# Robust Model Predictive Control with Scenarios for Aggregators in Grids with High Penetration of Renewable Energy Sources


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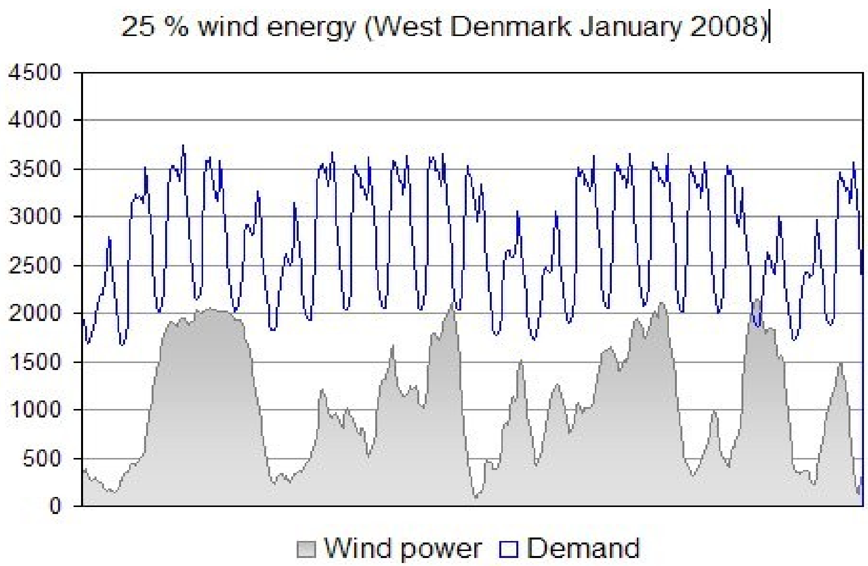
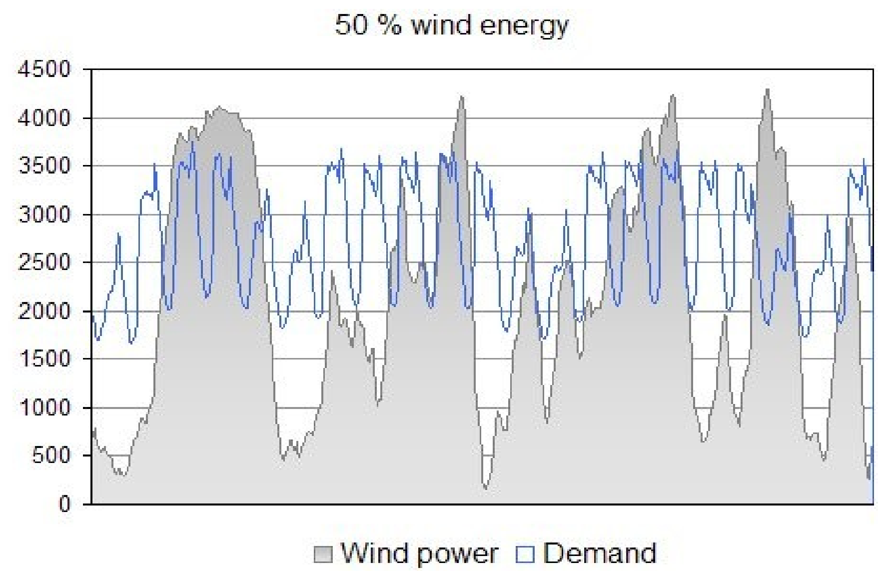
# The Danish Wind Power Case

*…. balancing of the power system*




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

**In 2017 more than 44 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

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# Challenges

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Preparatory study on Smart Appliances

European Commission

Ecodesign Preparatory Study performed for the European Commission

Welcome | **Project summary** | Planning & Meetings | Documents | Register for website | Register for meeting | Contact & Consortium

Home > Project summary

## Project Summary

**Almost no Flexibility**

The Ecodesign Preparatory Study on Smart Appliances (Lot 33) has analysed the technical, economic, market an[illegible]tal aspects with a view to a broad introduction of smart appliances and to develop adequate policy approaches supporting such uptake.

The study deals with Task 1 to 7 of the Methodology for Energy related products (MEErP) as follows:

- Scope, standards and legislation (Task 1, Chapter 1);
- Market analysis (Task 2, Chapter 2);
- User analysis (Task 3, Chapter 3);
- Technical analysis (Task 4, Chapter 4);
- Definition of Base Cases (Task 5, Chapter 5);
- Design options (Task 6, Chapter 6);
- Policy and Scenario analysis (Task 7, Chapter 7).

An executive summary of the project results can be downloaded here.

Throughout the study, new relevant aspects have come up which will be covered in a second phase of the Preparatory Study:

- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.

