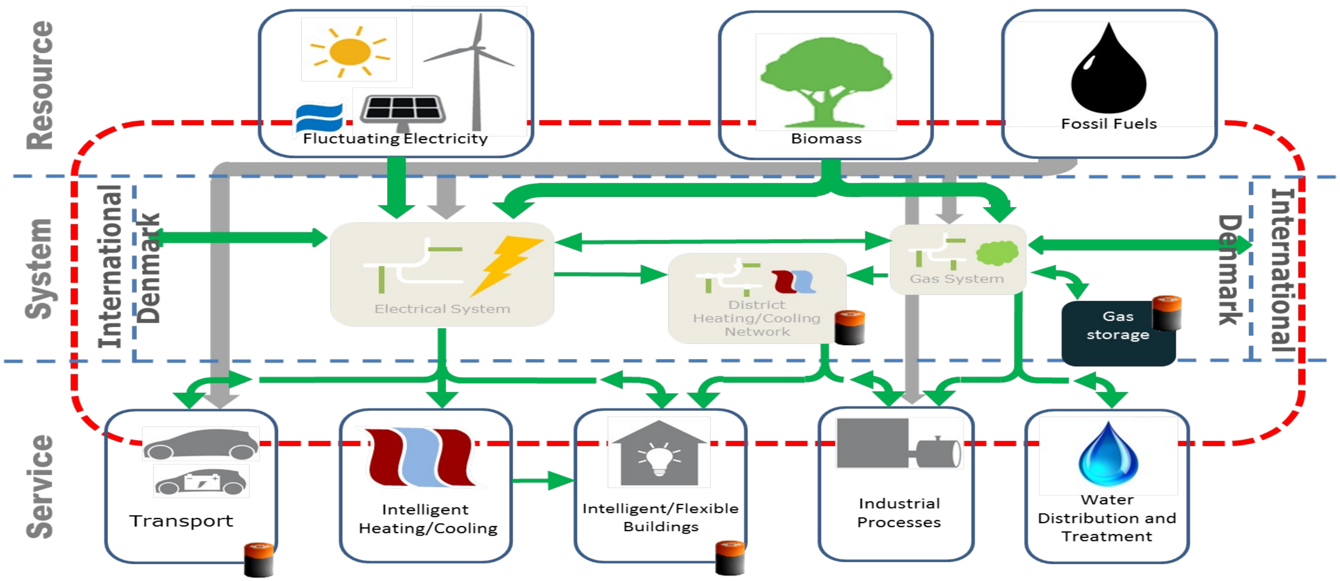
Forecasting, Control and Optimisation for Future Electric Energy Systems



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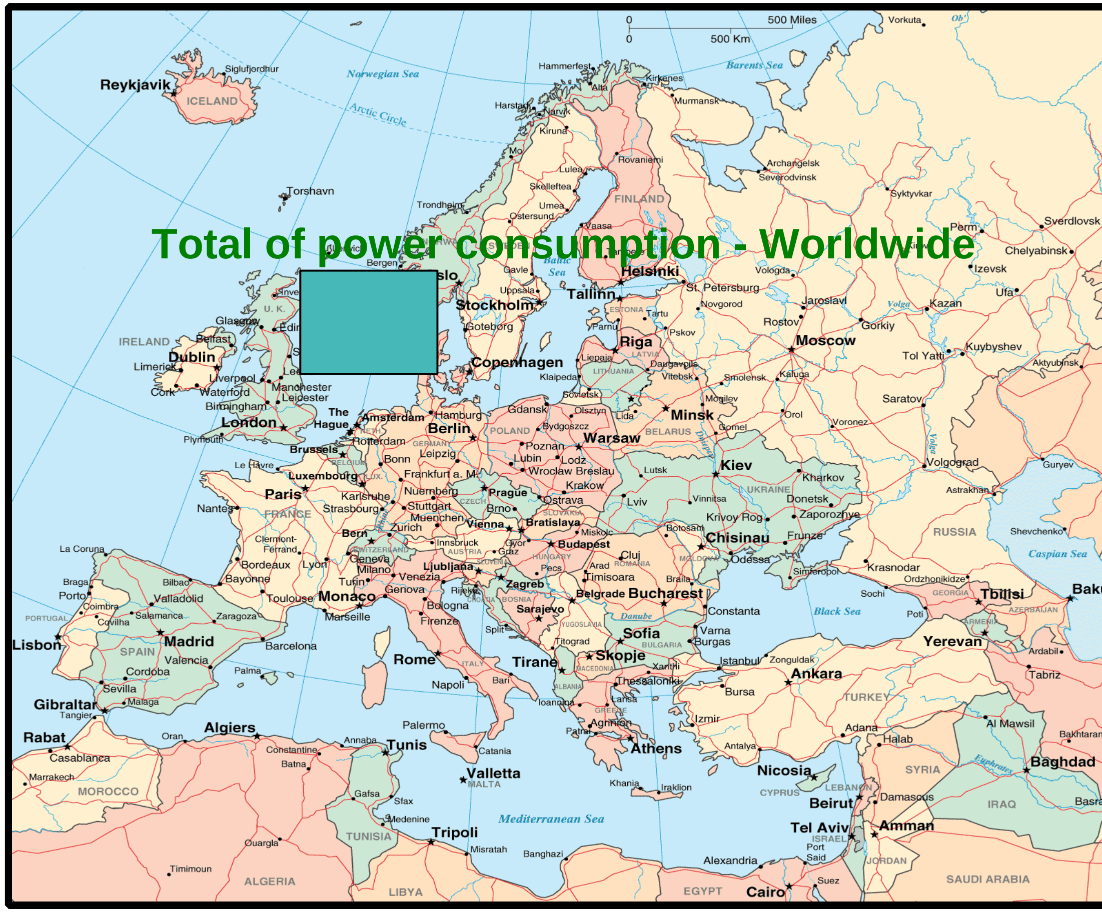
CITIES
Centre for IT Intelligent Energy Systems

Potentials and Challenges for renewable energy

- **Scenario**: We want to cover the worlds entire need for power using wind power.
- How large an area should be covered by wind turbines?

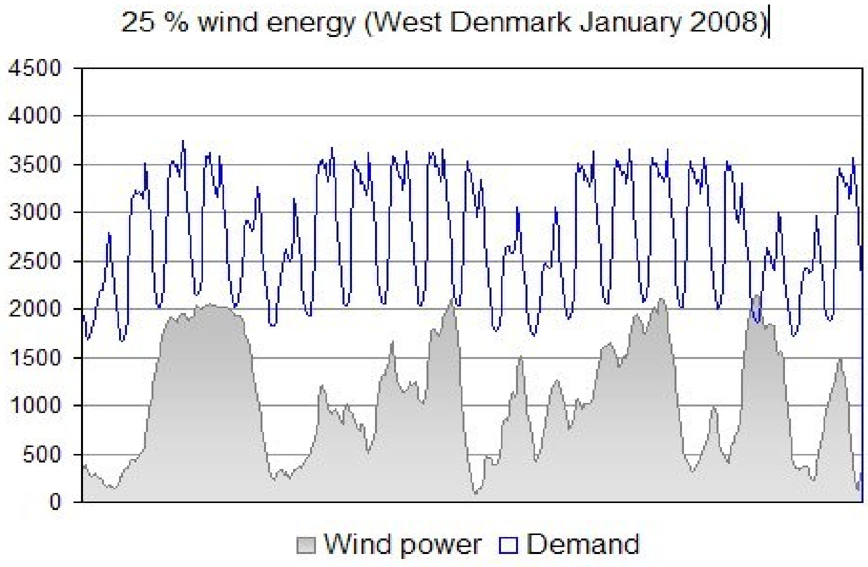
Potentials and Challenges for renewable energy

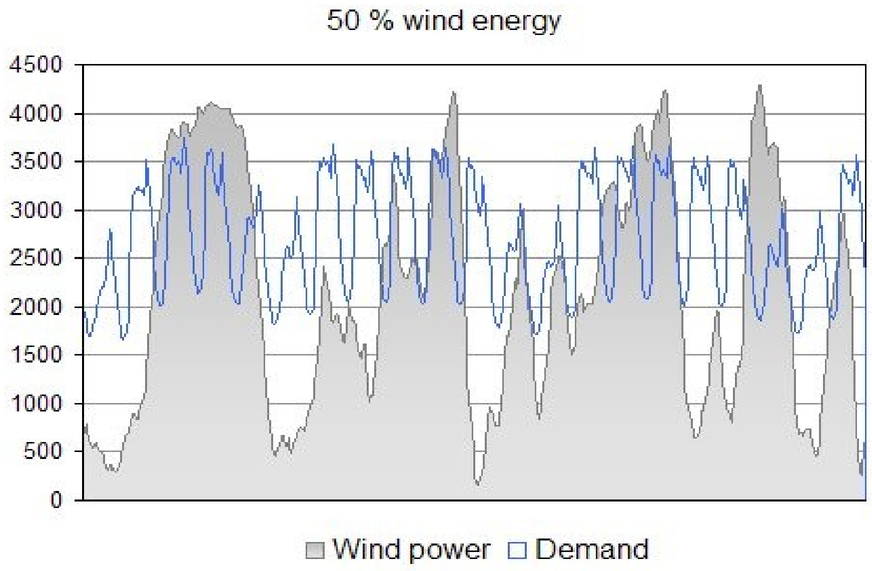
- **Scenario:** We want to cover the worlds entire need for power using wind power
- How large an area should be covered by wind turbines?
- **Conclusion**: Use intelligence ....
- Calls for **Smart Energy Solutions and Energy Systems Integration**



