Future Electric Energy Markets; with a focus on control based solutions

H. Madsen, J. Parvizi, N. O'Connell, N.K. Poulsen,

O. Corradi, G. De Zotti, S.A. Pourmousavi,

R. Halvgaard, J.B. Jørgensen, L.E. Sokoler

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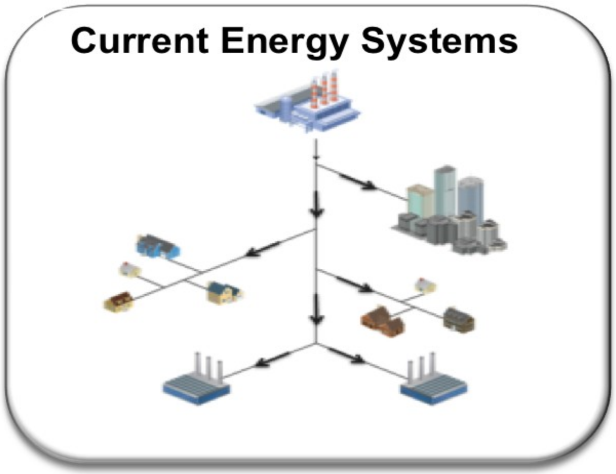
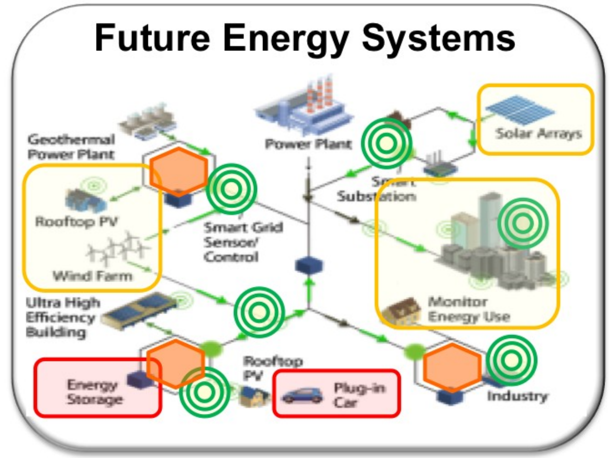
Transition in the Energy World





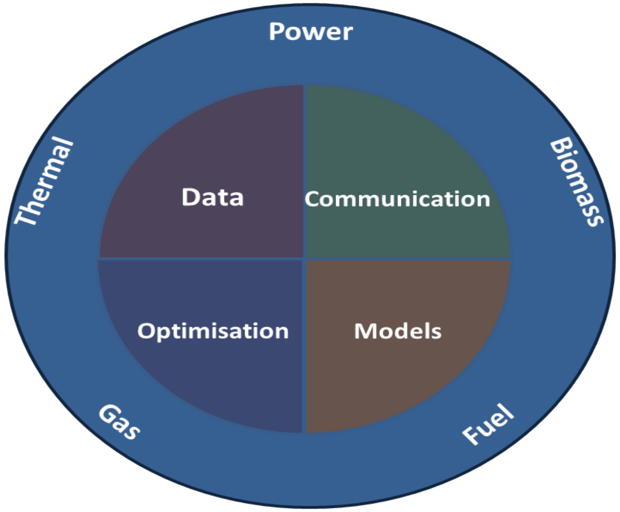
The rapidly changing energy world calls for a the next generation of tools for trading, simulation, planning, optimization, decision support, control and operation. These tools calls for research focusing on:

- **Balancing of variable RE using flexibility in markets**
- **Controllable and flexible loads**
- **New data, information, communications and controls**
- **Community markets, nested markets, multi-energy markets, ….**
- **Enable (virtual) energy storage by energy systems integration**
- **Interactions between electricity/thermal/fuels/data pathways**

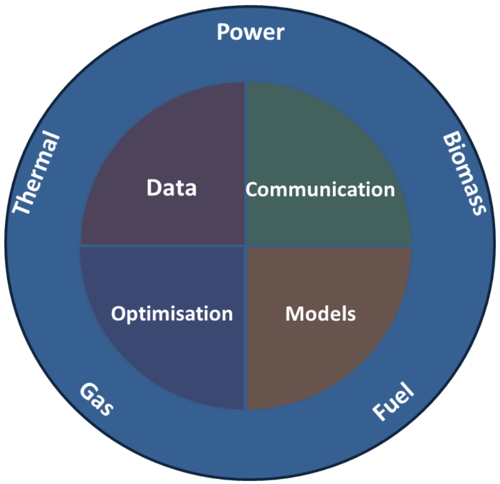
Flexible Solutions and CITIES

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 in CITIES



The **central hypothesis** is that by **intelligently integrating** currently distinct energy flows (heat, power, gas and biomass) in cities 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.)

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:

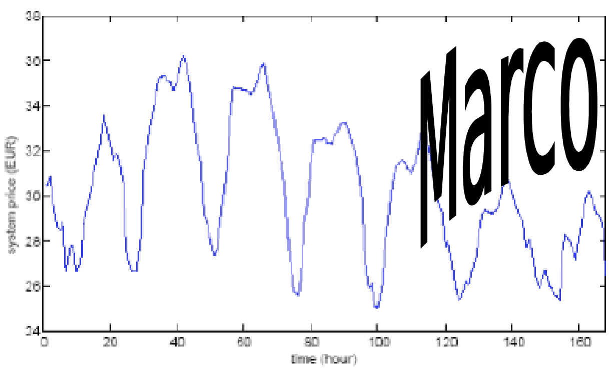
- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy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

