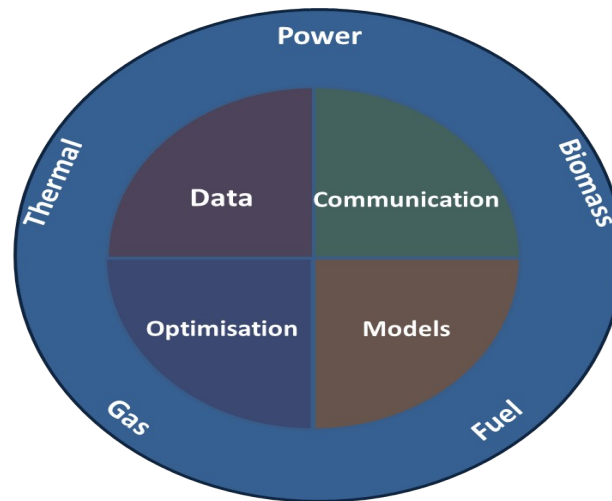


# Smart-Energy OS

**A platform for implementing energy related  
Smart Cities solutions**



**Henrik Madsen, DTU Compute**

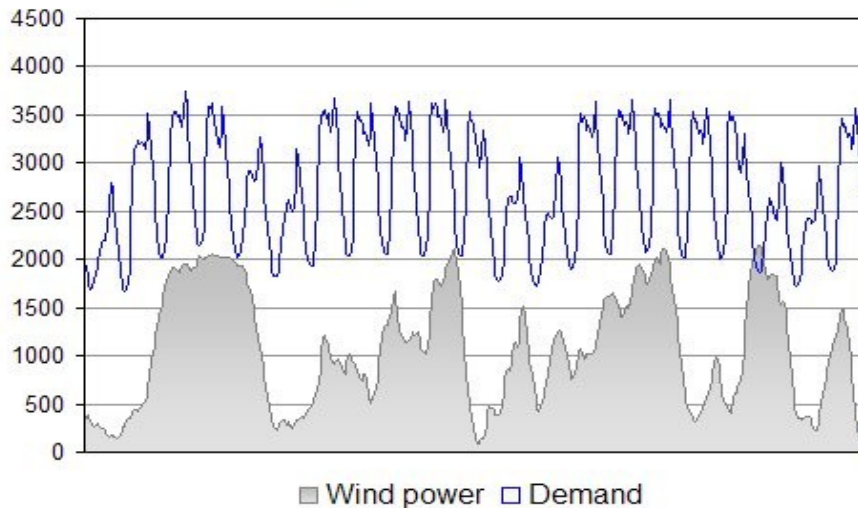
**<http://www.henrikmadsen.org>**

**<http://www.smart-cities-centre.org>**

# The Danish Wind Power Case

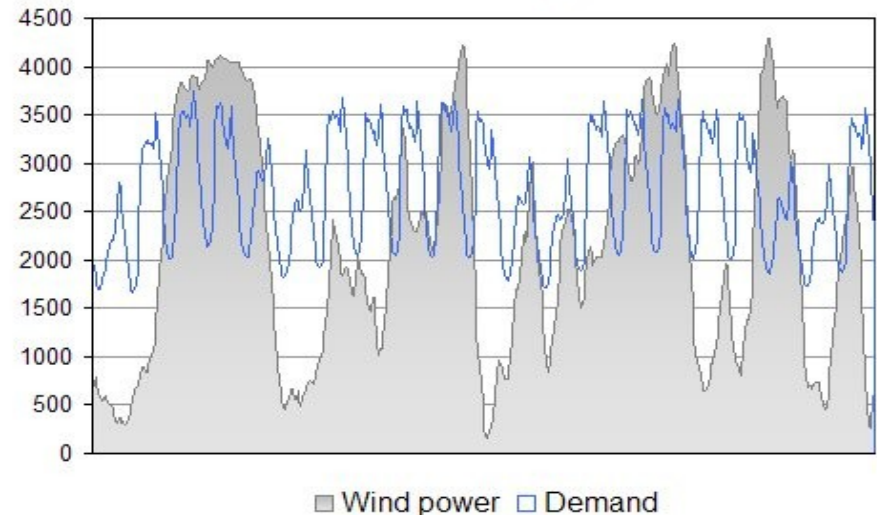
.... balancing of the power system

25 % wind energy (West Denmark January 2008)



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

50 % wind energy



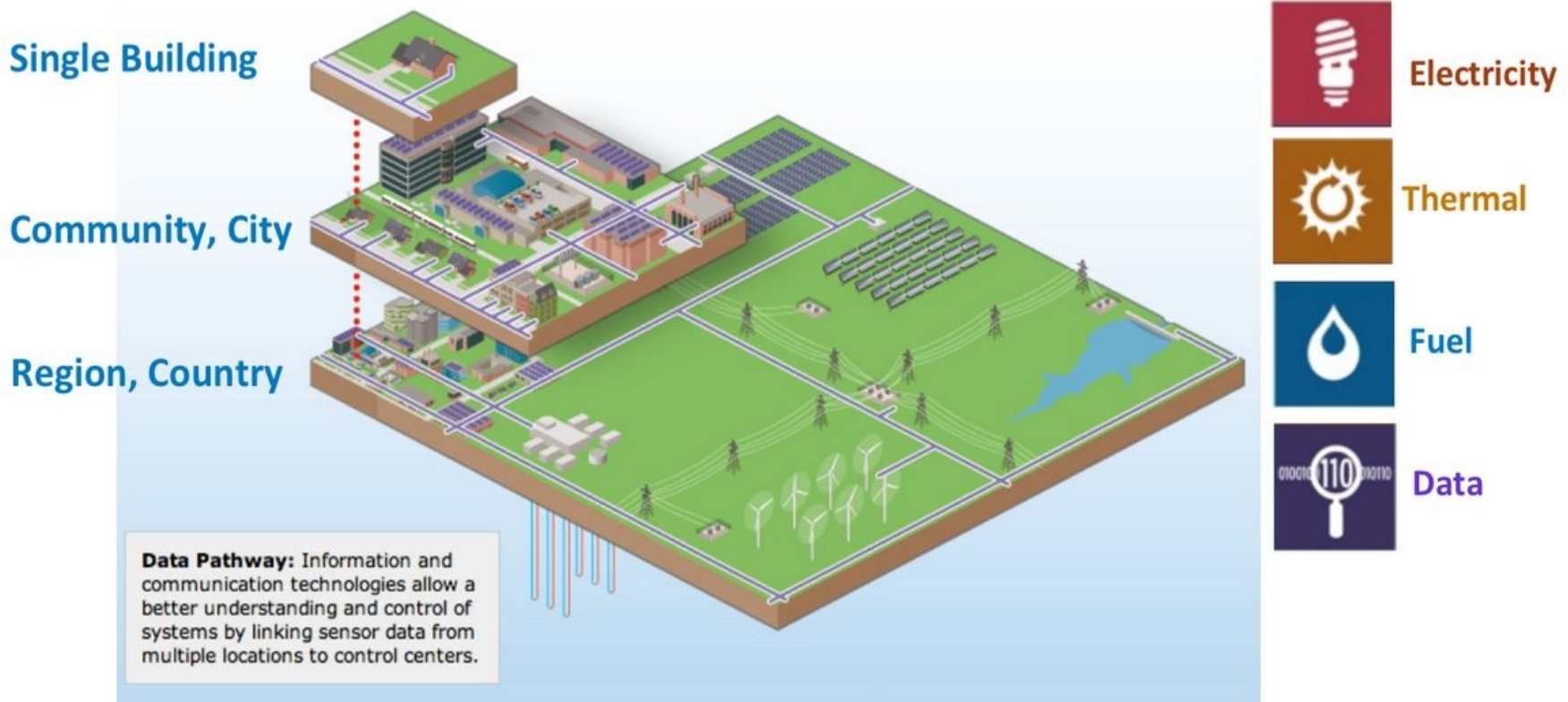
**In 2015 more than 42 pct of electricity load was covered by wind power.**