The Danish Wind Power Case

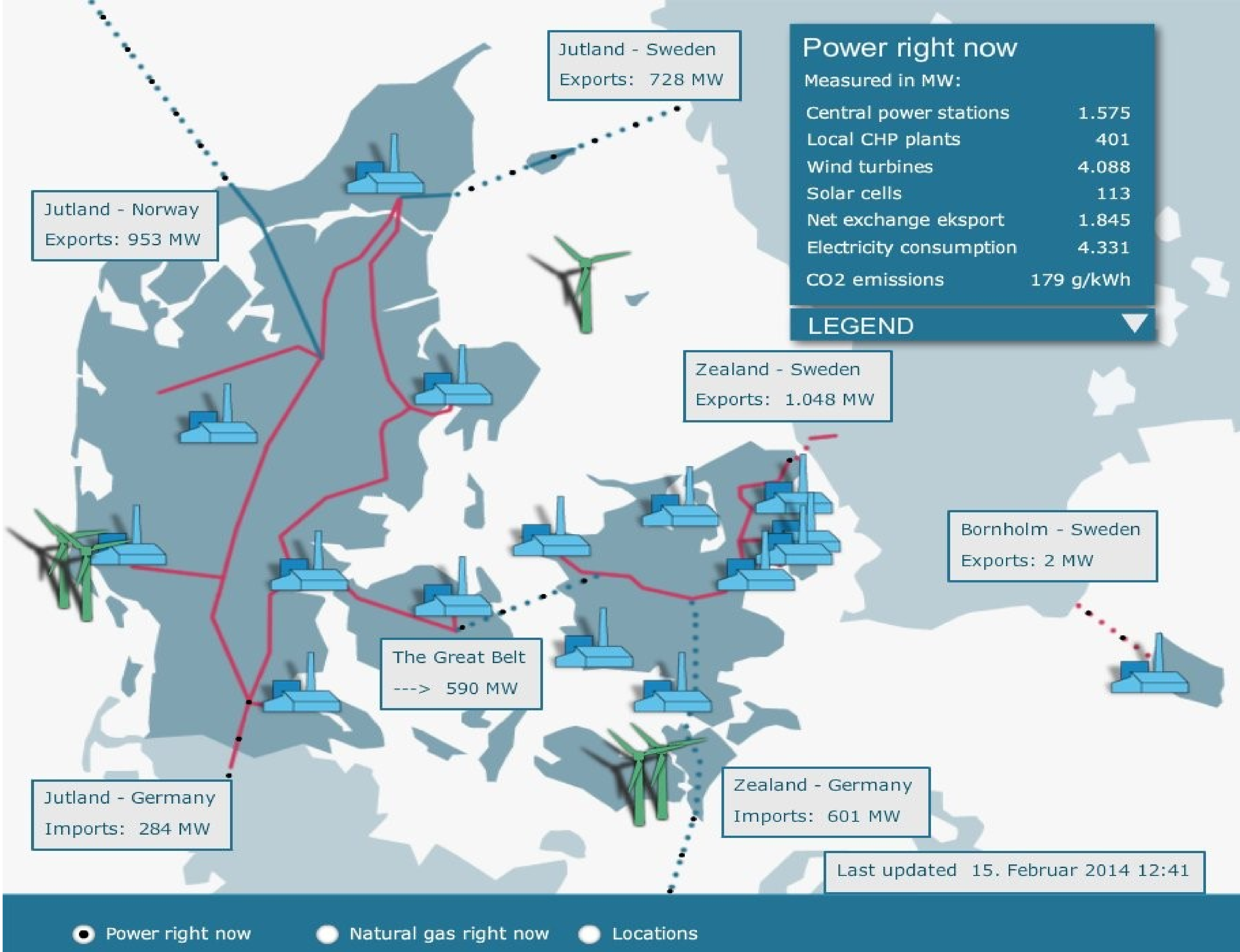
.... balancing of the power system





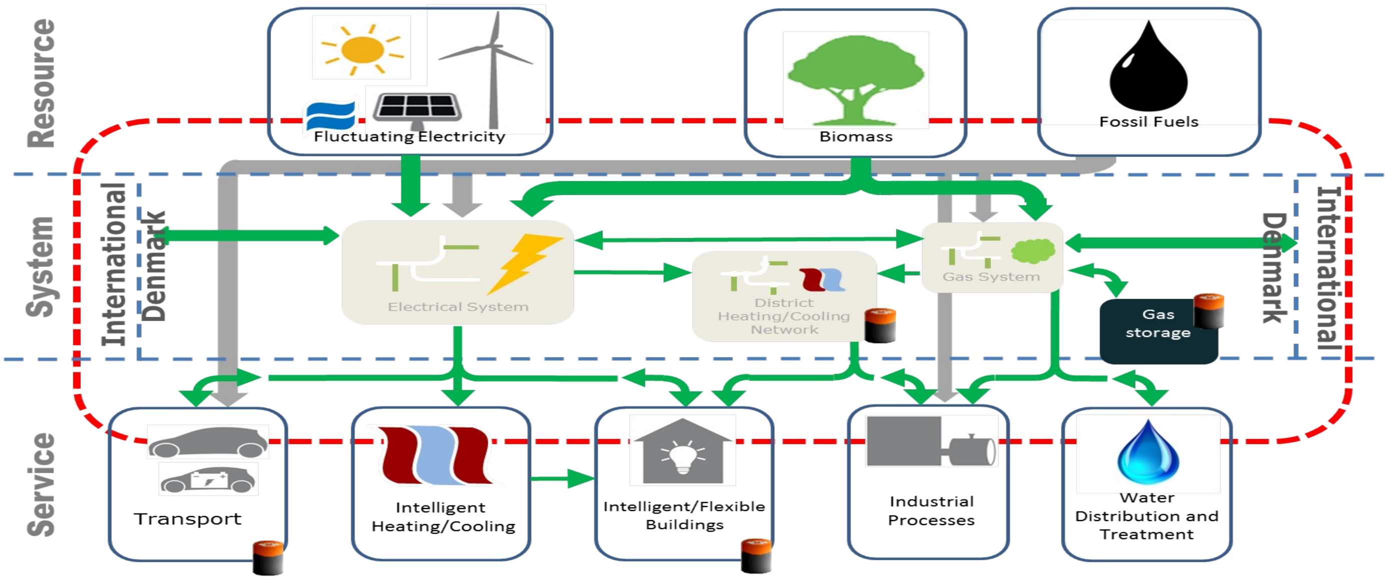
In 2008 wind power did cover the entire demand of electicity in 200 hours (West DK)

In December 2013 and January 2014 more than 55 pct of electricity load was covered by wind power. And for several days the wind power production was more than 120 pct of the power load



