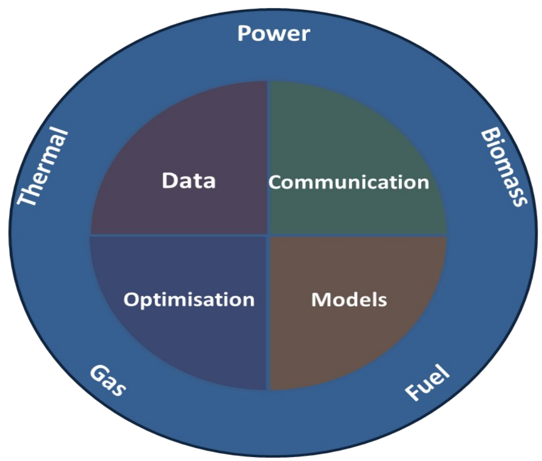
The role of ICT based methods in enabling thermal energy systems flexibility in Denmark



Henrik Madsen, DTU Compute

http://www.henrikmadsen.org

http://www.smart-cities-centre.org

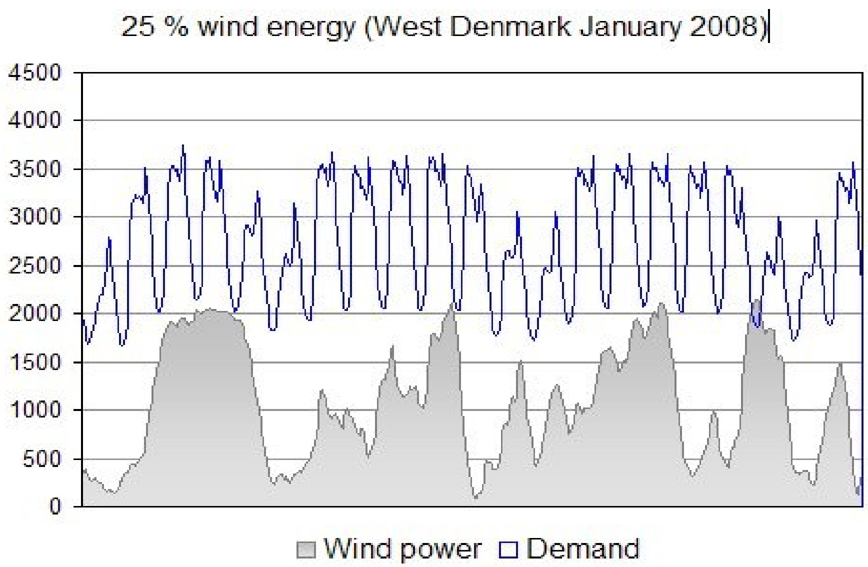
Danish Climate and Energy Policy / Goals

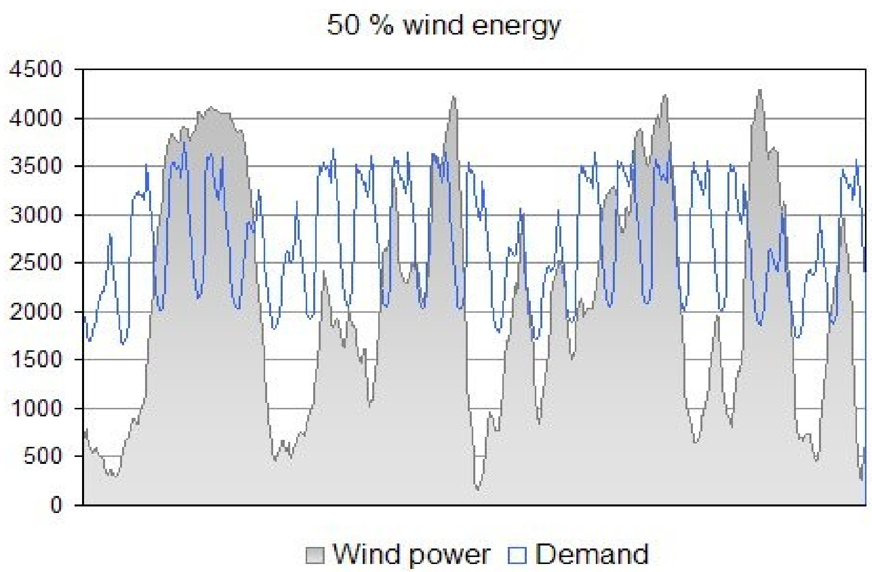
- 2020: 50 pct of electricity from wind power, and 35 pct of total energy consumption from renewable sources
- 2035: 100 pct of electricity and heating from renewable sources
- 2050: 100 pct of all (electricity, heating, transport, industry) from renewable sources

Wind Power and District Heating play an important role in our plans for future intelligent and integrated energy systems

The Danish Wind Power Case

.... balancing of the power system



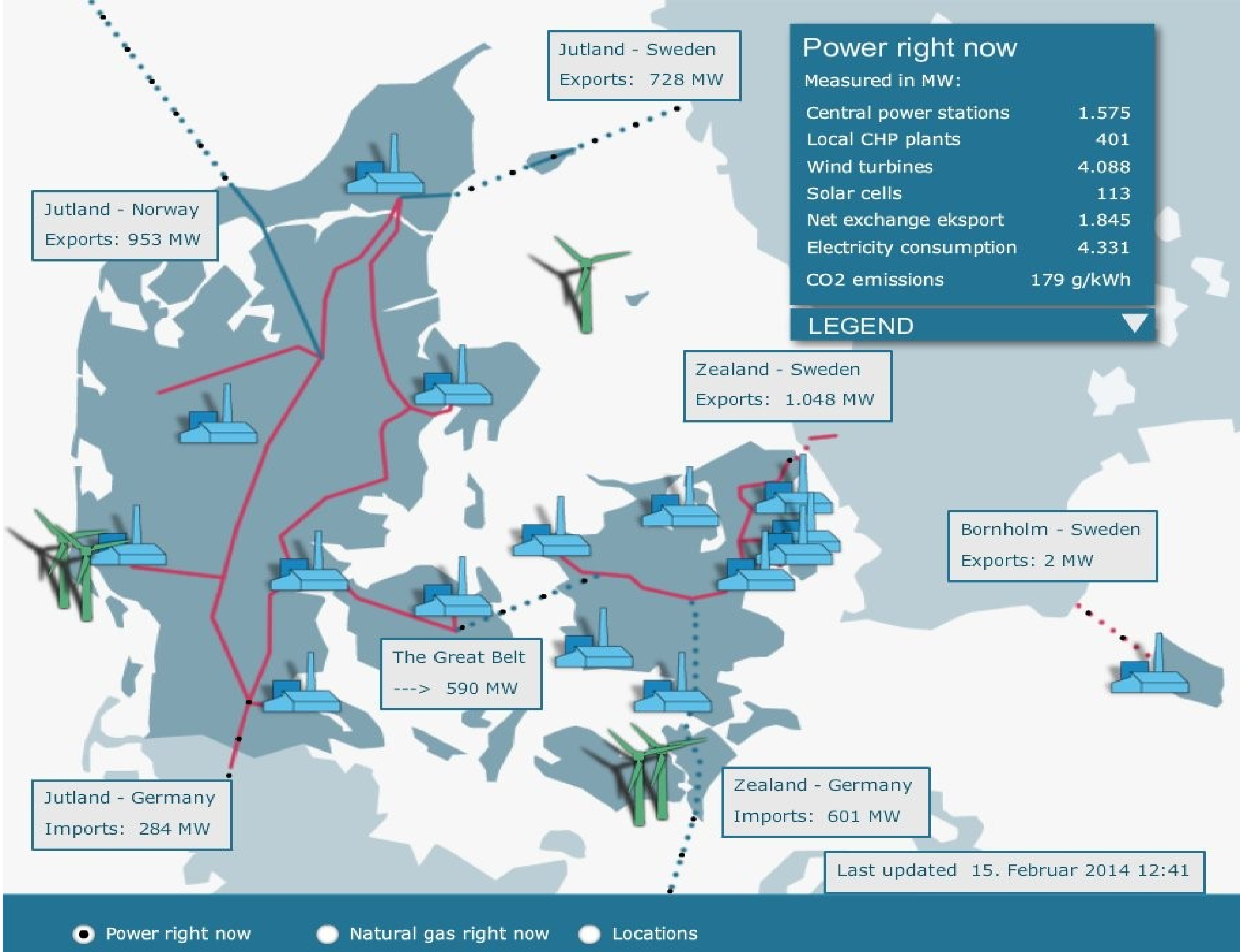


In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

In 2014 more than 40 pct of electricity load was covered by wind power.

