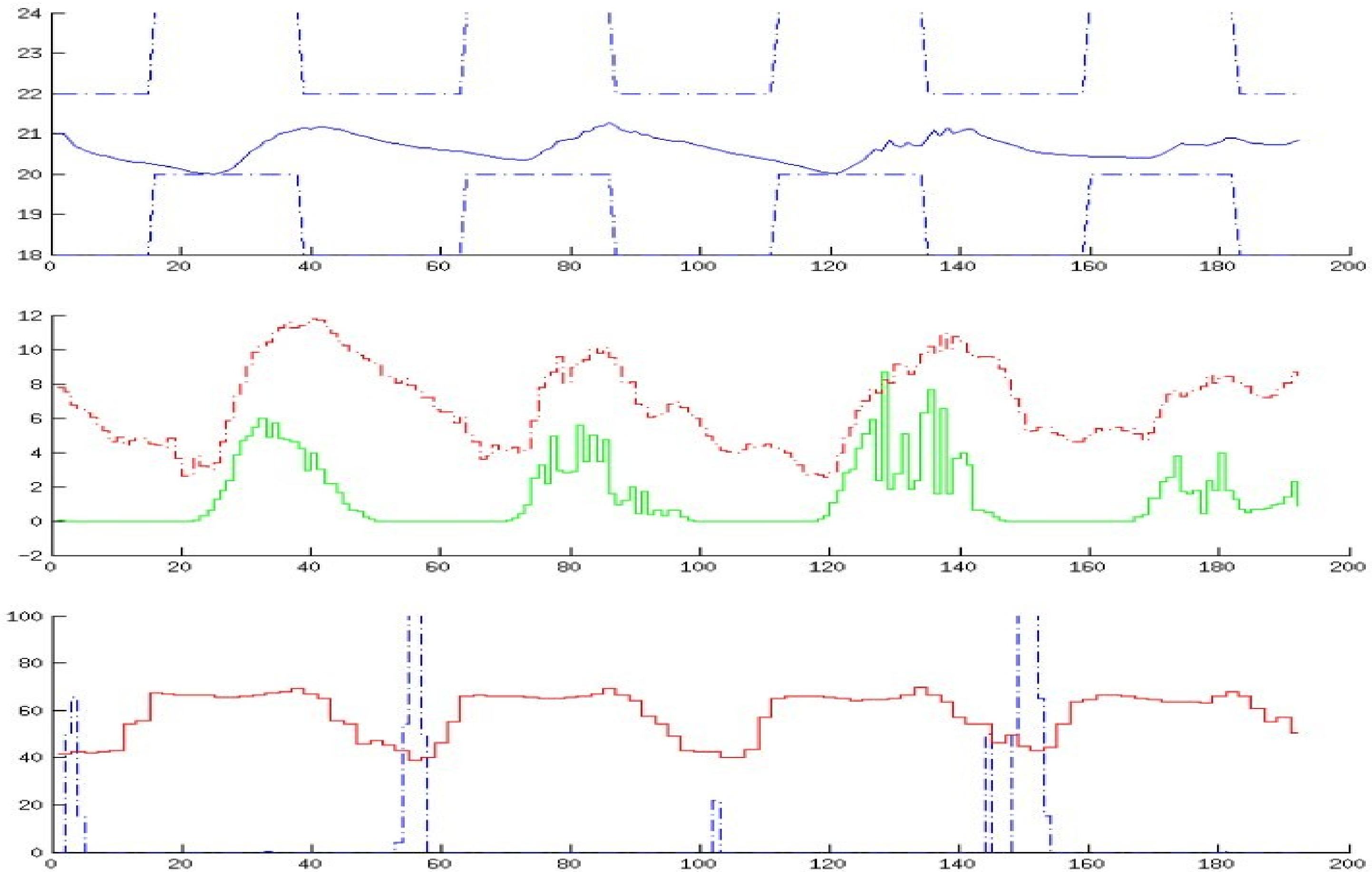
Economic Model Predictive Control

Formulation

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

$$
\begin{aligned}
&\min_{\{u_k\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c' u_k && && \text{(4a)}\\
&\text{Subject to} \quad x_{k+1} = Ax_k + Bu_k + Ed_k && k = 0, 1, \dots, N-1 && \text{(4b)}\\
&y_k = Cx_k && k = 1, 2, \dots, N && \text{(4c)}\\
