Intelligent Energy Systems in CITIES and Solar Power Forecasting

European Cooperation in Science and Technology

COST ES 1002 WIRE
Weather Intelligence for Renewable Energy

Henrik Madsen, Technical University of Denmark

COST WIRE and CITIES Workshop, DTU Risø, June 2014

DTU Compute
Department of Applied Mathematics and Computer Science

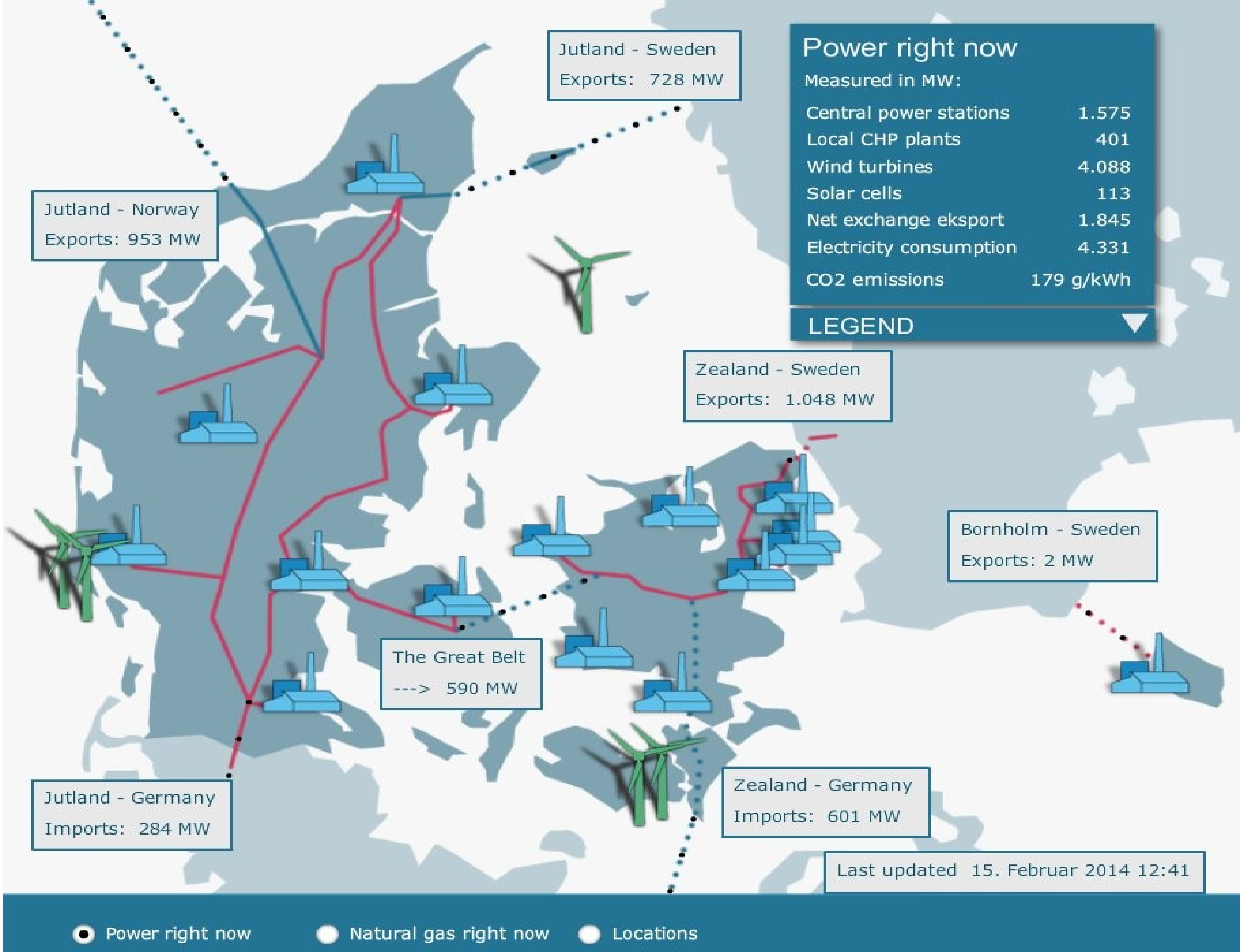
CITIES
Centre for IT Intelligent Energy Systems

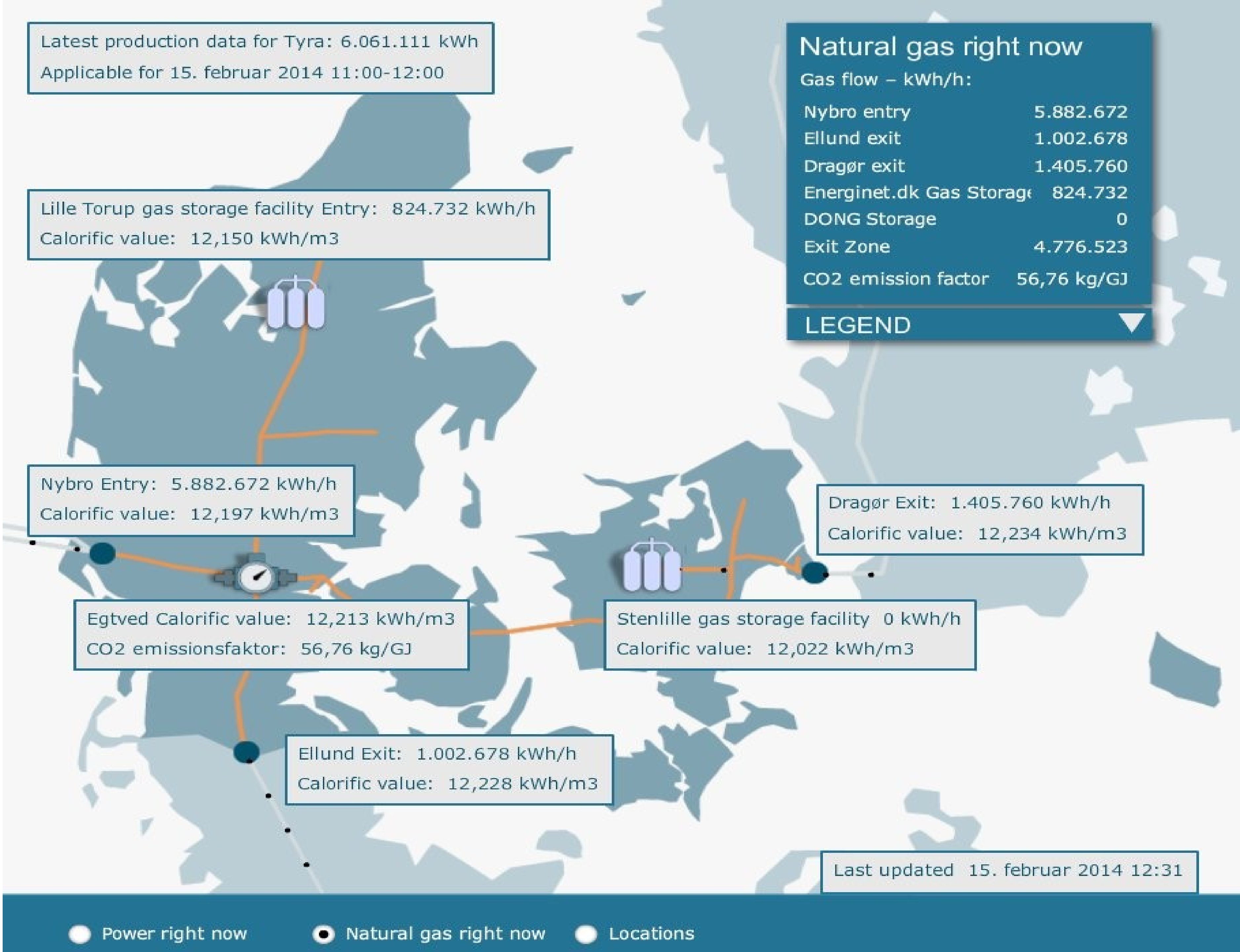
Wind integration in Denmark

- Notice – wind only:

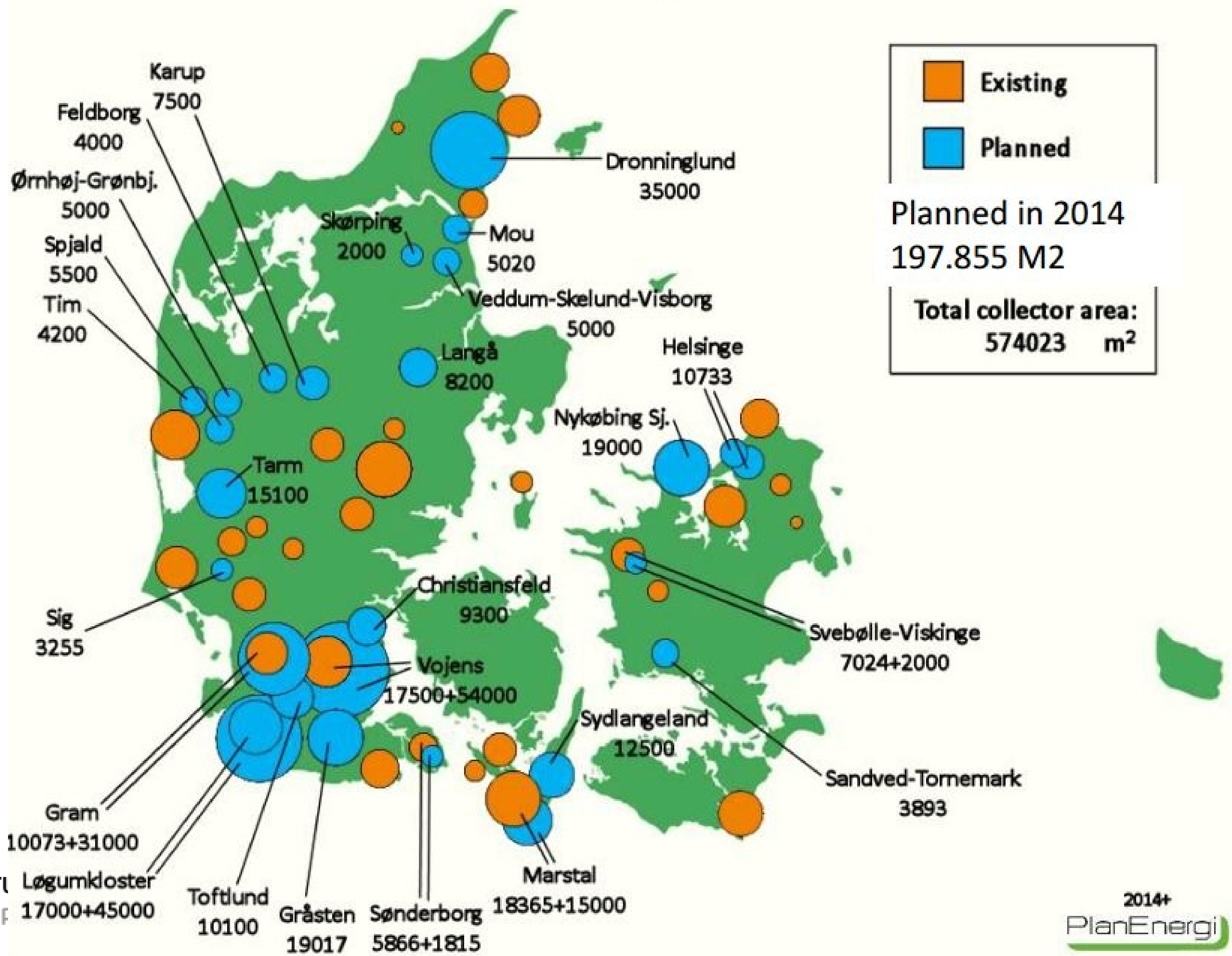
Key figures for wind power*

	2013	2012
Wind power generation	11.1 billion kWh	10.3 billion kWh
Electricity consumption (including loss in the electricity grid)	33.5 billion kWh	34.1 billion kWh
Wind power share of electricity consumption the entire year	33.2%	30.1%
Wind power share of electricity consumption in December	54.8%	33.5%
Wind power capacity at the end of the year	4,792 MW	4,166 MW
Energy content of the wind	Approx. 93% of a standard year	Approx. 102% of a standard year


Power right now
Measured in MW:
Central power stations 1.575
Local CHP plants 401
Wind turbines 4.088
Solar cells 113
Net exchange eksport 1.845
Electricity consumption 4.331
CO2 emissions 179 g/kWh
LEGEND
Jutland - Sweden
Exports: 728 MW
Jutland - Norway
Exports: 953 MW
Zealand - Sweden
Exports: 1.048 MW
Bornholm - Sweden
Exports: 2 MW
The Great Belt
---> 590 MW
Jutland - Germany
Imports: 284 MW
Zealand - Germany
Imports: 601 MW
Last updated 15. Februar 2014 12:41
Power right now
Natural gas right now
Locations

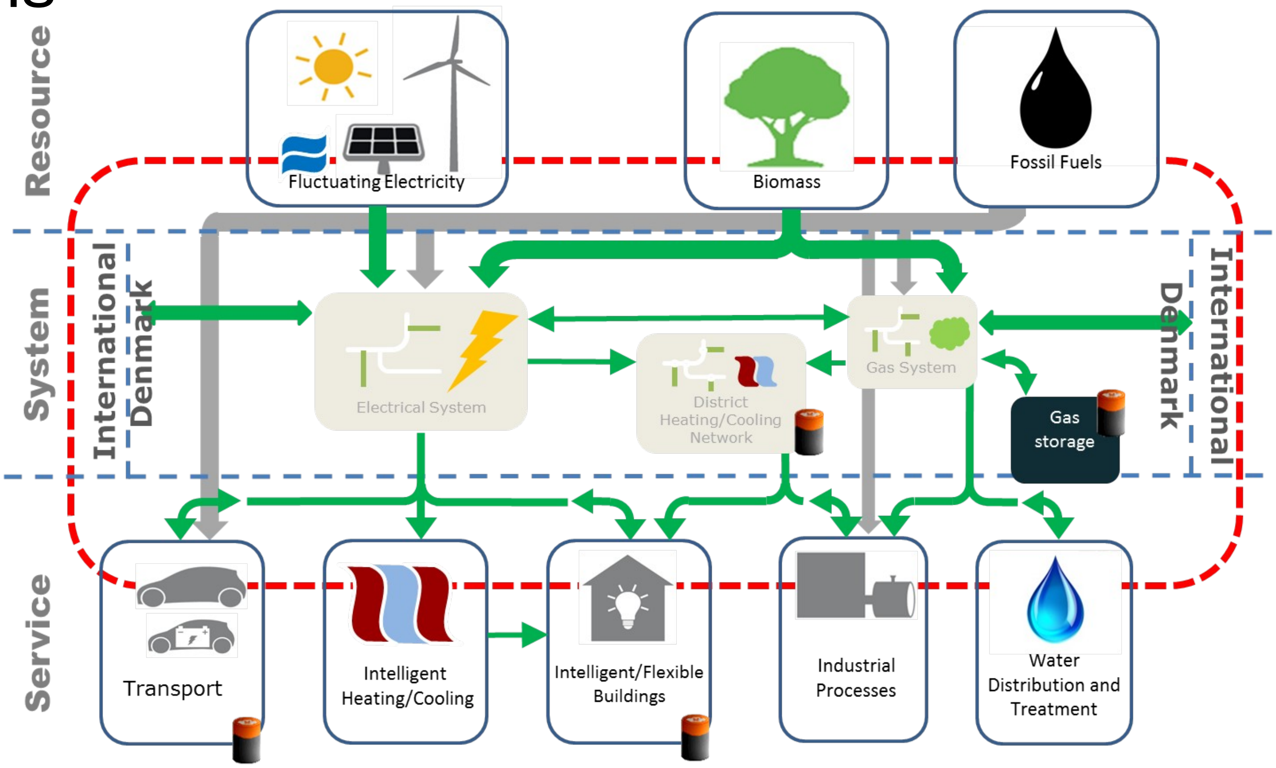

Latest production data for Tyra: 6.061.111 kWh
Applicable for 15. februar 2014 11:00-12:00
Natural gas right now
Gas flow – kWh/h:
Nybro entry 5.882.672
Ellund exit 1.002.678
Dragør exit 1.405.760
Energinet.dk Gas Storage 824.732
DONG Storage 0
Exit Zone 4.776.523
CO2 emission factor 56,76 kg/GJ
LEGEND
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

Solar district heating in Denmark

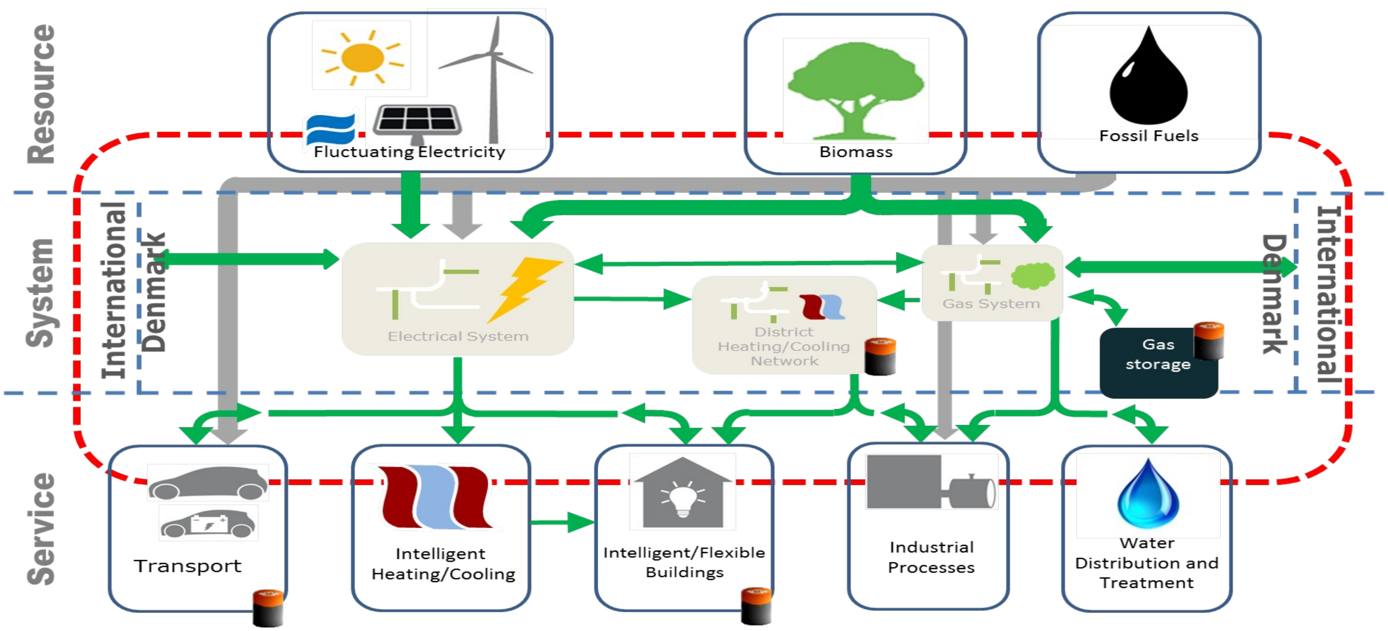


Concepts in CITIES

Integration based on *IT solutions and forecasting* leading to methods for *operation* and *planning* for future energy systems