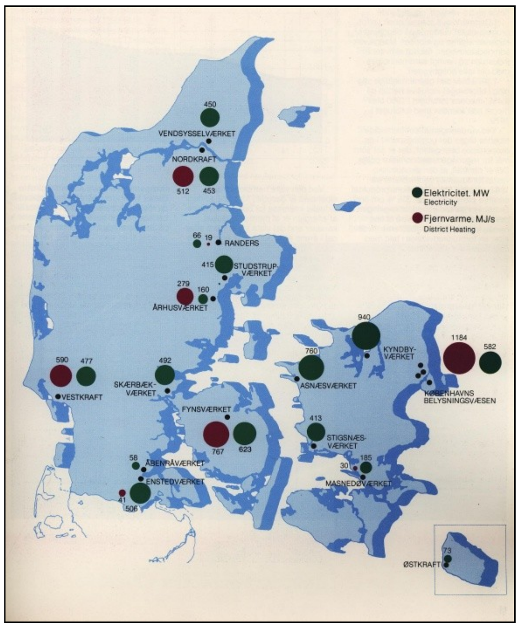
For several days in 2014 the wind power production was more than 120 pct of the power load.

July 10th, 2015 more than 140 pct of the power load was covered by wind power


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

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

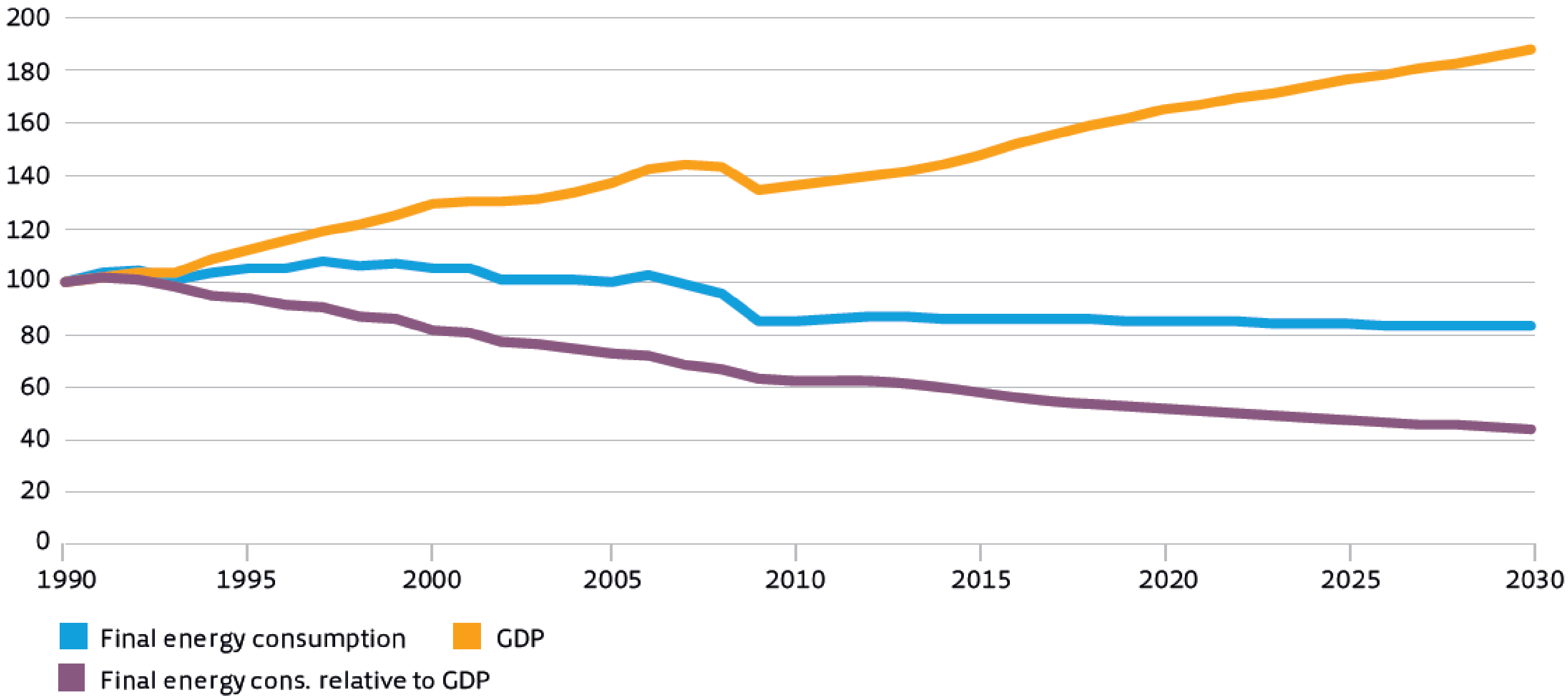
1980



Today

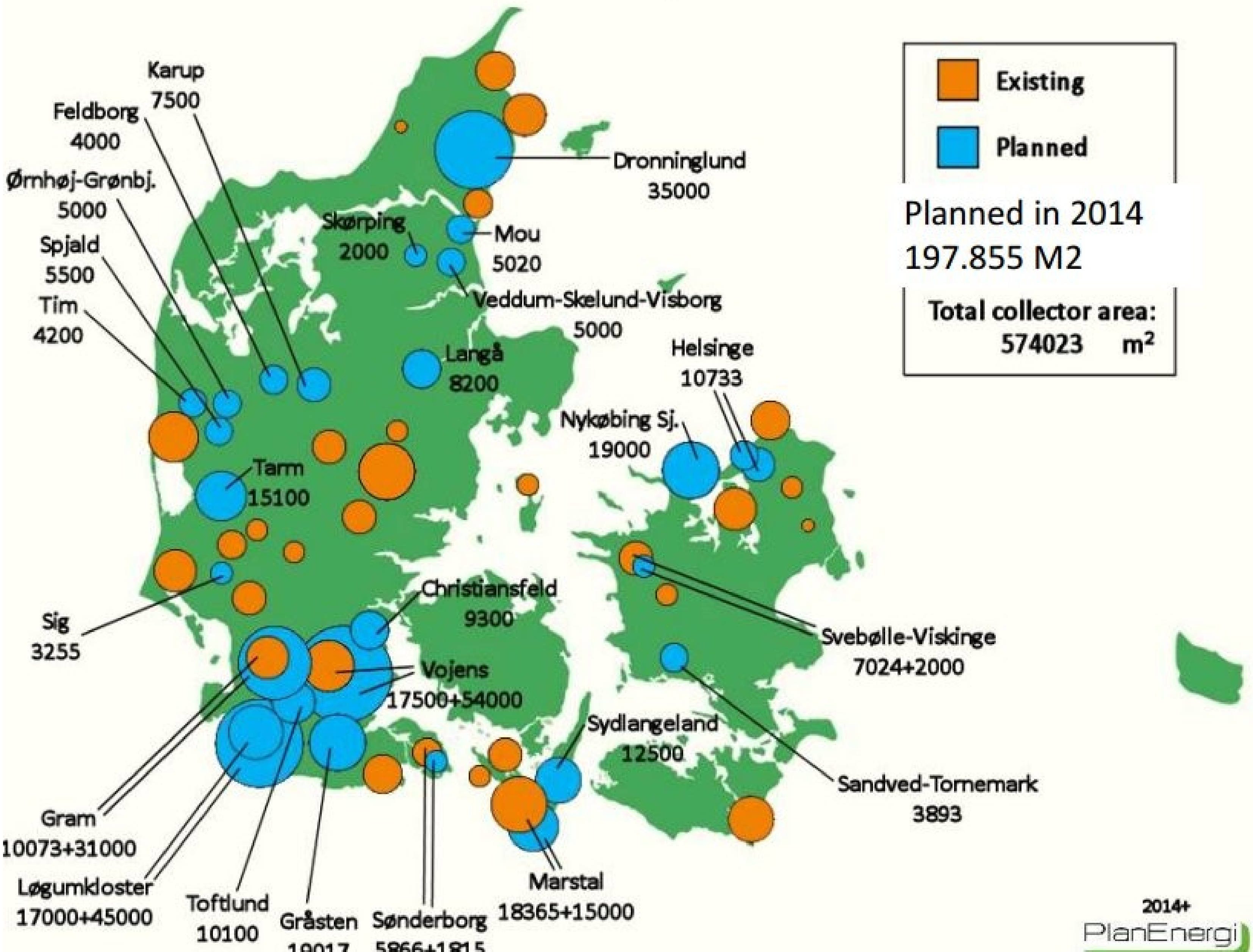
From a few big power plants to many small ***combined heat and power*** *plants – however most of them based on coal*