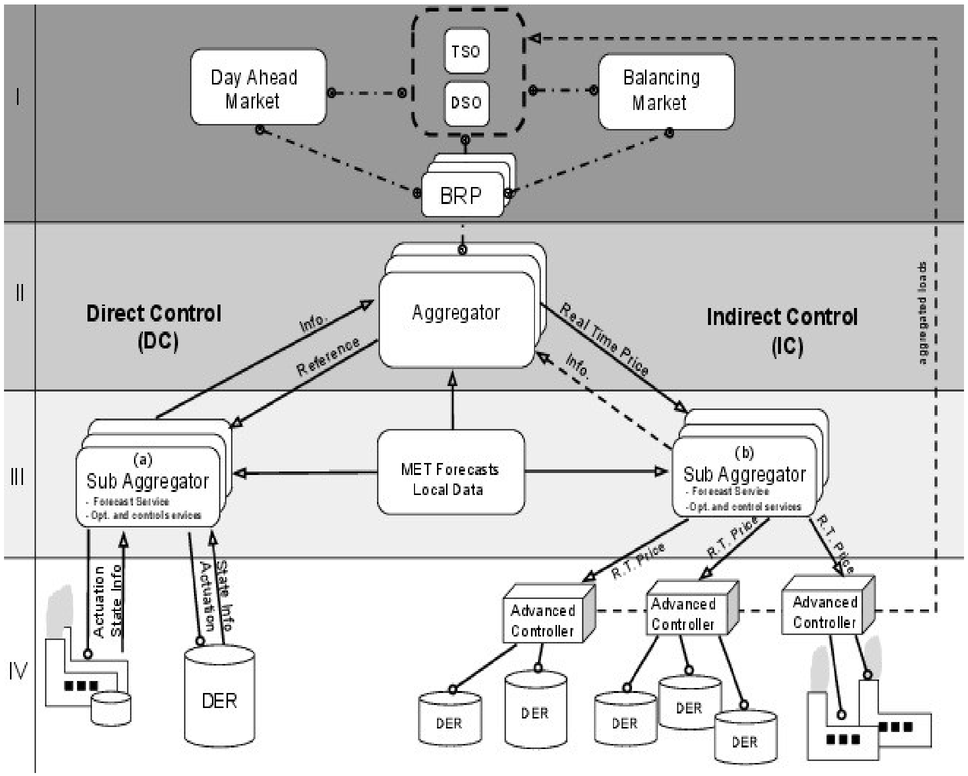
Jutland - Sweden
Exports: 728 MW
Power right now
Measured in MW:
Central power stations 1.575
Local CHP plants 401
Wind turbines 4.088
Solar cells 113
Net exchange eksport 1.845
Electricity consumption 4.331
CO2 emissions 179 g/kWh
LEGEND
Jutland - Norway
Exports: 953 MW
Zealand - Sweden
Exports: 1.048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

Example: Storage by Energy Systems Integration



- **Denmark (2014) : 46 pct of power load by renewables**
- **(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

Optim. and Control Challenges



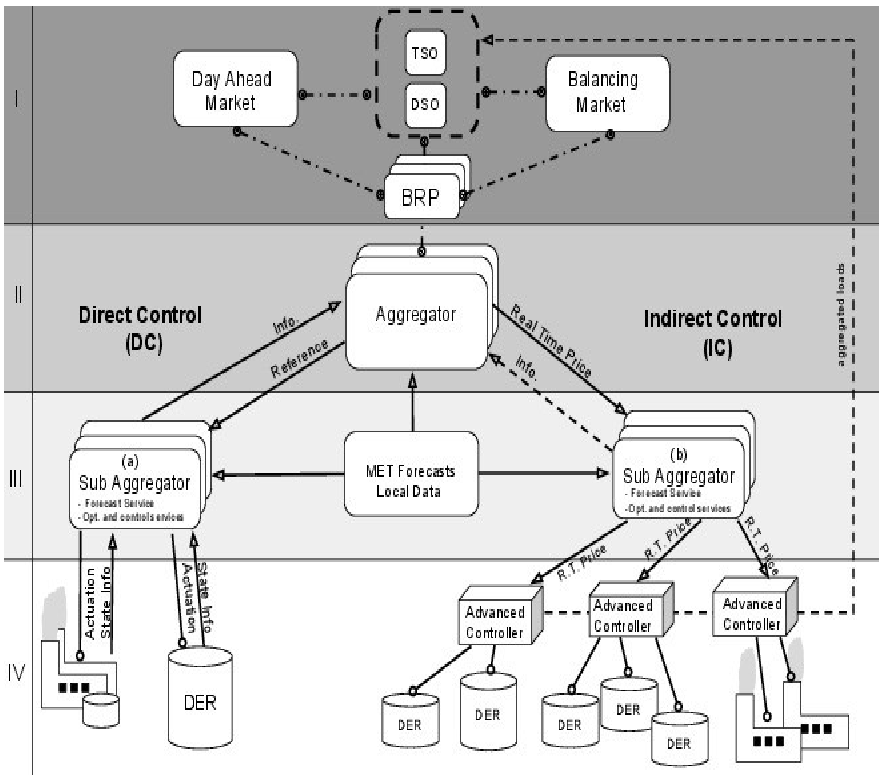
- **Day Ahead:**
  - Stoch. Programming based on eg. Scenarios
  - Cost: Related to the market (one or two levels)
  - Operational optimization – also for the grid
- **Direct Control:**
  - Actuator: **Power**
  - Cost: eg. MV, LQG, EMPC, ... (a single large problem)
  - Two-way communication
  - Models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

<table>
<tr><th>Level</th><th>Direct Control (DC)</th><th>Indirect Control (IC)</th></tr>
<tr><td>III</td><td rowspan="2">$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$
$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$
s.t. $\quad x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$</td><td>$\min_{\hat{z},p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$
s.t. $\quad \hat{z}_{k+1} = f(p_k)$</td></tr>
<tr><td>IV</td><td>$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$
s.t. $\quad x_{k+1} = f_j(x_k, u_k)$</td></tr>
</table>

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



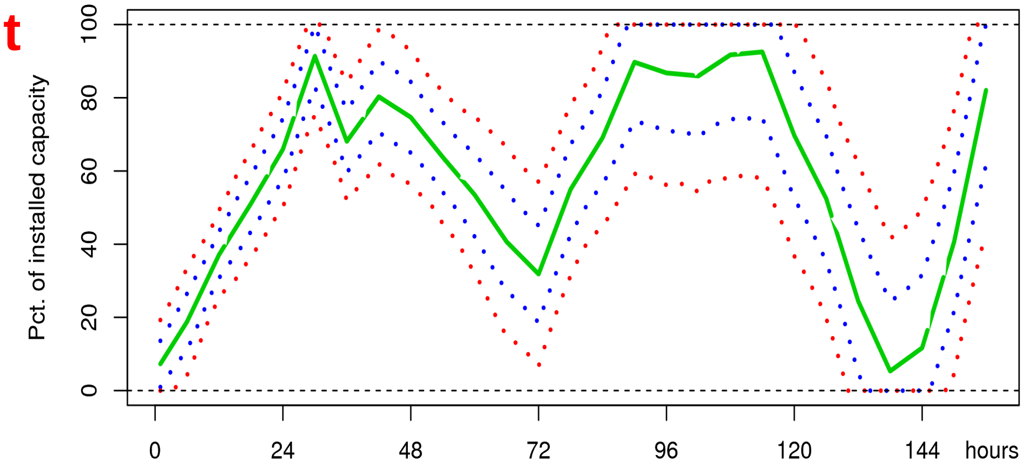
- **Day Ahead:**
  - Forecasts of loads
  - Forecast of Grid Capacity (using eg. DLR)
  - Forecasts of production (eg. Wind and Solar)
- **Direct Control:** .
  - Forecasts of states of DERs
  - Forecasts of load
- **Indirect Control:**
  - Forecasts of prices
  - Forecasts of load

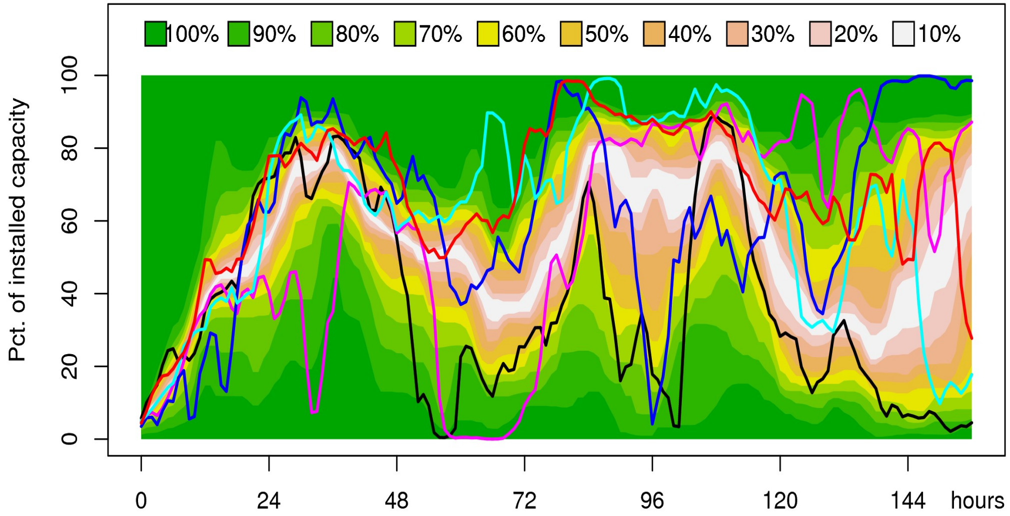
Forecasting ....

