Power System Balancing by Distributed Energy Resources (DER) and Flexible Demand

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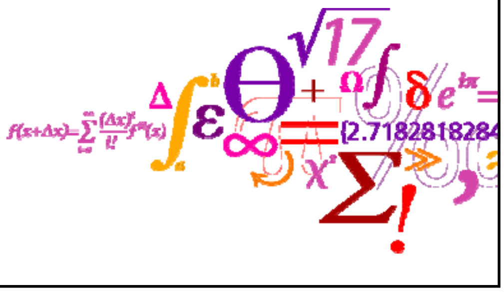
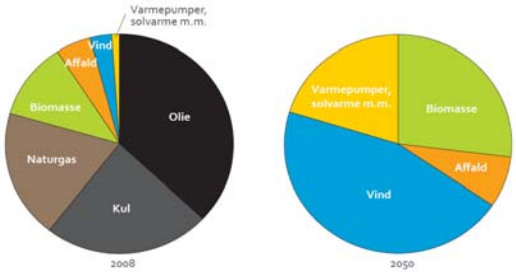
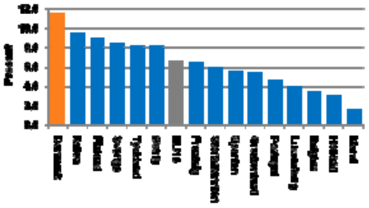


DTU Electrical Engineering
Department of Electrical Engineering

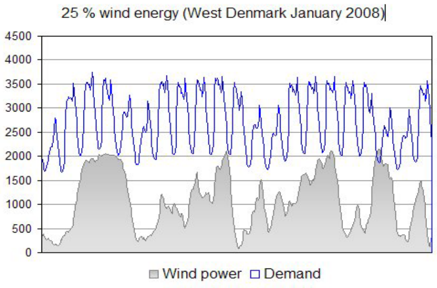
The Danish Energy Strategy and Goals

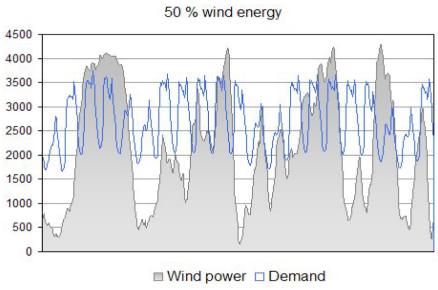
- Danish 2020-objectives
  - At least 30% renewable energy in the energy system
  - ~50% wind power penetration
- In 2050 (The governments strategy)
  - Fossil free energy system
  - 100% renewable based energy system





The Danish Wind Power Case





Wind power covers the entire demand for electricity in 200 hours (West DK)

In the future wind power will exceed demand in more than 1,000 hours

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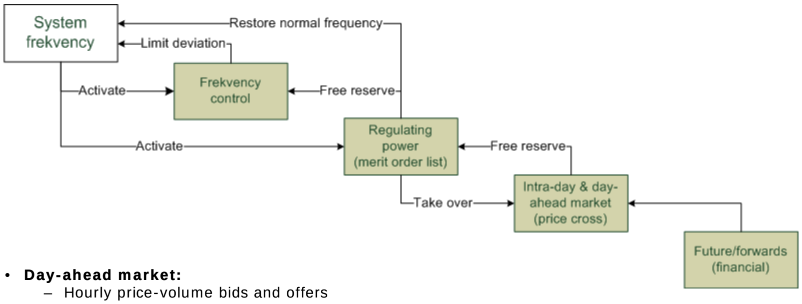
Balancing in the Nordic Power System



- **Day-ahead market:**
  - Hourly price-volume bids and offers
  - Price is set by intersection point between the supply and demand curves
  - The price is settled 12–36 h before the hour of delivery
- **Intra-day market:**
  - Adjustments to trades done in the day-ahead market are made until one hour prior to delivery
- **Balancing market:**
  - Real-time market operated during the hour of delivery
  - Up- and down regulation bids until one hour prior to hour of operation
  - Activated during hour of operation by TSO's
- **Frequency control:**
  - Governors with proportional controller
  - Speed droop

Homeostatic Utility Control

- In 1980 Prof. Schweppe publish a vision for a future power system
  - Fred Schweppe et al., “Homeostatic Utility Control”, *IEEE Transactions on Power Appartus and Systems*, Vol. PAS-99, No. 3, May-June 1980, pp. 1151-1163

- Homeostasis
  - Property of a system that regulates its internal environment and tends to maintain a stable, constant condition, typically used to refer to a living organism. Multiple dynamic equilibrium adjustment and regulation mechanisms make homeostasis possible.

