Flexibility Potentials in Combined Power and Thermal Systems

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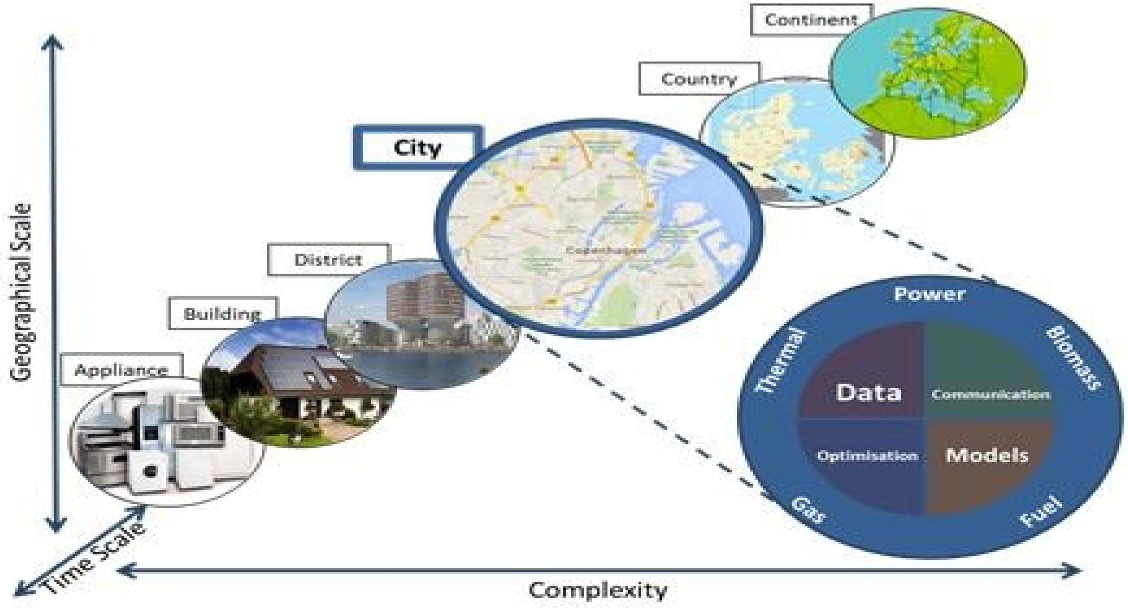
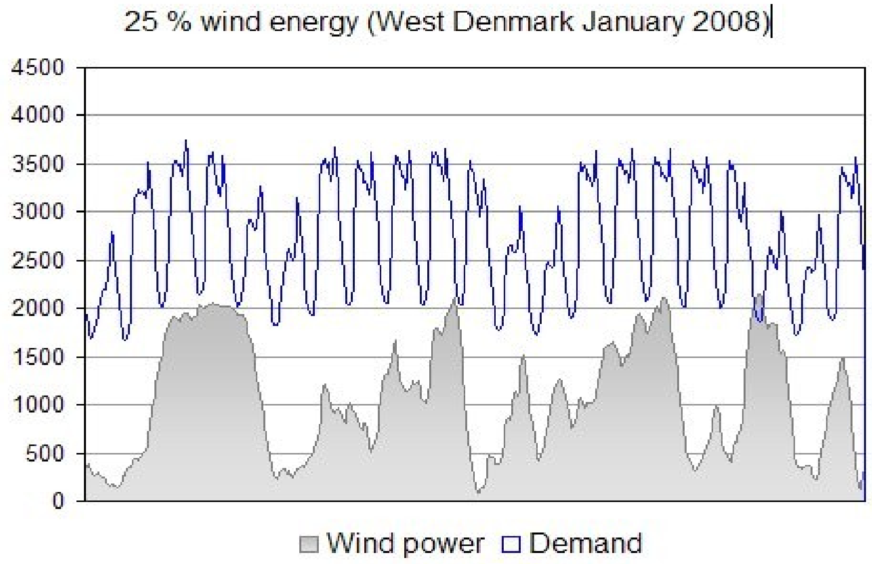
Flexible Solutions and CITIES

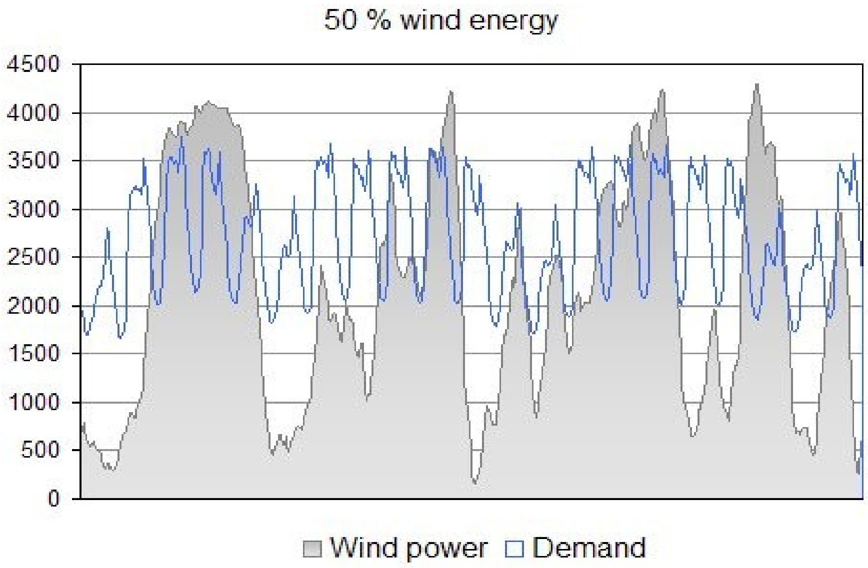
The ***Center for IT-Intelligent Energy Systems in Cities (CITIES)*** is aiming at establishing methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales.



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)

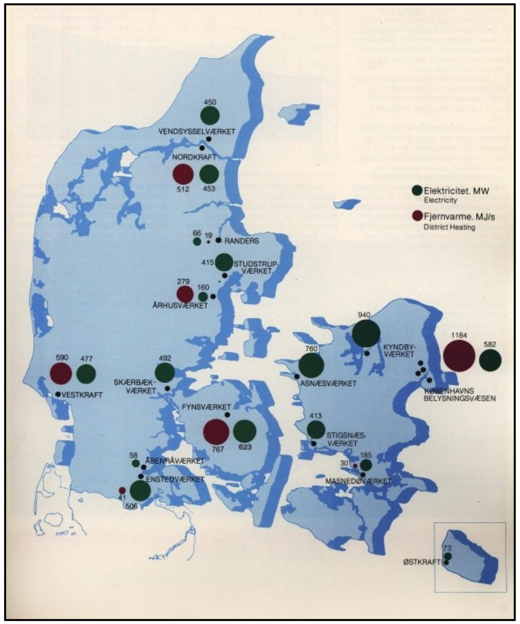
In 2015 more than 42 pct of electricity load was covered by wind power.

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

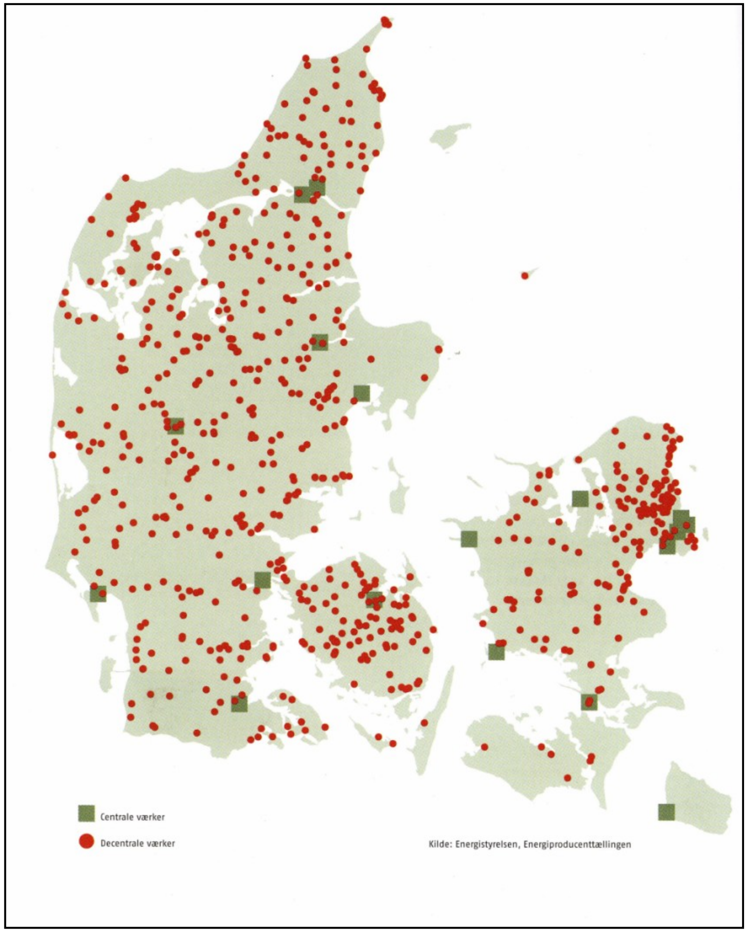
From large central plants to Combined Heat and Power (CHP) production