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

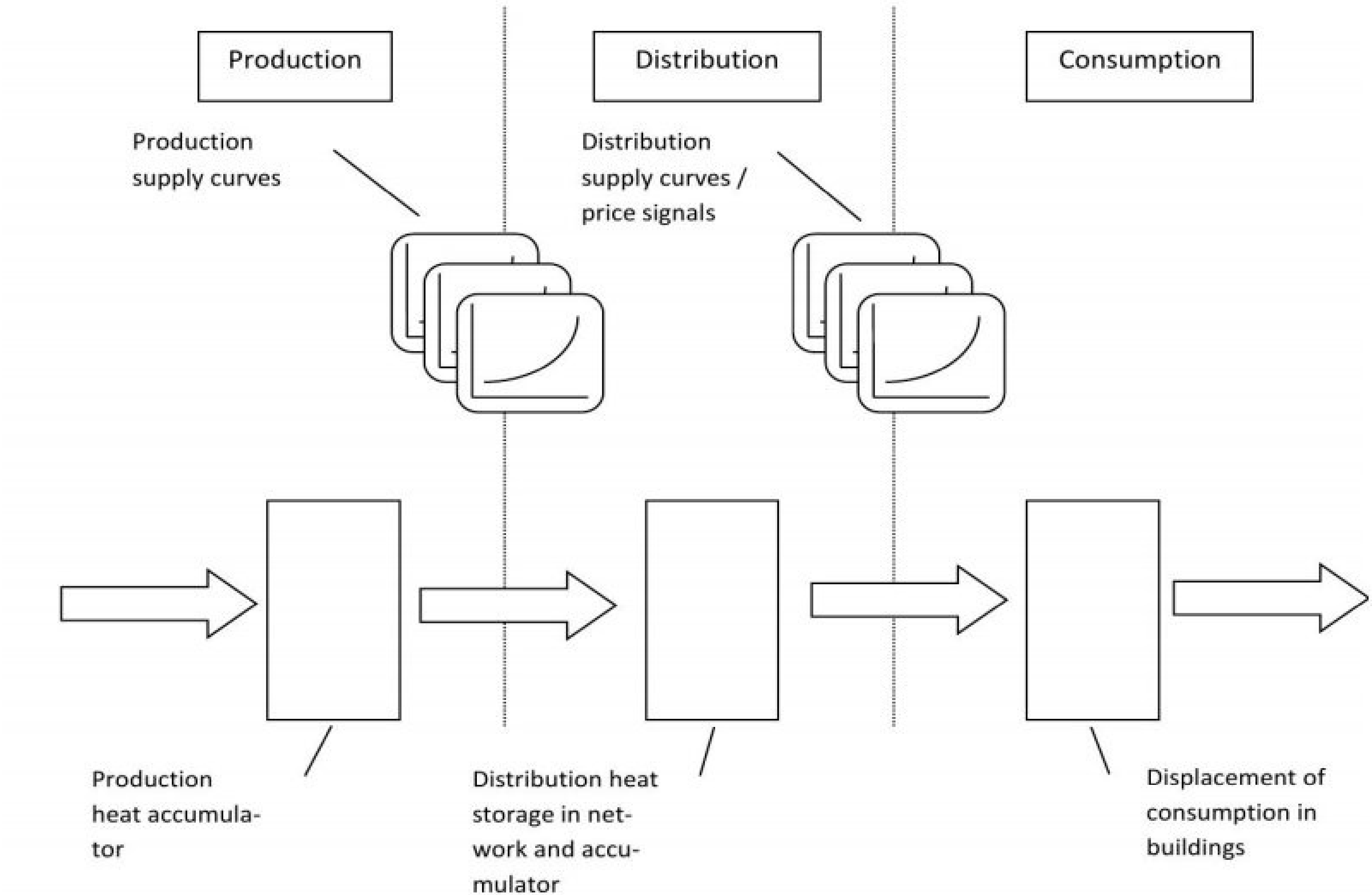


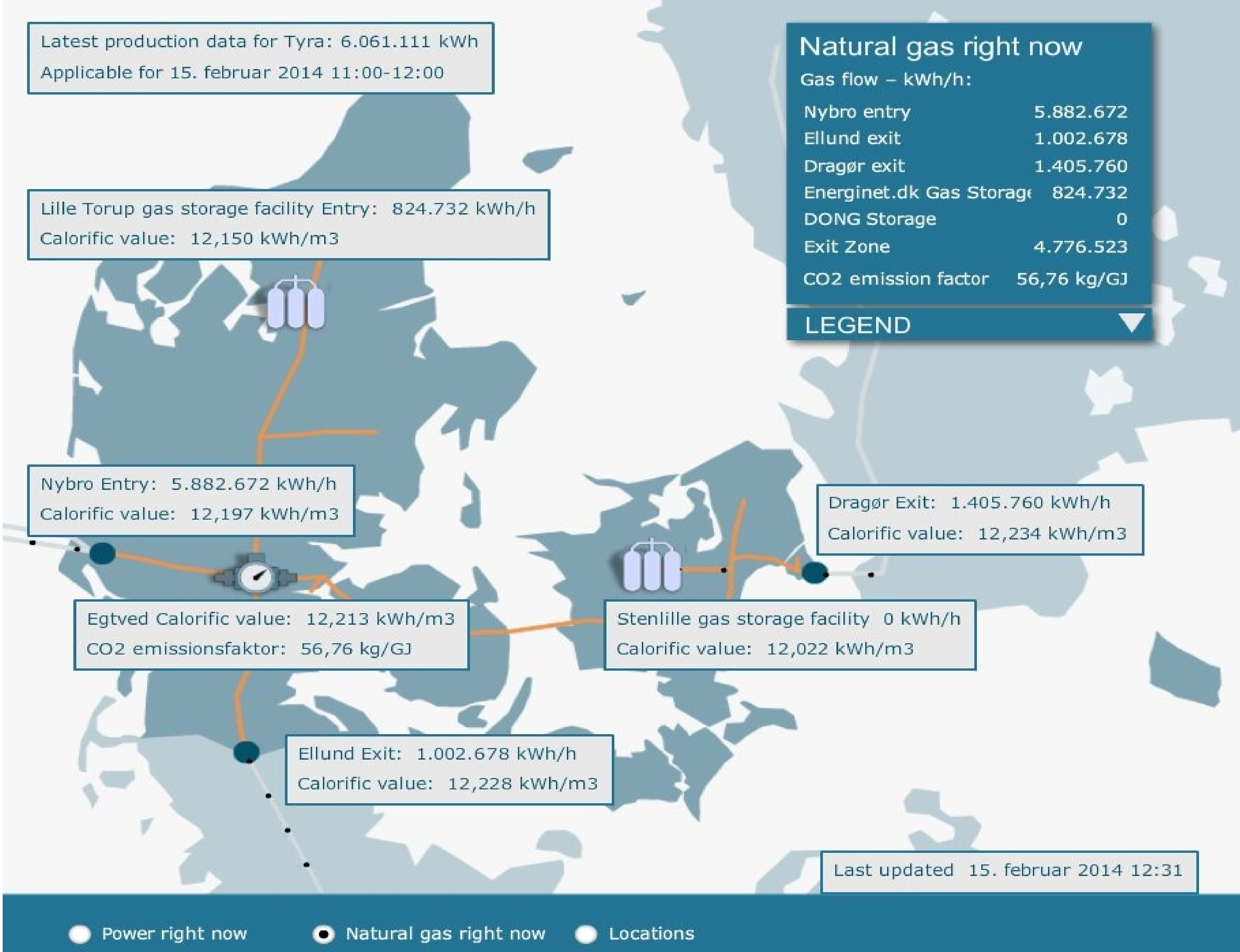
Source: Energy Policy in Denmark. Danish Energy Agency. December 2012