&u_{min} \leq u_k \leq u_{max} && k = 0, 1, \dots, N-1 && \text{(4d)}\\
&\Delta u_{min} \leq \Delta u_k \leq \Delta u_{max} && k = 0, 1, \dots, N-1 && \text{(4e)}\\
&y_{min} \leq y_k \leq y_{max} && k = 0, 1, \dots, N && \text{(4f)}
\end{aligned}
$$

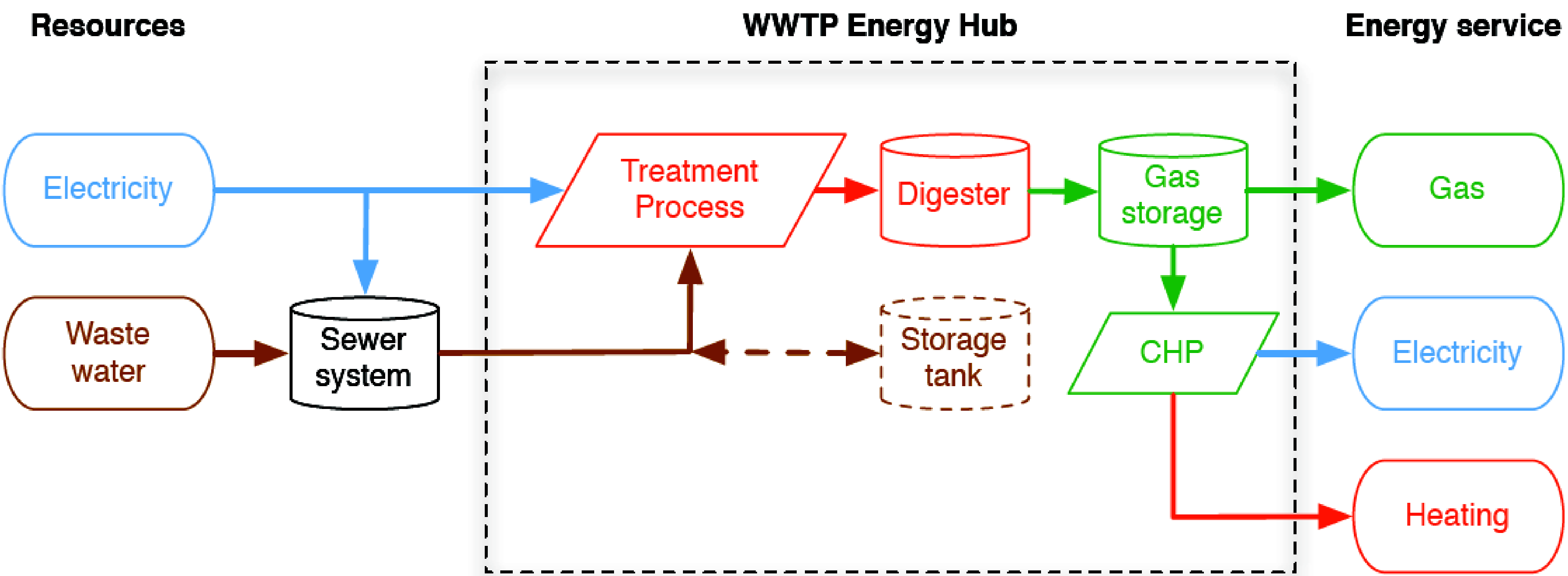
Heat pump with thermal solar collector and storage (savings up to 35 pct)