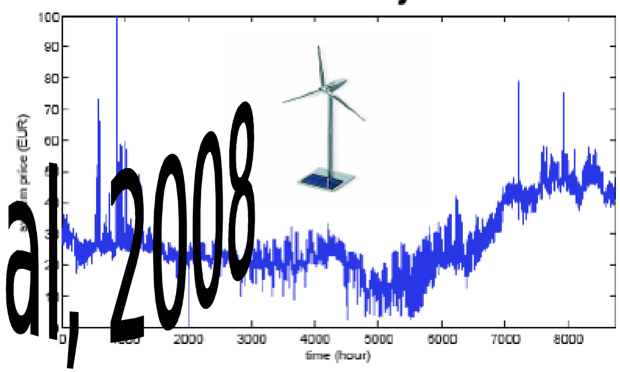
Advantages in handling effectively

Dynamics



Marco Zugno et.al, 2008

Uncertainty



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

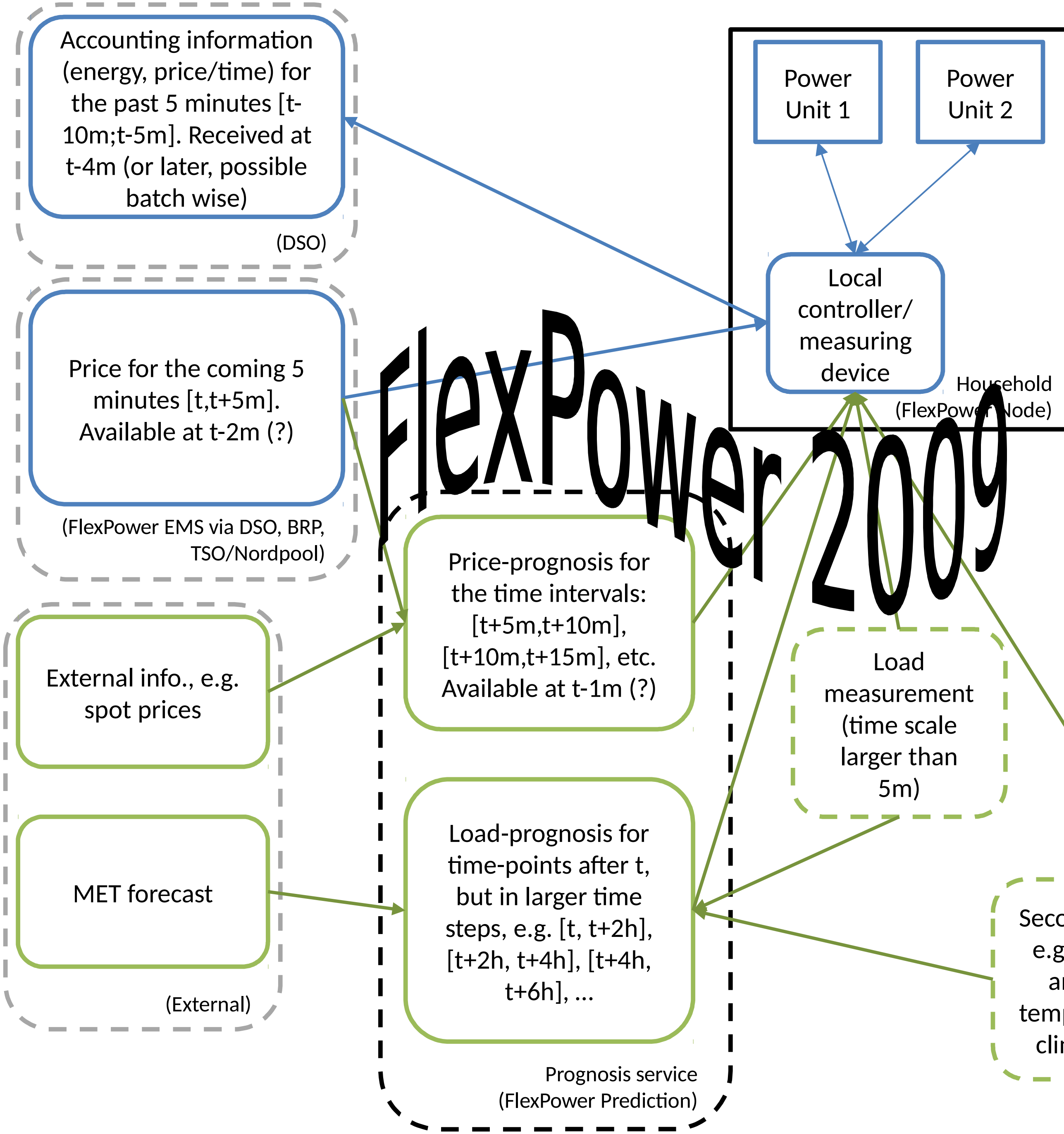
↓

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



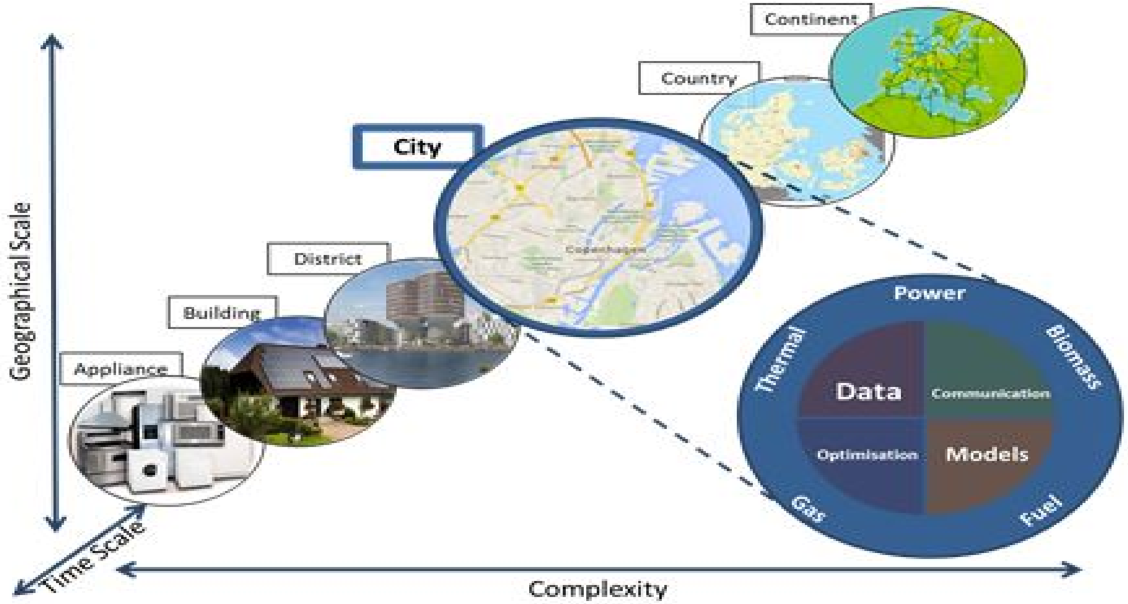
The blue color represent the minimal FlexPower requirements. The green color represents the additional requirements when external prognoses are used by the local controller. Possible multiple load forecasts may be required by the household. Also the load prognosis may be supplemented with additional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