Solar district heating in Denmark

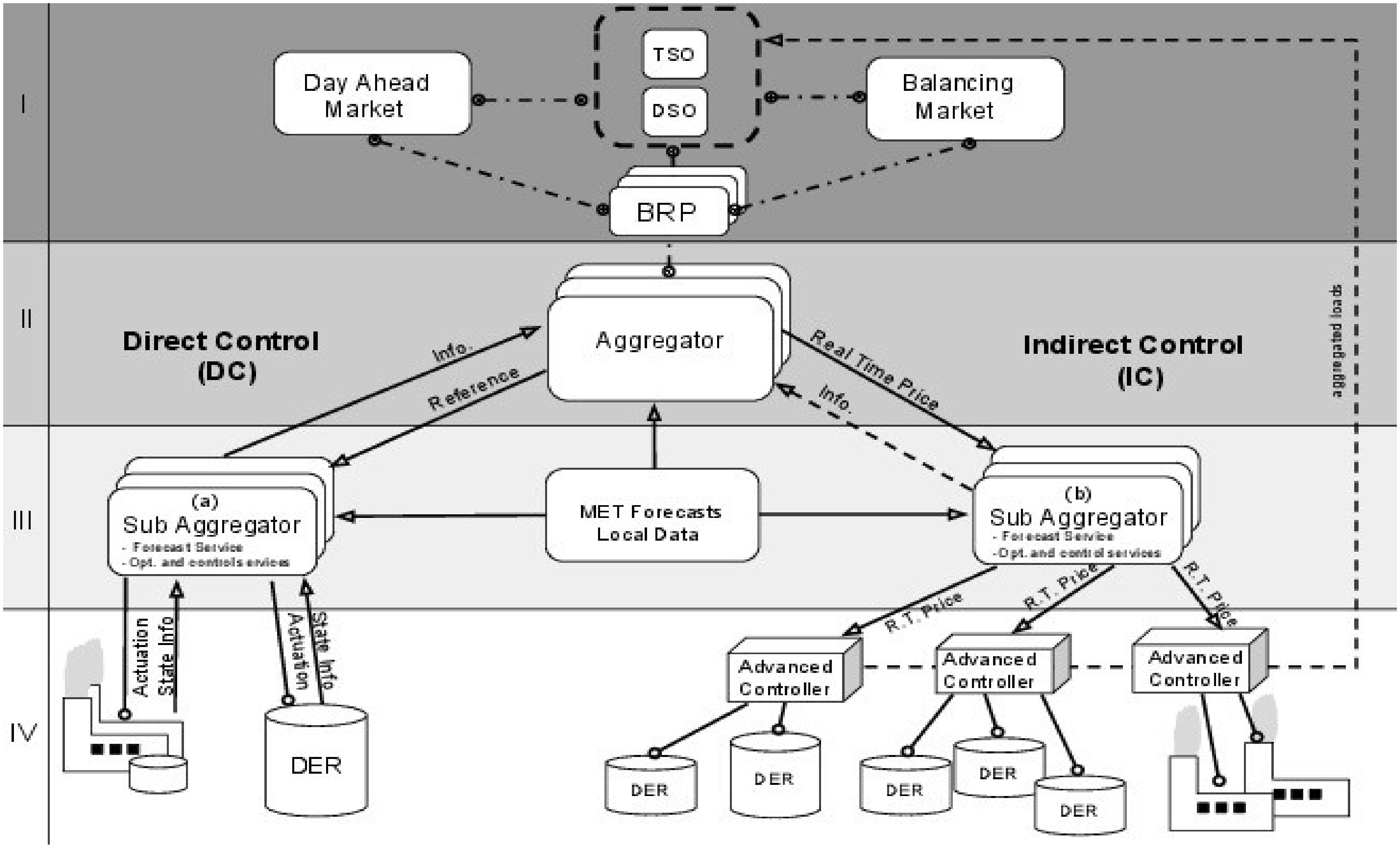


Flexibility in District Heating

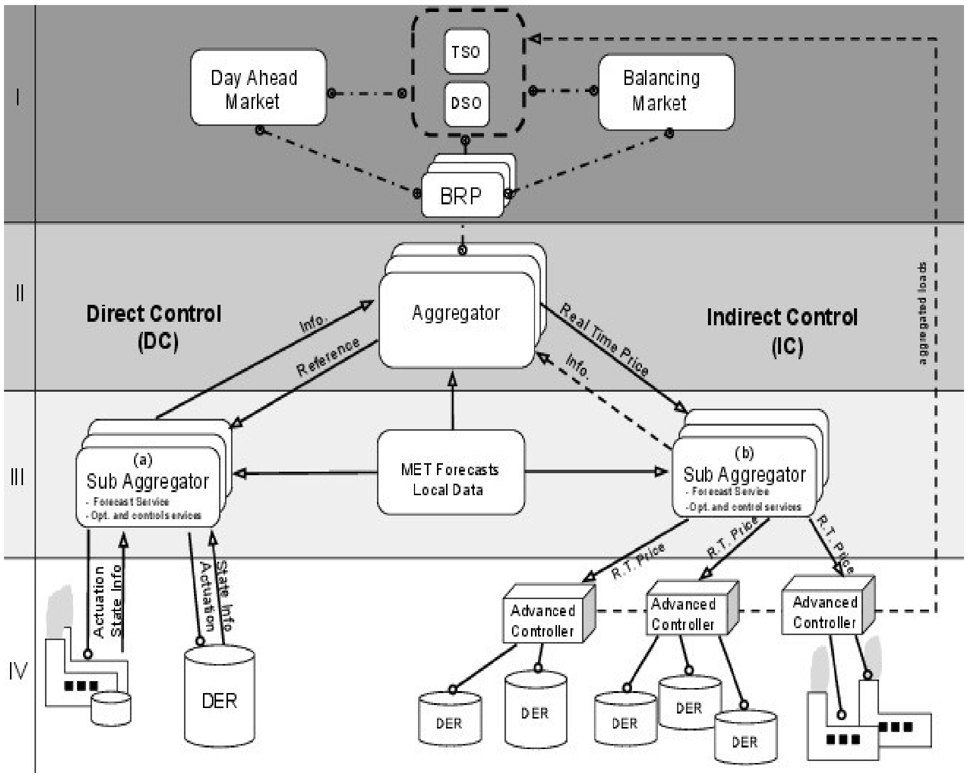



Latest production data for Tyra: 6.061.111 kWh
Applicable for 15. februar 2014 11:00-12:00
Natural gas right now
Gas flow – kWh/h:
Nybro entry 5.882.672
Ellund exit 1.002.678
Dragør exit 1.405.760
Energinet.dk Gas Storage 824.732
DONG Storage 0
Exit Zone 4.776.523
CO2 emission factor 56,76 kg/GJ
LEGEND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

Control and Optimization



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

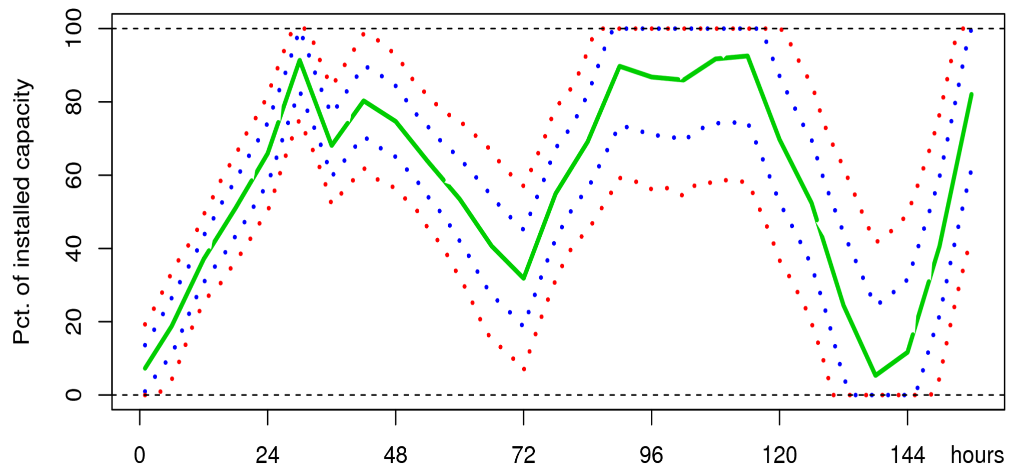
Level	Direct Control (DC)	Indirect Control (IC)
III	$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$	$\min_{\hat{z},p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$ s.t. $\hat{z}_{k+1} = f(p_k)$
IV	$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$ s.t. $x_{j,k+1}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

