

### **CITIES solutions for smart cities - some examples**

#### **INTERREG V - Smart City Accelerator**

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### Contents





- Use of data from smart meters
- Models for the termal performance of buildings
- Smart-Energy OS
- Price-based load control
- Control of Heat Pumps

#### **Examples from CITIES**





### **Case Study No. 1**

# Split of total readings into space heating and domestic hot water using data from smart meters





### Data



• 10 min averages from a number of houses







### **Splitting of total meter readings**







#### **Robust Polynomial Kernel**





Case Study No. 2

### Modelling of Thermal Performance using Smart Meter Data



### **Example**





Consequence of good or bad workmanship (theoretical value is U=0.16W/m2K)



## **Examples (2)**



Measured versus predicted energy consumption for different dwellings

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### **Characterization Smart Meter Data**

- Energy labelling
- Estimation of UA and gA values
- Estimation of energy signature
- Estimation of dynamic characteristics
- Estimation of time constants



# 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.



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### Results



	UA	$\sigma_{UA}$	$gA^{max}$	$wA_E^{max}$	$wA_S^{max}$	$wA_W^{max}$	$T_i$	$\sigma_{T_i}$
	$W/^{\circ}C$		W	$W/^{\circ}C$	$W/^{\circ}C$	$W/^{\circ}C$	°C	
4218598	211.8	10.4	597.0	11.0	3.3	8.9	23.6	1.1
4381449	228.2	12.6	1012.3	29.8	42.8	39.7	19.4	1.0
4711160	155.4	6.3	518.8	14.5	4.4	9.1	22.5	0.9
4836681	155.3	8.1	591.0	39.5	28.0	21.4	23.5	1.1
4836722	236.0	17.7	1578.3	4.3	3.3	18.9	23.5	1.6
4986050	159.6	10.7	715.7	10.2	7.5	7.2	20.8	1.4
5069878	144.8	10.4	87.6	3.7	1.6	17.3	21.8	1.5
5069913	207.8	9.0	962.5	3.7	8.6	10.6	22.6	0.9
5107720	189.4	15.4	657.7	41.4	29.4	16.5	21.0	1.6

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# Perspectives for using data from Smart Meter

- Reliable Energy Signature.
- Energy Labelling
- Time Constants (eg for night setback)
- Proposals for Energy Savings:
  - Replace the windows?
  - Put more insulation on the roof?
  - Is the house too untight?
  - .....
- Optimized Control
- Integration of Solar and Wind Power using DSM









#### **Control of Power Consumption**





### **Smart-Energy OS**



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### **Control and Optimization**



#### TSO Day Ahead Balancing Market DSO Market BRP Direct Control Aggregator Indirect Control (DC) (IC) (b) (a) MET Forecasts Sub Aggregator Sub Aggregator Local Data Entenet Retrine Forecast Service Opt. and control service Opt, and controls ervices Advanced Advanced Advanced Controller Controller Controller IV DER DER DER DER DER ...

### In New Wiley Book: Control of Electric Loads in Future Electric Energy Systems, 2015

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#### **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'







#### In 2014 more than 40 pct of electricity load was covered by wind power.

For several days in 2014 the wind power production was more than 120 pct of the power load.

July 10th, 2015 more than 140 pct of the power load was covered by wind power



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### **The Danish Wind Power Case**

.... balancing of the power system

4500

4000

3500

3000

2500

2000

1000



■ Wind power □ Demand

In 26088 wind power did cover the entire demand of electricity in demand of electricity in 200 (West DK) (West DK)

50 % wind energy





### **Forecasting is Essential**

# **Tools for Forecasting:** (Prob. forecasts)

- Power load
- Heat load
- Gas load
- Prices (power, etc)
- Wind power prod.
- Solar power prod.
- State variables (DER)







#### Case study No. 4

### Price-based Control of Power Consumption



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# **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





## Price responsivity

Flexibility is activated by adjusting the temperature reference (setpoint)



- **Standardized price** is the % of change from a price reference, computed as a mean of past prices with exponentially decaying weights.
- **Occupancy mode** contains a price sensitivity with its related comfort boundaries. 3 different modes of the household are identified (work, home, night).





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### Non-parametric Response on Price Step Change



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

#### **Olympic Peninsula**











# **Control performance**

With a price penality avoiding its divergence

- Considerable reduction in peak consumption
- Mean daily consumption shift







#### Case study No. 5

# Control of Heat Pumps (based on varying prices)





### **Grundfos Case Study**

Schematic of the heating system



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### Modeling Heat Pump and Solar Collector

Simplified System





ΠΤΙΙ



### **Avanced Controller**

Economic Model Predictive Control

#### Formulation

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

$$\min_{\{u_k\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c' u_k$$
Subject to  $x_{k+1} = Ax_k + Bu_k + Ed_k k = 0, 1, \dots, N-1$  (4b)  
 $y_k = Cx_k \qquad k = 1, 2, \dots, N$  (4c)  
 $u_{min} \le u_k \le u_{max} \qquad k = 0, 1, \dots, N-1$  (4d)  
 $\Delta u_{min} \le \Delta u_k \le \Delta u_{max} \qquad k = 0, 1, \dots, N-1$  (4e)  
 $y_{min} \le y_k \le y_{max} \qquad k = 0, 1, \dots, N$  (4f)



# EMPC for heat pump with solar collector (savings 35 pct)



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#### 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.

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#### Latest news

Ambassador Louise Bang Jespersen visited CITIES, October 29th 2015

CITIES Korean International Workshop – KIER, Daejeon, Korea, October 22nd 2015

Workshop on Mathematical Sciences Collaboration in Energy Systems Integration – DTU,



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## Some of the other Demo-Projects in CITIES

- Control of WWTP (with ED, Kruger, ..)
- Supermarket cooling (with Danfoss, ..)
- Summerhouses (with DC, ..)
- Dynamic prices in DH systems
- Green Houses
- CHP
- Industrial production
- VE (optimal charging)







## For more information ...

• See for instance

www.henrikmadsen.org

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