Use of Flexibility in Future Intelligent and Integrated Energy Systems

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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.
Energy Systems Integration

Energy system integration (ESI) = the process of optimizing energy systems across multiple pathways and scales.
Flexible Solutions and CITIES

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.

CITIES is currently the largest Smart Cities and ESI research project in Denmark – see http://www.smart-cities-centre.org.
The **central hypothesis** is that by **intelligently integrating** currently distinct energy flows (heat, power, gas and biomass) using grey-box models 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.
Existing Markets - Challenges

- Dynamics
- Stochasticity
- Nonlinearities
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, ...)
- Speed / problem size
- Characterization of flexibility
- Requirements on user installations
Challenges (cont.)

Preparatory study on Smart Appliances

Project Summary

The Ecodesign Preparatory Study on Smart Appliances (Lot 33) has analysed the technical, economic, market and societal aspects with a view to a broad introduction of smart appliances and to develop adequate policy approaches supporting such uptake.

The study deals with Task 1 to 7 of the Methodology for Energy related products (MEErP) as follows:

- Scope, standards and legislation (Task 1, Chapter 1);
- Market analysis (Task 2, Chapter 2);
- User analysis (Task 3, Chapter 3);
- Technical analysis (Task 4, Chapter 4);
- Definition of Base Cases (Task 5, Chapter 5);
- Design options (Task 6, Chapter 6);
- Policy and Scenario analysis (Task 7, Chapter 7).

An executive summary of the project results can be downloaded here.

Throughout the study, new relevant aspects have come up which will be covered in a second phase of the Preparatory Study:

- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.
Temporal and Spatial Scales

The *Smart-Energy Operating-System (SE-OS)* is used to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for *operating flexible electrical energy systems* at all scales.
Smart-Energy OS

Day Ahead Market

Transmission System Operator (TSO)

Distribution System Operator (DSO)

Balance Responsible Party

Aggregated loads

DIRECT CONTROL (DC)
Individual consumption schedules

INDIRECT CONTROL (IC)
Price signals

Sub Aggregator A
Forecast services

Sub Aggregator B
Forecast services

Meteorological forecasts
Local data

Advanced controller

Water distribution & treatment

Intelligent heating/cooling

Intelligent buildings

Solar thermal

Industrial processes

CHP plant

Actuation state info

Real-time price

Reference

info

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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'


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The ‘market’ of tomorrow

Space
Country
Region
City
District
House

Bidding +
Market clearing

Purpose based
Stochastic Control

Bidding &
Clearing

Control based

\[ \min_p (U - U_{ref})^2 \]

\[ \min \sum (pU) \]

Economic Model
Predictive Control

Time
Proposed methodology
Control-based methodology

\[
\min_{p} \quad E[\sum_{k=0}^{N} w_{j,k} ||\hat{z}_k - z_{ref,k}|| + \mu ||p_k - p_{ref,k}||]
\]
\[
s.t. \quad \hat{z}_{k+1} = f(p_k)
\]

We adopt a control-based approach where the price becomes the driver to manipulate the behaviour of a certain pool of flexible prosumers.
Models for systems of systems

Intelligent systems integration using data and ICT solutions are based on grey-box models for real-time operation of flexible energy systems.
Lab testing ....
SE-OS
Control loop design – logical drawing
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. 1

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

Olympic Peninsula

![Graph showing consumption step response](image)

**Consumption step response (Olympic Pen.):**

- Consumption [kW]
- Hours

- 5 hours

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Control of Energy Consumption
Considerable **reduction in peak consumption**

Mean daily consumption shift
Case study No. 2

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

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

Subject to

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

\[
y_k = Cx_k \quad k = 1, 2, \ldots, N \quad (4c)
\]

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

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

\[
y_{\min} \leq y_k \leq y_{\max} \quad k = 0, 1, \ldots, N \quad (4f)
\]
EMPC for heat pump with solar collector (savings 35 pct)
Case study No. 3

Control of heat pumps for swimming pools (CO2 minimization)
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.