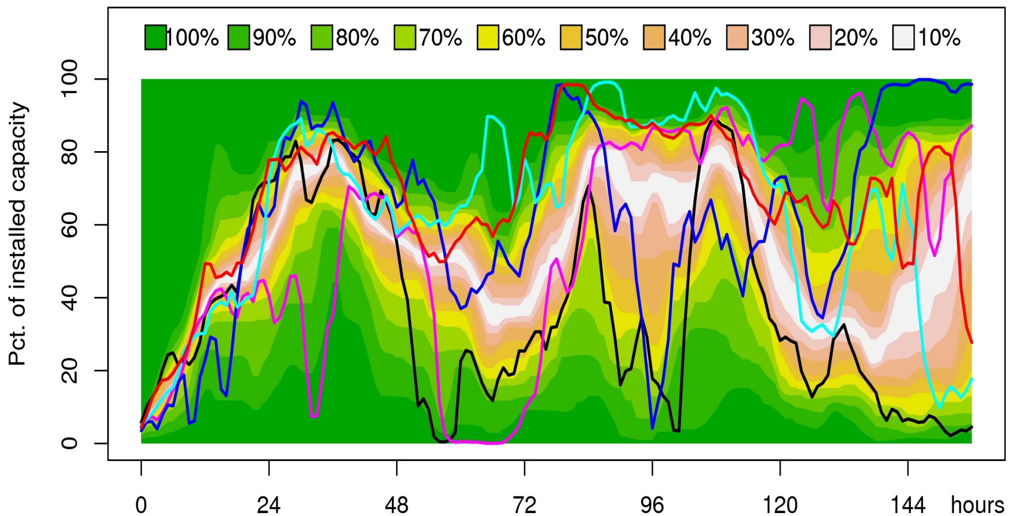
Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals u_j are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes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

Forecasting is Essential

Tools for Forecasting: (Prob. forecasts)

- **Power load**
- **Heat load**
- **Gas load**
- **Prices (power, etc)**
- **Wind power produc.**
- **Solar power produc.**
- **State variables (DER)**



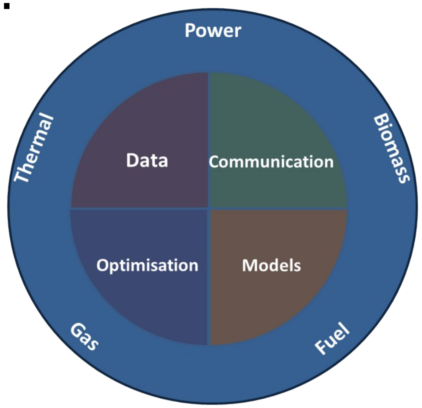


CITIES
Centre for IT Intelligent Energy Systems

Flexibility Idea

The **central idea** is that by **intelligently integrating** currently distinct energy flows (heat, power, gas and biomass) in we can enable **flexibility** and hence integrate very large shares of renewables, and consequently obtain substantial reductions in CO2 emissions.

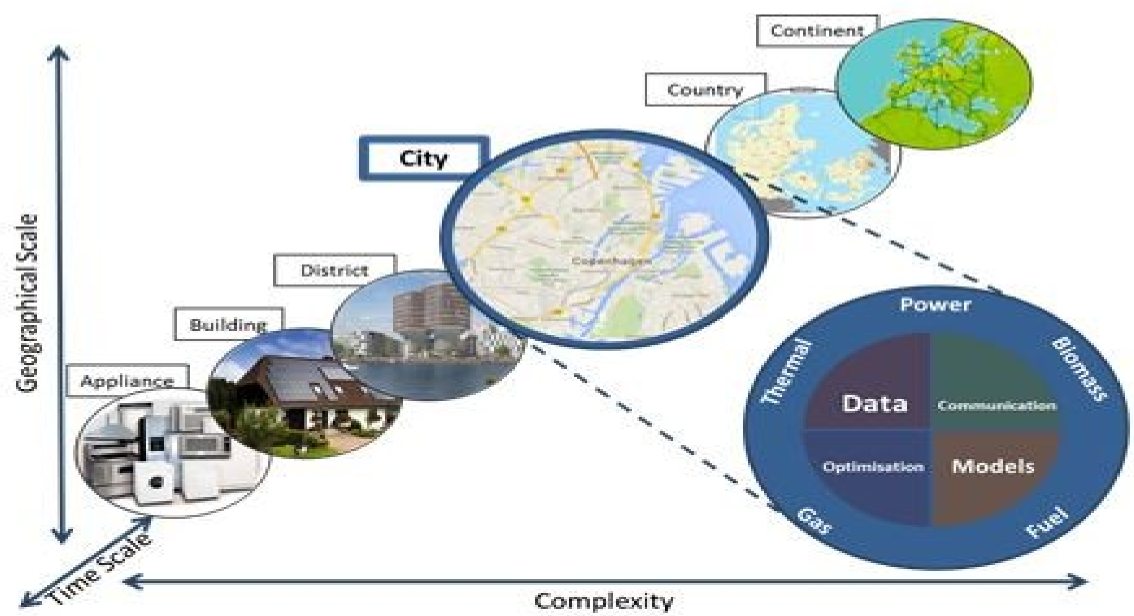
Intelligent integration will (for instance) enable lossless **virtual storage on a number of different time scales**.



Flexible Solutions and CITIES

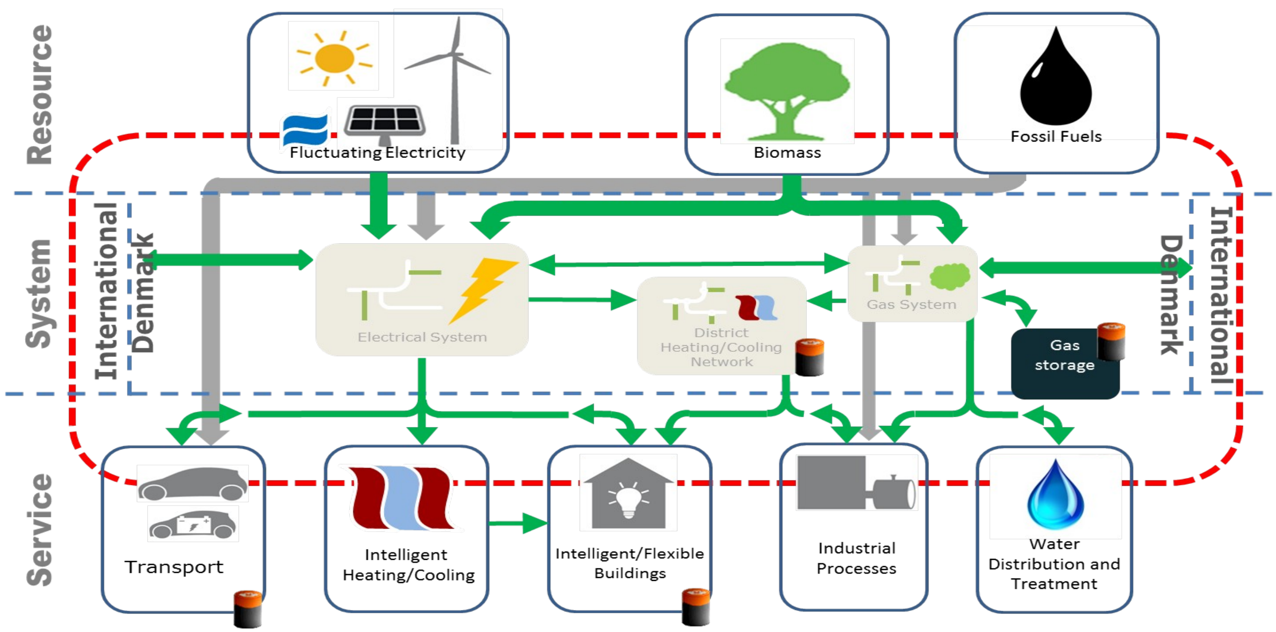
The ***Center for IT-Intelligent Energy Systems in Cities (CITIES)*** is aiming at establishing methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales.

