Methodologies for Operating Future Intelligent Power and Energy Systems

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The Danish Wind Power Case

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.
Wind integration in Denmark

**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

**Legend**
- Jutland - Sweden
  - Exports: 332 MW
- Jutland - Norway
  - Exports: 1,530 MW
- Zealand - Sweden
  - Exports: 1,026 MW
- Bornholm - Sweden
  - Exports: 16 MW
- Jutland - Germany
  - Imports: 473 MW
- Zealand - Germany
  - Imports: 336 MW

The Great Belt
--- > 590 MW

Last updated: 2. februar 2016 23:28
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

DK has enough excess heat to cover the entire need for heating .... but ...
Collector area now: 1.3 mill m²
CHP and Integrated Energy Systems
(Paradigmatic example - Denmark)

- Gas Turbine
- Steam Turbine
- District heating
- Heat tank

- Electricity
- Waste incinerators,
  Supermarket cooling,
  Industrial processes
Energy Systems Integration

Energy system integration (ESI) = the process of optimizing energy systems across multiple pathways and scales
Digital revolution

Courtesy of Niels Lassen

When we use their product, they gather information on how we use it, our preferences etc.
Crucial information regarding how the product can be further developed

The «Internet Of Things» (IoT), and Sensor Technology enables us to do the same for Buildings and Cities using Big Data Analytics
Collect data on three levels

<table>
<thead>
<tr>
<th>Physical environment</th>
<th>Sensed environment</th>
<th>Total user satisfaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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**By using a simple system for data collection via existing room automation systems, new smart sensors, smart phones with IoT and cloud computing we can achieve a high degree of accuracy for the automation system. Collecting data about the indoor environment and user at the same time**

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**Please submit your feedback:**

- Cooler
- Warmer
- Bad air
- Draft

**Smartphone or room tablet**

**Measurement of user satisfaction at entrance door**
# Big Data value chain

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<th>Sense</th>
<th>Think</th>
<th>Act</th>
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<tr>
<td><strong>Data Origins</strong>&lt;br&gt;The Internet, sensors, machines, etc.</td>
<td><strong>Data Collection</strong>&lt;br&gt;Web log, sensor data, images/audio, RFID and videos, etc.</td>
<td><strong>Analytics:</strong>&lt;br&gt;Predictive analytics, patterns in data, decision making</td>
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<td><strong>Data Storage</strong>&lt;br&gt;Technologies supporting data storage</td>
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<td><strong>Consumers:</strong>&lt;br&gt;Business processes, humans, and applications</td>
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**Sense**
- Data Origins: The Internet, sensors, machines, etc.

**Think**
- Data Collection: Web log, sensor data, images/audio, RFID and videos, etc.
- Data Storage: Technologies supporting data storage
- Analytics: Predictive analytics, patterns in data, decision making

**Act**
- Consumers: Business processes, humans, and applications
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.
Smart-Energy OS

Day Ahead Market

Transmission System Operator (TSO)

Distribution System Operator (DSO)

Intraday market

Balance Responsible Party

Direct Control (DC)
Individual consumption schedules

Indirect Control (IC)
Price signals

Sub Aggregator A
Forecast services

Meteorological forecasts
Local data

Sub Aggregator B
Forecast services

Advanced controller

Industrial processes
Transport

Water distribution & treatment
Intelligent heating/cooling
Intelligent buildings
Solar thermal
Industrial processes
CHP plant
Control and Optimization

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'

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

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.
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
Direct and Indirect Control

For DC info about individual states and constraints are needed
Grey-box modelling are used to establish models and methods for real-time operation of future electric energy systems.
SE-OS Characteristics

- Bidding – clearing – activation at higher levels
- Control principles at lower levels
- Cloud based solution for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ...)
- Allow for new players (specialized aggregators)
- Simple setup for the communication
- Simple (or no) contracts
- Rather simple to implement
- Harvest flexibility at all levels
SE-OS
Control loop design – **logical drawing**
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.
Lab testing ....
SN-10 Smart House Prototype
Which type of forecast?

- Point forecasts
- Conditional mean and covariances
- Conditional quantiles (Prob. forecasts)
- Conditional scenarios
- Conditional densities
- Stochastic differential equations
Wind and Solar Power Forecasting

- Methods for wind power forecasting have been continuously developed and used operationally since 1995 (solar power since 2005).
- Implemented for instance in WPPT, Anemos WPS, AWEFS, ASEFS, ..
- Sold for instance in systems provided by ENFOR (Denmark) and Overspeed GmbH (Germany)
- Today our systems are used worldwide (North America, Europe, Africa, Japan, Middle East, Australia).
- Used by all major players in Denmark (TSO, DSOs, BRPs, ...)