Case study

Control of Wastewater Treatment Plants

Waste-2-Energy



Kolding WWTP

Energy Flexibility in Wastewater Treatment

- Sludge -> Biogas -> Gas turbine ->Electricity
- Power management of the aeration process
- Pumps and storage in sewer system

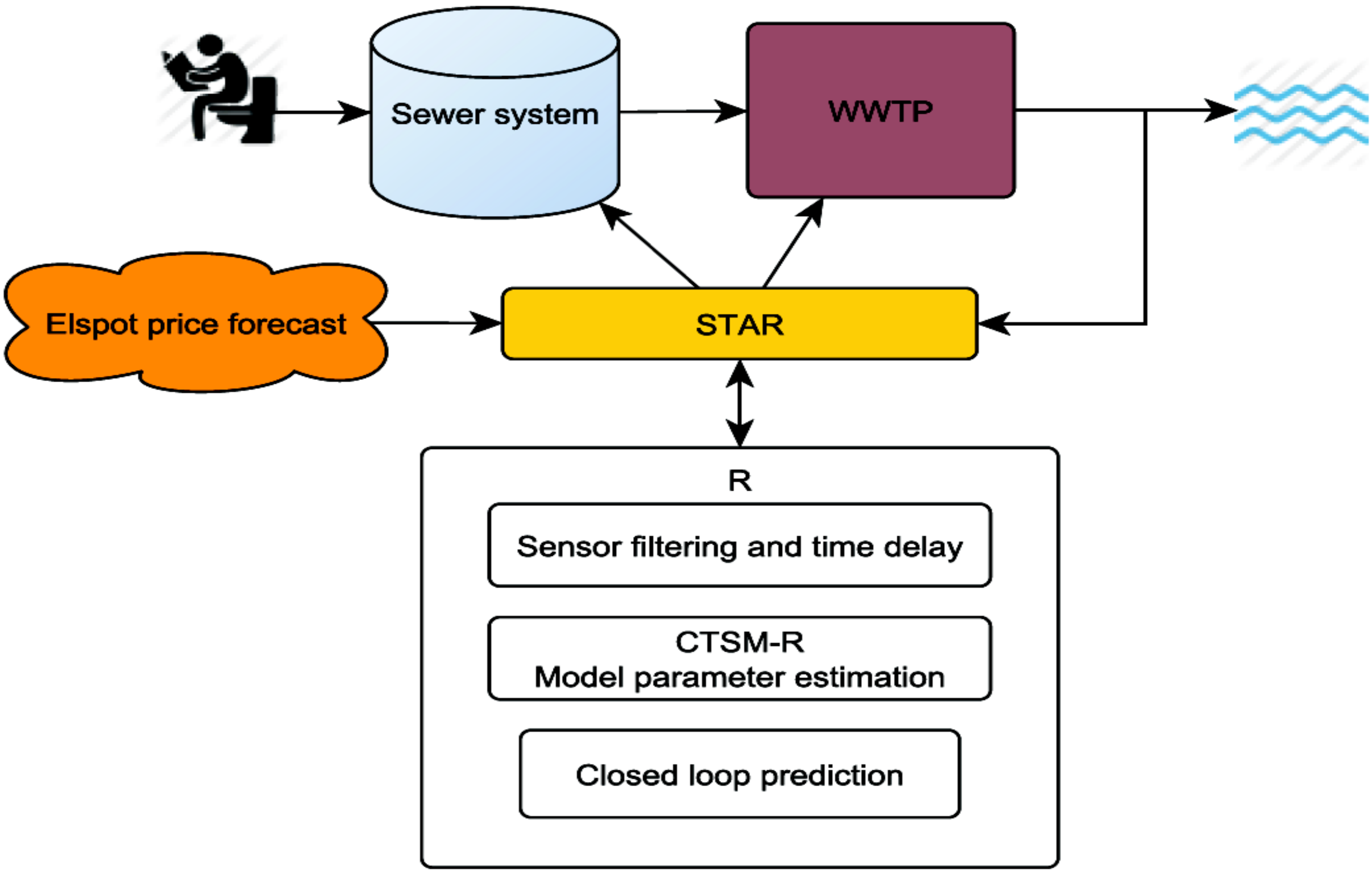
Overall goals:

Cost reduction

Minimize effluent concentration

Minimize overflow risk

Energy Flexibility in Wastewater Treatment



WWTP Control goal

$$\text{minimize } p_{fee} Q^T S_N + p_{elspot}^T u$$

Activated Sludge Model (ASM) No. 1

$$\dot{S}_{NH} = -i_{XB}\left(\rho_1 + \rho_2\right) - \left(i_{XB} + \frac{1}{Y_A}\right)\rho_3 + k_a S_{ND} X_{B,H}$$

$$\dot{S}_{NO} = -\frac{1 - Y_H}{2.68\,Y_H}\rho_2 + \frac{1}{Y_A}\rho_3$$

$$\dot{S}_{O} = -\frac{1 - Y_H}{Y_H}\rho_1 - \frac{4.57 - Y_A}{Y_A}\rho_3$$

$$\dot{S}_{S} = \rho_7 - \frac{1}{Y_H}\left(\rho_1 + \rho_2\right)$$

$$\dot{X}_{S} = (1 - f_p)(b_H X_{B,H} + b_A X_{B,A}) - \rho_7$$

$$\dot{X}_{B,H} = \rho_1 + \rho_2 - b_H X_{B,H}$$

$$\dot{X}_{B,A} = \rho_3 - b_A X_{B,A}$$

$$\dot{S}_{ND} = \rho_8 - k_a S_{ND} X_{B,H}$$

$$\dot{X}_{ND} = (i_{XB} - f_p i_{XP})(b_H X_{B,H} + b_A X_{B,A}) - \rho_8$$

(S_I, X_I, X_P, and S_{ALK})

Reaction Rates in ASM No. 1

$$\rho_1 = \hat{\mu}_H \frac{S_S}{K_S + S_S} \frac{S_O}{K_{O,H} + S_O} X_{B,H}$$

$$\rho_2 = \hat{\mu}_H \frac{S_S}{K_S + S_S} \frac{K_{O,H}}{K_{O,H} + S_O} \frac{S_{NO}}{K_{NO} + S_{NO}} \eta_g X_{B,H}$$