1980



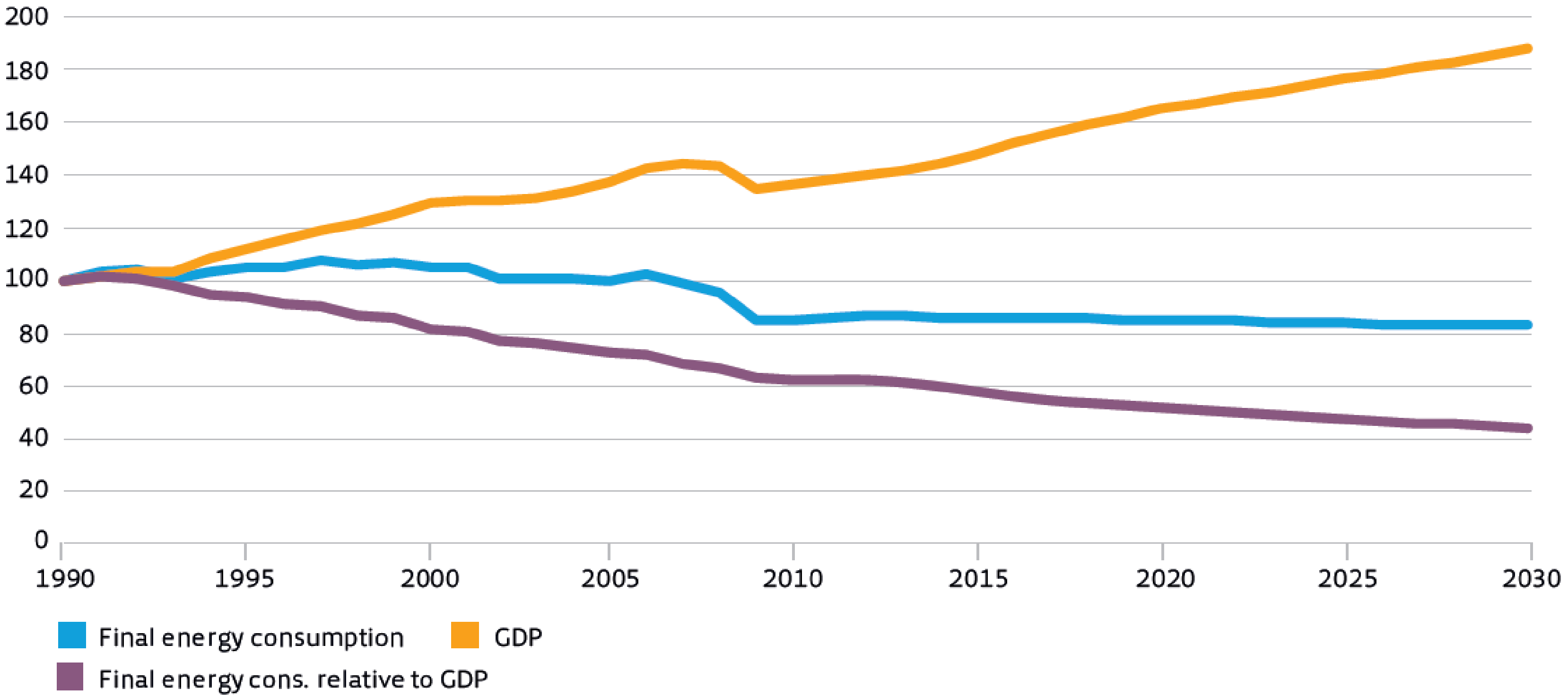
*From a few big power plants to many small **combined heat and power** plants – however most of them based on coal*

Today



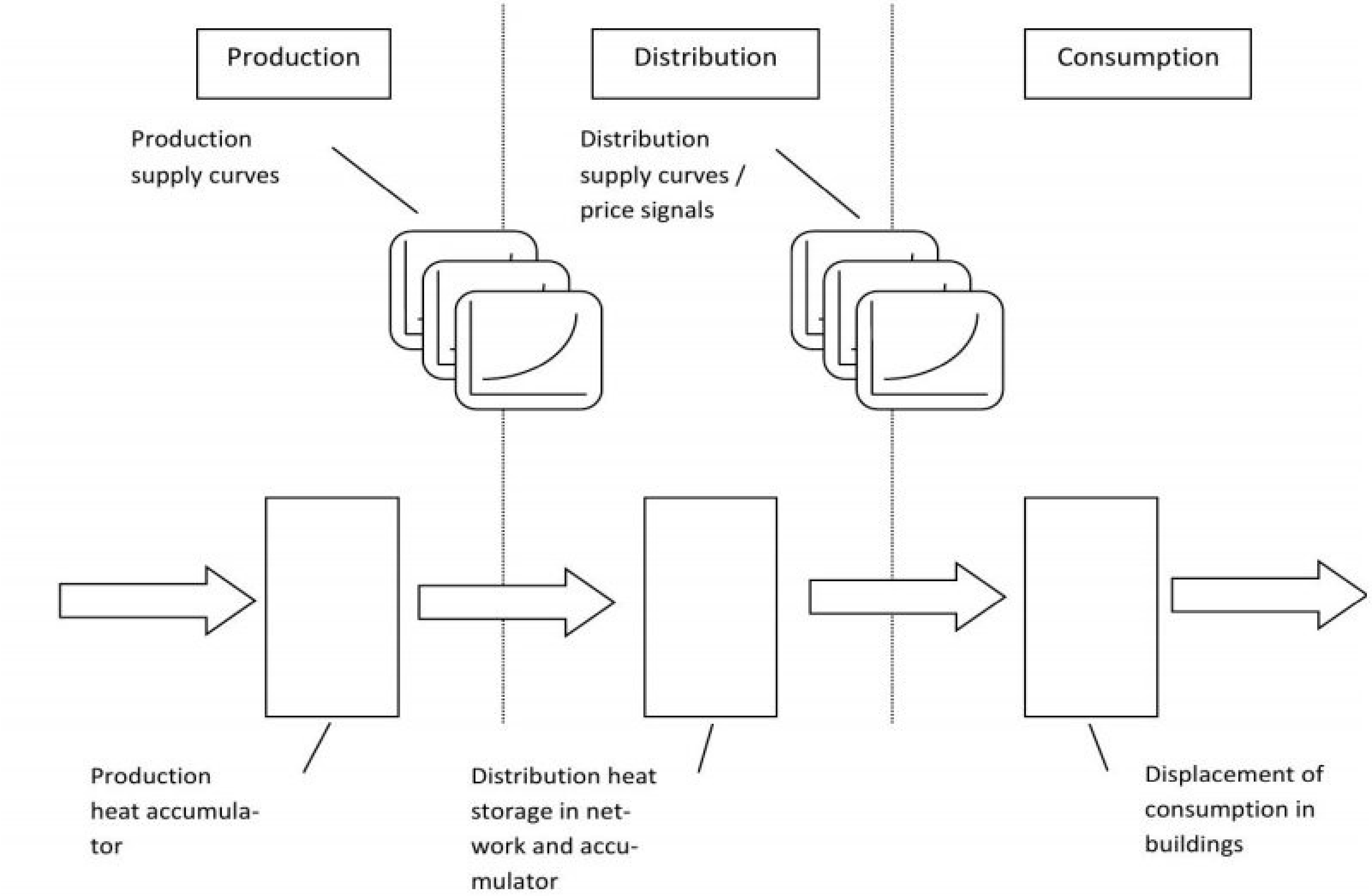
Kilde: Energistyrelsen, Energiproducenttællingen

What has since been achieved: De-coupling of consumption and GDP growth



Source: Energy Policy in Denmark. Danish Energy Agency. December 2012

Flexibility in District Heating



Production

Distribution

Consumption

Production supply curves

Distribution supply curves / price signals

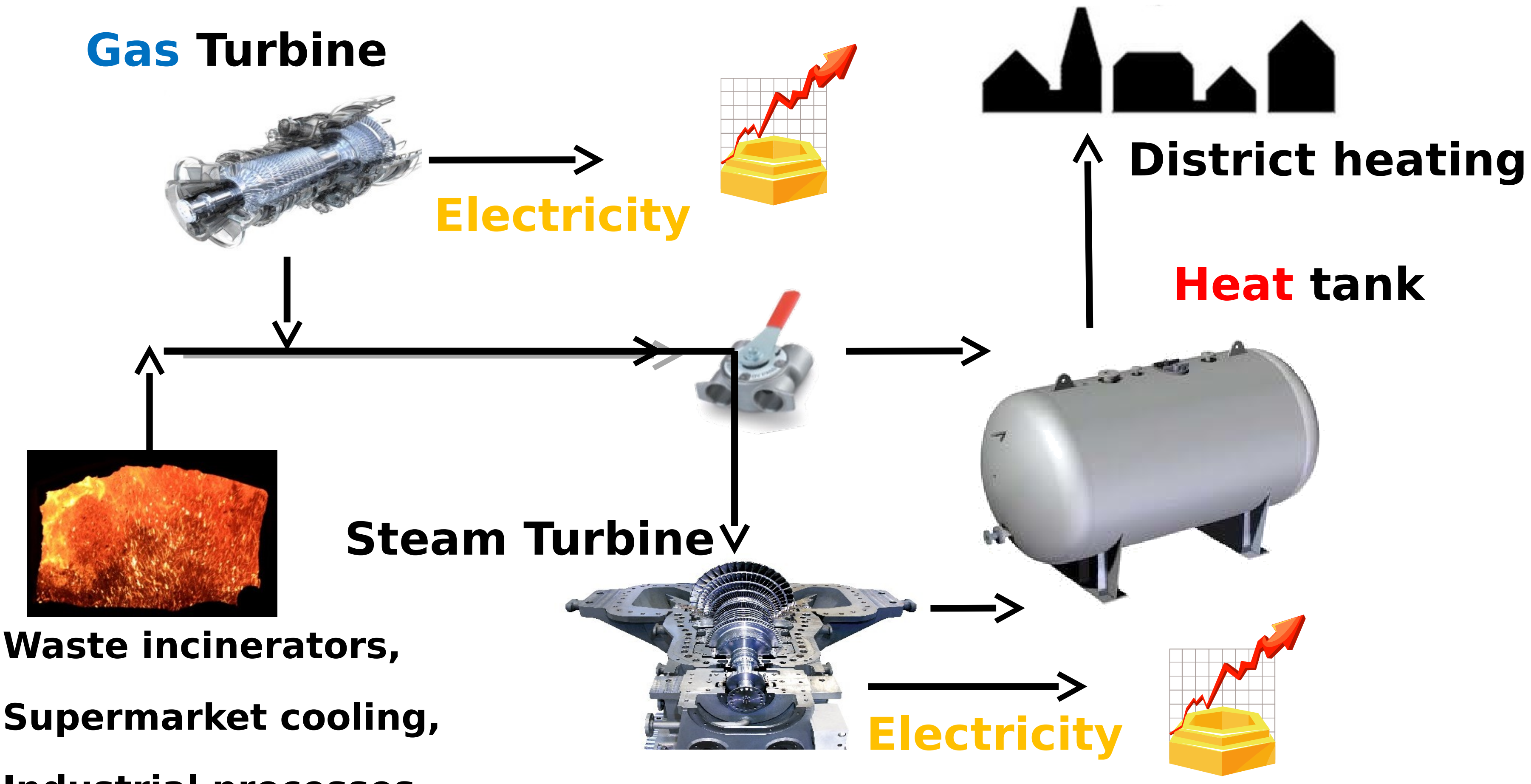
Production heat accumulator

Distribution heat storage in network and accumulator

Displacement of consumption in buildings

CHP and Integrated Energy Systems

(Paradigmatic example - Denmark)



