Innovation Fund Denmark

DTU

Integrated Modelling, Forecasting and Control for the Future Low-Carbon Society

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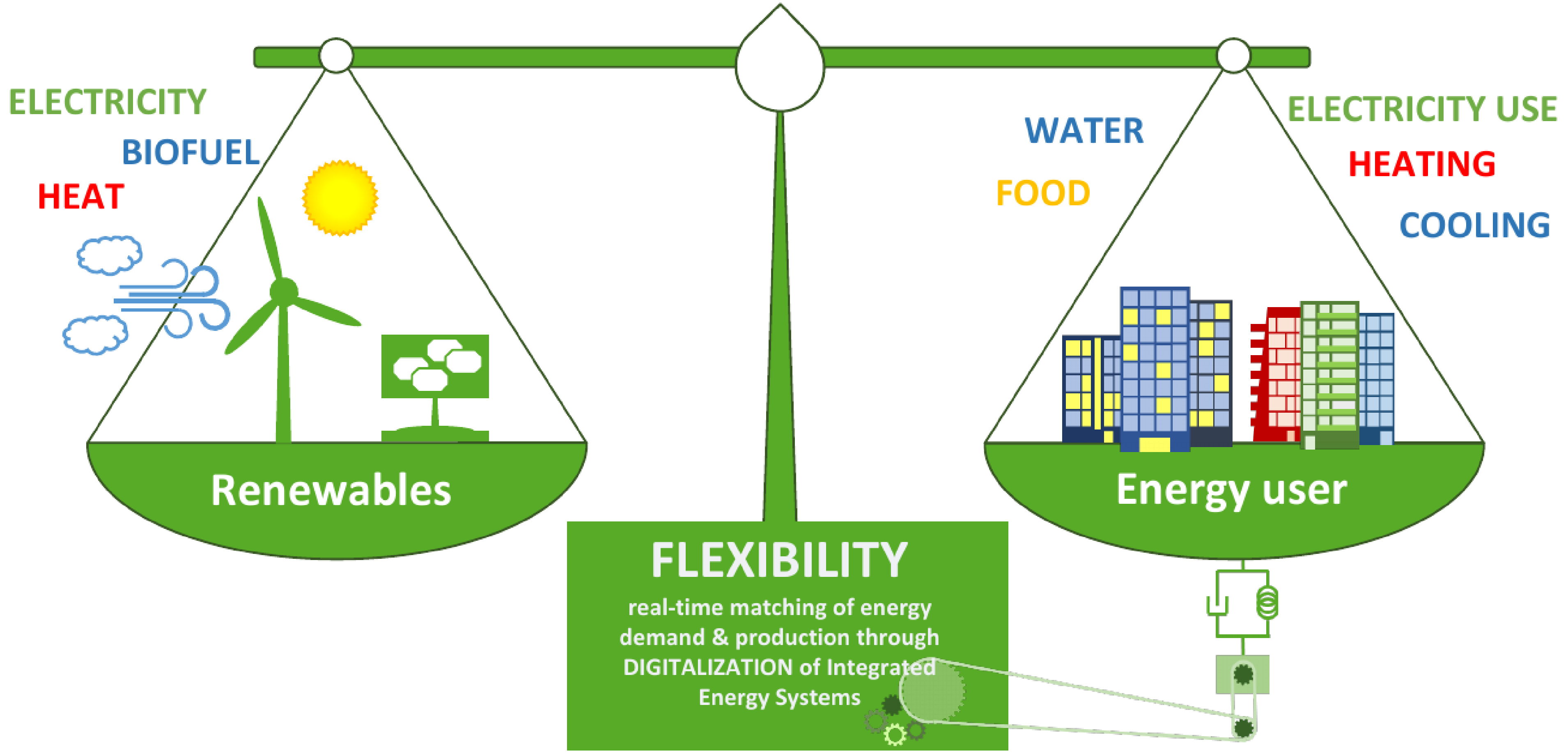
Centre for IT Intelligent Energy Systems

FED
FLEXIBLE
ENERGY
DENMARK

The Challenge: Denmark Fossil Free 2050



ELECTRICITY

BIOFUEL

HEAT

Renewables

WATER

FOOD

ELECTRICITY USE

HEATING

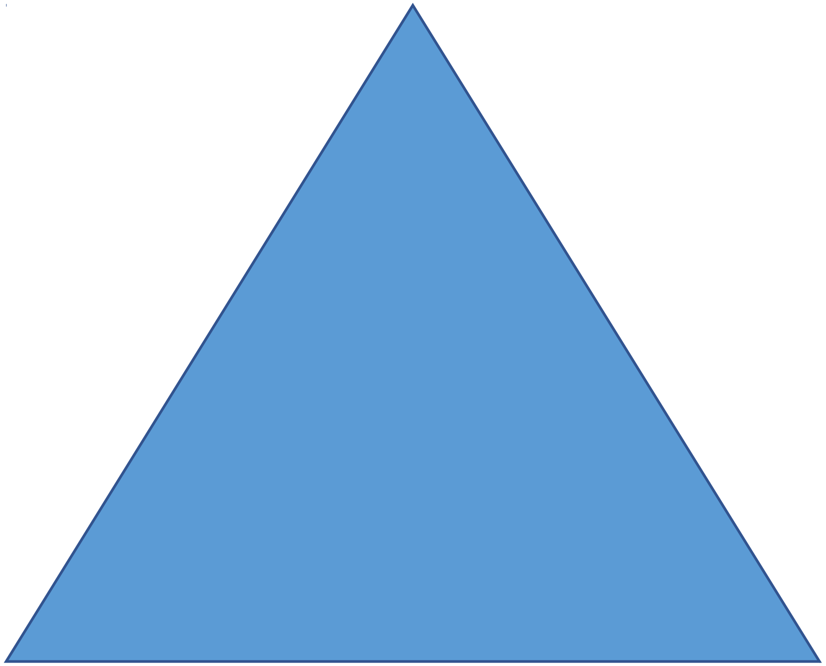
COOLING

Energy user

FLEXIBILITY

real-time matching of energy demand & production through DIGITALIZATION of Integrated Energy Systems

Space of Solutions



Flexibility / Virtual Storage

(enabled by Digitalisation and Energy Systems Integration)

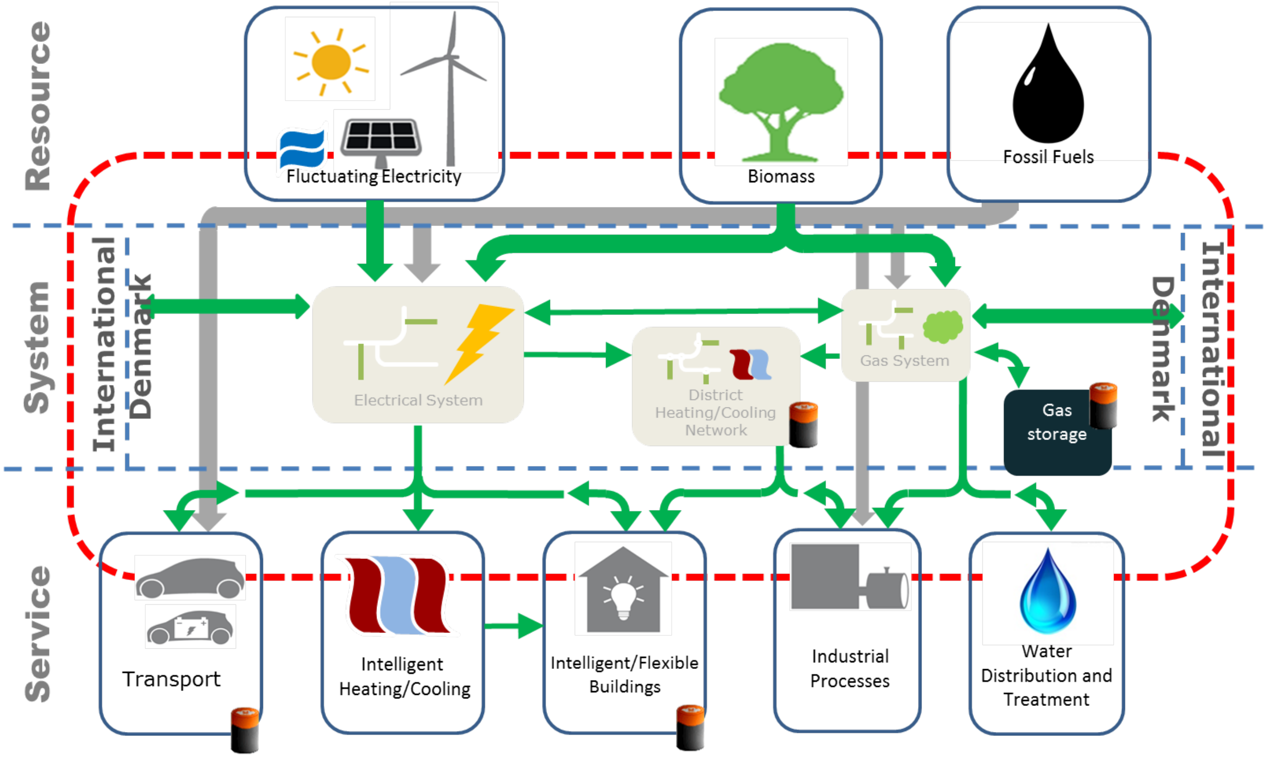
(Super) Grids

Batteries

Data-Intelligent and Flexible Energy Systems

Energy System Models for Real Time Applications and Data Assimilation

Grey-box models are simplified models for the individual components facilitating system integration and use of sensor data