CITIES is the largest Smart Cities and ESI research project in Denmark – see http://www.smart-cities-centre.org .

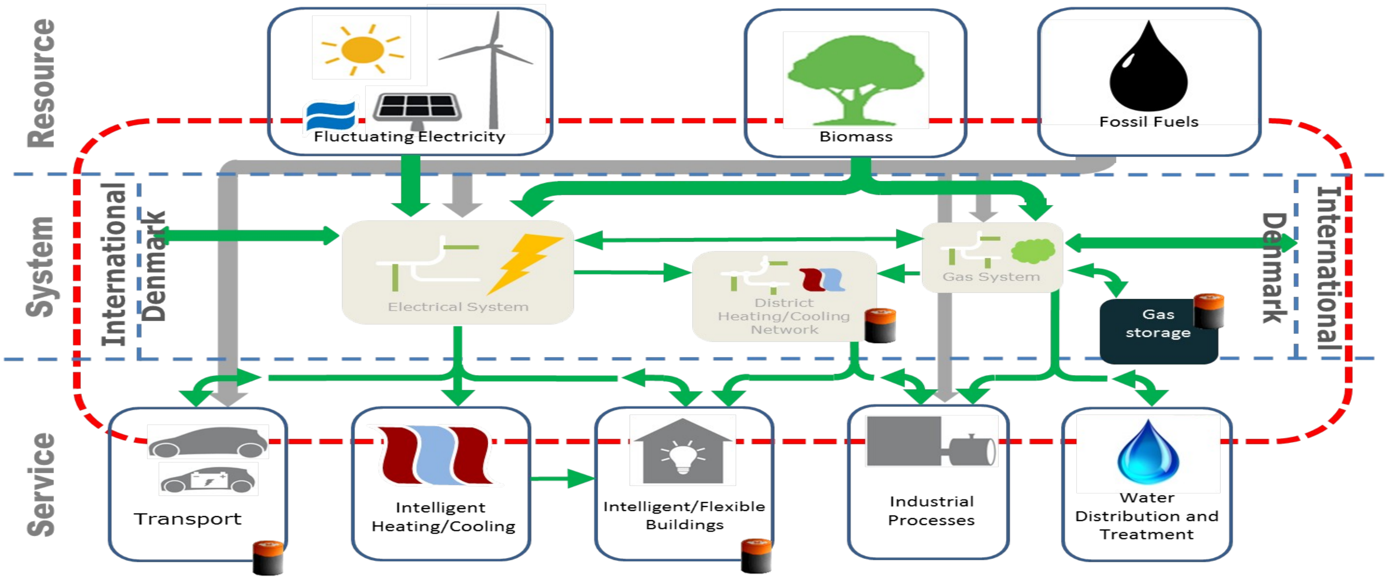


ICT implementable models

Energy Systems Integration using **data and ICT solutions** are used to establish (grey-box) **models and methods for planning and operation of flexible energy systems.**



Virtual Storage by Energy Systems Integration



- **Denmark (2014) : 48 pct of power load by renewables (> 100 pct for some days in January)**
- **(Virtual) storage principles:**
  - Buildings can provide storage up to, say, 5-12 hours ahead
  - District heating/cooling systems can provide storage up to 1-3 days ahead
  - Gas systems can provide seasonal storage

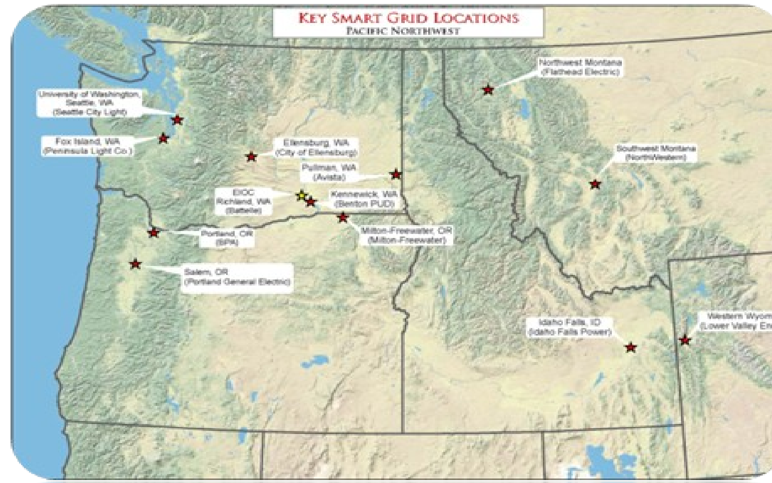
Case study

Control of Power Consumption using Price Signals (Thermal flexible buildings)

