SmartNet

DTU

Controlling the Electricity Load in Future Intelligent and Integrated Energy Systems

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

http://smartnet-project.eu

http://www.henrikmadsen.org

m² c = +e

mathematics × models × computations = more energy

A COST PROJECT

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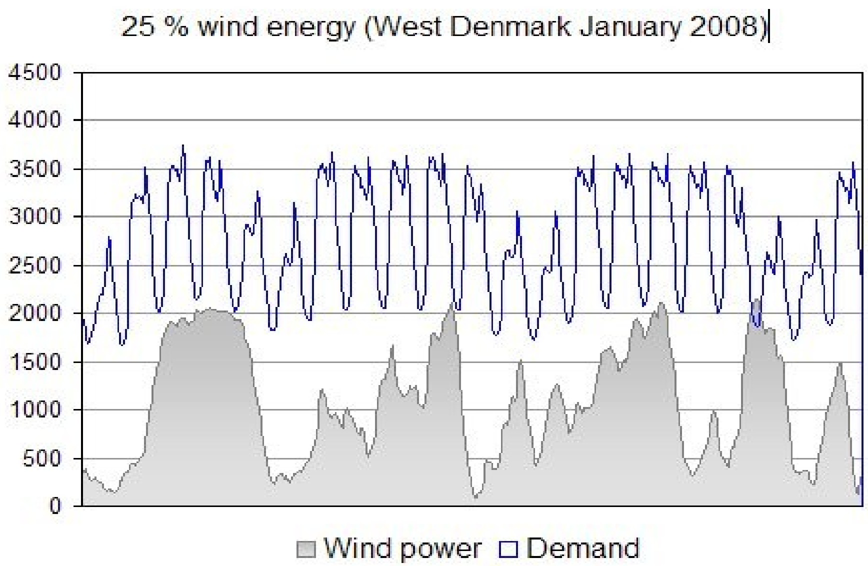
COST
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

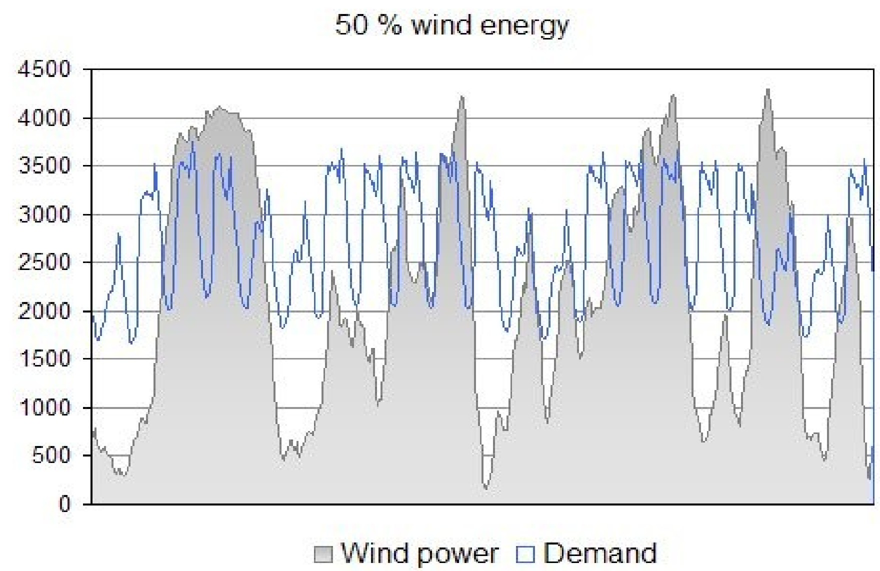
COST is supported by the EU RTD Framework Programme

COST TD1207 Final Conference, March 2017

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 2016 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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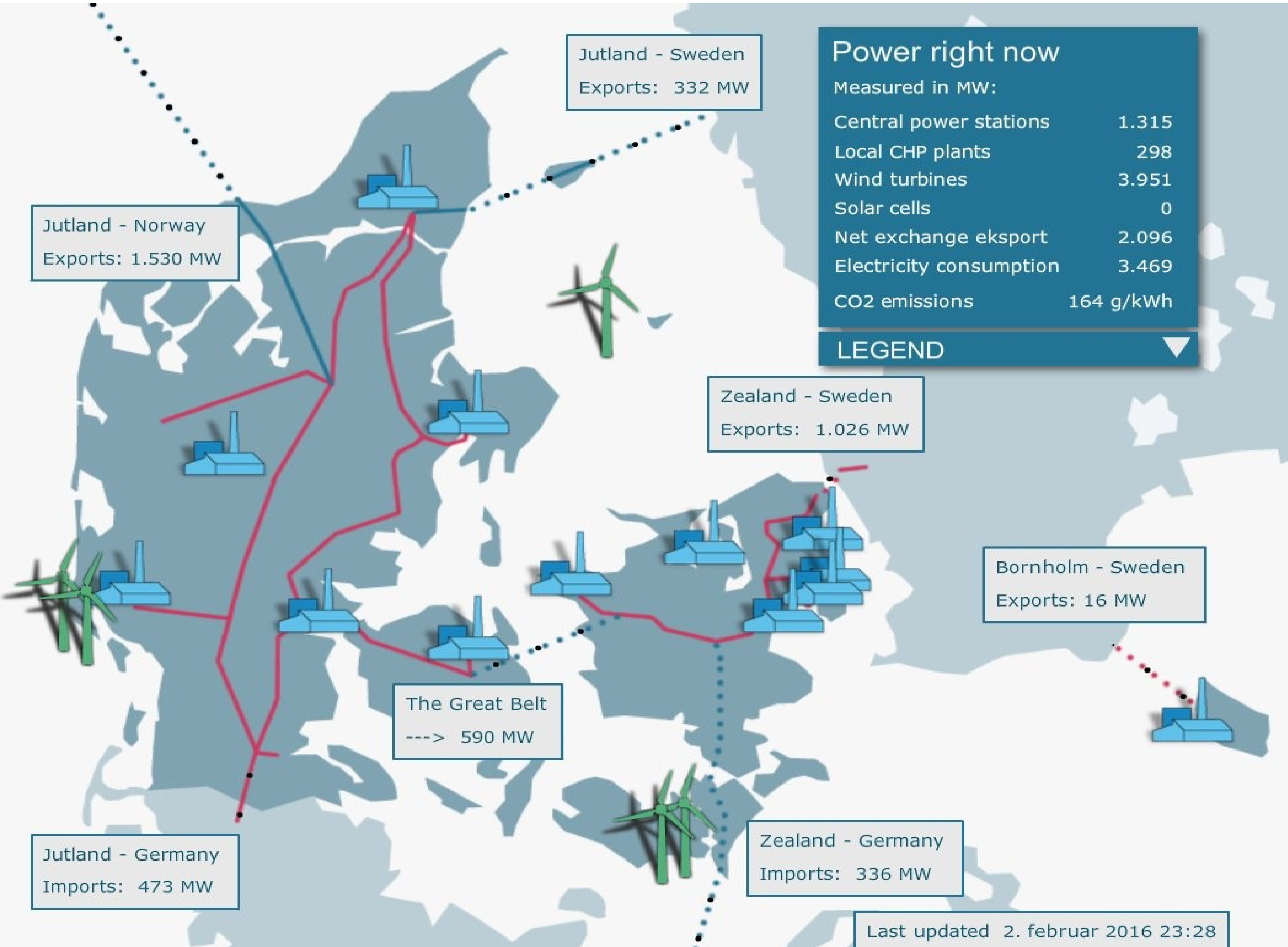
Jutland - Sweden
Exports: 332 MW
Power right now
Measured in MW:
Central power stations 1.315
Local CHP plants 298
Wind turbines 3.951
Solar cells 0
Net exchange eksport 2.096
Electricity consumption 3.469
CO2 emissions 164 g/kWh
LEGEND
Jutland - Norway
Exports: 1.530 MW
Zealand - Sweden
Exports: 1.026 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

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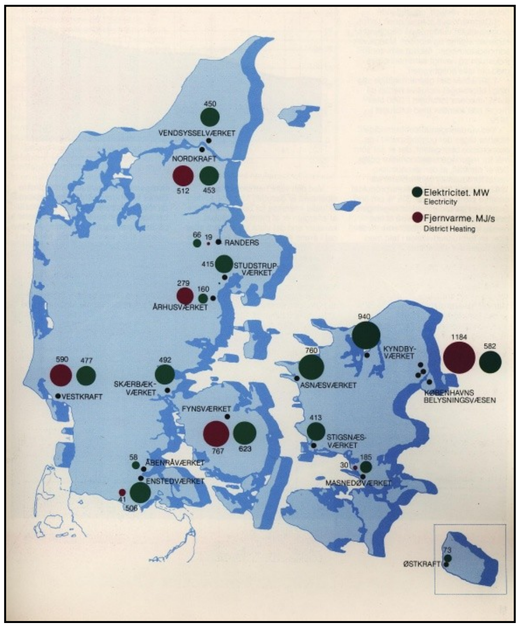
From large central plants to Combined Heat and Power (CHP) production

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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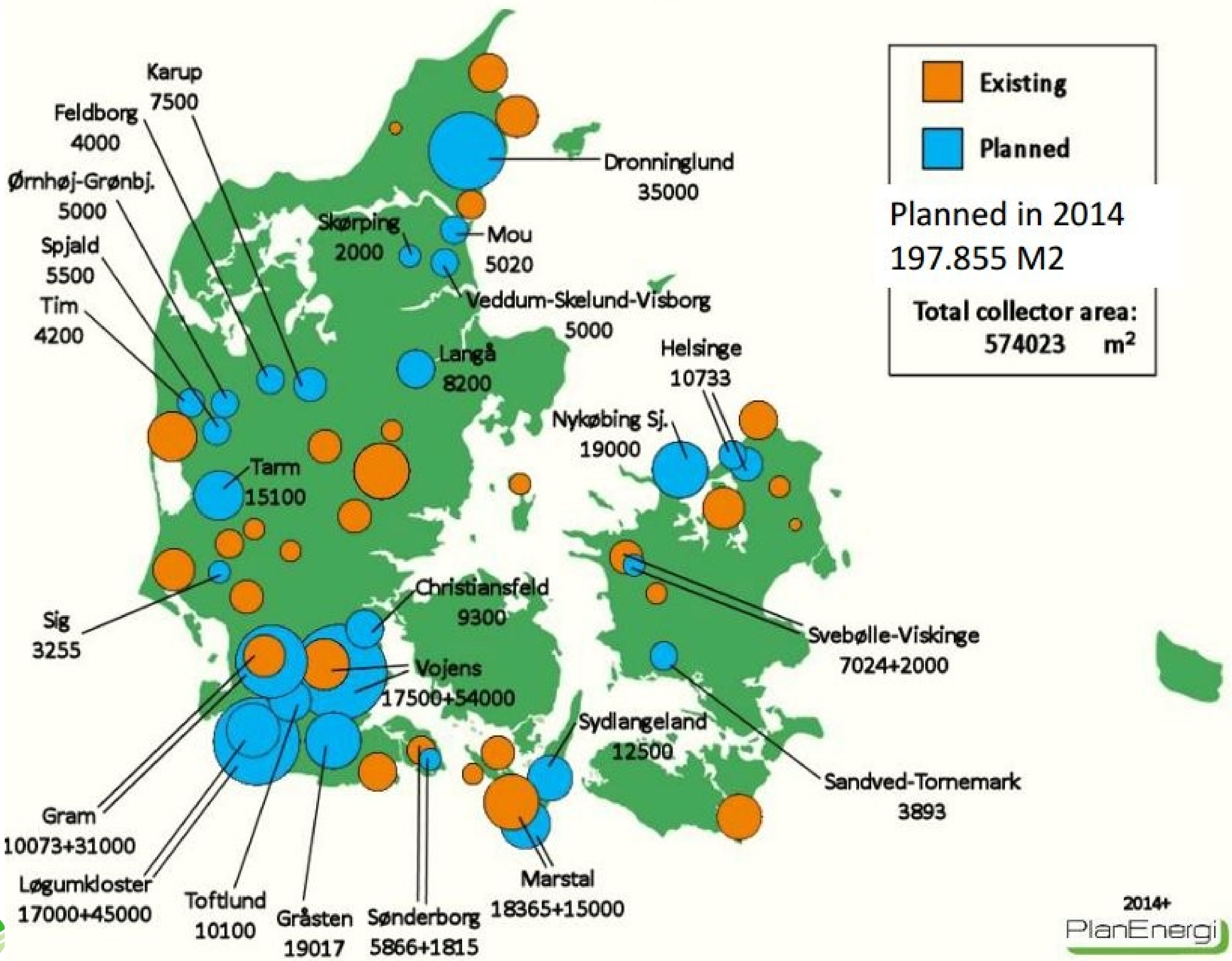
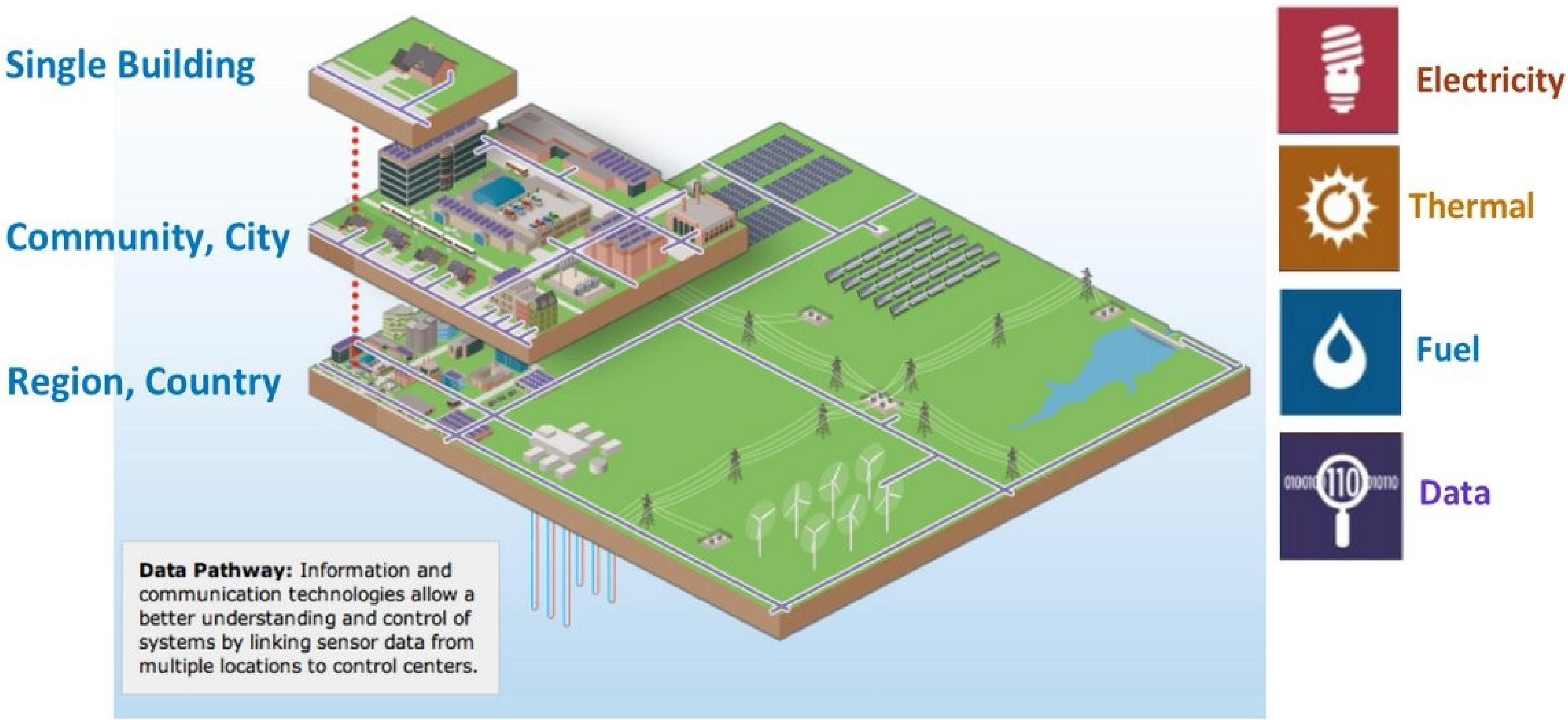
Solar district heating in Denmark