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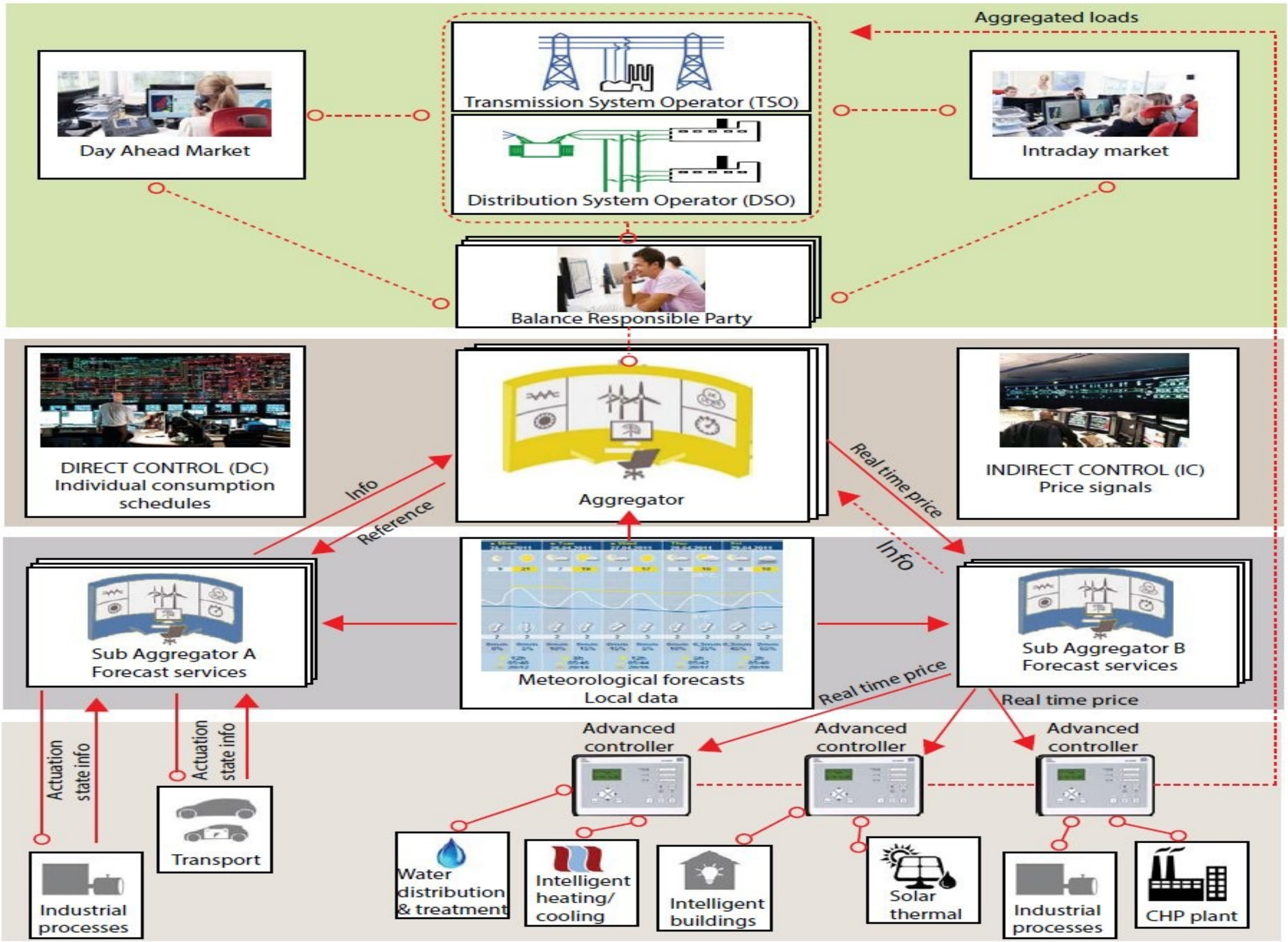
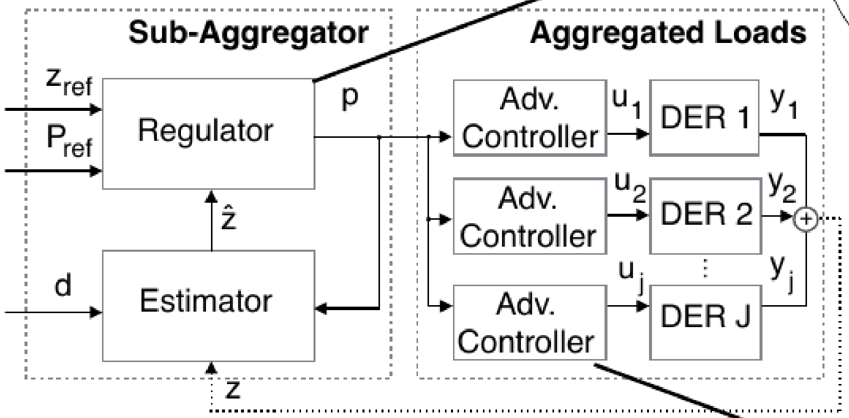
Smart-Energy OS



Proposed methodology
Control-based methodology

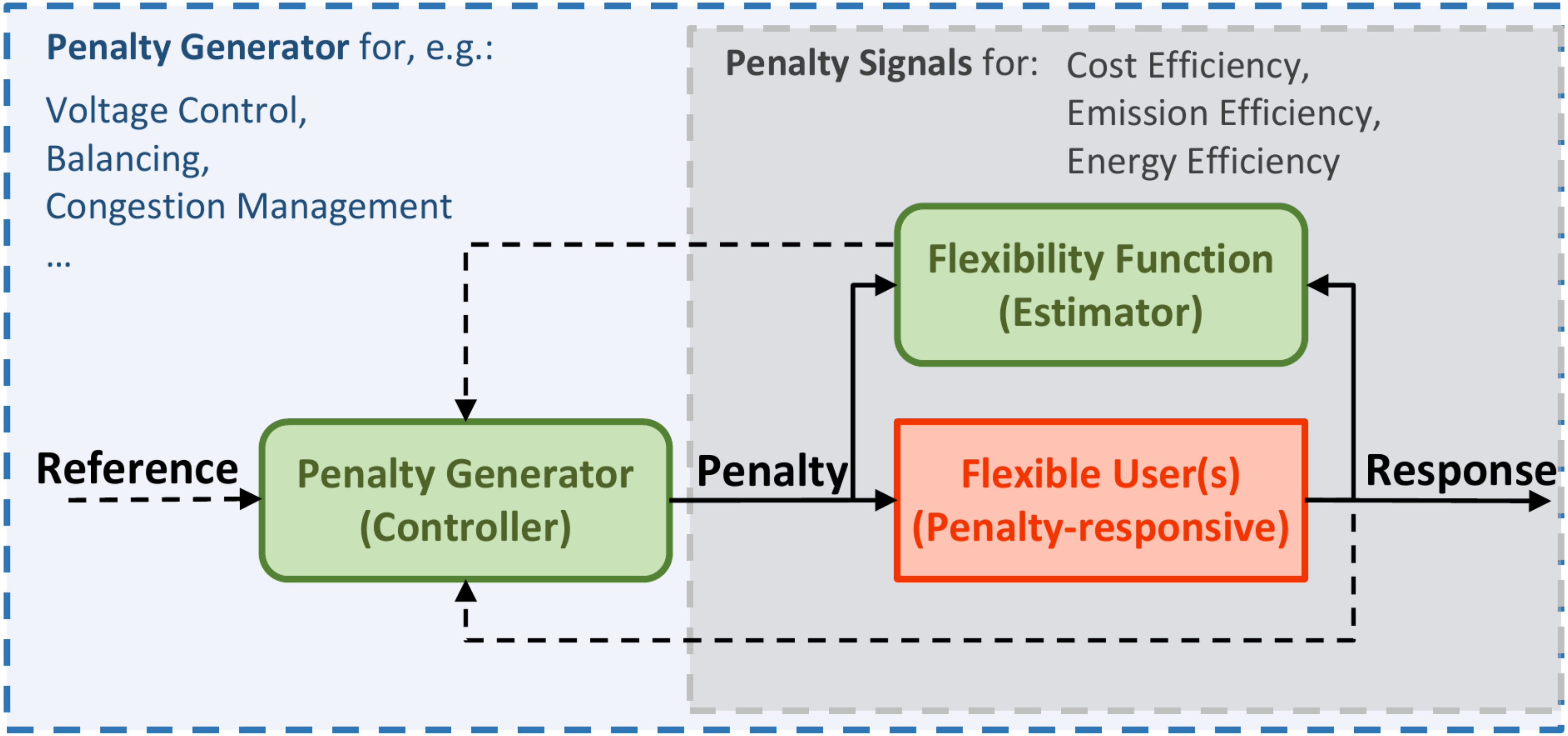


$$\min_{p} \quad \mathrm{E}\Big[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||\Big]$$
$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$

$$\min_{u} \quad \mathrm{E}\Big[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)\Big]$$
$$\begin{aligned} \text{s.t.} \quad x_{k+1} &= Ax_k + Bu_k + Ed_k, \\ y_k &= Cx_k, \\ y_k^{min} \leq y_k &\leq y_k^{max}, \\ u_k^{min} \leq u_k &\leq u_k^{max} \end{aligned}$$