# Data Intelligent and Flexible Energy Systems

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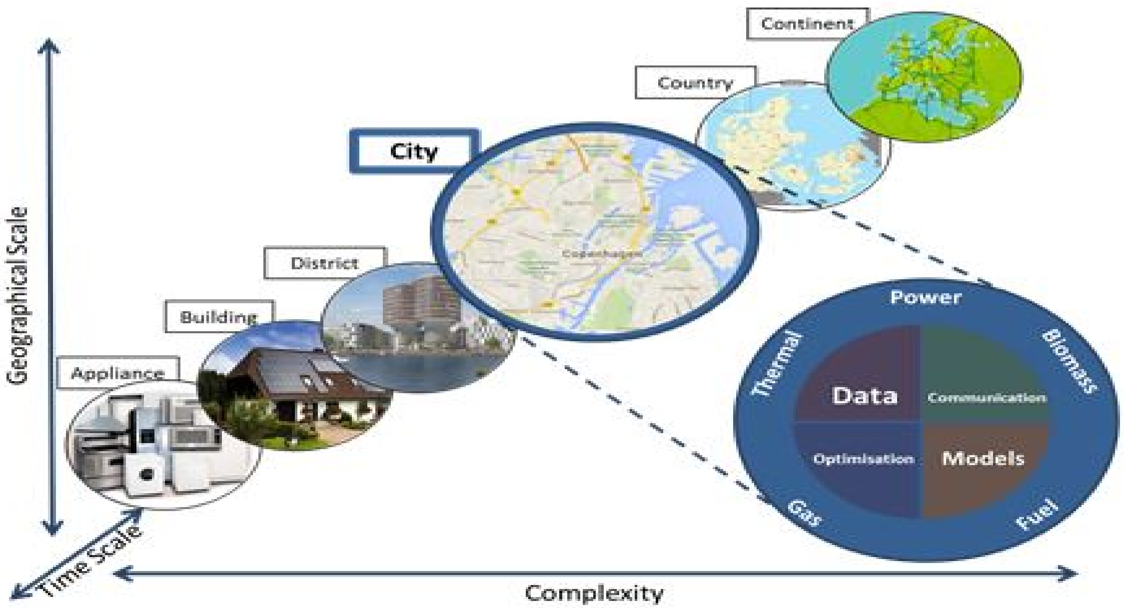
# Temporal and Spatial Scales

The ***Smart-Energy Operating-System (SE-OS)*** is used to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for ***operating flexible electrical energy systems*** at **all scales**.