2017

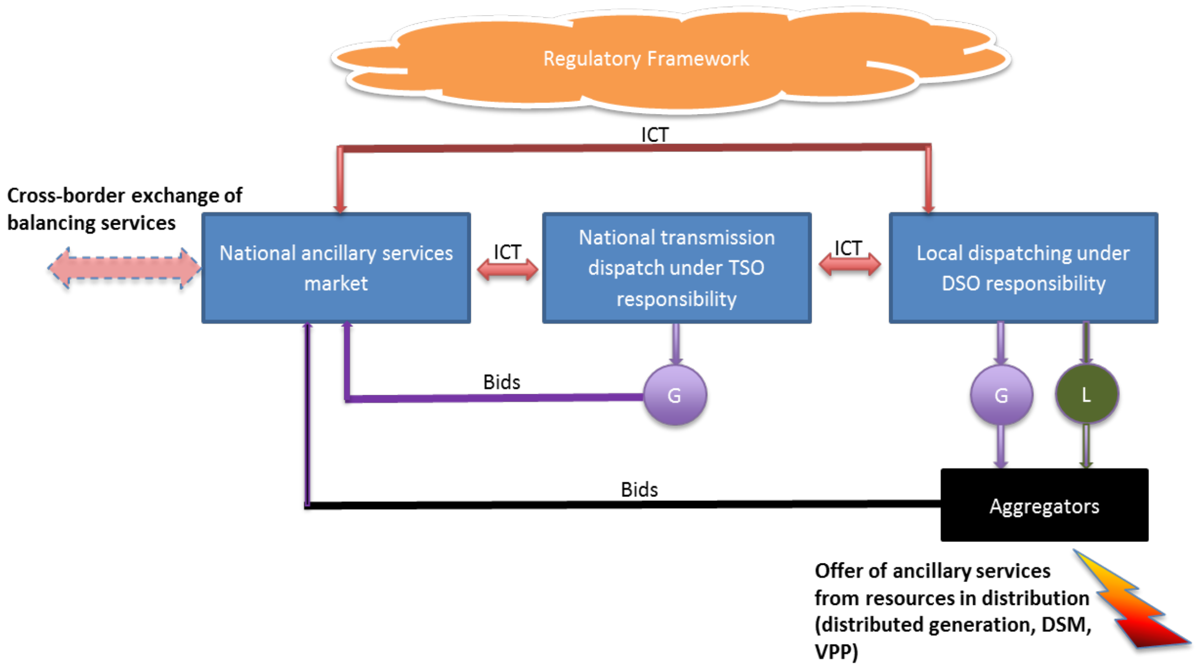
Energy Systems Integration

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



Power Grid is the Backbone - The SmartNet project
Lead by Gianluigi Migliavacca (RSE)

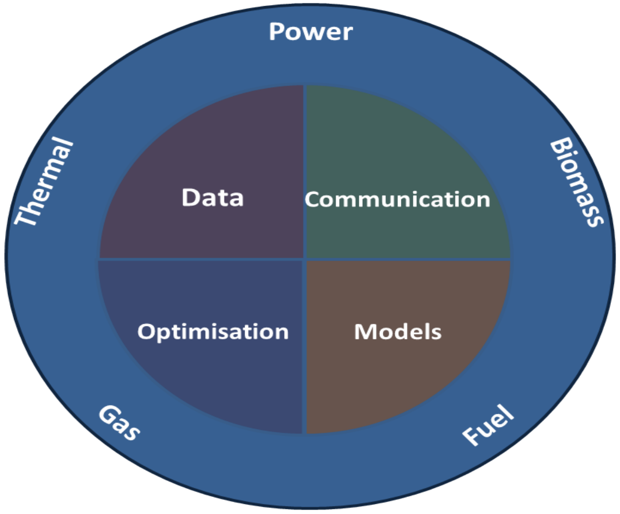
- The project SmartNet aims at comparing different **architectures for optimized interaction between TSOs and DSOs** in managing the purchase of ancillary services from subjects located in distribution.
- An *ad hoc* simulation platform is built (physical network, market and ICT) around **three national cases** (Italy, Denmark, Spain); a **CBA** is performed to assess which TSO-DSO coordination scheme is optimal for the three countries. The simulation platform is then implemented in a **full replica lab** to test performance of real controller devices.
- **Three physical pilots** are also developed to demonstrate capability to monitoring and control distribution by the TSO and flexibility services that can be offered by distribution (thermal inertia of indoor swimming pools, distributed storage of radio-base stations).



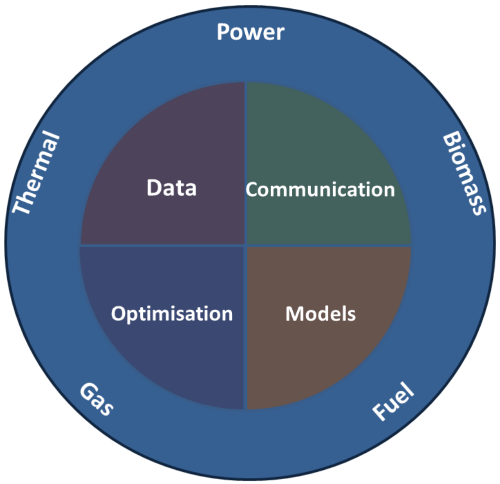
Flexible Solutions

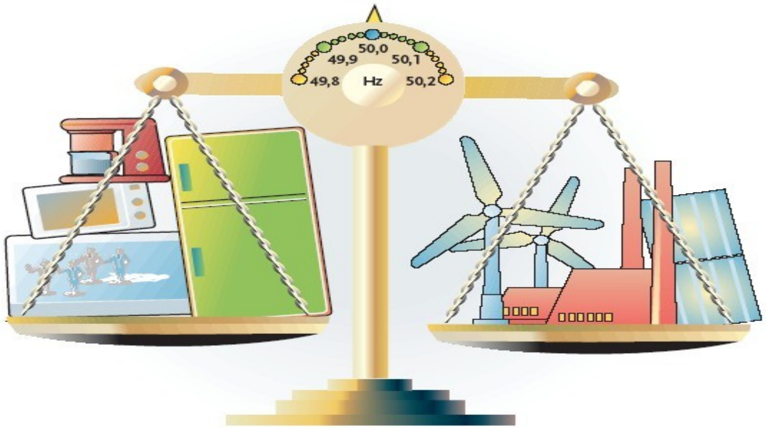
Center for IT-Intelligent Energy Systems in Cities (CITIES) is aiming at establishing methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales.

CITIES is currently the largest Smart Energy 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 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, …)
- Interaction between grid (voltage) levels
- Speed / problem size
- Characterization of flexibility
- Requirements on user installations

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Challenges (cont.)

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 [illegible]A-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.

Conclusion: Almost no flexibility?!?

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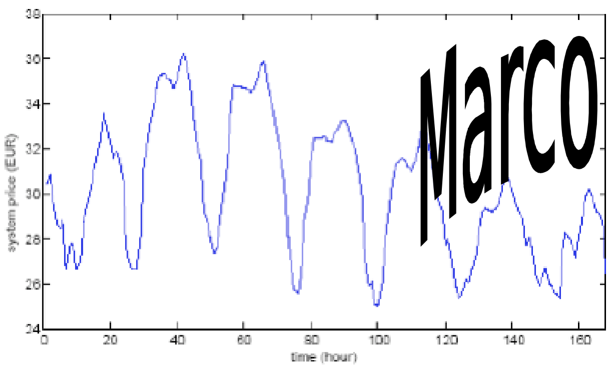
COMPETITIVE BIDDING AND STABILITY ANALYSIS IN ELECTRICITY MARKETS USING CONTROL THEORY

Main idea: **applying control theory to the study of power markets**

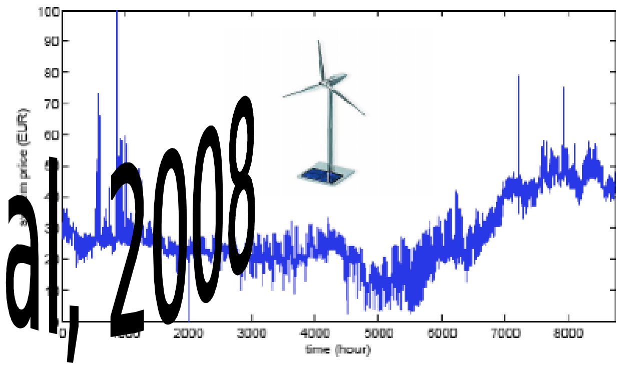
Advantages in handling effectively

Dynamics



Marco Zugno et.al, 2008

Uncertainty



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

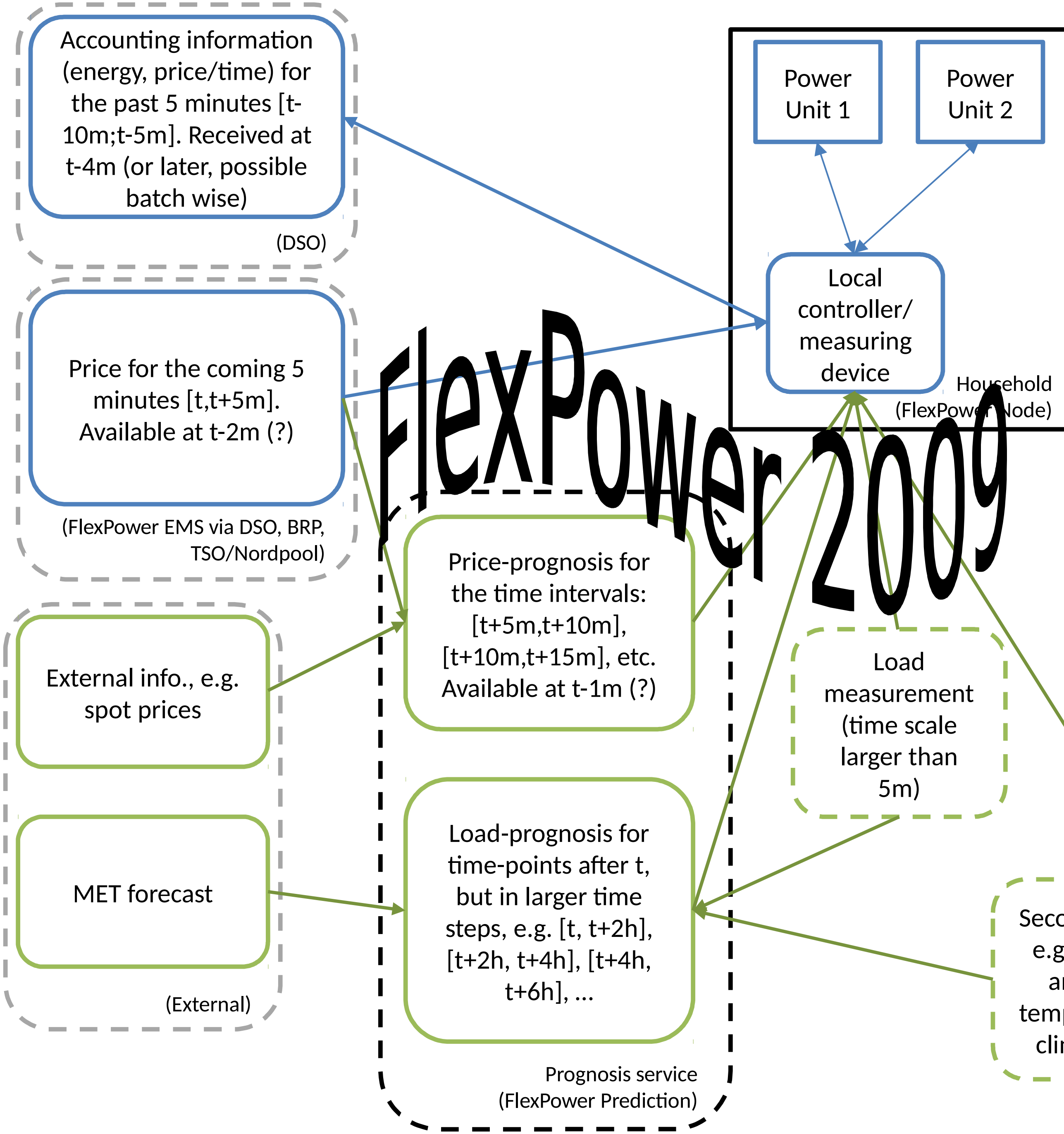
↓

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

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



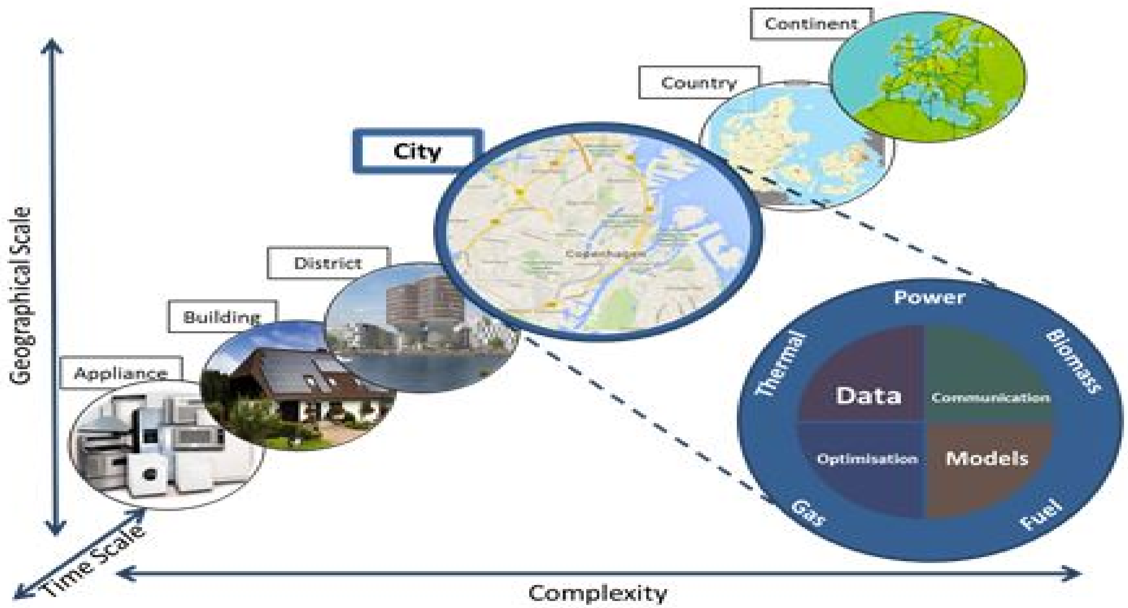
The blue color represent the minimal FlexPower requirements. The green color represents the additional requirements when external prognoses are used by the local controller. Possible multiple load forecasts may be required by the household. Also the load prognosis may be supplemented with additional 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.