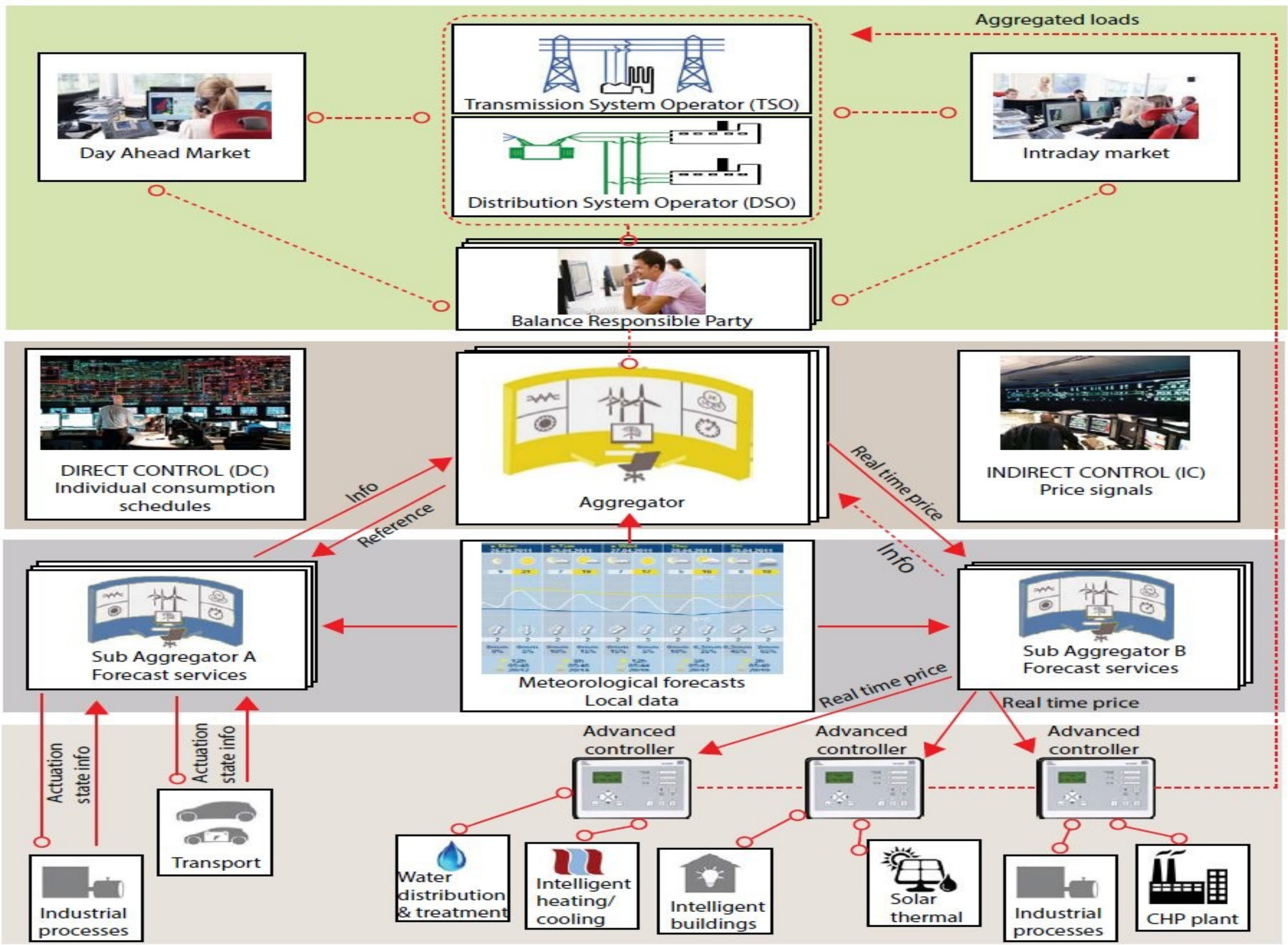
The time index t refers to the beginning of the next 5 minute interval.

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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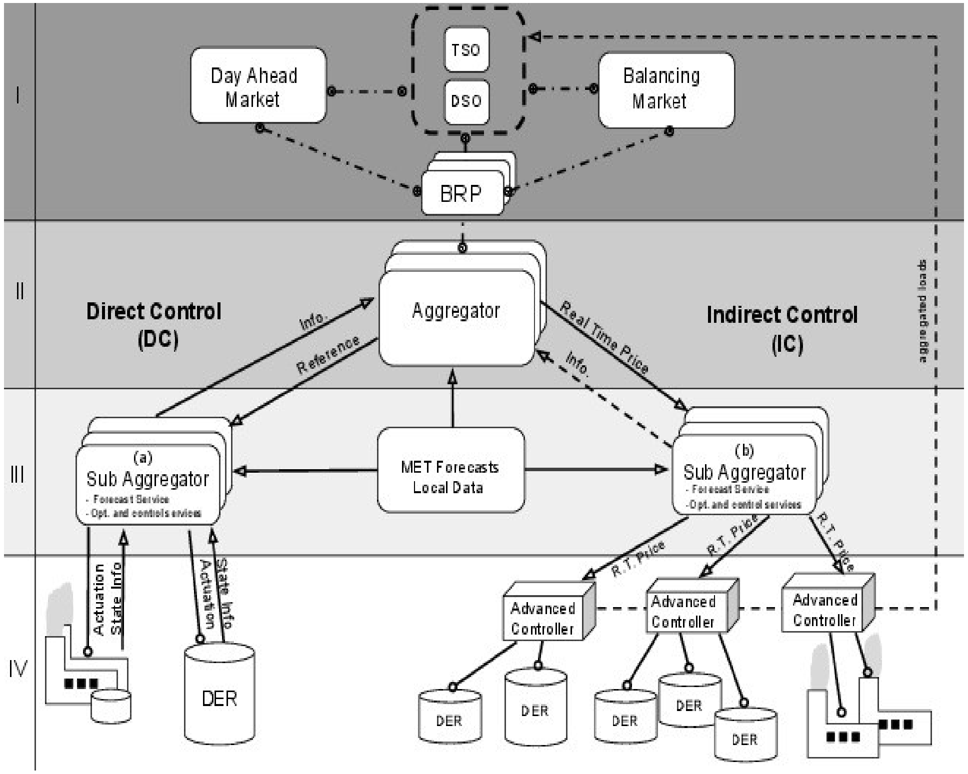
Control and Optimization



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

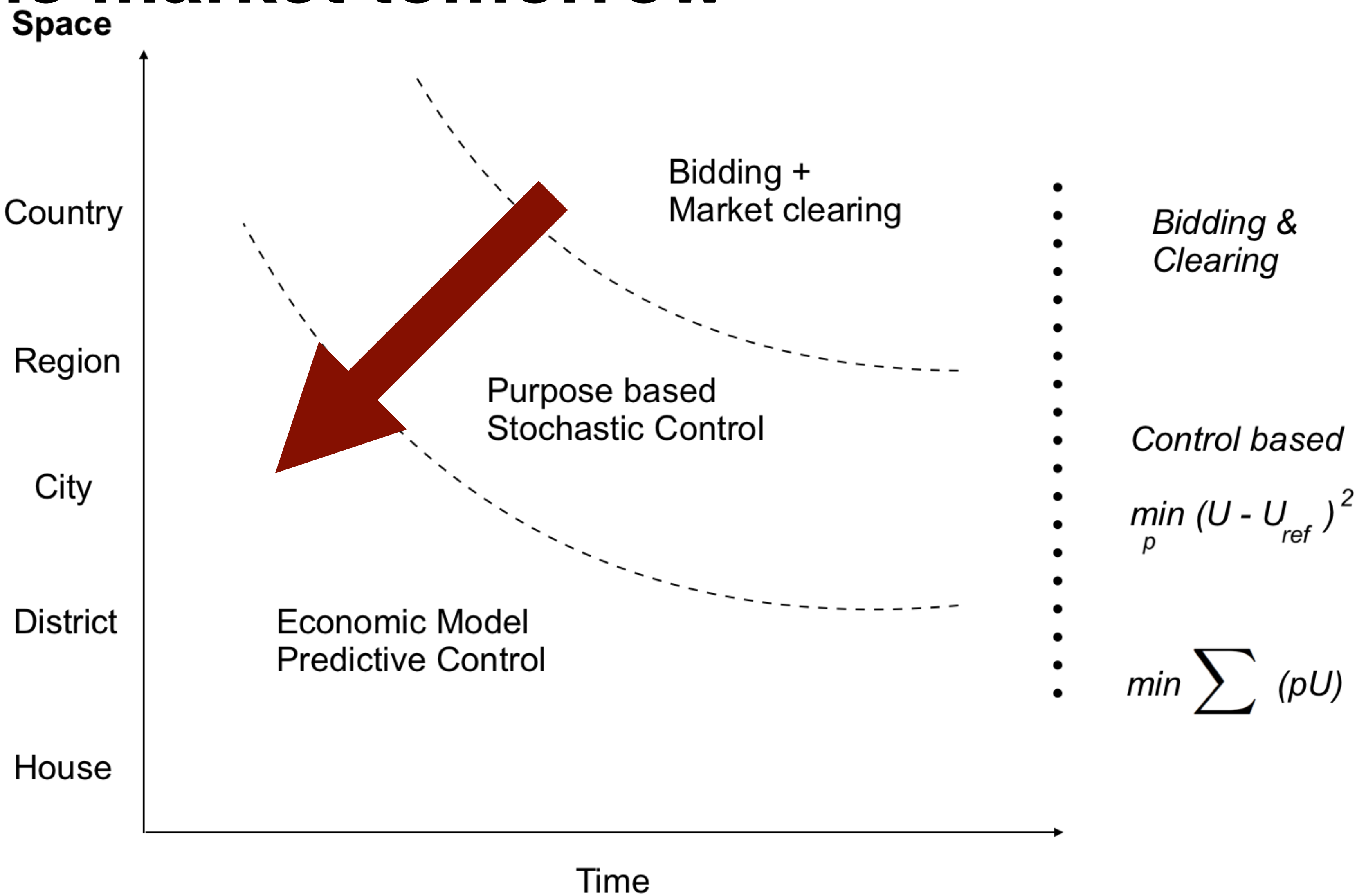
Simple 'contracts'