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

A FED example: Flexible Users and Penalty Signals



Penalty Generator for, e.g.:

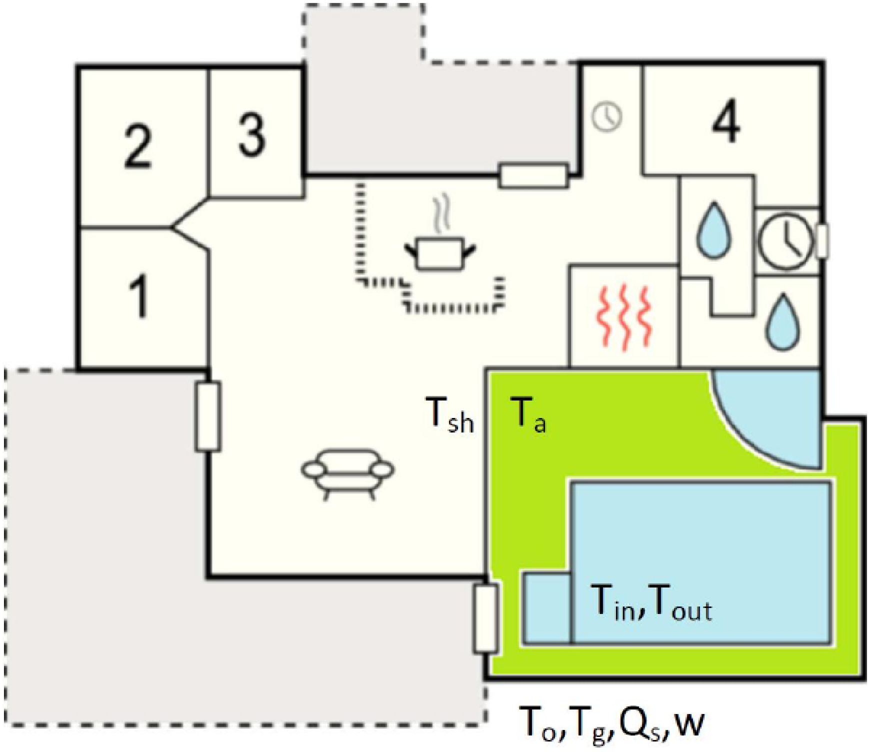
Voltage Control,
Balancing,
Congestion Management
…

Penalty Signals for: Cost Efficiency,
Emission Efficiency,
Energy Efficiency

Case study No. 1

Control of heat pumps for swimming pools (CO2 minimization)

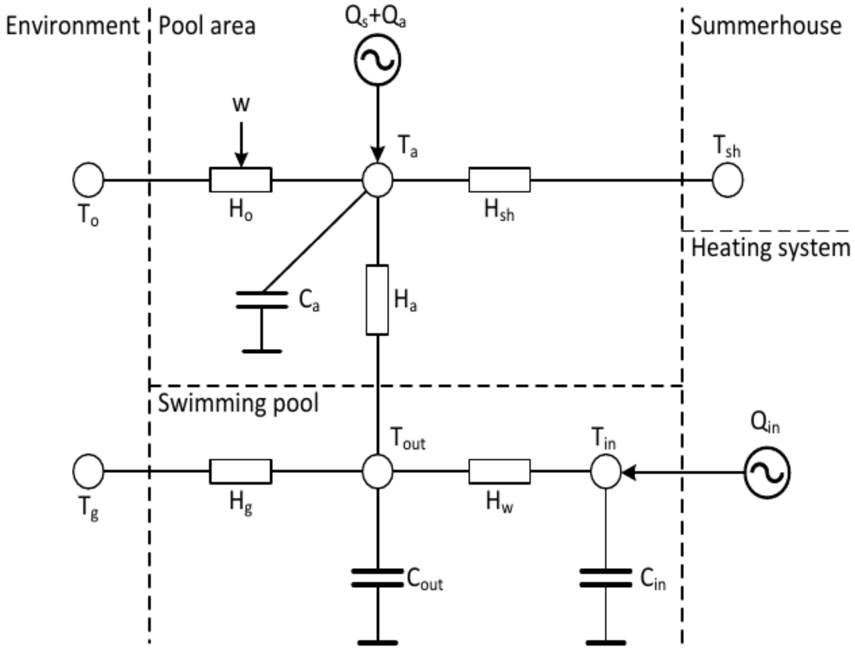
The considered house



- T_{sh} – summerhouse temperature
- T_a – temperature of air in the pool area
- T_{in} – water temperature into the swimming pool
- T_{out} – water temperature out of the swimming pool (controlled)
- T_o – outdoor temperature
- T_g – ground temperature
- Q_s – solar heat gain
- w – wind speed

Grey-box model

(lumped parameter model)



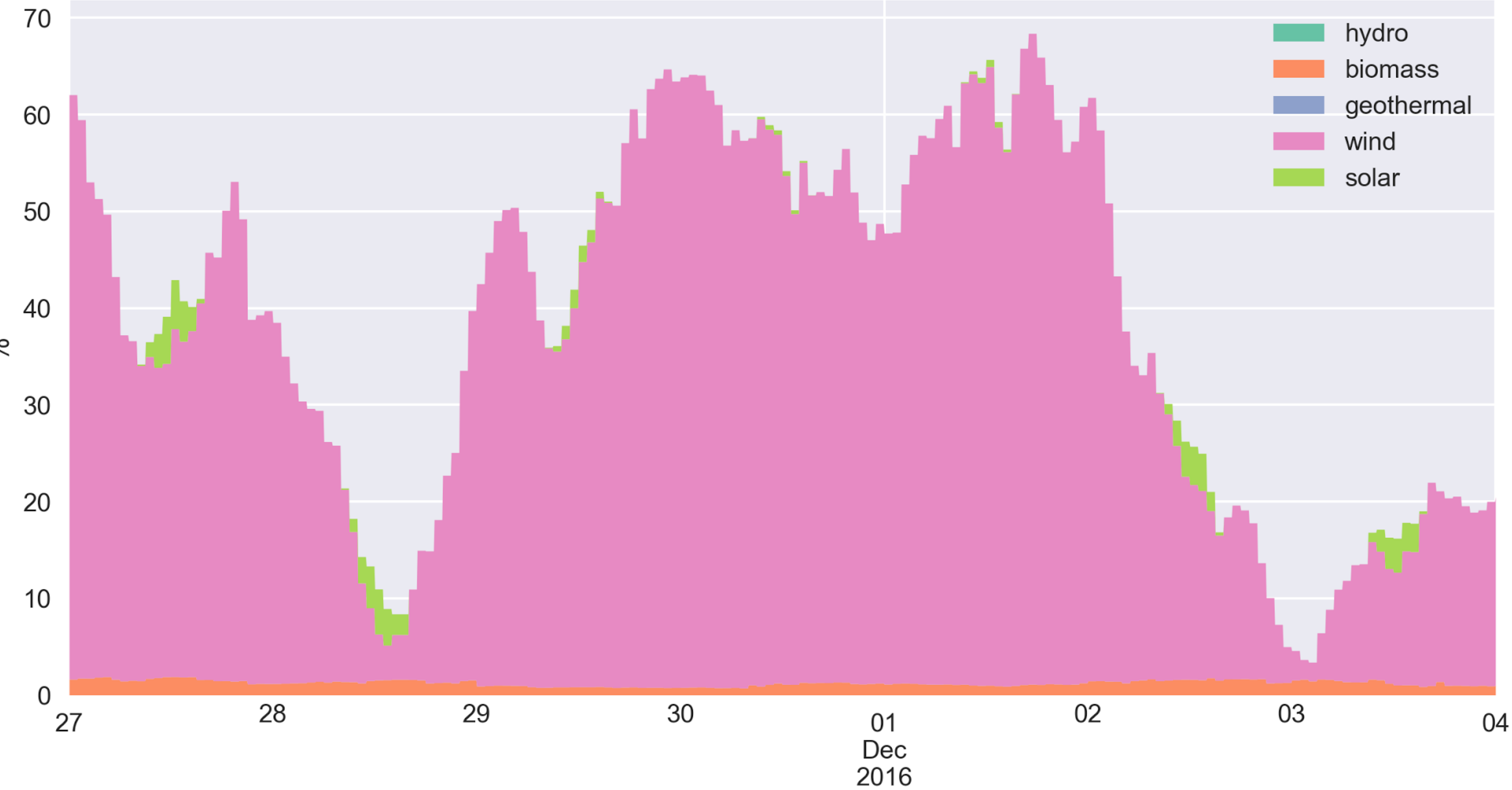
- Based on equivalent thermal parameters model
- Dynamics:

$$\frac{dT_{in}}{dt} = \frac{1}{C_{in}}[H_w(T_{out} - T_{in}) + Q_{in}]$$

$$\frac{dT_{out}}{dt} = \frac{1}{C_{out}}[H_w(T_{in} - T_{out}) + H_g(T_g - T_{out}) + H_a(T_a - T_{out})]$$

$$\frac{dT_a}{dt} = \frac{1}{C_a}[H_o(w)(T_o - T_a) + H_a(T_{out} - T_a) + H_{sh}(T_{sh} - T_a) + Q_s + Q_a]$$

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



Source: pro.electicitymap.