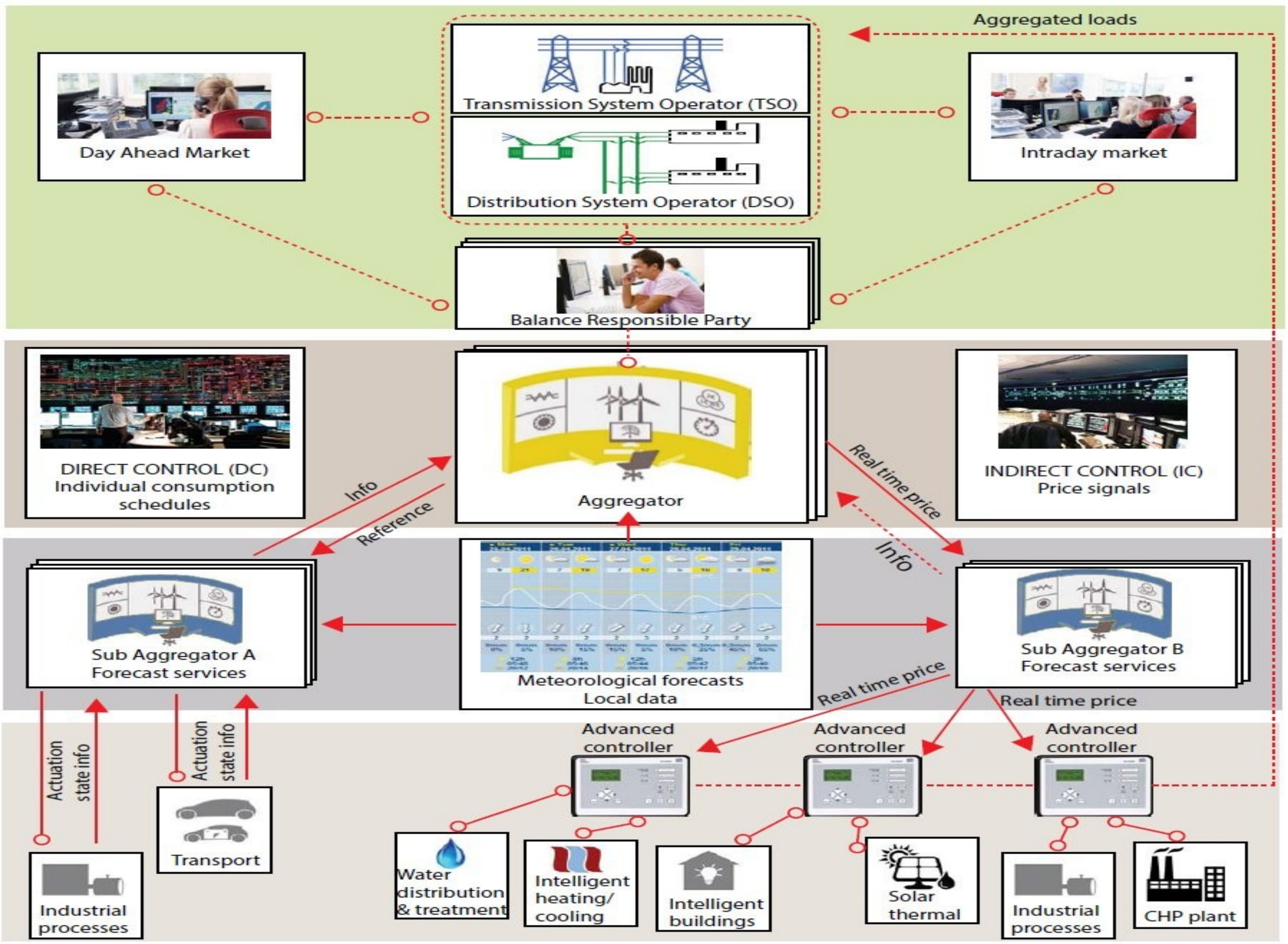
The time index t refers to the beginning of the next 5 minute interval.

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



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Control and Optimization

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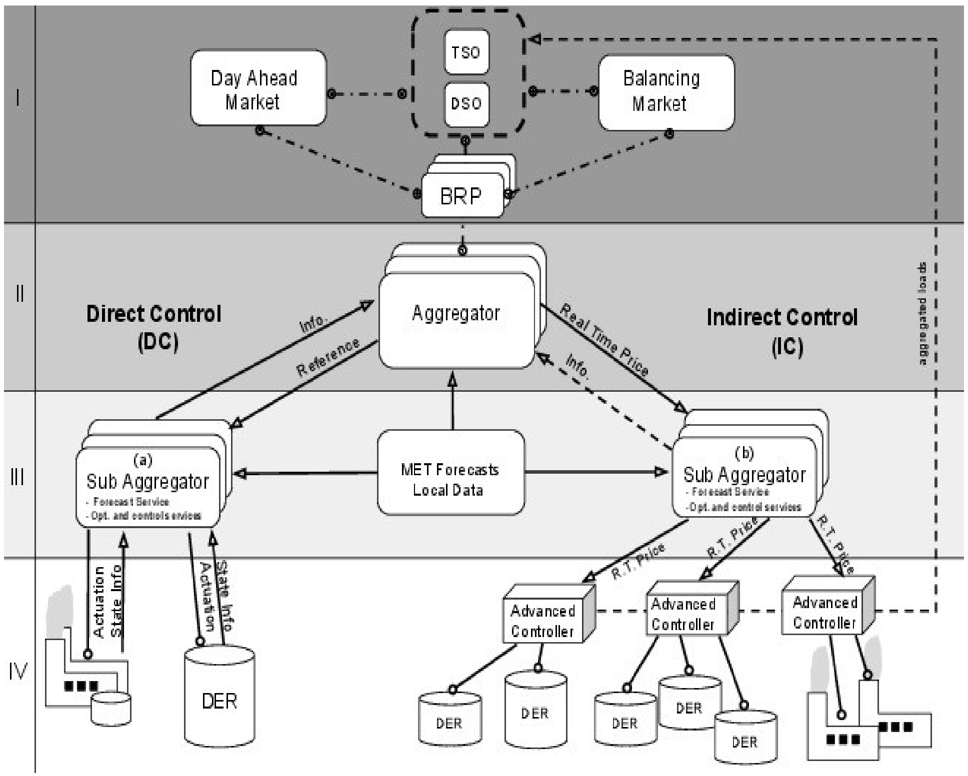


In New Wiley Book: Control of Electric Loads in Future Electric Energy Systems, 2015

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

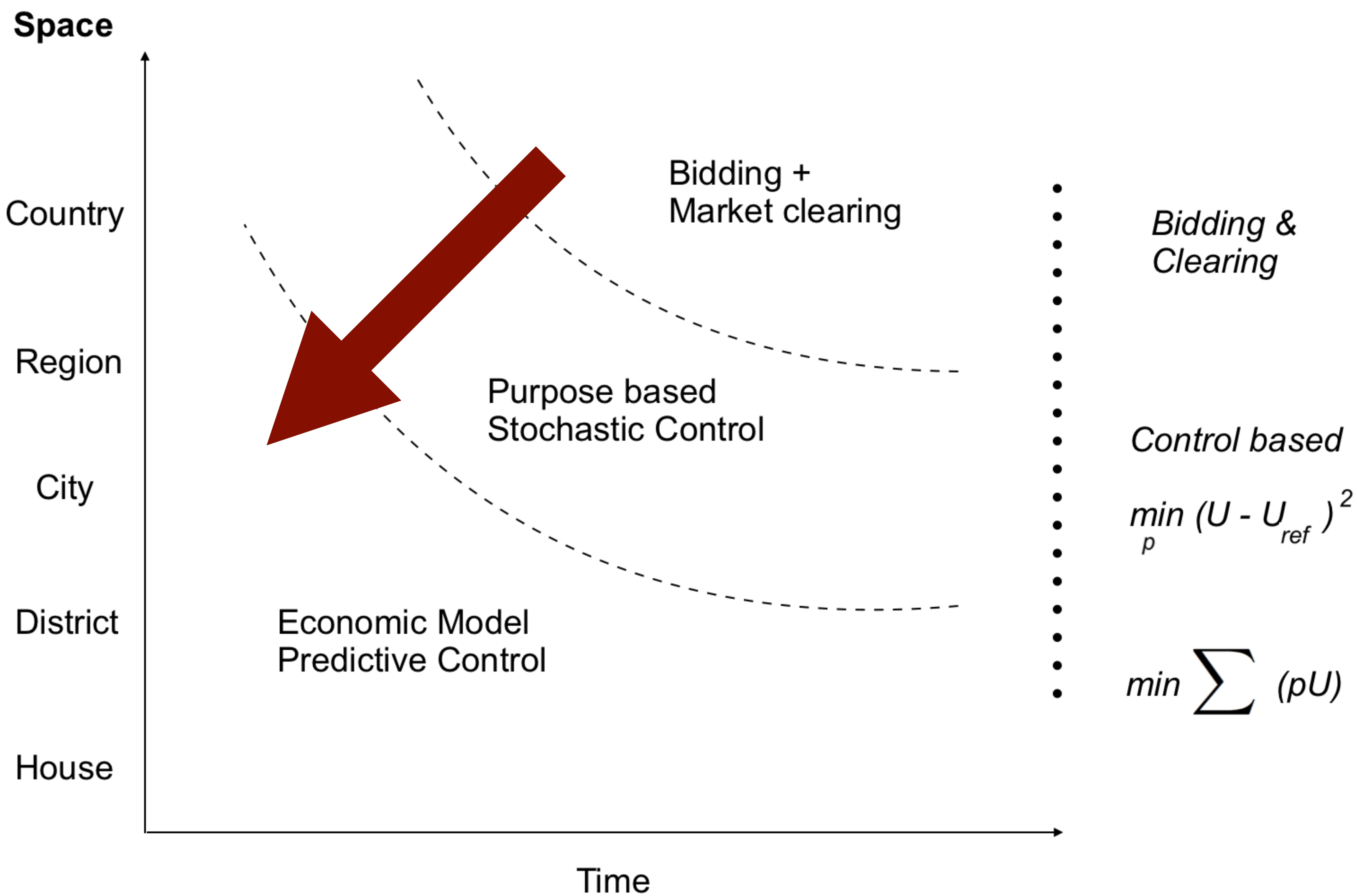
Simple 'contracts'

Direct vs Indirect Control

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

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.

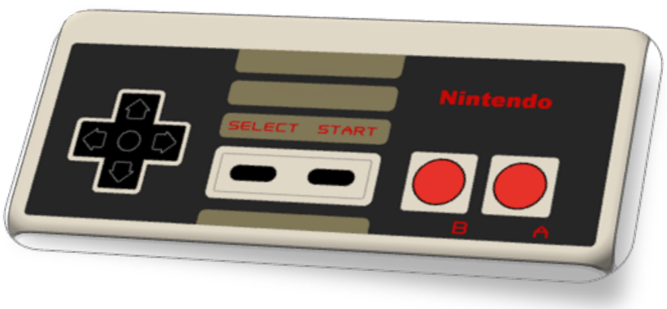
The ‘market’ of tomorrow



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

Probabilistic Forecasting



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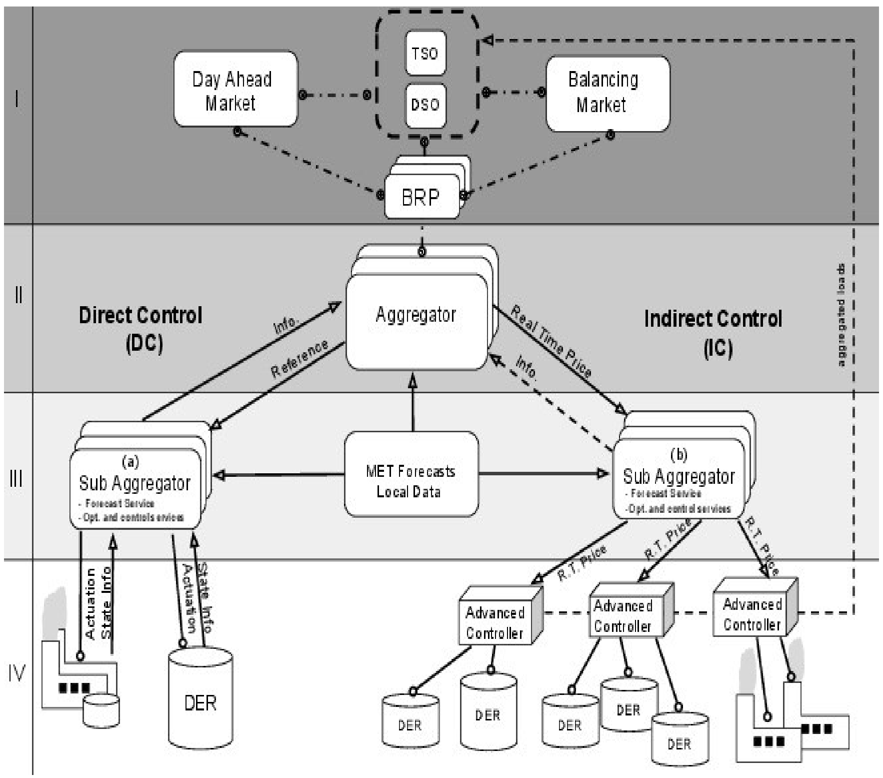
Forecast requirements



Day Ahead:

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

Direct Control: .