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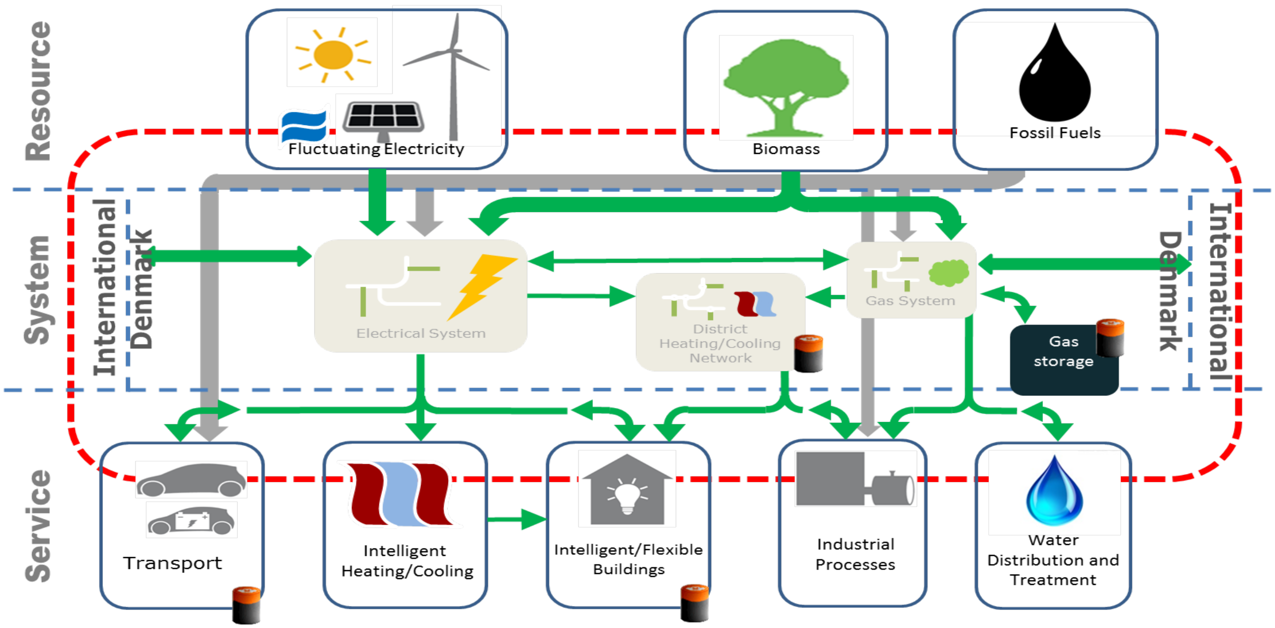
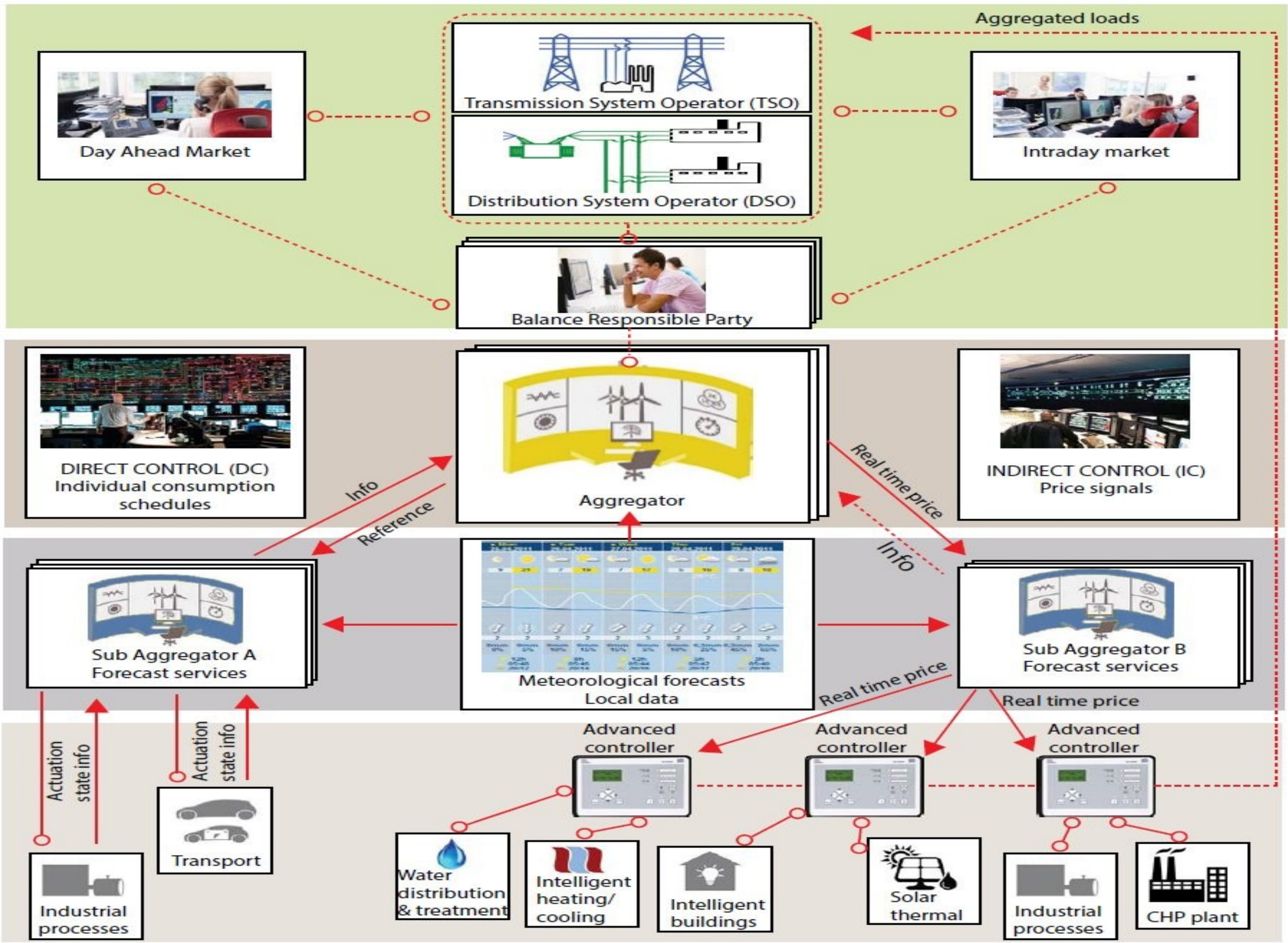
# Models for Systems of Systems

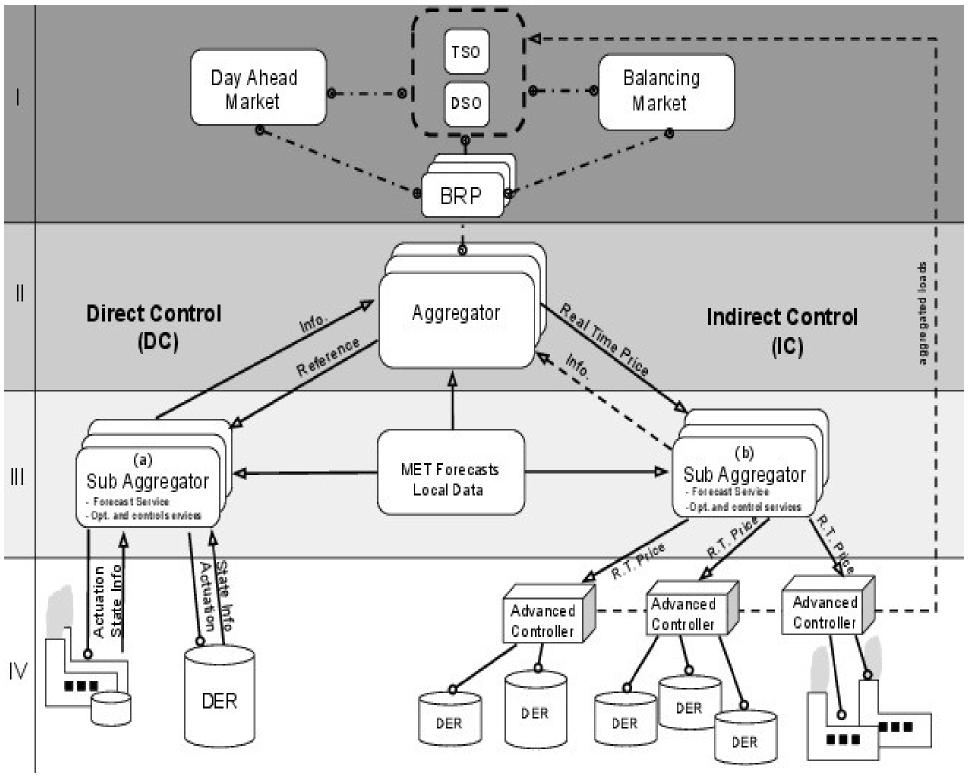
**Intelligent systems integration** using **big data and ICT solutions** are based on **models for real-time operation of flexible energy systems**