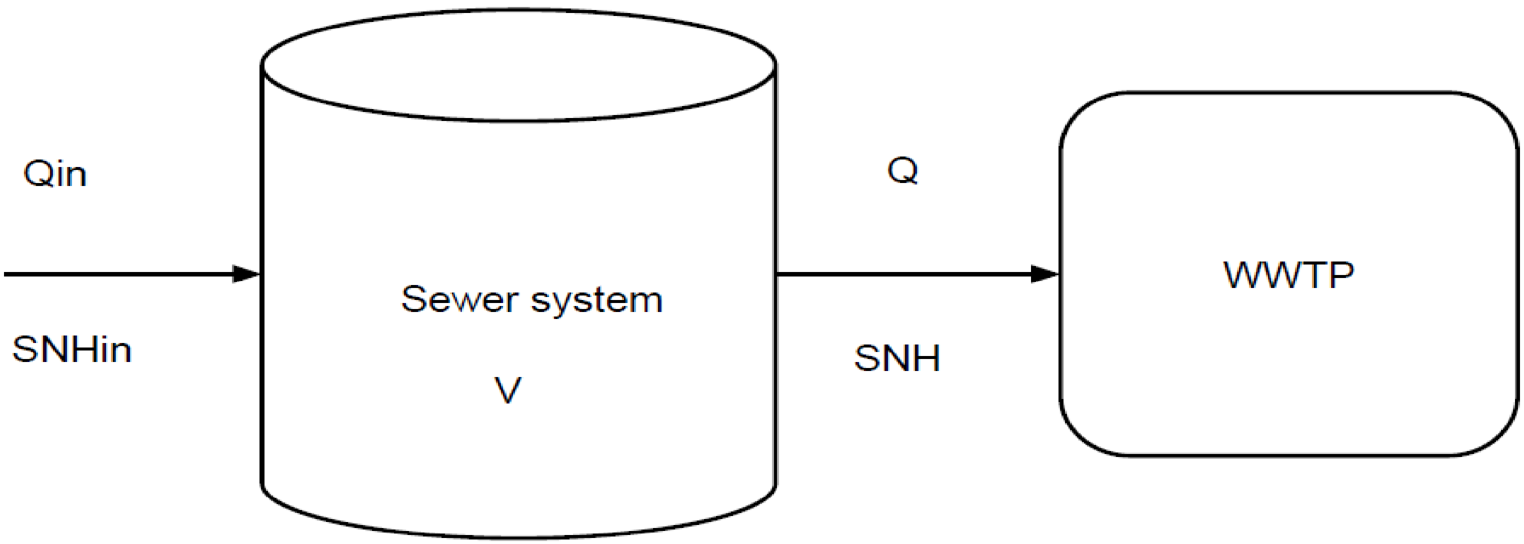
$$\rho_3 = \hat{\mu}_A \frac{S_{NH}}{K_{NH} + S_{NH}} \frac{S_O}{K_{O,A} + S_O} X_{B,A}$$

$$\rho_7 = k_h \frac{X_S / X_{B,H}}{K_X + X_S / X_{B,H}} \left(\frac{S_O}{K_{O,H} + S_O} + \eta_h \frac{K_{O,H}}{K_{O,H} + S_O} \frac{S_{NO}}{K_{NO} + S_{NO}} \right) X_{B,H}$$