Forecasting is very important

Type of forecasts:

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





Challenges with integrating RE in the distribution system

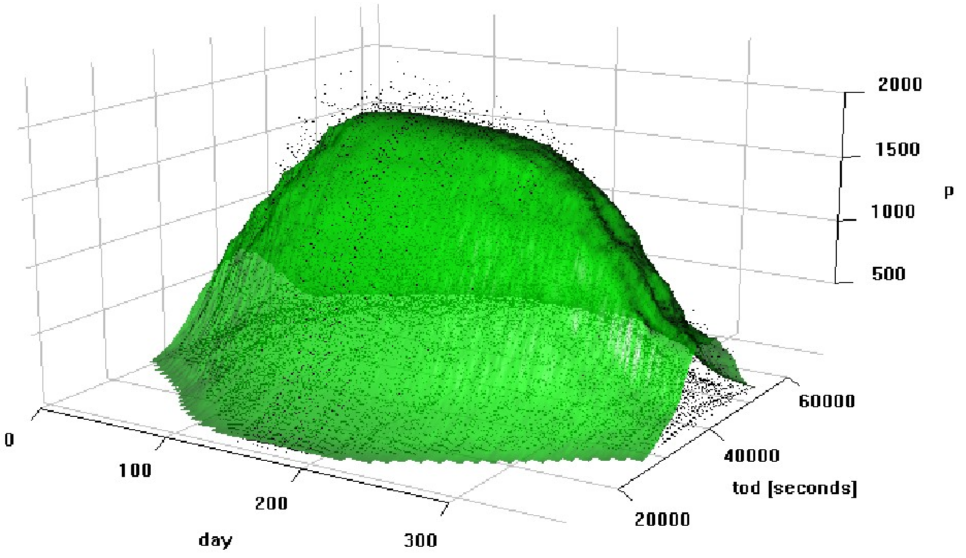
- **Adaptive and probabilistic forecasts become essential**
- **Methods for using prob. forecasts in decision making**
- **Correlation of forecast errors must be described**
- **Cross-correlation between eg wind and solar forecasting must be described**
- **Stochastic / operational models are needed (eg. for state estimation)**
- **Modeling of flexibility (direct control)**
- **Modeling of price-response (indirect control)**
- **Methods for stochastic optimization and control**

Some examples are provided in case studies later on

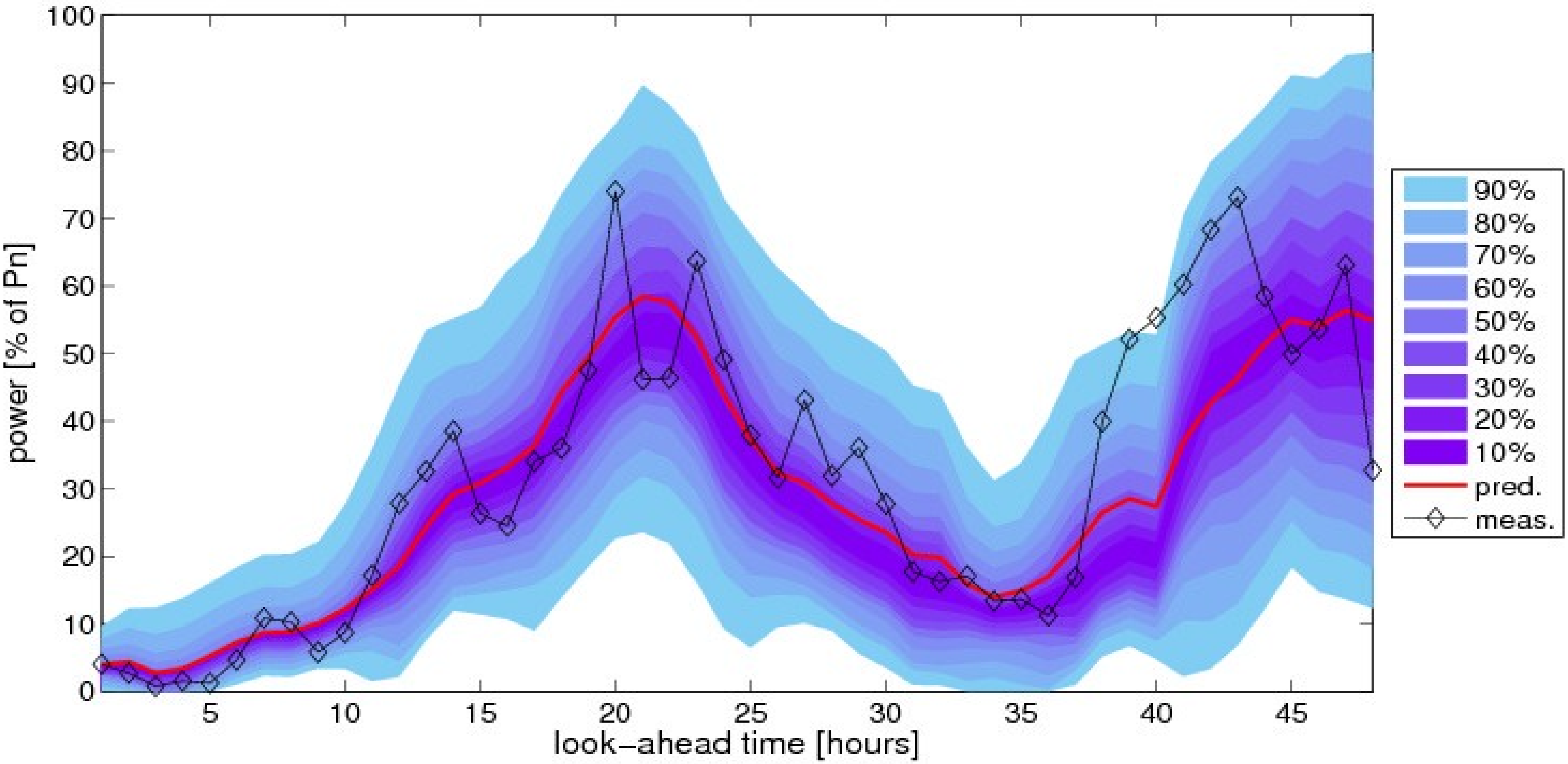
Solar Power Forecasting

Solar Power Forecasting

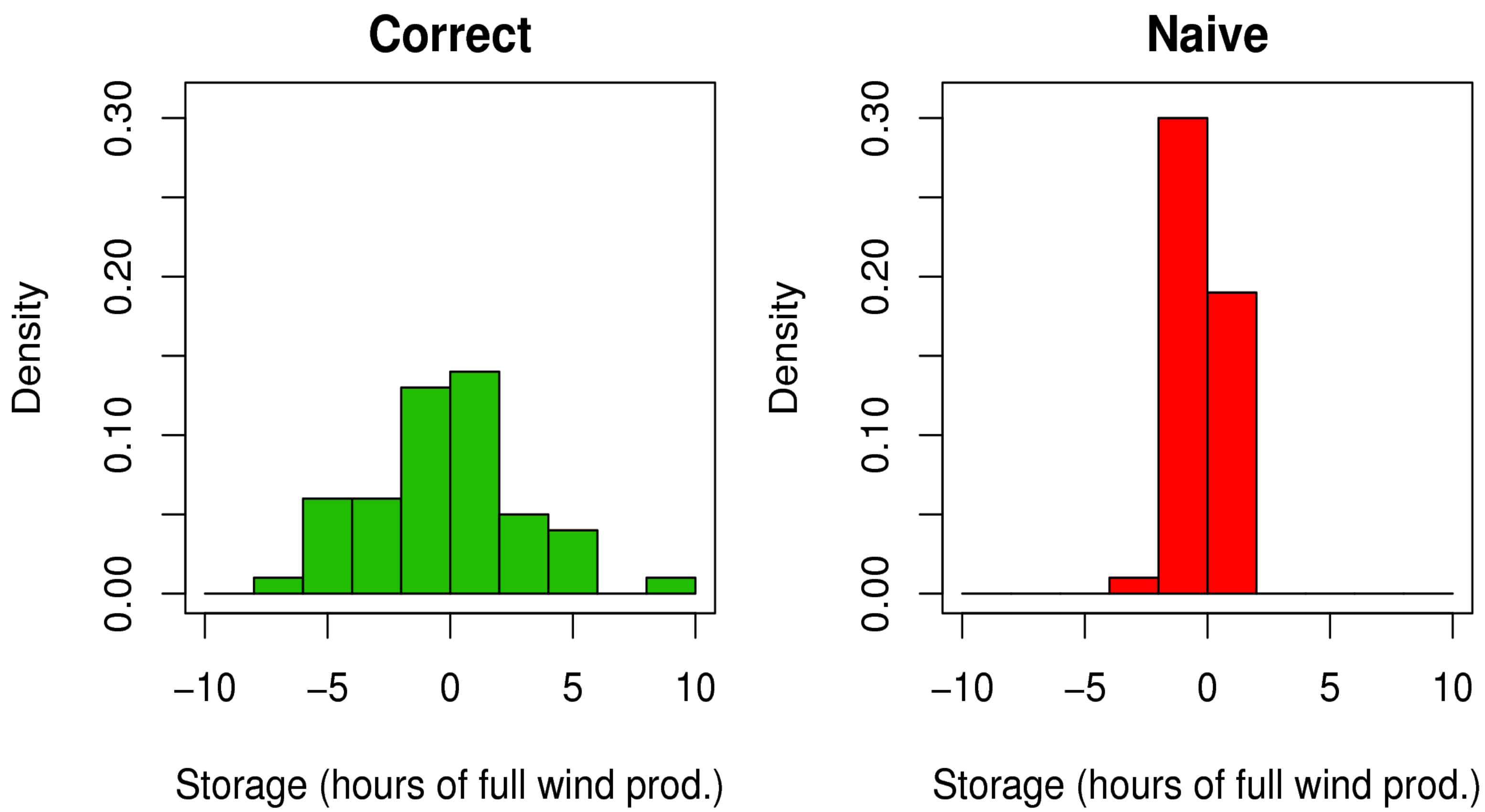
- Shading must be taking into account -> dedicated functions
- Dusts, etc -> need for adaptive models



Prob. Wind Power Forecasting



Storage sizing



Tools are developed for:

- Wind Power Forecasting
- Solar Power Forecasting
- Heat/Cooling load forecasting
- Gas load forecasting
- Price forecasting
- Forecasts for state control

  Our methods are eg embedded in Australian Wind Energy Forecasting Systems (AWEFS) and Australian Solar Energy Forecasting Systems (ASEFS) – see eg P. Coppin, CSIRO, ASI Energy Forecasting, Final Report, March 2012.