CITIES
Centre for IT Intelligent Energy Systems

Croatia - VIP / Smart Grid / Government - February 2017
Example

Solar Power Forecasting
Solar Power Forecasting

- Grid connected PV-systems mainly installed on rooftops
- Average of output from 21 PV systems in Brædstrup
Method

- Based on MET forecasts and online readings of output
- Two-step method:
  1) Transformation to atmospheric transmittance with statistically clear sky (see above),
  2) A dynamic model + adaptive quantile regression.
Example
(quantile forecasts – up to 36h ahead)
Grey Box Models for Integration

Energy Systems Integration using data leading to stochastic grey box models for real-time operation of future flexible energy systems.
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Case study

Control of Power Consumption to Summer Houses with a Pool
Services

- Balancing
  - The large inertia of pools allows for shift of electricity consumption by several hours.

- Voltage regulation (DSO)
  - Via active coordination of the flexibility below a critical node on the DSO grid.

- Congestion management
  - Active load management to help finding an optimal routing of the power.
Smart Control of Houses with a Pool

PilotB SN-10 signal overview
revision 1.0 (CITIES add-on)
Case study

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

Olympic Peninsula 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

![Graph showing consumption response to price step change. The graph indicates a 5-hour response time.](image)
Control of Power Consumption
Control performance

Considerable reduction in peak consumption
Case study

Heat Pumps and Local Storage
Grundfos Case Study

Schematic of the heating system
Modeling Heat Pump and Solar Collector

Simplified System
**Formulation**

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

\[
\begin{align*}
\min_{\{u_k\}_{k=0}^{N-1}} & \quad \phi = \sum_{k=0}^{N-1} c' u_k \\
\text{Subject to} & \quad x_{k+1} = Ax_k + Bu_k + Ed_k \quad k = 0, 1, \ldots, N - 1 \\
& \quad y_k = Cx_k \quad k = 1, 2, \ldots, N \\
& \quad u_{\min} \leq u_k \leq u_{\max} \quad k = 0, 1, \ldots, N - 1 \\
& \quad \Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max} \quad k = 0, 1, \ldots, N - 1 \\
& \quad y_{\min} \leq y_k \leq y_{\max} \quad k = 0, 1, \ldots, N 
\end{align*}
\]
Heat pump with thermal solar collector and storage (savings up to 35%)}
Case study

Control of Wastewater Treatment Plants
Waste-2-Energy

Resources

- Electricity
- Waste water

WWTP Energy Hub

- Treatment Process
- Digester
- Storage tank
- CHP

Energy service

- Gas
- Electricity
- Heating
Kolding WWTP
Energy Flexibility in Wastewater Treatment

- Sludge -> Biogas -> Gas turbine -> Electricity
- Power management of the aeration process
- Pumps and storage in sewer system

Overall goals:
- Cost reduction
- Minimize effluent concentration
- Minimize overflow risk
Energy Flexibility in Wastewater Treatment
WWTP Control goal

\[ \text{minimize } p_{\text{fee}} Q^T S_N + p_{\text{el,spot}}^T u \]
minimize overflow + \( p^T_{pspot} f(Q) \)
Sewer System Annual Elspot Savings

Savings [1000 DKK] vs. Storage volume [m³]

- Savings increase with increasing storage volume.
- A significant increase in savings is observed as storage volume increases.
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, ...)
- EV (charging) (Eurisco, ED, ...)

............
(Virtual) Storage Solutions

- 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
- DH systems with thermal solar collectors can often provide seasonal storage solutions
- Gas systems can provide seasonal/long term storage solutions
2017: Key Exponential Technologies

- Use of (smart) meters and many sensors
- Big Data, IoT, IoS Technologies
- Systems of Systems
- Aggregation (on all scales)
- Intelligent Data Analytics / Artificial Intelligence
- Community Driven Solutions
- Open Data / Open Source Solutions
- (Virtual) Energy Storage
- Energy flexible automated manufacturing / Robotics
- eMoney / eFinance
- 3D printing and visualization
EERA Joint Program on Energy Systems Integration

Workshop 2\textsuperscript{nd} to 4\textsuperscript{th} Nov. on DTU - Please join us.
We pioneer the green transition in a unique partnership with the industry, academia and state-actors.

100% renewable urban energy systems, is 100% possible. We are actors from the Danish industry, academia and public sector pioneering the green transition through integrated energy systems powered by intelligent data. Join us now for a safer and greener future.
Discussion

- IT-Intelligent Energy Systems Integration can provide virtual storage solutions (so maybe we should put less focus on electrical 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
- Smart Cities are just smart elements of a Smart Society
- 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).
- 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)
Summary

- A Smart-Energy/Grid OS for implementing flexibility energy systems in smart energy systems has been described.
- Built on: Big Data Analytics, Cyber Physical systems, Stochastic opt./control, Forecasting, IoT, IoS, Cloud computing, ...
- **Modelling**: Toolbox – CTSM-R - for combined physical and statistical modelling (grey-box modelling)
- **Control**: Toolbox – MPC-R - for Model Predictive Control
- **Simulation**: Framework for simulating flexible power systems.