- Idea of a electric energy system based on flow of:
  - Power
  - Money
  - Information

Outline

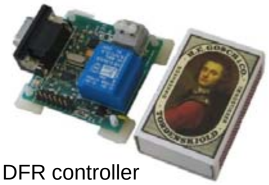
1. Two control concept for usage of distributed energy resources (DER) and demand response (DR) for power system balancing
   a. Frequency responsive demand
   b. 5 minute real-time market / control-by-prices

2. Feasibility is illustrated by simulation of the Nordic power system with realistic, verified and tested models

3. Future outlook
   - Two large-scale demonstrations in the Danish power system

Demand as Frequency Controlled Reserve (DFR)

- A large share of demand can be disconnected in a short period without reduction in delivered energy service
  - Air conditioning
  - Water heating
  - Refrigeration
  - Pumping
  - Ovens
  - Melting
- Potential benefits
  - Fast reaction
  - Not affected by tear and wear
  - Smooth collective response with numerous units
  - Low costs and utilization of intrinsic energy storage in appliances



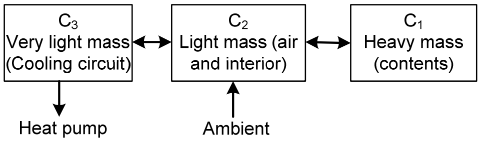
DFR controller

Refrigerator in PowerLabDK Laboratory at DTU

Vestfrost M200 Bottle Cooler w. Dixell XR30CX thermostat

Refrigerator Thermal Model

Model Verified by Measurements



Heat transfer between mass *j* and *k* is calculated:

$$Q_{jk,i+1} = U_{jk} \cdot \left(T_{j,i} - T_{k,i}\right) \cdot \Delta t$$

Temperature of mass *j* is calculated:

$$T_{j,i+1} = T_{j,i} + \frac{\sum Q_{i+1}}{C_j}$$

TABLE II

REFRIGERATOR MODEL PARAMETERS

Thermal mass, 1*	C_1	251 kJ/K ± 50%
Thermal mass, 2	C_2	13 kJ/K
Thermal mass, 3	C_3	1 kJ/K
Heat transfer coefficient, 1↔2	$U_{1\leftrightarrow 2}$	30 W/K
Heat transfer coefficient, 2↔3	$U_{2\leftrightarrow 3}$	12 W/K
Heat transfer coefficient, a↔2	$U_{a\leftrightarrow 2}$	5 W/K
Heat pump capacity (when ON)		421 W

* Randomly, represent a loading between 25 and 75% of capacity.

Refrigiator Control

Thermostat logic, *u* (1=on; 0=off), is calculated:

$$u_{i+1} = \begin{cases} u_i & T_{set}^{min} < T < T_{set}^{max} \\ 1 & T \le T_{set}^{min} \\ 0 & T \ge T_{set}^{max} \end{cases}$$

where:

$$\boxed{T_{set} = T_{set,0} + k(f - f_0)}$$

$$T_{set}^{min} = T_{set} - \Delta T_{hys}/2 \qquad T_{set}^{max} = T_{set} + \Delta T_{hys}/2$$

Parameters:

$\Delta T_{hys} = 2$ °C

$k = 20$ °C/Hz

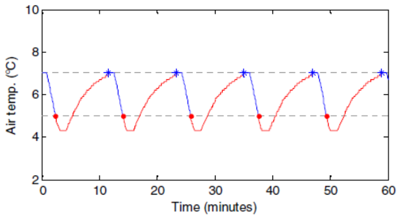
Limitation: Minimum 3 minutes off-time between on-cycles.

Frequency *f* is low pass filtered with time constant of 1 second.