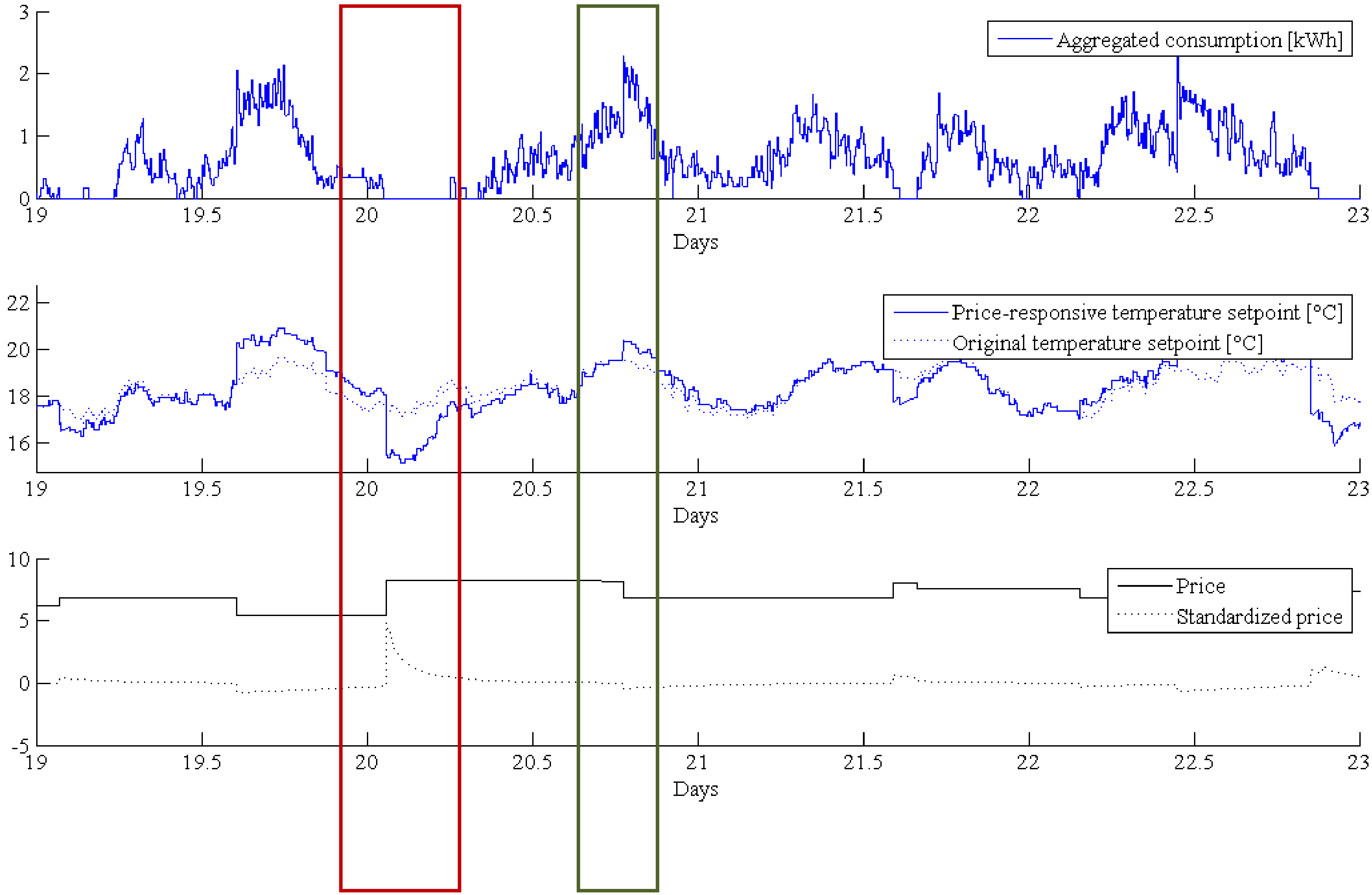
Data from BPA

Olympic Pensinsula project

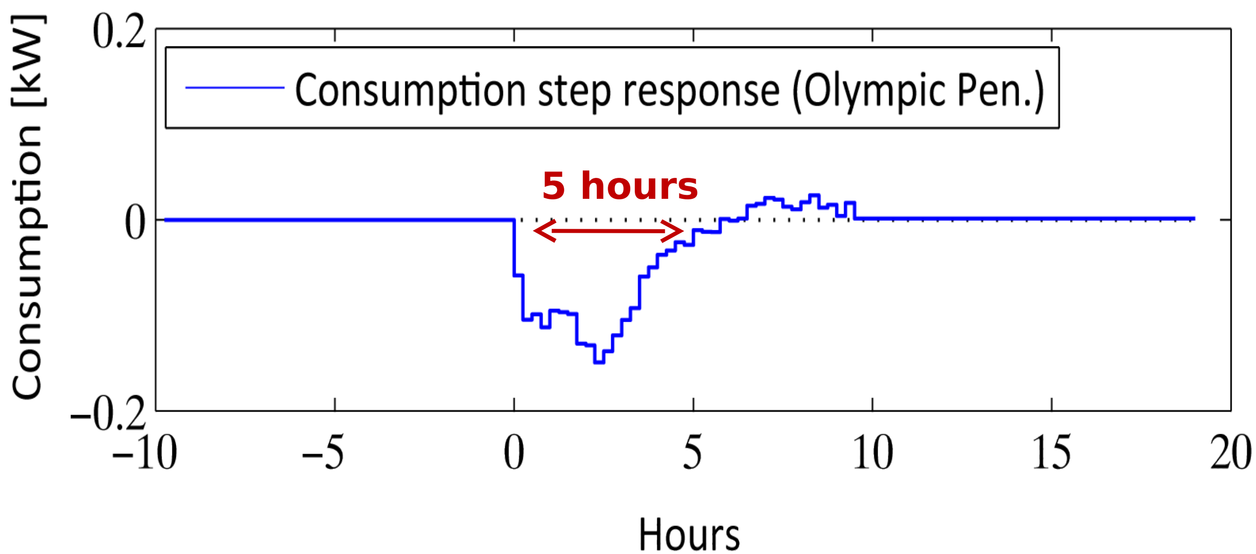
- 27 houses during one year
- Flexible appliances: HVAC, cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption



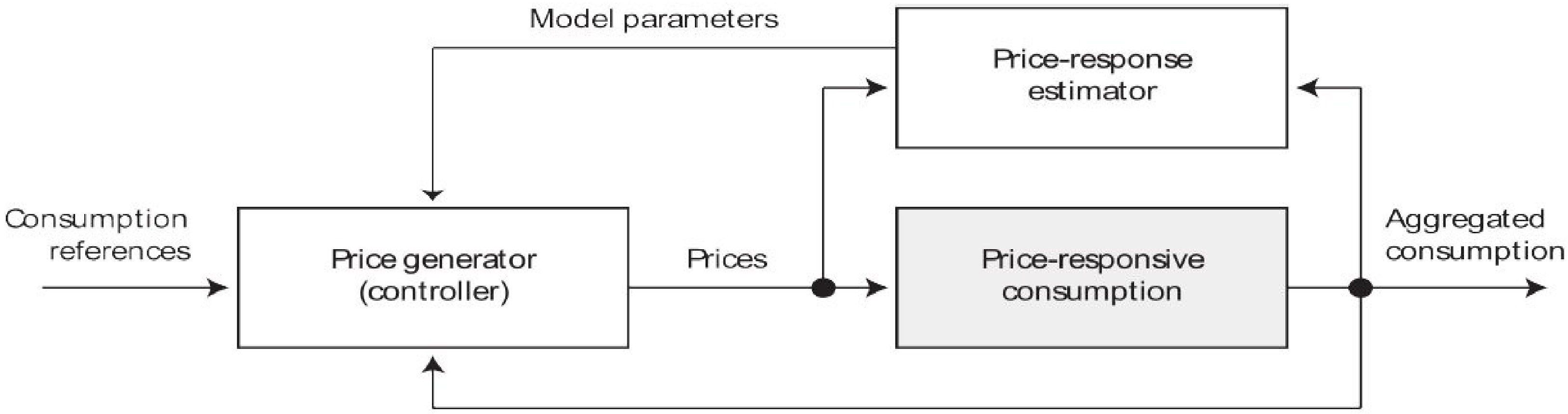
Aggregation (over 20 houses)

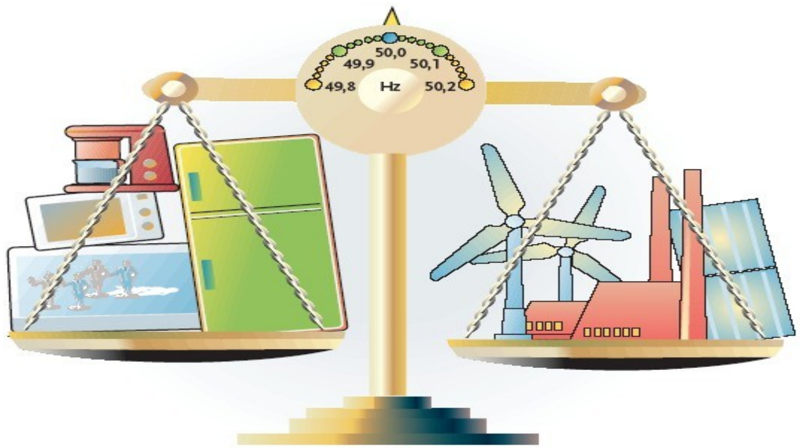


Response on Price Step Change



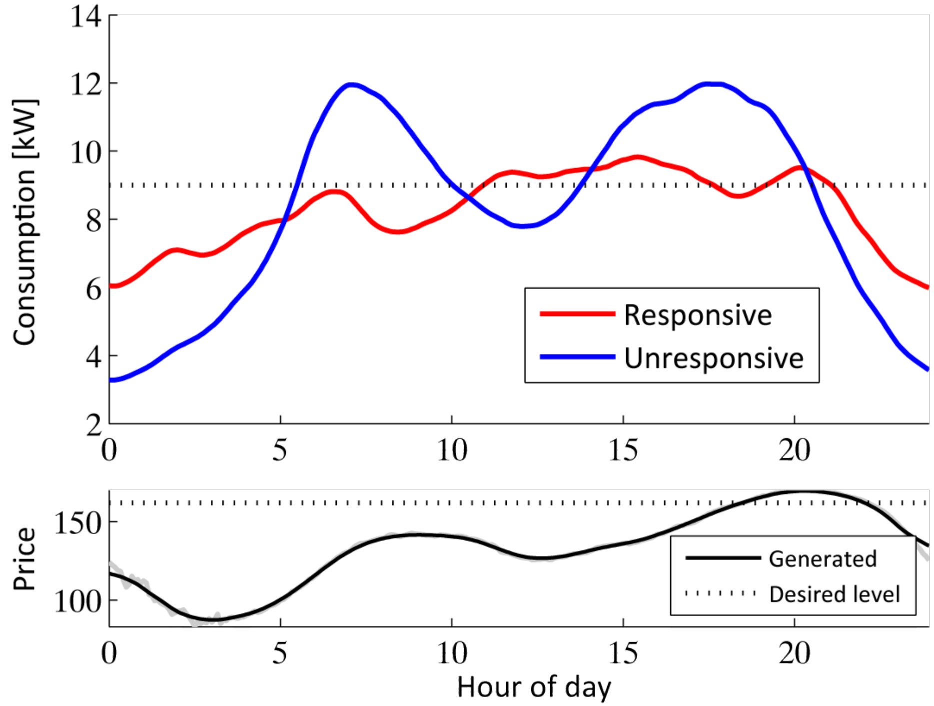
Control of Power Consumption





Control performance

Considerable **reduction in peak consumption**



Case study

Control of Heat Pumps (based on varying prices)