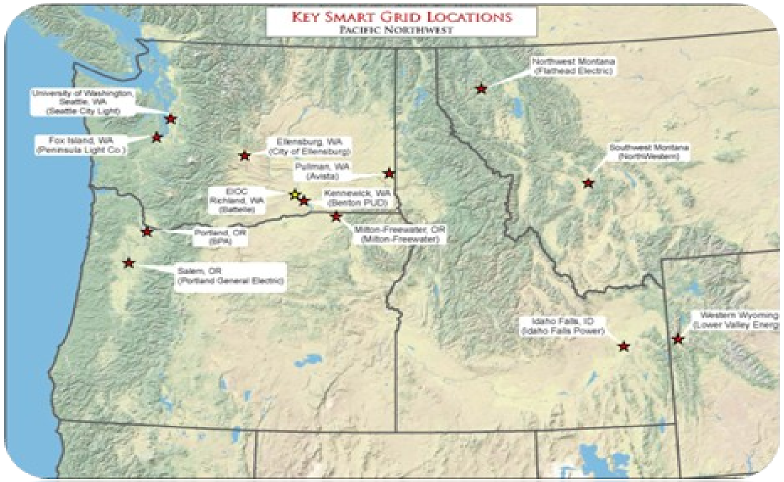
Case study

Control of Power Consumption (DSM)

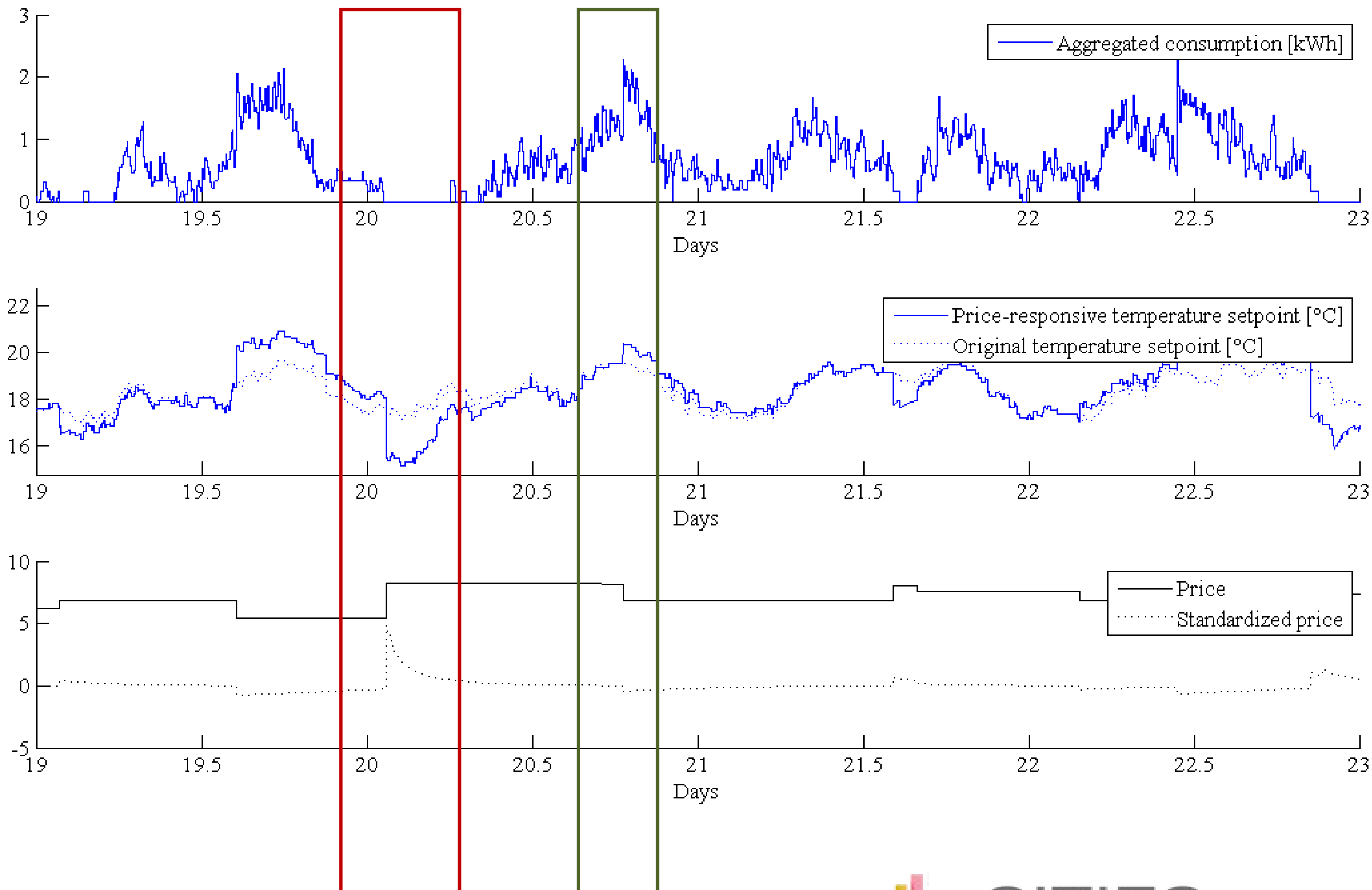
Data from BPA

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



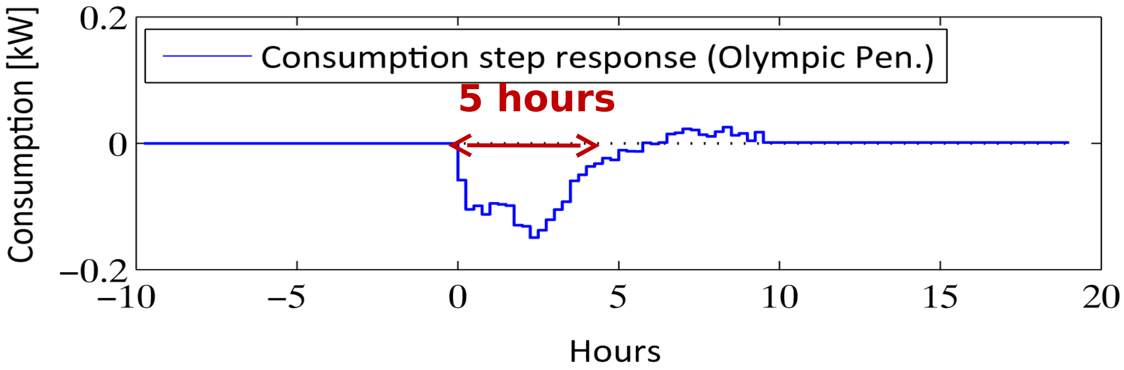
Aggregation (over 20 houses)



