Methods for using existing and new data

Results from CITIES, SCA and REBUS projects

IDA Energi: Cognitive Buildings, November 2017

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Results from REBUS and CITIES
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Contents

- Using meter data for characterizing the thermal performance of buildings
- Intelligent control of power load using data
- Smart-Energy OS
- Optimal control (Energy efficiency, Cost, Emission – or a combination)
Case Study No. 1

Modelling of Thermal Performance 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
Energy Labelling of Buildings

- Today building experts make judgements of the energy performance of buildings based on drawings and prior knowledge.
- This leads to 'Energy labelling' of the building.
- However, it is noticed that two independent experts can predict very different consumptions for the same house.
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
**Data**

**Measurements of:**

- $y_t$ Indoor air temperature
- $T_a$ Ambient temperature
- $\Phi_h$ Heat input
- $\Phi_s$ Global irradiance
Selection procedure

Iterative procedure using statistical tests

Begin with the simplest model

Model fitting

Likelihood-ratio tests of extended models

End selection

OK

Not OK

Evaluate the selected model

Simplest model

First extension: heater part

Start

\[ l(\theta; Y_N) \]

\[ m \]

\[ \text{Model}_{Ti} \]

\[ 2482.6 \]

\[ 6 \]

\[ \text{Model}_{TiTe} \]

\[ 3628.0 \]

\[ 10 \]

\[ \text{Model}_{TiTm} \]

\[ 3639.4 \]

\[ 10 \]

\[ \text{Model}_{TiTs} \]

\[ 3884.4 \]

\[ 10 \]

\[ \text{Model}_{TiTh} \]

\[ 3911.1 \]

\[ 10 \]

1 ...

<table>
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<th>( \text{Model}_{TiTe} )</th>
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## Results

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<th>$\sigma_{UA}$</th>
<th>$gA_{max}$ W</th>
<th>$wA_{E,max}$ W/°C</th>
<th>$wA_{S,max}$ W/°C</th>
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<td>21.0</td>
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</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
Perspectives (2)

"Skat, jeg kan se på k-værdierne, at vinduerne skal pudses"

IDA Energi - Cognitive Buildings

CITIES
Centre for IT Intelligent Energy Systems
Control of Indoor Climate
Log ind

brugernavn: hmad

adgangskode: ********

Login med dit brugernavn og adgangskode.

Ved log ind fejl skal du kontakte kontakt@skoleklima.dk
Control of Power Consumption using the Thermal Mass of Buildings
The Danish Wind Power Case

.... balancing of the power system

In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

In the first half of 2017 more than 44 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
The **central hypothesis** is that by **intelligently integrating** currently distinct energy flows (heat, power, gas and biomass) using **data intelligence** we can balance very large shares of renewables, and consequently obtain substantial reductions in CO2 emissions.

**Intelligent integration** will (for instance) enable lossless ‘virtual’ storage on a number of different time scales.
CITIES – Research Challenges

To establish methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales
We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool of flexible prosumers.
# Try to parallelize anyway

```r
require(multicore)
numcores <- multicore:::detectCores()
mclapply(1:N,
  function(i, data) {
    print(paste(i, "/", N))
  },
  .simplify = FALSE)
```

```r
# Find the indices of rows corresponding to everything
j <- which(data$dt_agg %in% aggdata$dt[i])
```

```r
# Filter out those who are NA
j <- j[!is.na(data$last_one_min_power[j])]
```

```r
# Count number of readings
aggdata$num_readings[i] <- length(j)
```
SE-OS
Control loop design – logical drawing

Data

Sensors

Termostat actuator
Lab testing ....
SN-10 Smart House Prototype
SE-OS Characteristics

- ‘Bidding – clearing – activation’ at higher levels
- Nested sequence of systems – systems of systems
- Hierarchy of optimization (or control) problems
- Control principles at higher spatial/temporal resolutions
- Cloud or Fog (IoT, IoS) based solutions – eg. for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ...)
- Allow for new players (specialized aggregators)
- Simple setup for the communication and contracts
- Provides a solution for all ancillary services
- Harvest flexibility at all levels
Case study No. 2

