A Hierarchy of Aggregators and Controllers for Future Electric Energy Systems

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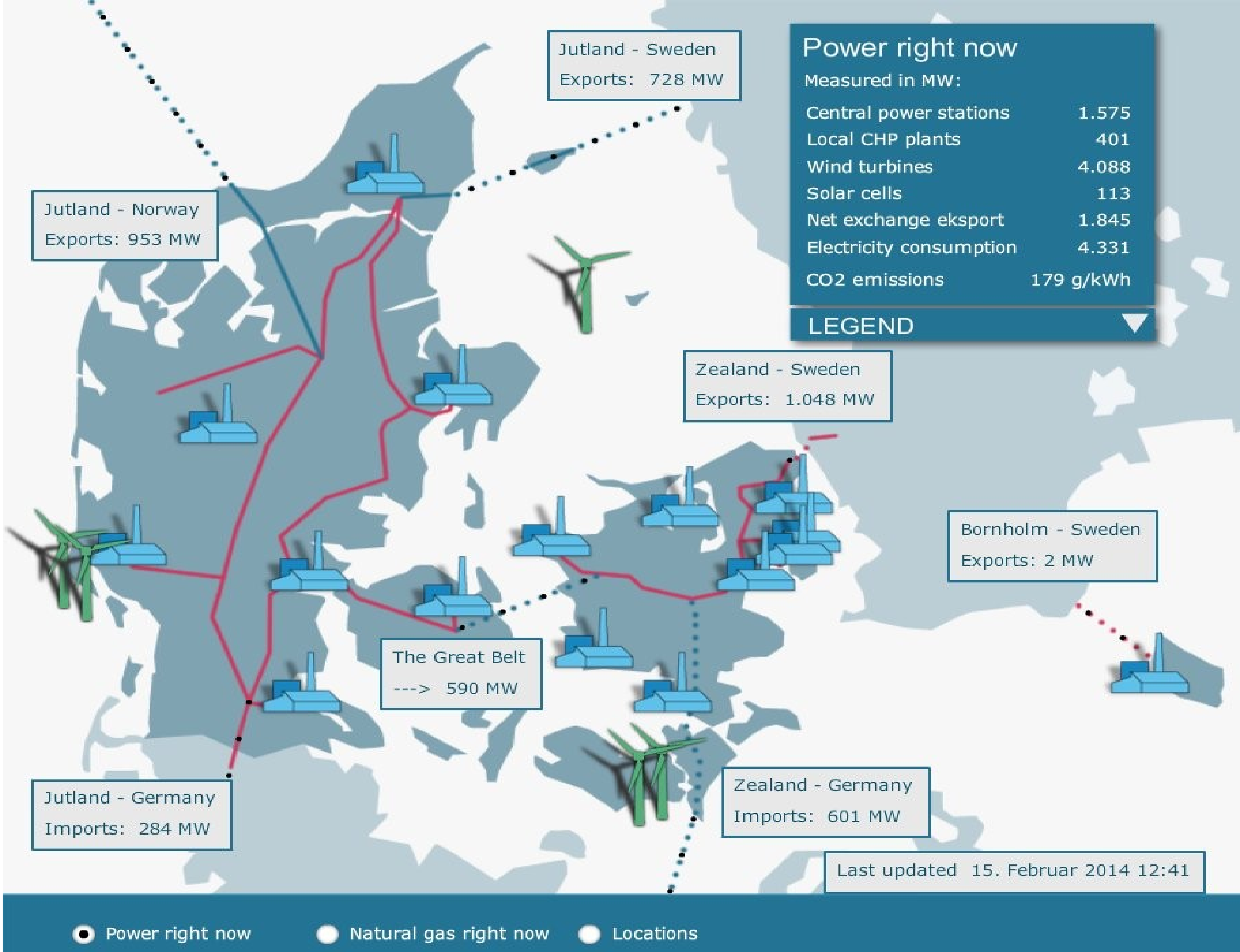
Wind integration in Denmark

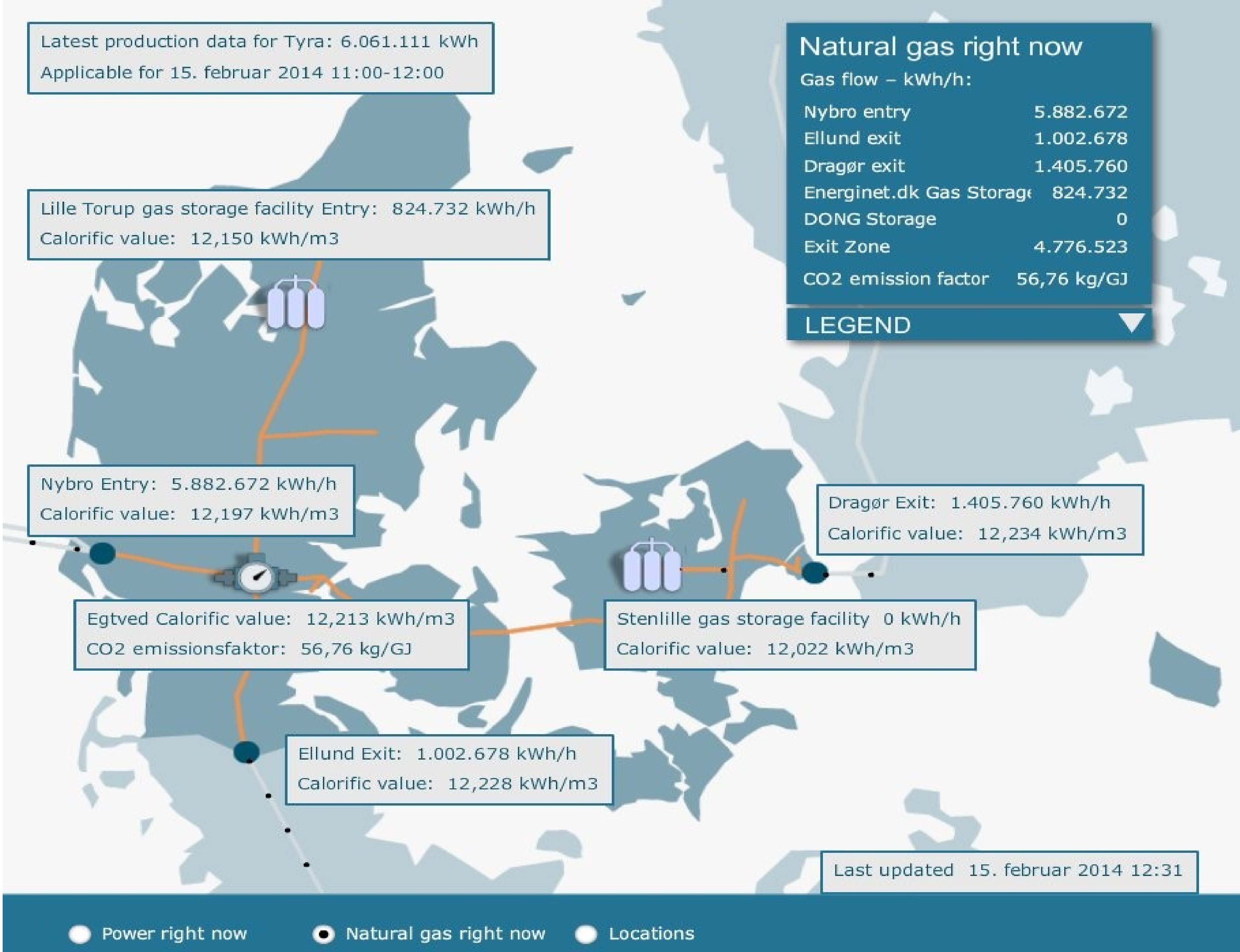
- Notice – wind only:

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



Jutland - Sweden
Exports: 728 MW
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 - 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 Storag 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
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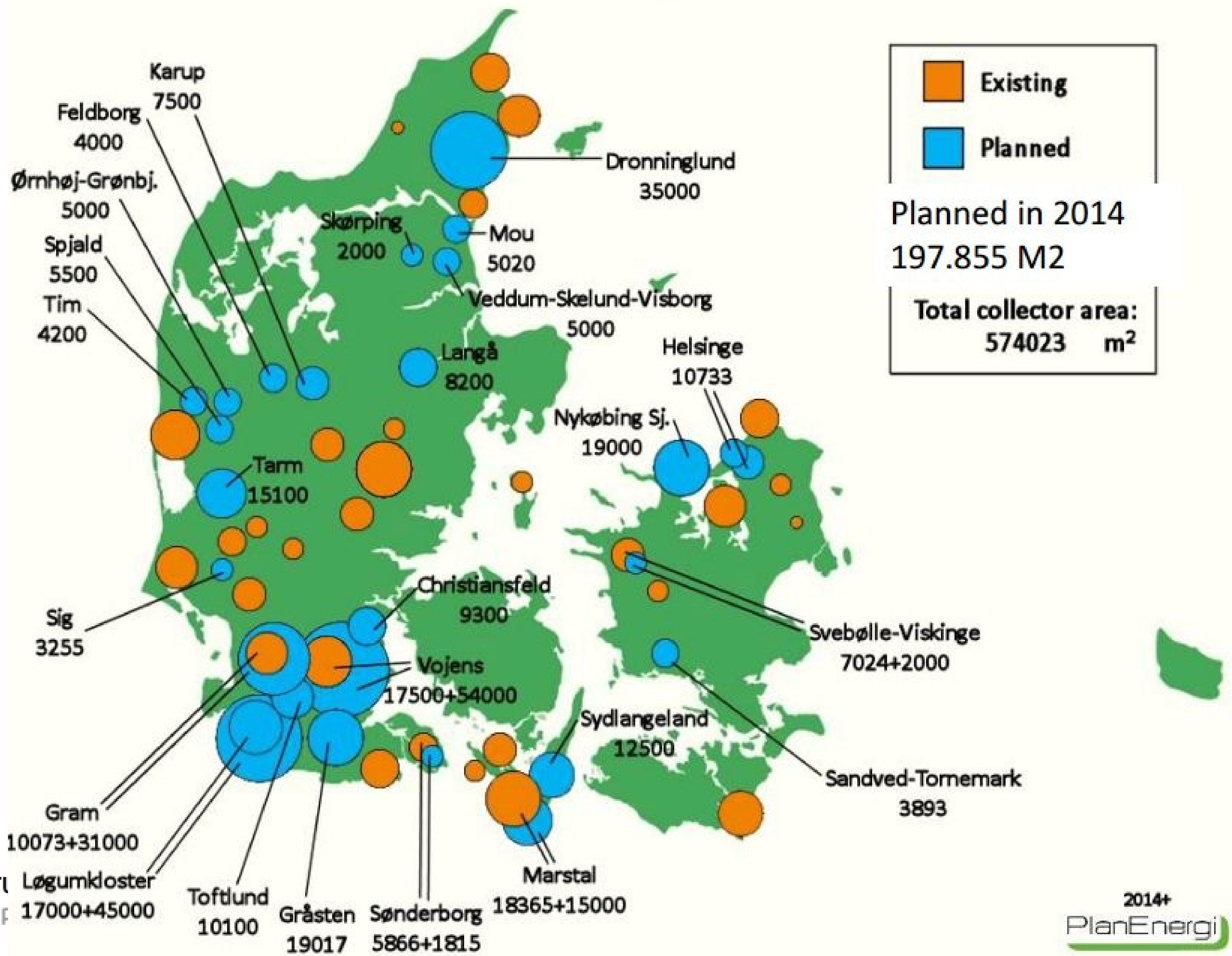
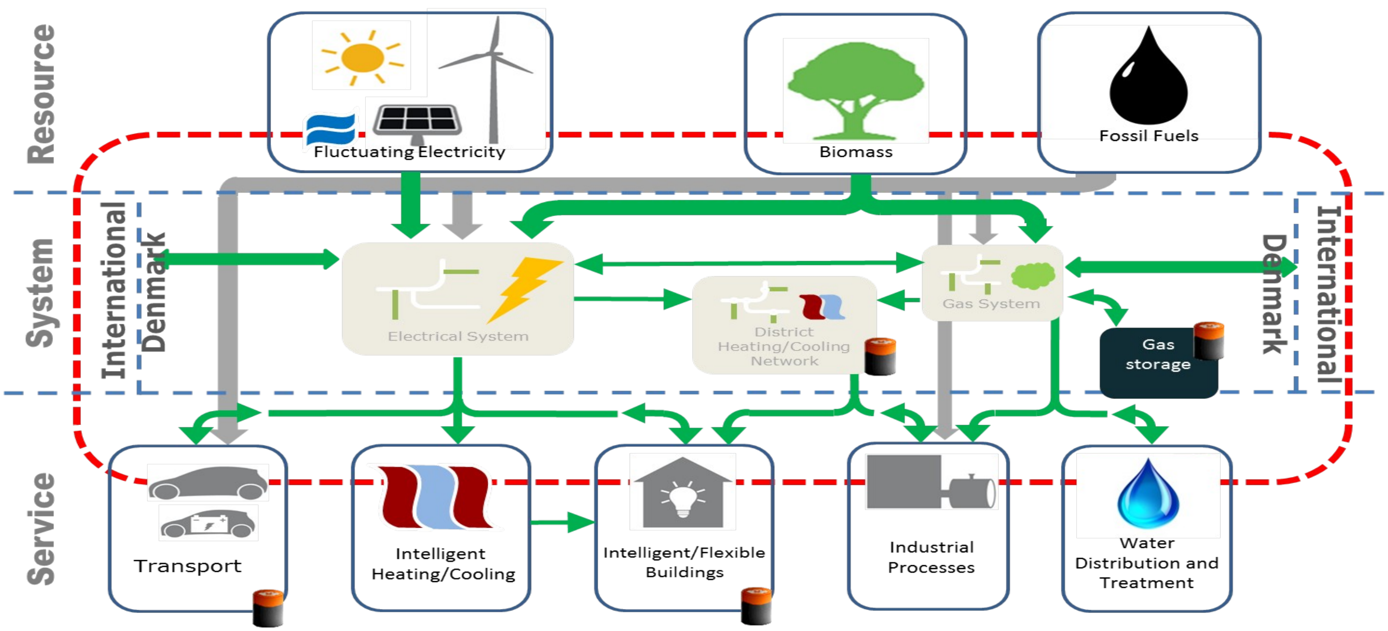
Power right now
Natural gas right now
Locations