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>

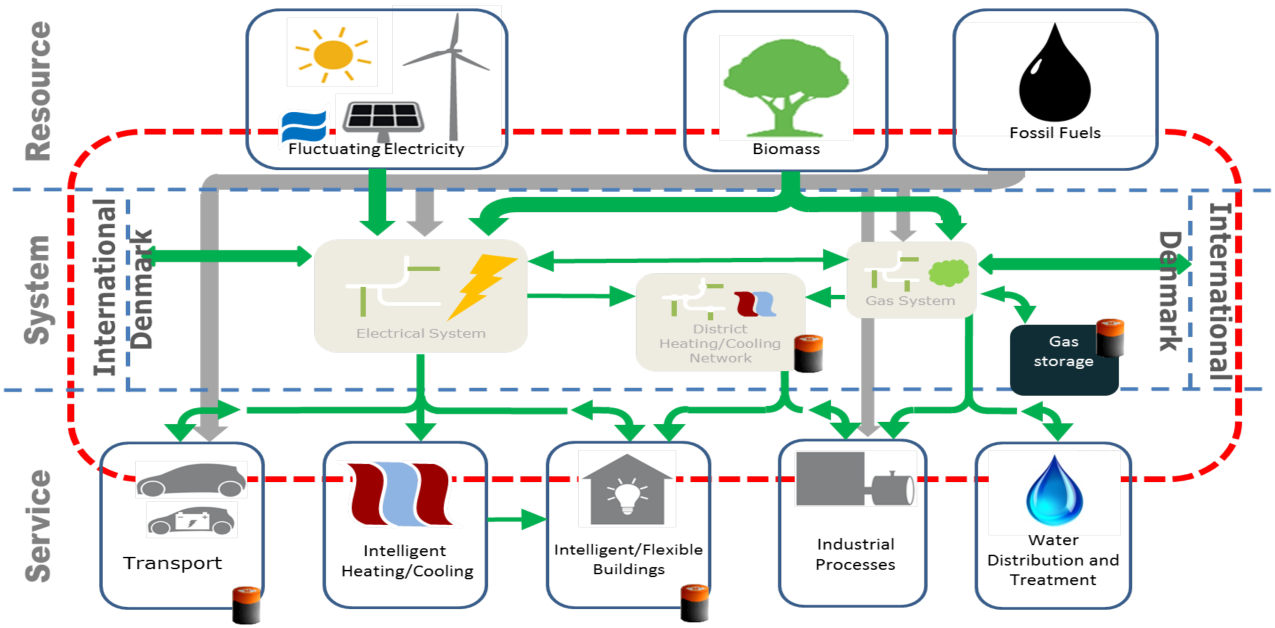
Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals u_j are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes 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.

The market tomorrow



Models for systems of systems

Intelligent systems integration using **data and ICT solutions** are used to establish **models and methods** **for real-time operation of flexible energy systems**



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

Methods and methodologies for implementing a fossil-free society on the Faroe Islands

L. E. Sokoler, N. K. Poulsen, H. Madsen, K. Edlund, R. Bærentsen, P. Vinter, and J. B. Jørgensen

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DONG energy

CITIES Second General Consortium Meeting
Kgs. Lyngby, Denmark. May 2015

Case study (Level III)

Price-based Control of Power Consumption

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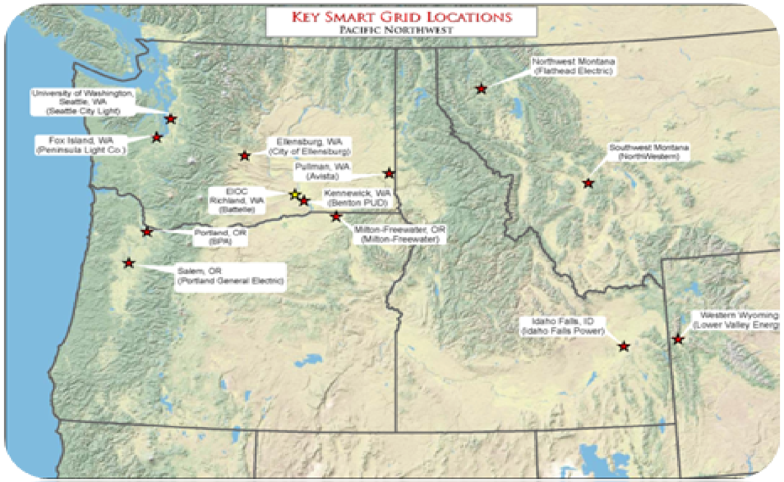
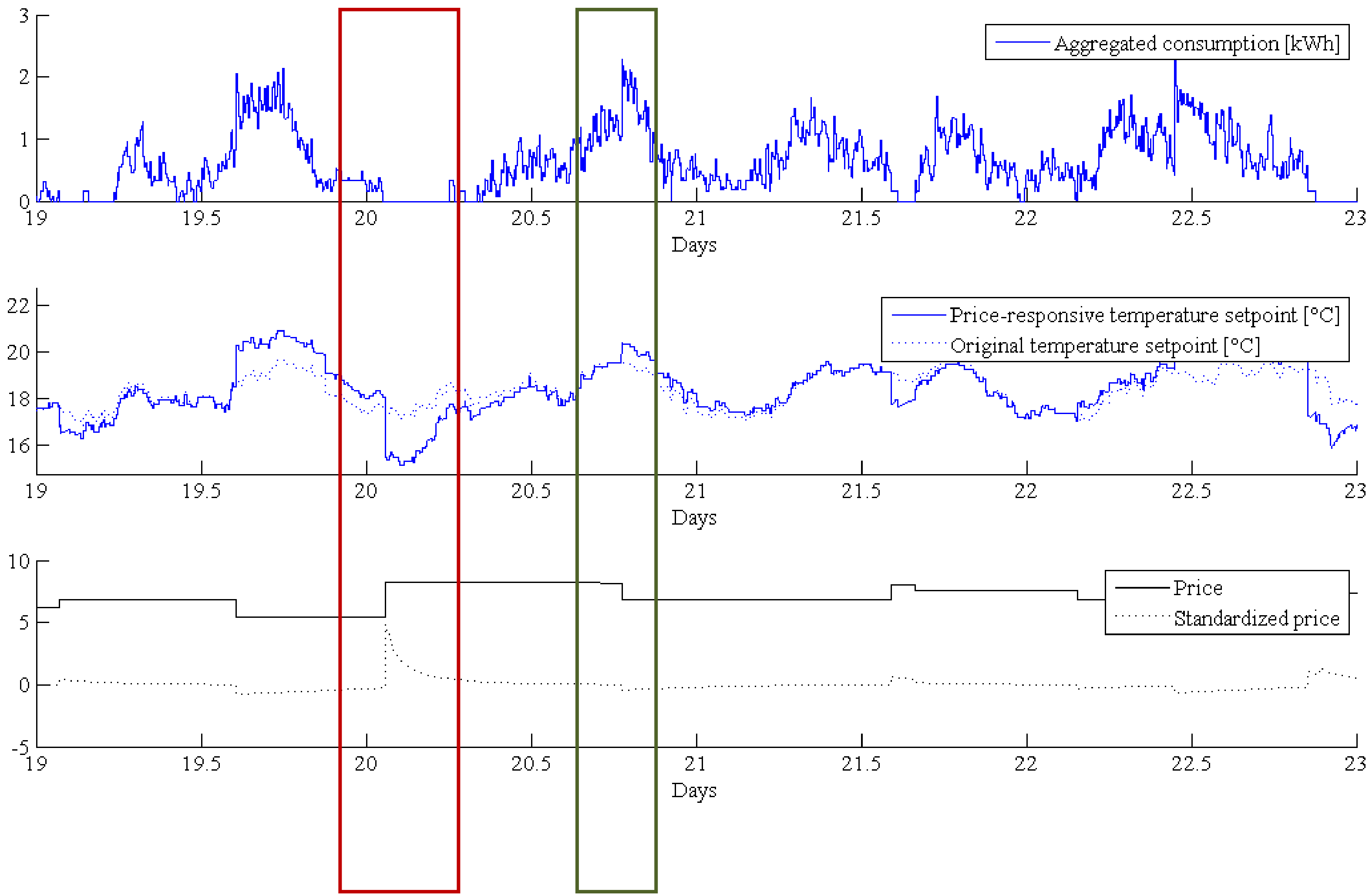
Data from BPA