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

Model inputs: price, minute of day, outside temperature/dewpoint, sun irradiance

Olympic Peninsula

![Diagram showing consumption step response](image)
Control of Energy Consumption

Model parameters

Price generator (controller)

Prices

Price-responsive consumption

Aggregated consumption

Consumption references
Control performance

*With a price penalty avoiding its divergence*

- Considerable **reduction in peak consumption**
- Mean daily consumption shift

![Graph showing consumption and price over the day](image)
Case study No. 3

Control of Heat Pumps for buildings with a thermal solar collector (minimizing cost)
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:

\[
\min_{\{u_k\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c^T u_k \tag{4a}
\]

Subject to

\[
x_{k+1} = Ax_k + Bu_k + Ed_k \quad k = 0, 1, \ldots, N - 1 \tag{4b}
\]

\[
y_k = Cx_k \quad k = 1, 2, \ldots, N \tag{4c}
\]

\[
u_{min} \leq u_k \leq u_{max} \quad k = 0, 1, \ldots, N - 1 \tag{4d}
\]

\[
\Delta u_{min} \leq \Delta u_k \leq \Delta u_{max} \quad k = 0, 1, \ldots, N - 1 \tag{4e}
\]

\[
y_{min} \leq y_k \leq y_{max} \quad k = 0, 1, \ldots, N \tag{4f}
\]
EMPC for heat pump with solar collector (savings 35 pct)
Case study No. 4

Control of heat pumps for swimming pools (CO2 minimization)
“Please stop”

“Please use”

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

Data measurement and information gathering

SN-10 backend

DTU/ENFOR backend

SmartNet

FlexGrid

Heat exchanger

Pool pump

RELAY1 RELAY2

S0 1 S0 PWR

S0 2 S0 PWR

Power
How does it work?

Price based Control

SN-10 backend

DTU/ENFOR backend

SmartNet

[Diagram of a heating system with various components and connections]
Example: CO2-based control
MARKANTE FAGFOLK TIL POLITIKERNE:

Her er vejen til smarte energiafgifter

Prisen på energi skal afspejle, hvilken forurening den medfører. Det er nødvendigt for at fremme den grønne omstilling, mener en gruppe fagfolk bag nyt udspil.

ENERGIPOLITIK
Af Søren Witting sp@ing.dk

Fået fysikken. Det er hovedprincip- pet i et forslag til en ny model for energiafgifter fra et perlerække af store danske virksomheder, forskningsinstitutter og forsyningsvirksomheder.

Gruppen foreslår, at de enkelte brændselser skal pålægges en 'foreningafgift', der afspejler, hvad det koster at neutralisere forureningen fra brændset. Hvad enten det så er CO₂, partikler eller svovl. Afgiften skal lægges på energien, når den går ind i værket, bilen eller fyret.

Samtidig skal også selve værket, bilen eller vindmøllen pålægges en afgift, der afspejler anlæggets miljø-effekt fra fremstilling til og med nedtagning i et livscyklusperspektiv – og hvilket koster at neutralisere denne effekt.

Ideen er så, at stærkt varierende forbrugerpriser på energi skal opnås for at forhindre at flyve deres energiforbrug.

MED FORSLAGET BLANDER FAGFOLK MED INDIKTION I DYNAMIKKEN ENS ENERGISYSTEK

Med forslaget blander fagfolk med indikation i dynamikken i energisektoren sig nu i debatten om, hvordan fremtidens energiafgifter skal indrettes. En debat, som Skatte- ministeriet tog hul på i sommer med et såkaldt ‘flagligt oplys’ til en ny afgiftsmodel.