Solar district heating in Denmark

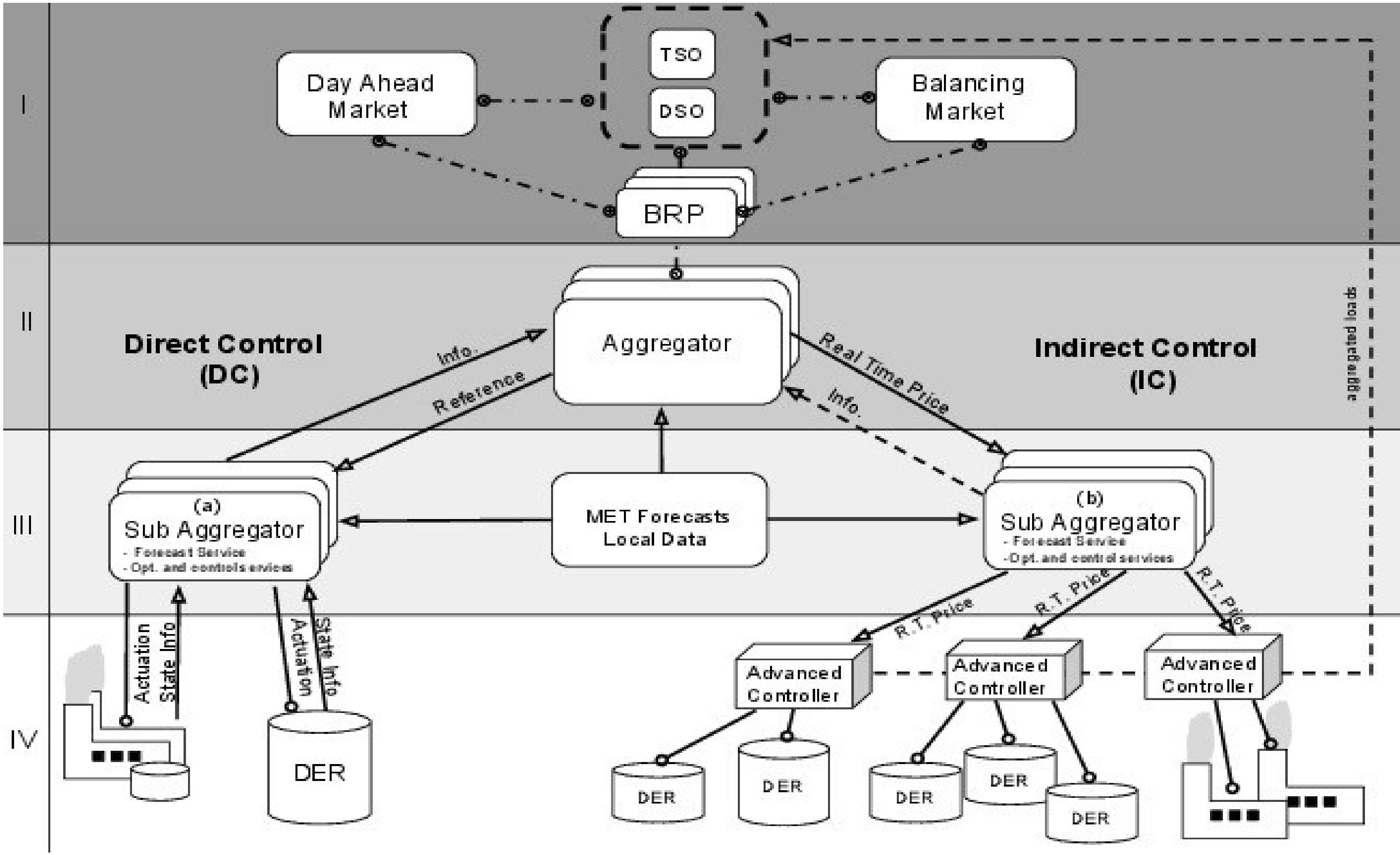


Control and Storage by Energy Systems Integration

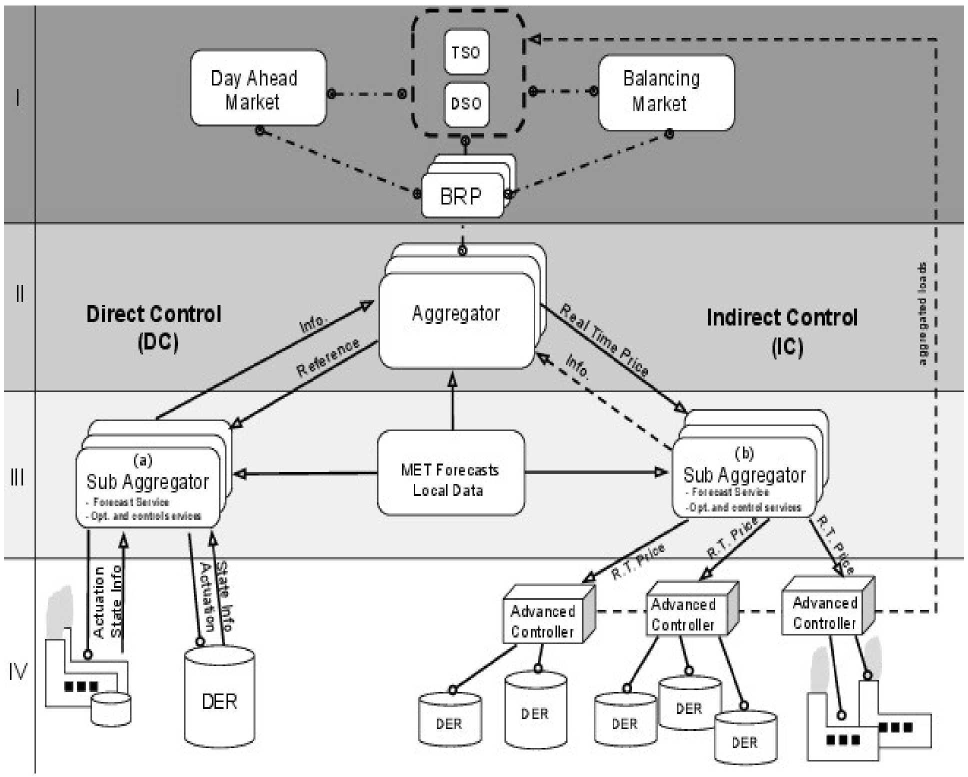


- Operational (simplified) models, optimization and control
- (Virtual) storage principles:
  - Buildings provide storage up to, say, 10 hours ahead
  - District heating systems lead provide storage up to 2-3 days ahead
  - Gas systems provide seasonal storage