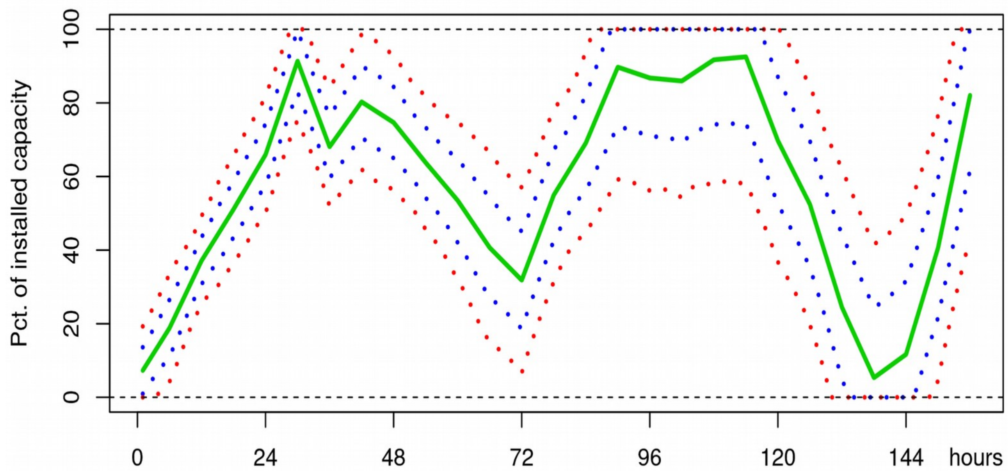
- Forecasts of states of DERs
- Forecasts of load

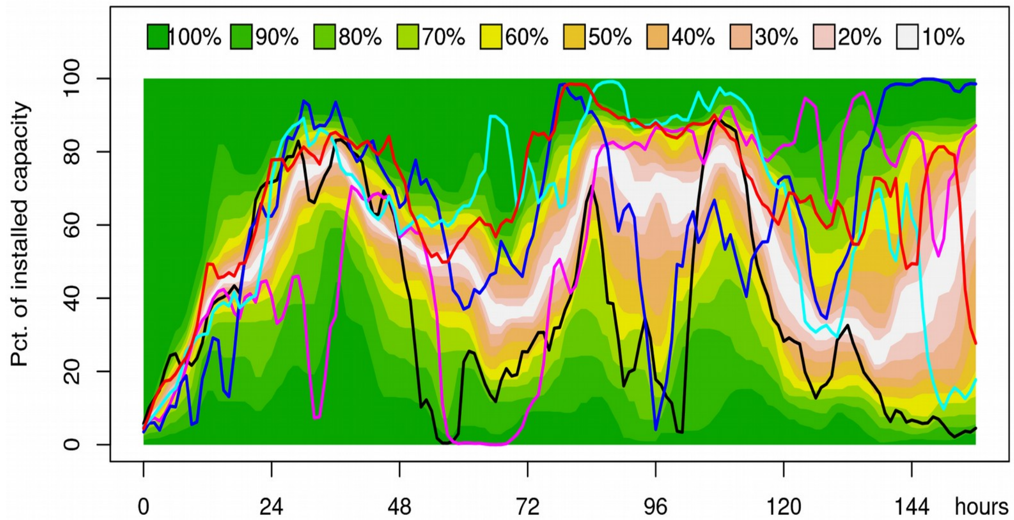
Indirect Control:

- 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





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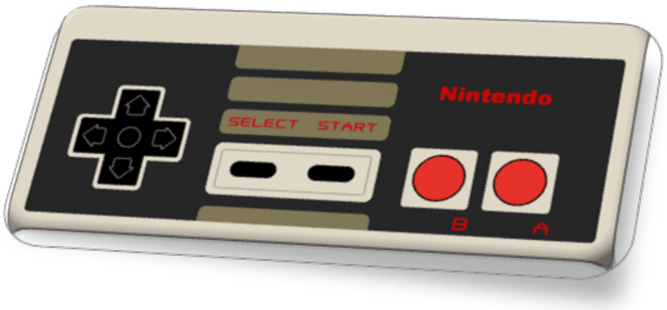
Wind and Solar Power Forecasting

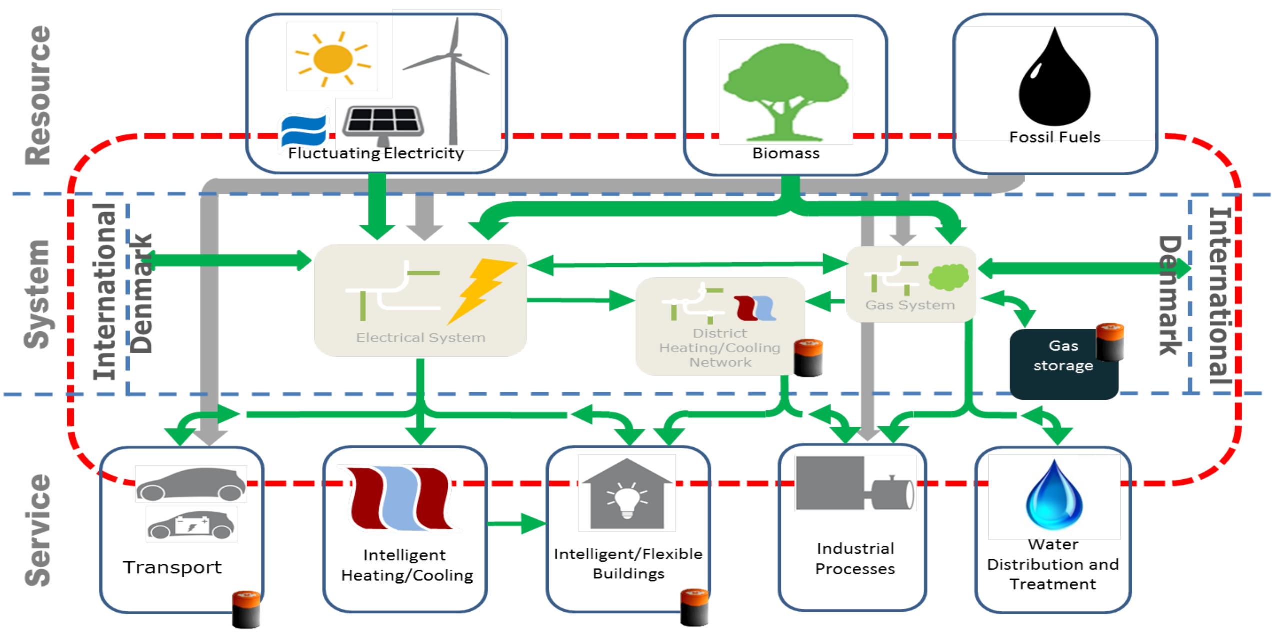
- Methods for wind power forecasting have been continuously developed and used operationally since 1995 (solar power since 2005).
- Implemented for instance in WPPT, Anemos WPS, AWEFS, ASEFS, ..
- Sold for instance in systems provided by ENFOR (Denmark) and Overspeed GmbH (Germany)
- Today our systems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

Grey-box Modelling



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 power/energy systems**



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The grey-box model

Drift term

Diffusion term

$$\begin{aligned} d\boldsymbol{X}_t &= \boldsymbol{f}(\boldsymbol{X}_t, \boldsymbol{u}_t, t, \boldsymbol{\theta})dt + \boldsymbol{\sigma}(\boldsymbol{X}_t, \boldsymbol{u}_t, t, \boldsymbol{\theta})d\boldsymbol{\omega}_t \\ \boldsymbol{Y}_k &= \boldsymbol{h}(\boldsymbol{X}_k, \boldsymbol{u}_k, t_k, \boldsymbol{\theta}) + \boldsymbol{e}_k, \end{aligned}$$

System equation

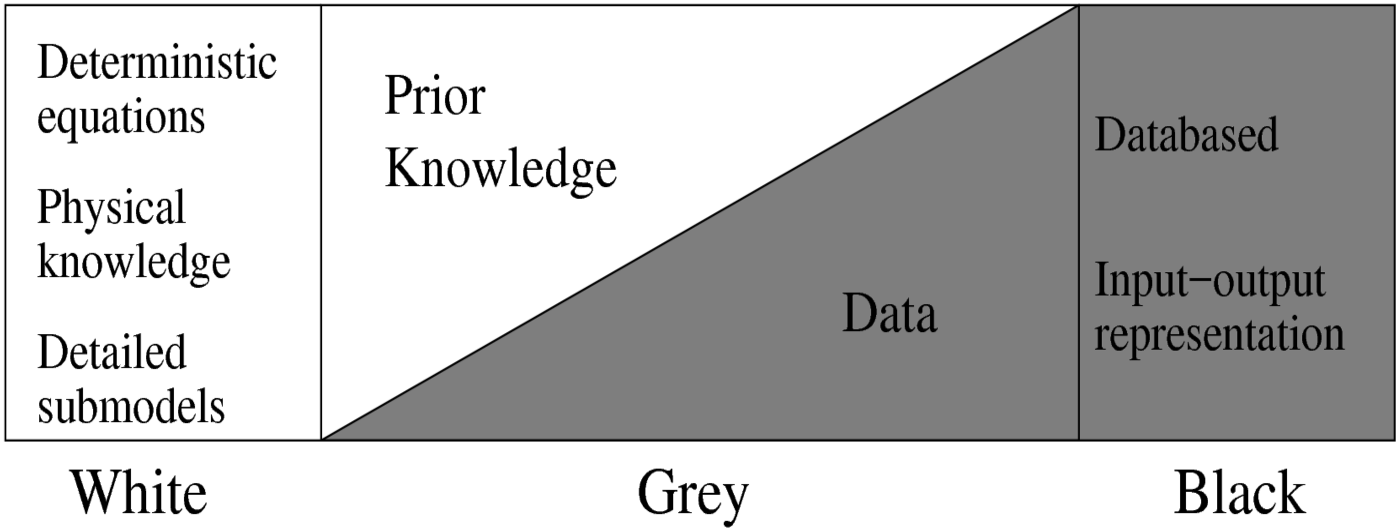
Observation equation

Observation noise

Notation:

$\boldsymbol{X}_t$:	State variables
$\boldsymbol{u}_t$:	Input variables
$\boldsymbol{\theta}$:	Parameters
$\boldsymbol{Y}_k$:	Output variables
t:	Time
$\boldsymbol{\omega}_t$:	Standard Wiener process
$\boldsymbol{e}_k$:	White noise process with $N(\boldsymbol{0}, \boldsymbol{S})$

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

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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

Intelligent Smart Grid

Control of Power Consumption,
Summer Houses with a Pool
(H2020 SmartNet Project – Danish Pilot)

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Goals for Pilot Project

- Demonstrate aggregation services (30 summer houses).

Aggregation

- Implementation in field of ICT technology to exchange data between TSO, DSO, aggregator and the summer houses.

Communication

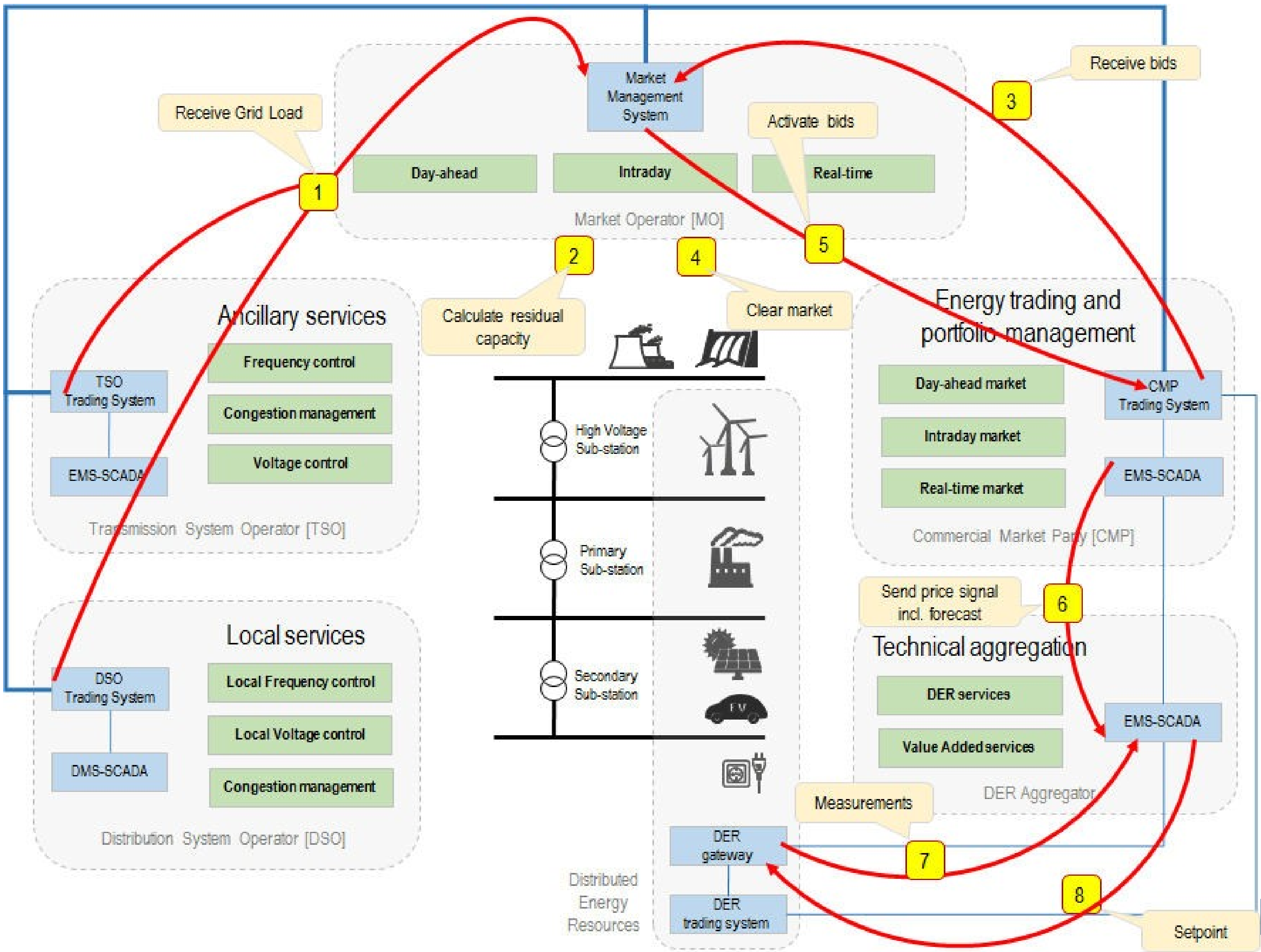
- Use of on-line services for price and load forecasting + model predictive control.