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



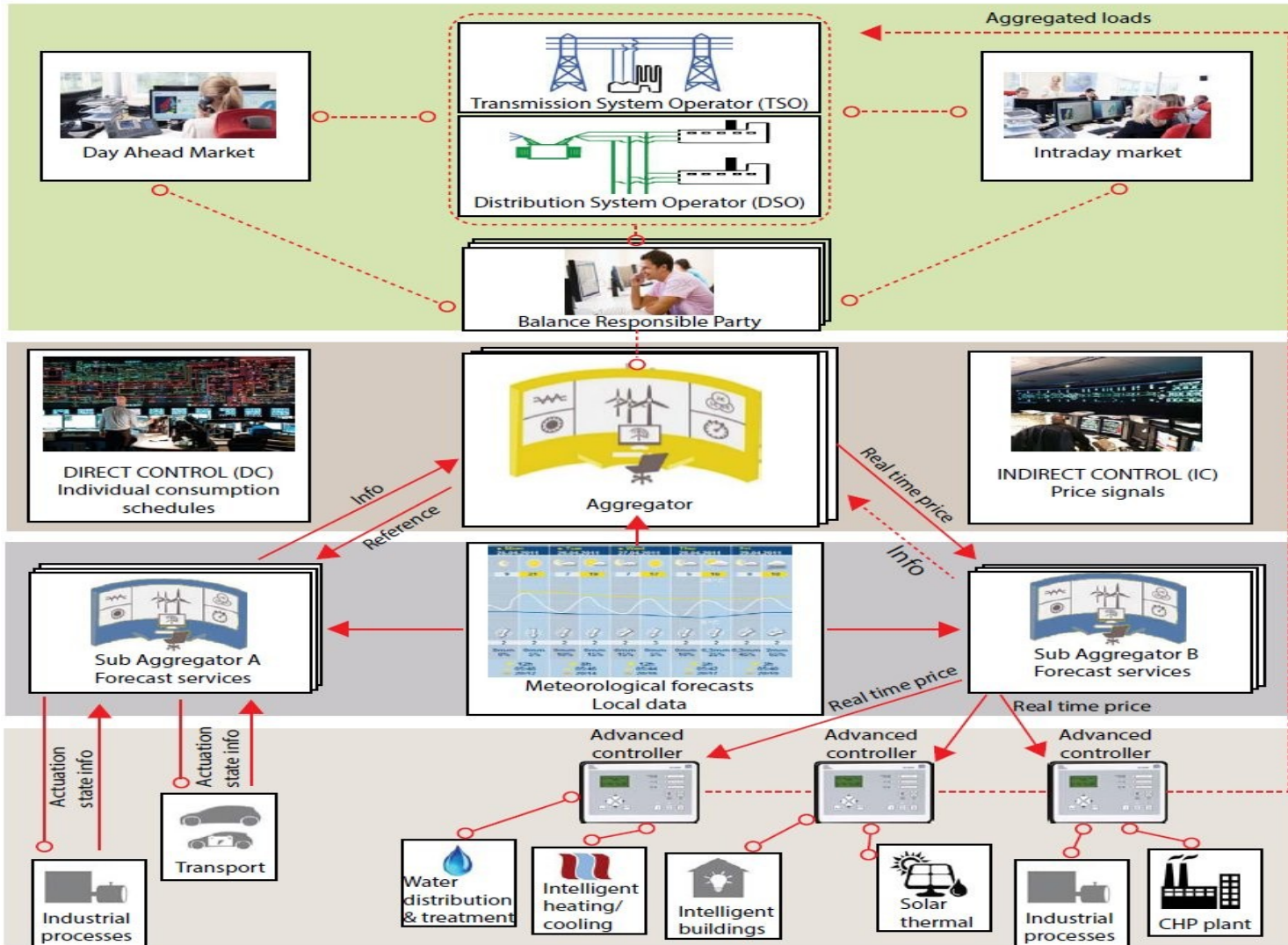
# Temporal and Spatial Scales

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**.

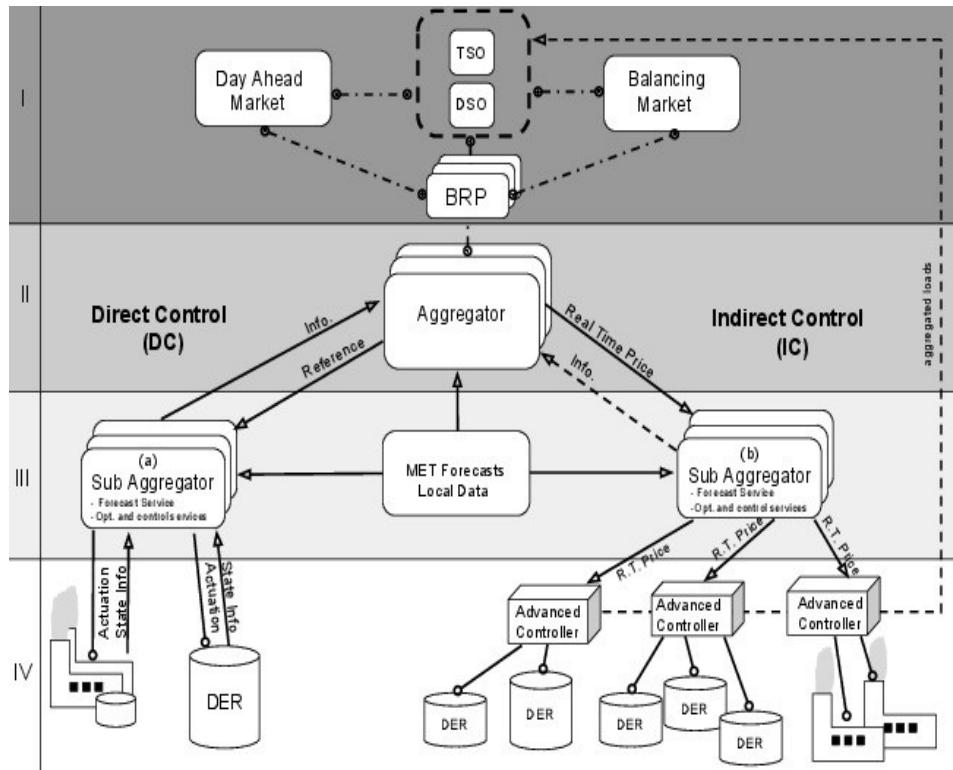




# Smart-Energy OS



# Control and Aggregation



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

## 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**

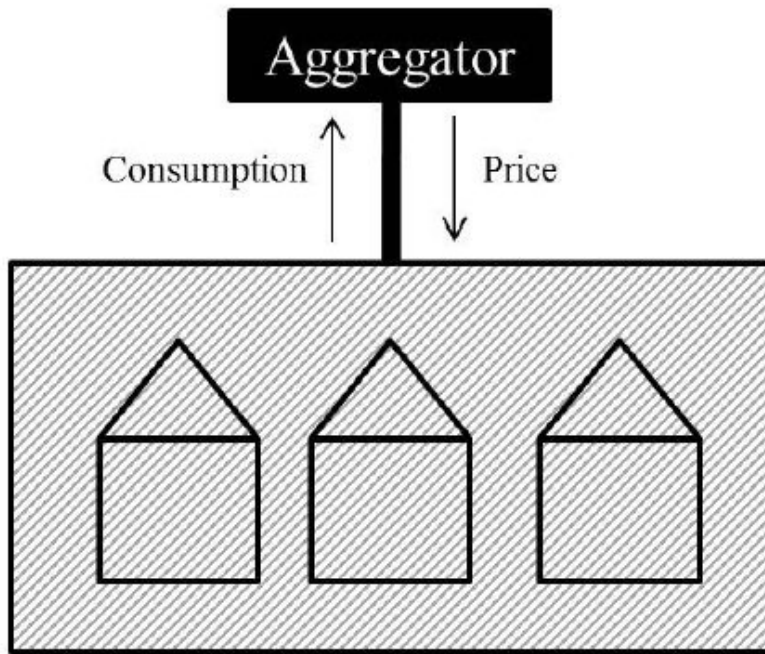
Cost: E-MPC at **low (DER) level**, One-way communication

Models for DERs are not needed

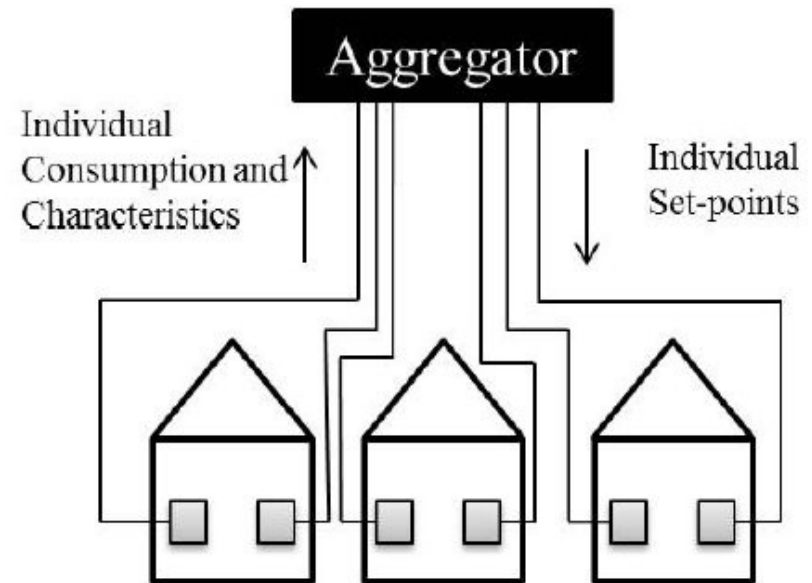
Simple 'contracts'