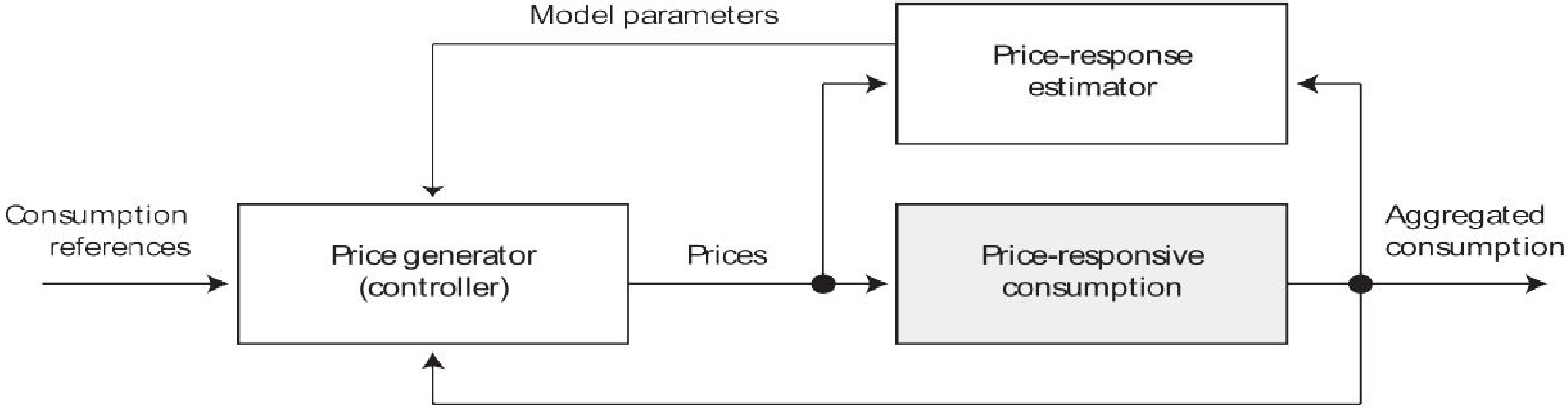
Non-parametric Response on Price Step Change

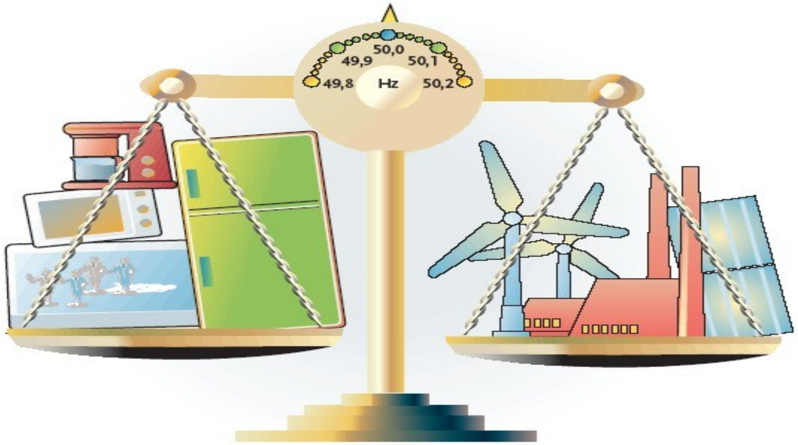
Model inputs: pice, minute of day, outside temperature/dewpoint, sun irrandianc

Olympic Peninsula



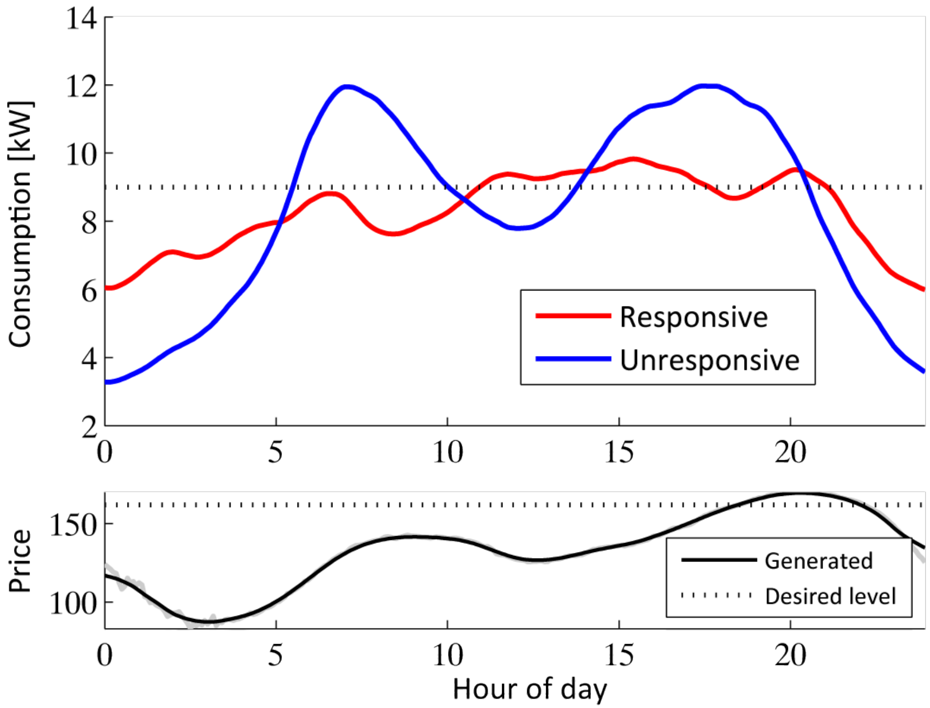
Control of Energy Consumption





Control performance

- Considerable **reduction in peak consumption**
- Mean daily consumption shift



Case study

Super Market Cooling

Simulations – DER Controllers

- Direct Control
  - **Temperature Reference Tracking**

$$\min \sum_{n=1}^{N} \left(T_n - T_n^{ref}\right)^2 + \gamma_1 \Delta P_{1,t-1}$$

s.t:

- System Temperature/Power Dynamics from ARMAX model
- $T_{max}, T_{min}, P_{max}$

  - **Power Reference Tracking**

$$\min \sum_{n=1}^{N} \left(P_n - P_n^{ref}\right)^2$$

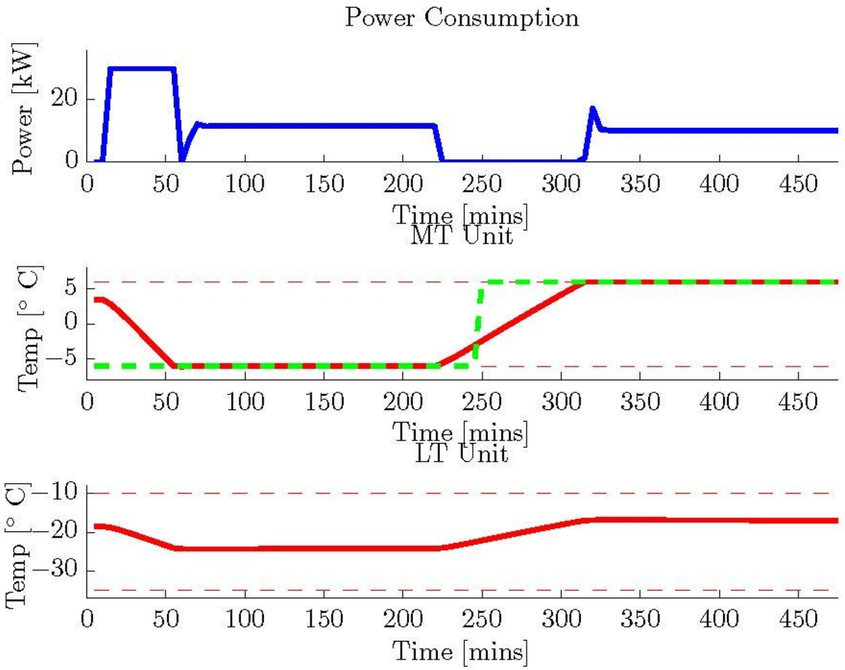
- Indirect Control
  - **Economic MPC**

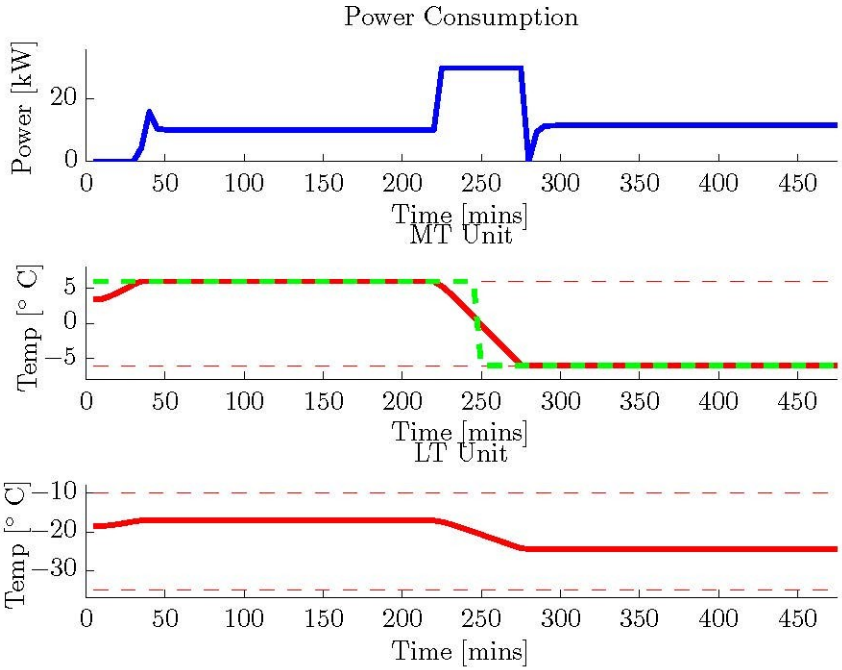
$$\min \sum_{n=1}^{N} \lambda_n P_n + \gamma_1 T_N^{MT} + \gamma_2 T_N^{LT}$$