Gas Turbine

Electricity

District heating

Heat tank

Steam Turbine

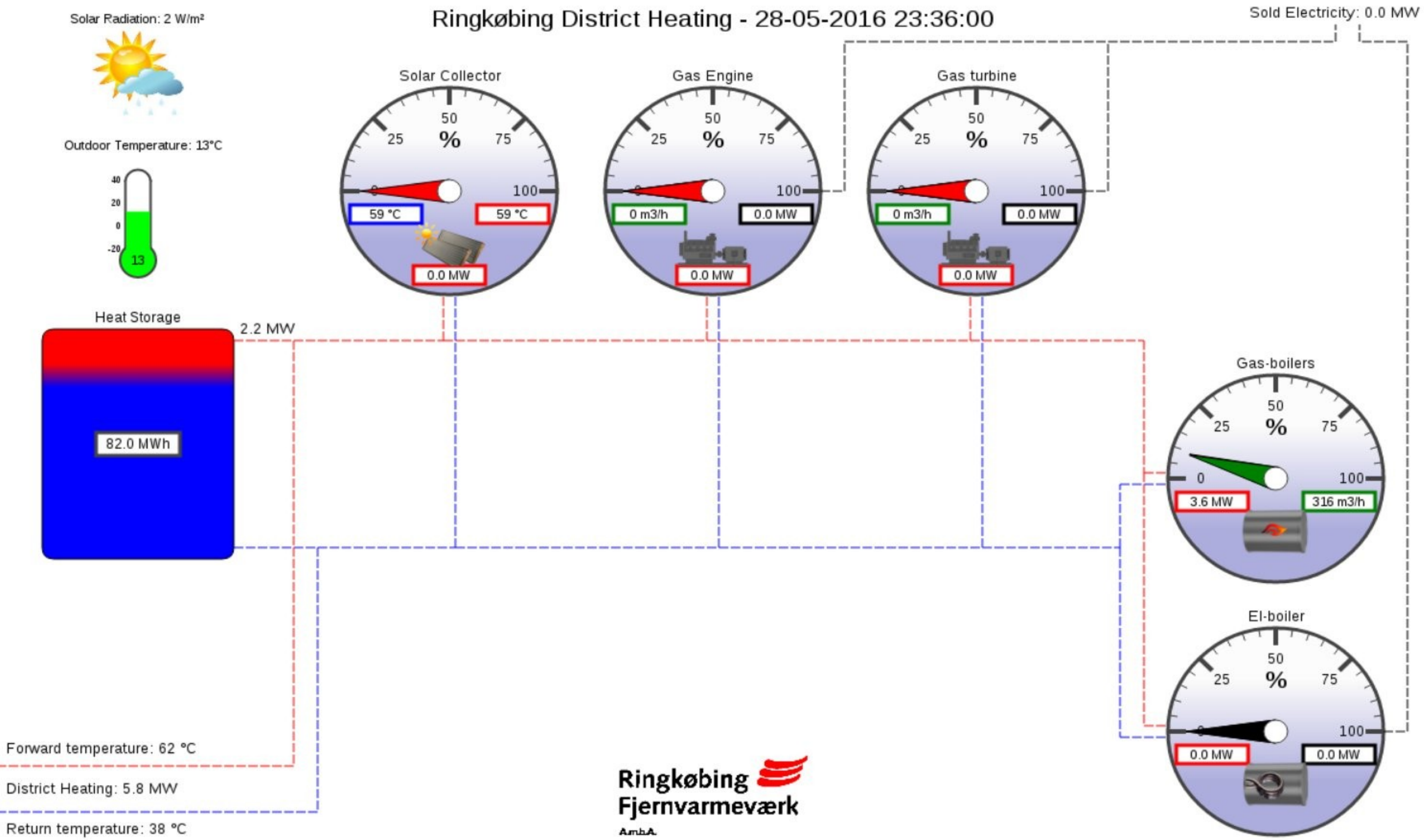
Electricity

Waste incinerators,

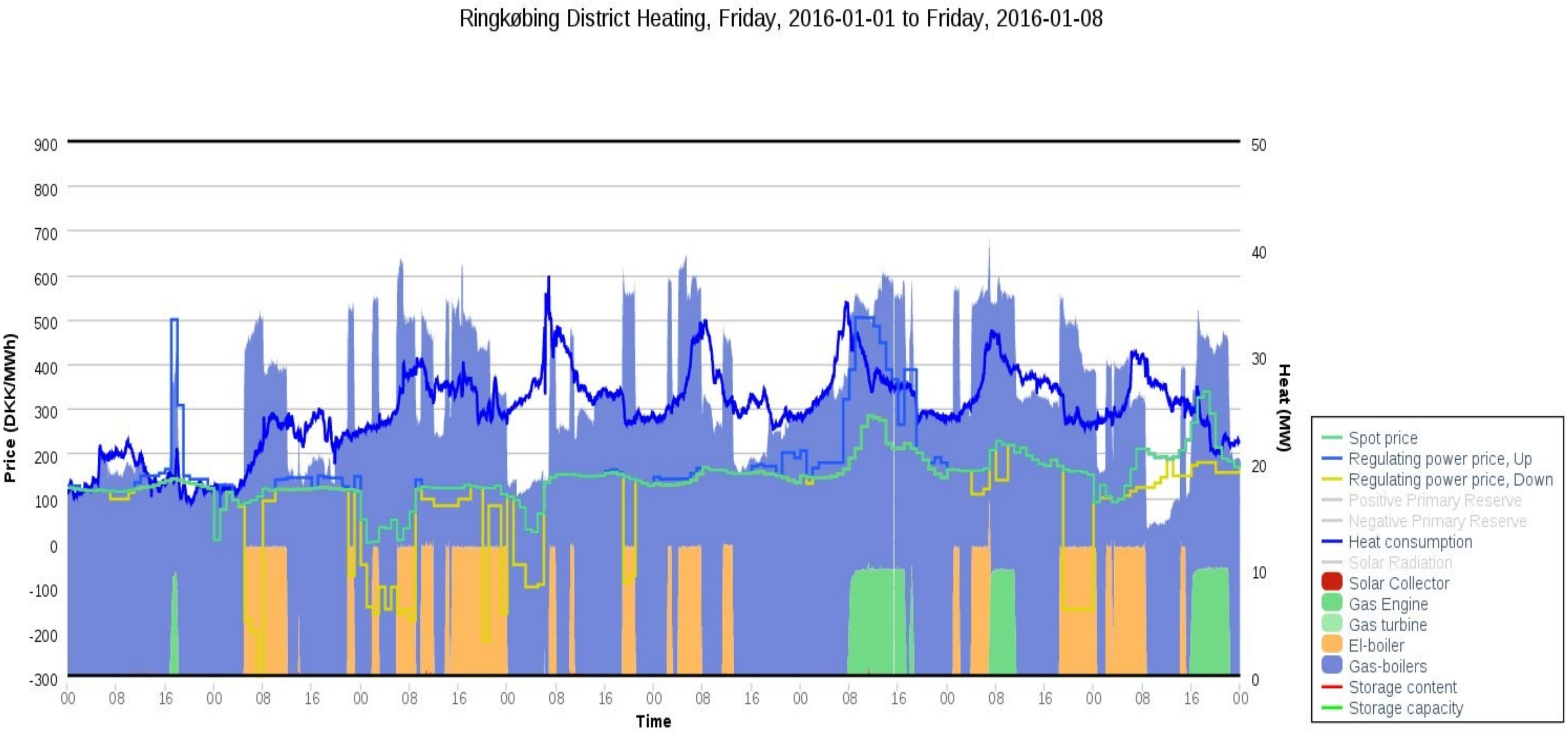
Supermarket cooling,

Industrial processes

Flexibility – Ringkøbing CHP



Flexibility – Ringkøbing CHP


Ringkøbing District Heating, Friday, 2016-01-01 to Friday, 2016-01-08

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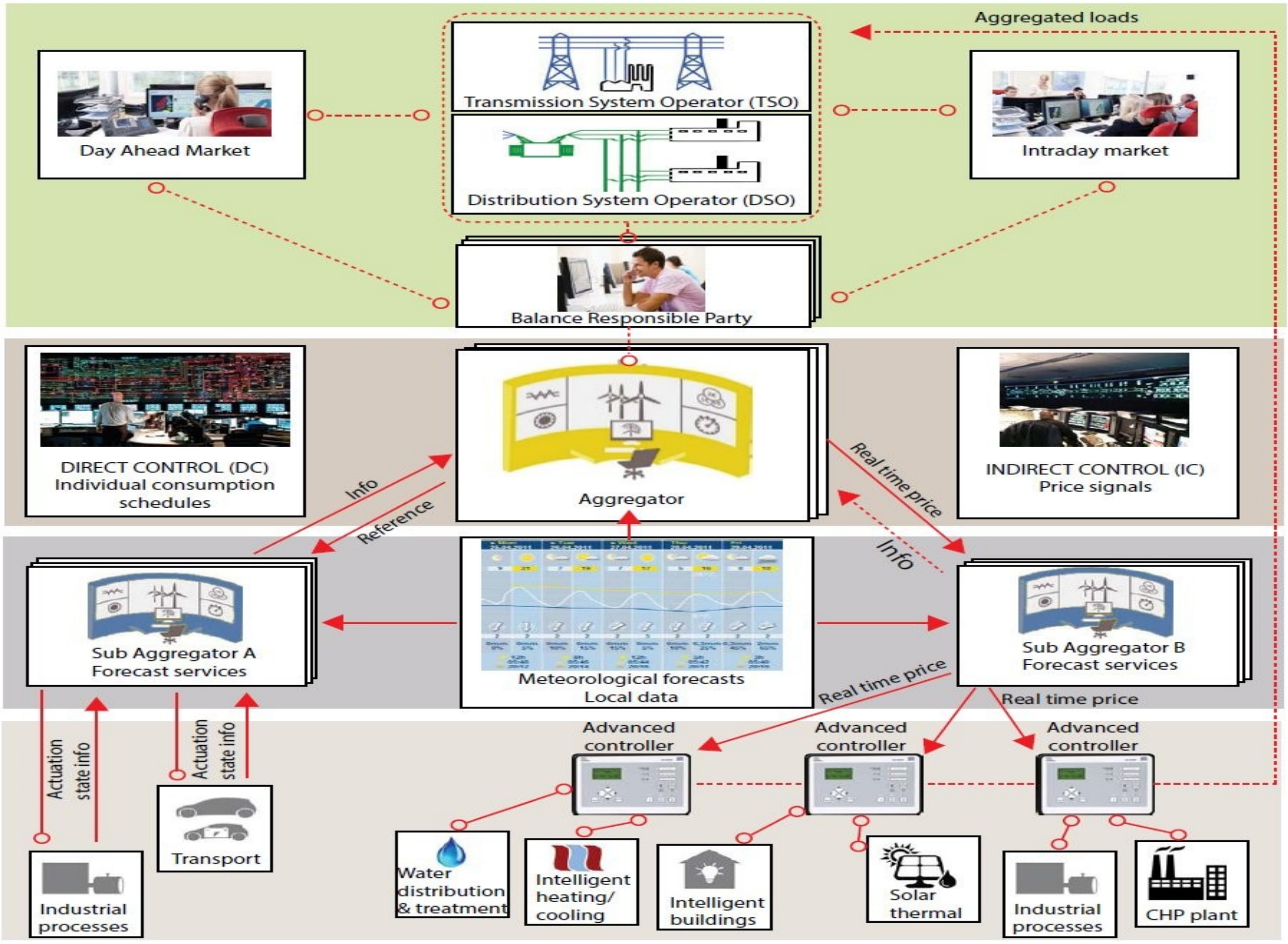
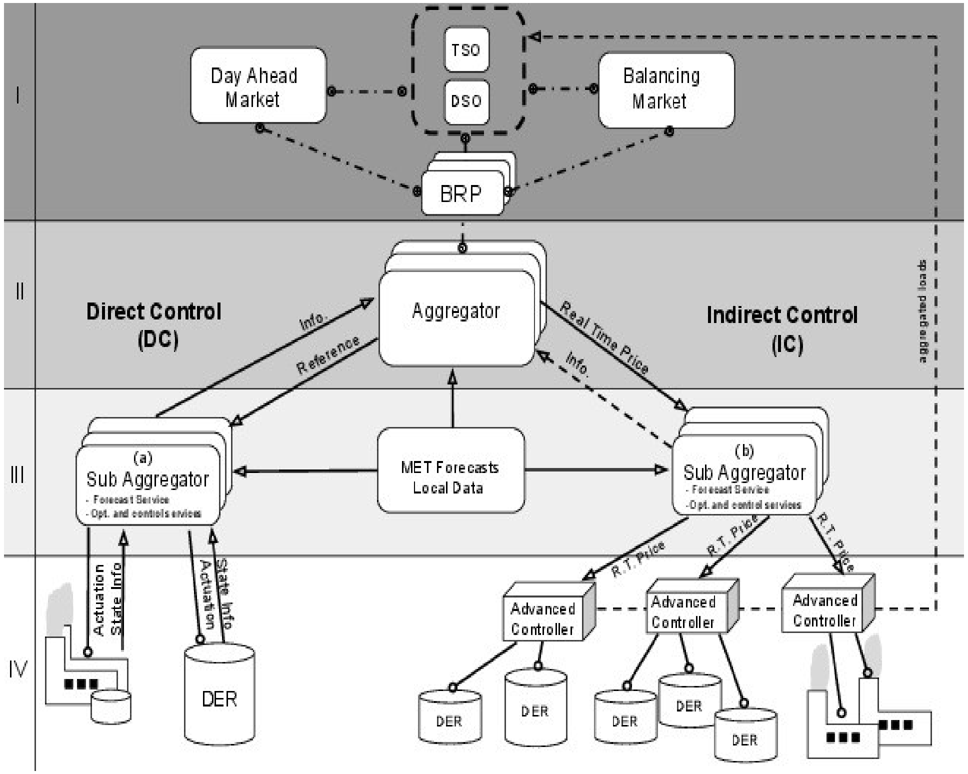
Smart-Energy OS