# Direct and Indirect Control

For DC info about individual states and constraints are needed



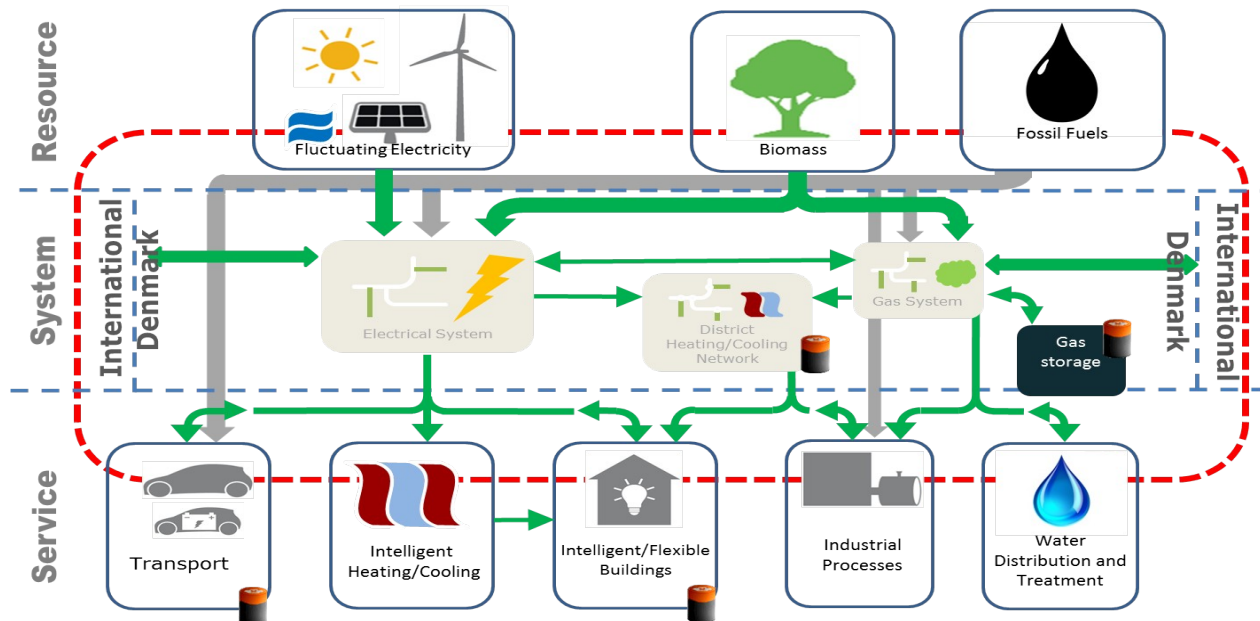
(a) Indirect control



(b) Direct control

# Models

Grey-box 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](#).

#### Latest news

Summer School at DTU, Lyngby, Denmark – July 4th-8th 2016

Summer School – Granada, Spain, June 19th-24th 2016

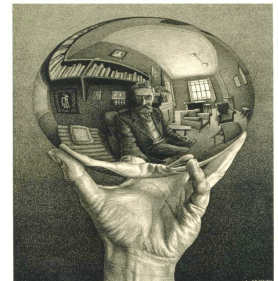
Third general consortium meeting – DTU, May 24th-25th 2016