Olympic Pensinsula project

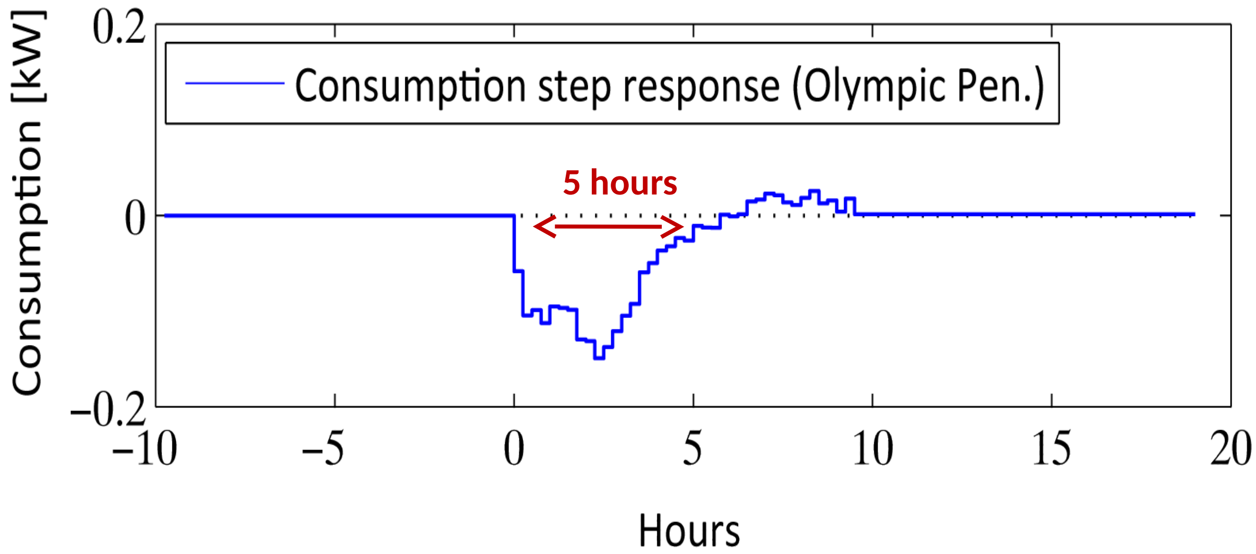
- 27 houses during one year
- Flexible appliances: HVAC,
  cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption



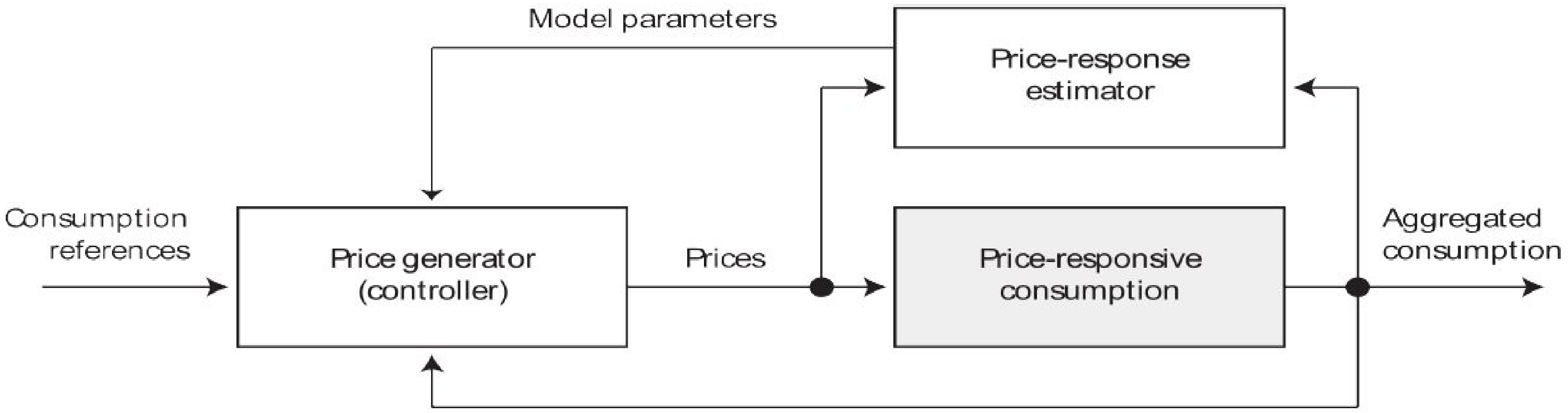
Aggregation (over 20 houses)