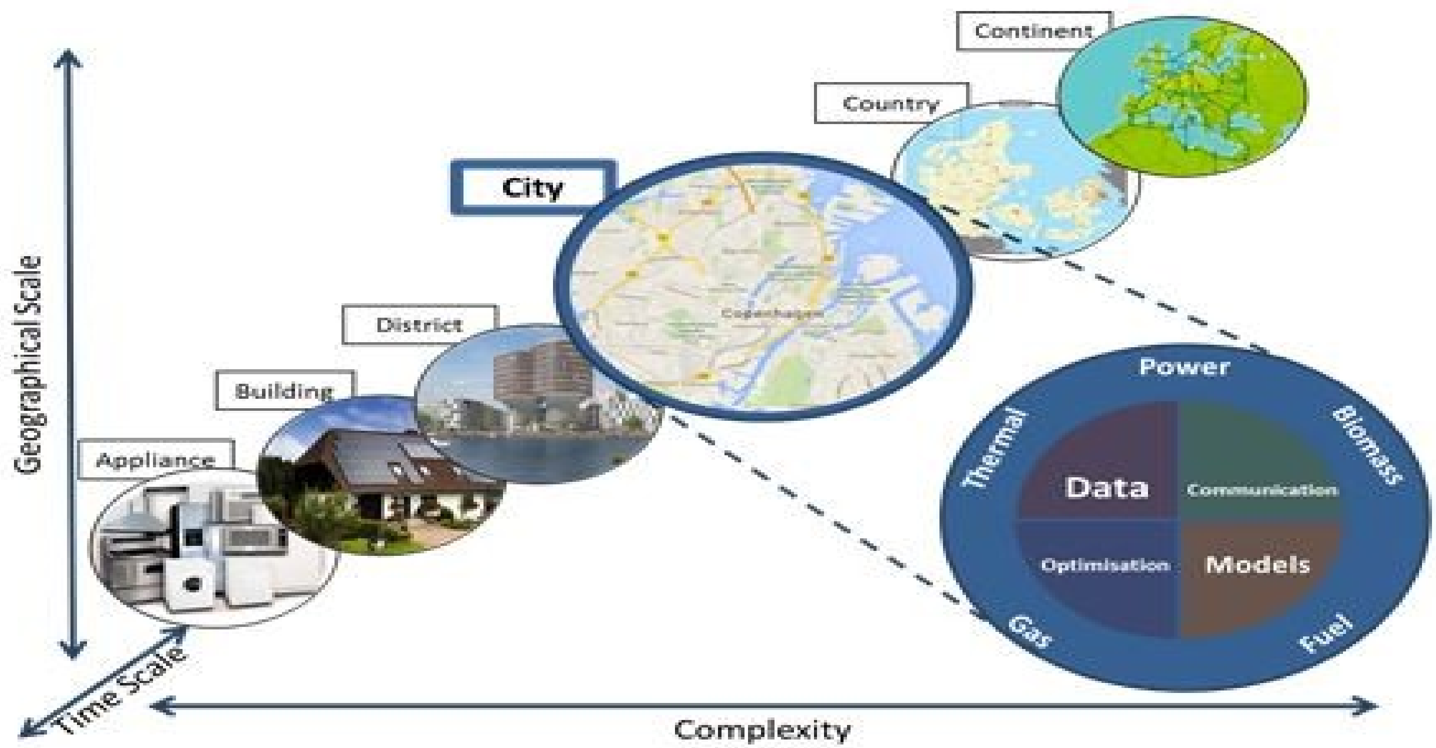
Example: Storage by Energy Systems Integration



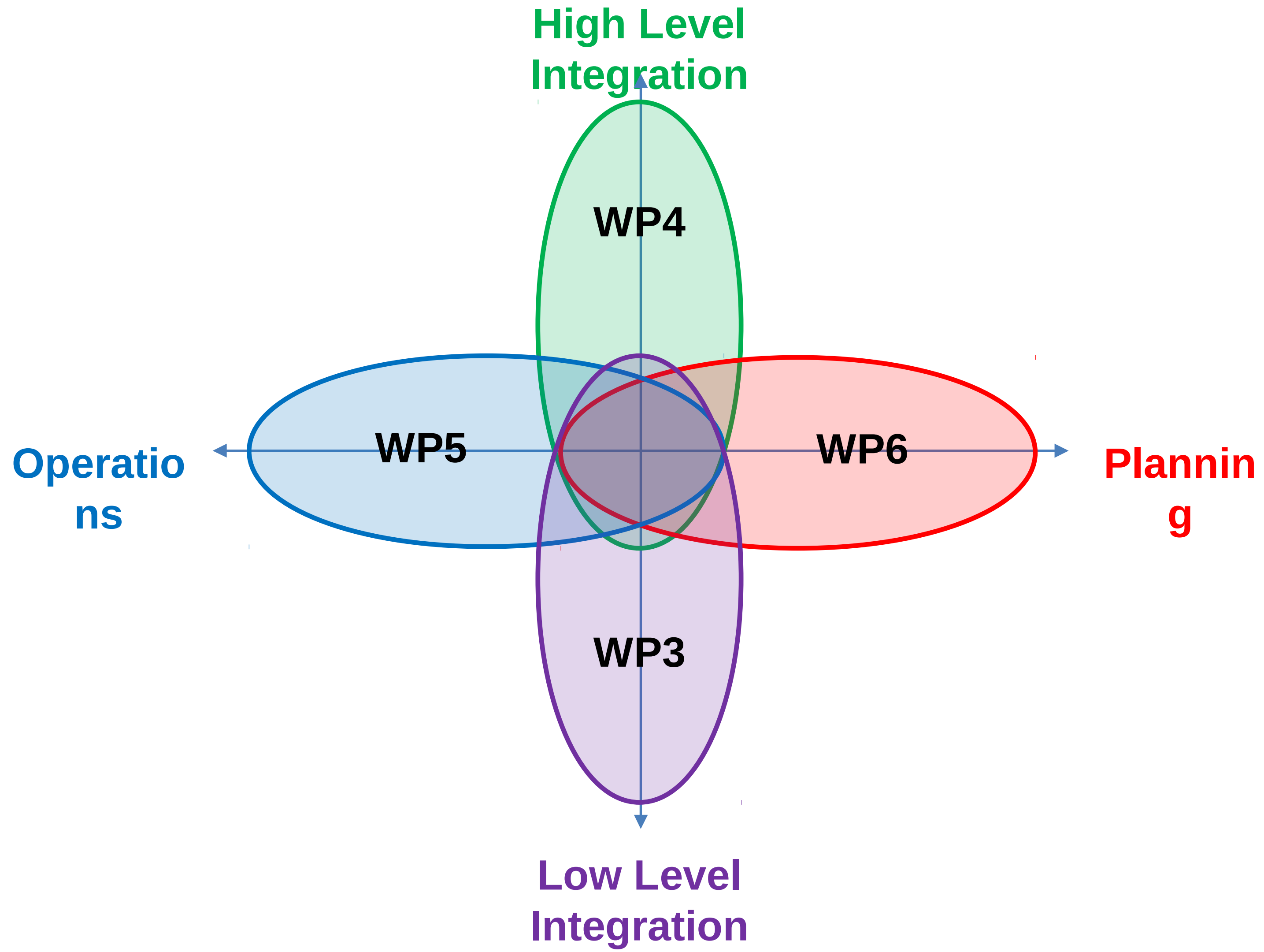
- Operational (simplified) models for integration, optimization and control
- (Virtual) storage principles:
  - Buildings provide storage up to, say, 5-10 hours ahead
  - District heating systems can provide storage up to 1-2 days ahead
  - Gas systems can provide seasonal storage