Smart City Challenge in Copenhagen – April 20th 2016

Guest lecture by Pierluigi Mancarella at DTU, April 6th 2016

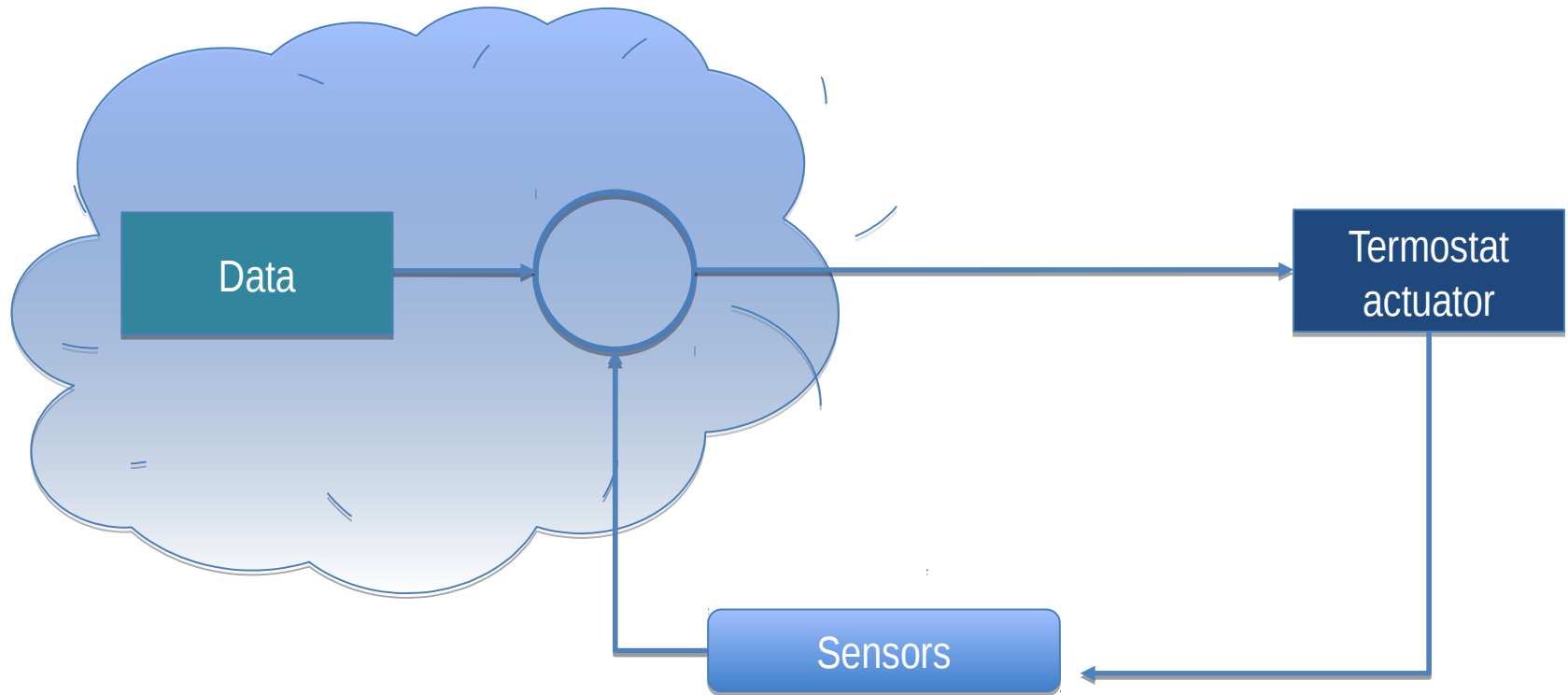
# SE-OS Characteristics

- 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

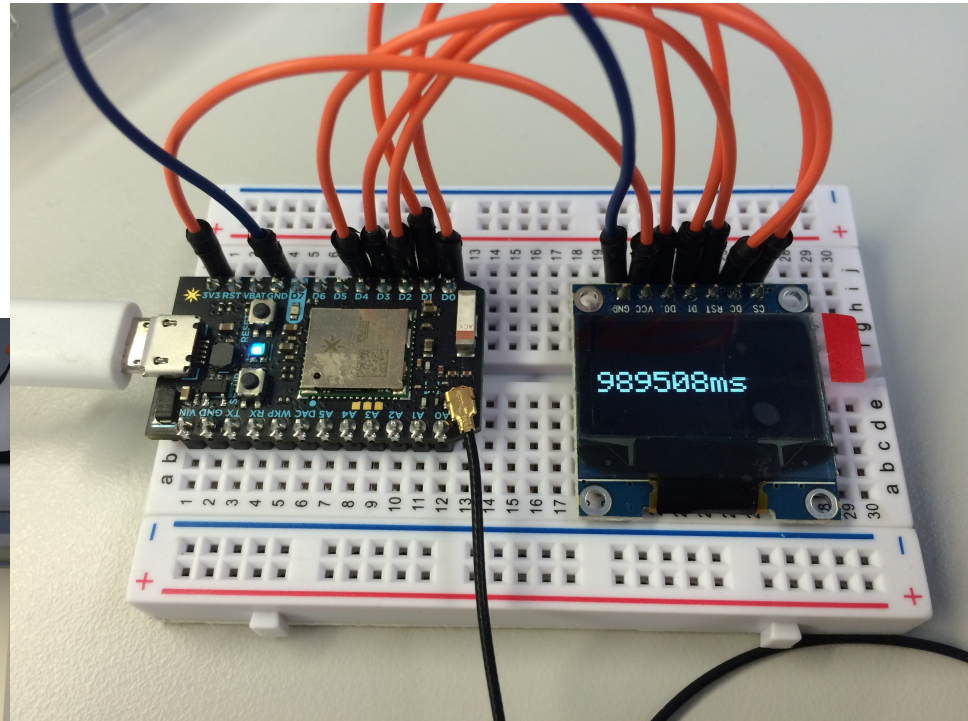
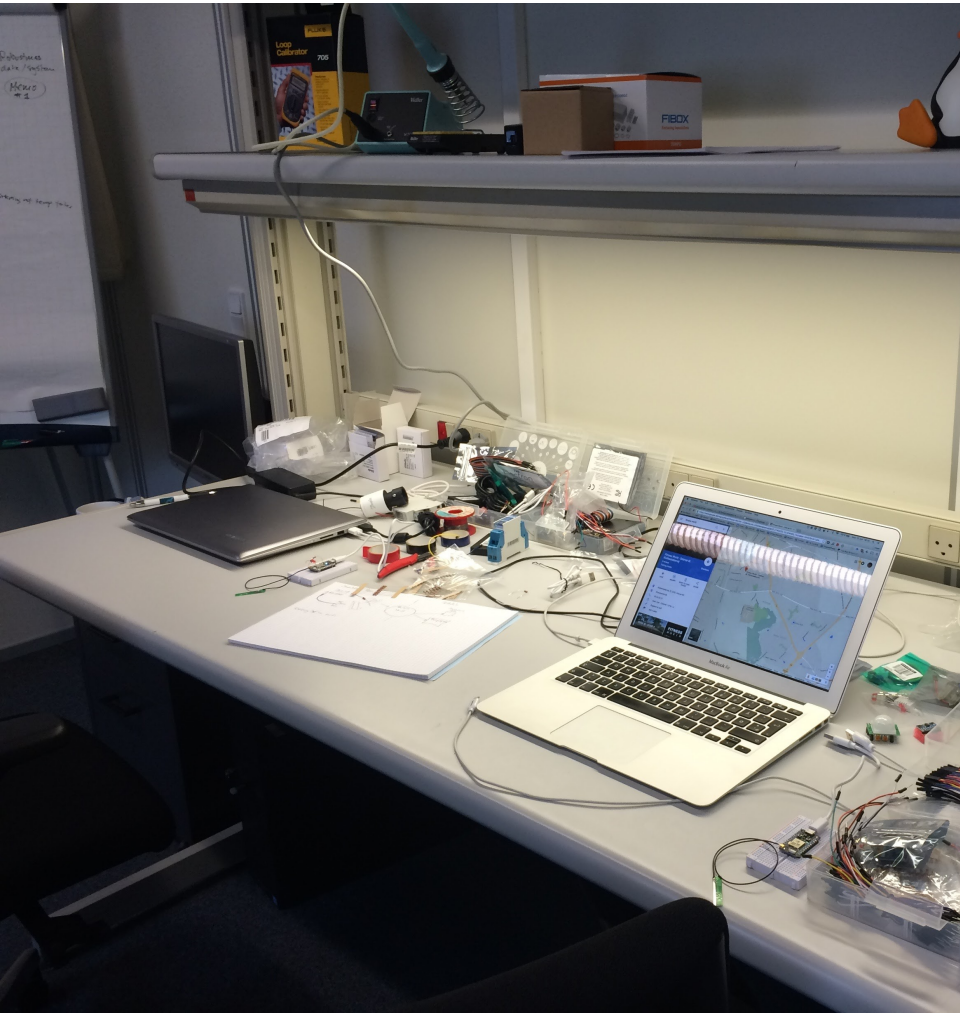


