A Framework for Implementing Flexible Electric Energy Systems using IoT

With a focus on thermal flexibility

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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
Energy Systems Integration in Smart Cities

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

Data Pathway: Information and communication technologies allow a better understanding and control of systems by linking sensor data from multiple locations to control centers.
Temporal and Spatial Scales

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

Direct Control (DC)
- Individual consumption schedules

Indirect Control (IC)
- Price signals

Aggregated loads

Balance Responsible Party

Day Ahead Market

Transmission System Operator (TSO)

Distribution System Operator (DSO)

Meteorological forecasts
- Local data

Advanced controller

Industrial processes

Transport

Water distribution & treatment

Intelligent heating/cooling

Intelligent buildings

Solar thermal

Industrial processes

CHP plant

Sub Aggregator A
- Forecast services

Sub Aggregator B
- Forecast services

Real-time price
Control and Aggregation

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 and Indirect Control

For DC info about individual states and constraints are needed

(a) Indirect control

(b) Direct control
Models

Grey-box or Cyber-Physical modelling are used to establish models and methods for real-time operation of future electric 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.
SE-OS Characteristics

- Bidding – clearing – activation at higher levels
- Control principles at lower levels
- Cloud based solution for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ...)
- Allow for new players (specialized aggregators)
- Simple setup for the communication
- Simple (or no) contracts
- Rather simple to implement
- Harvest flexibility at all levels in Smart Cities
SE-OS and IoT
Control loop design – logical drawing
Lab testing ....
SN-10 Smart House Prototype
Case study

Control of Power Consumption (DSM) using the Thermal Mass of Buildings
Models

Grey-box modelling are used to establish models and methods for real-time operation of future electric energy systems.
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 step response with 5 hours marked]

- Consumption step response (Olympic Pen.)
Control of Power Consumption

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

CITIES
Centre for IT Intelligent Energy Systems
Considerable **reduction in peak consumption**
Case study

Heat Pumps and Local Storage
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:

$$\min_{\{u_k\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c' u_k$$  \hspace{1cm} (4a)$$

Subject to

$$x_{k+1} = Ax_k + Bu_k + Ed_k \hspace{0.5cm} k = 0, 1, \ldots, N - 1$$  \hspace{1cm} (4b)$$
$$y_k =Cx_k \hspace{5cm} k = 1, 2, \ldots, N$$  \hspace{1cm} (4c)$$
$$u_{\min} \leq u_k \leq u_{\max} \hspace{5cm} k = 0, 1, \ldots, N - 1$$  \hspace{1cm} (4d)$$
$$\Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max} \hspace{5cm} k = 0, 1, \ldots, N - 1$$  \hspace{1cm} (4e)$$
$$y_{\min} \leq y_k \leq y_{\max} \hspace{5cm} k = 0, 1, \ldots, N$$  \hspace{1cm} (4f)$$
Heat pump with thermal solar collector and storage (savings up to 35 pct)
Case study

Control of Power Consumption to Summer Houses with a Pool
Services

- The large inertia of pools allows for shift of electricity consumption by several hours.
- Via active coordination of the flexibility below a critical node on the DSO grid.
- Active load management to help finding an optimal routing of the power.

Balancing

Voltage regulation (DSO)

Congestion management
Smart Control of Houses with a Pool

PilotB SN-10 signal overview
revision 1.0 (CITIES add-on)
Smart-Energy OS
Examples from the CITIES project

- 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, ...)
- EV (charging) (Eurisco, ED, ...)
- ............
Virtual Storage solutions in Smart Cities

- **Flexibility (or virtual storage) 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

- IT-Intelligent Energy Systems Integration in Smart Cities 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
- Smart Cities are just smart elements of a Smart Society
- 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).
- 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)
Summary

- A Smart-Energy OS for implementing flexibility energy systems in smart cities has been described
- Built on: Big Data Analytics, Cyber Physical systems, Stochastic opt./control, Forecasting, IoT, IoS, Cloud computing, ...
- **Modelling:** Toolbox – CTSM-R - for combined physical and statistical modelling (grey-box modelling)
- **Control:** Toolbox – MPC-R - for Model Predictive Control
- **Simulation:** Framework for simulating flexible power systems.