Methodologies for Operating Future Intelligent Energy Systems

Henrik Madsen, DTU Compute
http://www.henrikmadsen.org
http://www.smart-cities-centre.org
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 export: 2,096
- Electricity consumption: 3,469
- CO2 emissions: 164 g/kWh

LEGEND

- The Great Belt: 590 MW
- Jutland - Sweden: Exports: 332 MW
- Zealand - Sweden: Exports: 1,026 MW
- Jutland - Norway: Exports: 1,530 MW
- Zealand - Germany: Imports: 336 MW
- Jutland - Germany: Imports: 473 MW
- Bornholm - Sweden: Exports: 16 MW

Last updated: 2. februar 2016 23:28
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 kWh/h
- Ellund exit: 1,002,678 kWh/h
- Dragør exit: 1,405,760 kWh/h
- Energinet.dk Gas Storage: 824,732 kWh/h
- DONG Storage: 0 kWh/h
- Exit Zone: 4,776,523 kWh/h
- CO2 emission factor: 56,76 kg/GJ

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

Egtved Calorific value: 12,213 kWh/m³
CO2 emissions faktor: 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

Dragør Exit: 1,405,760 kWh/h
Calorific value: 12,234 kWh/m³

Last updated: 15. februar 2014 12:31
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 ...
CHP and Integrated Energy Systems
(Paradigmatic example - Denmark)

Gas Turbine

Steam Turbine

Electricity

District heating

Heat tank

Waste incinerators,
Supermarket cooling,
Industrial processes

Electricity
Solar district heating in Denmark

Planned in 2014
197,855 M²

Total collector area: 574,023 m²
Energy Systems Integration

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

Direct vs Indirect Control

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

For DC info about individual states and constraints are needed.

(a) Indirect control

(b) Direct control
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, ...)
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)
Adaptive correction method
Adaptive correction method
Adaptive correction method (correction function)
Adaptive correction method
Example

Grey-box Modelling
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.
The grey-box model

Notation:

\[ X_t: \text{ State variables} \]
\[ u_t: \text{ Input variables} \]
\[ \theta: \text{ Parameters} \]
\[ Y_k: \text{ Output variables} \]
\[ t: \text{ Time} \]
\[ \omega_t: \text{ Standard Wiener process} \]
\[ e_k: \text{ White noise process with } N(0, \Sigma) \]
Grey-box modelling concept

- Combines prior physical knowledge with information in data
- Equations and parameters are physically interpretable
Grey-box model building

Model (re)formulation → Non-parametric modelling → Statistical tests → Falsification or unfalsification → Stochastic state-space model

→ Parameter estimation → Residual analysis
Grey-Box Modelling

- Bridges the gap between physical and statistical modelling
- Provides methods for model identification
- Provides methods for model validation
- Provides methods for pinpointing model deficiencies
- Enables methods for a reliable description of the uncertainties, which implies that the same model can be used for k-step forecasting, simulation and control

CITIES
Centre for IT Intelligent Energy Systems
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Case study

Control of Power Consumption to Summer Houses with a Pool
Services

- The large inertia of pools allows for shift of electricity consumption by several hours.
- Via active coordination of the flexibility below a critical node on the DSO grid.
- 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 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

![Graph showing consumption step response](chart.png)

- Consumption step response (Olympic Pen.)
- 5 hours
Control of Power Consumption

Diagram:

- Consumption references
- Model parameters
- Price generator (controller)
- Prices
- Price-responsive consumption
- Aggregated consumption

Diagram includes scales balancing various elements related to power consumption and price response.
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
Advanced Controller
Economic Model Predictive Control

Formulation

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

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

Control of Wastewater Treatment Plants
Waste-2-Energy

Resources

- Electricity
- Waste water

WWTP Energy Hub

- Treatment Process
- Digester
- Storage tank
- Gas storage
- CHP

Energy service

- Gas
- Electricity
- Heating
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

$$\text{minimize } p_{fee} Q^T S_N + p_{elspot}^T u$$
Activated Sludge Model (ASM) No. 1

\[
\begin{align*}
\dot{S}_{NH} &= -i_{XB} (\rho_1 + \rho_2) - \left( i_{XB} + \frac{1}{Y_A} \right) \rho_3 + k_a S_{ND} X_{B,H} \\
\dot{S}_{NO} &= -\frac{1 - Y_H}{2.68 Y_H} \rho_2 + \frac{1}{Y_A} \rho_3 \\
\dot{S}_O &= -\frac{1 - Y_H}{Y_H} \rho_1 - \frac{4.57 - Y_A}{Y_A} \rho_3 \\
\dot{S}_S &= \rho_7 - \frac{1}{Y_H} (\rho_1 + \rho_2) \\
\dot{X}_S &= (1 - f_p)(b_H X_{B,H} + b_A X_{B,A}) - \rho_7 \\
\dot{X}_{B,H} &= \rho_1 + \rho_2 - b_H X_{B,H} \\
\dot{X}_{B,A} &= \rho_3 - b_A X_{B,A} \\
\dot{S}_{ND} &= \rho_8 - k_a S_{ND} X_{B,H} \\
\dot{X}_{ND} &= (i_{XB} - f_p i_{XP})(b_H X_{B,H} + b_A X_{B,A}) - \rho_8
\end{align*}
\]

\((S_I, X_I, X_P, \text{ and } S_{ALK})\)
Reaction Rates in ASM No. 1

\[
\rho_1 = \hat{\mu}_H \frac{S_S}{K_S + S_S} \frac{S_O}{K_{O,H} + S_O} X_{B,H}
\]

\[
\rho_2 = \hat{\mu}_H \frac{S_S}{K_S + S_S} \frac{K_{O,H}}{K_{O,H} + S_O} \frac{S_{NO}}{K_{NO} + S_{NO}} \eta_g X_{B,H}
\]

\[
\rho_3 = \hat{\mu}_A \frac{S_{NH}}{K_{NH} + S_{NH}} \frac{S_O}{K_{O,A} + S_O} X_{B,A}
\]

\[
\rho_7 = k_h \frac{X_S / X_{B,H}}{K_X + X_S / X_{B,H}} \left( \frac{S_O}{K_{O,H} + S_O} + \frac{K_{O,H}}{K_{O,H} + S_O} \frac{S_{NO}}{K_{NO} + S_{NO}} \right) X_{B,H}
\]

\[
\rho_8 = \rho_7 \left( X_{ND} / X_S \right)
\]
Sewer System Control Goal

\[
\text{minimize overflow} + p_{\text{elspot}}^T f(Q)
\]
Sewer System Annual Elspot Savings
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

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
- DH systems with thermal solar collectors can often provide seasonal storage solutions
- Gas systems can provide seasonal/long term storage solutions
EERA Joint Program on Energy Systems Integration
Workshop 2\textsuperscript{nd} to 4\textsuperscript{th} Nov. on DTU - Please join us.
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)
A Smart-Energy OS for implementing flexibility energy systems in smart cities 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.
Some 'randomly picked' books on modeling....

2008

2011