# SE-OS

## Control loop design – **logical drawing**

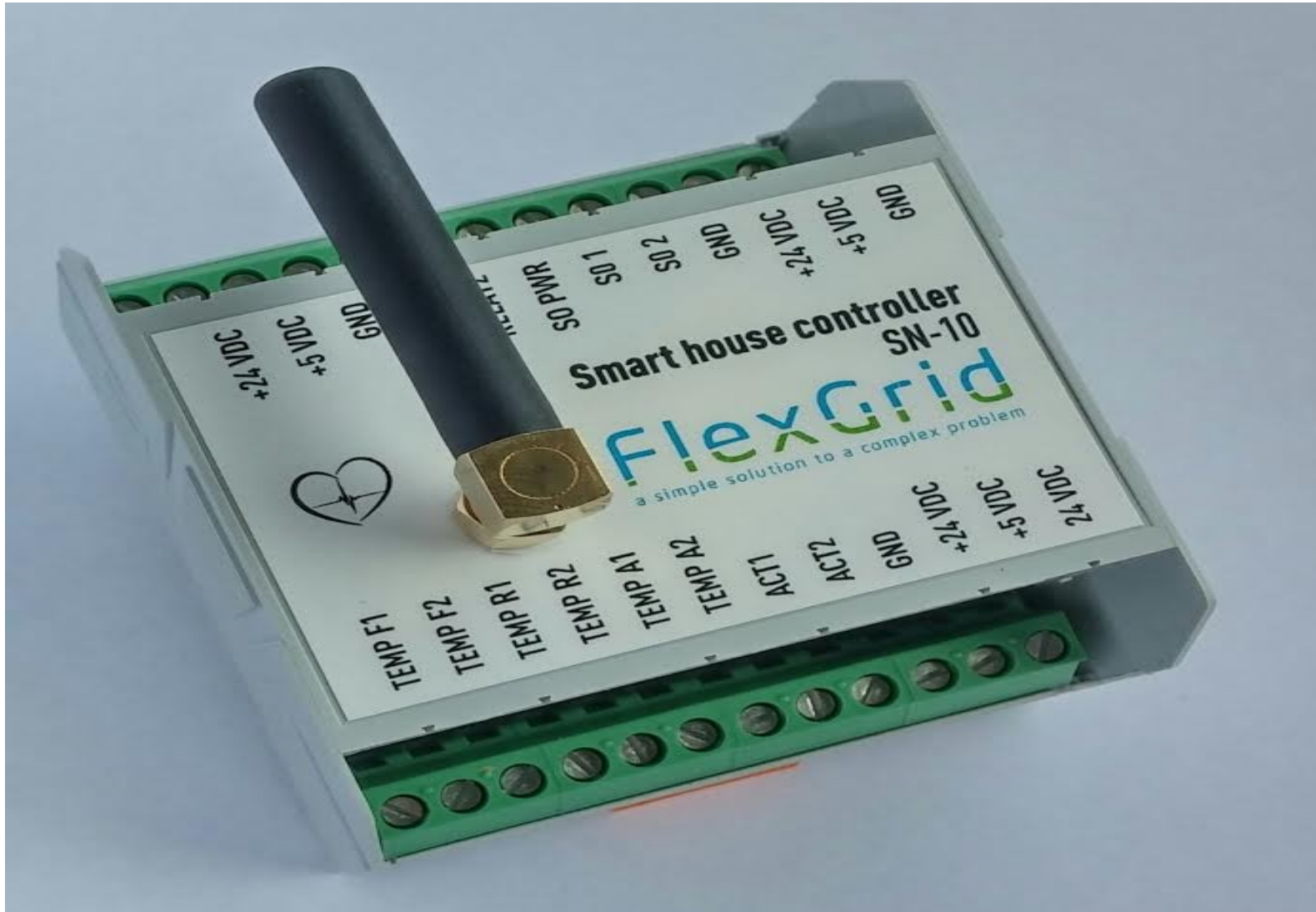


# Lab testing ....





# SN-10 Smart House Prototype





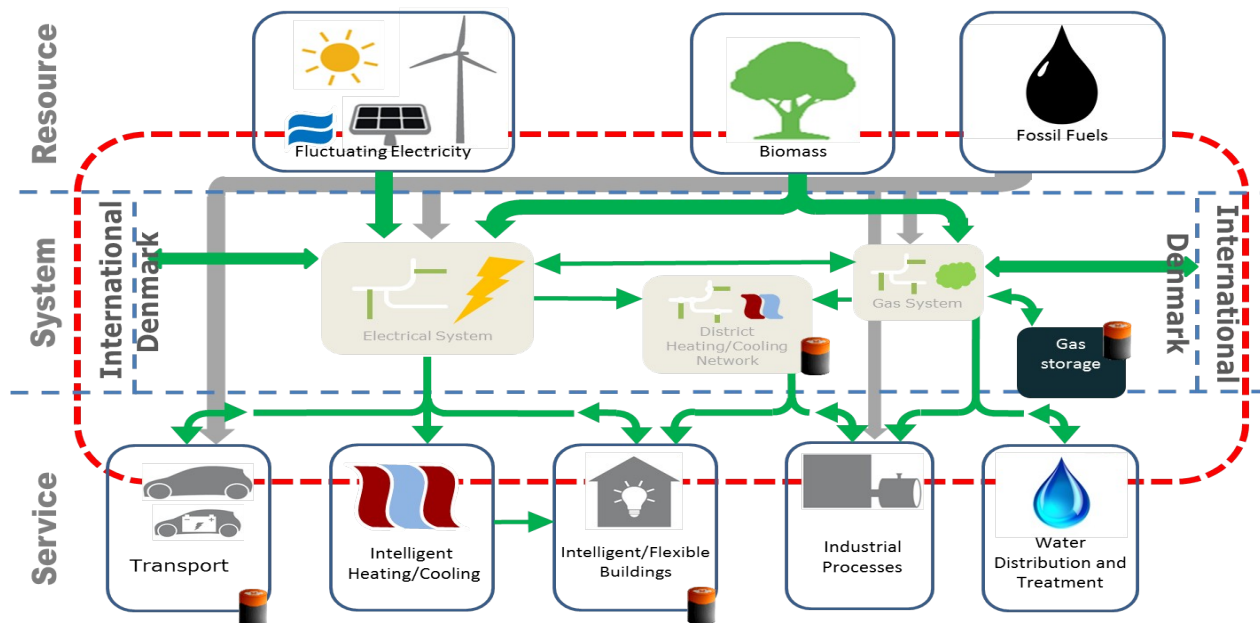
## Case study

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



# Models

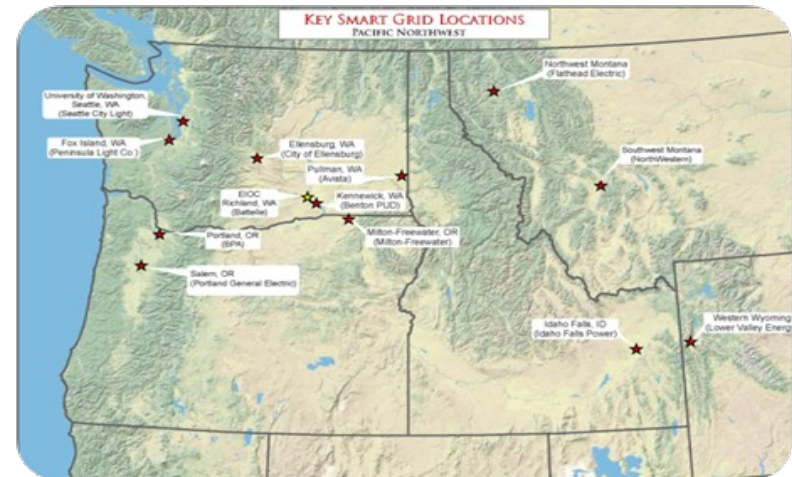
Grey-box modelling are used to establish **models and methods** for real-time operation of future electric energy systems



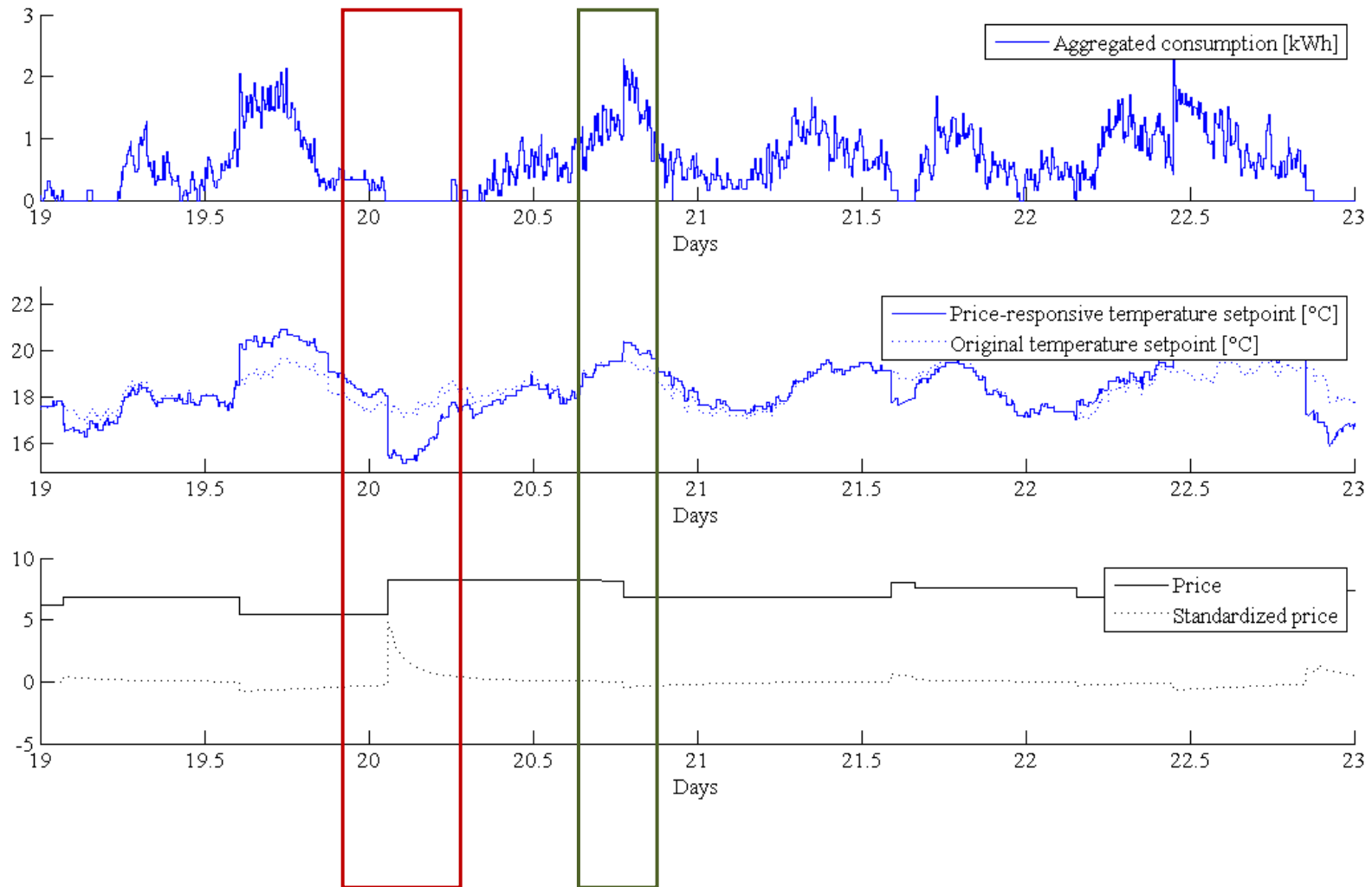
# Data from BPA

## Olympic Peninsula project

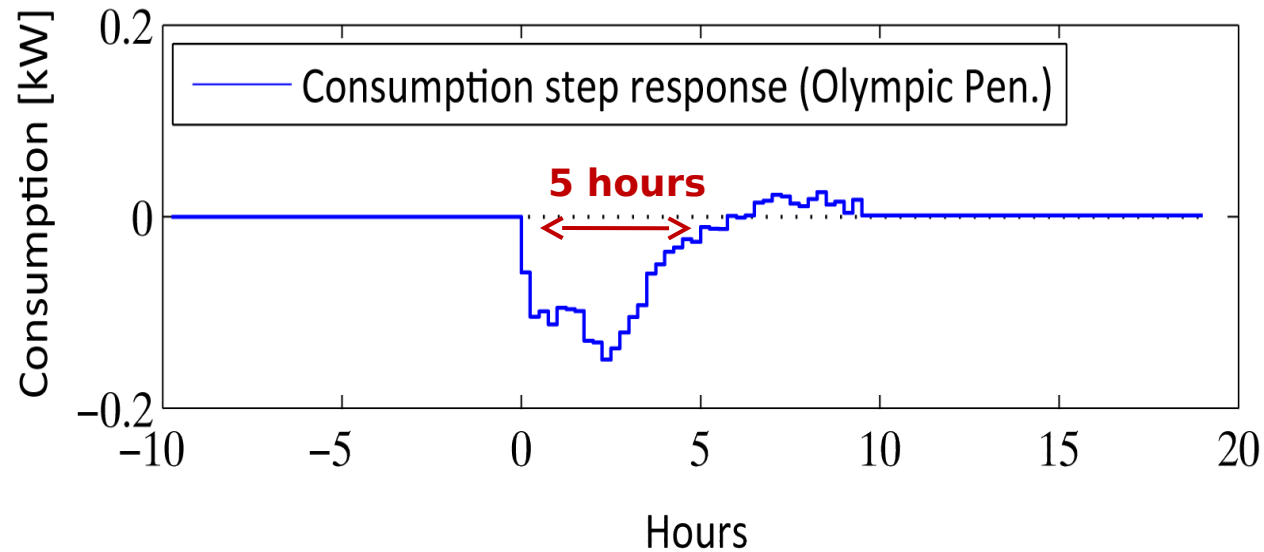
- 27 houses during one year
- Flexible appliances: HVAC, cloth dryers and water boilers
- 5-min prices, 15-min consumption
- Objective: limit max consumption