Control/Optimization Principles



Control/Opt. Principles



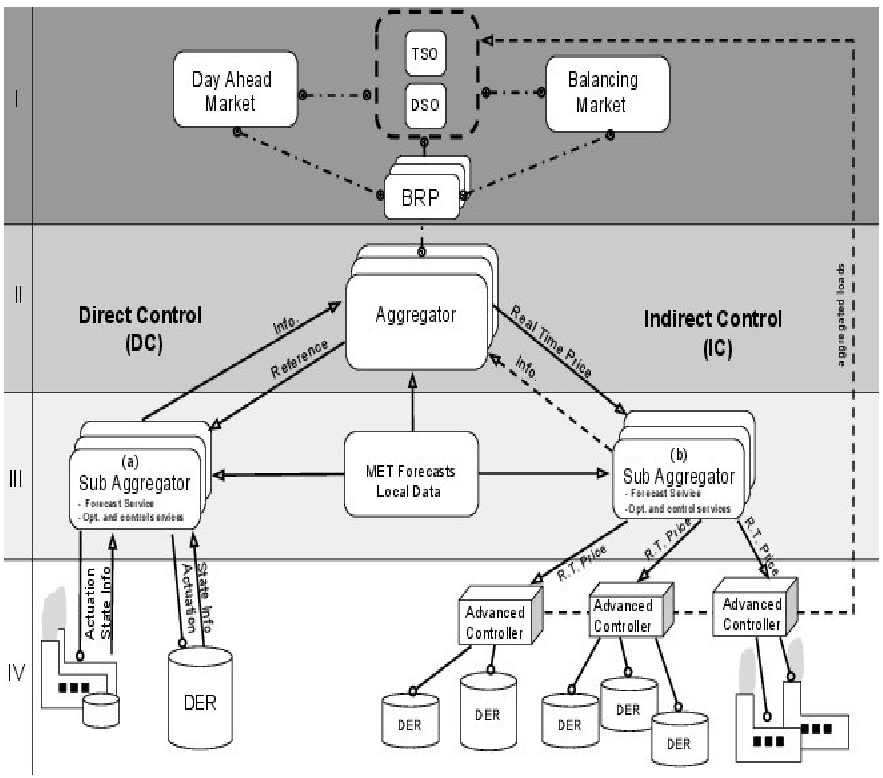
- **Day Ahead:**
  - Stoch. Programming based on eg. Scenarios
  - Cost: Related to the market (one or two levels)
  - Operational optimization – also for the grid
- **Direct Control:**
  - Actuator: **Power**
  - Cost: eg. MV, LQG, EMPC, ... (a single large problem)
  - Two-way communication
  - Models 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.