How does it work?

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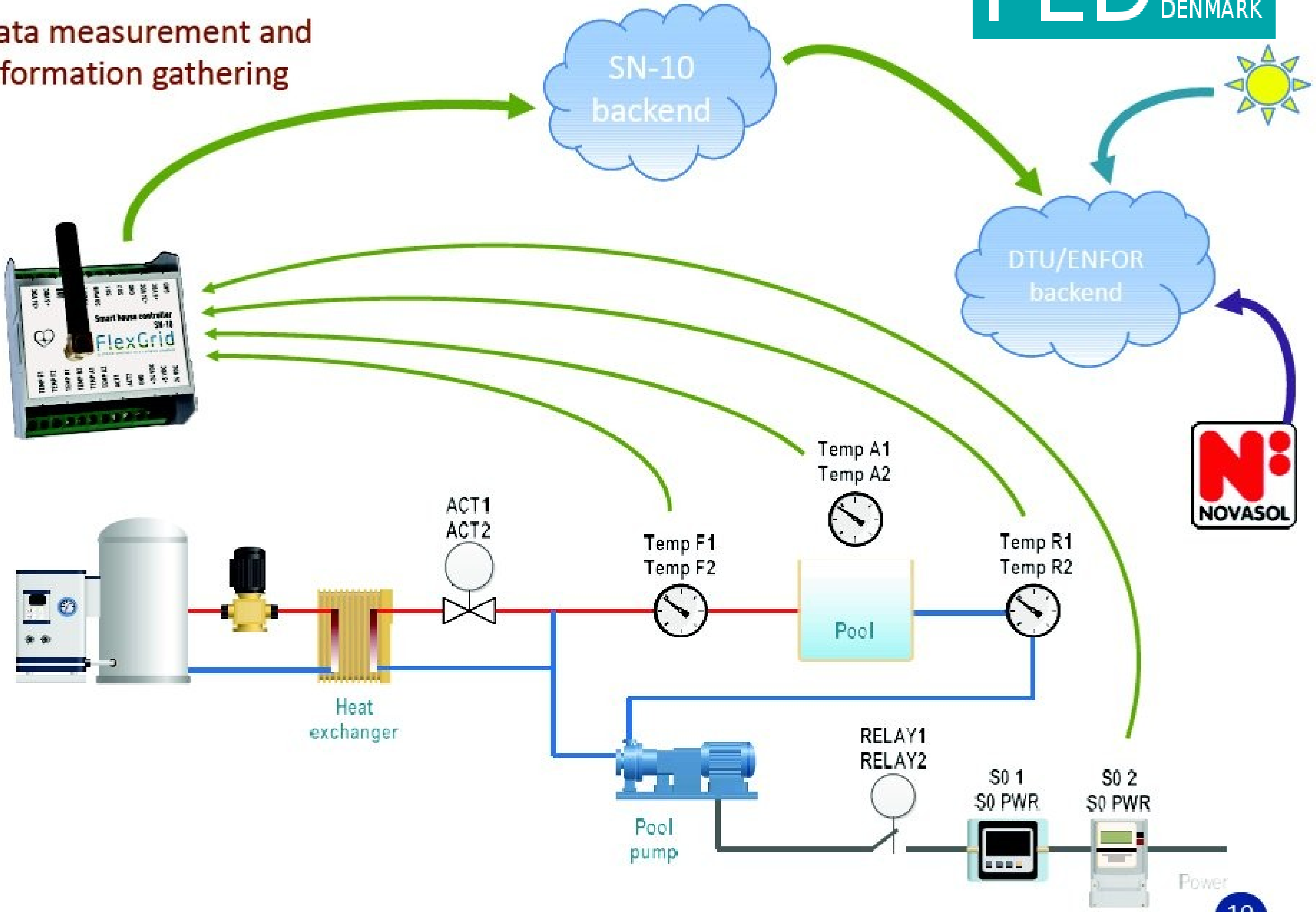
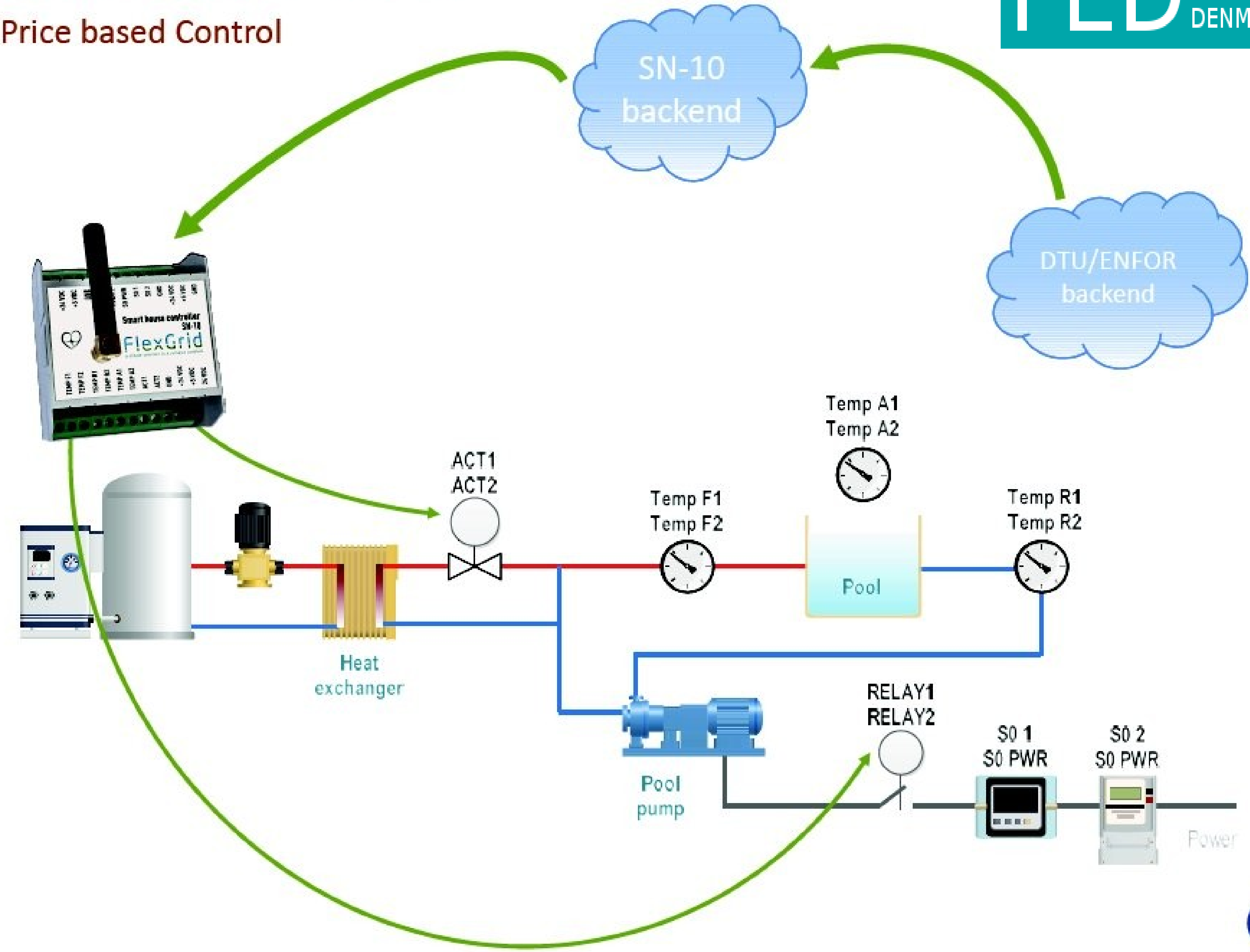
Data measurement and information gathering



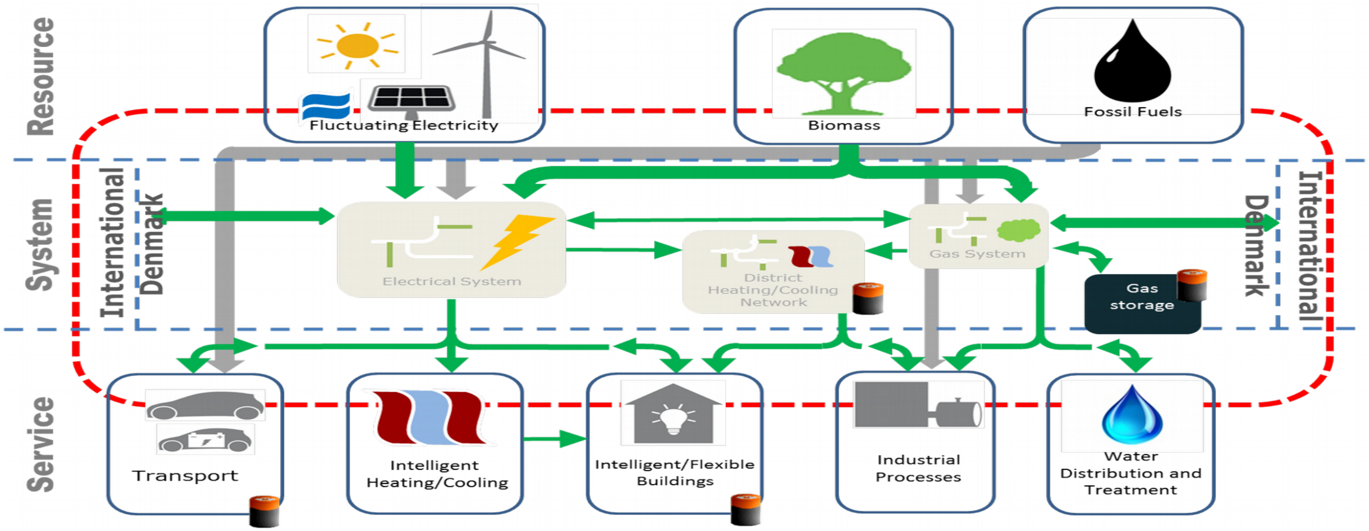
How does it work?

