Data-Intelligent Energy Performance and Flexibility of Buildings

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CITIES Solutions Brochures

- Energy taxes for the transition to a low-carbon society
- Dynamic CO2 based control
- Stability of electricity smart meter clusters
- Integrated energy planning for a caribbean island
- Potential of district cooling
- Clustering based analysis of residential district heating data
- Storage in Thermal Building Mass
- Integrated Market for Electricity and Natural Gas
- Coupled Electricity and Natural Gas Markets
Case Study No. 1

Thermal Performance Characterization of Buildings using (Smart) Meter Data
Example

Consequence of good or bad workmanship (theoretical value is $U=0.16\text{W/m}^2\text{K}$)
Examples (2)

Measured versus predicted energy consumption for different dwellings.
Model for the heat dynamics

Measurements:
- Indoor air temp
- Radiator heat sup.
- Ambient air temp
- Solar radiations

Hidden states are:
- Heat accumulated in the building
- $k$: Fraction of solar radiation entering the interior
## Results

<table>
<thead>
<tr>
<th>UA</th>
<th>$\sigma_{UA}$</th>
<th>$gA_{\text{max}}$</th>
<th>$wA_{E_{\text{max}}}$</th>
<th>$wA_{S_{\text{max}}}$</th>
<th>$wA_{W_{\text{max}}}$</th>
<th>$T_i$</th>
<th>$\sigma_{T_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/°C</td>
<td>W</td>
<td>W/°C</td>
<td>W/°C</td>
<td>W/°C</td>
<td>W/°C</td>
<td>°C</td>
<td>°C</td>
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<td>4218598</td>
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<td>10.4</td>
<td>597.0</td>
<td>11.0</td>
<td>3.3</td>
<td>8.9</td>
<td>23.6</td>
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<td>9.1</td>
<td>22.5</td>
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<td>8.1</td>
<td>591.0</td>
<td>39.5</td>
<td>28.0</td>
<td>21.4</td>
<td>23.5</td>
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<tr>
<td>4836722</td>
<td>236.0</td>
<td>17.7</td>
<td>1578.3</td>
<td>4.3</td>
<td>3.3</td>
<td>18.9</td>
<td>23.5</td>
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<tr>
<td>4986050</td>
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<td>10.7</td>
<td>715.7</td>
<td>10.2</td>
<td>7.5</td>
<td>7.2</td>
<td>20.8</td>
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<tr>
<td>5069878</td>
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<td>10.4</td>
<td>87.6</td>
<td>3.7</td>
<td>1.6</td>
<td>17.3</td>
<td>21.8</td>
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<tr>
<td>5069913</td>
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<td>9.0</td>
<td>962.5</td>
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<td>8.6</td>
<td>10.6</td>
<td>22.6</td>
</tr>
<tr>
<td>5107720</td>
<td>189.4</td>
<td>15.4</td>
<td>657.7</td>
<td>41.4</td>
<td>29.4</td>
<td>16.5</td>
<td>21.0</td>
</tr>
</tbody>
</table>
Perspectives

- Identification of most problematic buildings
- Automatic energy labelling
- Recommendations:
  - Should they replace the windows?
  - Or put more insulation on the roof?
  - Or tighten the building?
  - Should the wall against north be further insulated?
  - ......
- Better control of the heat supply (.. see later on ..)
Perspectives (2)

Better utilization of renewable energy (solar and wind power)

Decision system regarding cleaning of the windows!

"Skat, jeg kan se på k-værdierne, at vinduerne skal pudses"
Case study No. 2

Control of Power Consumption using the Thermal Mass of Buildings (Peak shaving)
Aggregation (over 20 houses)
Response on Price Step Change

Olympic Peninsula

![Graph showing consumption step response (Olympic Peninsula) with a 5 hour step change.](image)
Control of Energy Consumption

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

Diagram:
- A balance scale with books, a computer, a refrigerator, and a wind turbine on one side, and a factory and a building on the other side.
Control performance

Considerable **reduction in peak consumption**

Mean daily consumption shift

![Graph showing control performance](image-url)
Flexibility Setup and Control
Characteristics

Figure 1: A smart building is able to respond to a penalty or external control signal.
Flexibility Function

Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,
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*. 
Smart Grid Application

Figure 8: Smart buildings and penalty signals.
FF for three buildings

Figure 5: The Flexibility Function for three different buildings.
Realistic Penalties for DK

Figure 6: Penalty signals based on wind and solar power production in Denmark during some days in 2017.
Expected Flexibility
Savings Index for Denmark

Table 1: Expected Flexibility Savings Index (EFSI) for each of the buildings based on wind, solar and ramp penalty signals.

<table>
<thead>
<tr>
<th>Building</th>
<th>Wind (%)</th>
<th>Solar (%)</th>
<th>Ramp (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building 1</td>
<td>11.8</td>
<td>3.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Building 2</td>
<td>4.4</td>
<td>14.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Building 3</td>
<td>6.0</td>
<td>10.0</td>
<td>18.4</td>
</tr>
</tbody>
</table>
Reference Penalties

Figure 7: Reference scenarios of penalty signals related to ramping or peak issues as well as the integration of wind and solar power.
Table 2: Flexibility Index for each of the buildings based reference penalty signals representing wind, solar and ramp problems.