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:

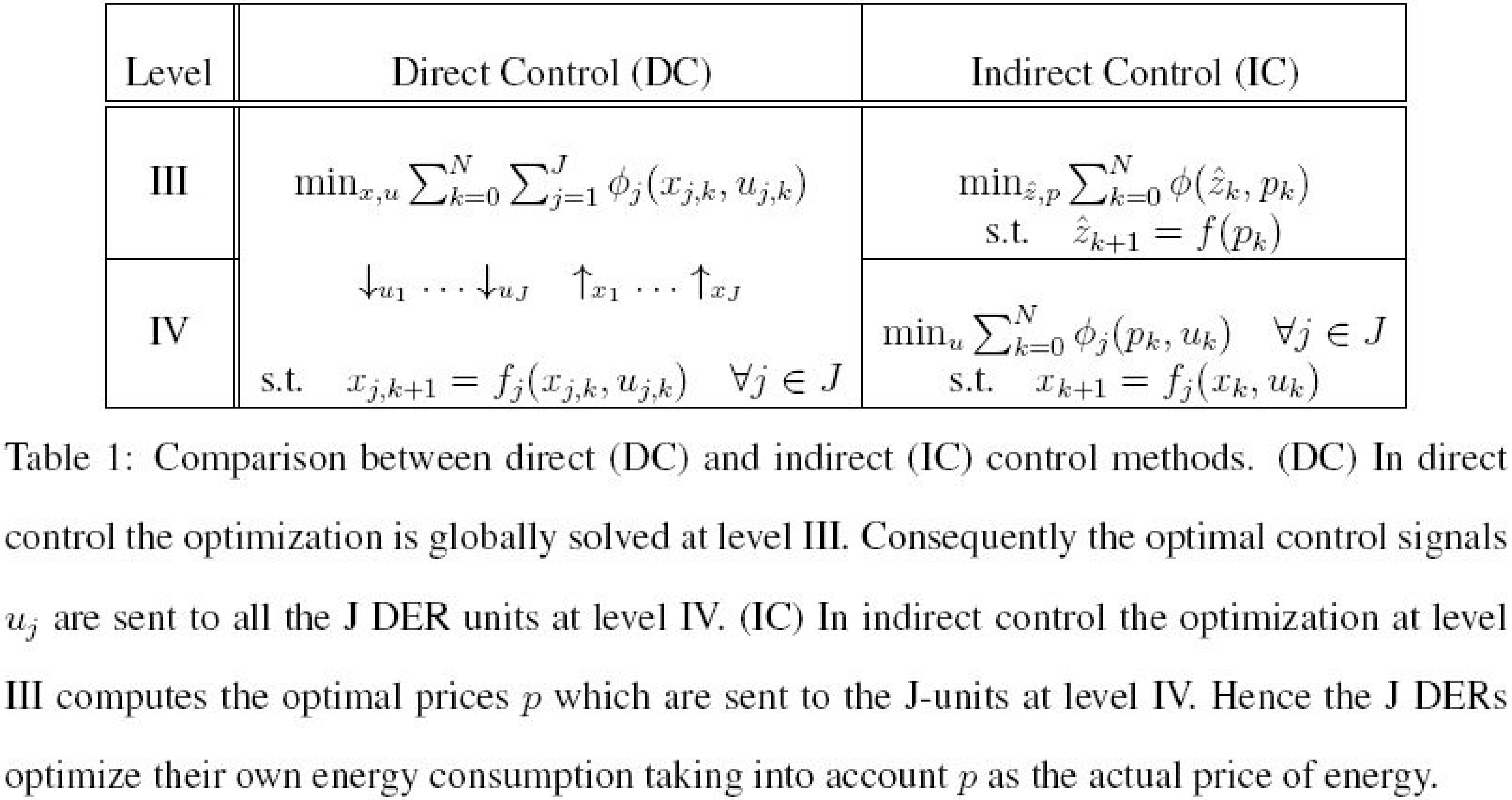
Actuator: **Price**

Cost: E-MPC at **low (DER) level**, One-way communication

Models for DERs are not needed

Simple 'contracts'

Direct vs Indirect Control

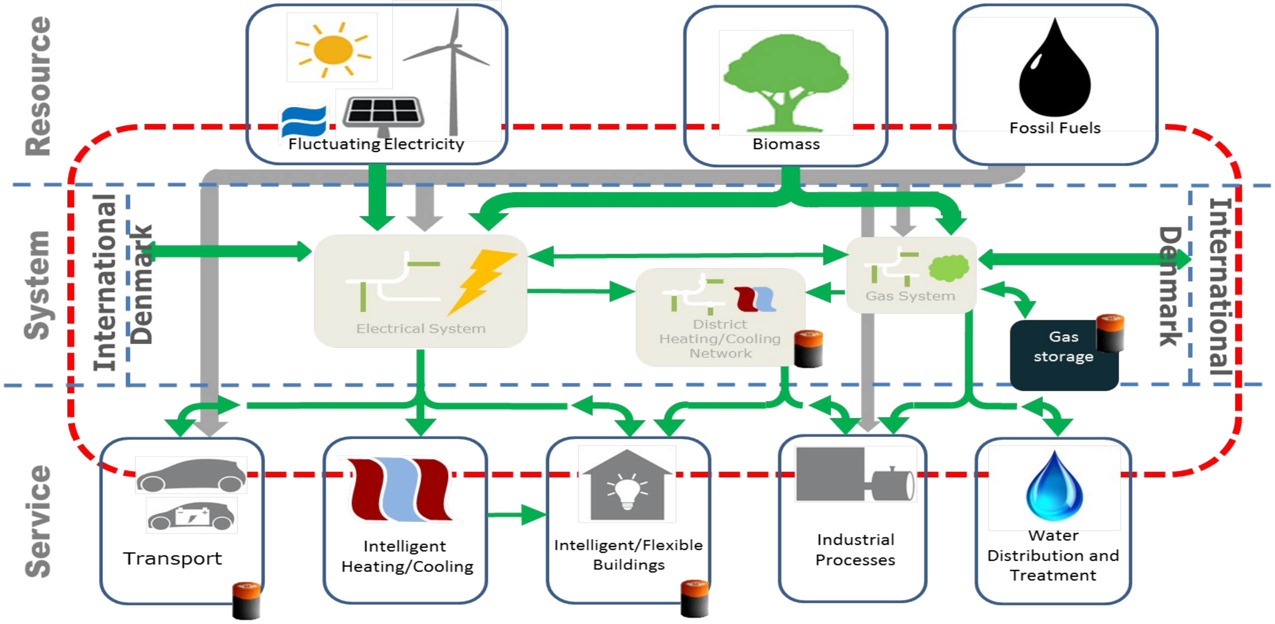


Level	Direct Control (DC)	Indirect Control (IC)
III	$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$ $\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$ s.t. $\quad x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$	$\min_{\hat{z},p} \sum_{k=0}^{N}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

Grey Box Models for Integration

Energy Systems Integration using **data** leading to **stochastic grey box models for operation of future flexible energy systems.**



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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.