- Note all controller formulations are “MPC” – i.e. forecasts of price/references only available up to a fixed horizon – control consists of a sequence of receding horizon optimisations

Simulations – Temperature Tracking

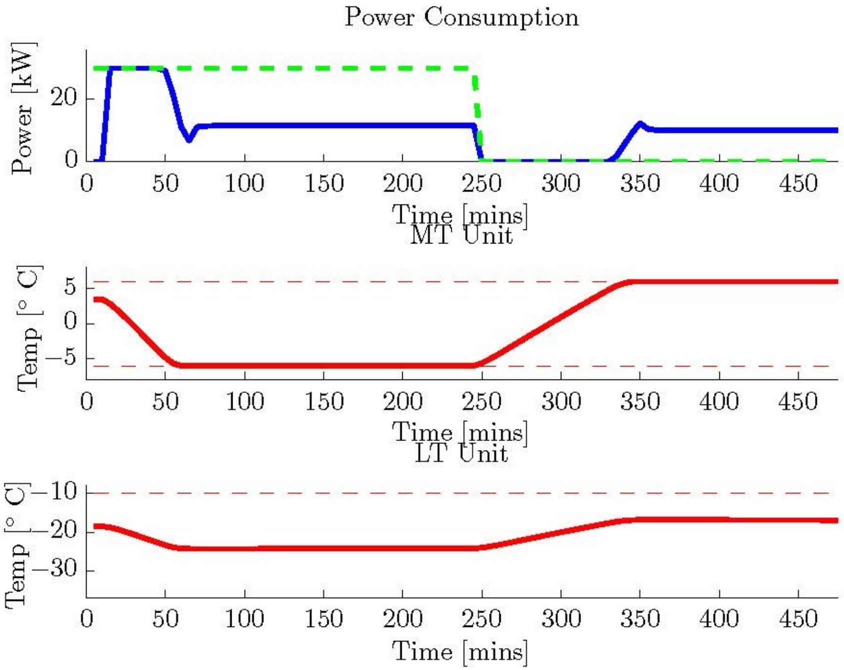
- Asymmetry



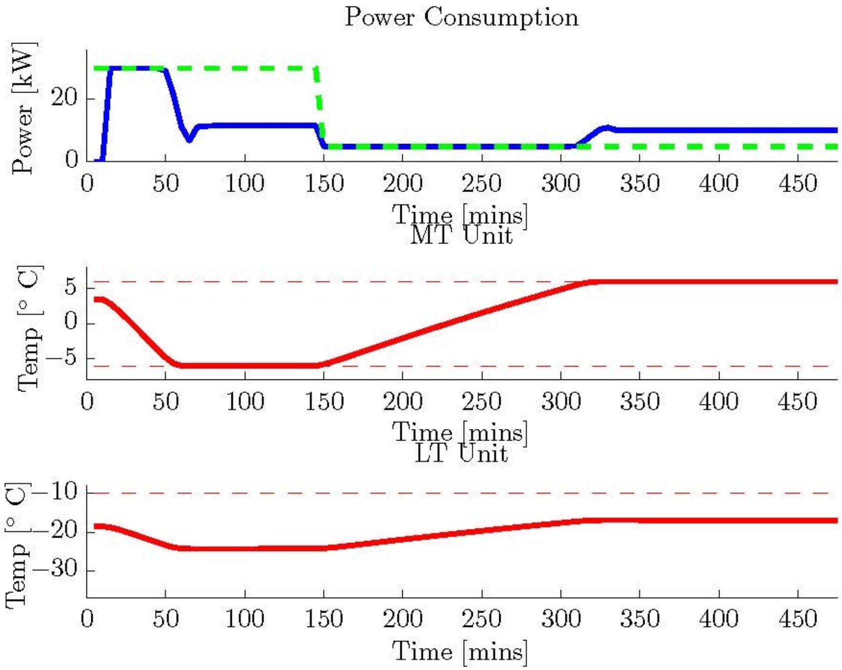


Simulations – Power Tracking

- Saturation Time

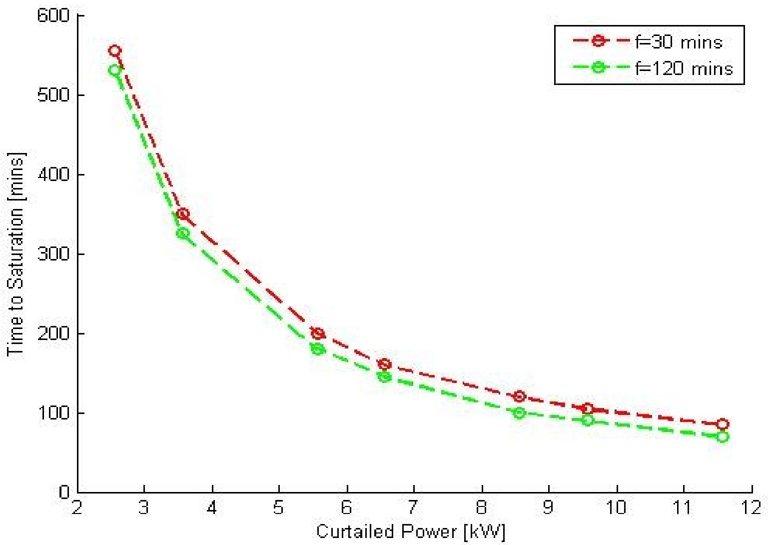


Pcurt: 0 kW



Pcurt: 5kW

Simulations - Power Tracking



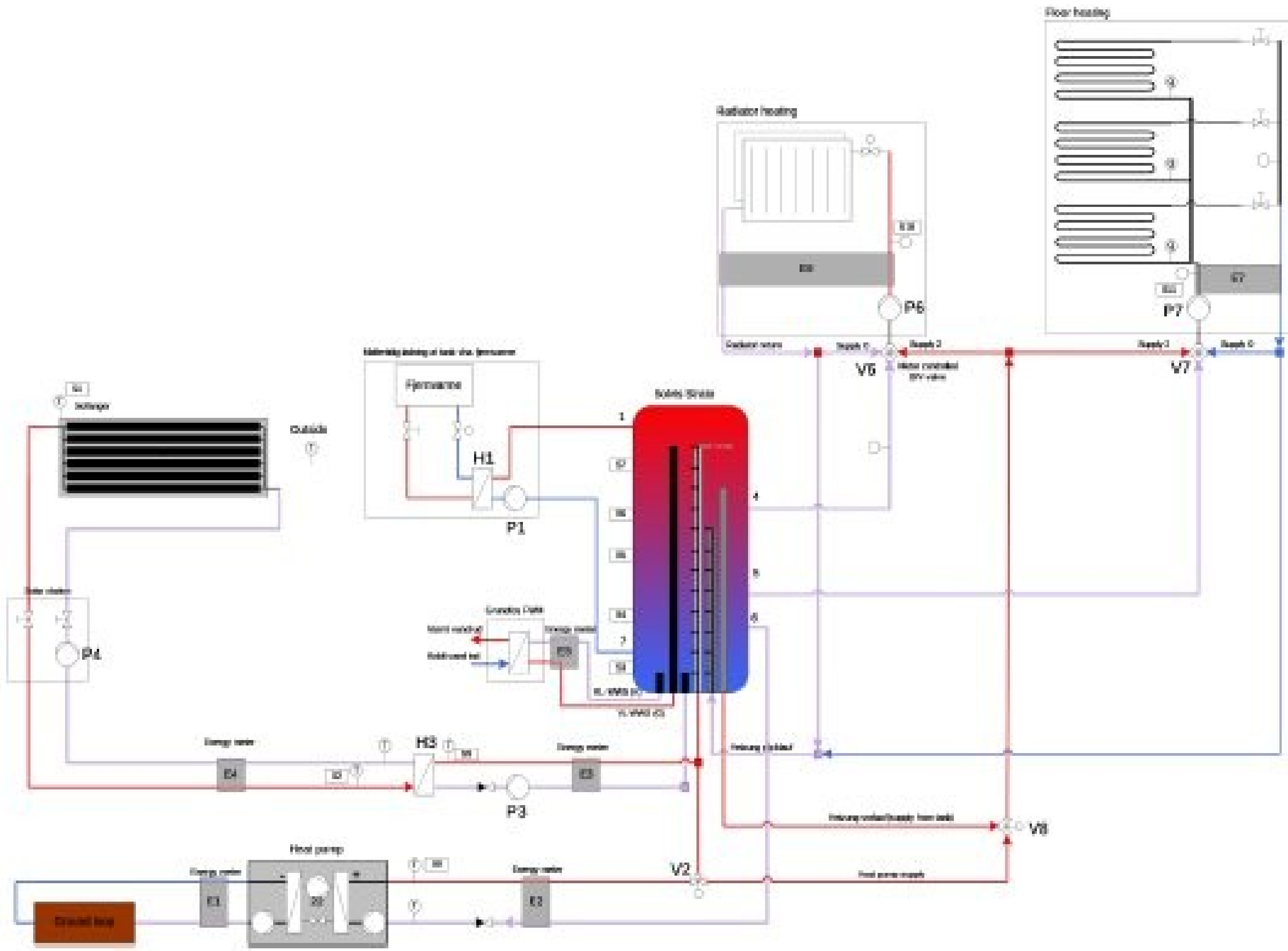
- Starting from maximum steady-state power consumption (to maintain **minimum** allowable temperature)
- Saturation defined as time until an increase in power consumption from the curtailed level (e.g. approximately time to reach **maximum** allowed temperature)
- Forecast of 30 minutes; initial work shows a longer forecasts decreases the time to saturation