Scientific Objectives

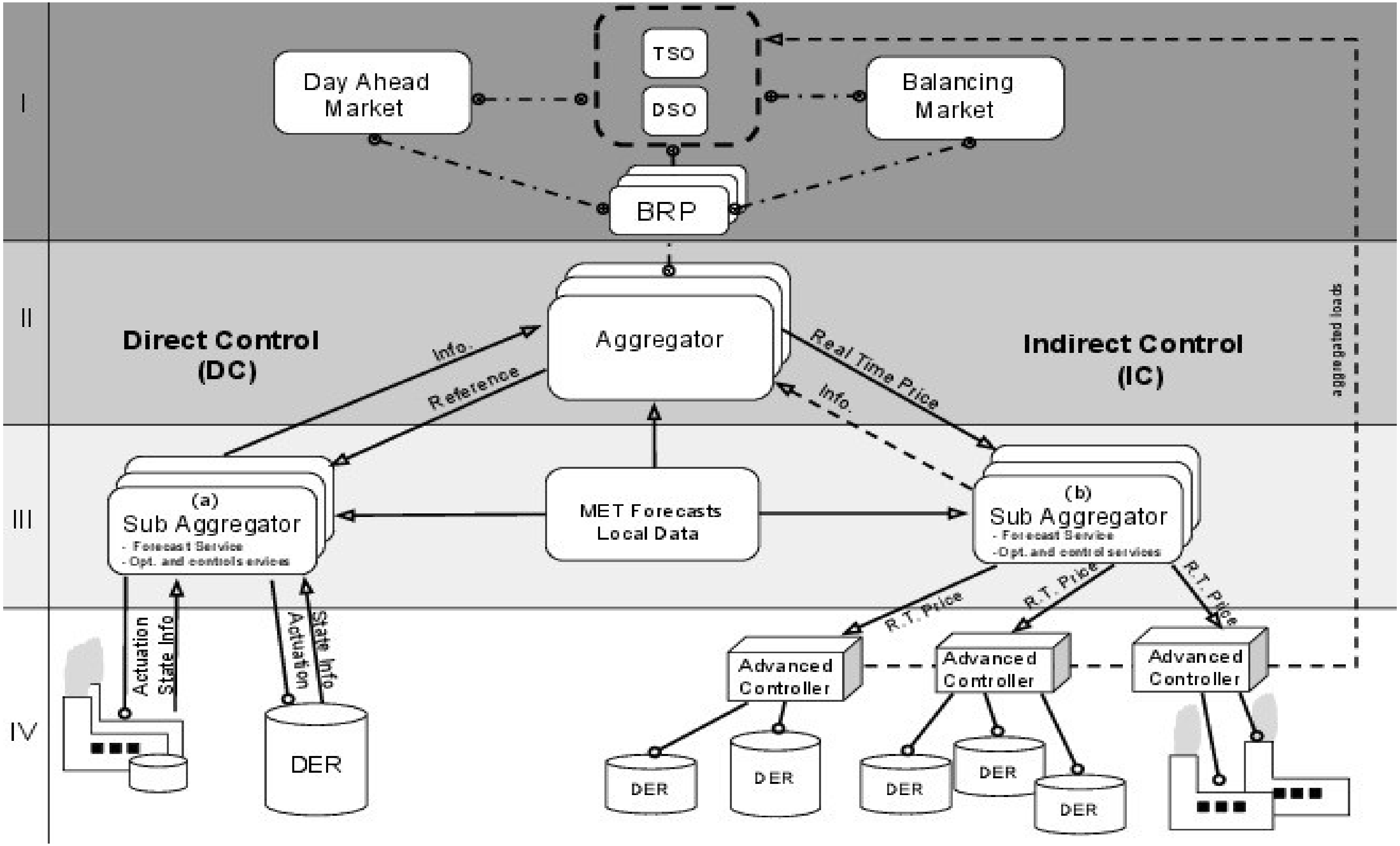
To establish forecasts and ITC solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales (budget 10 mill. Euros)



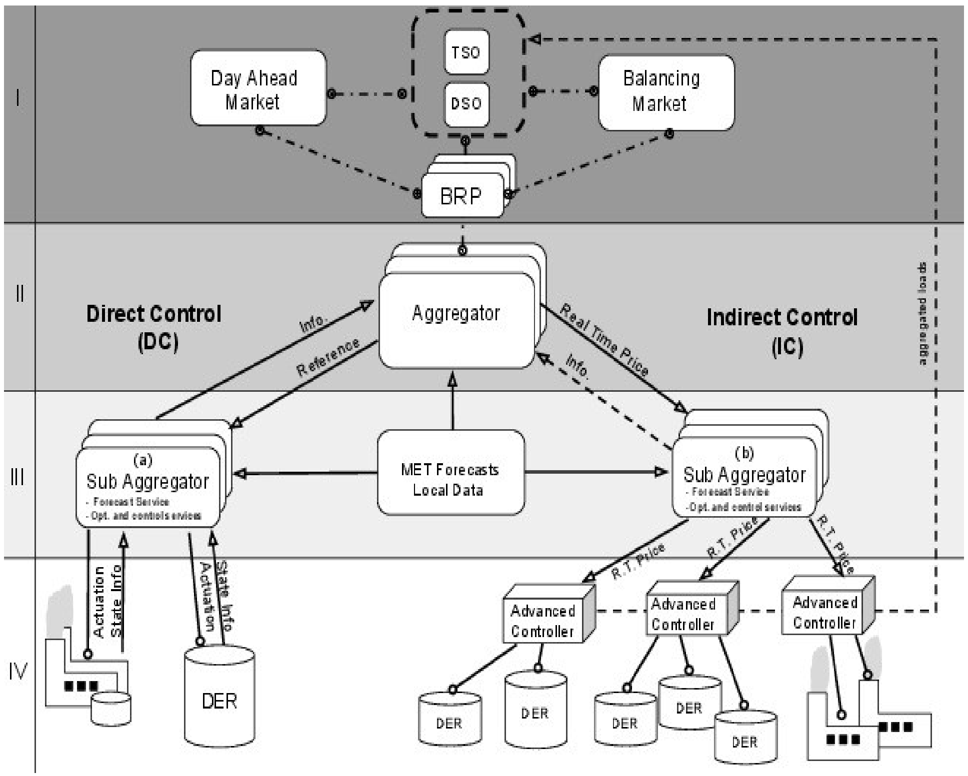
Energy Systems Integration and Management



Control/Forecasting Principles



Control/Opt. Principles



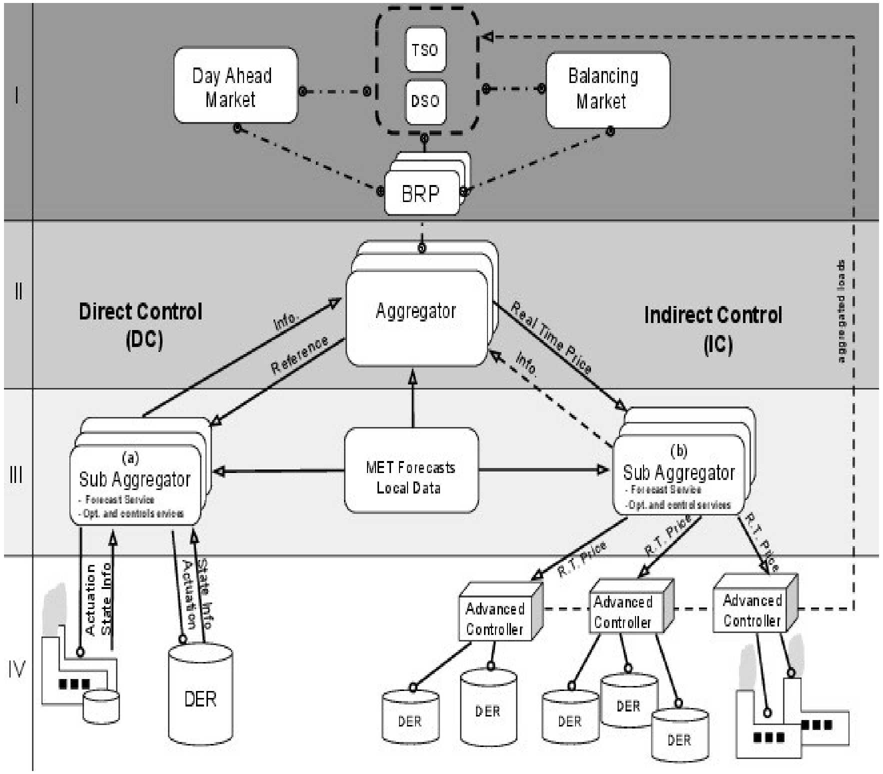
- **Day Ahead:**
  - Stoch. Programming based on eg. Scenarios
  - Cost: Related to the market (one or two levels)
  - Operational optimization – also for the grid
- **Direct Control:**
  - Actuator: **Power**
  - Cost: eg. MV, LQG, EMPC, ... (a single large problem)
  - Two-way communication
  - Models for DERs are needed
  - Constraints for the DERs (calls for state est.)
  - Contracts are complicated
- **Indirect Control:**
  - Actuator: **Price**
  - Cost: GPC, LQG at **high level**, VaR-alike
  - 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. $\quad \hat{z}_{k+1} = f(p_k)$
IV	$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$ s.t. $\quad x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$	$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$ 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.