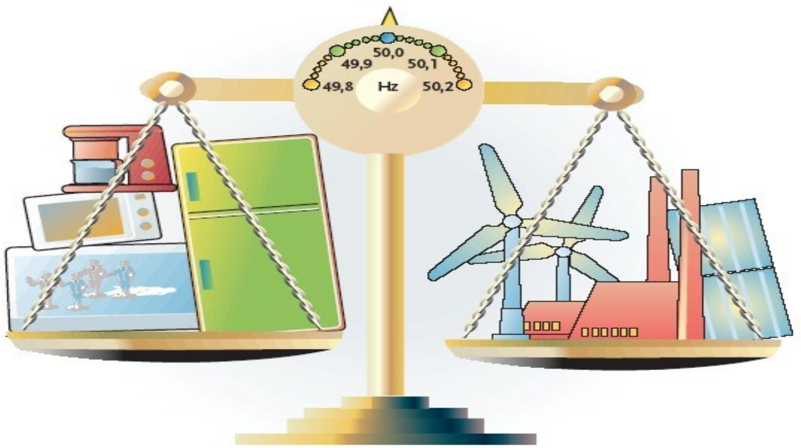


Response on Price Step Change



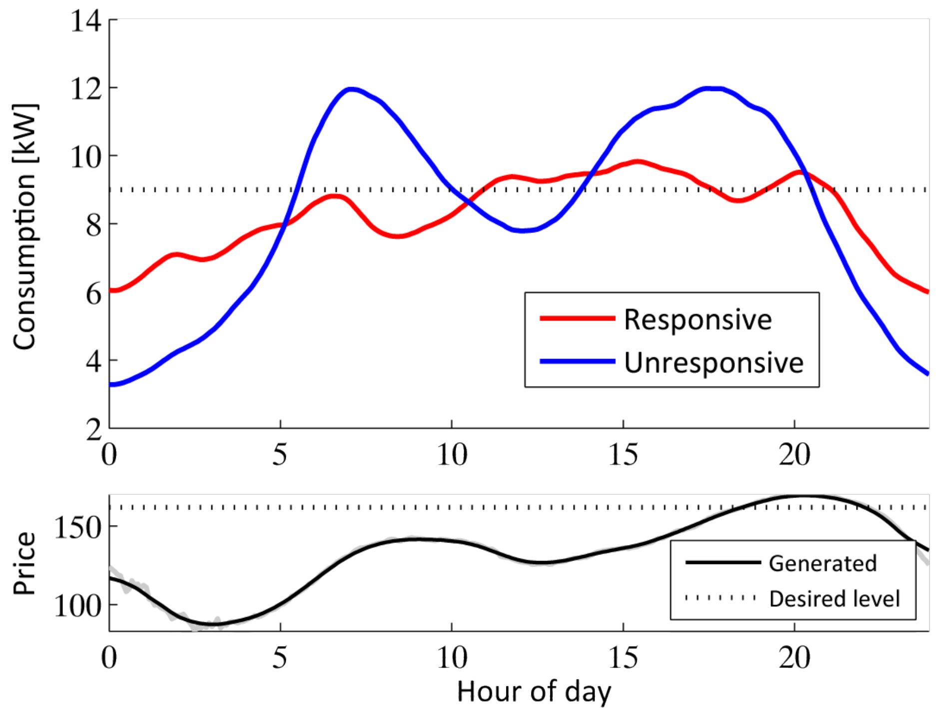
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**

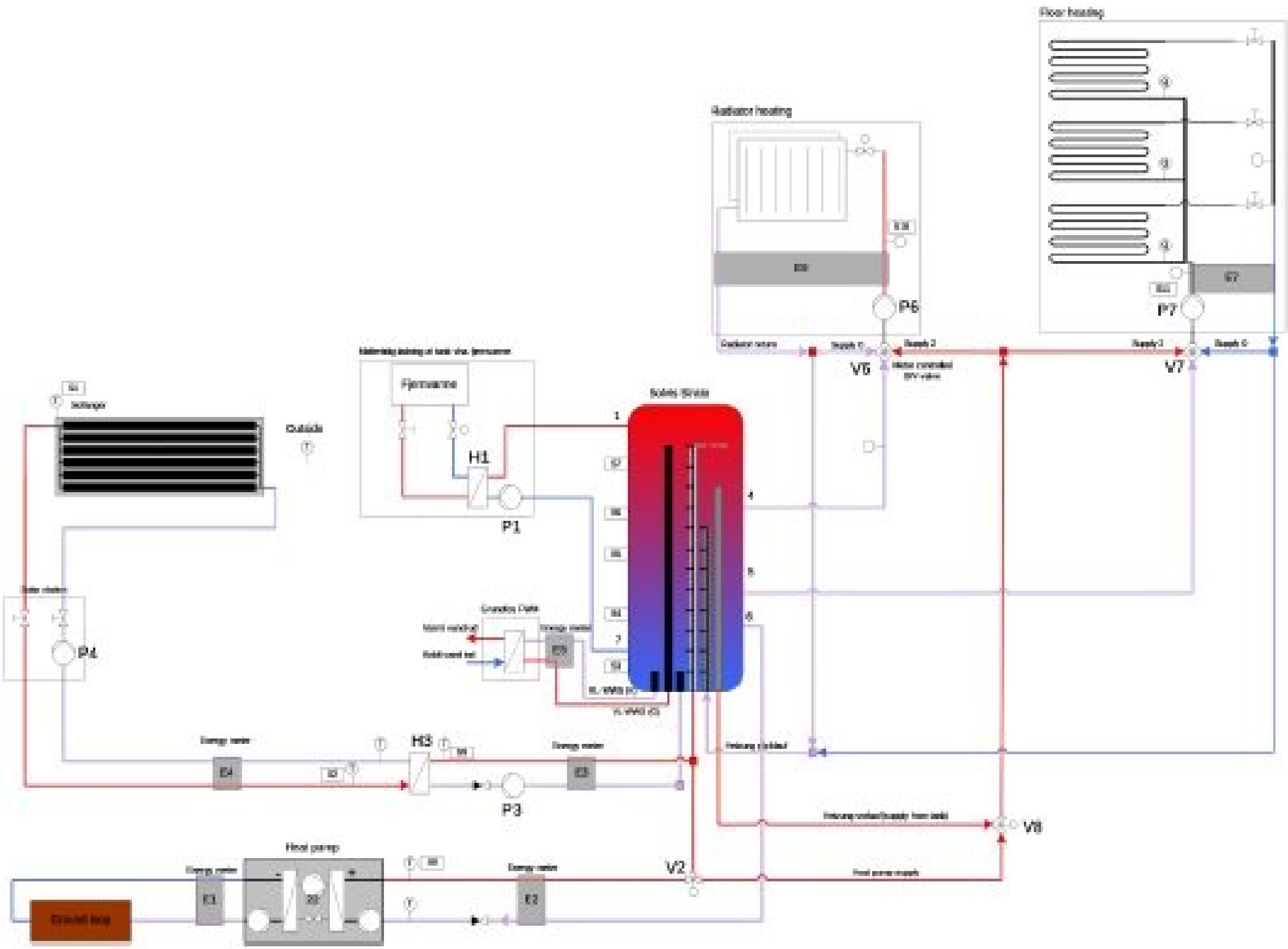


Case study
(Level IV – Indirect Control)