CITIES
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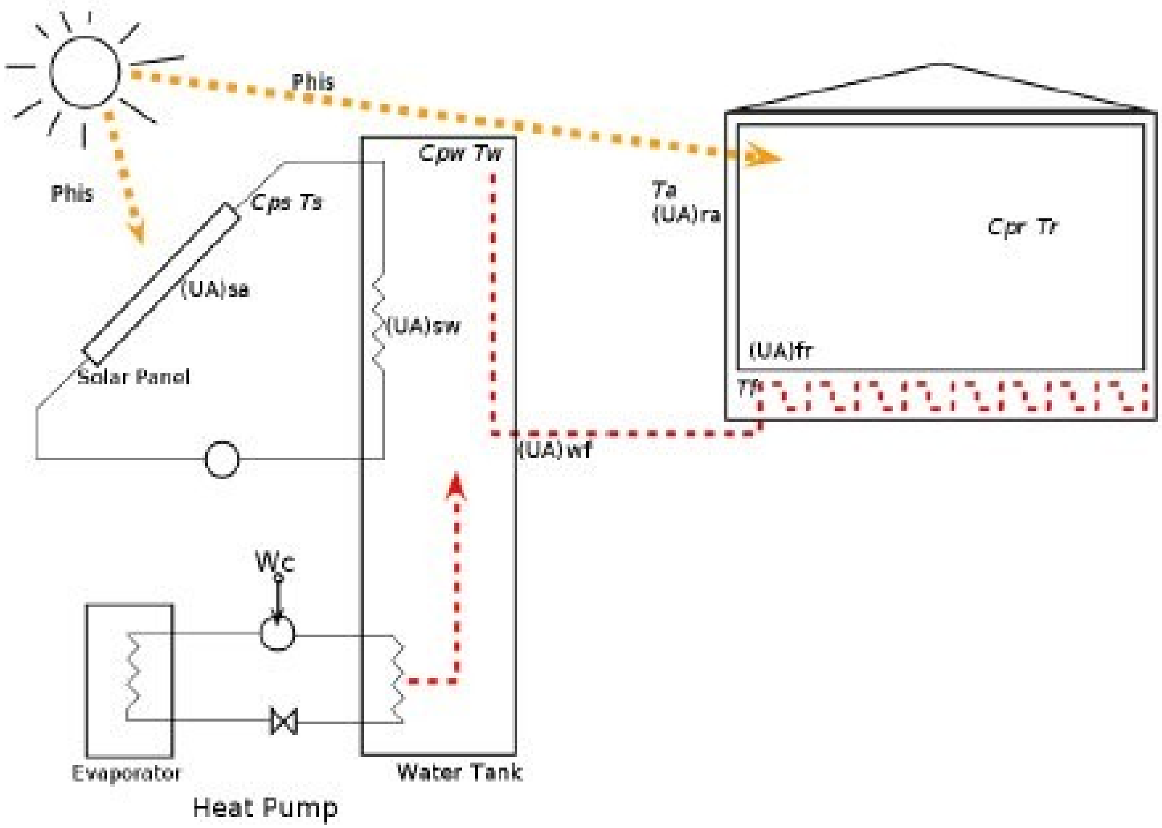
Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

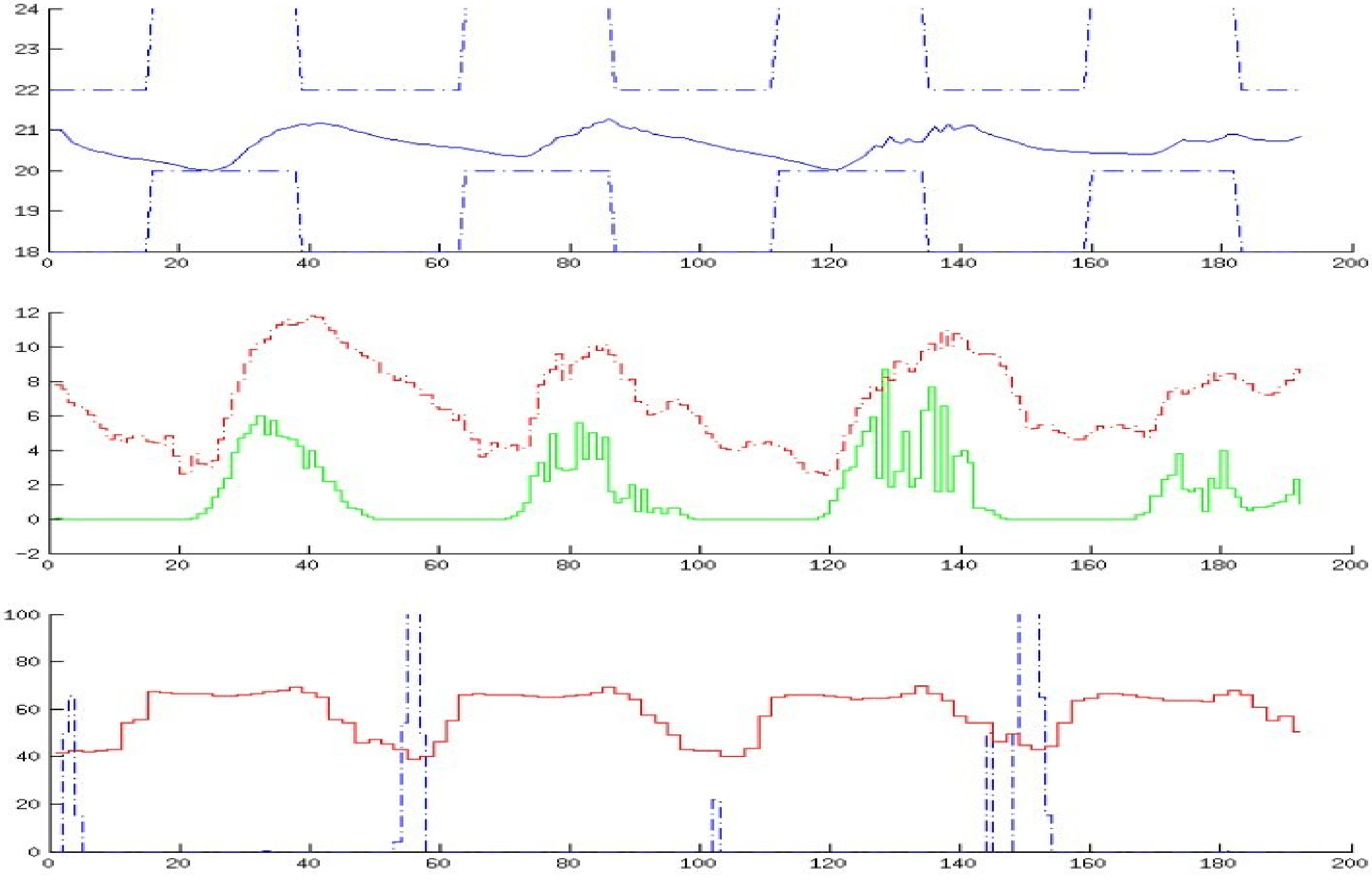
Formulation

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

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

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

EMPC for heat pump with solar collector (savings 35 pct)



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Discussion

- In Denmark more than 100 pct of the power is covered by wind generation from time to time
- District heating plays an important role in Denmark for the succesfull integration
- ICT technologies – including model based methods for forecasting and control – are essential for using the thermal flexibility
- Models must be formulated using (online) data (since very often a deductive model cannot be found)
- Price based control of electricity load gives a perfect setup for an economial interaction (however, model based and automatic) between power, heat and gas systems
- Energy Systems Integration can provide virtual and lossless storage solutions
- District heating (or cooling) provide virtual storage on the essential time scale (up to a few days)
- We see a large potential in Demand Side Management. Automatic control and end-user focus is important
- Design of buildings must pay more attention to the storage capabilities
- We see a large potential in coupling cooling (eg. for comfort) and heating systems using DH networks
- DH networks are used extensively in both Korea and Denmark (and a number of other countries)
- 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)

For more information ...

See for instance

www.henrikmadsen.org

www.smart-cities-centre.org

...or contact

– Henrik Madsen (DTU Compute)
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Acknowledgement CITIES (DSF 1305-00027B)