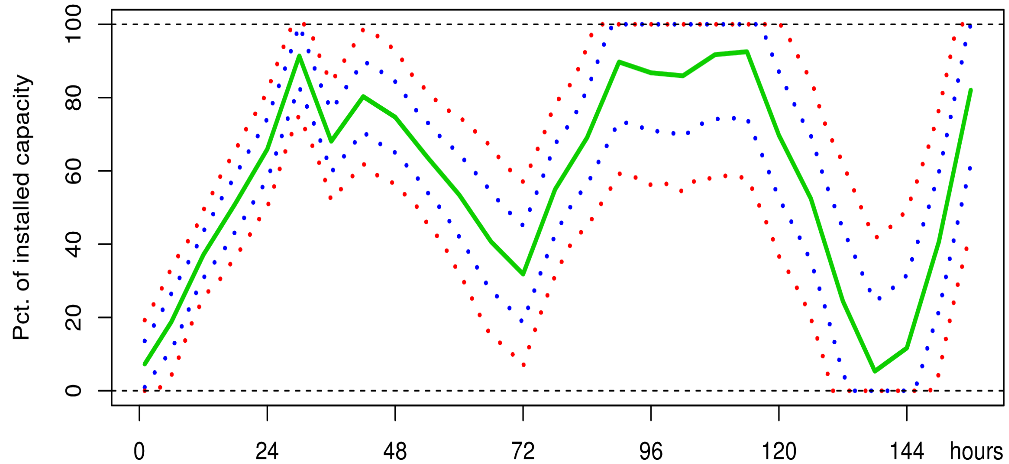
Forecast requirements

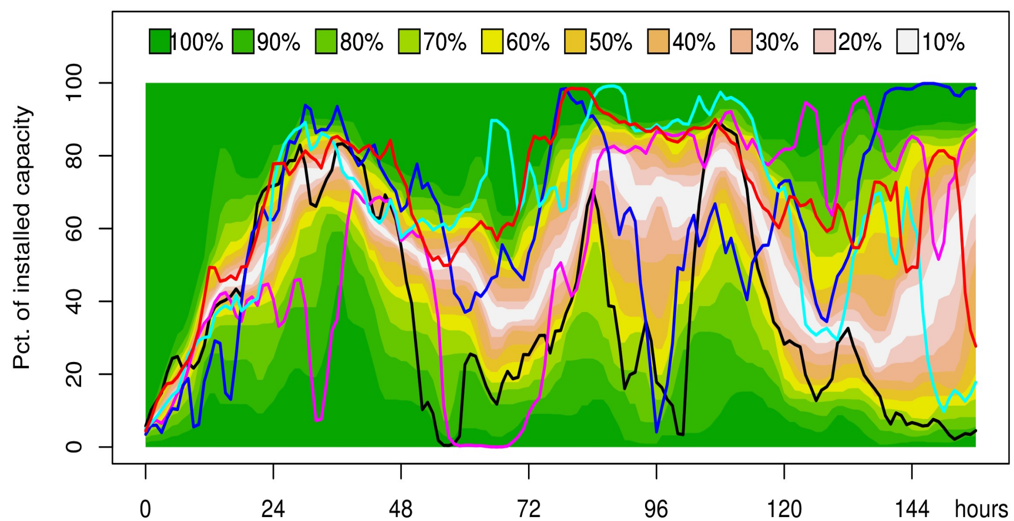


- **Day Ahead:**
  - Forecasts of loads
  - Forecast of Grid Capacity (using eg. DLR)
  - Forecasts of production (eg. Wind and Solar)
- **Direct Control:** .
  - Forecasts of states of DERs
  - Forecasts of load
- **Indirect Control:**
  - Forecasts of prices
  - Forecasts of load

Which type of forecast to use?

- Point forecasts
- Conditional mean and covariances
- Conditional quantiles
- Conditional scenarios
- Conditional densities
- Stochastic differential equations





Ongoing CITIES projects using MET forecasts

- **Temperature control in houses (Grundfos, ENFOR)**
- **HVAC systems (Grundfos)**
- **Supermarket cooling (Danfoss, UCD)**
- **Consumption in family houses (TI, ENFOR, ...)**
- **District heating networks (Cowi, ENFOR, Rambøll, DFF-EDB)**
- **Combined Heat and Power plants (Dong Energy)**
- **Heat Pumps in District Heating networks (HOFOR, Cowi, ENFOR)**
- **Rainfall Run-off Systems (DHI and Rambøll)**
- **Wastewater treatment plants (Krüger)**
- **.............**

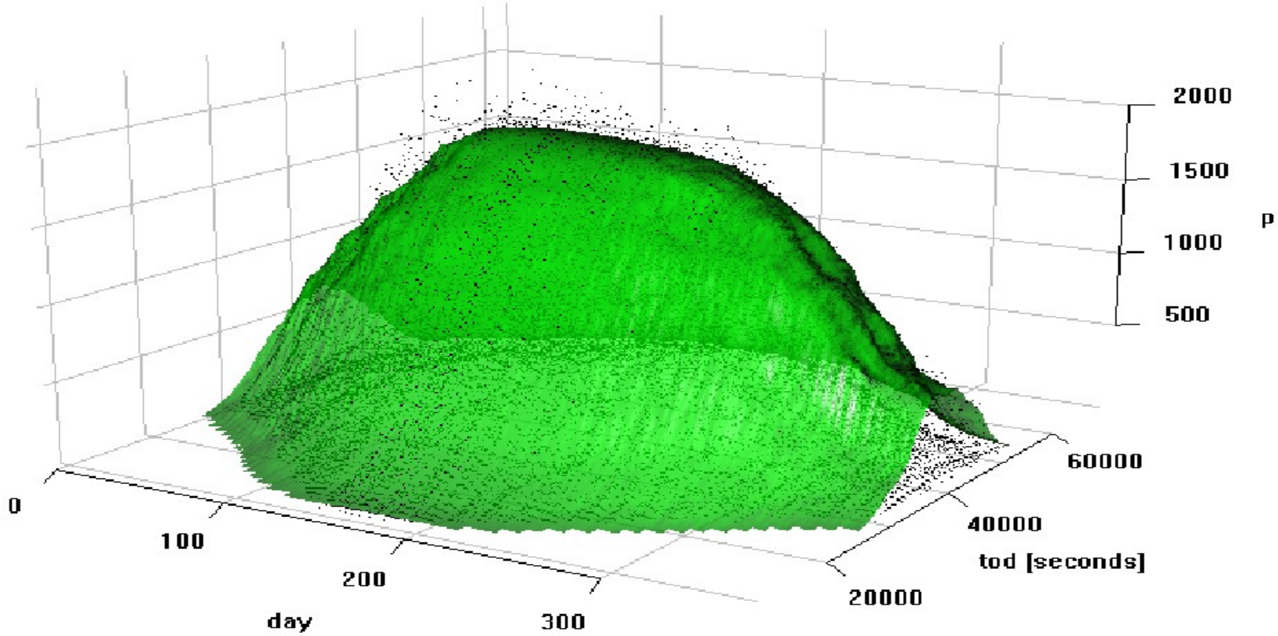
Example

Solar Power Forecasting in CITIES

Solar Power Forecating

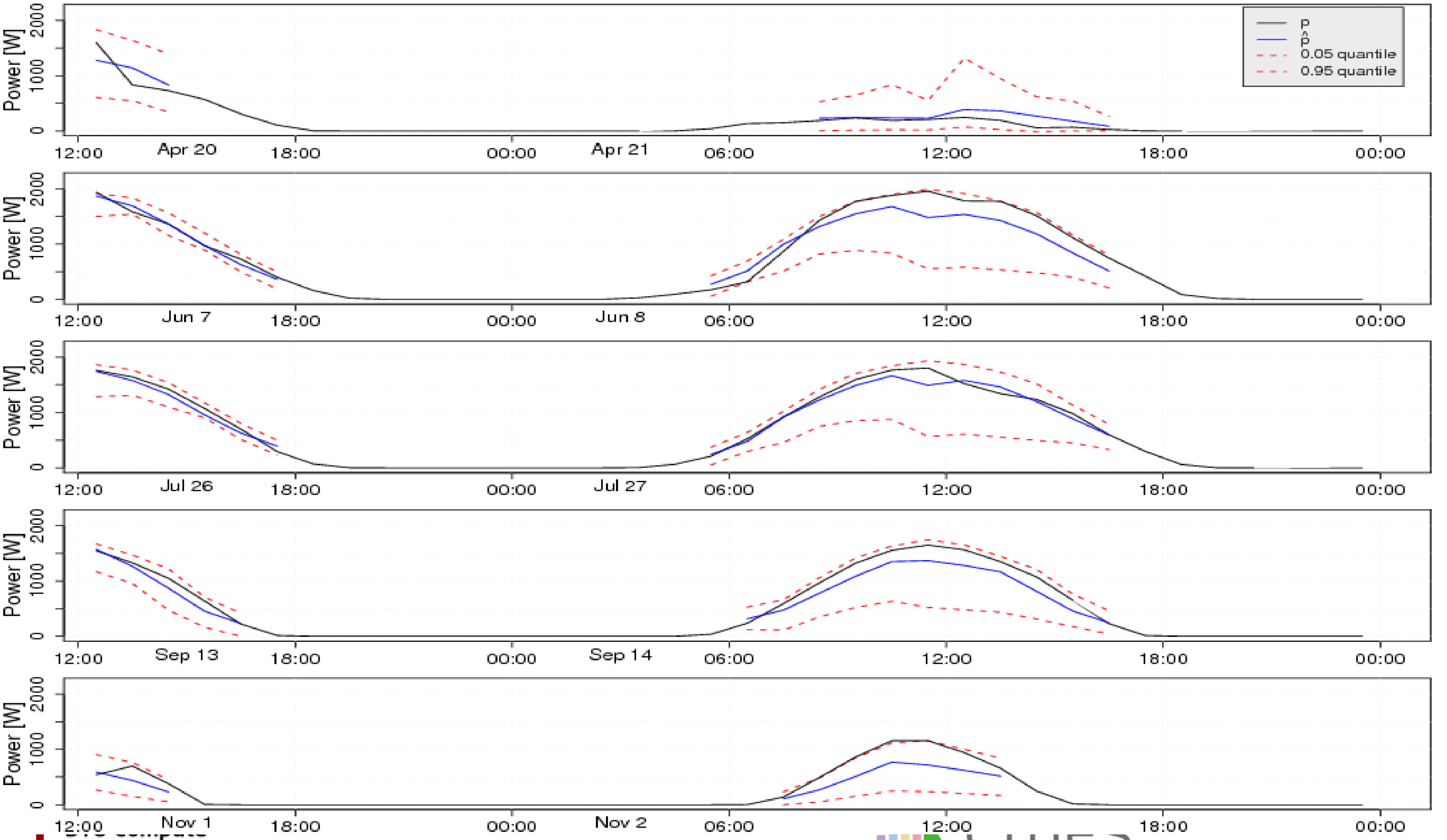
- Grid connected PV-systems mainly installed on rooftops
- Average of output from 21 PV systems in Brædstrup