Forecasting

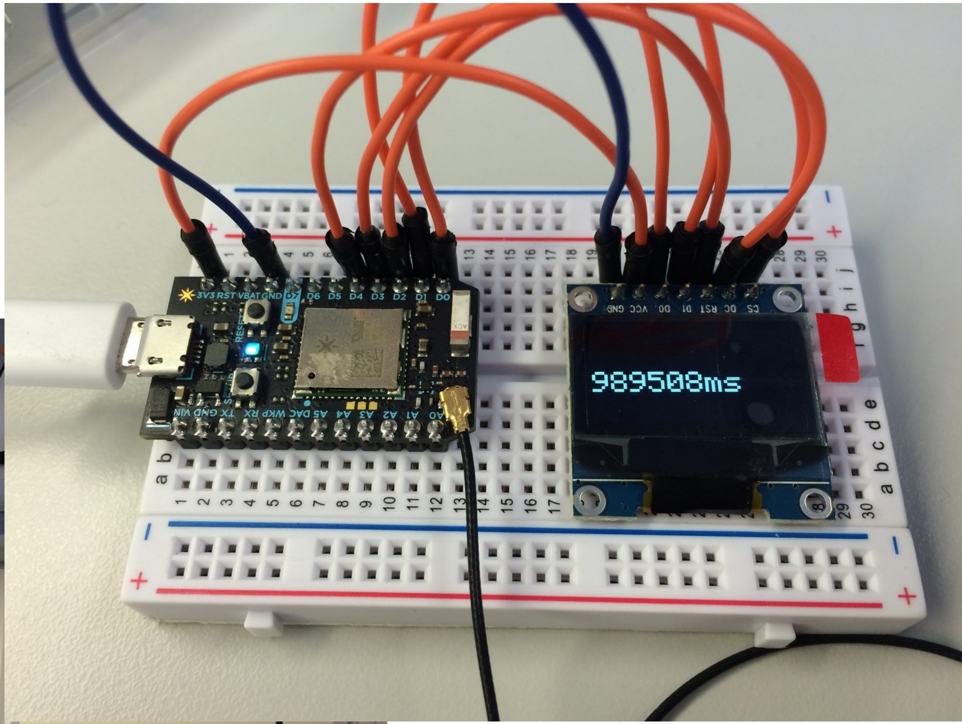
- Development of architecture for ancillary services.

Ancillary services

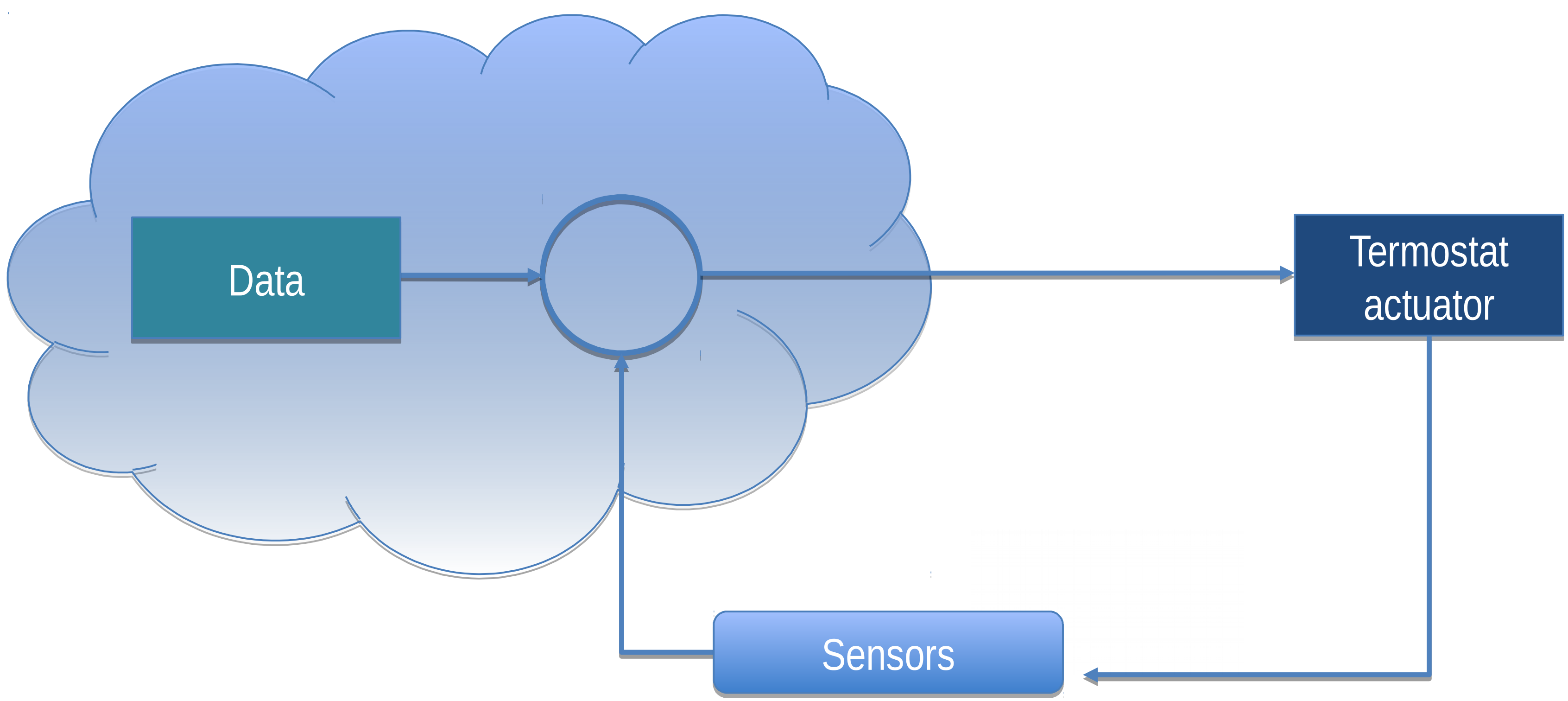
Overview – Danish Pilot



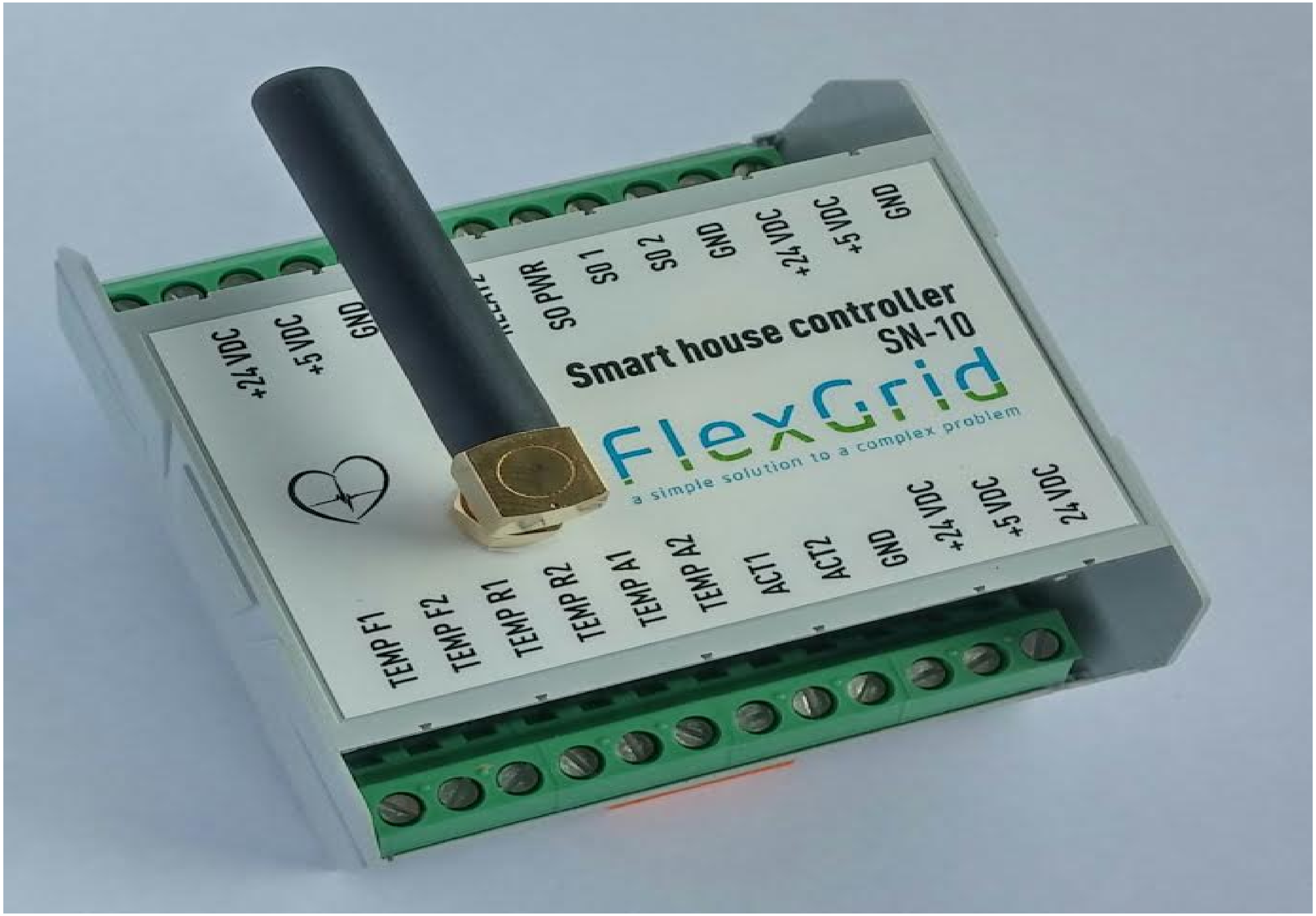
Lab testing ….



Control loop design – **logical drawing**



SN-10 Smart House Gateway



How does it work?

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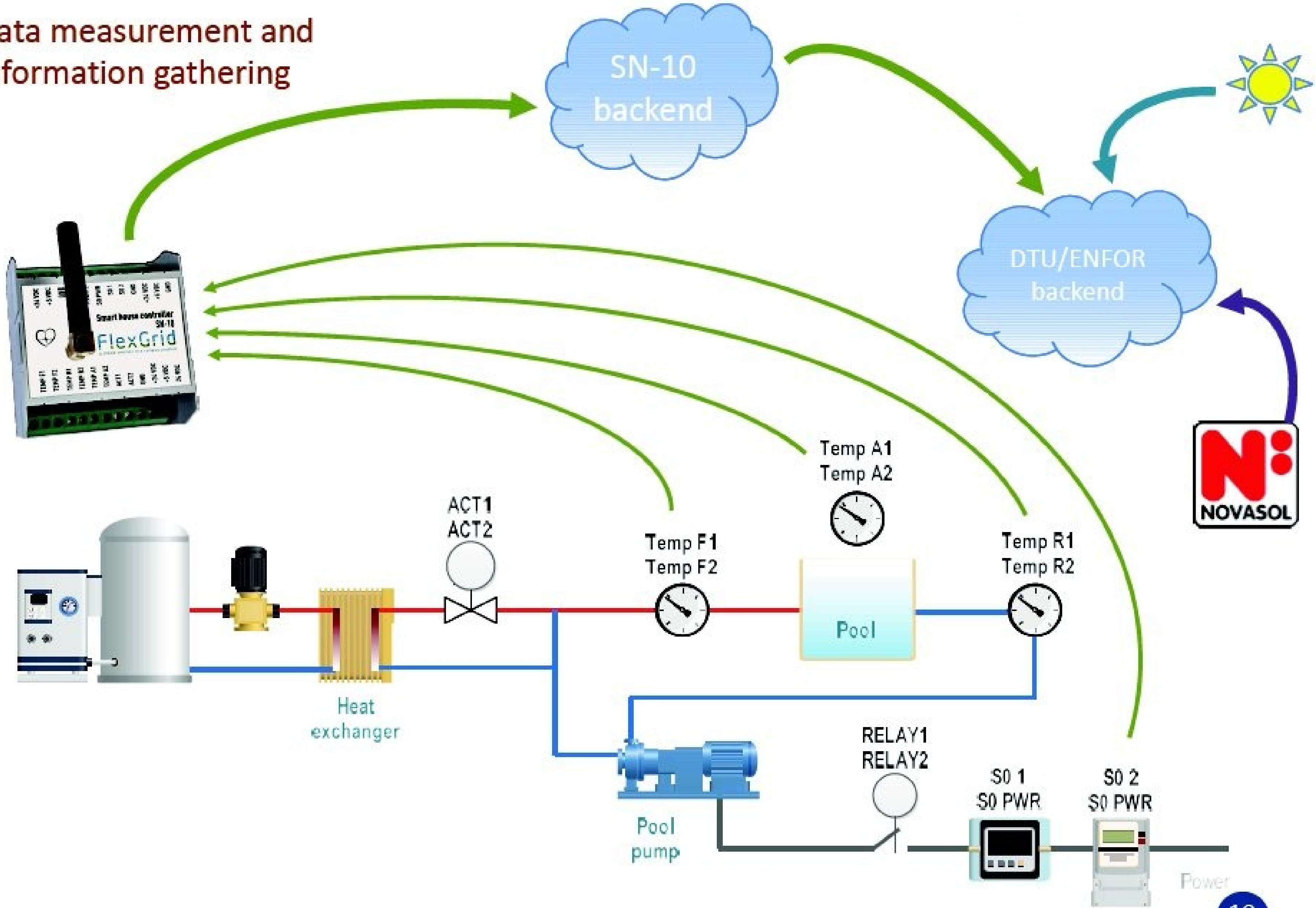
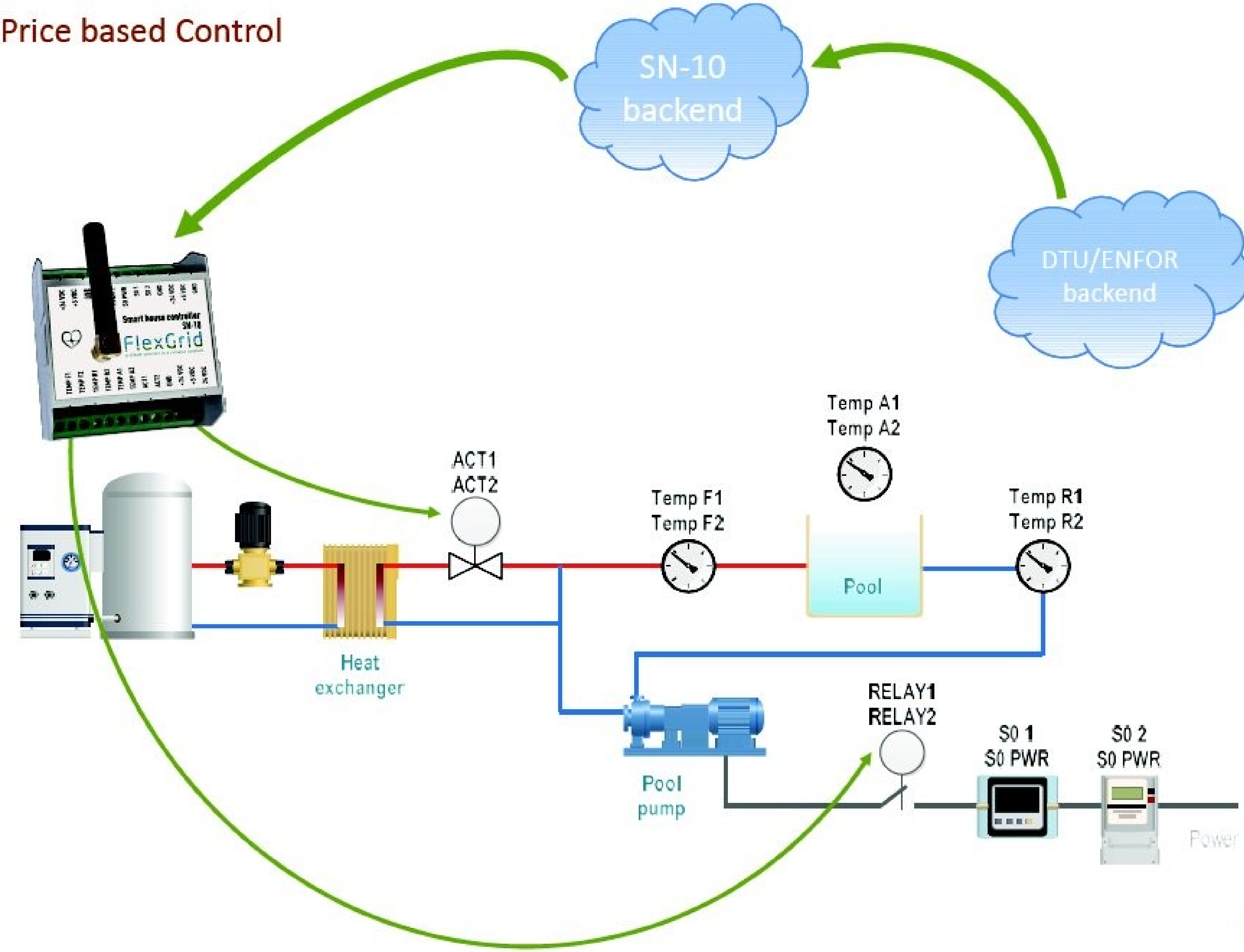
Data measurement and information gathering