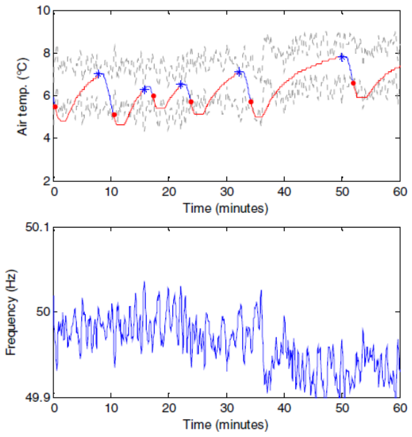
Refrigerator Operation

Measurements in Laboratory

Without DFR:



With DFR:



Statistical Representation of Frequency Response

Measurements in Laboratory

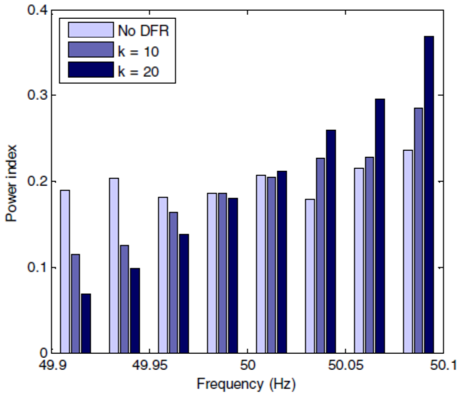


Fig. 9. Statistical representation of DFR response in 25 mHz frequency slots. Different values of k clearly impact the slope of the frequency response.

Response to 50 mHz Frequency Step and 300 MW Loss of Load, respectively

Simulation of 1,000 Instances/ 2,000 MW (rated power)

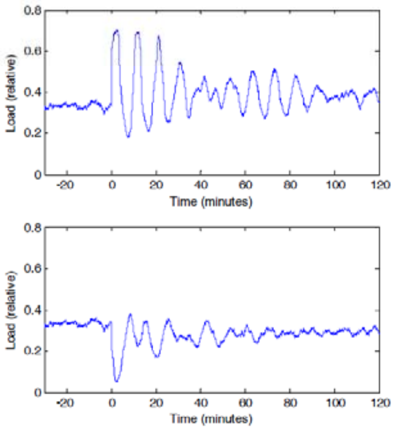


Fig. 4. Aggregate DFR response to step input of 50 mHz. The top figure shows a positive step, and the bottom figure a negative step.

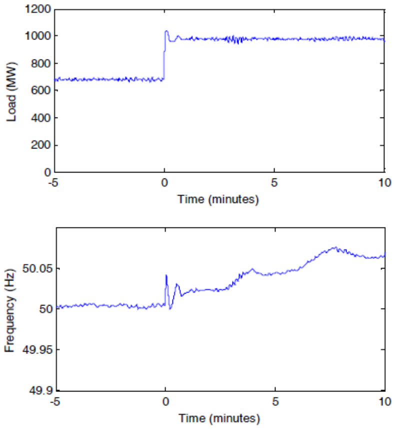


Fig. 5. Aggregate DFR response to power imbalance step of 300 MW with inertia power system model included. The top figure shows the aggregate refrigerator load, and the bottom figure the system frequency.

Business Case for DFR

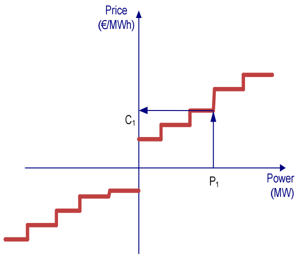
- Cost of frequency controlled reserves (Nordic power system)
  - 25.000-100.000 €/MW/year

- Assumptions:
  - DFR production cost is 20 €/unit (not mass production)
  - Unit average power demand 100 W
- Simple payback time of DFR:
  - 2-8 years

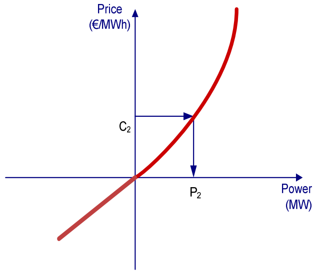
Control-by-price

Extention of Market to Shorter Time Scale and Smaller Users (DER and Flexible Demand)

