Flexibility Potentials in Combined Power and Thermal Systems

Henrik Madsen, DTU Compute
http://www.henrikmadsen.org
http://www.smart-cities-centre.org
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.
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.
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
What has since been achieved: De-coupling of consumption and GDP growth

Flexibility in District Heating

Production

Production supply curves

Distribution

Distribution supply curves / price signals

Consumption

Displacement of consumption in buildings

Production heat accumulator

Distribution heat storage in network and accumulator
CHP and Integrated Energy Systems
(Paradigmatic example - Denmark)

Gas Turbine → Electricity

District heating → Heat tank

Steam Turbine

Waste incinerators,
Supermarket cooling,
Industrial processes

Electricity
Flexibility – Ringkøbing CHP

Ringkøbing District Heating - 28-05-2016 23:36:00

- Solar Collector: 59 °C, 0.0 MW, 100%
- Gas Engine: 0 m³/h, 0.0 MW, 100%
- Gas turbine: 0 m³/h, 0.0 MW, 100%
- Heat Storage: 2.2 MW, 82.0 MWh
- Forward temperature: 62 °C
- District Heating: 5.8 MW
- Return temperature: 38 °C

Sold Electricity: 0.0 MW

CITIES
Centre for IT Intelligent Energy Systems

IIESI & Skoltech 2nd International Conference
Flexibility – Ringkøbing CHP

Ringkøbing District Heating, Friday, 2016-01-01 to Friday, 2016-01-08
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>$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$</td>
<td>$\min_{\hat{z}, p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$</td>
</tr>
<tr>
<td></td>
<td>$\downarrow u_1 \ldots \downarrow u_J$</td>
<td>s.t. $\hat{z}_{k+1} = f(p_k)$</td>
</tr>
<tr>
<td>IV</td>
<td>$\uparrow x_1 \ldots \uparrow x_J$</td>
<td>$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k)$</td>
</tr>
<tr>
<td></td>
<td>s.t. $x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \forall j \in J$</td>
<td>s.t. $x_{k+1} = f_j(x_k, u_k)$</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.
Grey Box Models for Integration

Energy Systems Integration using data leading to stochastic grey box models for operation of future flexible energy systems.
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.
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 response to price step change with a time delay of 5 hours.](image-url)
Control of Power Consumption
Case study

Heat Pumps and Local Storage
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:

\[
\min_{\{u_k\}_{k=0}^{N-1}} \sum_{k=0}^{N-1} c'u_k
\]

Subject to

\[
x_{k+1} = Ax_k + Bu_k + Ed_k \quad k = 0, 1, \ldots, N - 1
\]

\[
y_k = Cx_k \quad k = 1, 2, \ldots, N
\]

\[
u_{\text{min}} \leq u_k \leq u_{\text{max}} \quad k = 0, 1, \ldots, N - 1
\]

\[
\Delta u_{\text{min}} \leq \Delta u_k \leq \Delta u_{\text{max}} \quad k = 0, 1, \ldots, N - 1
\]

\[
y_{\text{min}} \leq y_k \leq y_{\text{max}} \quad k = 0, 1, \ldots, N
\]
Heat pump with thermal solar collector and storage (savings up to 35 pct)
Case study

(Direct Control and Bids for Markets)

Virtual Storage Related to Super Market Cooling using Thermal Demand Response
Synergize: Virtual Storage using Thermal Demand Response

Thermal mass in refrigeration display cases facilitates the adjustment of power consumption while maintaining acceptable temperatures for food.

6kW of DR

Recovery period
The physical system

Fig. 2: Simplified graphical representation of the display case system
Fig. 3: Temperature, environmental (open/closed status, defrost status, ambient temperature) and control input (valve) data for an open medium temperature display case in a supermarket in Funen, Denmark
The grey-box model

Fig. 6: RC-Representation of a four time constant model ($T_i T_e T_f T_s$)
Flexibility Represented by Saturation Curves
(for market integration using block bids)
Case study

Use of Heat from Supermarket Cooling in DH Systems
Using Heat from Supermarket Cooling in the District Heating System

SuperBrugsen in Høruphav

- Area: 1000 m² from 2010
- Compressors: 5 MT (1 VS), 4 LT
- Cooling Capacity: 160 kW

- Heating:
  - Sanitary water (1800 l tank (65 °C )
  - Floor heating/low temp coils (35 °C )
  - District heating production
Using Heat from Supermarket Cooling in the District Heating System

Old setup

New setup
Using Heat from Supermarket Cooling in the District Heating System

- SuperBrugsen gets paid for energy they would have otherwise have paid for to get removed.
- Corresponds to the total consumption of 15-20 households.
- Payback time for SuperBrugsen is 1-2 years.
- Payback time for DH system is 3-4 years.
- This is a small supermarket. Business case even better for large supermarkets.
Virtual Storage or Flexibility 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
- Gas systems can provide seasonal storage
Discussion

- Intelligent Energy Systems Integration can provide virtual storage solutions (so maybe we should put less focus on physical 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.
- 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). 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)
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, ..)
- VE (charging) (Eurisco, ED, ..)