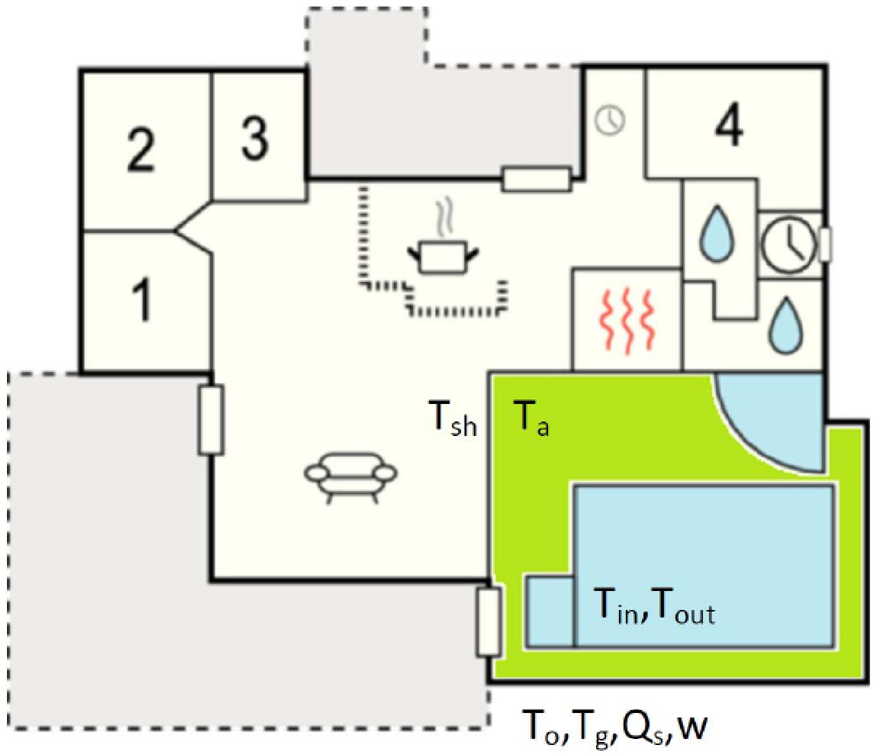


How does it work?

Price based Control



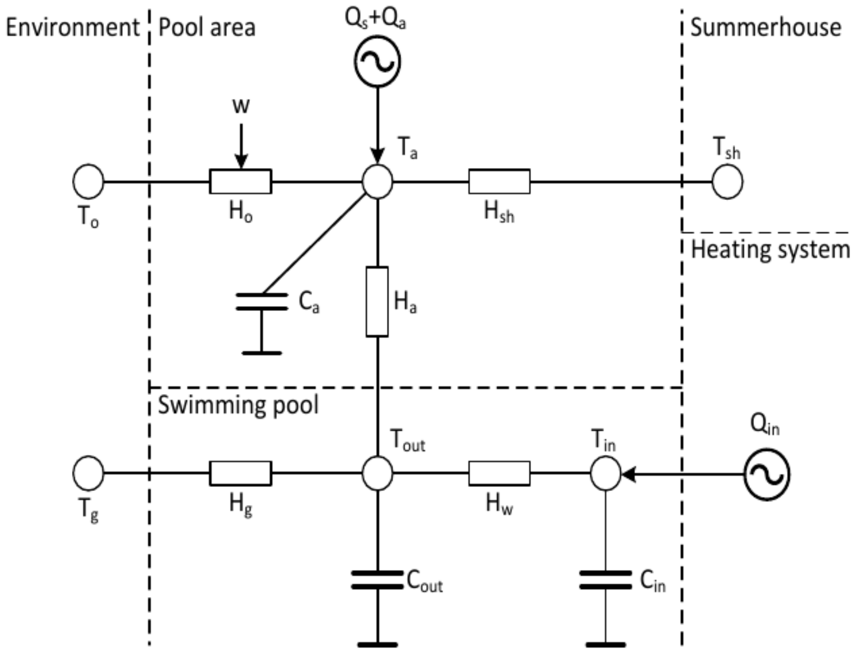
The considered house



- T_{sh} – summerhouse temperature
- T_a – temperature of air in the pool area
- T_{in} – water temperature into the swimming pool
- T_{out} – water temperature out of the swimming pool (controlled)
- T_o – outdoor temperature
- T_g – ground temperature
- Q_s – solar heat gain
- w – wind speed

Model for simulation

(Using lumped parameter model)



- Based on equivalent thermal parameters model

- Dynamics:

$$\frac{dT_{in}}{dt} = \frac{1}{C_{in}}[H_w(T_{out} - T_{in}) + Q_{in}]$$

$$\frac{dT_{out}}{dt} = \frac{1}{C_{out}}[H_w(T_{in} - T_{out}) + H_g(T_g - T_{out}) + H_a(T_a - T_{out})]$$

$$\frac{dT_a}{dt} = \frac{1}{C_a}[H_o(w)(T_o - T_a) + H_a(T_{out} - T_a) + H_{sh}(T_{sh} - T_a) + Q_s + Q_a]$$

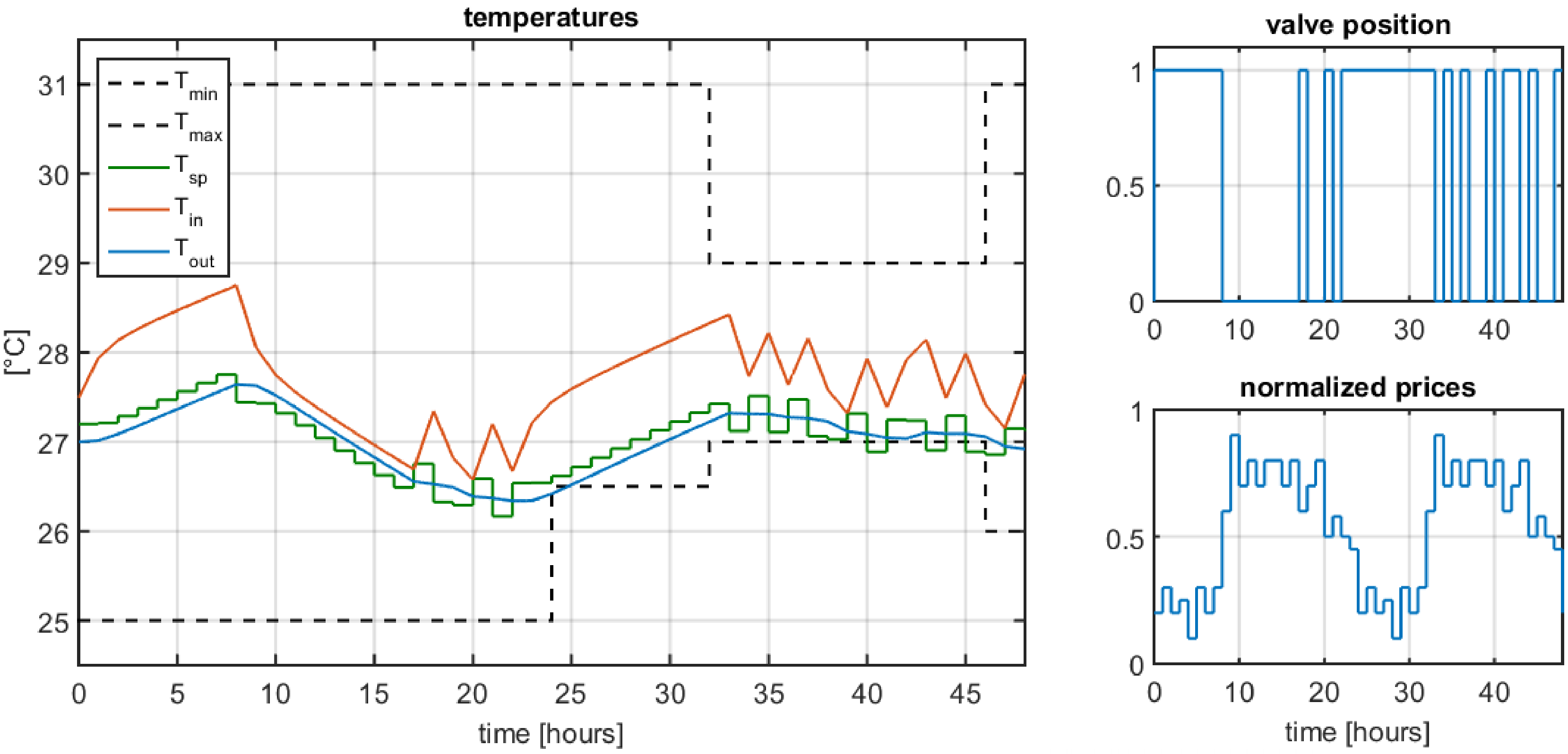
Control problem (simplified)

$$\min_{u} \sum_{k=0}^{N-1} c_k u_k$$

$$\begin{aligned} s.t. \quad x_{k+1} &= f_x(x_k, u_k, \theta_k) \\ y_k &= f_y(x_k, \theta_k) \\ y_{min} &\leq y_k \leq y_{max} \\ u_k &\in \{0, 1\} \end{aligned}$$

- N – predictive horizon
- c_k – electricity prices
- f_x and f_y – discretized LPV model
- y_{min} and y_{max} – output constraints which guarantee customers' comfort

Simulation Results



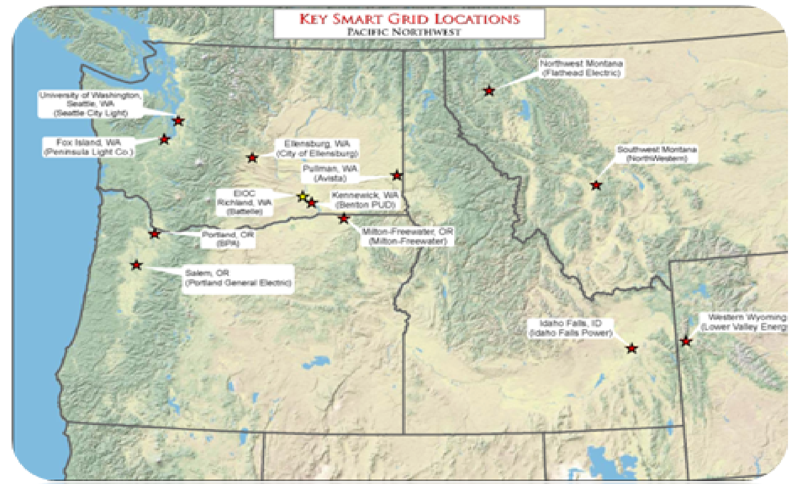
Case study (Level III)