Price based Control



Example: CO2-based control (savings 15 pct)

Flexibility (or Virtual Storage) Solutions



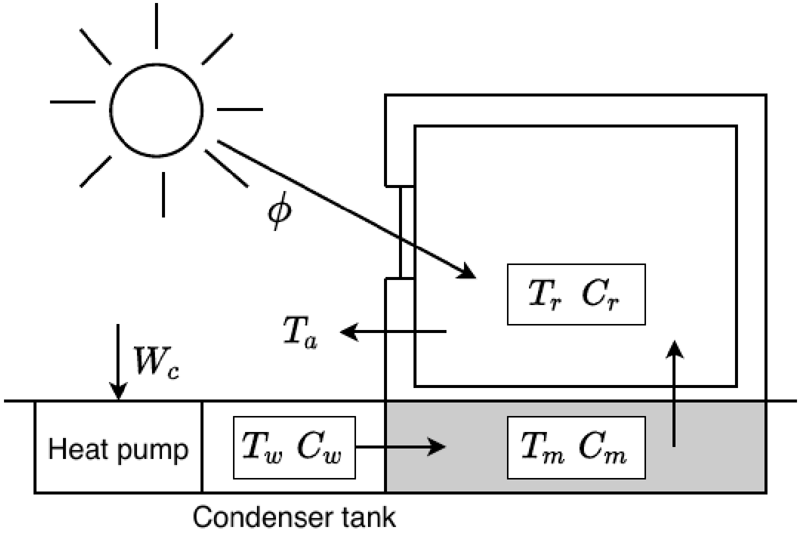
- **Flexibility (or virtual storage) characteristics:**
  - Wastewater systems can provide storage 0.2-6 hours ahead
  - Supermarket refrigeration can provide storage 0.5-2 hours ahead
  - Buildings thermal capacity can provide storage up to, say, 2-10 hours ahead
  - Buildings with local water storage can provide storage up to, say, 2-18 hours ahead
  - District heating/cooling systems can provide storage up to 1-4 days ahead
  - DH systems can provide seasonal storage solutions
  - Gas systems can provide seasonal/long term storage solutions

Case study No. 2

Control of smart buildings using integrated weather forecasting

A Smart House

The smart house components:



The smart building and its components are also modelled using grey-box modelling. The optimal model for the building turns out to be a linear grey-box model.

Model for weather forecasting

Disturbance model

$$\begin{cases} \mathrm{d}Z_\kappa = f_\psi(Z_\kappa)\mathrm{d}t + \sigma_\psi \mathrm{d}\omega_\kappa \\ \kappa = \psi^{-1}(Z_\kappa) \\ \phi = I_N(\kappa, t) + I_D(\kappa, t) \\ R_n = R_n(\kappa, \phi, t) \\ \mathrm{d}T_s = f_{T_s}(T_l, T_s)\mathrm{d}t + \sigma_s \mathrm{d}\omega_s \\ \mathrm{d}T_l = f_{T_l}(T_l, T_s, R_n)\mathrm{d}t + \sigma_l \mathrm{d}\omega_a \\ \boldsymbol{d} = [T_a, \phi]^T \end{cases}$$

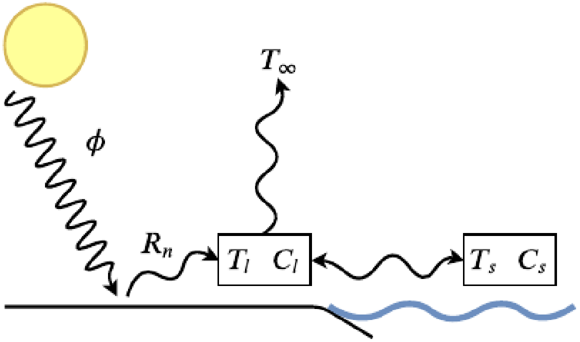
Observation equation

$$\begin{cases} d_\phi = \phi + v_\phi, \quad v_\phi \sim N_{iid}(0, R_\phi) \\ d_{T_a} = T_l + v_{T_a}, \quad v_{T_a} \sim N_{iid}(0, R_{T_a}) \\ \boldsymbol{y}_d = \left[d_{T_a}, d_\phi\right]^T, \end{cases}$$

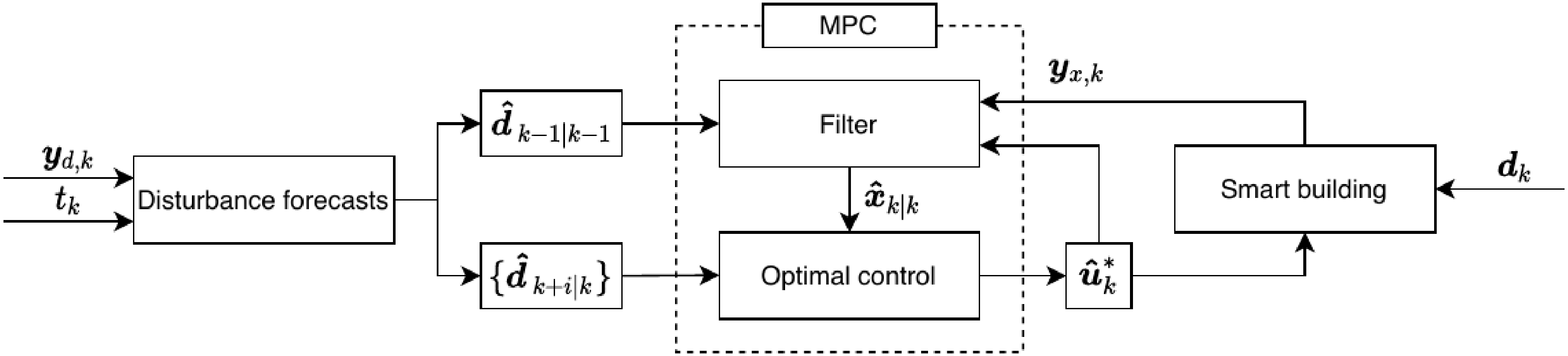
Grey-box model for air temperature

One of the elements is a model for the ambient air temperature which uses net radiation as input:

$$
\begin{aligned}
C_s \mathrm{d}T_s(t) &= \left(\frac{1}{R_{sl}} (T_l(t) - T_s(t)) \right) \mathrm{d}t + \sigma_s \mathrm{d}\omega_s(t)\,, \\
C_l \mathrm{d}T_l(t) &= \left(\frac{1}{R_{sl}} (T_s(t) - T_l(t)) \right. \\
&\quad \left. + \frac{1}{R_{l\infty}} (T_\infty - T_l(t)) + R_n(t) \right) \mathrm{d}t + \sigma_l \mathrm{d}\omega_l(t)\,, \\
d_{T_a}(t_k) &= T_l(t_k) + v_{T_a}(t_k)\,,
\end{aligned}
$$