# Smart-Energy OS



# Control and Optimization




**In 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

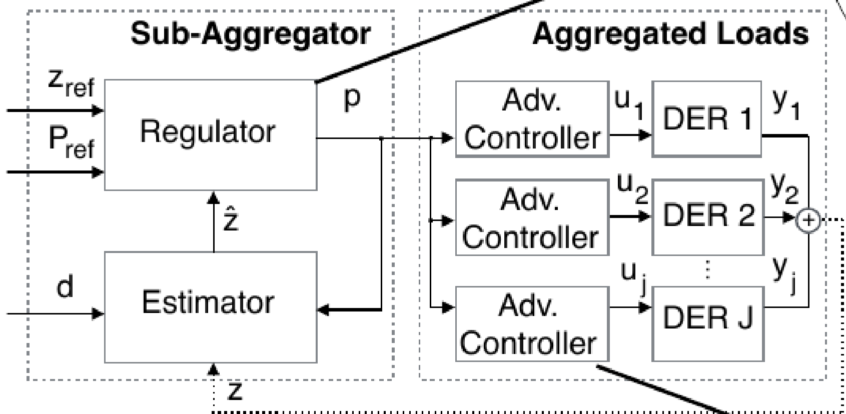
Models for DERs are not needed

Simple 'contracts'

```
# slow approach, but we are sure things get don
# Try to parallelize anyway
require(multicore)
numcores<-multicore:::detectCores()
mclapply(
  1:N, 
  function(i,data) {
    print(paste(i, "/", N))

    # Find the indices of rows corresponding to
    j <- which(data$dt_agg %in% aggdata$dt[i])

    # Filter out those who are NA
    j <- j[!is.na(data$last_one_min_power[j])]

    # Count number of readings
    aggdata$num_readings[i] <- length(j)
```

# Proposed methodology
# Control-based methodology

$$\min_{p} \quad \mathrm{E}[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||]$$
$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$




$$\begin{aligned} \min_{u} \quad & \mathrm{E}[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)] \\ \text{s.t.} \quad & x_{k+1} = Ax_k + Bu_k + Ed_k, \\ & y_k = Cx_k, \\ & y_k^{min} \leq y_k \leq y_k^{max}, \\ & u_k^{min} \leq u_k \leq u_k^{max} \end{aligned}$$

We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

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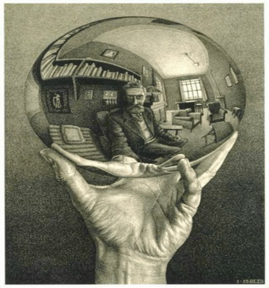
# Data Intelligent Energy Systems

- Automatic and self-cal. methods based on Big Data analytics and AI
- Labs – Virtual, HiL, Live
- Peer-to-peer communication (incl. blockchain)
- Nested sequence of systems – systems of systems
- Hierarchy of stoch. optimization (or control) problems
- Multivariate probabilistic forecasting
- Control principles at higher spatial/temporal resolutions
- Cloud or Fog (IoT, IoS) based solutions – eg. for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ...)
- Allow for new players (specialized aggregators)
- Simple setup for the communication and contracts
- Harvest flexibility at all levels



# Robust and
# Scenario-based
# Control at Aggregator Level

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# Example: Scenario-based Robust Control (Level III)

The scenarios generated $k = 1, \ldots, K, \forall k \in \mathcal{K}$ are applied to a robust optimization problem by minimizing the cost at the worst case scenario. This leads to the formulation of the robust Aggregator problem as:

$$\begin{aligned} \underset{u}{\text{minimize}} \quad & \max_{k=1,\ldots,K} \sum_{j=1}^{J} \phi_j^{(k)}(u_j^{(k)}) \\ \text{subject to} \quad & \sum_{j=1}^{J} u_j^{(k)} = 0, && \forall k \in \mathcal{K} \\ & u_j^{(1)}(t) = u_j^{(k)}(t), && \forall k \in \mathcal{K}, j \in \mathcal{J} \end{aligned} \tag{2}$$

