Integrated Modelling, Forecasting and Control for the Future Low-Carbon Society

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The Challenge: Denmark Fossil Free 2050

Renewables

FLEXIBILITY
real-time matching of energy demand & production through DIGITALIZATION of Integrated Energy Systems

Energy user

ELECTRICITY
BIOFUEL
HEAT

WATER
FOOD
HEATING
COOLING

CITIES, DiCyPs, FED – Green Digitalization 2020
Space of Solutions

Flexibility / Virtual Storage
(enabled by Digitalisation and Energy Systems Integration)

(Super) Grids

Batteries
Data-Intelligent and Flexible Energy Systems
Grey-box models are simplified models for the individual components facilitating system integration and use of sensor data.
Smart-Energy OS
Proposed methodology
Control-based methodology

\[
\begin{align*}
\min_p & \quad \mathbb{E}\left[ \sum_{k=0}^{N} w_{j,k} |\hat{z}_k - z_{ref,k}| + \mu |p_k - p_{ref,k}| \right] \\
\text{s.t.} & \quad \hat{z}_{k+1} = f(p_k)
\end{align*}
\]

We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.
A FED example: Flexible Users and Penalty Signals

**Penalty Generator** for, e.g.:
Voltage Control,
Balancing,
Congestion Management

**Penalty Signals** for:
Cost Efficiency,
Emission Efficiency,
Energy Efficiency

**Flexibility Function (Estimator)**

**Flexible User(s) (Penalty-responsive)**

Reference → **Penalty Generator (Controller)** → Penalty → Response
Case study No. 1

Control of heat pumps for swimming pools (CO2 minimization)
The considered house

- $T_{sh}$ – summerhouse temperature
- $T_a$ – temperature of air in the pool area
- $T_{in}$ – water temperature into the swimming pool
- $T_{out}$ – water temperature out of the swimming pool (controlled)
- $T_o$ – outdoor temperature
- $T_g$ – ground temperature
- $Q_s$ – solar heat gain
- $w$ – wind speed
Grey-box model
(lumped parameter model)

- Based on equivalent thermal parameters model

- Dynamics:
  
  \[
  \frac{dT_{in}}{dt} = \frac{1}{C_{in}} \left[ H_w (T_{out} - T_{in}) + Q_{in} \right]
  \]
  
  \[
  \frac{dT_{out}}{dt} = \frac{1}{C_{out}} \left[ H_w (T_{in} - T_{out}) + H_g (T_g - T_{out}) + H_a (T_a - T_{out}) \right]
  \]
  
  \[
  \frac{dT_a}{dt} = \frac{1}{C_a} \left[ H_o (w) (T_a - T_{a}) + H_a (T_{out} - T_a) + H_{sh} (T_{sh} - T_a) + Q_s + Q_a \right]
  \]
Share of electricity originating from renewables in Denmark Late Nov 2016 - Start Dec 2016

Source: pro.electricitymap.org
How does it work?

Data measurement and information gathering
How does it work?
Price based Control
Example: CO2-based control (savings 15 pct)
Flexibility (or Virtual Storage) Solutions

- Wastewater systems can provide storage 0.2-6 hours ahead
- Supermarket refrigeration can provide storage 0.5-2 hours ahead
- Buildings thermal capacity can provide storage up to, say, 2-10 hours ahead
- Buildings with local water storage can provide storage up to, say, 2-18 hours ahead
- District heating/cooling systems can provide storage up to 1-4 days ahead
- DH systems can provide seasonal storage solutions
- Gas systems can provide seasonal/long term storage solutions
Case study No. 2

Control of smart buildings using integrated weather forecasting
A Smart House

The smart house components:

The smart building and its components are also modelled using grey-box modelling. The optimal model for the building turns out to be a linear grey-box model.
Model for weather forecasting

\[
\begin{align*}
\text{Disturbance model} & \quad \left\{ \begin{array}{l}
    dZ_\kappa = f_\psi(Z_\kappa)\,dt + \sigma_\psi\,d\omega_\kappa \\
    \kappa = \psi^{-1}(Z_\kappa) \\
    \phi = I_N(\kappa, t) + I_D(\kappa, t) \\
    R_n = R_n(\kappa, \phi, t) \\
    d_{T_S} = f_{T_S}(T_l, T_S)\,dt + \sigma_S\,d\omega_S \\
    d_{T_l} = f_{T_l}(T_l, T_S, R_n)\,dt + \sigma_l\,d\omega_a \\
    \mathbf{d} = [T_a, \phi]^T
    \end{array} \right.
\end{align*}
\]

\[
\begin{align*}
\text{Observation equation} & \quad \left\{ \begin{array}{l}
    d\phi = \phi + v_\phi, \quad v_\phi \sim N_{iid}(0, R_\phi) \\
    d_{T_a} = T_l + v_{T_a}, \quad v_{T_a} \sim N_{iid}(0, R_{T_a}) \\
    \mathbf{y}_d = [d_{T_a}, d_\phi]^T,
    \end{array} \right.
\end{align*}
\]
Grey-box model for air temperature

One of the elements is a model for the ambient air temperature which uses net radiation as input:

\[
C_s \frac{d T_s(t)}{dt} = \left( \frac{1}{R_{sl}} (T_l(t) - T_s(t)) \right) dt + \sigma_s d\omega_s(t),
\]

\[
C_l \frac{d T_l(t)}{dt} = \left( \frac{1}{R_{sl}} (T_s(t) - T_l(t)) + \frac{1}{R_{l\infty}} (T_{\infty}(t) - T_l(t)) + R_n(t) \right) dt + \sigma_l d\omega_l(t),
\]

\[
d_{T_a}(t_k) = T_l(t_k) + v_{T_a}(t_k),
\]
Combined Forecasting and Control
15 days out of 7 months simulation