# Aggregation (over 20 houses)

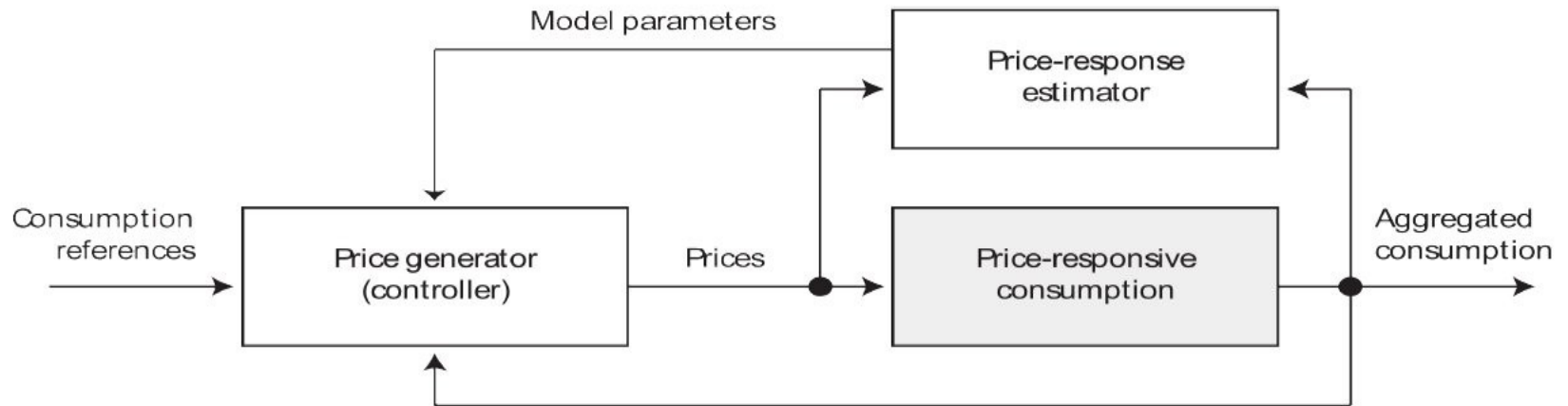


# Response on Price Step Change



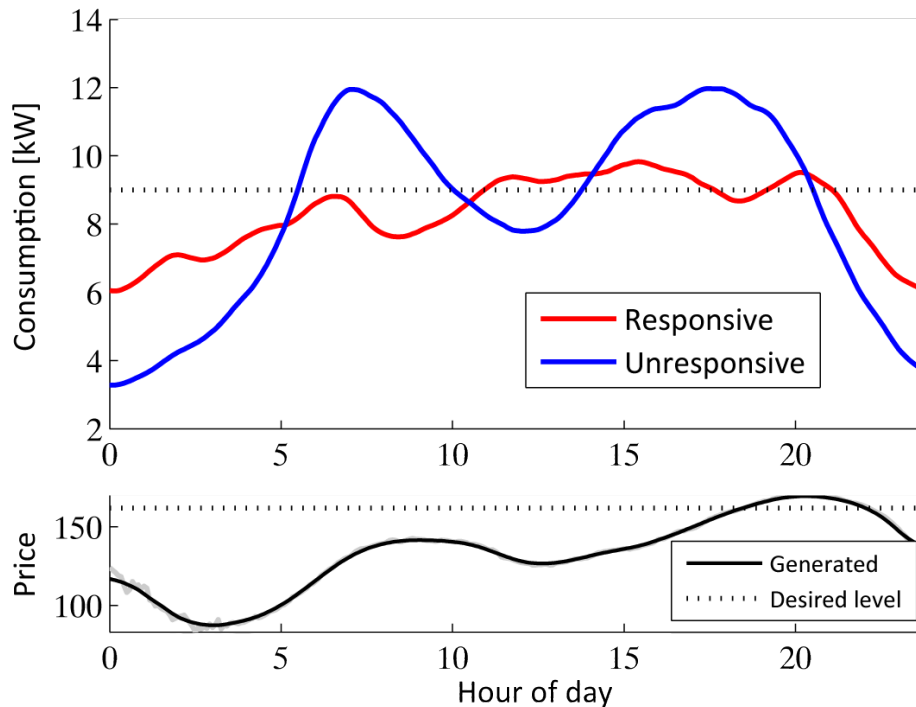


# Control of Power Consumption



# Control performance

Considerable **reduction in peak consumption**



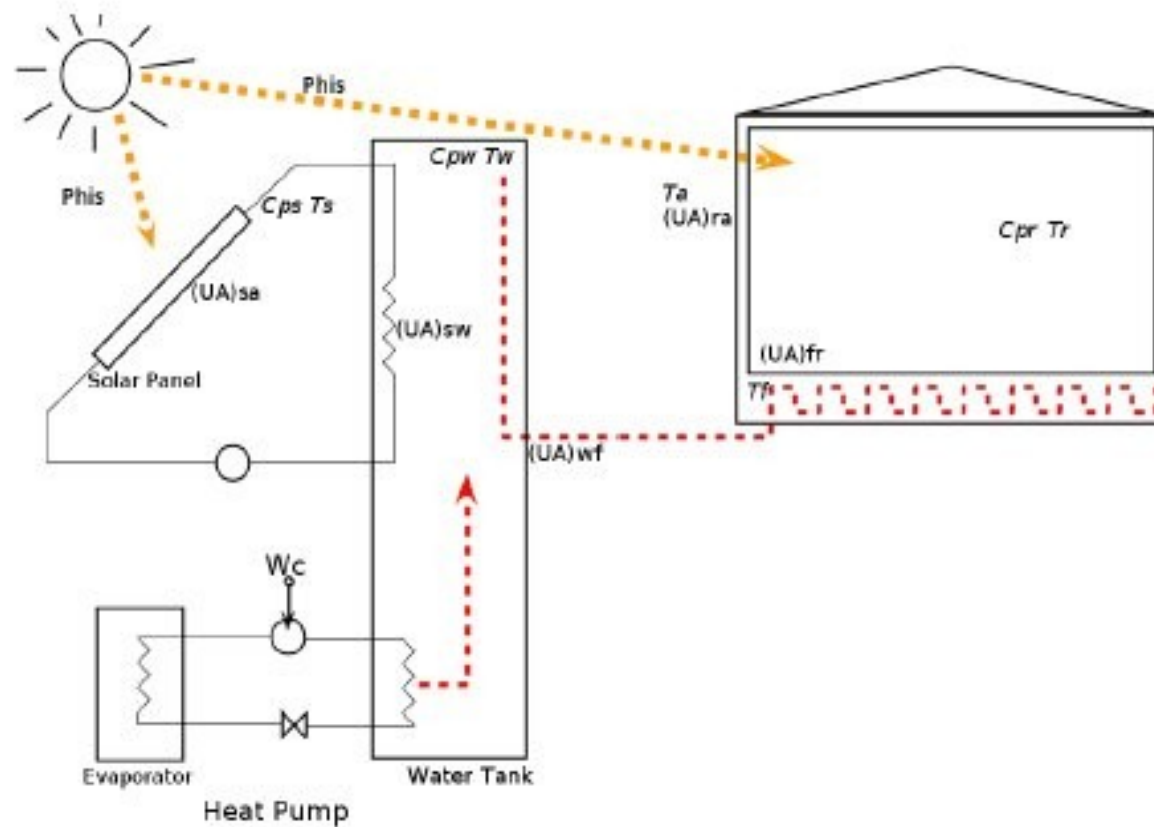
# Case study

## 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:

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

$$\text{Subject to } x_{k+1} = Ax_k + Bu_k + Ed_k \quad k = 0, 1, \dots, N-1 \quad (4b)$$

$$y_k = Cx_k \quad k = 1, 2, \dots, N \quad (4c)$$

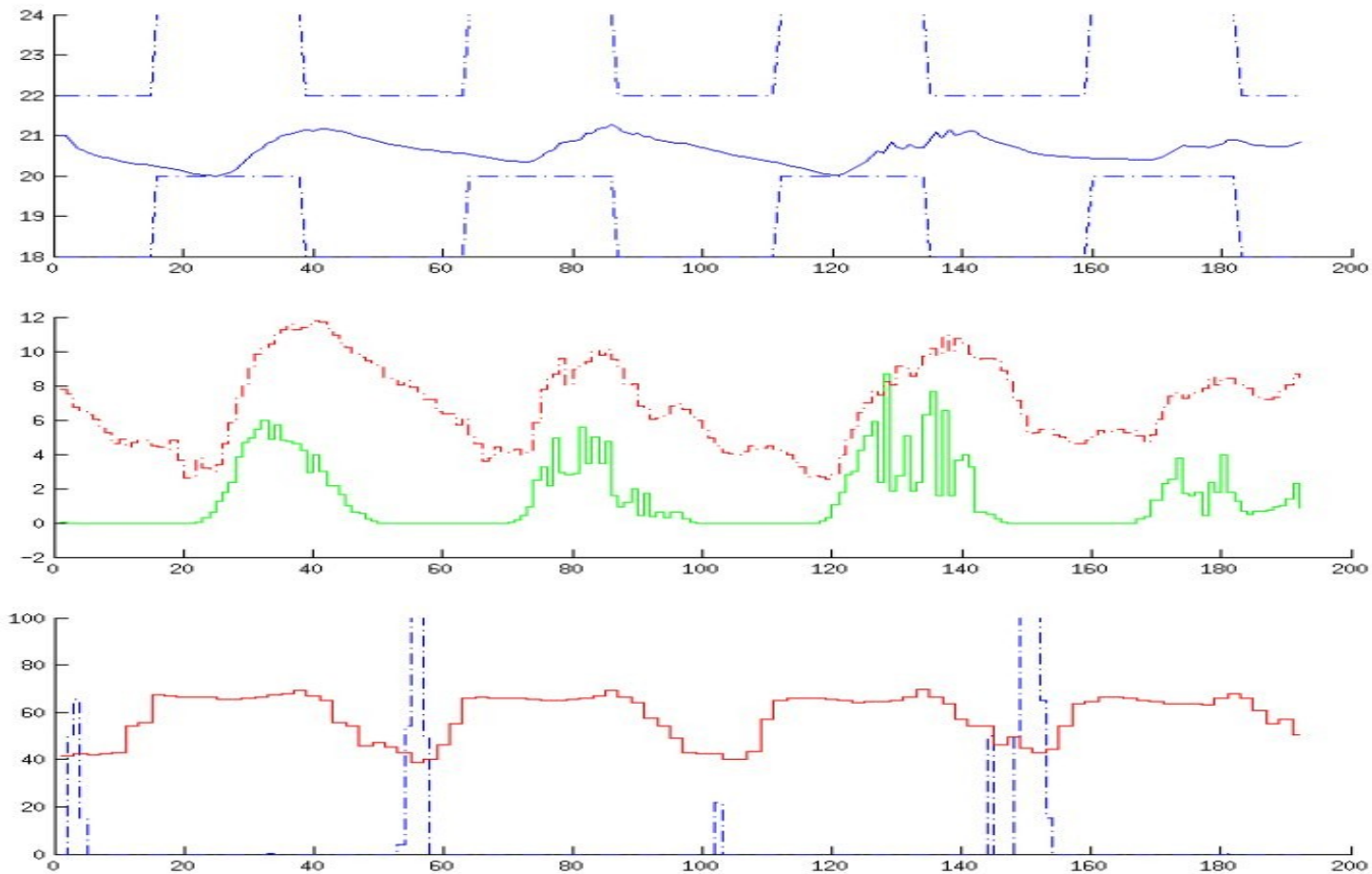
$$u_{min} \leq u_k \leq u_{max} \quad k = 0, 1, \dots, N-1 \quad (4d)$$