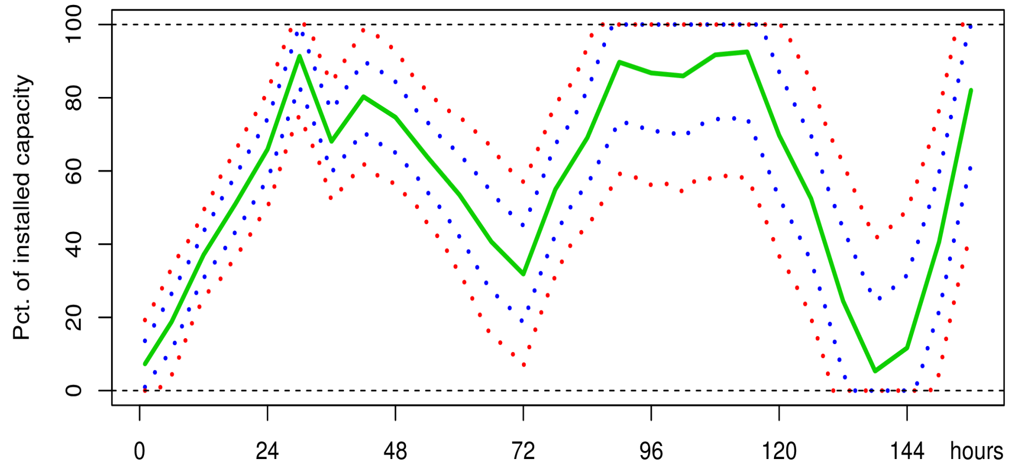
Forecast requirements

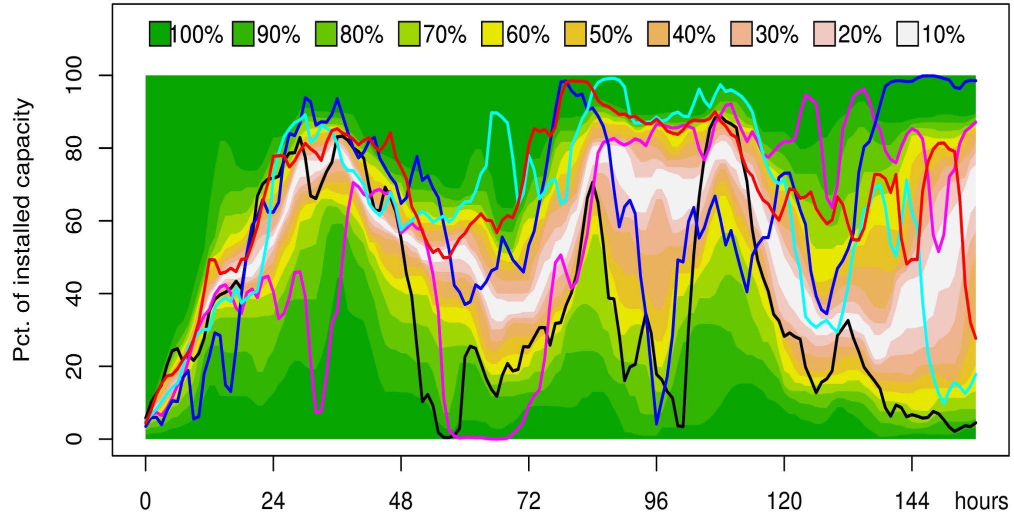


- **Day Ahead:**
  - Forecasts of loads
  - Forecast of Grid Capacity (using eg. DLR)
  - Forecasts of production (eg. Wind and Solar)
- **Direct Control:** .
  - Forecasts of states of DERs
  - Forecasts of load
- **Indirect Control:**
  - Forecasts of prices
  - Forecasts of load

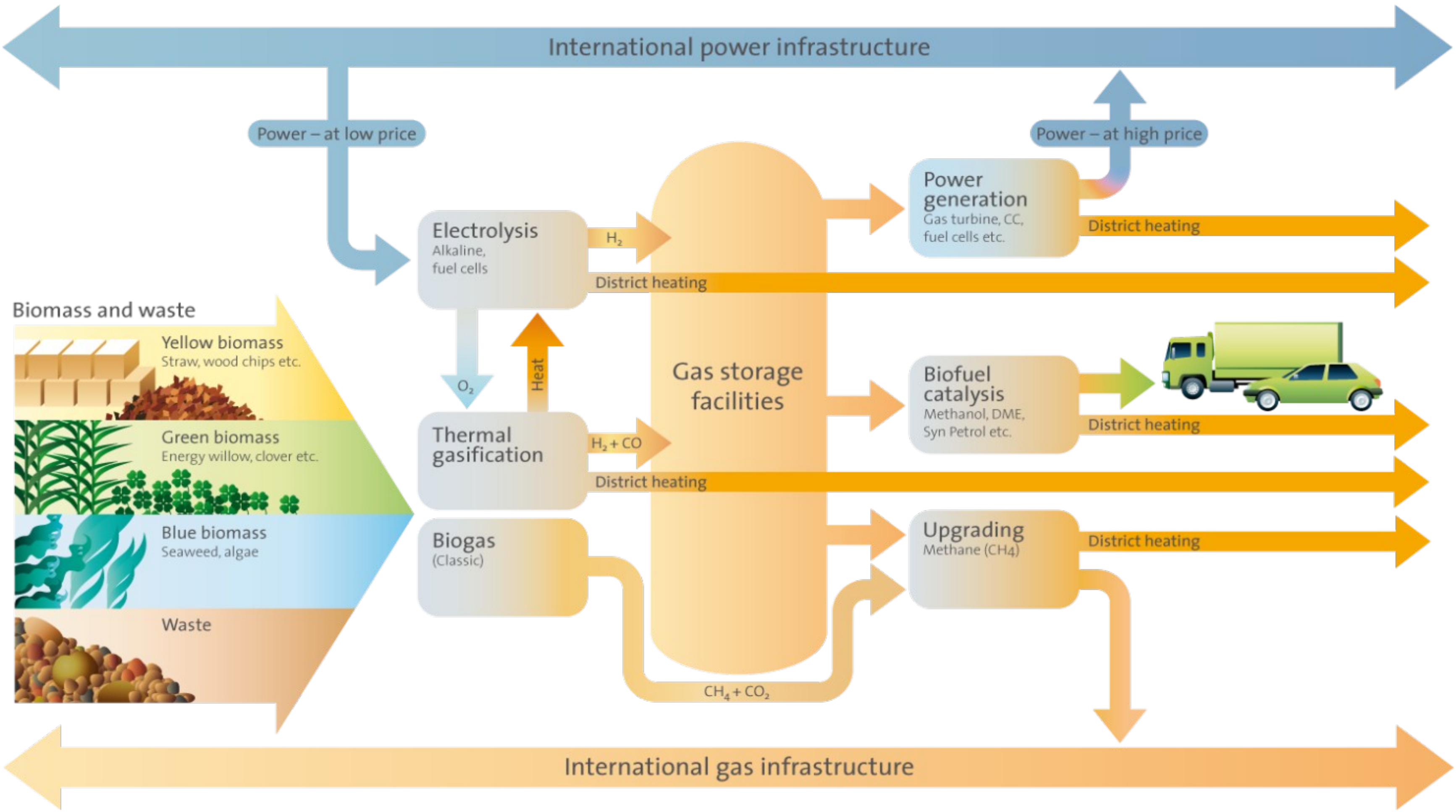
Which type of forecast to use?

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





Interactions between power, gas, DH, and biomass systems



Ongoing projects

- 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)
- ....