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

Grundfos Case Study

Schematic of the heating system



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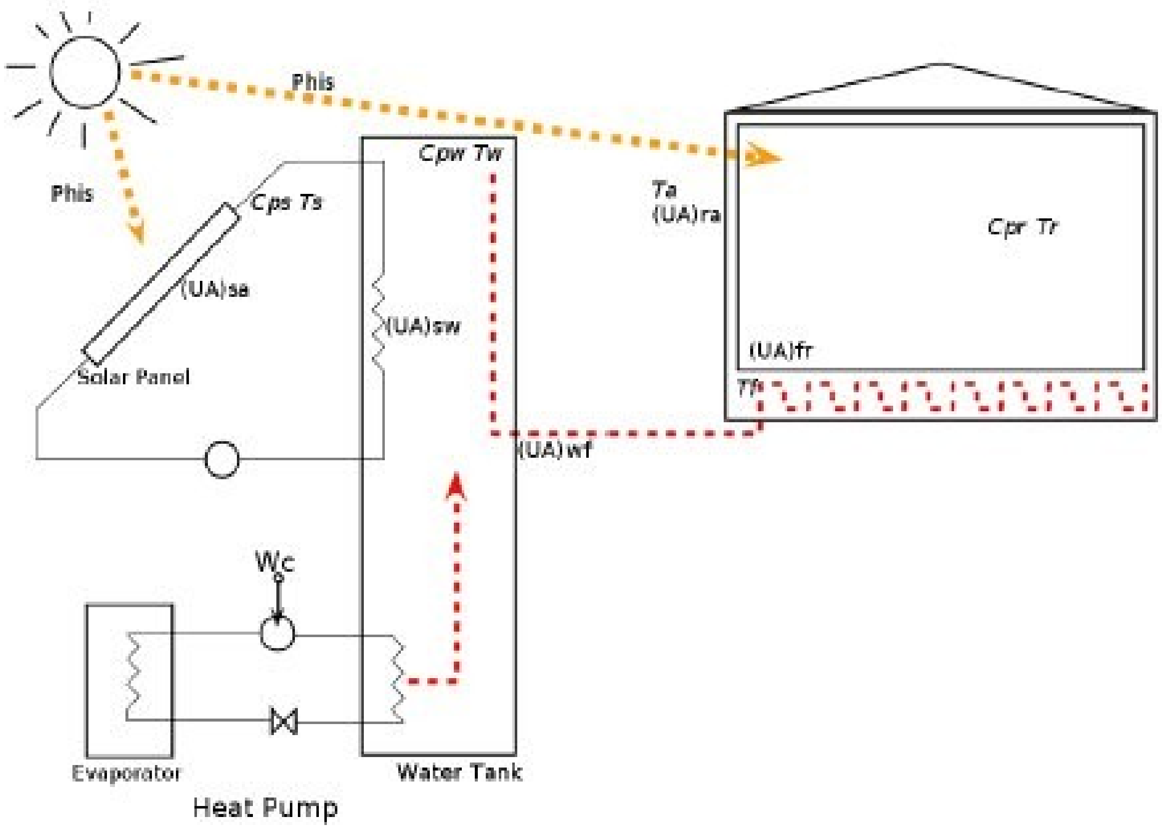
Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