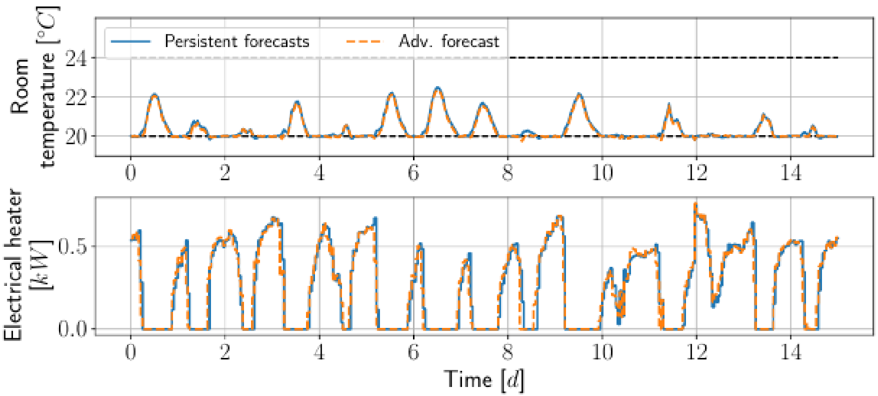


Combined Forecasting and Control

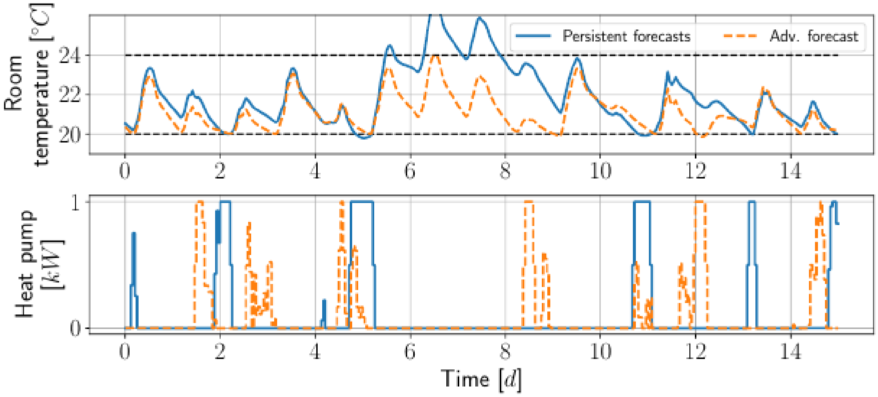


15 days out of 7 months simulation

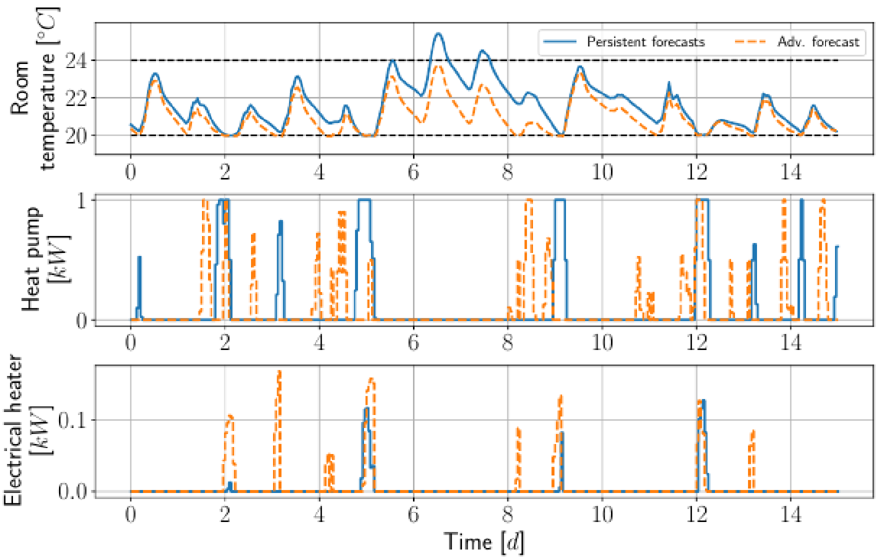
Strategy 1: Electrical Heaters



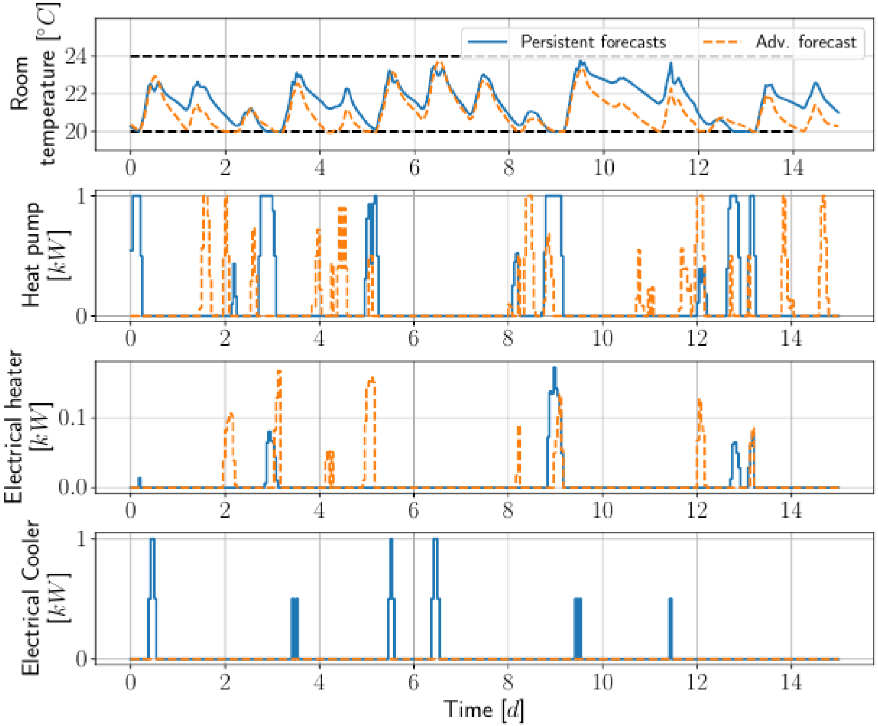
Strategy 2: Heat Pump



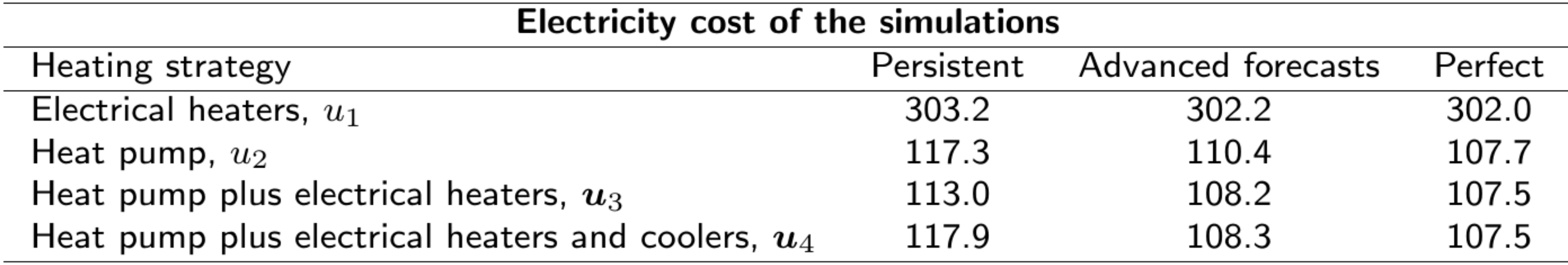
Strategy 3: Heat Pump & Electrical Heaters



Strategy 4: Heat Pump & Electrical Heaters & Coolers



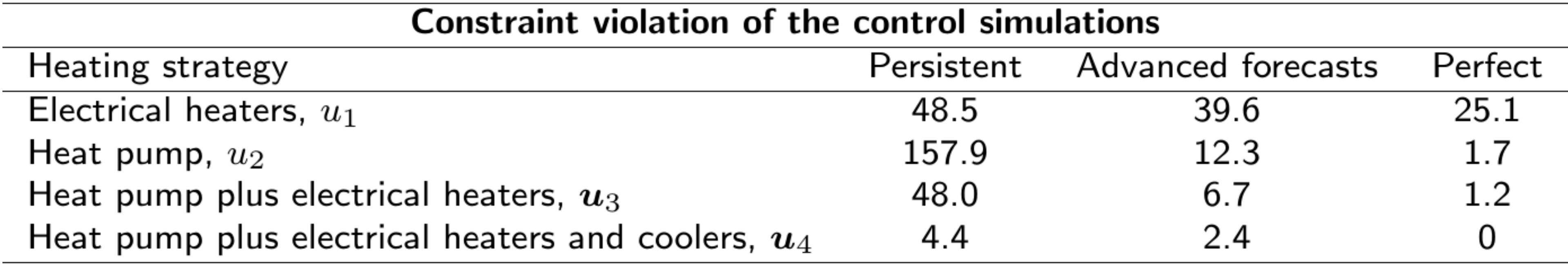
Electricity cost (EUR)



Electricity cost of the simulations

Heating strategy	Persistent	Advanced forecasts	Perfect
Electrical heaters, u_1	303.2	302.2	302.0
Heat pump, u_2	117.3	110.4	107.7
Heat pump plus electrical heaters, $\boldsymbol{u}_3$	113.0	108.2	107.5
Heat pump plus electrical heaters and coolers, $\boldsymbol{u}_4$	117.9	108.3	107.5