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

Case study

Control of Power Consumption (DSM) using the Thermal Mass of Buildings

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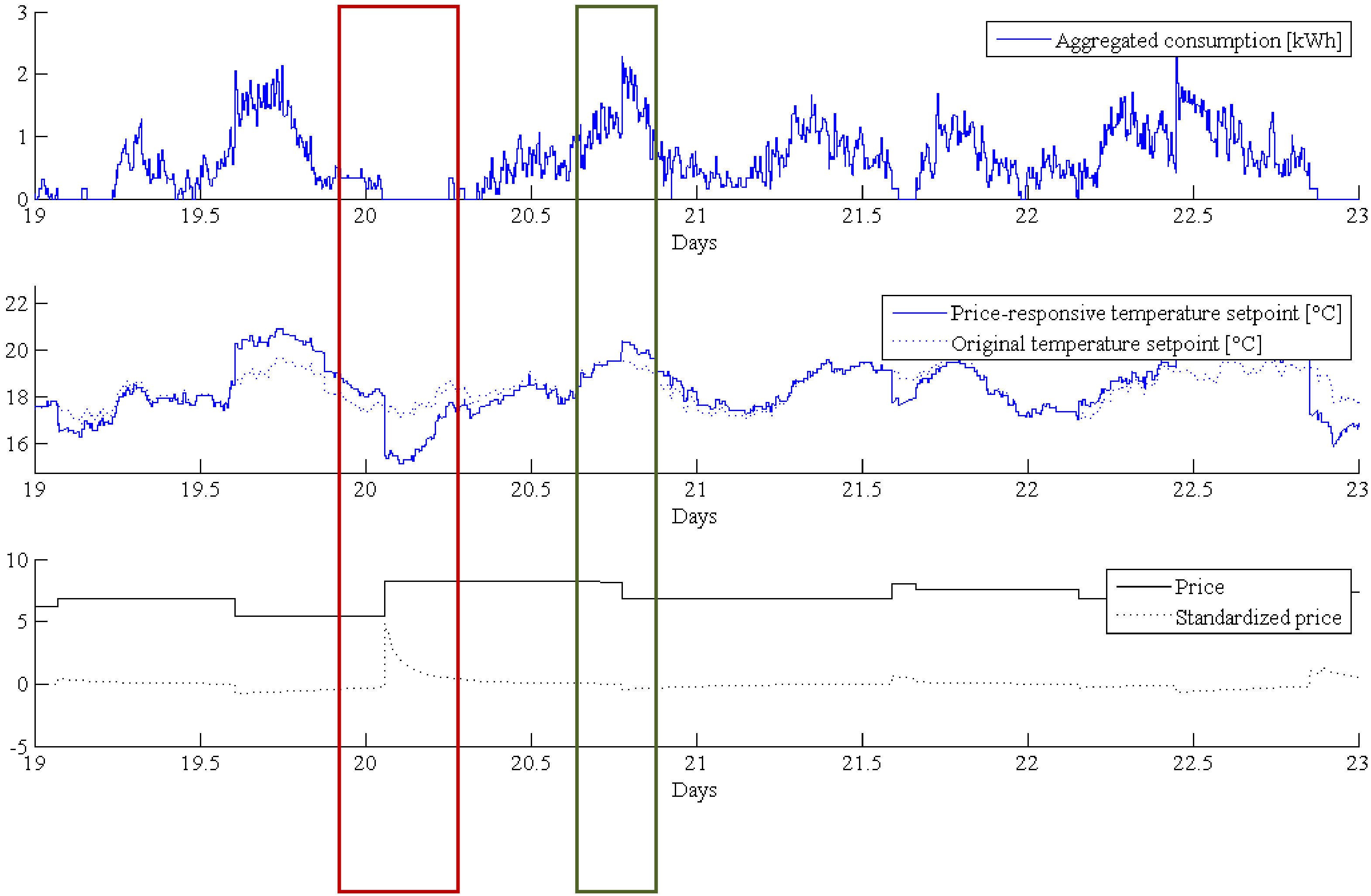
Data from BPA

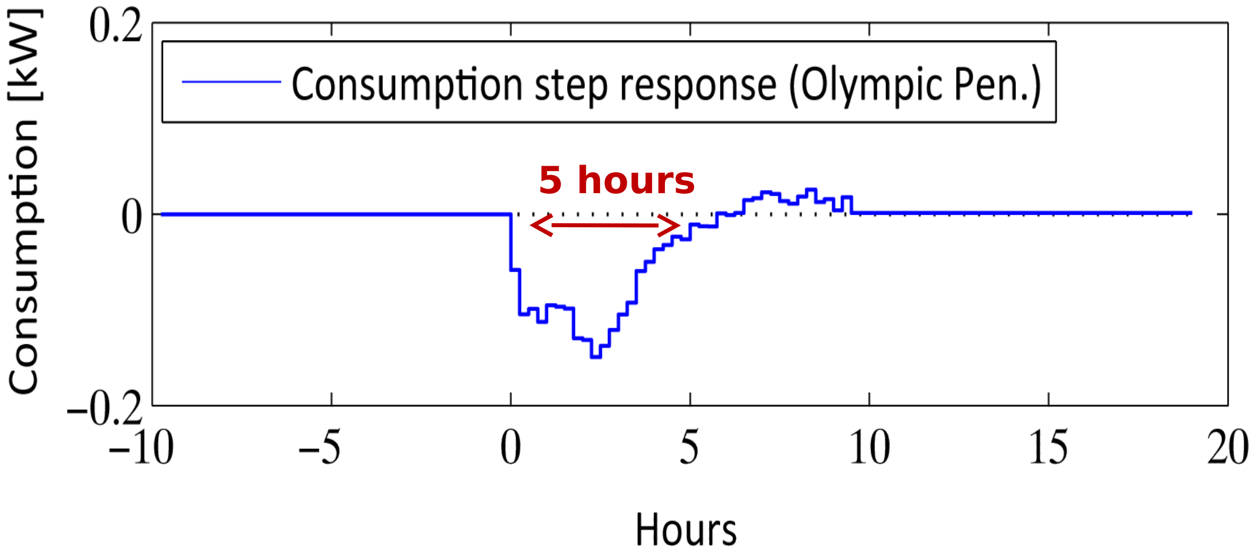
Olympic Pensinsula project

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

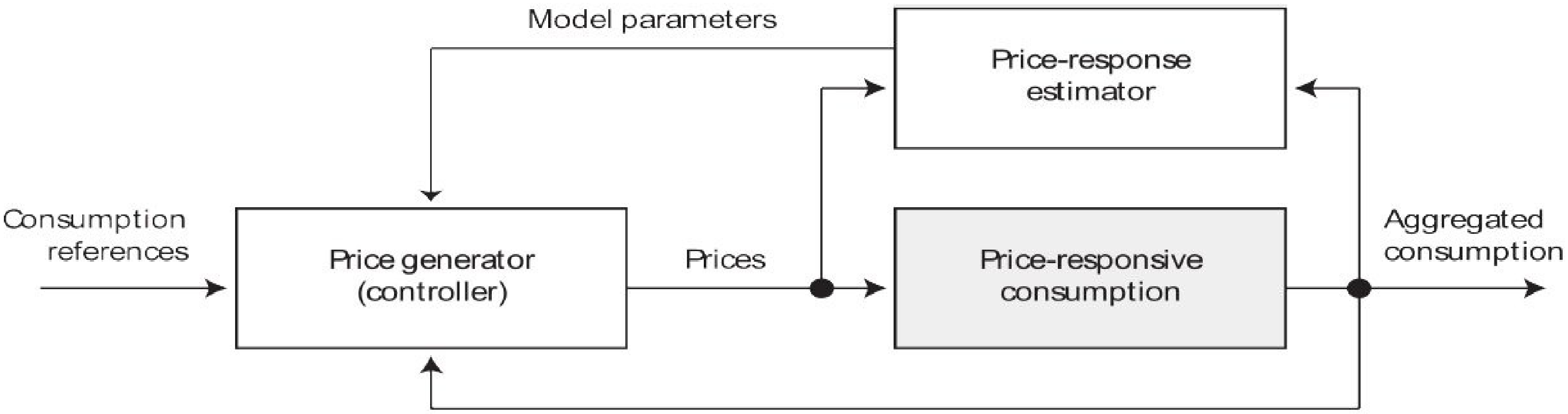
Aggregation (over 20 houses)



Response on Price Step Change



Control of Power Consumption



Model parameters

Price-response estimator

Consumption references

Price generator (controller)