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

$$y_{min} \leq y_k \leq y_{max} \quad k = 0, 1, \dots, N \quad (4f)$$



# Heat pump with thermal solar collector and storage (savings up to 35 pct)



## Case study

# Control of Wastewater Treatment Plants

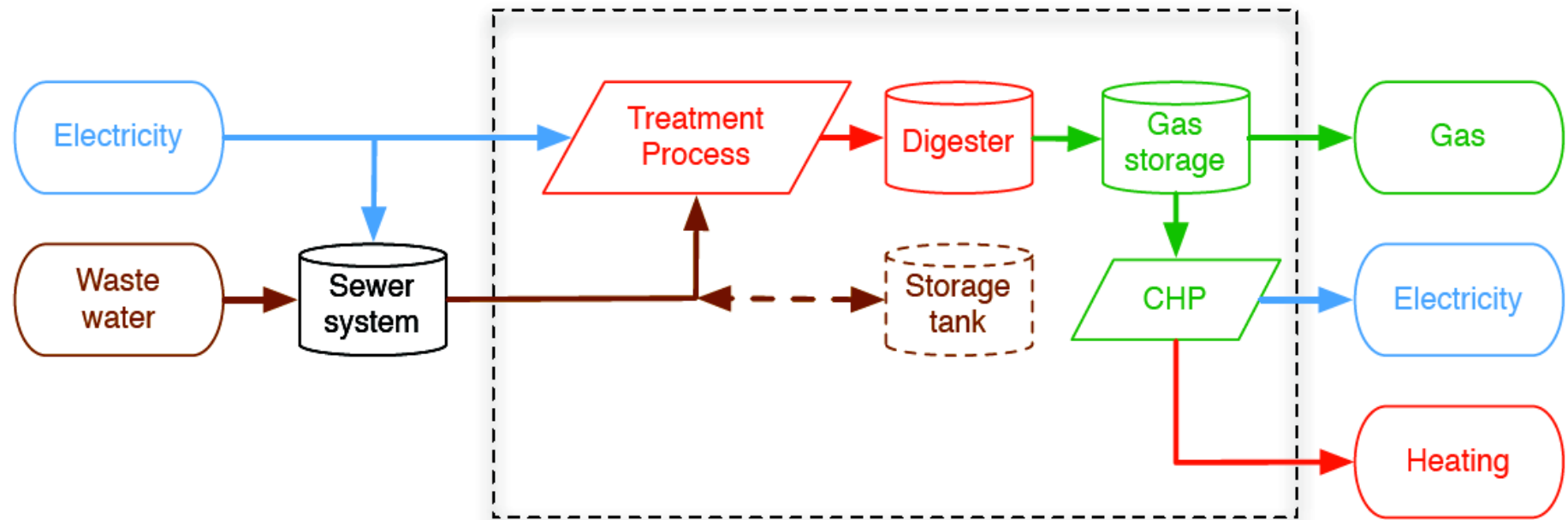


# Waste-2-Energy

Resources

WWTP Energy Hub

Energy service



# Kolding WWTP



# Energy Flexibility in Wastewater Treatment

- **Sludge -> Biogas -> Gas turbine -> Electricity**
- **Power management of the aeration process**
- **Pumps and storage in sewer system**