Constraint violations



Constraint violation of the control simulations

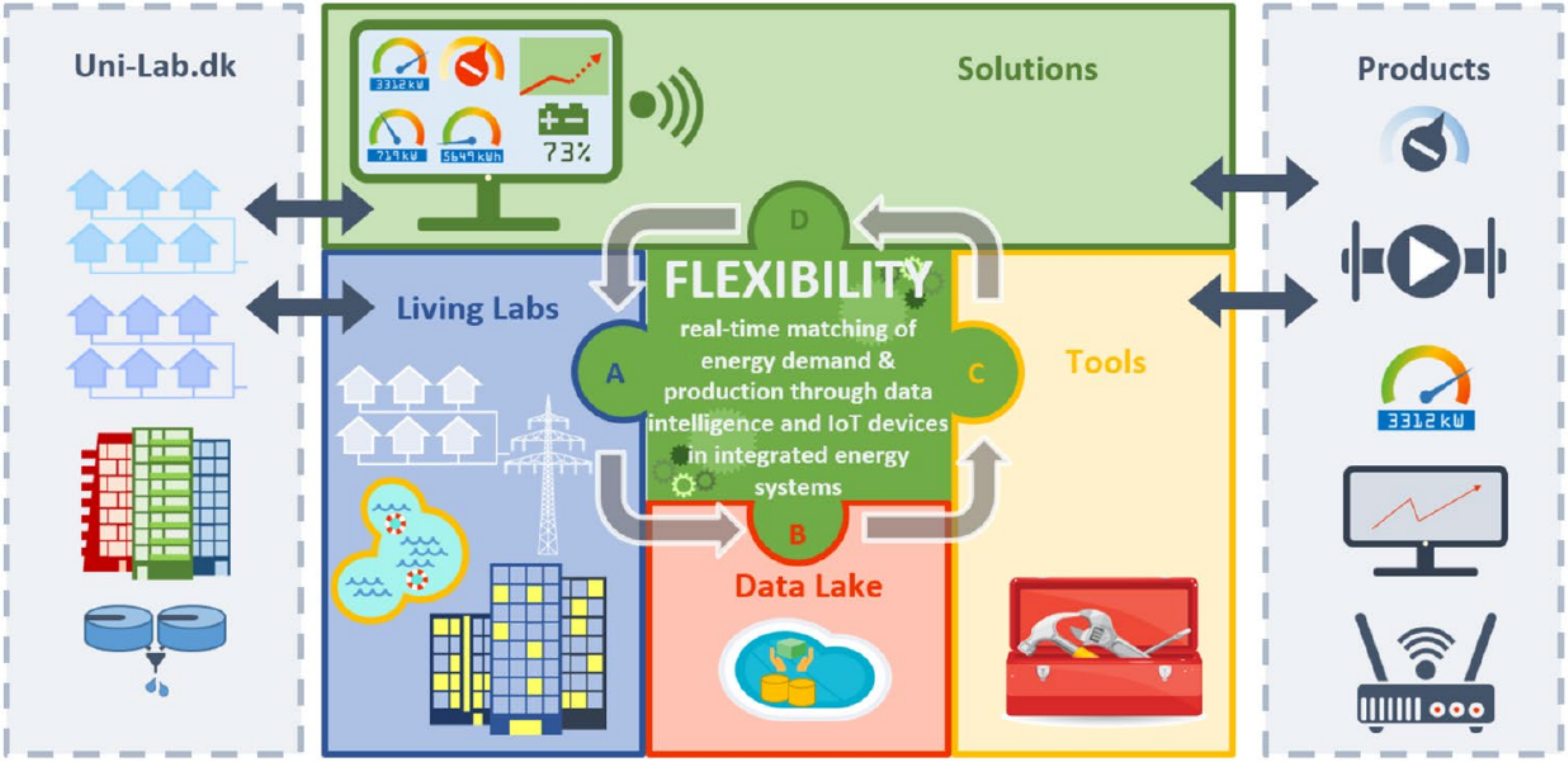
Heating strategy	Persistent	Advanced forecasts	Perfect
Electrical heaters, u_1	48.5	39.6	25.1
Heat pump, u_2	157.9	12.3	1.7
Heat pump plus electrical heaters, $\boldsymbol{u}_3$	48.0	6.7	1.2
Heat pump plus electrical heaters and coolers, $\boldsymbol{u}_4$	4.4	2.4	0

Center Denmark

Digitalization Hub for Integrated Smart Solutions

Center Danmark – Digitaliserings Hub

Circularity in the development of digital energy systems

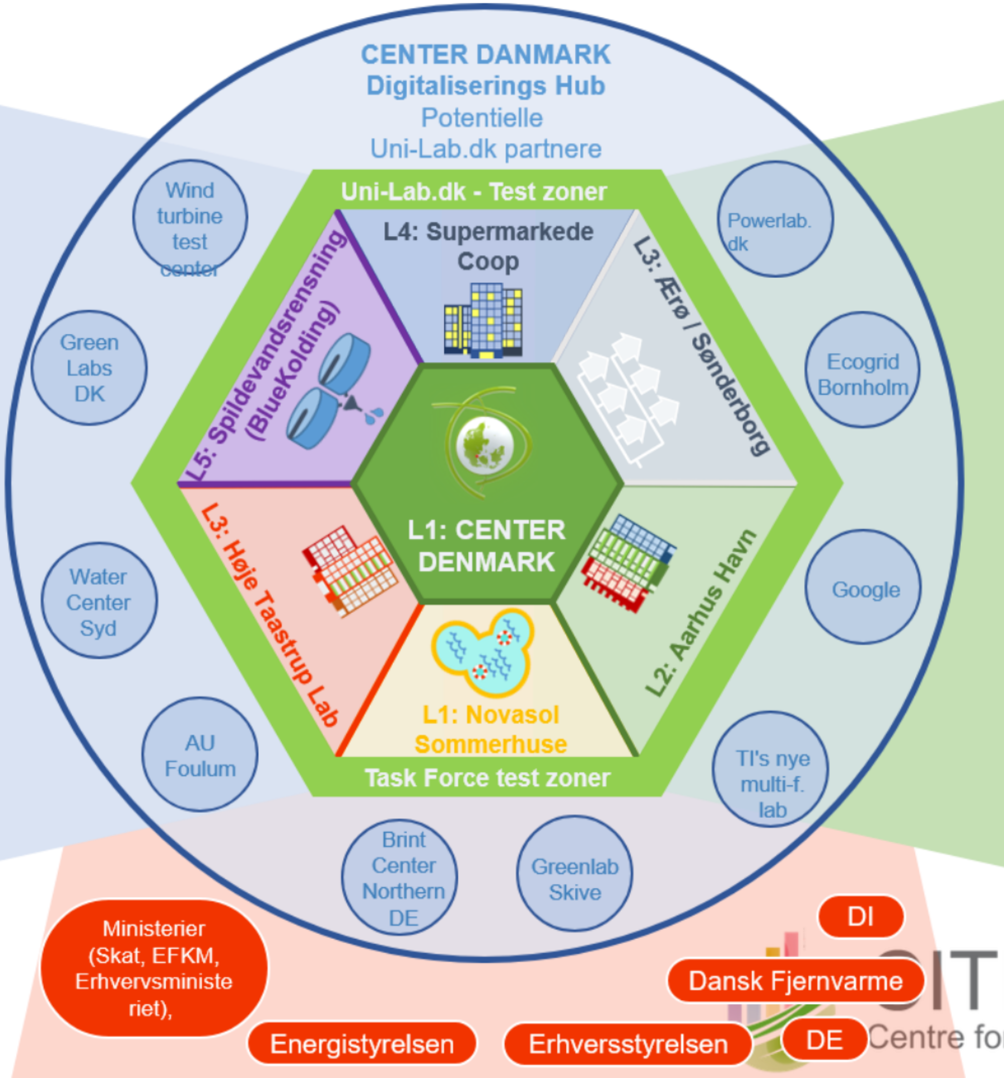


Uni-Lab.dk

Internationalt:

UNILAB consortium

- Cardiff University
- Danmarks Tekniske Universitet (DTU), Denmark
- Royal Institute of Technology (KTH), Sweden
- German Technical and Scientific Association for Gas and Water (DVGW), Germany
- Imperial College, United Kingdom
- Tianjing University, P.R. China
- TNO - Netherlands
- Toshiba Research Laboratory (TRL), UK
- Tsinghua University - P.R. of China
- Katholieke Universiteit Leuven (KUL), Belgium
- Malardalen University, Sweden



CENTER DANMARK
Digitaliserings Hub
Potentielle
Uni-Lab.dk partnere

Uni-Lab.dk - Test zoner

L4: Supermarkede Coop

L3: Ærø / Sønderborg

L5: Spildevandsrensning (BlueKolding)

L1: CENTER DANMARK

L3: Høje Taastrup Lab

L2: Aarhus Havn

L1: Novasol Sommerhuse

Task Force test zoner

Wind turbine test center

Green Labs DK

Water Center Syd

AU Foulum

Brint Center Northern DE

Greenlab Skive

TI's nye multi-f. lab

Google

Ecogrid Bornholm

Powerlab. dk

Ministerier (Skat, EFKM, Erhvervsministeriet),

Energistyrelsen

Erhversstyrelsen

DE

Dansk Fjernvarme

DI

Nationale samarbejdspartnere

- Energi og IT relaterede virksomheder
- Teknologisk Institut
- Energinet.dk
- Grøn Energi
- Alle Universiteter
- CLEAN + Inno SE
- House of Energy
- Forsyninger og Grid operatører
- ....