**Strategy 1: Electrical Heaters**

- Room temperature [°C]
- Electrical heater [kW]

**Strategy 2: Heat Pump**

- Room temperature [°C]
- Heat pump [kW]

**Strategy 3: Heat Pump & Electrical Heaters**

- Room temperature [°C]
- Heat pump [kW]
- Electrical heater [kW]

**Strategy 4: Heat Pump & Electrical Heaters & Coolers**

- Room temperature [°C]
- Heat pump [kW]
- Electrical heater [kW]
- Electrical Cooler [kW]
## Electricity cost (EUR)

<table>
<thead>
<tr>
<th>Heating strategy</th>
<th>Persistent</th>
<th>Advanced forecasts</th>
<th>Perfect</th>
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</thead>
<tbody>
<tr>
<td>Electrical heaters, $u_1$</td>
<td>303.2</td>
<td>302.2</td>
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<tr>
<td>Heat pump, $u_2$</td>
<td>117.3</td>
<td>110.4</td>
<td>107.7</td>
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<tr>
<td>Heat pump plus electrical heaters, $u_3$</td>
<td>113.0</td>
<td>108.2</td>
<td>107.5</td>
</tr>
<tr>
<td>Heat pump plus electrical heaters and coolers, $u_4$</td>
<td>117.9</td>
<td>108.3</td>
<td>107.5</td>
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</tbody>
</table>
Constraint violations

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</tr>
</thead>
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<tr>
<td>Electrical heaters, $u_1$</td>
<td>48.5</td>
<td>39.6</td>
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<tr>
<td>Heat pump, $u_2$</td>
<td>157.9</td>
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<td>Heat pump plus electrical heaters, $u_3$</td>
<td>48.0</td>
<td>6.7</td>
<td>1.2</td>
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<tr>
<td>Heat pump plus electrical heaters and coolers, $u_4$</td>
<td>4.4</td>
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</table>
Center Denmark

Digitalization Hub for Integrated Smart Solutions
Center Danmark – Digitaliserings Hub

Circularity in the development of digital energy systems

Uni-Lab.dk

Solutions

Products

Living Labs

FLEXIBILITY
real-time matching of energy demand & production through data intelligence and IoT devices in integrated energy systems

Data Lake

Tools
Uni-Lab.dk

Internationalt:

UNILAB consortium

Cardiff University
Danmarks Tekniske Universitet (DTU), Denmark
Royal Institute of Technology (KTH), Sweden
German Technical and Scientific Association for Gas and Water (DVGW), Germany
Imperial College, United Kingdom
Tianjing University, P.R. China
TNO - Netherlands
Toshiba Research Laboratory (TRL), UK
Tsinghua University - P.R. of China
Katholieke Universiteit Leuven (KUL); Belgium
Mälardalen University, Sweden

Nationale samarbejdspartnere

Energi og IT relationerde virksomheder
Teknologisk Institut
Energinet.dk
Grøn Energi
Alle Universiteter
CLEAN + Inno SE
House of Energy
Forsyninger og Grid operatører

Ministerier (Skat, EFKM, Erhvervsministeriet),
Energistyrelsen
Erhvervsstyrelsen
Dansk Fjernvarme

CITIES Centre for IT Intelligent Energy Systems
Center Denmark

Become a partner – see www.centerdenmark.com

It will increase possibilities for eg. EU projects and support – also since Center Denmark is approved by the Commission
Summary

- Methods for integrated modelling, forecasting and control are presented
- Using the Smart-Energy OS we have seen large potentials for Demand Response and Virtual Storage on all relevant time scales
- Automatic solutions are important
- Solutions are implemented at Center Denmark
- Solutions are tested and further developed using Uni-Lab.dk
- Digitalization and sector coupling is essential
- The controllers can provide
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency
  - Peak Shaving
  - Smart Grid Services (like ancillary services needs, ... )
Control problem

In control the input, $u_k$, is piece-wise constant. Hence the cost function can be written as

$$\varphi = \sum_{i \in \mathcal{N}} c_{k+i}^T u_{k+i} + \sum_{i \in \mathcal{N}} \rho_{k+i+1}^T s_{k+i+1},$$

(7)

Given the linear model for the smart building the optimal control problem is

$$J(\hat{x}_k|k, \{\hat{d}_{k+i}|k\}_{i \in \mathcal{N}}) = \min_{u, s} \varphi,$$

(8a)

s.t.  $x(t_k) = \hat{x}_k|k,$

(8b)

$x(t_{k+i+1}) = A x(t_{k+i}) + B u_{k+i} + E \hat{d}_{k+i}|k,$

(8c)

$x(t_{k+i+1}) \in \mathcal{X}_{k+i+1},$

(8d)

$u_{k+i} \in \mathcal{U}_{k+i},$

(8e)

$s_{k+i+1} \geq 0,$

(8f)

$i \in \mathcal{N},$

(8g)
Grey-box Modelling

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<thead>
<tr>
<th>White</th>
<th>Grey</th>
<th>Black</th>
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</thead>
<tbody>
<tr>
<td>Physics</td>
<td>Data</td>
<td>Data</td>
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<tr>
<td>Deterministic equations</td>
<td>Stochastic models</td>
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<td>Detailed submodels</td>
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<tr>
<td>Parameter calibration often problematic</td>
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<tr>
<td>Parameters~physics</td>
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