Case study

Control of Heat Pumps

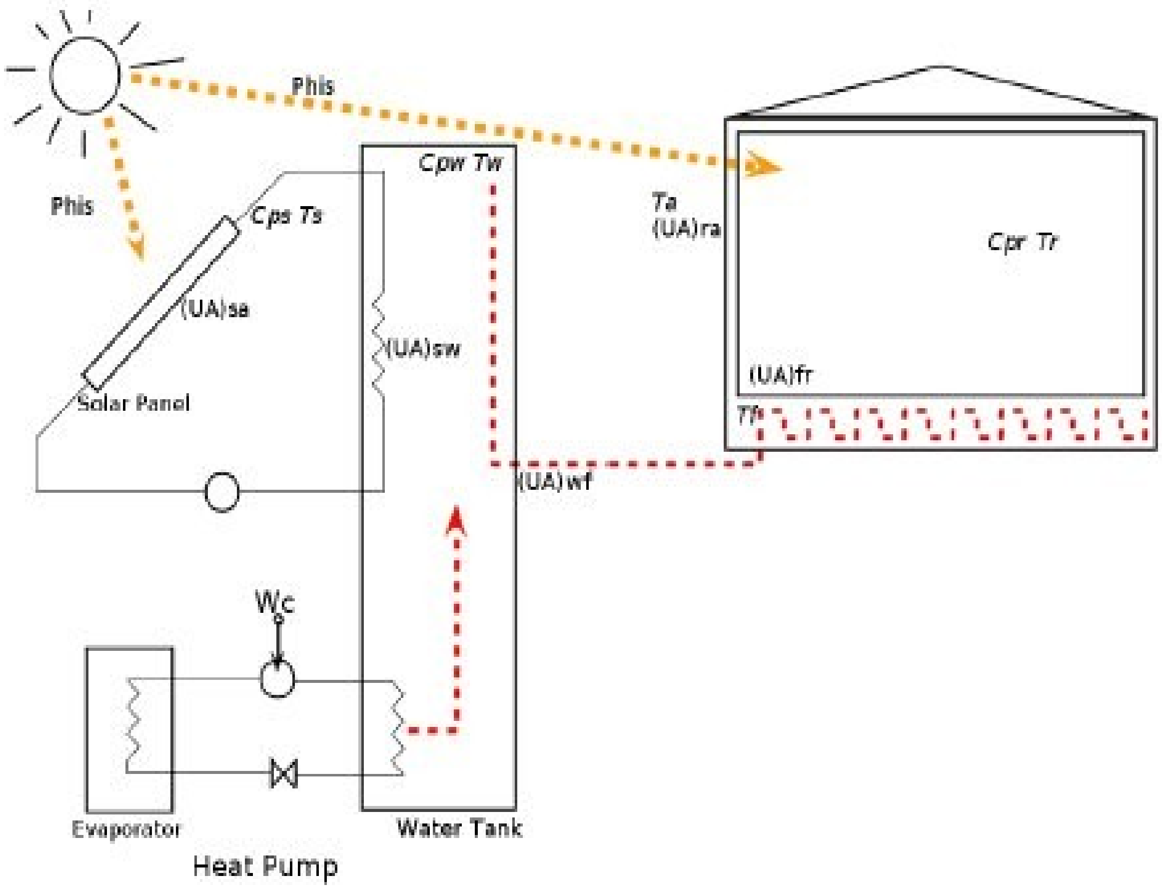
Grundfos Case Study

Schematic of the heating system



Modeling Heat Pump and Solar Collector

Simplified System



DTU

Modeling Heat Pump and Solar Collector

System Equations - Differential Equations

Equations

$$C_s \dot{T}_s = \eta \Phi_s - (UA)_{sw}(T_s - T_w) - (UA)_{sa}(T_s - T_a) \quad (2a)$$

$$C_w \dot{T}_w = \eta W_c + (UA)_{sw}(T_s - T_w) - (UA)_{wf}(T_w - T_f) \quad (2b)$$

$$C_f \dot{T}_f = (UA)_{wf}(T_w - T_f) - (UA)_{fr}(T_w - T_f) + p\Phi_s \quad (2c)$$

$$C_r \dot{T}_r = (UA)_{fr}(T_f - T_r) - (UA)_{ra}(T_r - T_a) + (1 - p)\Phi_s \quad (2d)$$

Avanced Controller

Economic Model Predictive Control

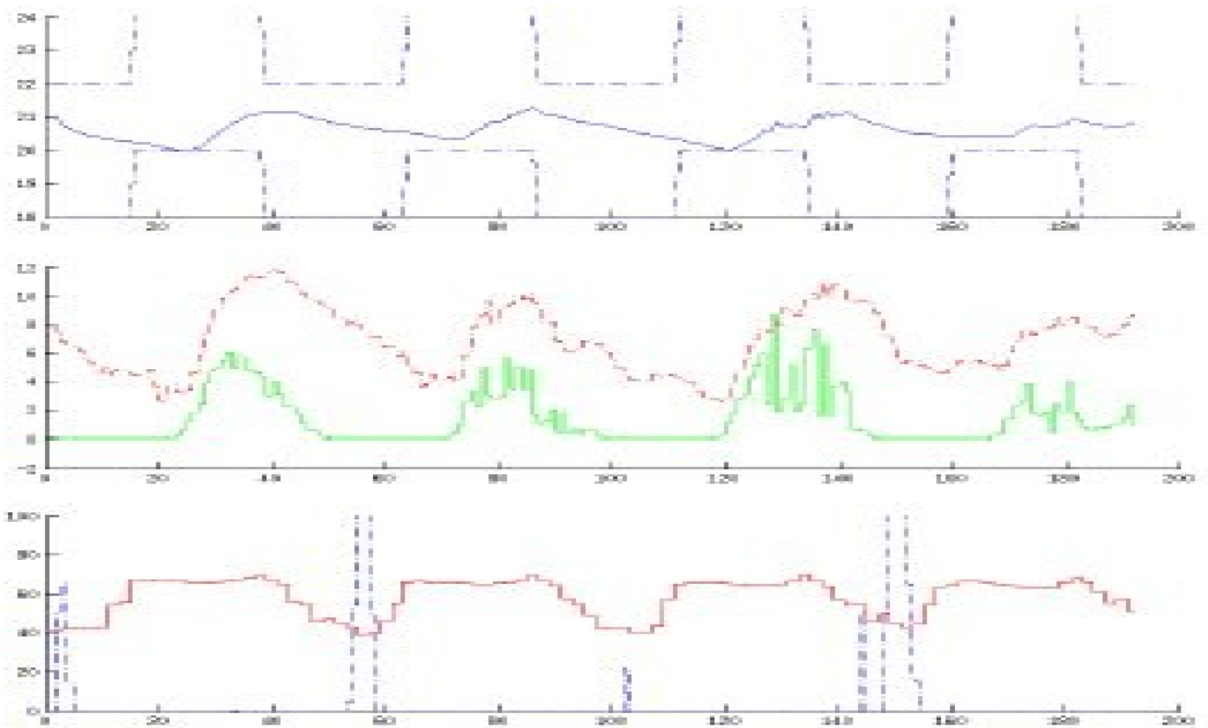
Formulation

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

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

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

EMPC for heat pump with solar collector



Conclusions

- A hierarchi of optimization/control problems with integrated forecasting for both direct and indirect control have been described. This structure facilitates energy systems integration.
- Examples of relevance for DSO's are outlined:
    - Control of heat accumulated in the thermal mass
    - Control of supermarket cooling (both direct and indirect control)
    - Control of heat pump and thermal solar collector system for a family house
- All examples have illustrated the used of forecasts
- For the moment direct control is mostly used for DSO DSM
- However, indirect control is now used more and more.

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