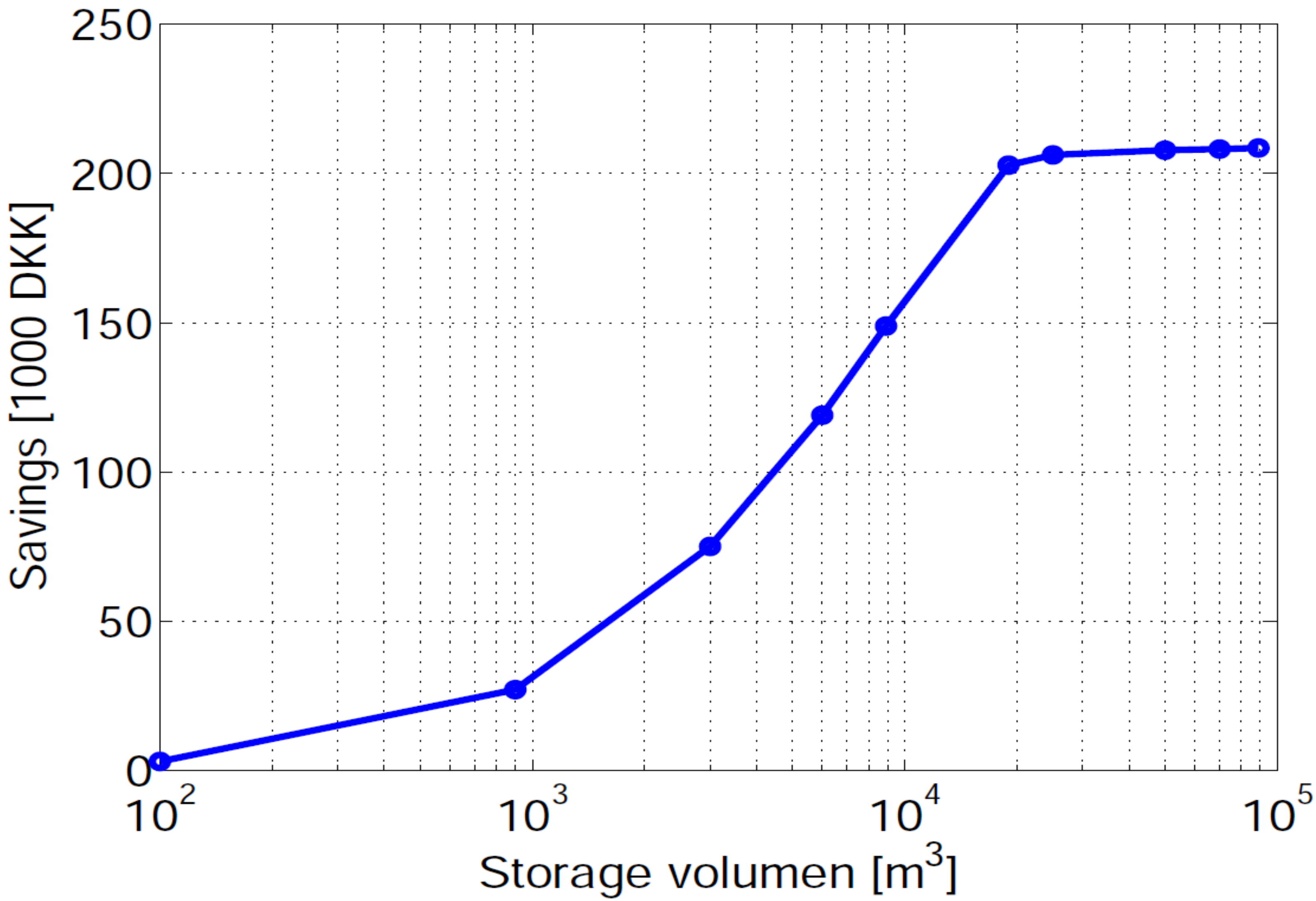
$$\rho_8 = \rho_7 \left(X_{ND} / X_S \right)$$

Sewer System Control Goal

$$\text{minimize overflow} + p_{elspot}^{T} f(Q)$$

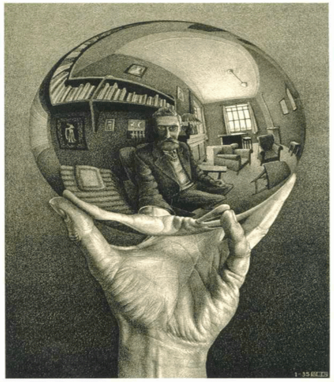


Sewer System Annual Elspot Savings



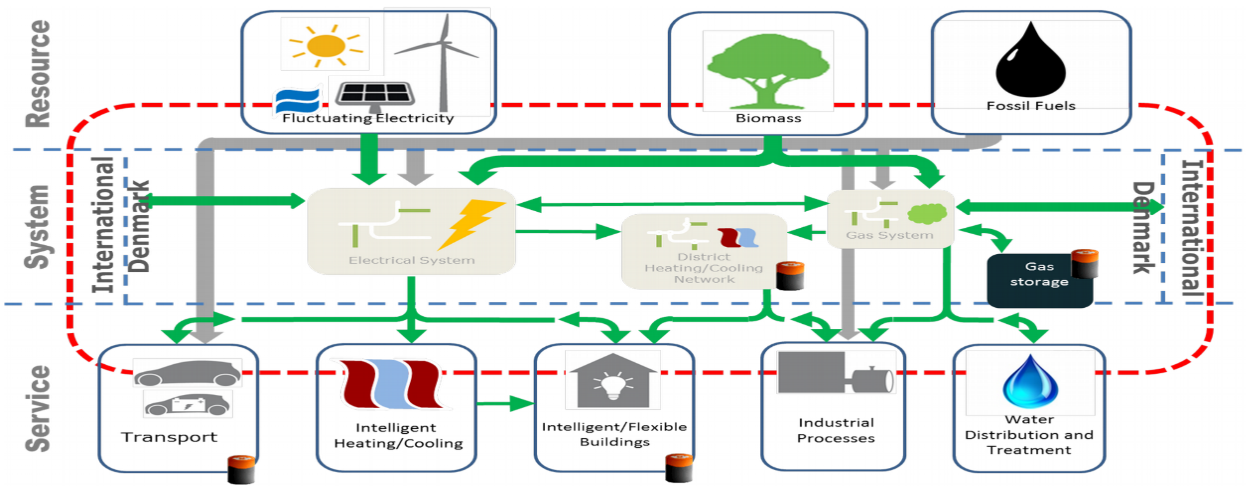
CITIES
Centre for IT Intelligent Energy Systems