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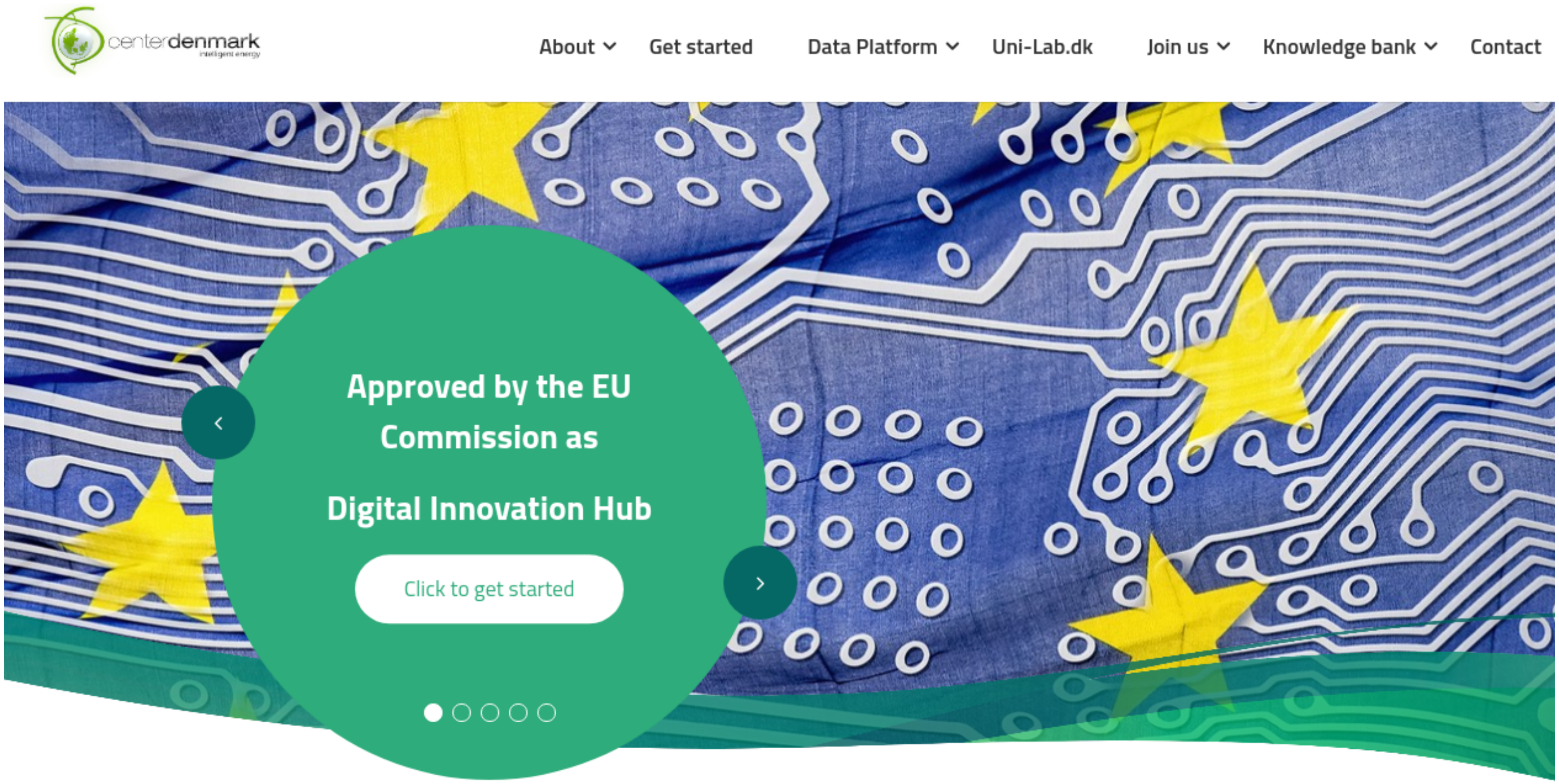
Center Denmark

Become a partner – see www.centerdenmark.com

It will increase possibilities for eg. EU projects and support – also since Center Denmark is approved by the Commission



Approved by the EU Commission as

Digital Innovation Hub

Center Denmark is an independent and non-profit national research center with the aim to unify and embed research results within the field of digitalization of energy systems and put

Summary

- Methods for integrated modelling, forecasting and control are presented
- Using the Smart-Energy OS we have seen large potentials for Demand Response and Virtual Storage on all relevant time scales
- Automatic solutions are important
- Solutions are implemented at Center Denmark
- Solutions are tested and further developed using Uni-Lab.dk
- Digitalization and sector coupling is essential
- The controllers can provide
    - Energy Efficiency
    - Cost Minimization
    - Emission Efficiency
    - Peak Shaving
    - Smart Grid Services (like ancillary services needs, ...)

Control problem

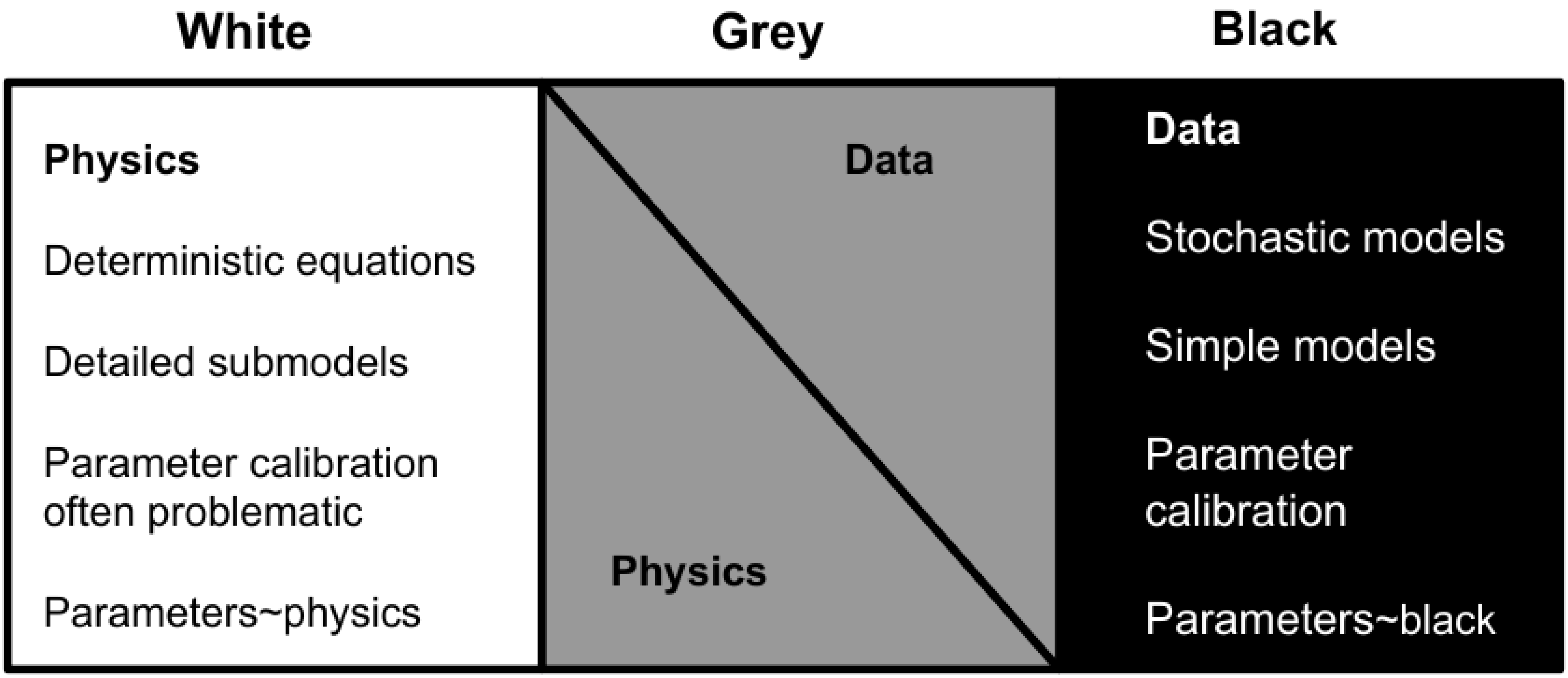
In control the input, $\boldsymbol{u}_k$, is piece-wise constant. Hence the cost cost function can be written as

$$\bar{\varphi} = \sum_{i \in \mathcal{N}} \boldsymbol{c}_{k+i}^T \boldsymbol{u}_{k+i} + \sum_{i \in \mathcal{N}} \boldsymbol{\rho}_{k+i+1}^T \boldsymbol{s}_{k+i+1} \,, \tag{7}$$

Given the linear model for the smart building the optimal control problem is

$$\begin{aligned}
J(\hat{\boldsymbol{x}}_{k|k}, \{\hat{\boldsymbol{d}}_{k+i|k}\}_{i \in \mathcal{N}}) = \min_{\boldsymbol{u},\boldsymbol{s}} \quad & \bar{\varphi} \,, & \text{(8a)} \\
s.t. \quad \boldsymbol{x}(t_k) &= \hat{\boldsymbol{x}}_{k|k} \,, & \text{(8b)} \\
\boldsymbol{x}(t_{k+i+1}) &= A\boldsymbol{x}(t_{k+i}) + B\boldsymbol{u}_{k+i} + E\hat{\boldsymbol{d}}_{k+i|k} \,, & \text{(8c)} \\
\boldsymbol{x}(t_{k+i+1}) &\in \mathcal{X}_{k+i+1} \,, & \text{(8d)} \\
\boldsymbol{u}_{k+i} &\in \mathcal{U}_{k+i} \,, & \text{(8e)} \\
\boldsymbol{s}_{k+i+1} &\geq \boldsymbol{0} \,, & \text{(8f)} \\
i &\in \mathcal{N} \,, & \text{(8g)}
\end{aligned}$$

Grey-box Modelling



White

Physics

Deterministic equations

Detailed submodels

Parameter calibration often problematic

Parameters~physics

Grey

Data

Physics

Black

Data

Stochastic models

Simple models

Parameter calibration

Parameters~black