# Example: DER advanced controller (Level IV)

*D. Advanced Controllers*

Advanced controllers are DER units that operate with a more complex controller such as MPC. Their optimization problem is represented in (6).

$$\underset{u,s}{\text{minimize}} \quad \sum_{k=0}^{N-1} p' u_k + \rho' s_k \tag{6a}$$

$$\text{subject to} \quad x_{k+1} = Ax_k + Bu_k + Ed_k \tag{6b}$$

$$y_k = Cx_k \tag{6c}$$

$$u_{min} \leq u_k \leq u_{max} \tag{6d}$$

$$\Delta u_{min} \leq \Delta u_k \leq \Delta u_{max} \tag{6e}$$

$$y_k + s_k \geq y_{min} \tag{6f}$$

$$y_k - s_k \leq y_{max} \tag{6g}$$

$$s_k \geq 0 \tag{6h}$$

# Example: Wind turbine scenarios

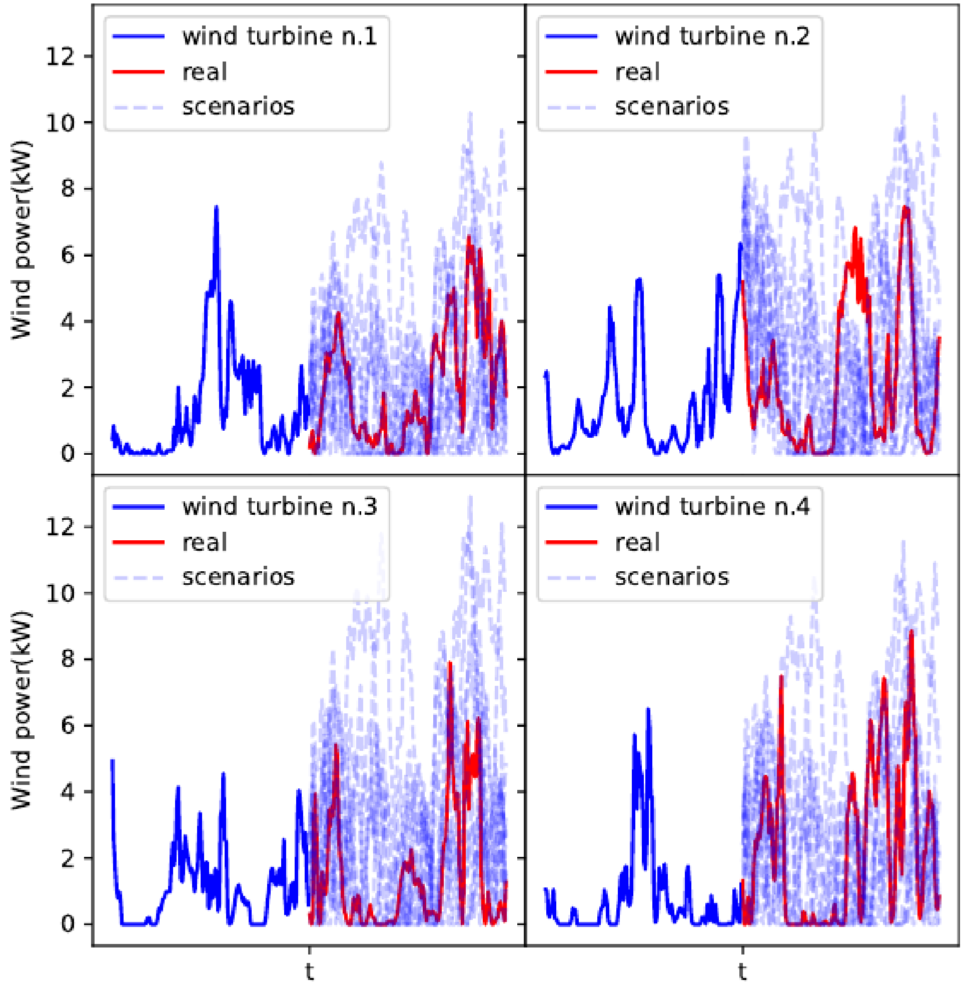


Fig. 2. Four wind turbines scenarios. For each turbine, 10 different scenarios are calculated for a period of 6 days starting from time $t$. In dark blue the real production data from the wind turbines, while the scenarios are represented by the light dash blue lines. In red the real power production for each turbine.