Price-based Control of Power Consumption

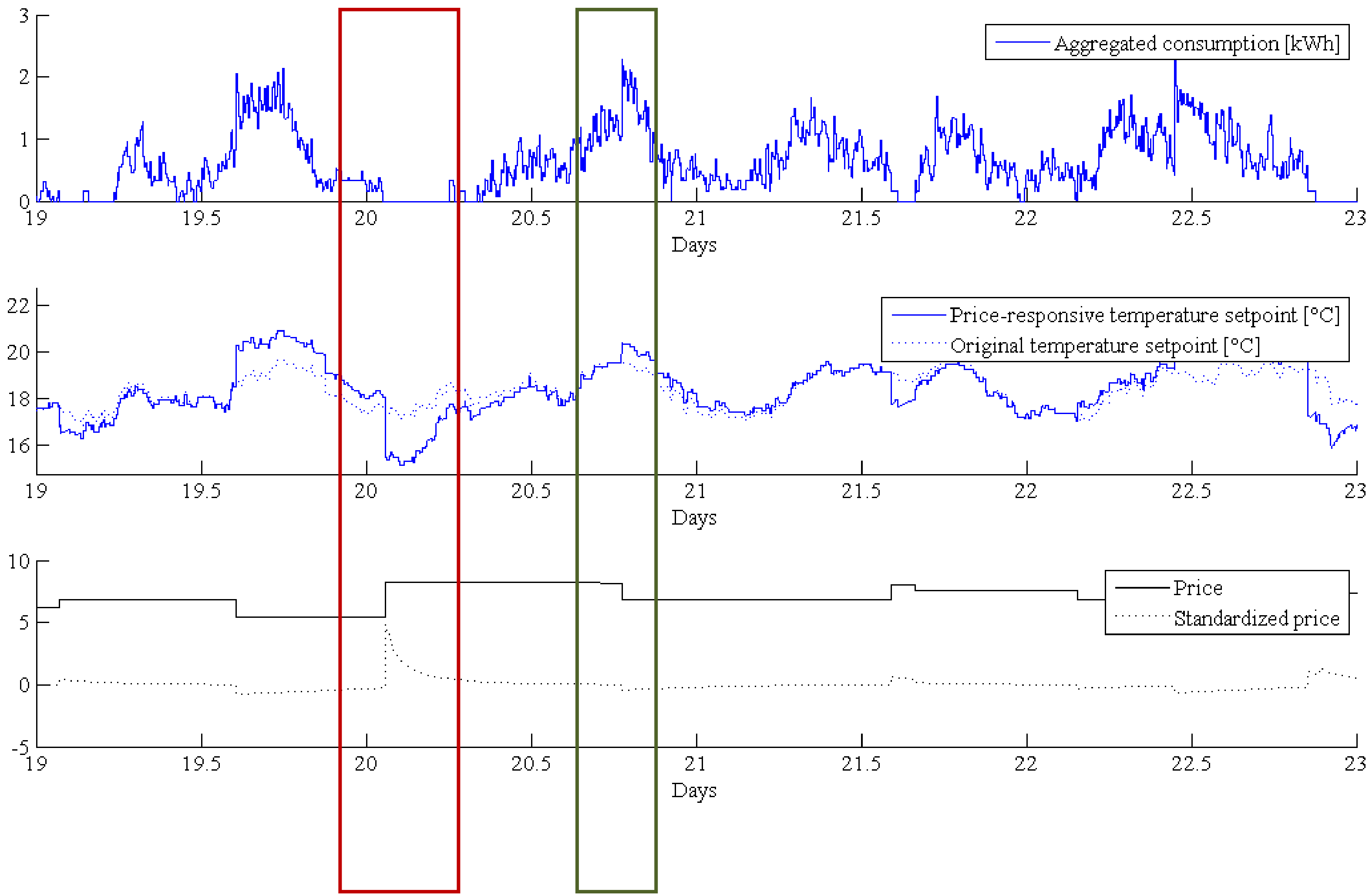
Data from BPA

Olympic Pensinsula project

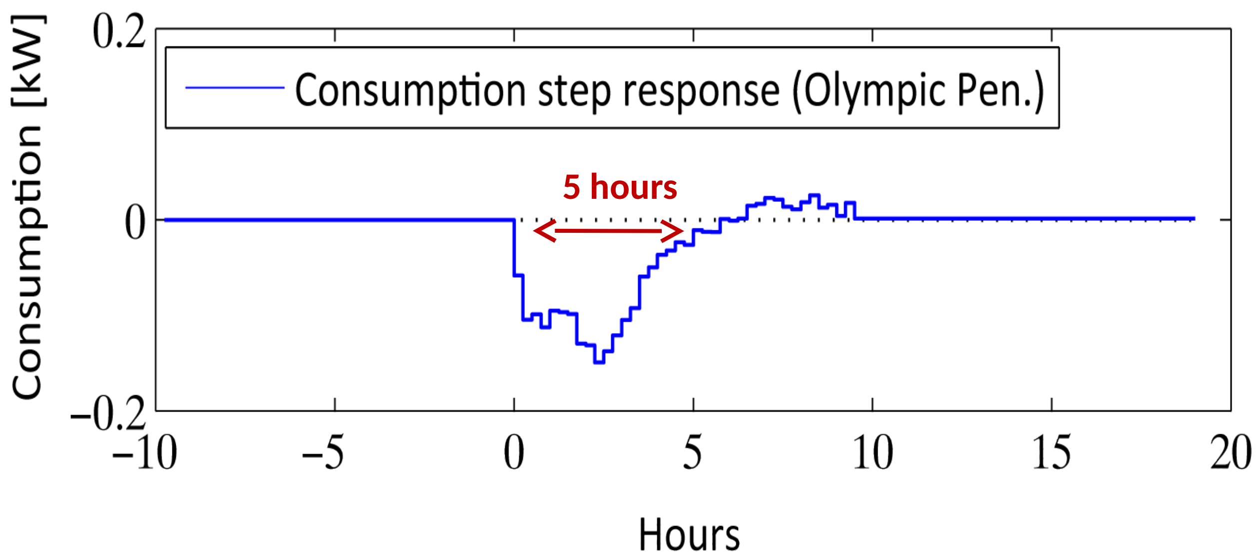
- 27 houses during one year
- Flexible appliances: HVAC,
  cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption



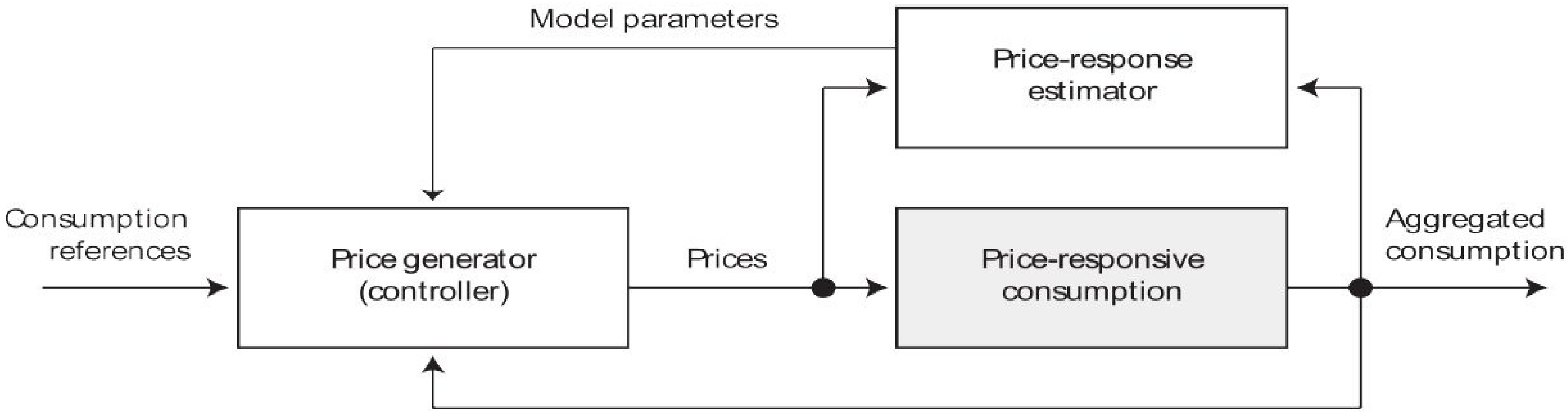
Aggregation (over 20 houses)

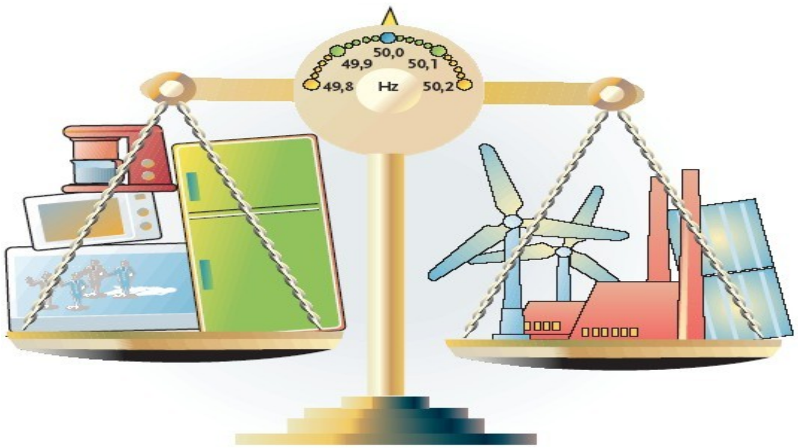


Response on Price Step Change



Control of Power Consumption





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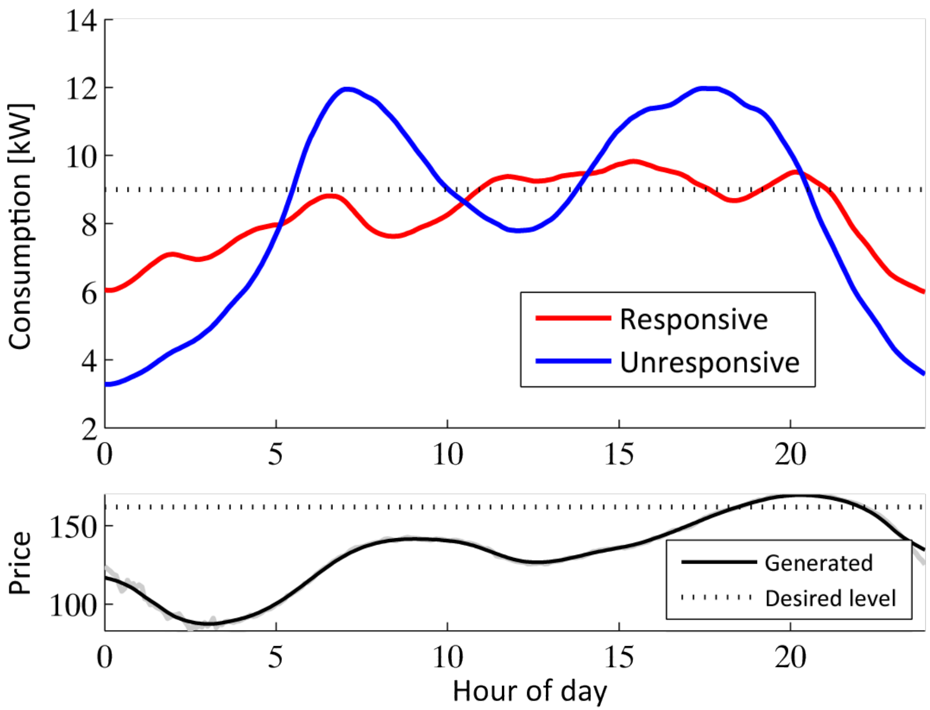
Control performance

Considerable **reduction in peak consumption**

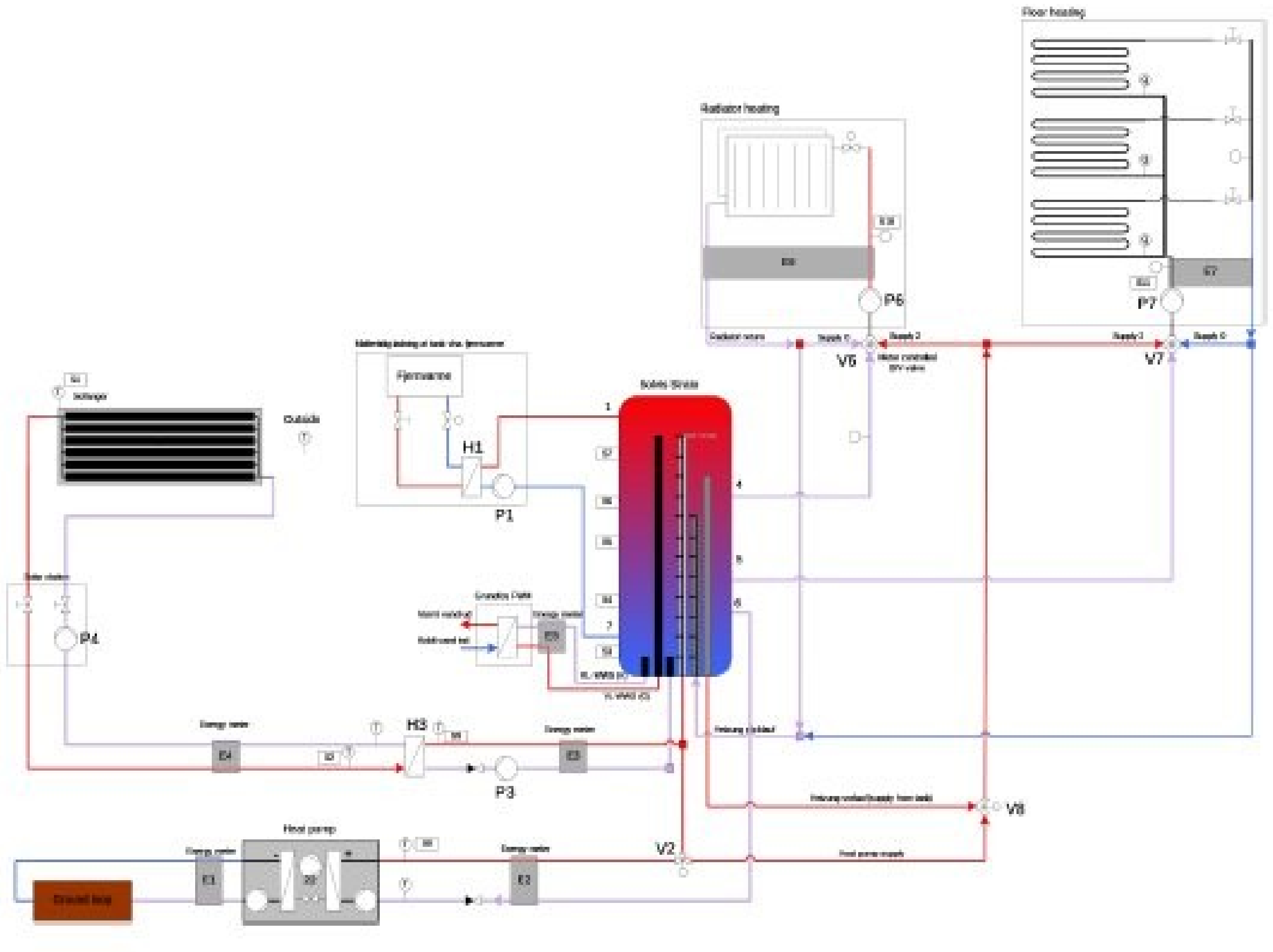


Case study
(Level IV – Indirect Control)

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

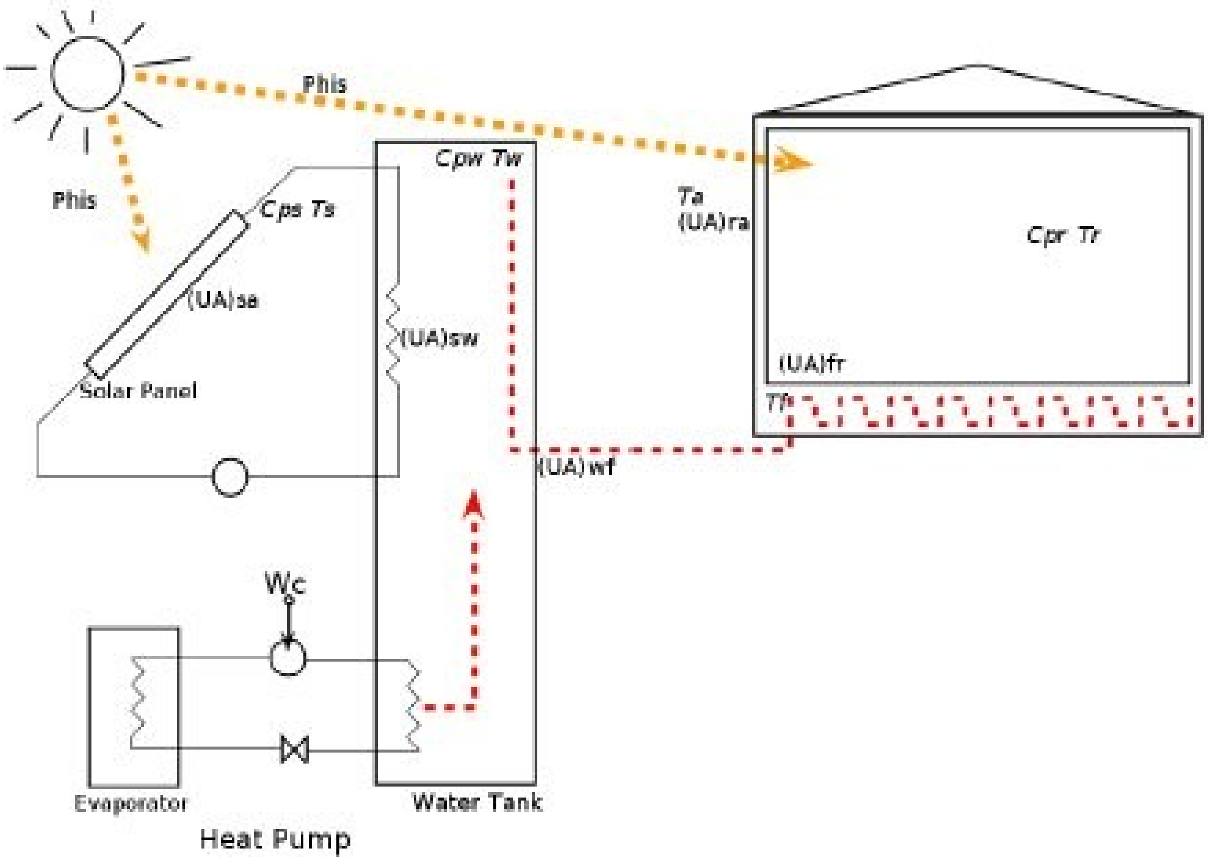
Grundfos Case Study

Schematic of the heating system



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:

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

Subject to

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

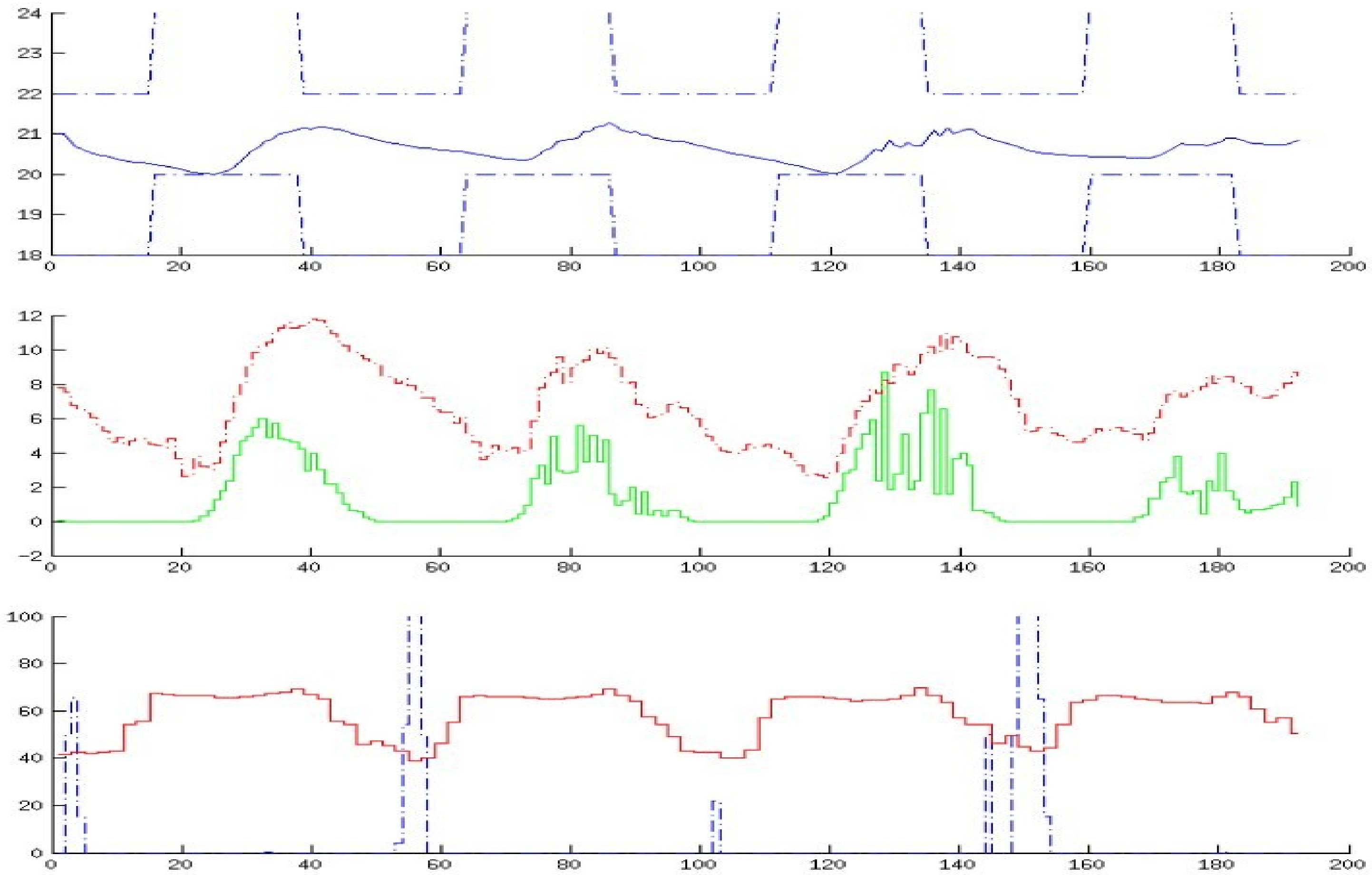
$$y_k = Cx_k \quad k = 1, 2, \ldots, N \tag{4c}$$

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

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

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

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



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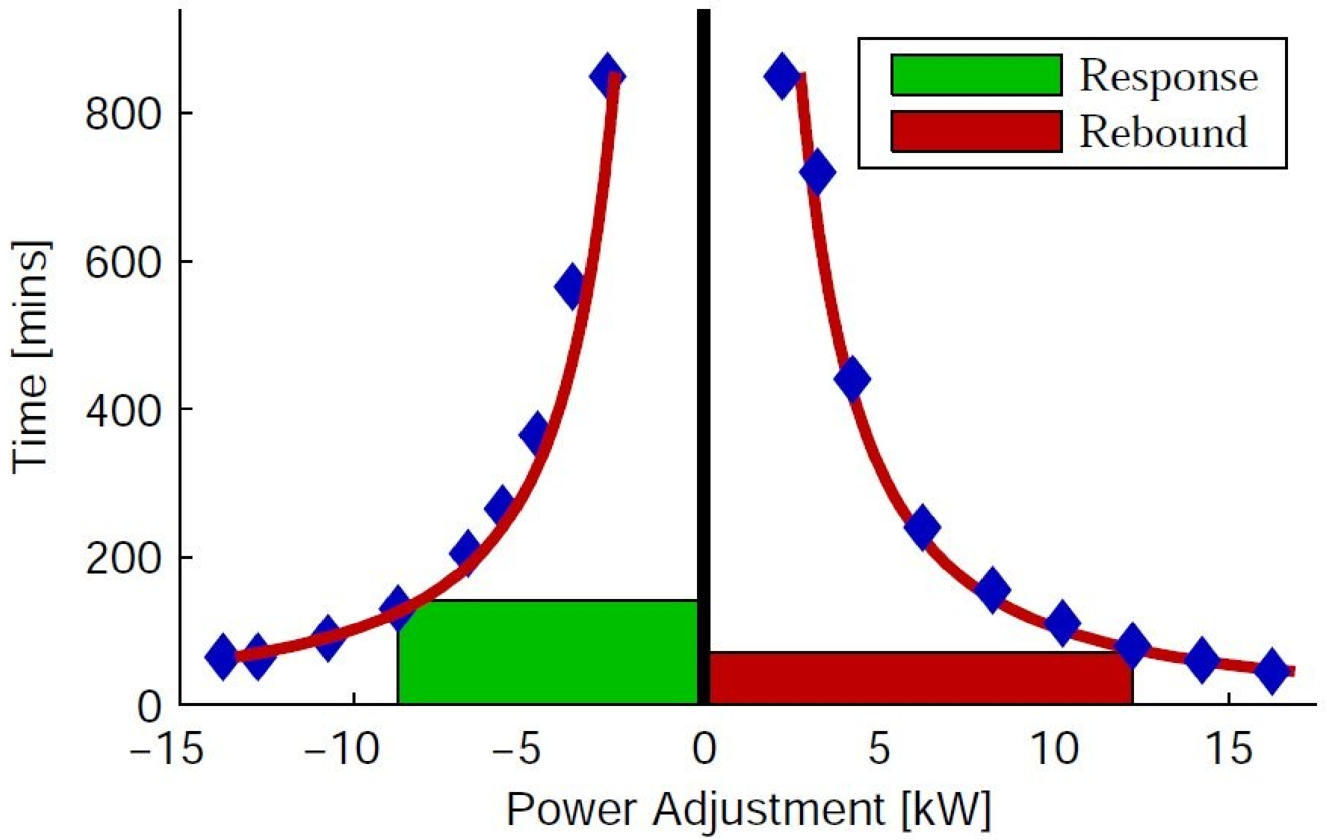
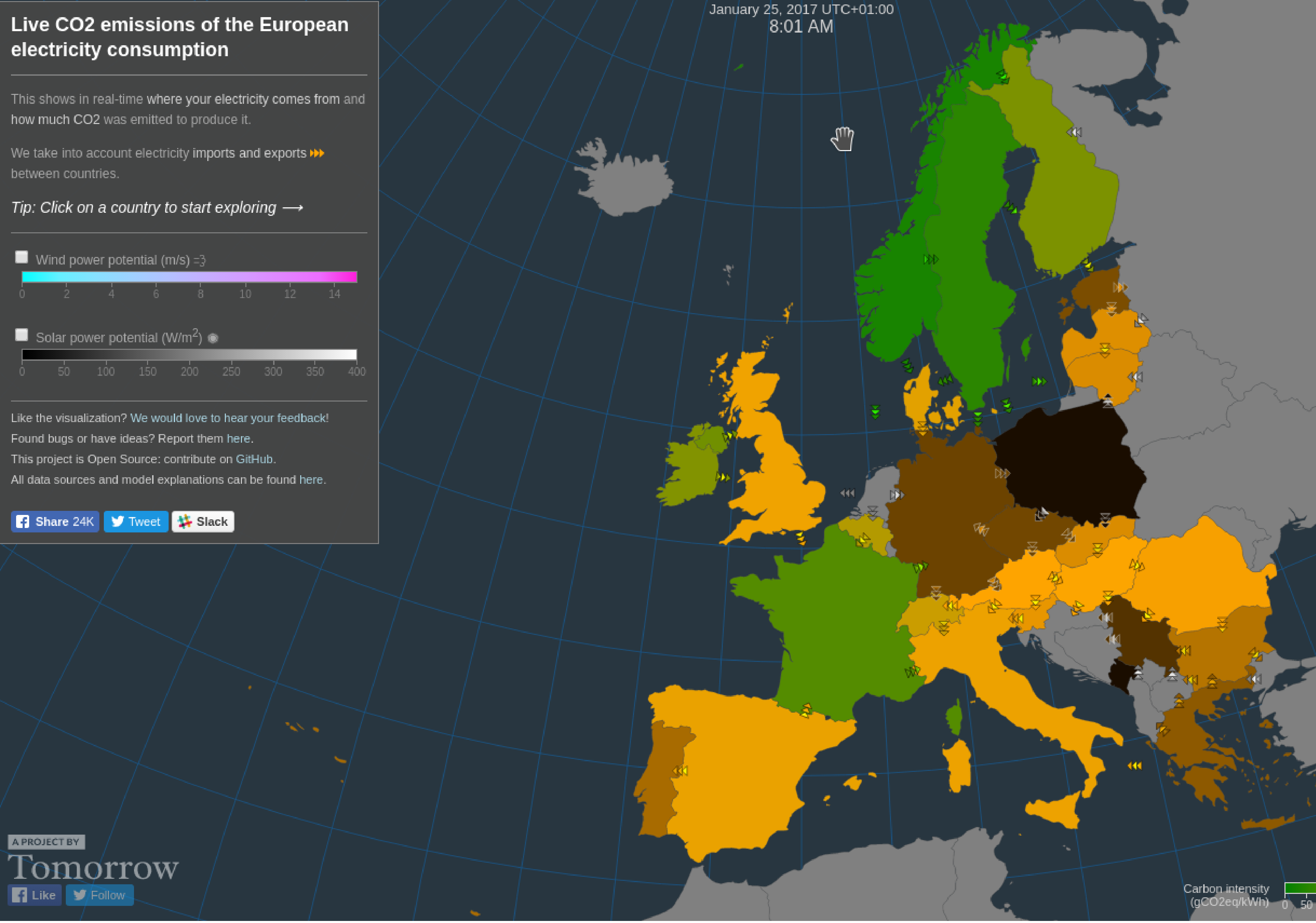
Further Aspects

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





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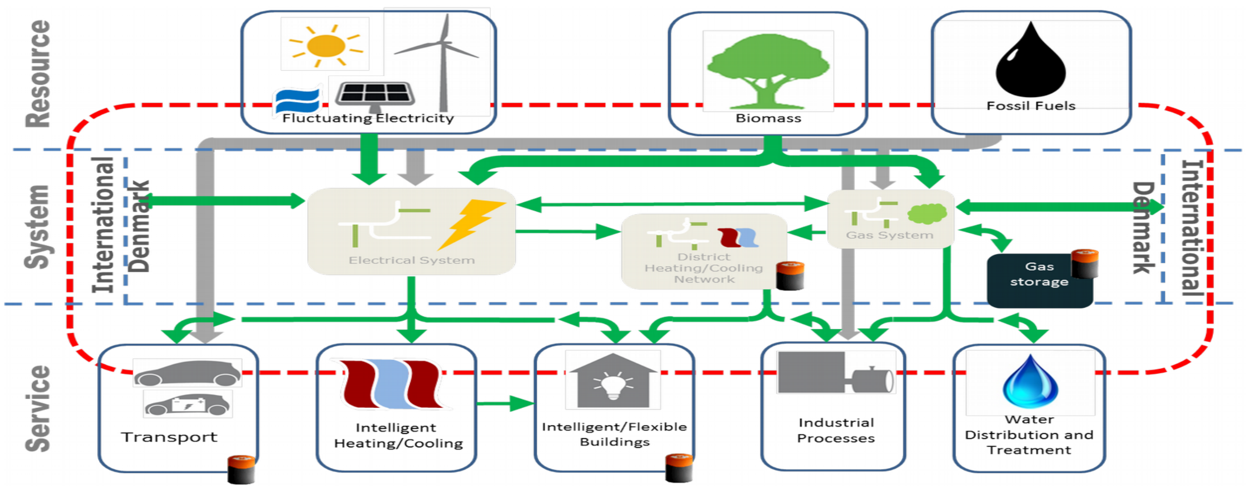
Control of Electricity Load
Some Projects

- Control of WWTP (ED, Kruger, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Summerhouses (**SmartNet**: ONE, ENDK, SE, ..)
- 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

Summary

- A **Smart-Energy OS** for implementing future and integrated future electric energy systems has been described. It consists of a **hierarchy of nested stochastic optimization/control problems**.
- The **Power Grid is the backbone** – we need an **Intelligent** Smart Grid – also across voltage levels – focus on TSO-BRP-DSO interactions for providing the needed services. Intelligence using either **Coordination Schemes** (H2020 SmartNet) or **Control Theory** (the full Smart-Energy OS)
- **Modelling**: Toolbox – CTSM-R - for combined physical and statistical modelling (**grey-box modelling**)
- **Control and Optimization:** Toolbox – for Optimization and Model Predictive Control
- **Forecasting**: Toolbox - for wind, solar, price, and load forecasting
- Two models for ***characterizing the flexibility*** have been suggested:
    - **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.smartnet-project.eu

www.smart-cities-centre.org

...or contact

– Henrik Madsen (DTU Compute)
– Gianluigi Migliavacca (RSE, Milan)

Acknowledgement: DSF 1305-00027B + H2020 SmartNet Project

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