Prices

Price-responsive consumption

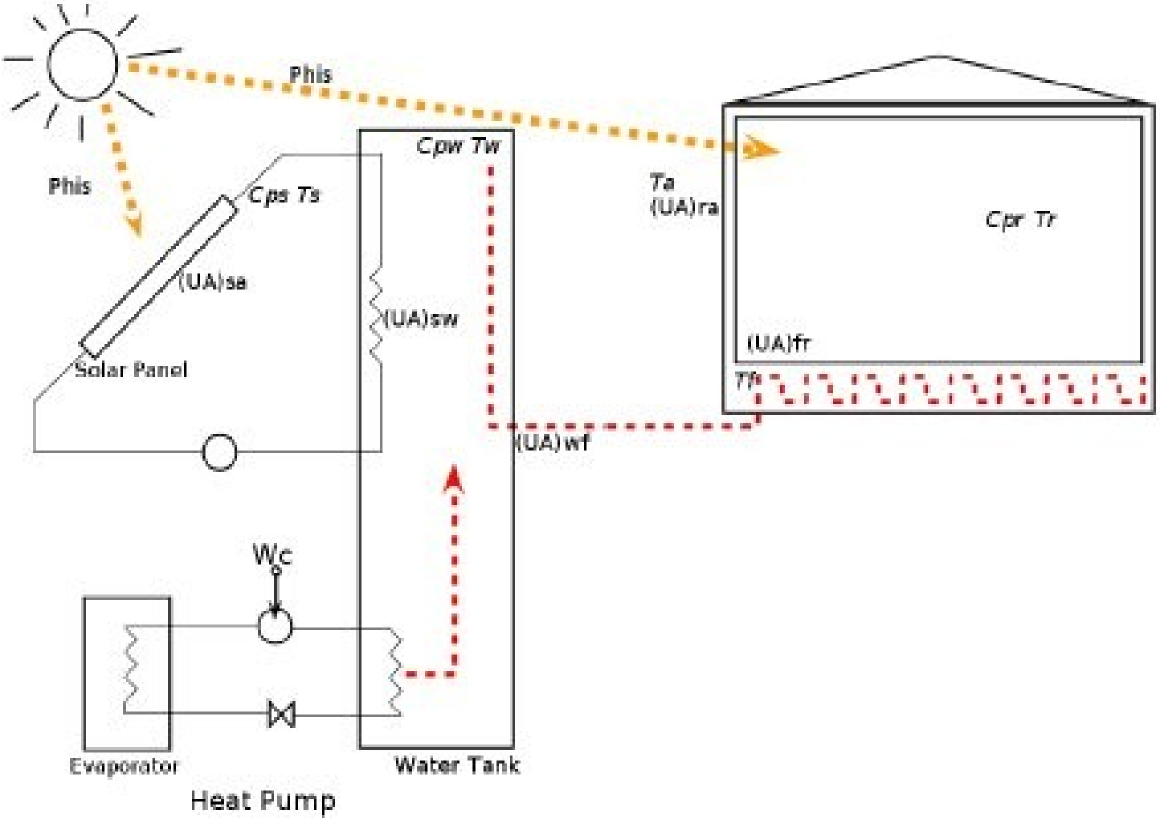
Aggregated consumption

Case study

Heat Pumps and Local Storage

Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

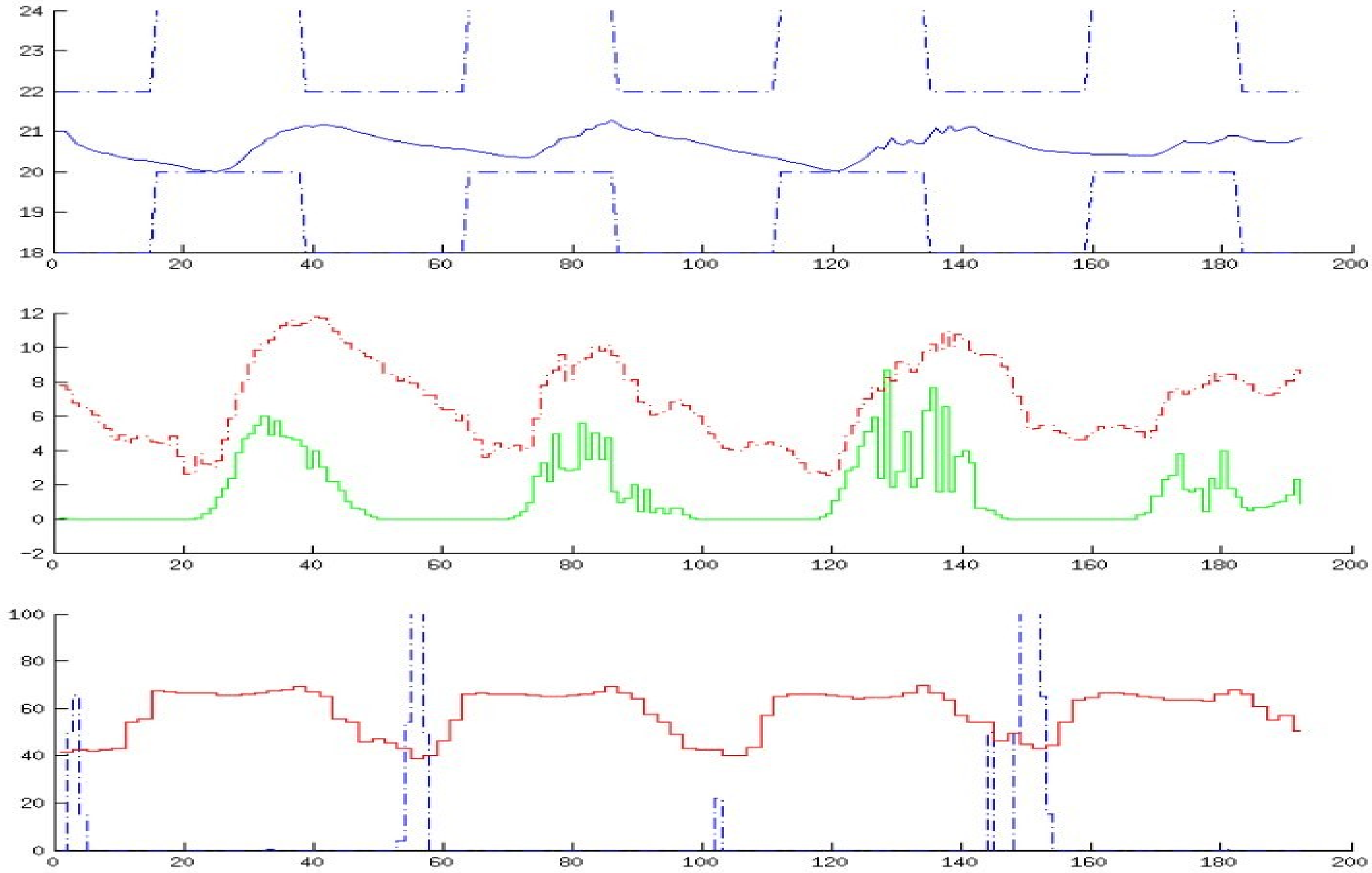
Formulation

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

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

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

Heat pump with thermal solar collector and storage (savings up to 35 pct)



Case study

(Direct Control and Bids for Markets)

Virtual Storage Related to Super Market Cooling using Thermal Demand Response

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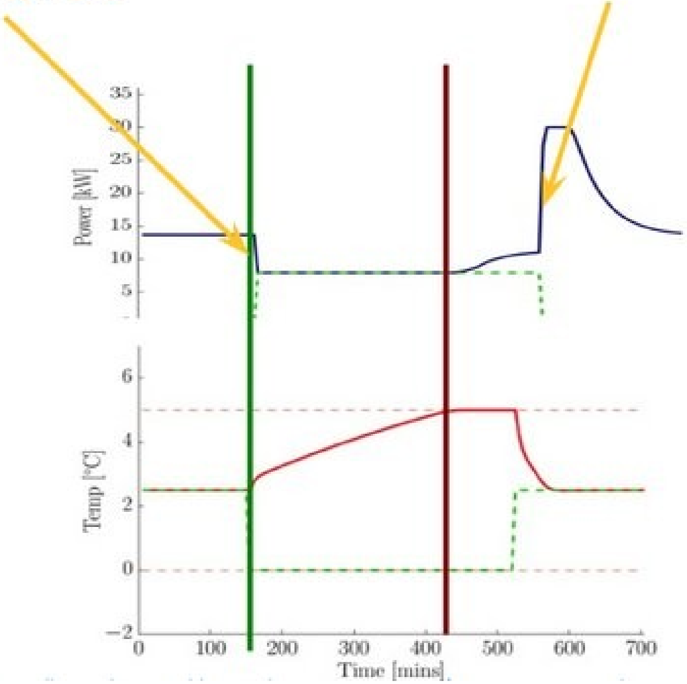
Synergize: Virtual Storage using Thermal Demand Response

Thermal mass in refrigeration display cases facilitates the adjustment of power consumption while maintaining acceptable temperatures for food.