Method

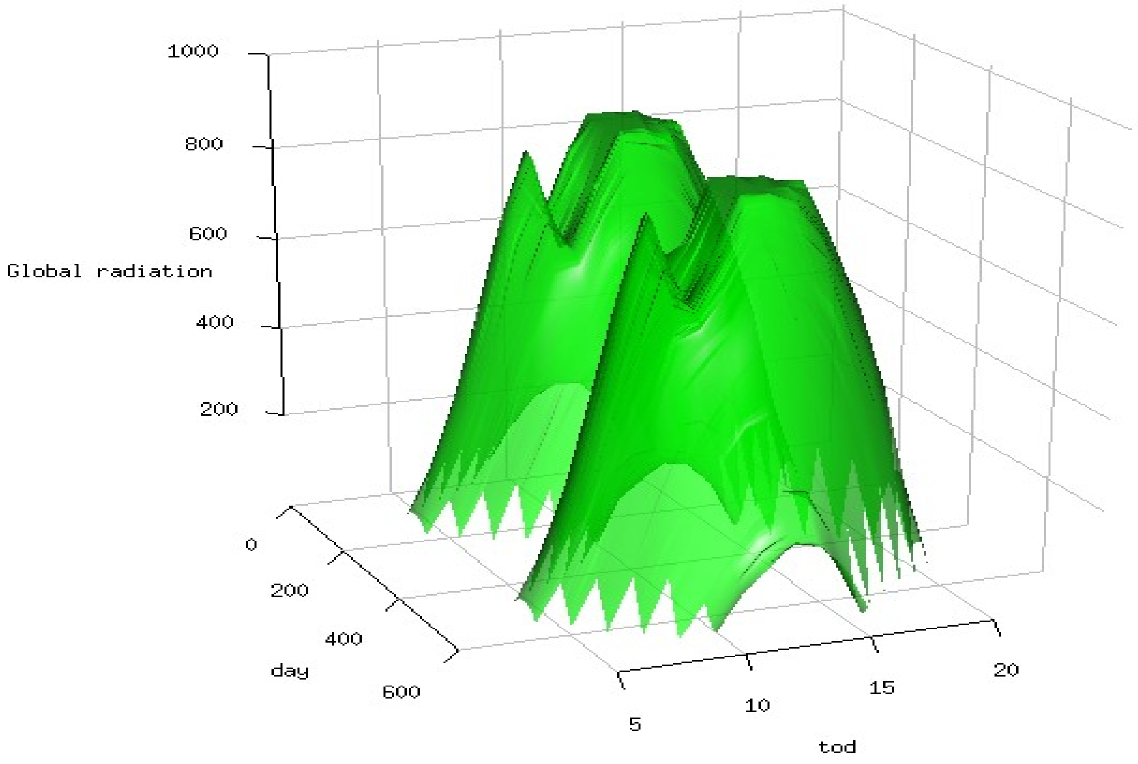


- Based on MET forecasts and online readings of output
- Two-step method:
  - 1) Transformation to atmospheric transmittance with statistically clear sky (see above),
  - 2) A dynamic model + adaptive quantile regression.

Example
(quantile forecasts – up to 36h ahead)

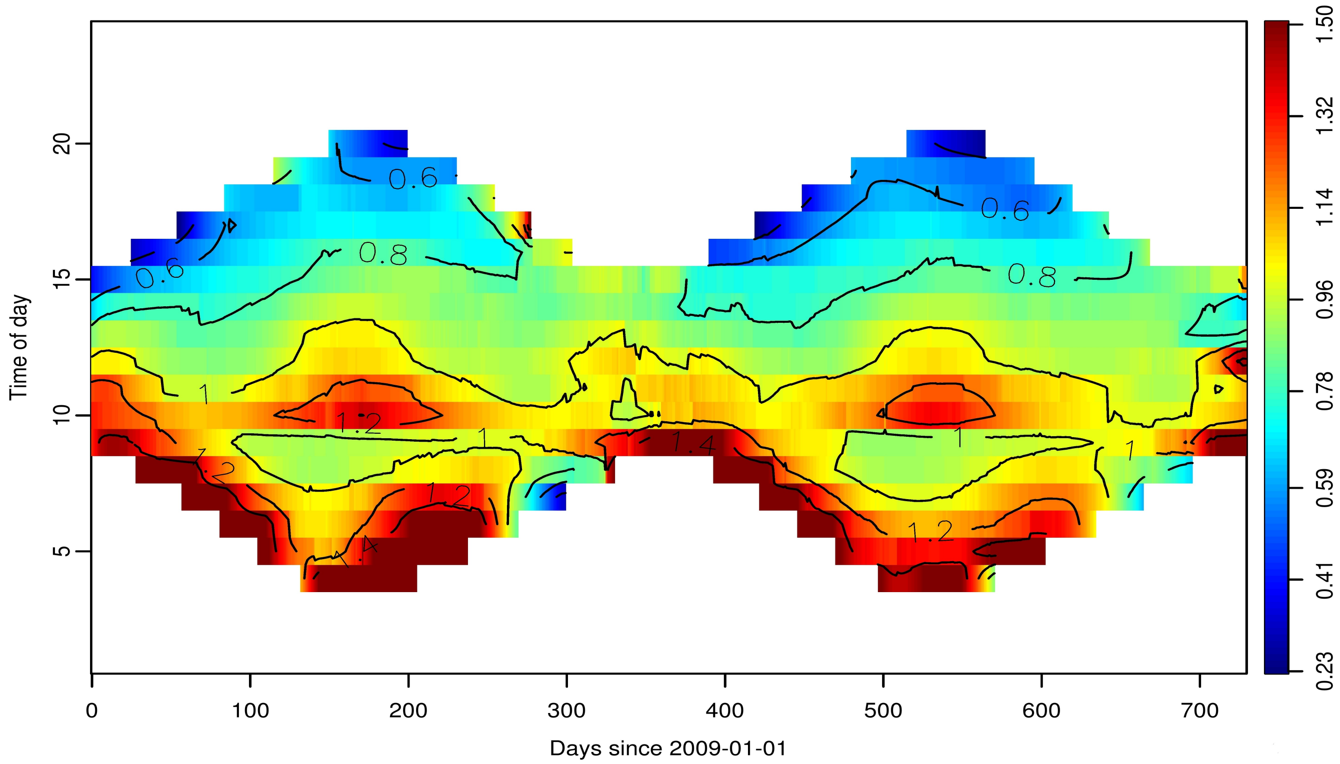


Adaptive correction method

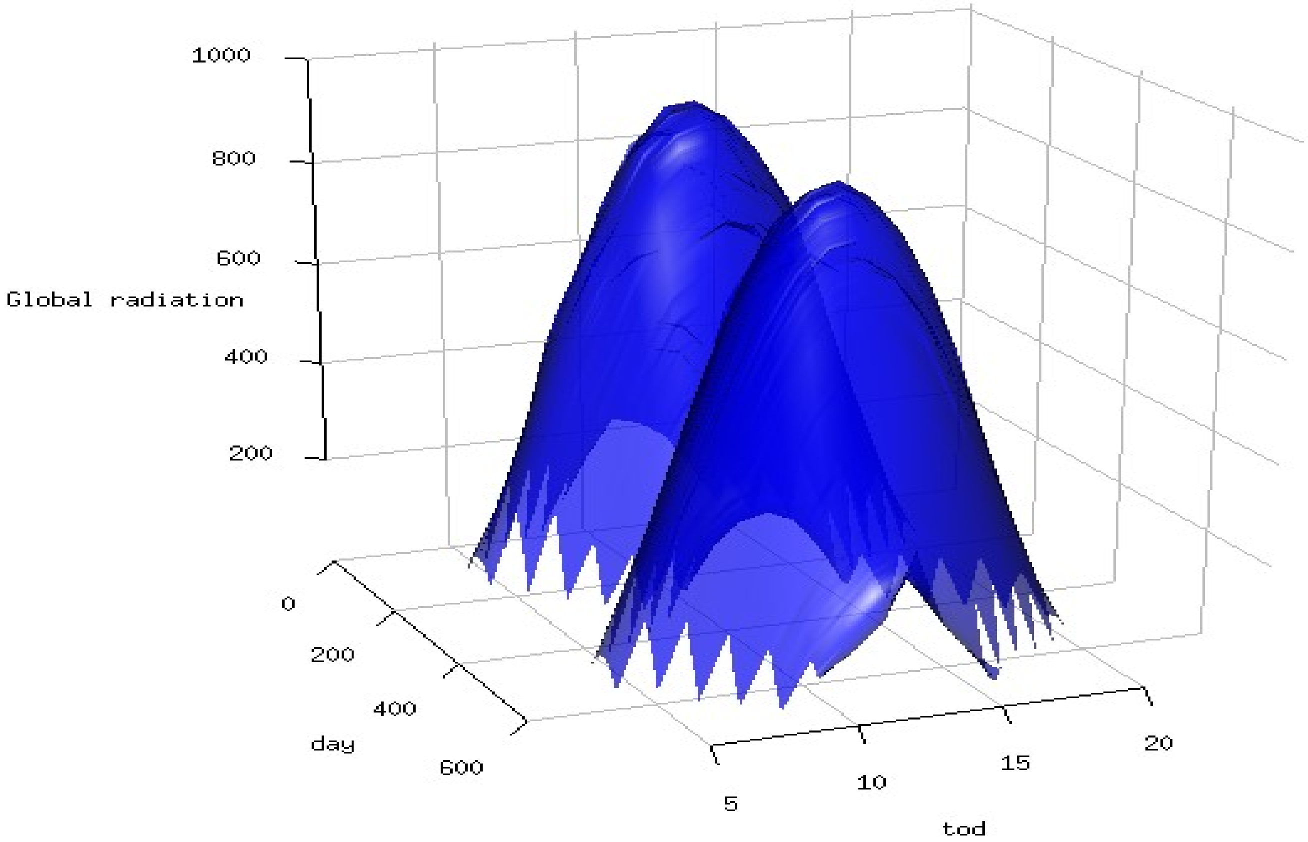


Adaptive correction method

Adaptive correction method (correction function)