# Results:

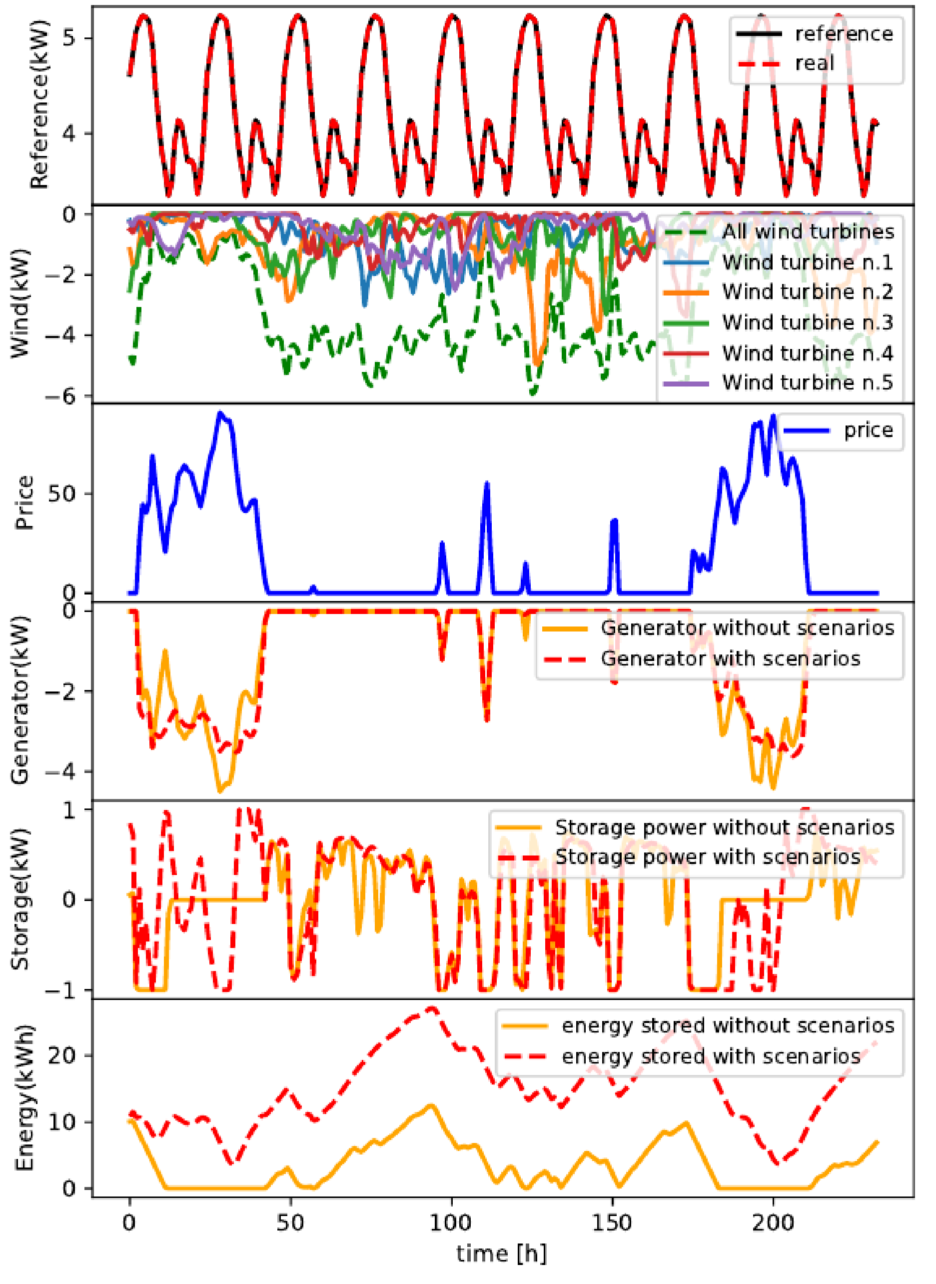


Fig. 4. Closed loop robust MPC simulation over ten days of data using 10 scenarios and 48 hours ahead prediction horizon.