## **Overall goals:**

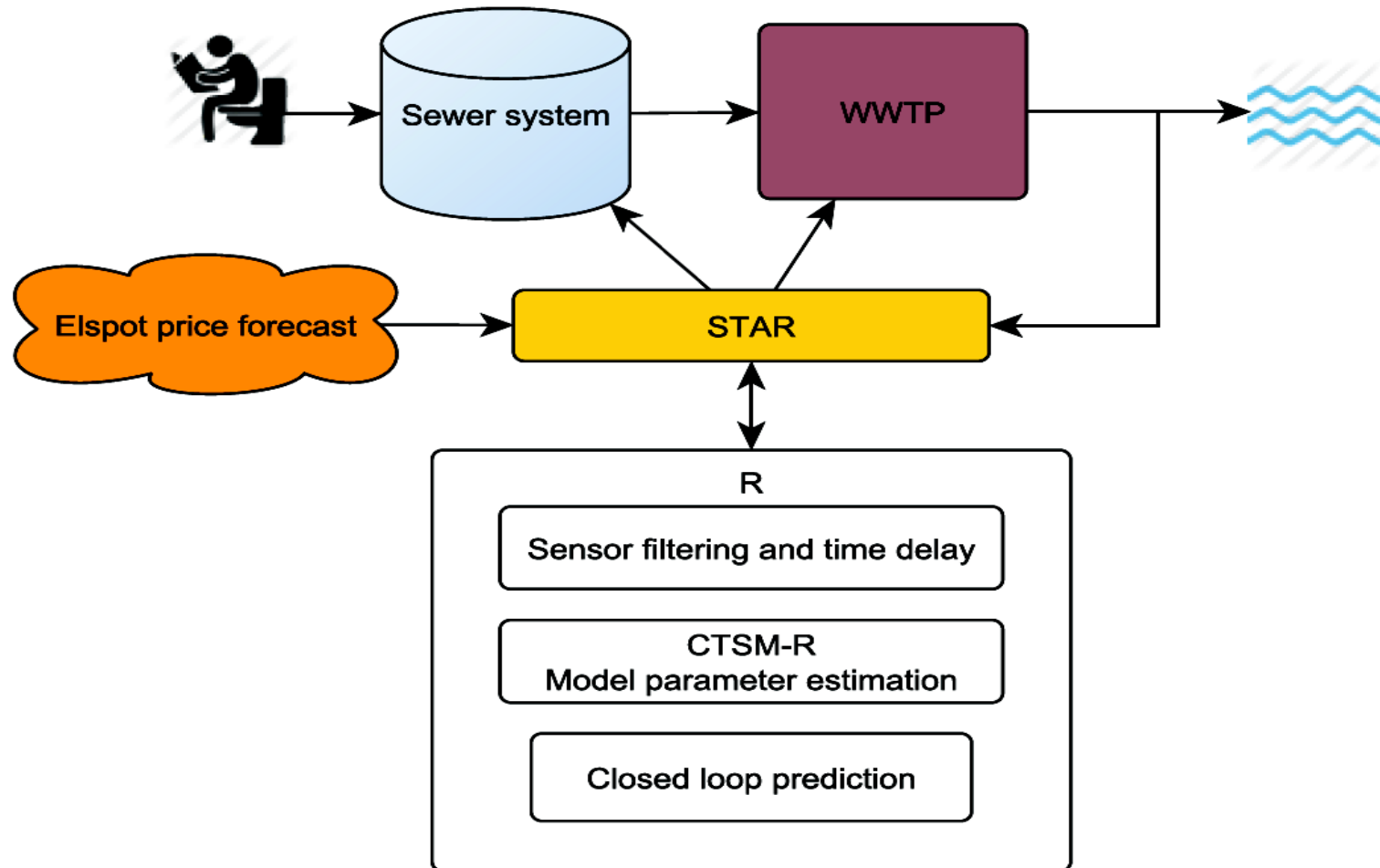
**Cost reduction**

**Minimize effluent concentration**

**Minimize overflow risk**

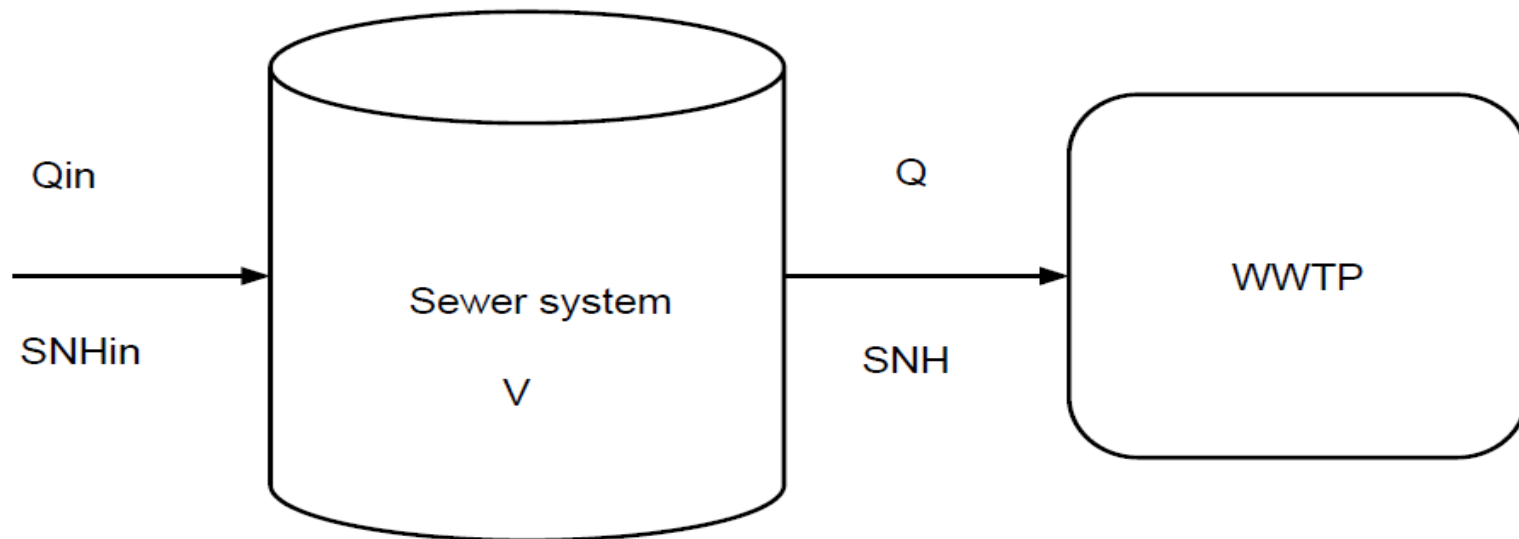


# Energy Flexibility in Wastewater Treatment

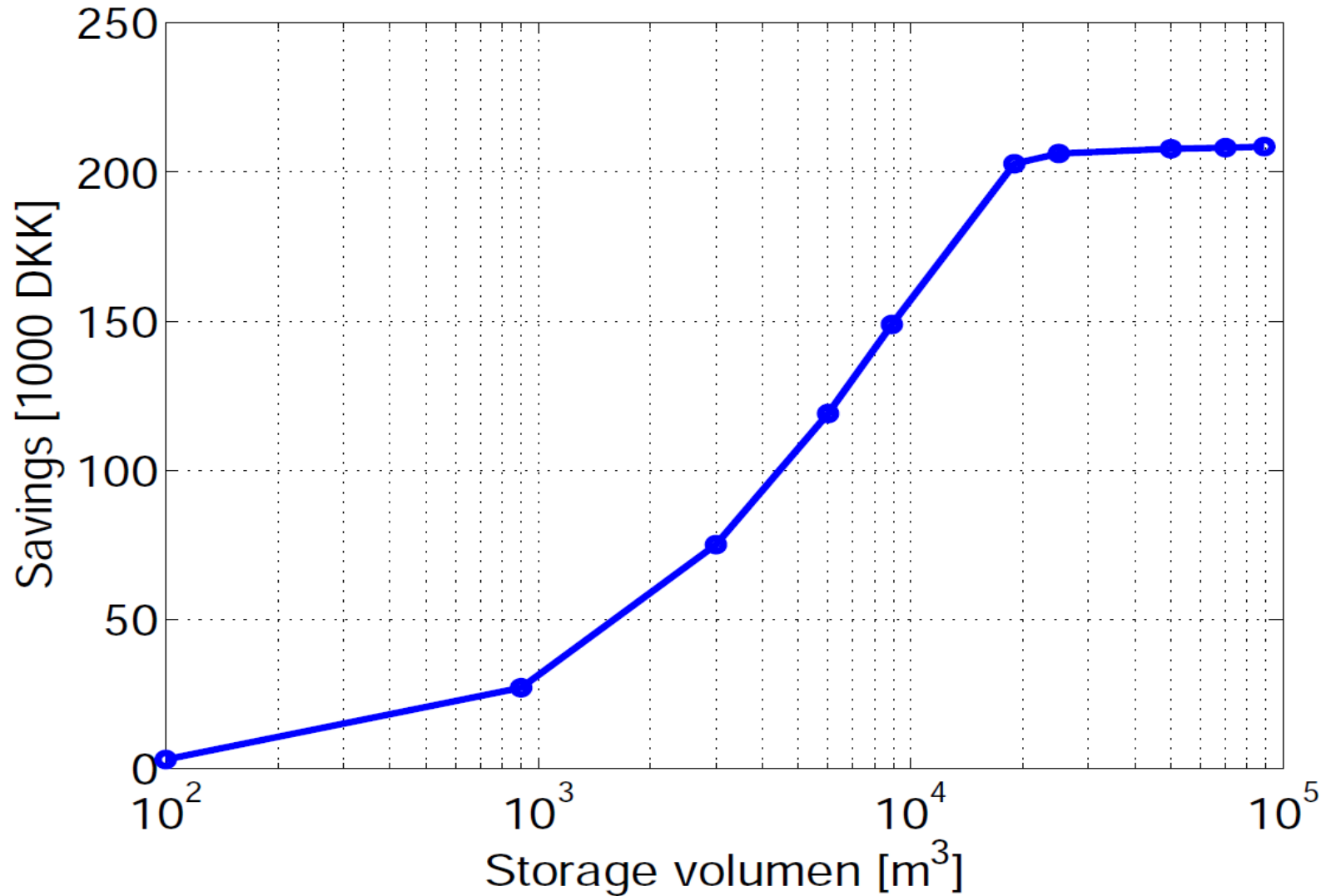


# Sewer System Control Goal

minimize overflow +  $p_{elspot}^T f(Q)$



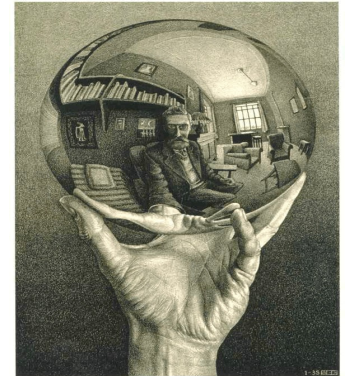
# Sewer System Annual Elspot Savings



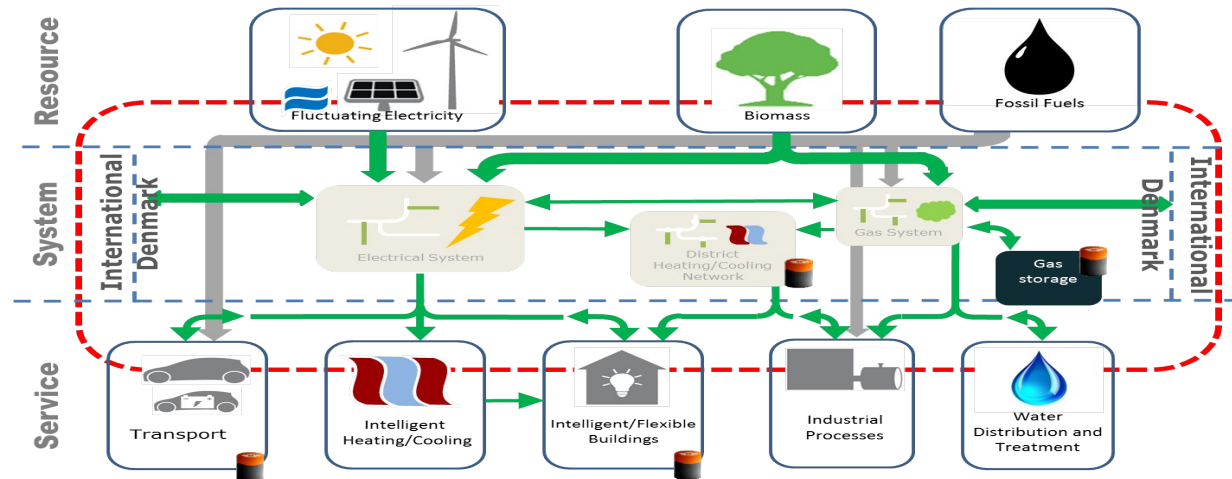
# Smart-Energy OS

## 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.