6kW of DR

Recovery period

The physical system

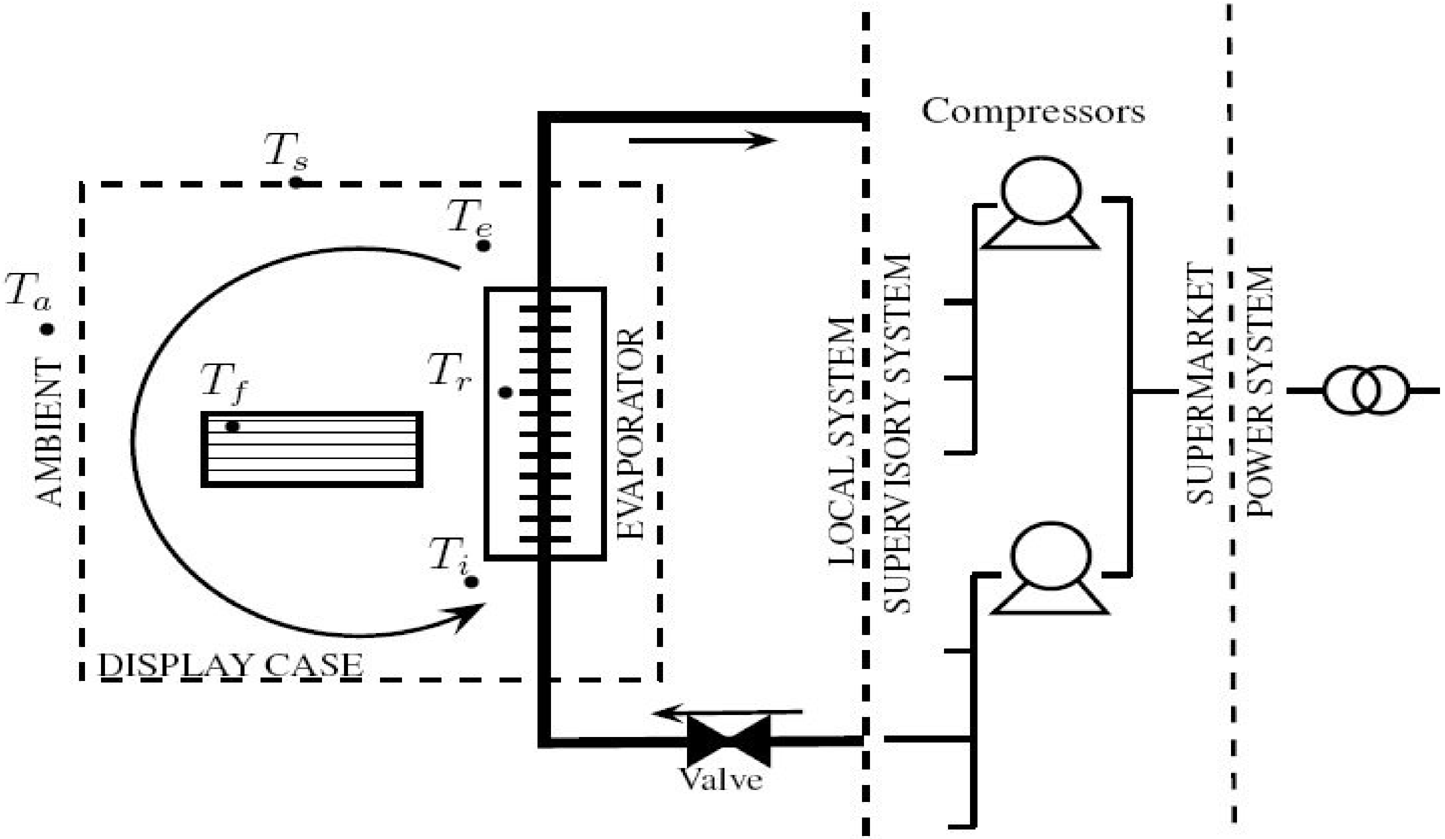


Fig. 2: Simplified graphical representation of the display case system

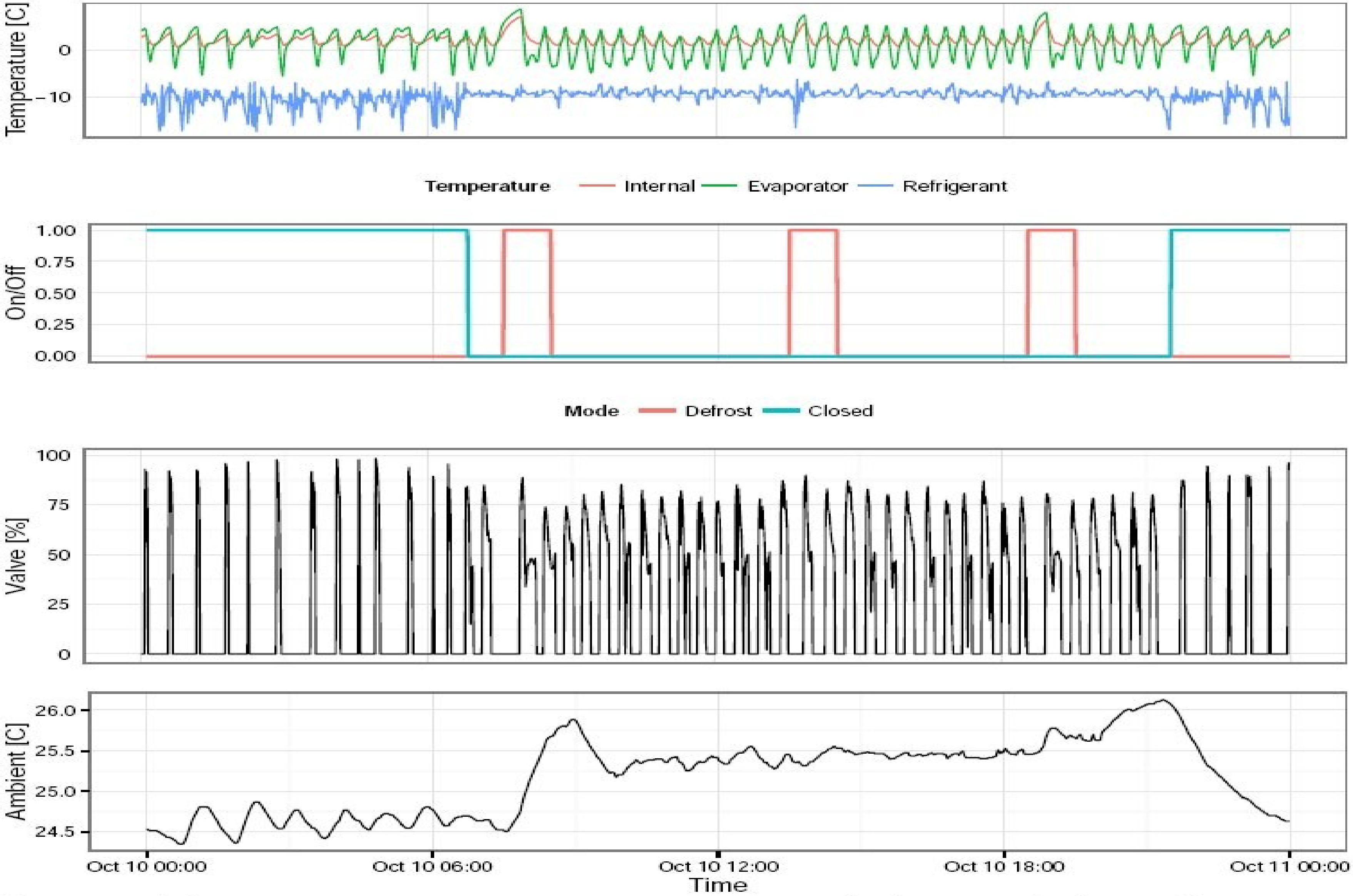


Fig. 3: Temperature, environmental (open/closed status, defrost status, ambient temperature) and control input (valve) data for an open medium temperature display case in a supermarket in Funen, Denmark

The grey-box model

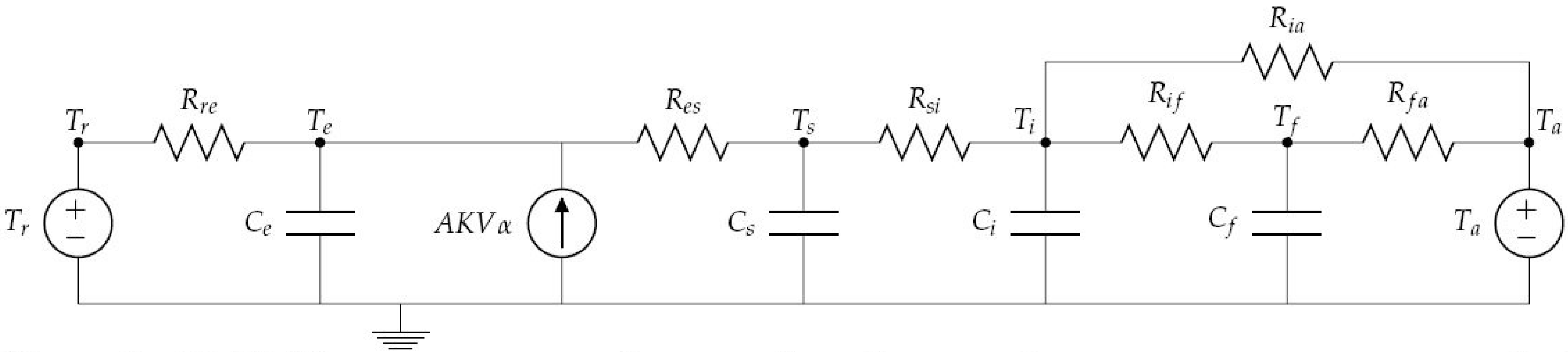
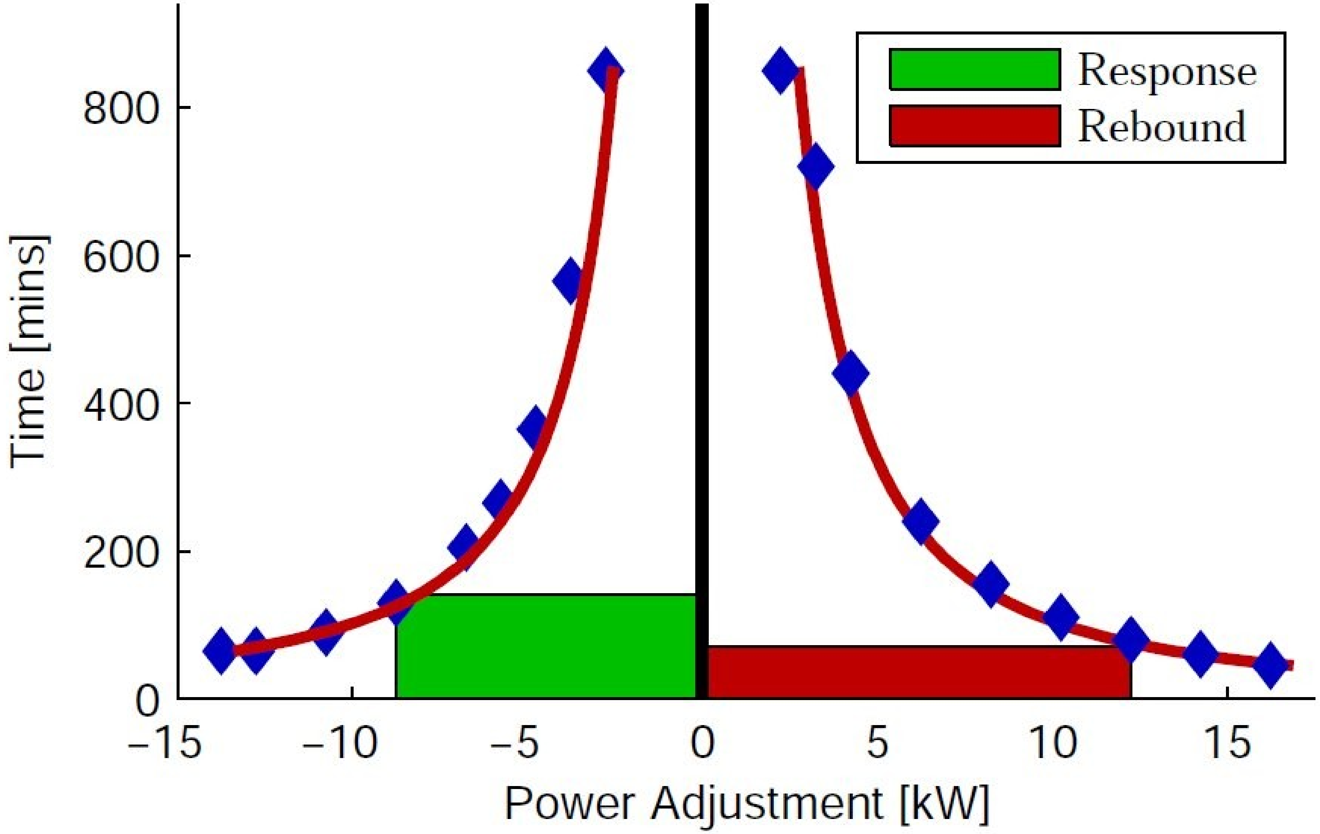


Fig. 6: RC-Representation of a four time constant model ($T_iT_eT_fT_s$)

Flexibility Represented by Saturation Curves

(for market integration using block bids)



Case study

Use of Heat from Supermarket Cooling in DH Systems

Using Heat from Supermarket Cooling in the District Heating System

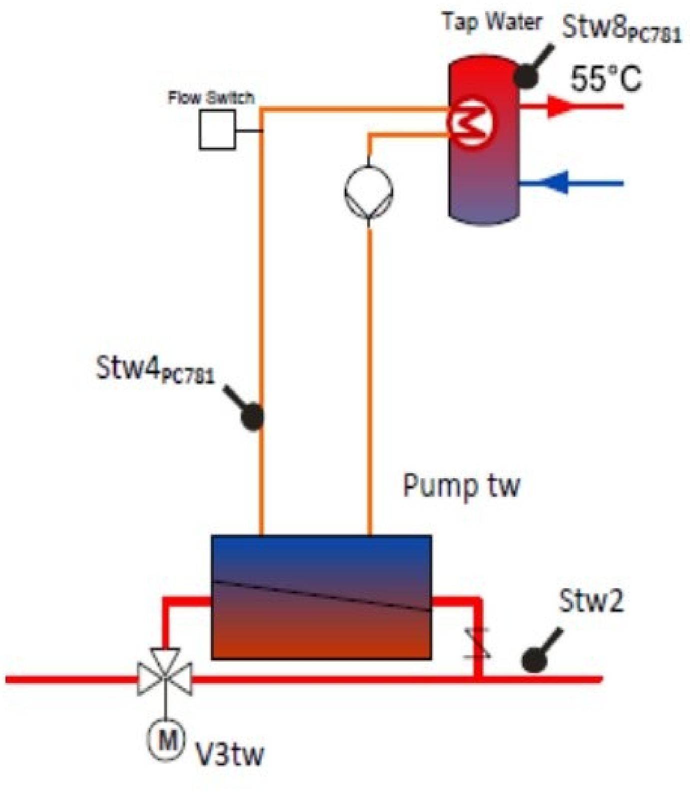
SuperBrugsen in Høruphav

- Area: 1000 m^2 from 2010
- Compressors: 5 MT (1 VS), 4 LT
- Cooling Capacity: 160 kW