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# Case study No. 1

# Control of heat pumps for swimming pools (Minimization of Cost / CO2)

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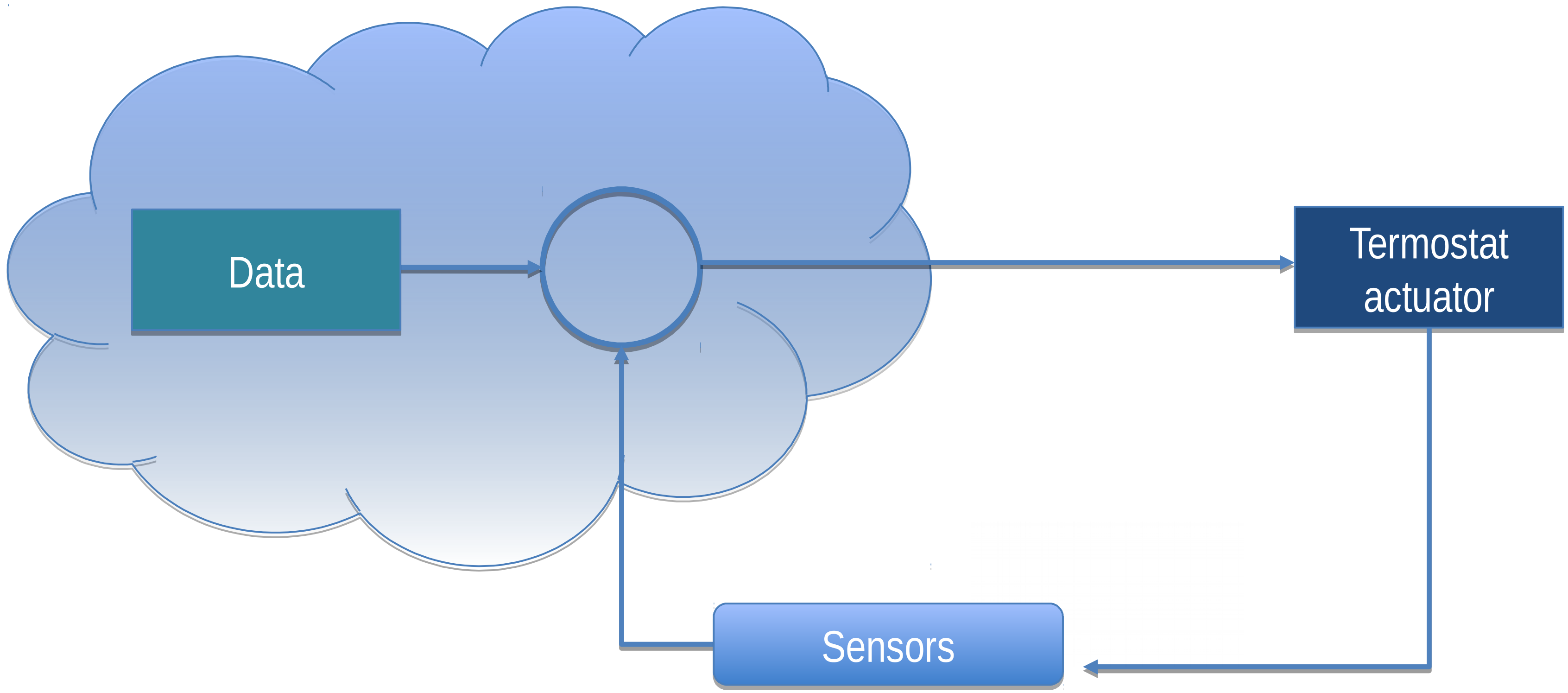
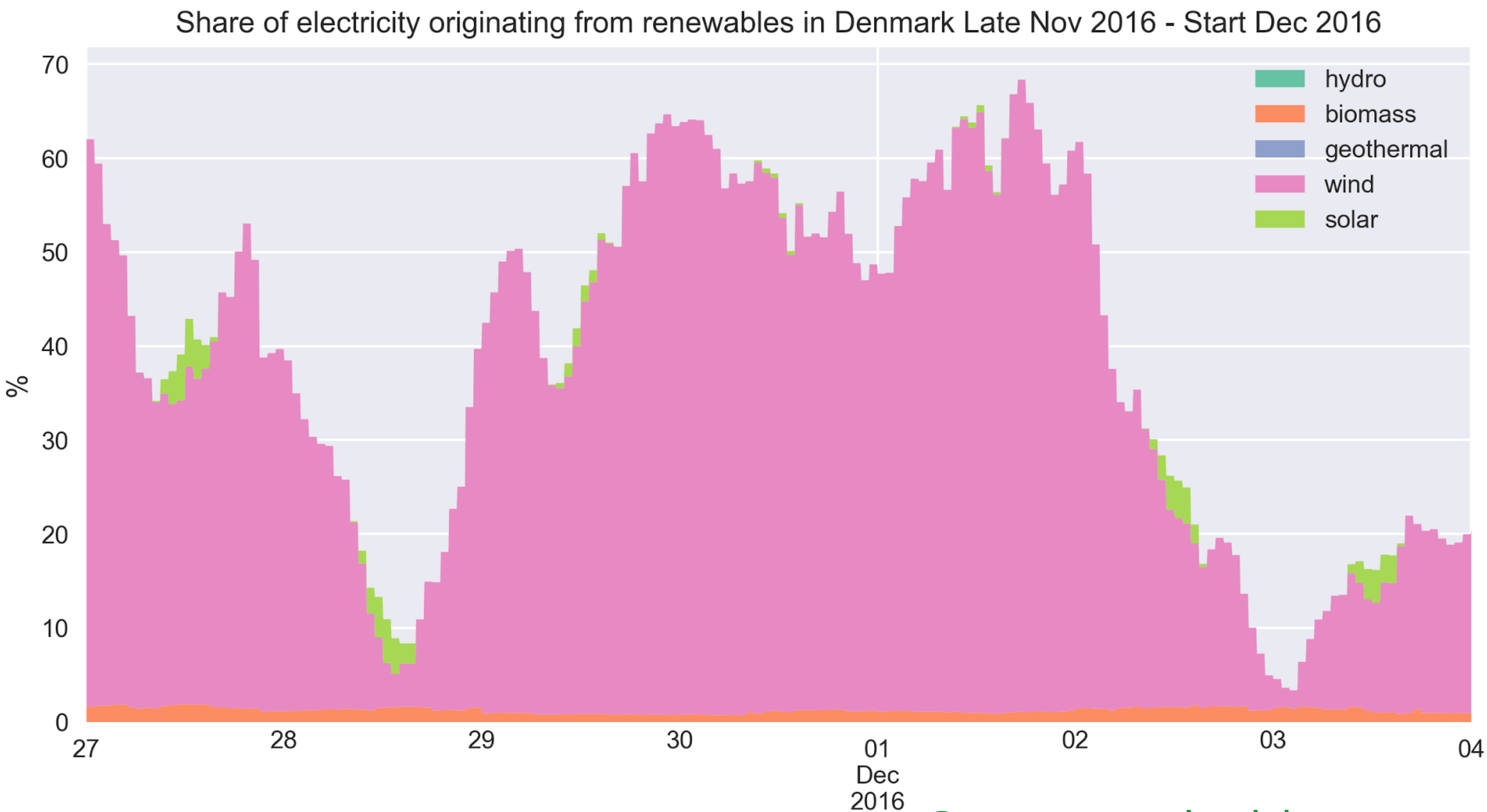
# SE-OS
# Control loop design – **logical drawing**