Energy Flexibility
Some Demo Projects in CITIES



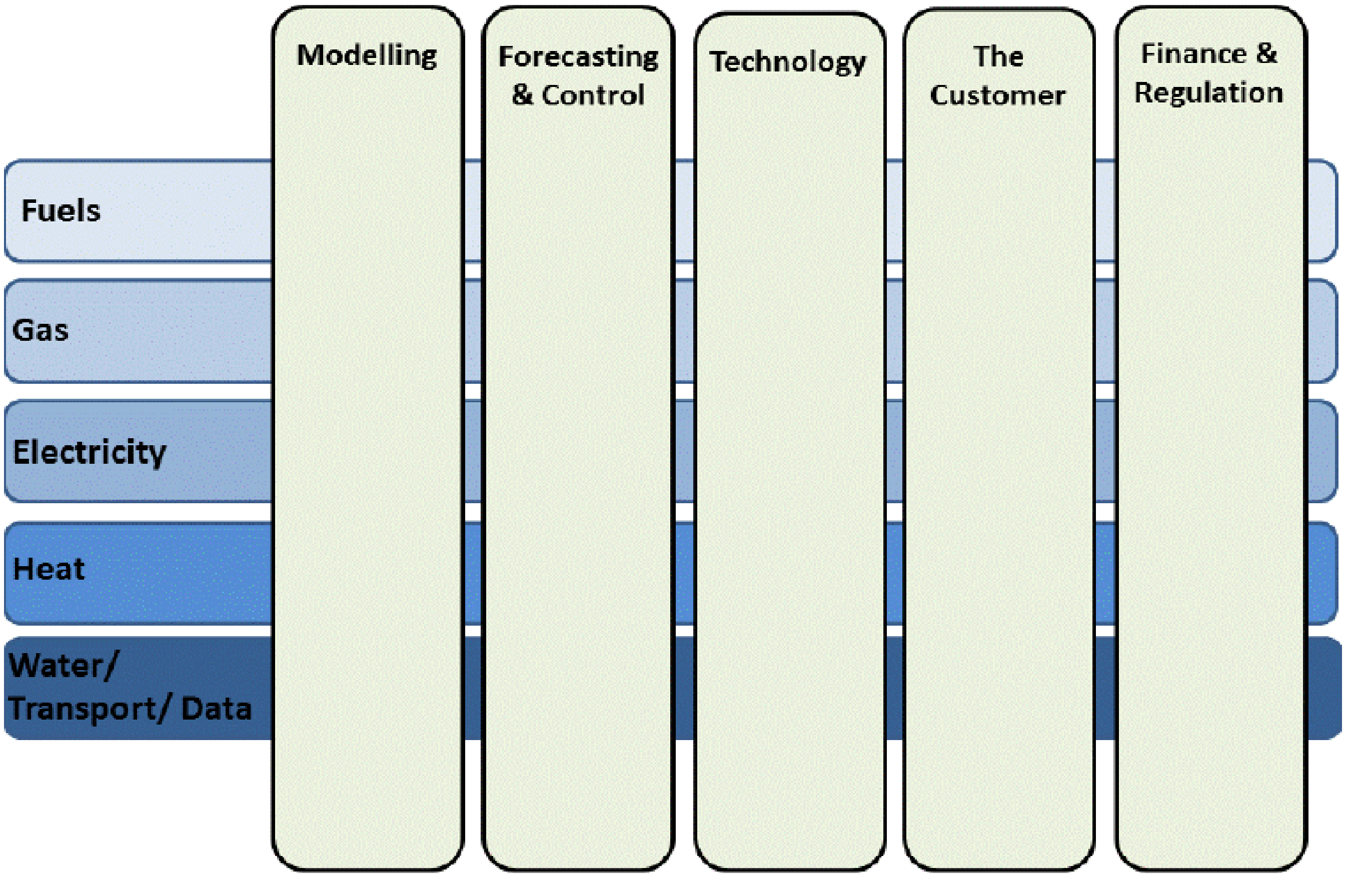
- Control of WWTP (ED, Krüger, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Summerhouses (DC, SE, Energinet.dk, ..)
- Green Houses (NeoGrid, Danfoss, F.Fyn, ...)
- CHP (Dong Energy, FjernvarmeFyn, HOFOR, NEAS, ...)
- Industrial production (DI, ...)
- EV (charging) (Eurisco, ED, ...)
- ....