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Tomorrow

CITIES
Centre for IT Intelligent Energy Systems

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Share of electricity originating from renewables in Denmark Late Nov 2016 - Start Dec 2016

Source: pro.electricitymap.org
“Please stop”

“Please use”

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

Data measurement and information gathering
How does it work?

Price based Control

SN-10 backend

DTU/ENFOR backend

ACT1
ACT2

Temp F1
Temp F2

Temp A1
Temp A2

Temp R1
Temp R2

Pool

RELAY1
RELAY2

Pool pump

SmartNet
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 Sanne Witrup sw@ing.dk

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

Gruppen foreslår, at de enkelte brændstofskuaper pålægges en 'forureningsafgift', der afspejler, hvad det koster at neutralisere forureningen fra brændslet. Hvad enten det så er CO₂, partikler eller svovl. Afgiften skal bagges på energien, når den går ind i værket, bilen eller fæt.

Samtidig skal også sælve værket, bilen eller vindmøllen pålægges en afgift, der afspejler anlæggets mulige effekt fra fremsættelsen og med nedlagning i et livscyklusperspektiv – og hvad det koster at neutralisere denne effekt.

Ideen er så, at stærkt varierende forbrugerpris på energi skal opmuntre forbrugerne til at flytte deres energiforbrug.

Med forsklaget blander fagfolk med indsigt i dynamikken i energi-sektoren sig ind i debatten om, hvordan fremtidens energiafgifter skal indrettes. En debat, som Kattede- ministeriet tog hul på i sommer med et såkaldt 'fagligt oplæg' til en ny afgiftsområde.

Gruppen mener, at en af afgifts- modellen er helt nødvendigt for at få frem en mere fleksibel energiforbrug, som ifølge dem er nøglen til en effektiv grøn omstilling, og som vil kunne åbne for at realisere masser af innovative, danske styringsmodelle 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, inden det forladde løsninger, der er i strid med den dynamiske og fleksible, hvilket 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 tæt sammen.

Danfoss er en af virksomhederne bag den nye model. Leder af Danfoss' øksterne aktiviteter Torben Funder-Kristensen påbegynder, at Danmark har en unik mulighed for at udvikle disse nye løsninger, fordi vi har teknologien, knowhow og en moderne og samarbejdssvrig forsy- ningssektor.

»Vi har kun et vindue på fem til ti år, før andre lande kommer ind og tager over, så det hæser med at få omlagt energiafgifterne, der reelt dræber mange demonstrationsprojekter. Vi kan ikke vente, siger han.

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

»Når man primært lægger afgift på input af brændslet, risikerer man, at der ikke er incitamenter for virksomhederne til at undgå for- urerning, f.eks., ved at rens-reksekt eller bruge ren teknologi. Det går imod corret økonomisk tænkning, siger han.

Samtidig påpeger han, at den foreslåede afgift på selve produktionsmålene kan blive en meget svært form for at administrere.

»Det vigtige er jo, at der gives kla- re økonomiske incitamenter til, at både økonomien og miljøet tilgode- ses, siger han.

Det nye forslag er baseret på møder og diskussioner med markante personer fra Danfoss, Grundfos, Kamstrup, Dansk Fjervarme, Eniog, AffaldsCenter Aarhus, Tekno- logisk Institut, DTU, KU, Project- Zero og Aarhus Kommune.

I den kommende tid vil gruppen gå videre med sit forslag til de relevante ministerier og har allerede en aftale i Energ-, Forsynings- og Klimaministeriet.
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.
Further Aspects
Flexibility Represented by Saturation Curves
(for market integration using block bids)
Understanding Power/Energy Flexibility

Some Demo Projects in CITIES:

- Control of WWTP (ED, Kruger, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Summerhouses (DC, ENDK, Nyfors, ..)
- Green Houses (NeoGrid, ENFOR, ....)
- CHP (Dong Energy, EnergiFyn, ...)
- Industrial production
- EV (Eurisco, Enfor, ...)

.............
(Virtual) Storage Solutions

- 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
Summary

- A procedure for data intelligent control of power load, 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 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).

- 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.smart-cities-centre.org

...or contact

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