Adaptive correction method



Use of MET forecasts for:

- Electricity Load
- Wind Power Production
- Solar Power Production
- Gas Load
- District Heating Load
- Price forecasts
- Urban Meteorologi
- Grid operations

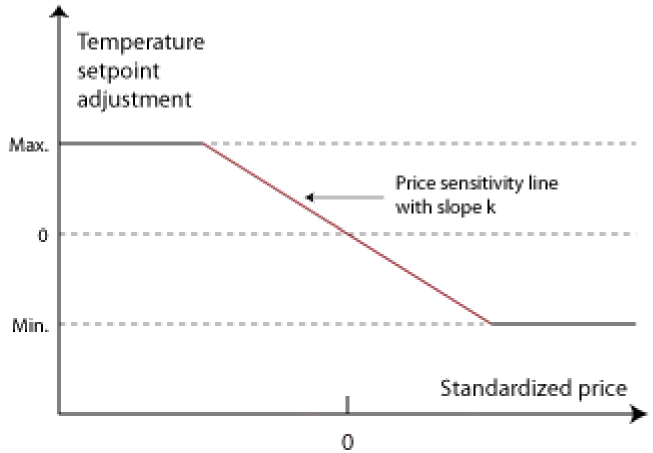
- ***Important aspects**:*
  - *Use the same MET service(s)*
  - *Adaptivity*
  - *Corrections*
  - *Full probabilistic*
  - *'Correlation' (auto- and cross correlation)*

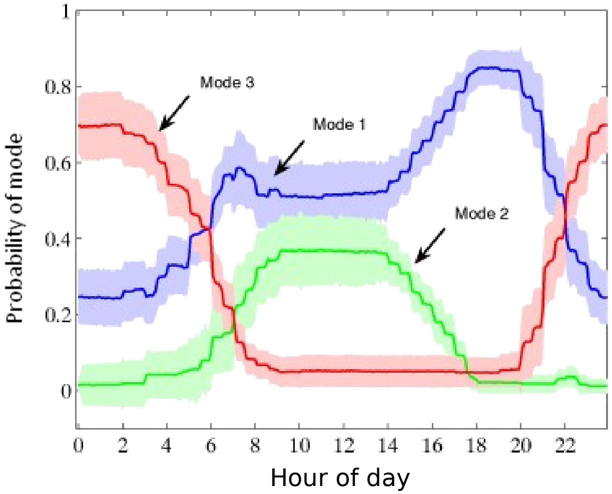
Case study

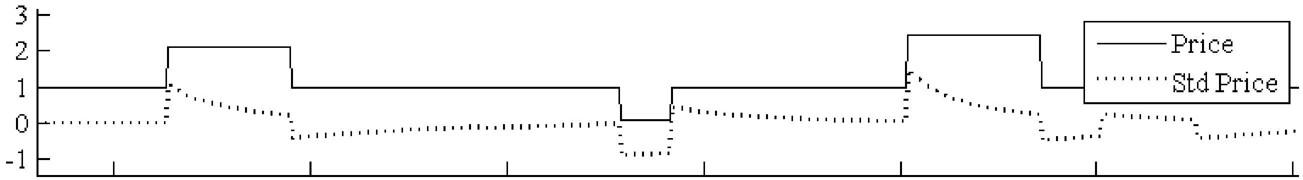
Electrical Heating of Buildings; Control of Load by Price

Price responsivity

Flexibility is activated by adjusting the temperature reference (setpoint)

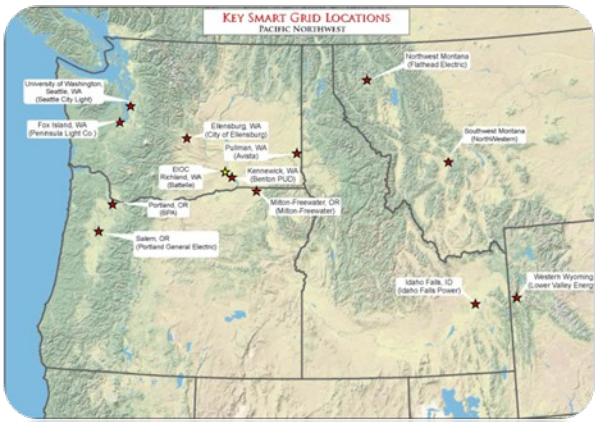


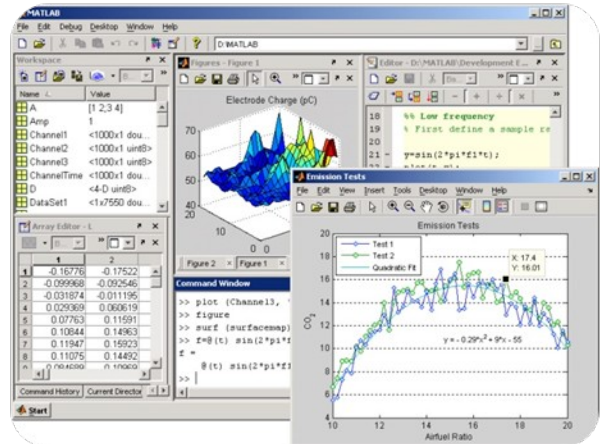




- **Standardized price** is the % of change from a price reference, computed as a mean of past prices with exponentially decaying weights.
- **Occupancy mode** contains a price sensitivity with its related comfort boundaries. 3 different modes of the household are identified (work, home, night)

Two data sources





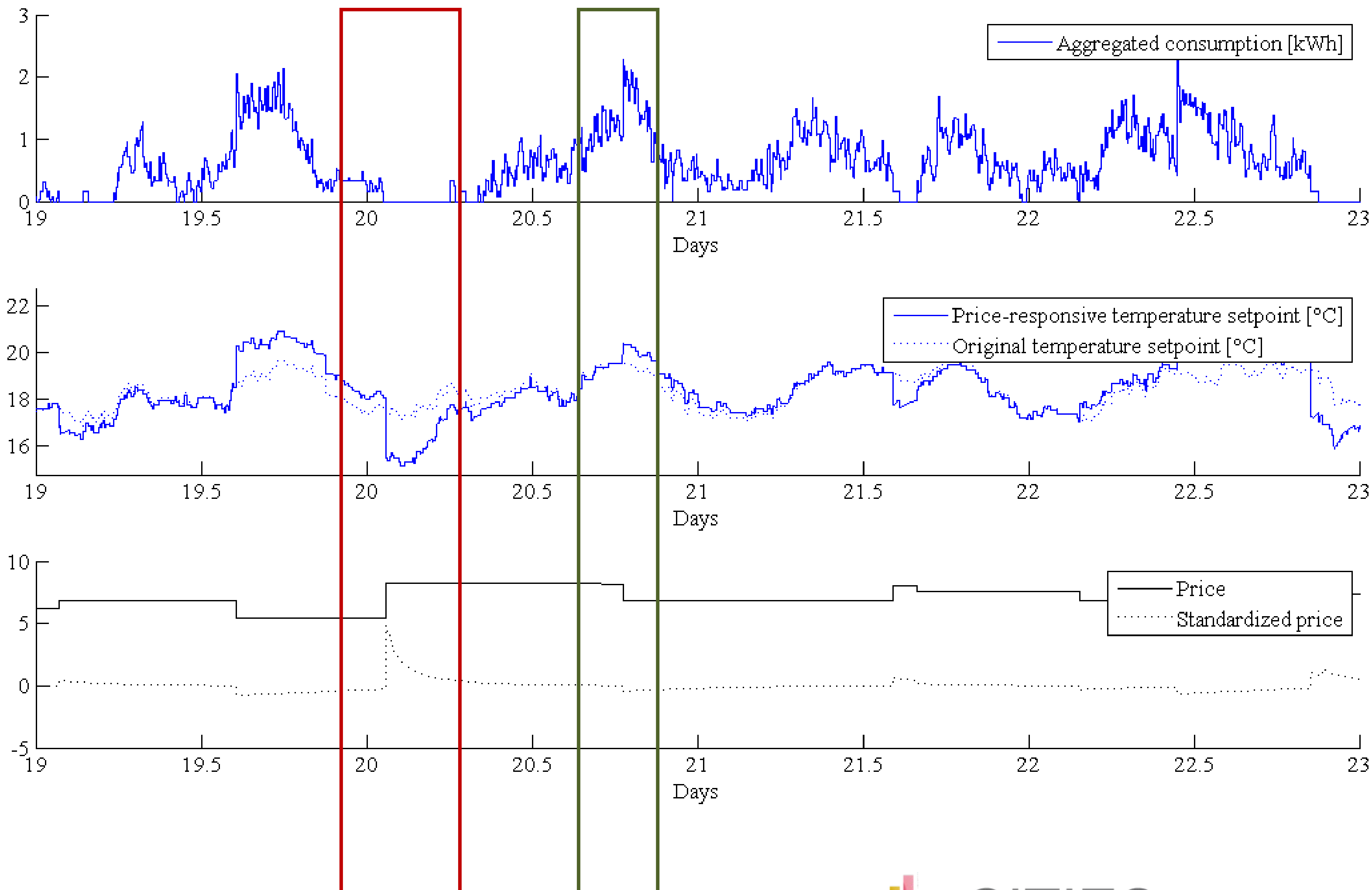
Olympic Pensinsula project

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

Simulation framework

- Modular design
- Runge-Kutta solver (diff. equations)
- Scalable (linear computation time)
- Variable sampling rate