Current regulating power market



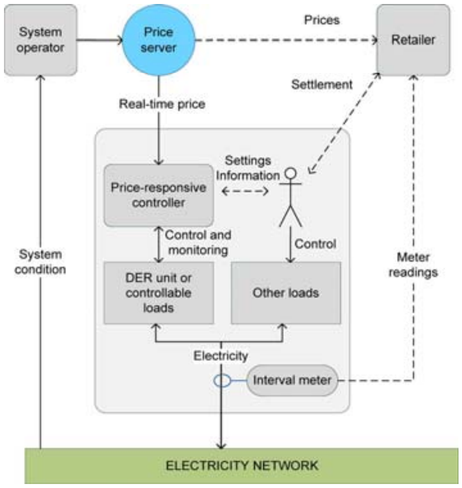
New control-by-price concept



- 10+ MW bids
- Online monitoring
- Transactions

- One-way price signal every 5 minutes
- Fit small units

Control-by-price (5 min real-time market)



Micro-CHP Unit in PowerLabDK Laboratory at DTU

Gas-engine based Senertec DACHS

TABLE V
MICRO-CHP CHARACTERISTICS

Electric power	5.5 kW
Heating power	12.5 kW
Start-up delay	90 seconds
Shut-down time	Immediately
Minimum on-time	30 minutes

Overview of Micro-CHP System

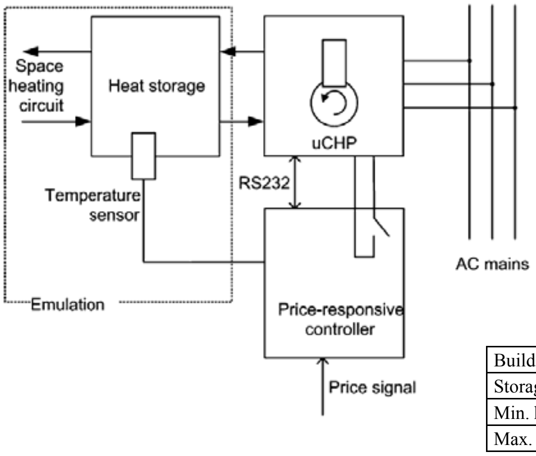


TABLE V
MICRO-CHP THERMAL PARAMETERS

Building heat demand	6 kW ± 50%
Storage tank capacity	750 liter
Min. heat storage av. temperature	50 ºC
Max. heat storage av. temperature	80 ºC

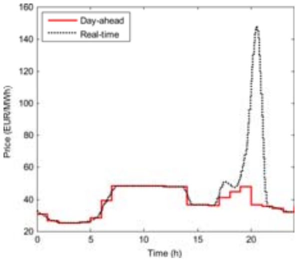
Relative Price

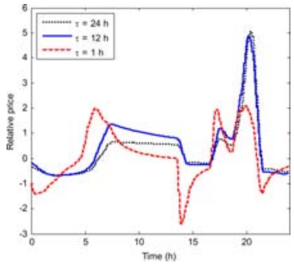
Example from the Nordic System 25 September 2009

Relative price:

$$P_{rel} \equiv \frac{P - P_{avg}}{P_{dev}}$$

$$P_{avg,i} = P_{avg,i-1} + \frac{\Delta t}{\Delta t + \tau} \cdot \left(P - P_{avg,i-1}\right)$$
$$P_{\mathrm{var},i} = P_{\mathrm{var},i-1} + \frac{\Delta t}{\Delta t + \tau} \cdot \left(\left(P - P_{avg,i}\right)^2 - P_{\mathrm{var},i-1}\right)$$
$$P_{dev,i} = \sqrt{P_{\mathrm{var},i}}$$

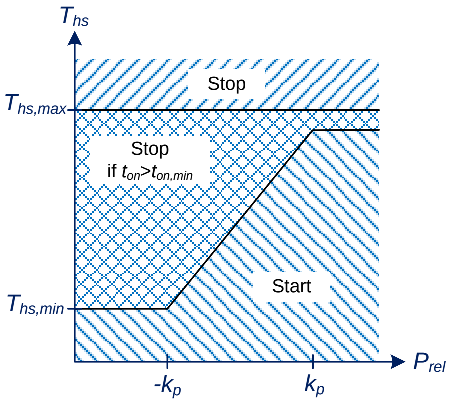




Very simple implementation

Micro-CHP Control

Decision diagram:



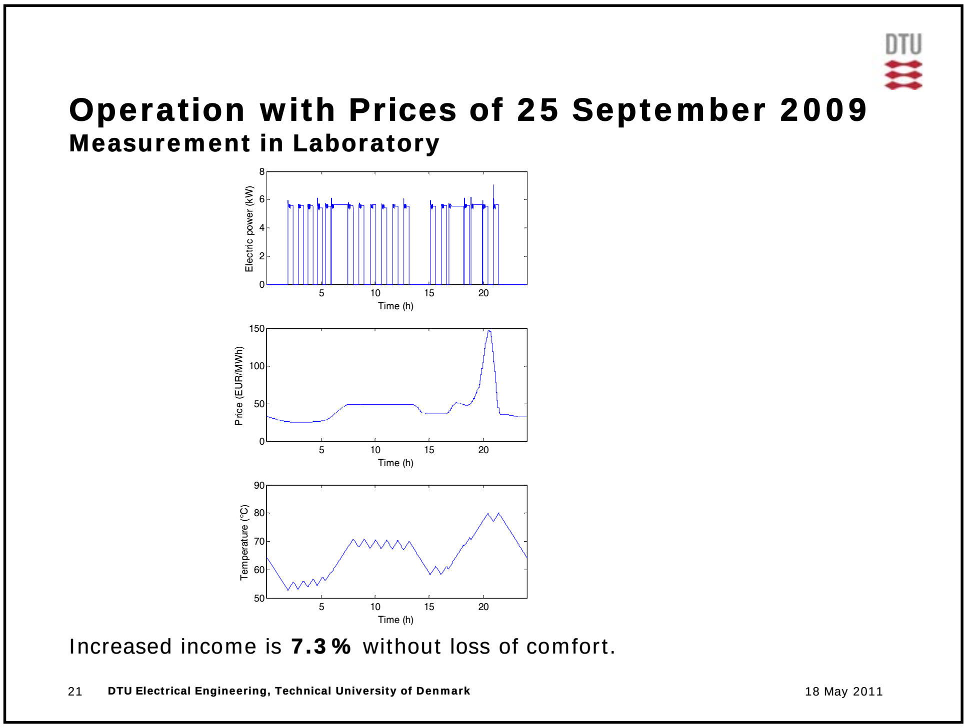
T_{hs}: Heat storage average temperature (state-of-charge)

t_{on}: Minimum operating time per start

k_p: The relative price at which the controller will fully charge the heat storage

TABLE V
MICRO-CHP CONTROLLER

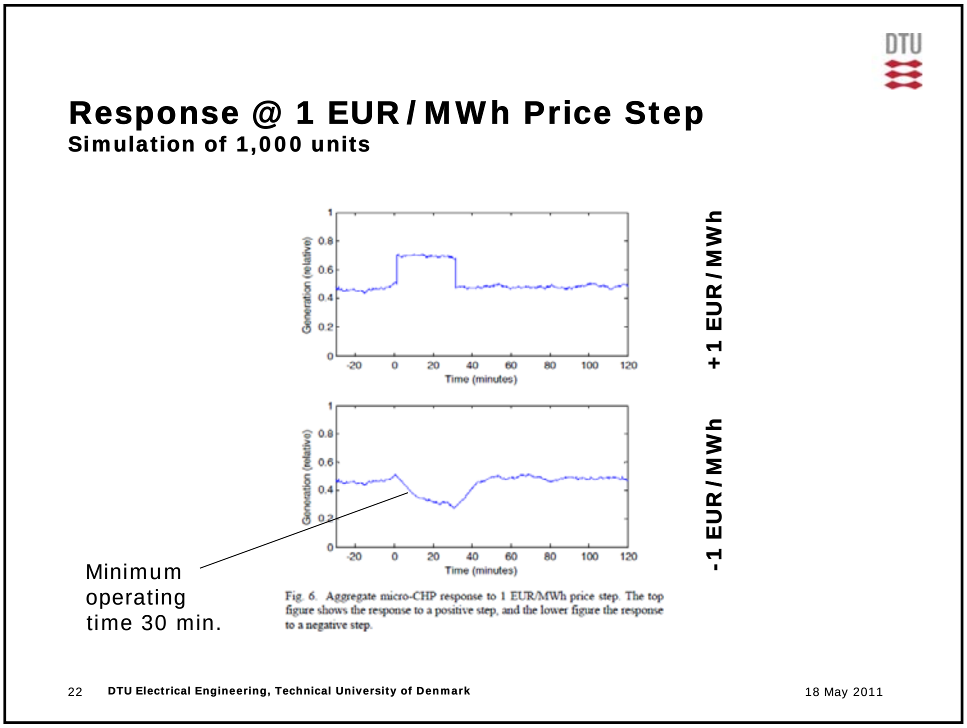
Price constant, k_p	1
Relative price time constant, τ	12 h