<table>
<thead>
<tr>
<th>Building</th>
<th>Wind (%)</th>
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</thead>
<tbody>
<tr>
<td>Building 1</td>
<td>36.9</td>
<td>10.9</td>
<td>5.2</td>
</tr>
<tr>
<td>Building 2</td>
<td>7.2</td>
<td>24.0</td>
<td>11.1</td>
</tr>
<tr>
<td>Building 3</td>
<td>17.9</td>
<td>35.6</td>
<td>67.5</td>
</tr>
</tbody>
</table>
Flexibility enabled using grey-box modelling
Case study No. 3

Control of Heat Pumps for buildings with a thermal solar collector (minimizing cost)
Modeling Heat Pump and Solar Collector

Simplified System
EMPC for heat pump with solar collector (savings 25 pct; + 8 pct)
Case study No. 4

Control of heat pumps for summer houses with a swimming pools (CO2 minimization)
Share of electricity originating from renewables in Denmark Late Nov 2016 - Start Dec 2016

- **hydro**
- **biomass**
- **geothermal**
- **wind**
- **solar**

Source: pro.electricitymap.org

Workshop: Give Brains to Buildings, TUDelft, Febr. 2020
Live CO2 emissions of the European electricity consumption

This shows in real-time where your electricity comes from and how much CO2 was emitted to produce it.

We take into account electricity imports and exports between countries.

Tip: Click on a country to start exploring.

Wind power potential (m/s)

Solar power potential (W/m²)

Like the visualization? We would love to hear your feedback!

Found bugs or have ideas? Report them here.

This project is Open Source: contribute on GitHub.

All data sources and model explanations can be found here.

Share 24K  Tweet  Slack

A PROJECT BY

Tomorrow

CITIES

Centre for IT Intelligent Energy Systems

Workshop: Give Brains to Buildings, TUDelft, Febr. 2020
How does it work?

Data measurement and information gathering

SN-10 backend

DTU/ENFOR backend

SmartNet

Novasol

Heat exchanger

Pool

Pool pump

ACT1 ACT2

Temp F1 Temp F2

Temp A1 Temp A2

Temp R1 Temp R2

RELAY1 RELAY2

S0 1 S0 PWR

S0 2 S0 PWR

Power
How does it work?

Price based Control

SN-10 backend

DTU/ENFOR backend

Heat exchanger

Pool pump

Pool

ACT1 ACT2

Temp F1 Temp F2

Temp A1 Temp A2

Temp R1 Temp R2

RELAY1 RELAY2

S0 1 S0 PWR

S0 2 S0 PWR

Power
Example: CO2-based control (savings 15 pct)
Case study No. 5

Indoor Climate;
Grey-box Model for Occupancy Estimation
Occupancey estimation using CO2 measurements

- Reducing HVAC to required extent offers energy-saving potential
- Hence, occupancy estimates important for model-based control
- Occupancy estimation model based on CO2 mass balance
- Presented model was tested in three scenarios (Copenhagen, Trondheim, Aachen)
$$\frac{dX_t}{dt} = - (n_{\text{nat}} + n_{\text{mec}} + n_{\text{inf}}) (X_t - c_e) + \dot{c}_{\text{occ}} \cdot n_{\text{occ}}$$

**States**

<table>
<thead>
<tr>
<th>$X_t$</th>
<th>room $CO_2$ concentration [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{occ}}$</td>
<td>number of occupants in the room [–]</td>
</tr>
</tbody>
</table>

**Known parameters**

<table>
<thead>
<tr>
<th>$V_r$</th>
<th>room volume $[m^3]$</th>
</tr>
</thead>
</table>

**Parameters estimated**

<table>
<thead>
<tr>
<th>$c_e$</th>
<th>outdoor $CO_2$ concentration [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{c}_{\text{occ}}$</td>
<td>$CO_2$ increment per occupant $[ppm/h]$</td>
</tr>
<tr>
<td>$n_{\text{nat}}$</td>
<td>air exchange rate (nat. vent) $[1/h]$</td>
</tr>
<tr>
<td>$n_{\text{mec}}$</td>
<td>air exchange rate (mech. vent.) $[1/h]$</td>
</tr>
<tr>
<td>$n_{\text{inf}}$</td>
<td>air exchange rate (infiltration) $[1/h]$</td>
</tr>
</tbody>
</table>
Grey-box Model
- and the states

System equation

\[ dX_t = -\left[ n_{\text{inf}} \cdot (X_t - c_e) + \dot{c}_{\text{occ}} \cdot n_{\text{occ}} \right] dt + \sigma \cdot d\omega \]

\[ n_{\text{air}} = n_{\text{nat}} + n_{\text{mec}} + n_{\text{inf}} \]

Observation equation

\[ Y_k = X_{t_k} + \varepsilon_k, \quad \varepsilon_k \sim N(0, \sigma_\varepsilon) \]
Estimated and Observed Occupancy

![Graph showing CO2 levels and estimated vs. observed occupancy over a week. The graph displays a steady CO2 level with fluctuations in occupancy on different days.]
Summary

- Methods for evidence-based energy performance characterization is outlined for buildings
- Automated methods for evidence-based energy labelling
- Automated methods for evidence-based flexibility labelling
- Flexibility Index for buildings (peak, solar, wind, ...)
- Flexibility Functions and Index can be used for everything (e.g. also wastewater treatment plants)
- Automated methods for providing hints on how to improve the energy performance of buildings
- Provides hints on how to design a building such that it is optimized for the given climate zone
Summary (2)

- We need to put more focus on energy efficiency – but using meter data (which is now possible)
- Procedures for data intelligent control of power load using FF are also suggested
- The controllers can provide
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
- We have demonstrated a large potential in Demand Response. Automatic solutions, and end-user focus are important
- We see large problems with the tax and tariff structures in many countries (eg. Denmark; we are working on a new design of taxes and tariffs.
For more information ...

See for instance

www.smart-cities-centre.org

...or contact

– Henrik Madsen (DTU Compute)
  hmad@dtu.dk

Acknowledgement - DSF 1305-00027B
Some references

Grey-box models for buildings:


Some references

Grey-box modelling techniques:


Some references (cont.)

Forecasting, Flexibility and Control:


Some references (cont.)

Indoor climate and occupancy:


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