(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

EERA Joint Program on Energy Systems Integration Workshop 2nd to 4th Nov. on DTU - Please join us.



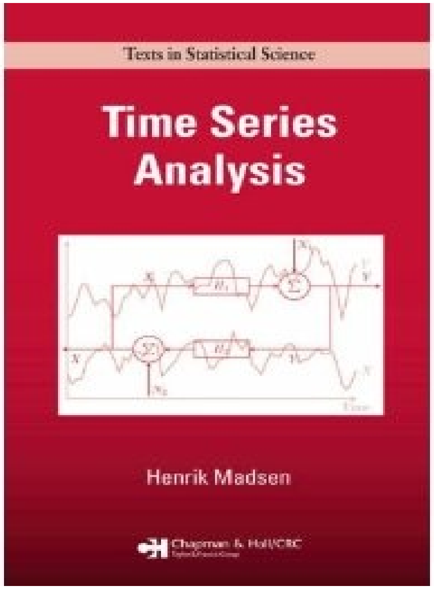
Discussion

- IT-Intelligent Energy Systems Integration 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)

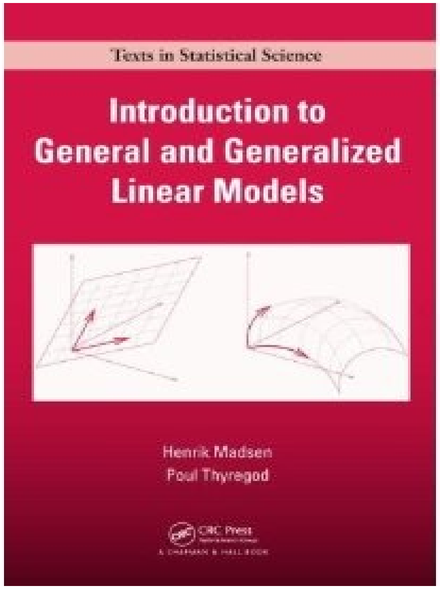
Summary

- A Smart-Energy OS for implementing flexibility energy systems in smart cities has been described
- Built on: Big Data Analytics, Cyber Physical systems, Stochastic opt./control, Forecasting, IoT, IoS, Cloud computing, ...
- **Modelling**: Toolbox – CTSM-R - for combined physical and statistical modelling (grey-box modelling)
- **Control:** Toolbox – MPC-R - for Model Predictive Control
- **Simulation:** Framework for simulating flexible power systems.

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



2008



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