Operation with Prices of 25 September 2009

Measurement in Laboratory

Increased income is **7.3 %** without loss of comfort.



Response @ 1 EUR / MWh Price Step

Simulation of 1,000 units

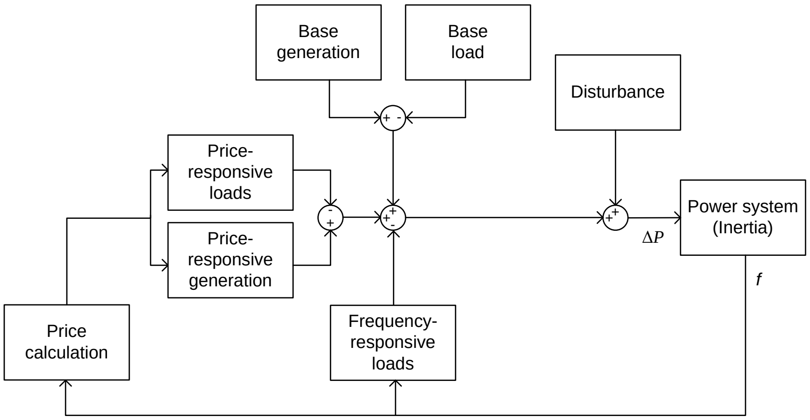
+1 EUR / MWh

-1 EUR / MWh

Minimum operating time 30 min.

Fig. 6. Aggregate micro-CHP response to 1 EUR/MWh price step. The top figure shows the response to a positive step, and the lower figure the response to a negative step.

Power System Control Scheme Overview



Power System Balancing by Distributed Energy Resources and Flexible Demand

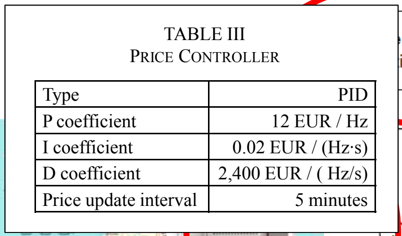


TABLE III
PRICE CONTROLLER

Type	PID
P coefficient	12 EUR / Hz
I coefficient	0.02 EUR / (Hz·s)
D coefficient	2,400 EUR / (Hz/s)
Price update interval	5 minutes

Power System Model
Equivalent to the Nordic Power System

System frequency f is calculated recursively for each time step Δt:

$$f_{i+1} = f_i + \frac{\Delta P_i}{f_i} \cdot \frac{f_0^{2}}{2 \cdot H \cdot S} \cdot \Delta t$$