Case study

Electrical Heating of Buildings; Control of Load by Price

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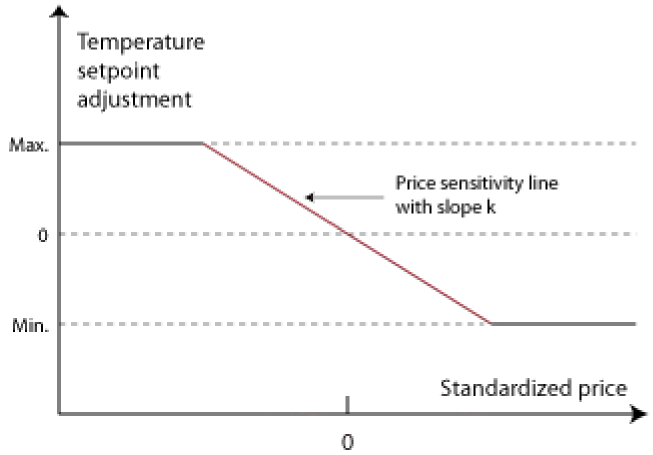
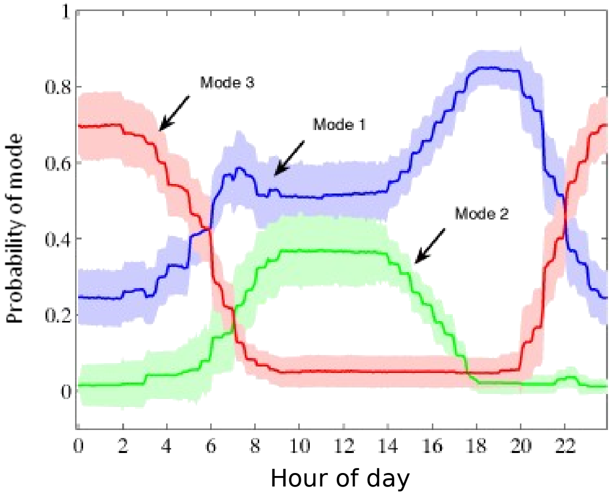
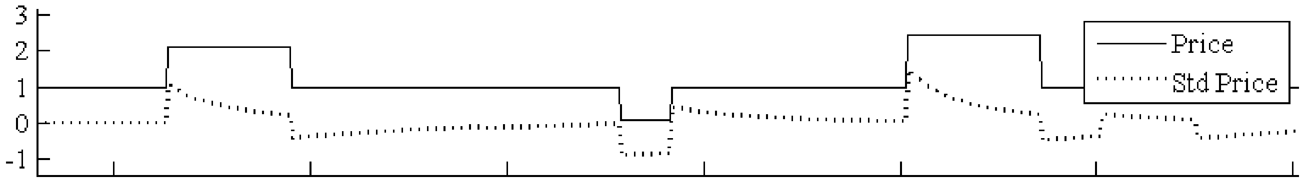
Price responsivity

Flexibility is activated by adjusting the temperature reference (setpoint)

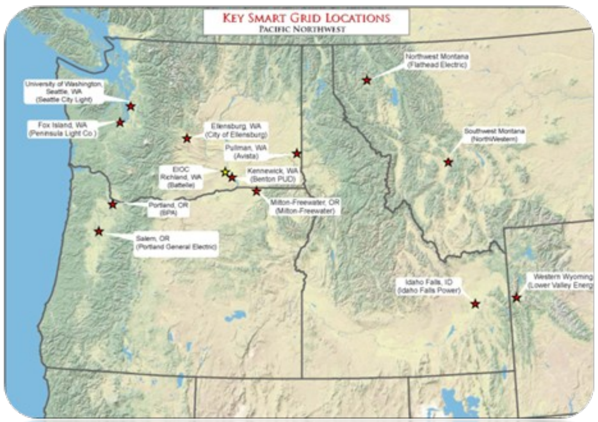


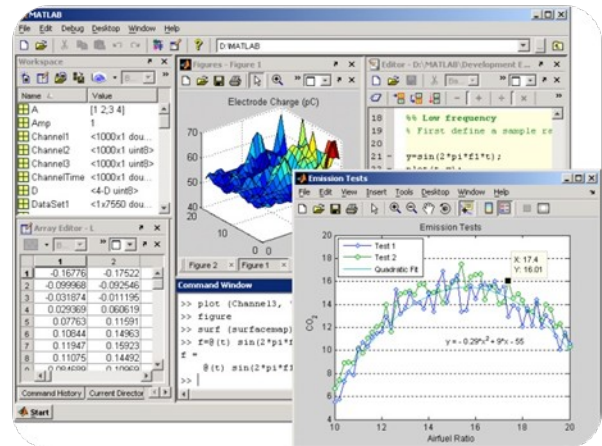




- **Standardized price** is the % of change from a price reference, computed as a mean of past prices with exponentially decaying weights.
- **Occupancy mode** contains a price sensitivity with its related comfort boundaries. 3 different modes of the household are identified (work, home, night)

Two data sources





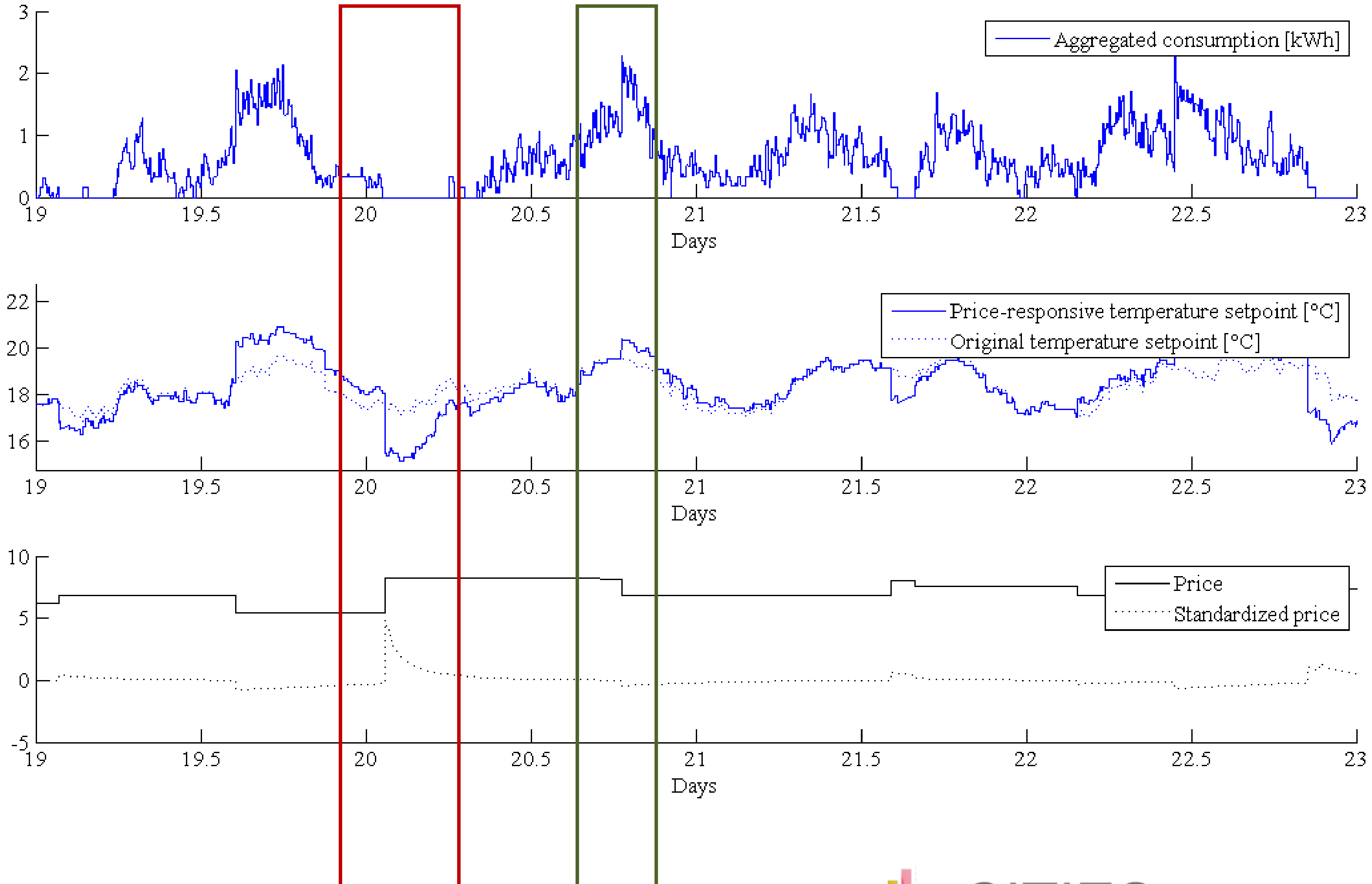
Olympic Pensinsula project

- 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)