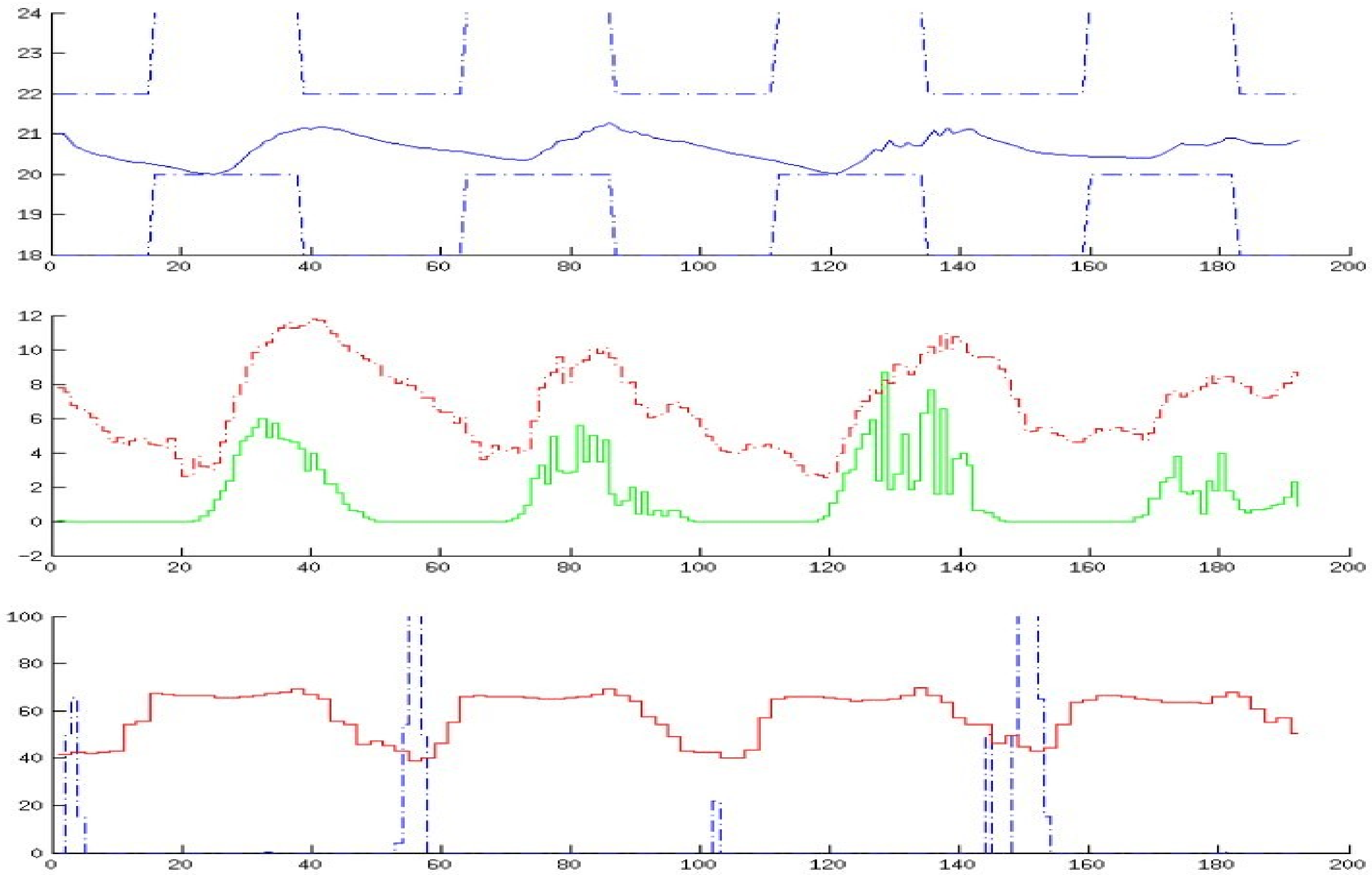
Formulation

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

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

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

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



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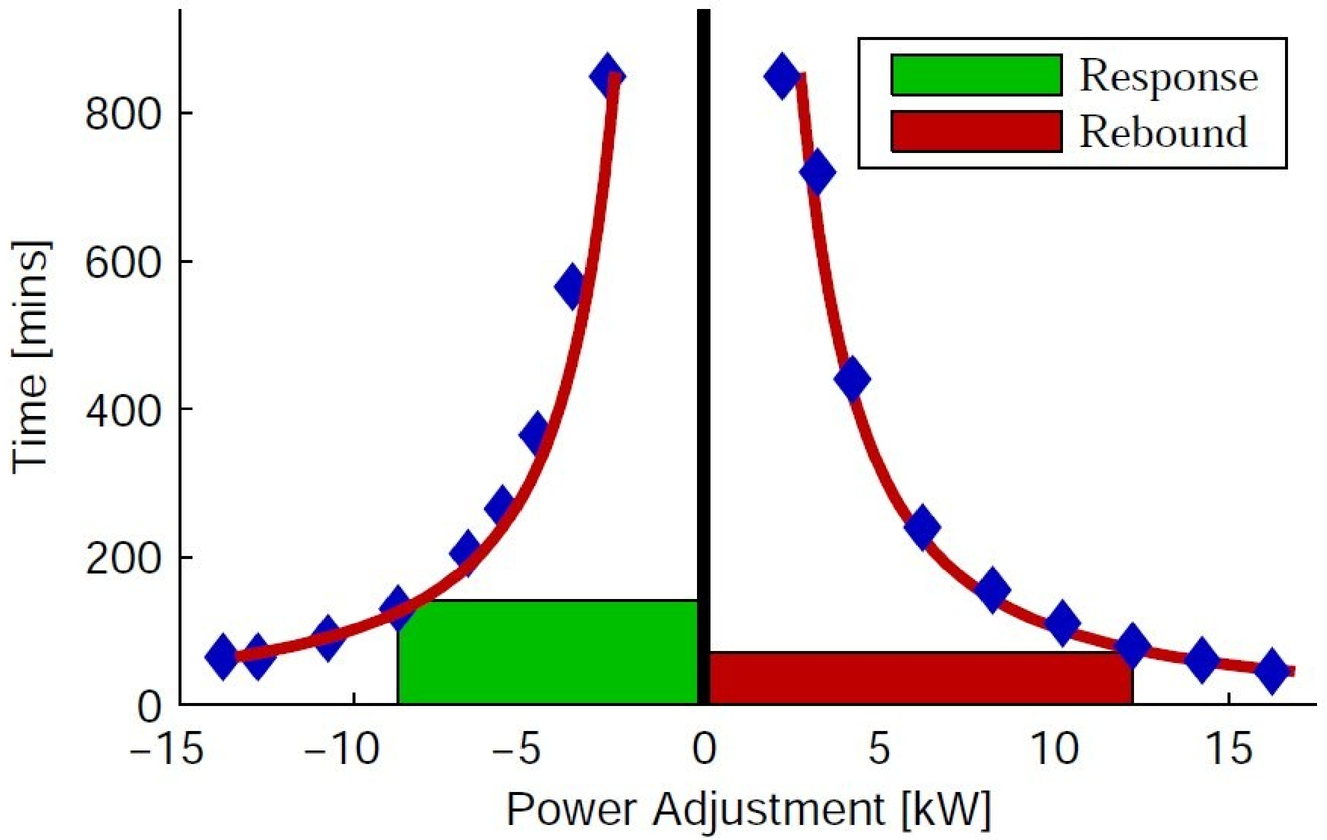
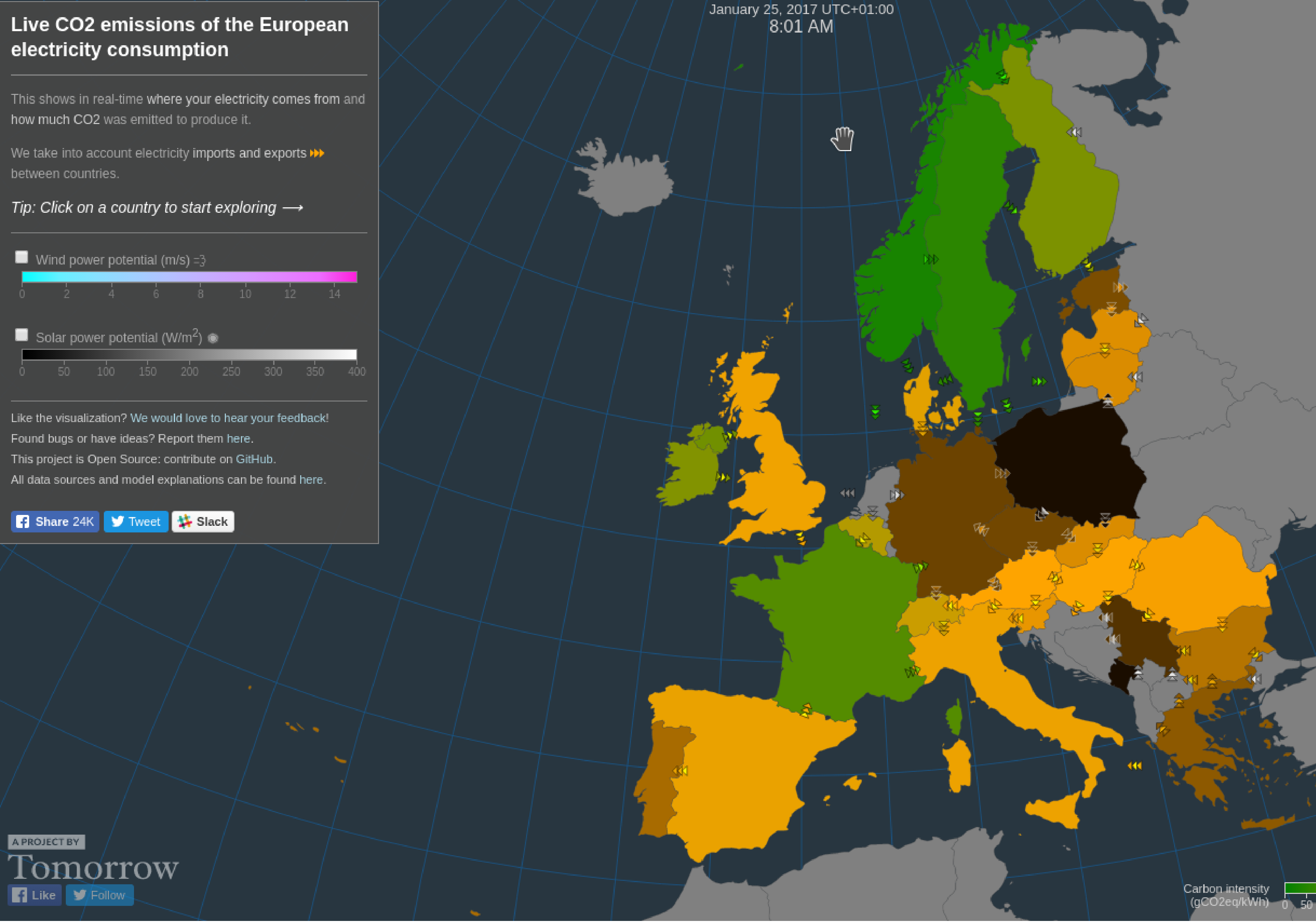
Further Aspects

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





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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
- VE (Eurisco, Enfor, ...)
- ....

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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 at GitHub.

Search ...

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,

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