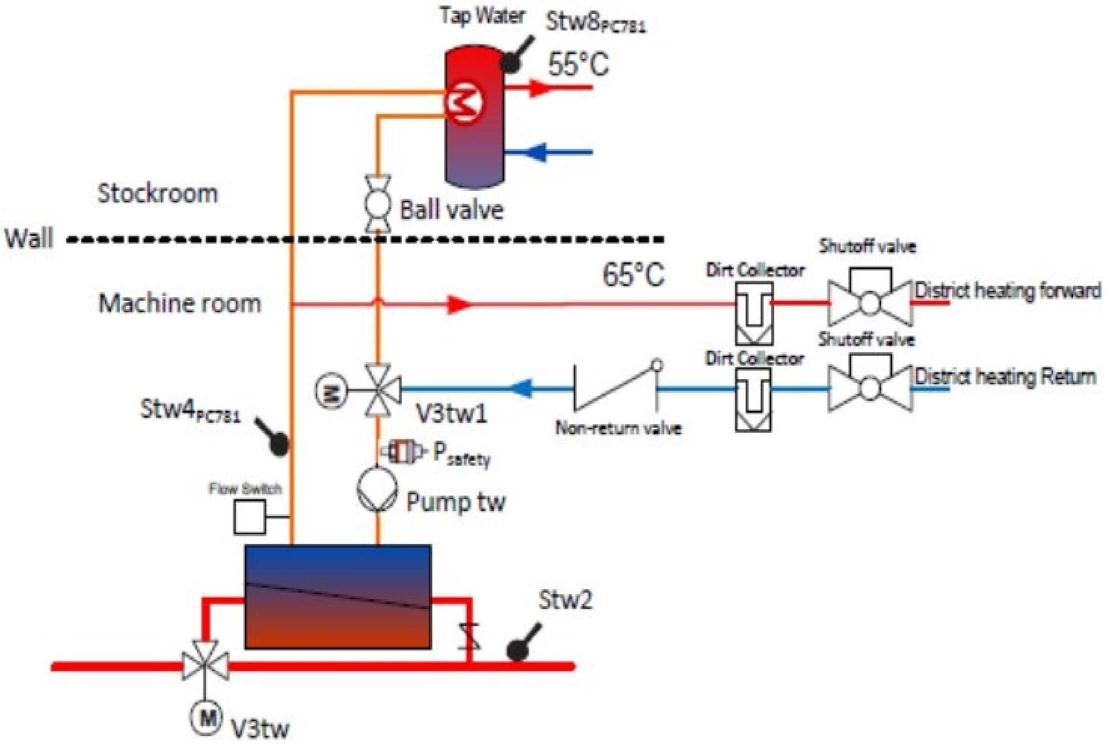
- Heating :
  - Sanitary water (1800 l tank (65 ^{o}C)
  - Floor heating/low temp coils (35 ^{o}C)
  - District heating production

Using Heat from Supermarket Cooling in the District Heating System

Old setup



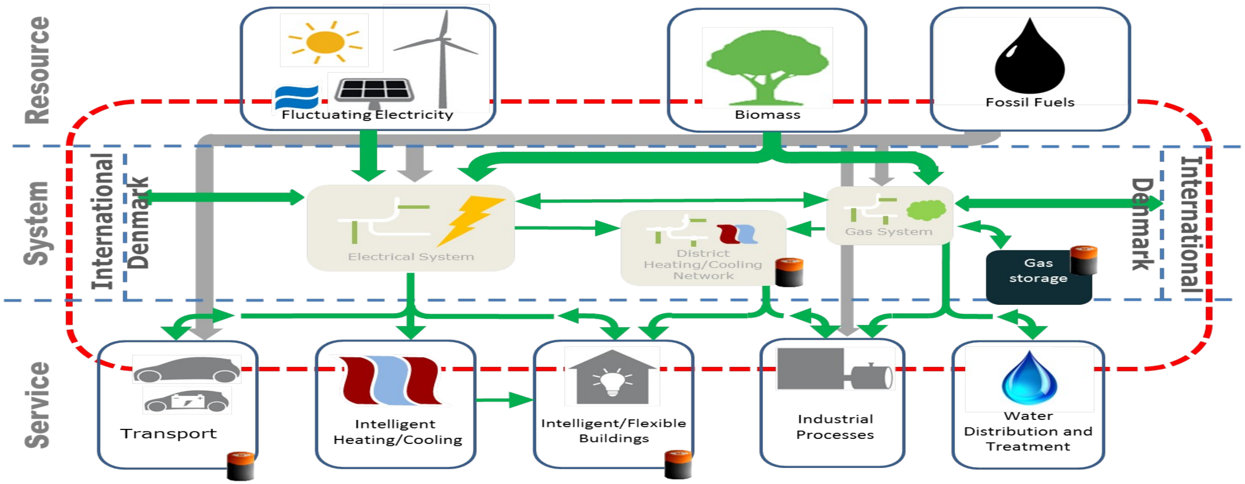
New setup



Using Heat from Supermarket Cooling in the District Heating System

- SuperBrugsen gets paid for energy they would have otherwise have paid for to get removed
- Corresponds to the total consumption of 15-20 households
- Payback time for SuperBrugsen is 1-2 years
- Payback time for DH system is 3-4 years
- This is a small supermarket. Business case even better for large supermarkets

Virtual Storage or Flexibility Characteristics

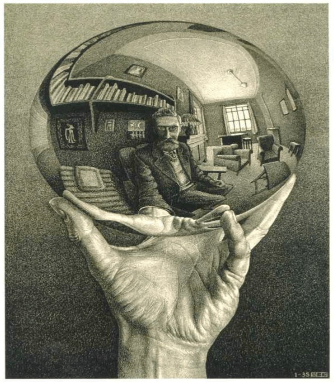


- **Flexibility (or virtual storage) characteristics:**
  - Supermarket refrigeration can provide storage 0.5-2 hours ahead
  - Buildings thermal capacity can provide storage up to, say, 5-10 hours ahead
  - Buildings with local water storage can provide storage up to, say, 2-12 hours ahead
  - District heating/cooling systems can provide storage up to 1-3 days ahead
  - Gas systems can provide seasonal storage

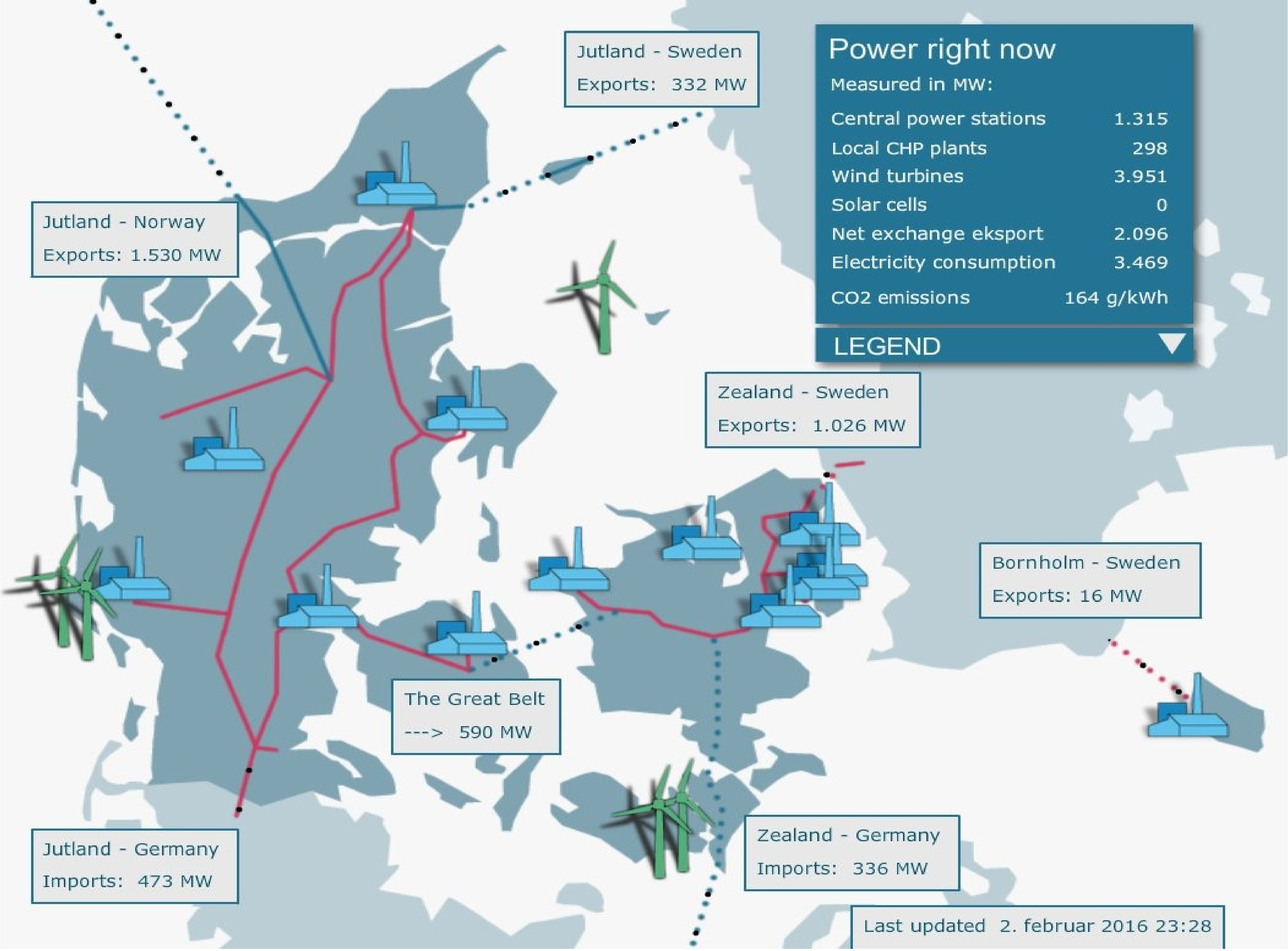
Discussion

- Intelligent Energy Systems Integration can provide virtual storage solutions (so maybe we should put less focus on physical storage solutions)
- District heating (or cooling) systems can provide flexibility on the essential time scale (up to a few days)
- Gas systems can provide seasonal virtual storage solutions.
- We see a large potential in Demand Response. Automatic solutions, price based control, and end-user focus are important
- We see large problems with the tax and tariff structures in many countries (eg Denmark). Coupling to prices for carbon capture could be advantageous.
- Markets and pricing principles need to be reconsidered; we see an advantage of having a physical link to the mechanism (eg. nodal pricing, capacity markets)

Energy Flexibility
Some Demo Projects in CITIES



- Control of WWTP (ED, Krüger, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Summerhouses (DC, SE, Energinet.dk, ..)
- Green Houses (NeoGrid, Danfoss, F.Fyn, ...)
- CHP (Dong Energy, FjernvarmeFyn, HOFOR, NEAS, ...)
- Industrial production (DI, ...)
- VE (charging) (Eurisco, ED, ...)
- ....



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

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