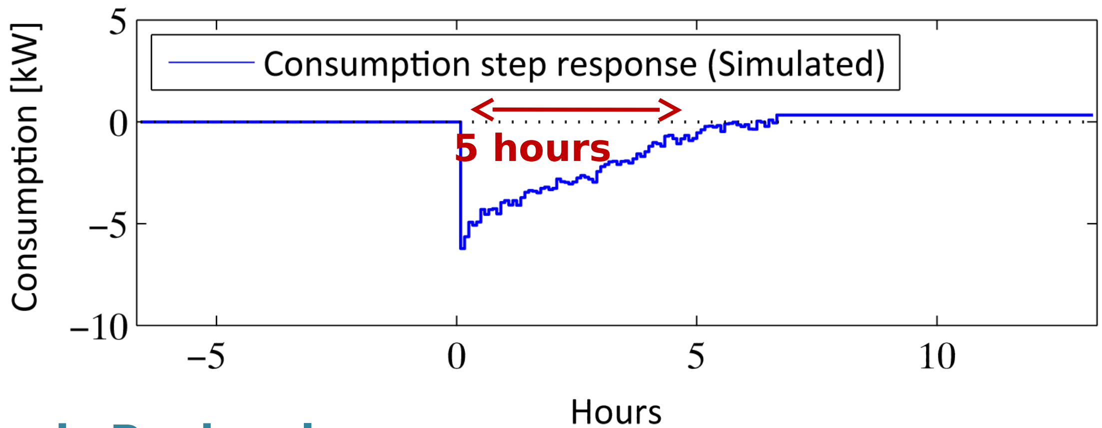


Identify price response

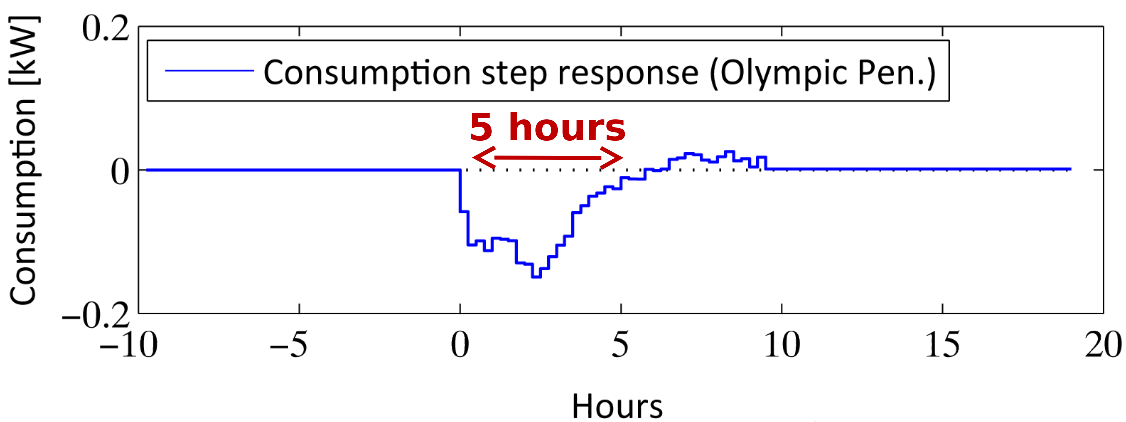
Response on Price Step Change

Model inputs: price, minute of day, outside temperature/dewpoint, sun irrandiance