Gruppen mener, at en ny afgiftsmodel er helt nødvendig for at få fremmet et mere fleksibelt energiforbrug, som ifølge dem er nøglen til en effektiv grøn omstilling, og som vil kunne åbne for at realisere masser af innovative, danske styringsmodeller og systemløsninger på energiområdet.

Professor Henrik Madsen fra Institut for Matematik og Computer Science på DTU, der taler på vegne af gruppen, synes nemlig ikke, at Skatte ministeriet har gjort sit arbejde færdigt, blandt andet fordi anbefalingerne ikke tager tilstrækkelig højde for dynamikken i energisystemet.

«Den rigtige omkalkulation af energiafgifter og tilsynlig vil kunne bringe Danmark helt i front med fleksible løsninger og forretningsmodeller. Vi oplever, at både virksomheder og private investorer står i kø for at komme i gang med at udvikle og demonstrere kommersielle løsninger, der kan udnytte strømmen, når der er grøn og billig. » fordeler Henrik Madsen og understreger, at virksomhederne gør det, fordi de er overbeviste om, at de kan tjene store penge på at kunne udvikle og demonstrere løsninger i Danmark og senere tilbyde dem til andre lande.

Gruppen er dannet af deltager i et stort forskningsprojekt ved navn ‘Cities’, hvor man har udviklet styringer og systemløsninger til forskellige elementer i fremtidens intelligente og integrerede energisystem.

Disse demonstrationprojekter har vist, at der rent teknisk findes mange muligheder for at integrere store mængder vind- og solenergi, hvis man på en intelligente måde kan udnytte den dynamik og fleksibilitet, der er i et energisystem, hvor produktion og forbrug af el, varme, vand, affald og transport er tænkt sammen.

Danfoss er en af virksomhederne bag den nye model. Leder af Danfoss’ øksterne aktiviteter Torben Funder-Kristensen, peger på, at Danmark har en unik mulighed for at udvikle disse nye løsninger, fordi vi har teknologien, knowhow og en moderne og samarbejdsvillig forsyningssektor.

Men vi har kun et vindue på fem til ti år, før andre lande kommer ind og tager over, så det hæfter med at få omlagt energiafgifterne, der reelt dræber mange demonstrationprojekter. Vi kan ikke ventes sig her.

Professor i ressourceøkonomi på KU Peder Andersen – som sidder i referencegruppen for Skatte ministeriets afgiftsrapport – finder, at gruppens afgiftsforløg ser interessant ud, men at det samtidig er lidt svært at gennemse, om de økonomiske incitamenter rammer rigtigt.

«Når man primært lægger afgift på input af brændsel, risikerer man, at der ikke er incitamenter for virksomhederne til at undgå forurening, f.eks. ved at rene effektivt eller bruge ren teknologi. Det går imod det korrekt økonomisk tænkning,» siger han.

Samtidig påpeger han, at den foreslåede afgift på selve produktionen kan blive en meget fornuftig ordning at administrere.

«Det vigtige er jo, at der gives klare økonomiske incitamenter til, at både økonomien og miljøet tilgodeses,» siger han.

Det nye forslag er baseret på møder og diskussioner med markante personer fra Danfoss, Grundfos, Kamstrup, Dansk Fjernvarme, EniQ, Aalborg Aarhus, Teknologisk Institut, DTU, KU, Project Zero og Aarhus Kommune.

I den kommende tid vil gruppen gå videre med at forslå til de relevante ministerier og har allerede en aftale i Energ-, Forsynings- og Klimaministeriet.

LÆS SIDE 4-5
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 at GitHub.
Summary

- Data can be used for reliable performance characterization of buildings (energy labelling, etc.)

- A procedure for data intelligent control of power load in buildings, using the Smart-Energy OS (SE-OS) setup, is suggested.

- The SE-OS controllers can focus on
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency

- We see 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).

- 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)
For more information ...

• See for instance
  www.henrikmadsen.org
  www.smart-cities-centre.org
  www.citiesinnovation.org

• ...or contact
  - Henrik Madsen (DTU Compute)
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