Flexibility, the Smart-Energy OS, and Dynamic Tariffs

A Path for Efficient Flexibility Management at the Edge

Henrik Madsen
DTU Compute

(IFD projects: FED + IoT Annex + Cool Data)
(EU projects: ELEXIA + ARV + ebalance-plus + CitCom.ai)

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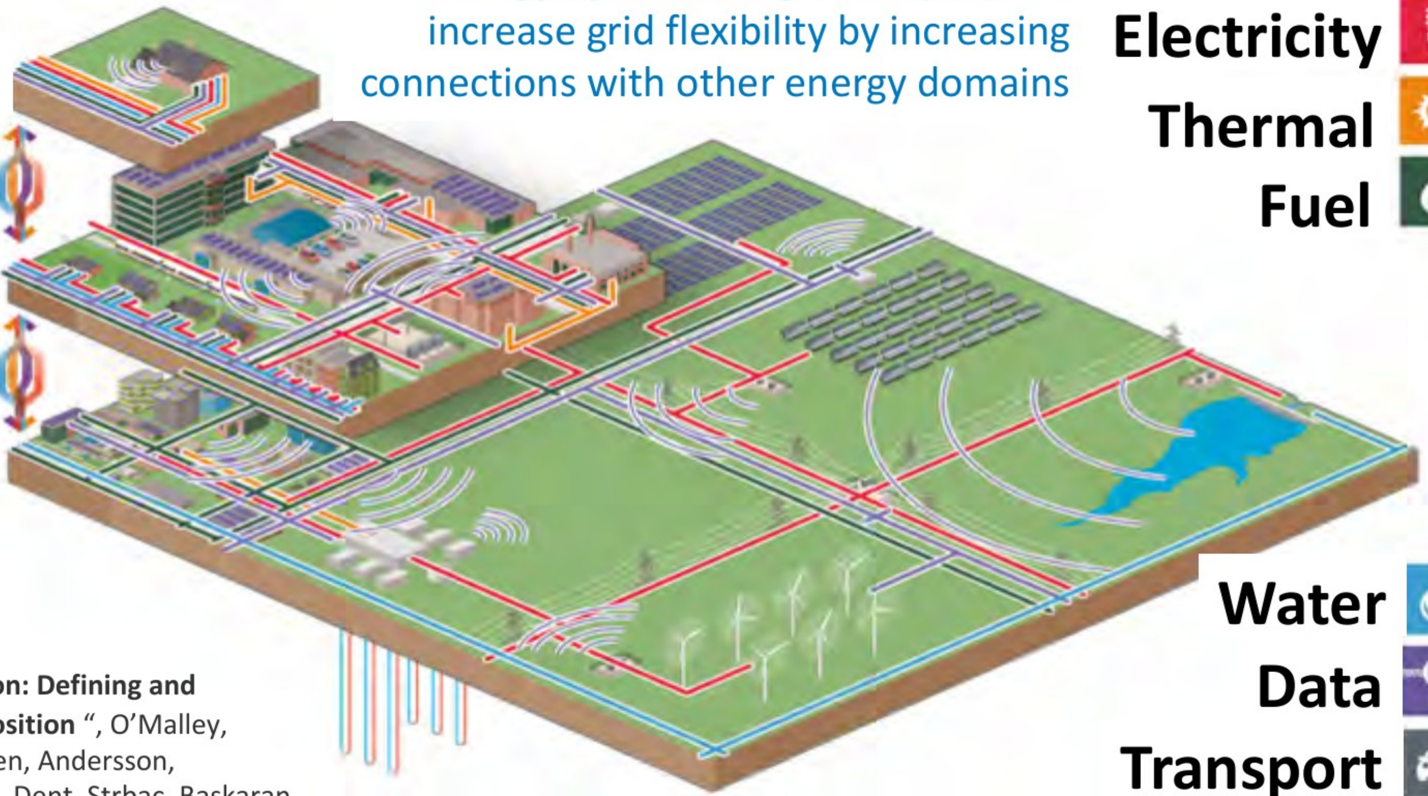
ebalanceplus
www.h2020-bridge.eu

This initiative is funded by

Energy Systems Integration

Energy System Integration (ESI) can increase grid flexibility by increasing connections with other energy domains



Customer

City

Region

Electricity

Thermal

Fuel

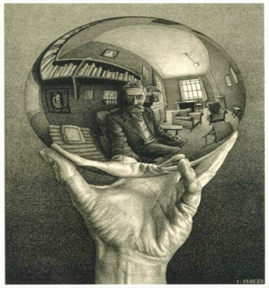
Water

Data

Transport

"Energy Systems Integration: Defining and Describing the Value Proposition ", O'Malley, Kroposki, Hannegan, Madsen, Andersson, D'haeseleer, McGranaghan, Dent, Strbac, Baskaran, Rinker., NREL/TP-5D00-66616. June 2016

European and International Initiatives on Smart Energy Systems



- Data Spaces for Energy Systems
- Digitalization of Energy Systems
- Key elements mentioned in EU and UN reports:
  - Minimum Interoperability Mechanicsms (MIMs)
  - Some MIMs for energy systems:

    Flexibility Functions, Digital Twins, Data Spaces, Shared Data Models, Transparent AI
  - New market structures (using also control theory)
- UN Deliverable on “Redefining smart city platforms: Setting the stage for Minimal Interoperability Mechanisms” has been published.