Simulated

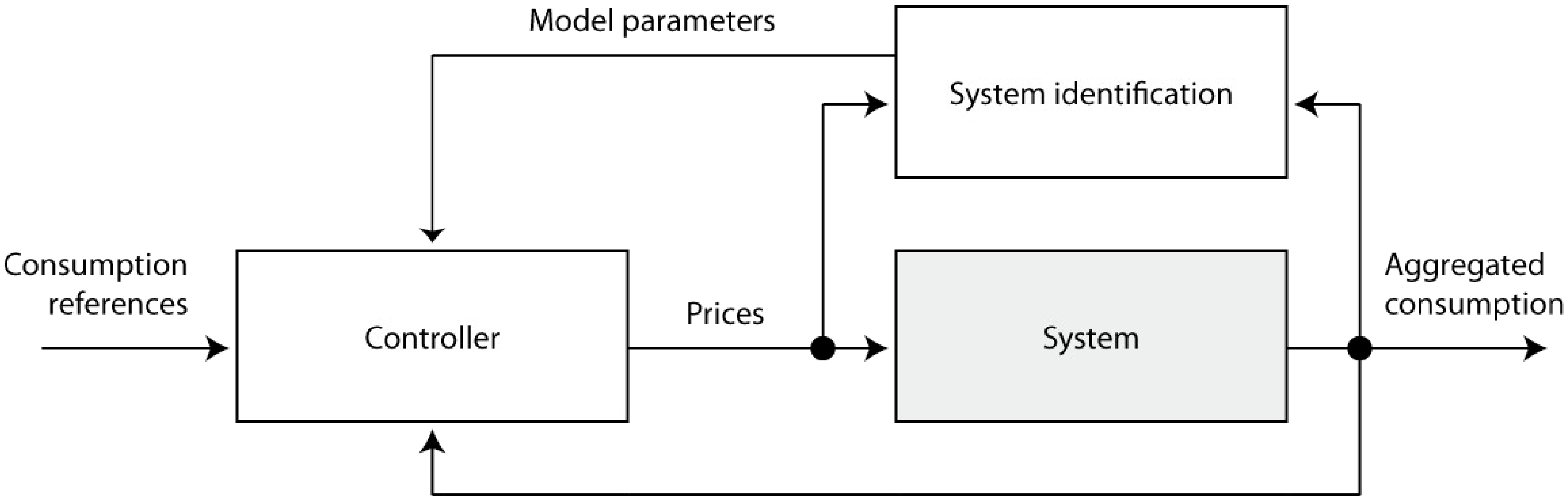


Olympic Peninsula



Adaptive control setup

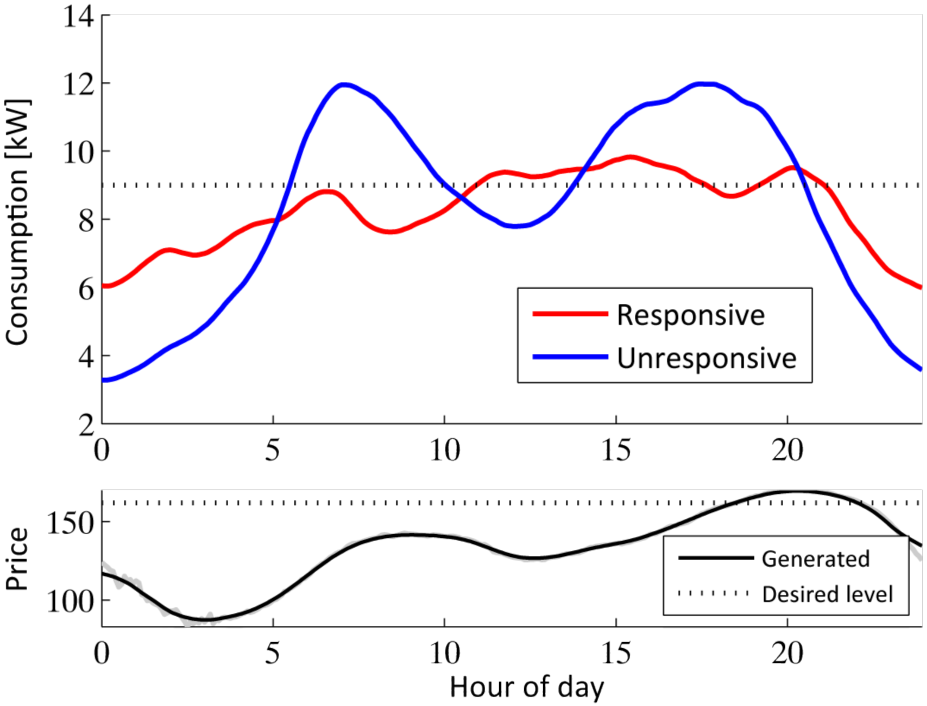
As the systems changes over time



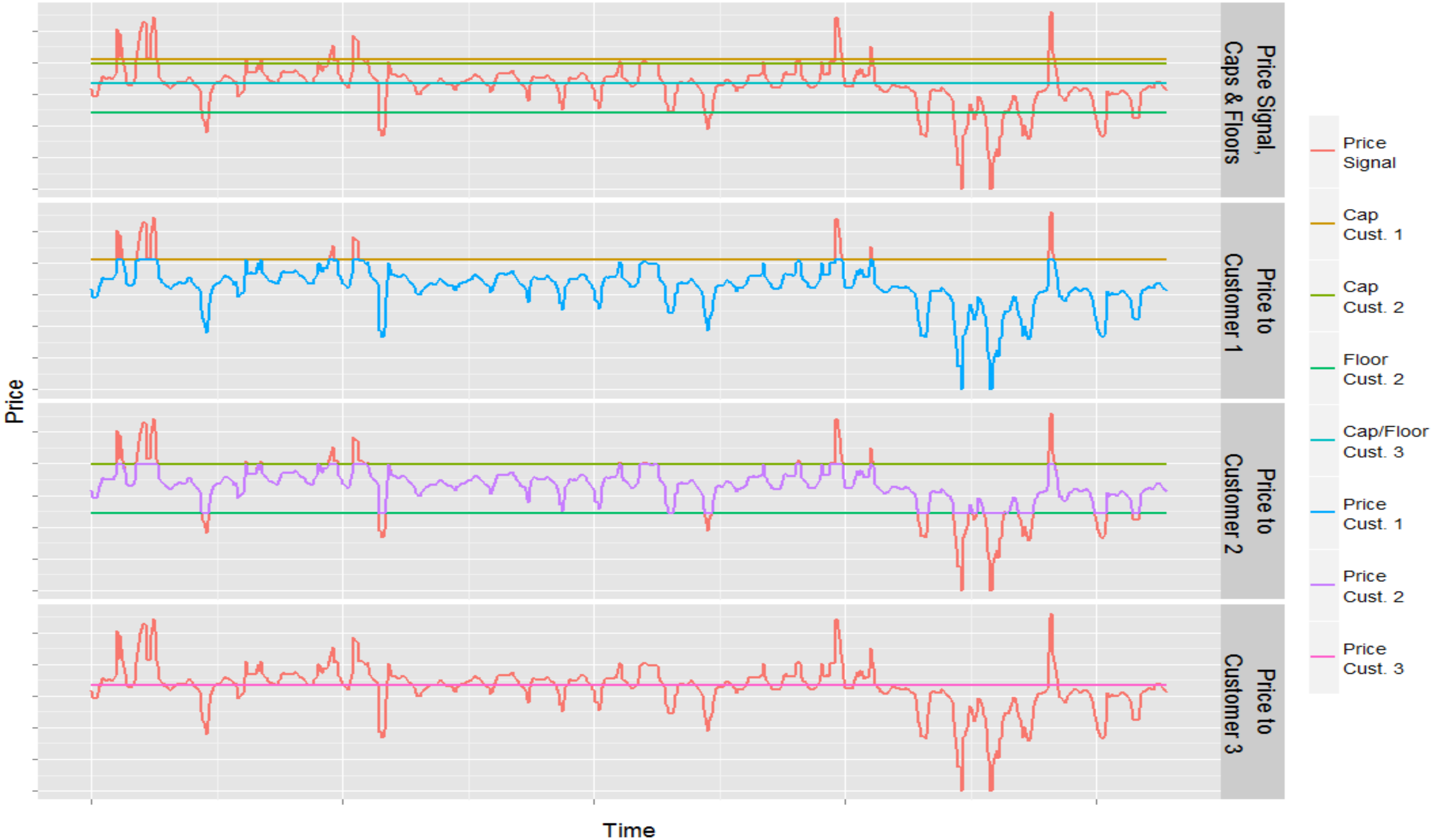
Control performance

With a price penality avoiding its divergence

- Considerable reduction in max consumption
- Mean daily consumption shift



Contracts / Products



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