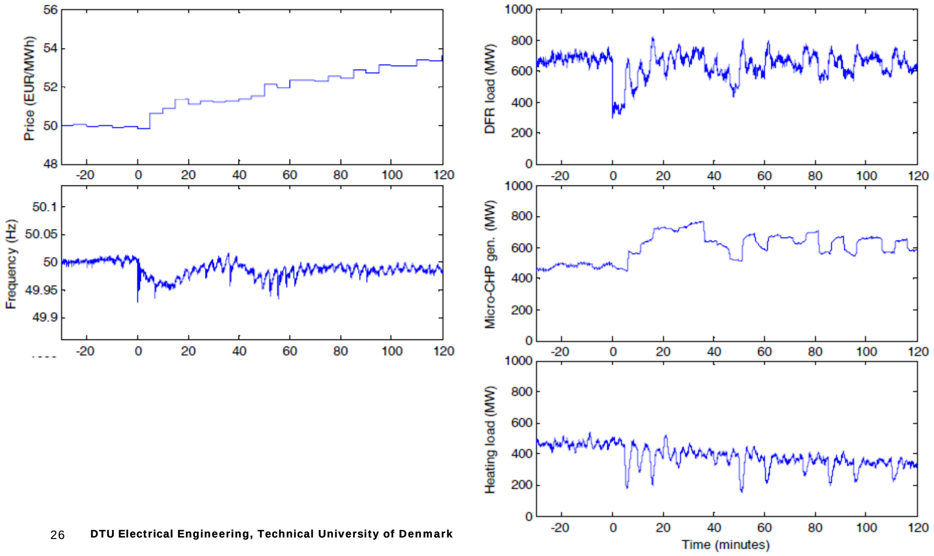
where

- ΔP is the immediate power imbalance
- f_0 is the nominal system frequency
- H is the system's inertia constant
- S is the rated apparent power of the generators

TABLE I
SYSTEM PARAMETERS

Nominal system frequency	f_0	50 Hz
Rated apparent power	S	70,000 MVA
Inertia constant	H	4 s

Total system response @ 300 MW disturbance (loss of generation)

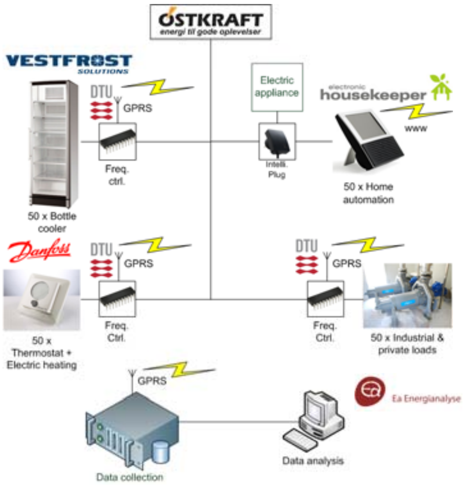


Results of simulation

- It is showed that frequency-controlled demand and control-by-price of DER and flexible demand can contribute to system balance in time scale from seconds to hours.
  - Simulations based on verified models
  - Control methods implemented in the laboratory
- Both DFR and control-by-price has tendency to synchronise switching pattern (predominant for the micro-CHP units)
  - Adding randomness in the simulations dissolve this
  - Unlikely to occur in real-life applications
- Frequency is stressed
  - The control-by-price stress the frequency reserves compared to conventional methods
  - Stress the need for the DFR (fast and no tear and wear)
- Control-by-price control algorithm are not optimal (e.g. the synchronised start of micro-CHP units)
  - Optimized for unit profit
  - Need for win-win algorithms

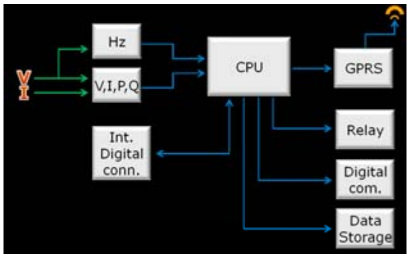
Field test with 200 DFCR-units

Supported by the EUDP programme



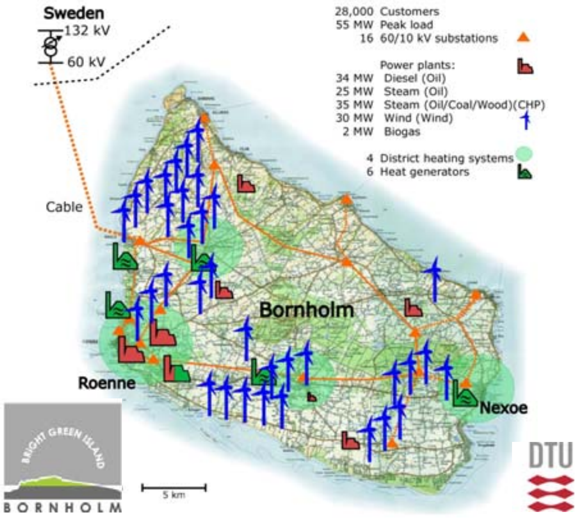
SmartBox – a Multi Purpose Controller for Real-Life Experiments