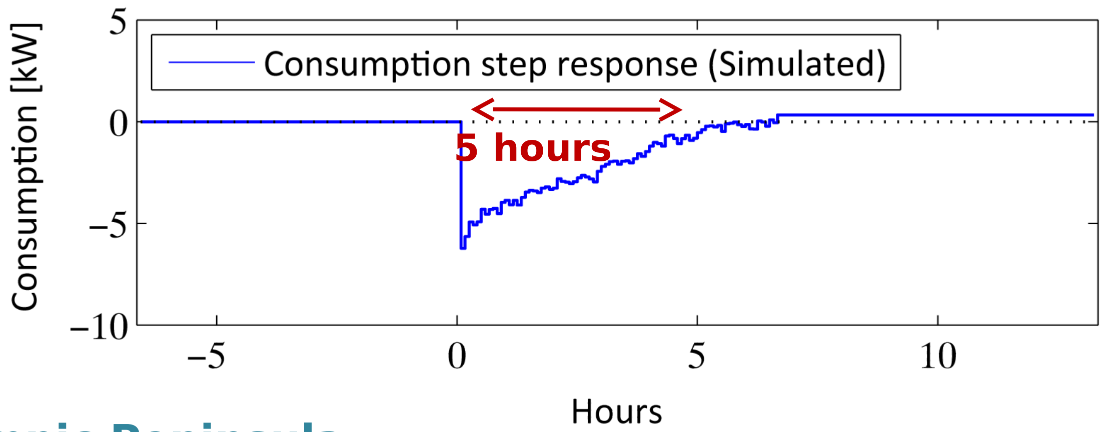
Aggregation (over 20 houses)



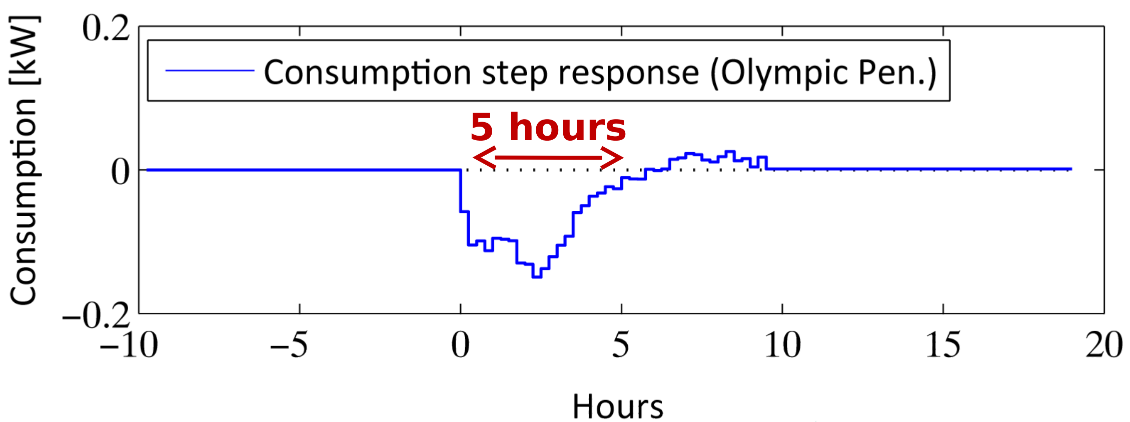
Identify price response

Forecasted Response on Price Step Change

Simulated

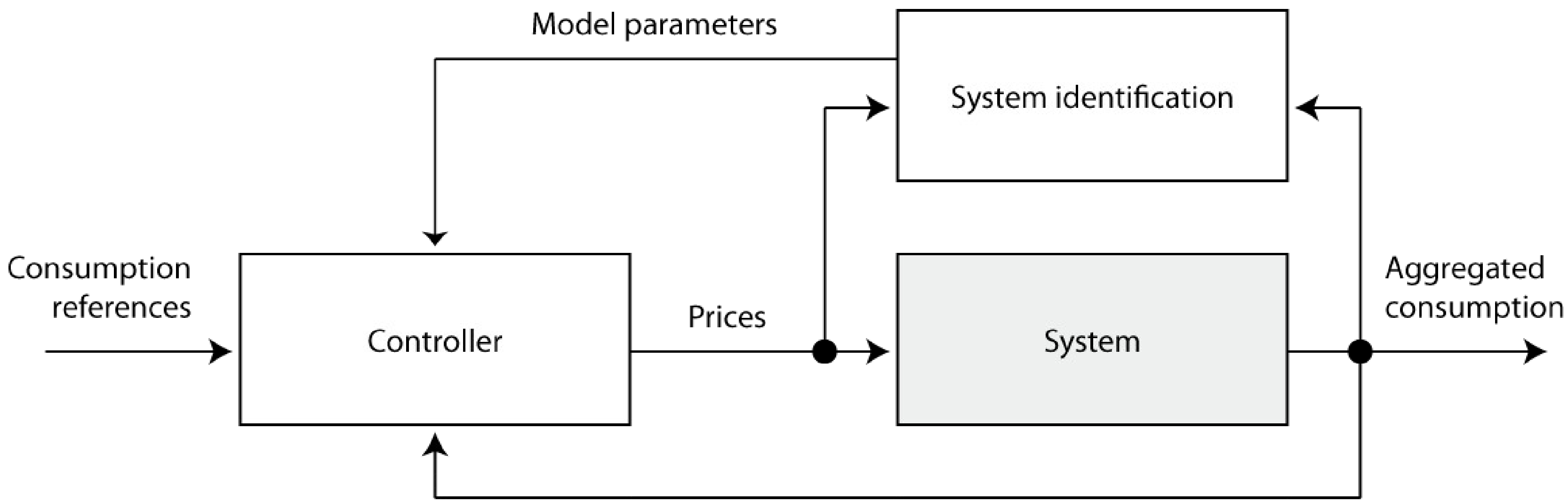


Olympic Peninsula



Adaptive control setup

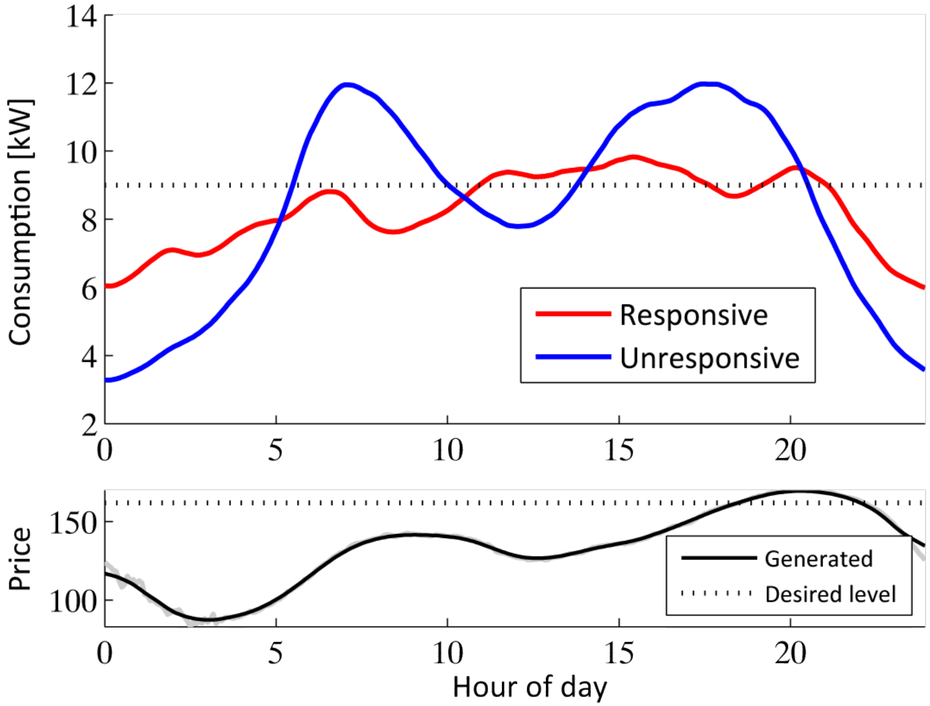
As the systems changes over time



Control performance

With a price penality avoiding its divergence

- Considerable reduction in max consumption
- Mean daily consumption shift



Thanks to

Jacopo Parvizi,
Niamh O'Connell,
John Bagterp Jørgensen,
Rasmus Halvgaard,
Olivier Corradi,
Henning Ochsenfeld,
Tryggvi Jónsson,
Sven Creutz Thomsen,