Source: pro.electicitymap.org

# Example: Price-based control

# Example: $CO_2$-based control

# Penalty Function (examples)

- **Real time $CO_2$**. If the real time (marginal) $CO_2$ emission related to the actual electricity production is used as penalty, then, a smart building will minimize the total carbon emission related to the power consumption. Hence, the building will be *emission efficient*.

- **Real time price**. If a real time price is used as penalty, the objective is obviously to minimize the total cost. Hence, the building is *cost efficient*.

- **Constant**. If a constant penalty is used, then, the controllers would simply minimize the total energy consumption. The smart building is, then, *energy efficient*.

# Summary

- A framework called Smart-Energy OS based on AI and Big Data Analytics is described for implementing smart energy systems
- The SE-OS setup can focus on
  - Energy Efficiency
  - Cost Efficiency (Minimization)
  - Emission Efficiency (-> accelerating the transition to a low-carbon energy system)
  - Smart Grid demand (like ancillary services needs, ...)
- We have demonstrated <u>a large potential for unlocking the flexibility</u> and for demand response using big data analytics and AI
- We have suggested a method for characterizing the energy flexibility which facilitates smart grid applications

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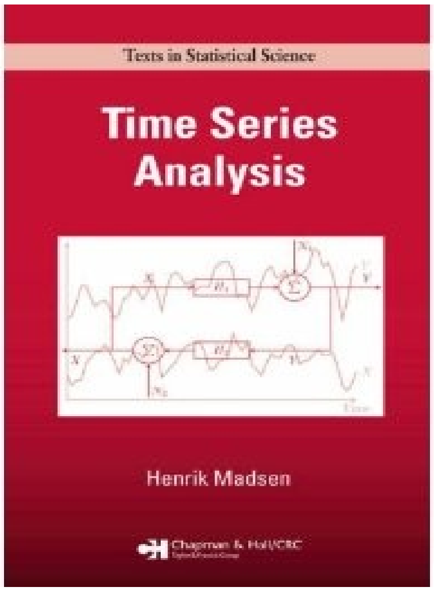
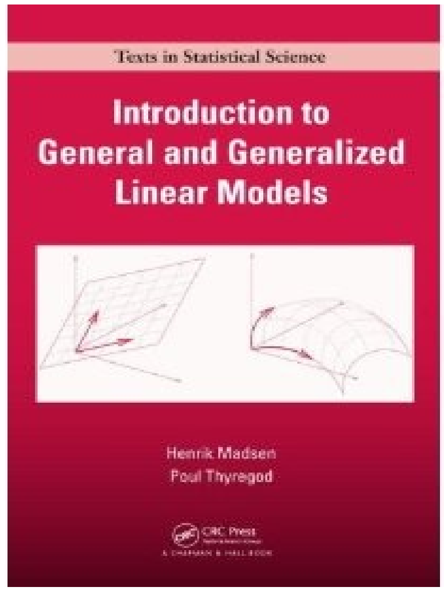
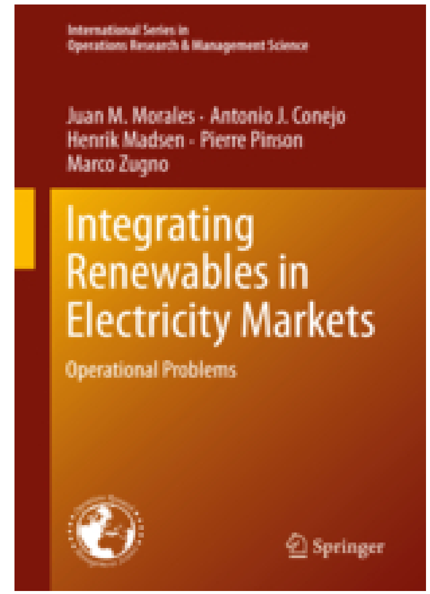
## Some 'randomly picked' books on modeling ....



# For more information ...

See for instance

www.smart-cities-centre.org

...or contact

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