Demand as Frequency Controlled Reserve / Control-by-price



Bornholm Full-Scale Laboratory

33% Wind Power Penetration, 55 MW Peak Load and Islanding Capability



Strong strategy and political support

Energy resources
- Customers
- Wind power
- Biogas plant
- CHP-plants
- District heating
- PV roll-out
- eCar roll-out

Nordpool market (DK2)

Part of PowerLabDK (www.powerlab.dk)

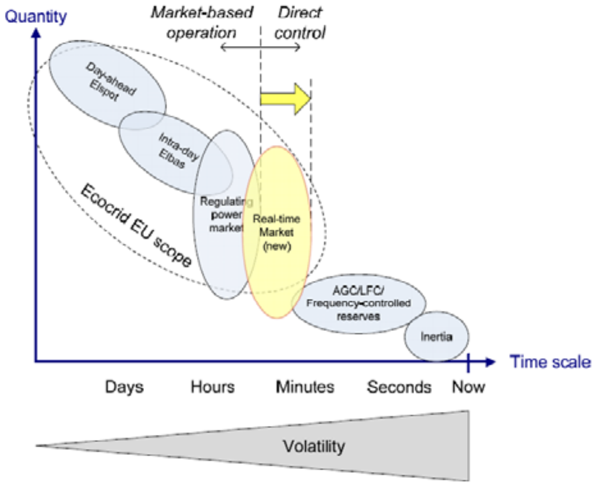
EcoGrid EU Project

A Prototype for European Smart Grids

- A large scale demonstration of a real-time market place for distributed energy resources
- A demonstration of a *real* power system with more than 50 % renewable energy
- ~2000 active customers
- Total budget: 21 million Euro
- Preparation for a fast track towards European real-time market operation of RES & DR

Extention of the Market Solutions

Smaller Units and Shorter Time Constants



Conclusion and Outlook

- Some evidence of feasibility of frequency-controlled demand and control-by-price of DER and flexible demand is provided
- The concepts will be further developed and real-life demonstrated
- Contribute to enable a renewable-based power system
  - Control-by-price provides more resources for balancing comparable to resources in the Nordic regulating power market
  - Reduce the cost for balancing, which is covered by those who cause imbalances
  - In the long run, this would make investment in intermittent renewable energy sources more attractive
  - The control-by-price concept is an important step towards the ambitious targets in that direction

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Thank you for the attention!

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PowerLabDK
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www.powerlab.dk

Contributions
Preben Nyeng (DTU/Energinet.dk), Mikael Togeby (Ea Energy Analysis), Zhao Xu (DTU/KHPoly), German Tarnowski (DTU/Vestas)

References

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- P. Nyeng, C. F. Mieritz, J. Østergaard, "Modeling and Simulation of Power System Balancing by Distributed Energy Resources and Flexible Demand", *Submitted to IEEE Transactions on Smart Grid*.

Extra

DFR’s Impact on Refrigiator Temperature

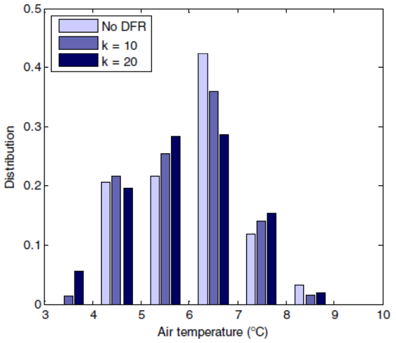

Fig. 6. Air temperature distribution

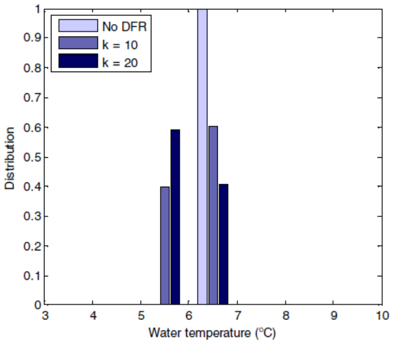

Fig. 7. Water temperature distribution