Please find the deliverable here: https://www.itu.int/en/publications/Documents/tsb/2022-U4SSC-Redefining-smart-cityplatforms/index.html#p=1

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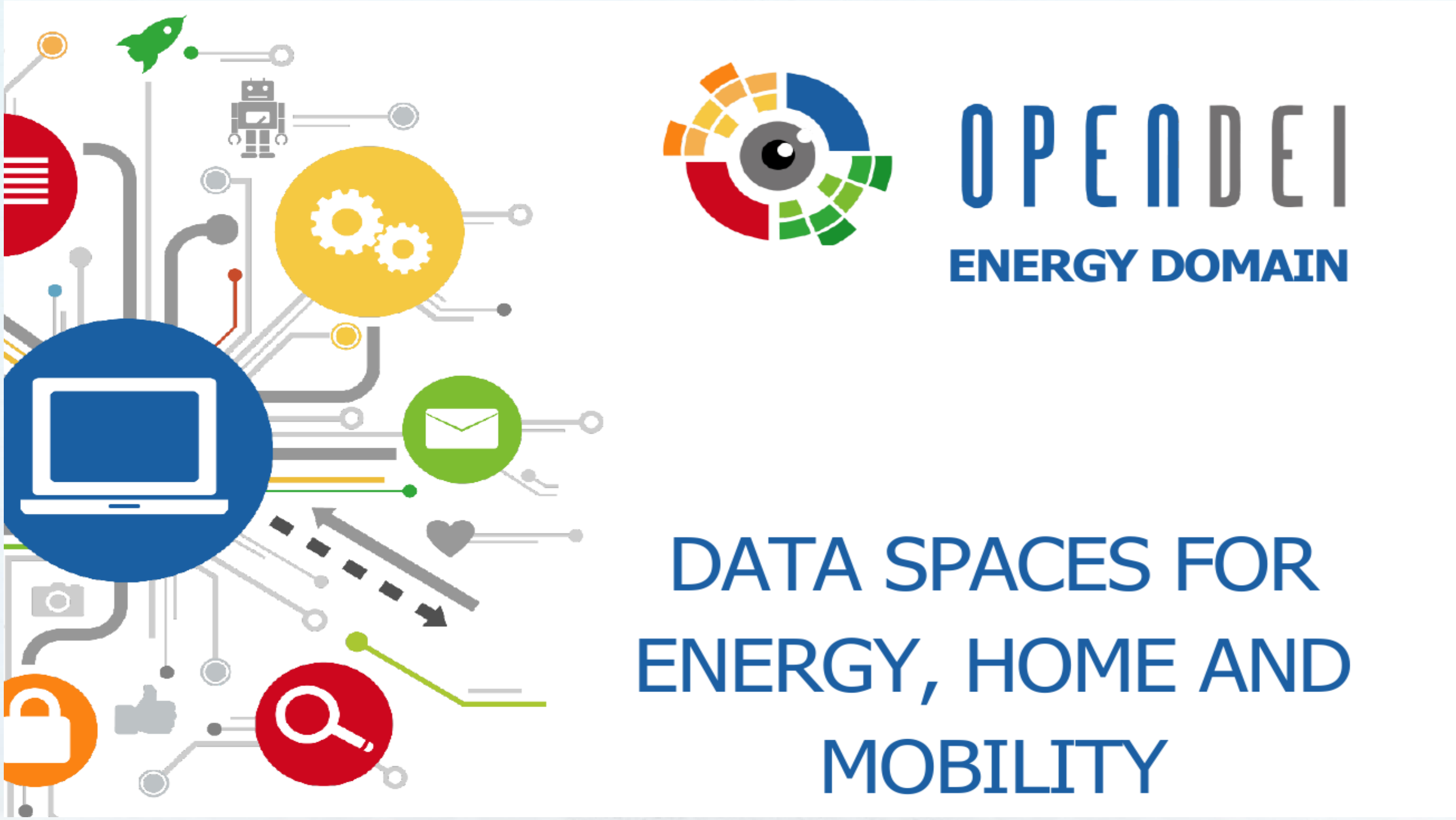
EU Report on Data Spaces



OPENDEI

ENERGY DOMAIN

DATA SPACES FOR ENERGY, HOME AND MOBILITY

Dognini, Alberto, Challagonda, Chandra, Maqueda Moro, Erik, Helmholt, Kristian,
Madsen, Henrik, Daniele, Laura, Schmitt, Laurent, Genest, Olivier, Riemenschneider, Rolf,
Böhm, Robert, Ebrahimy, Razgar, Temal, Lynda, Calvez, Philippe, & Ben Abbes, Sarra. (2022).
Data Spaces for Energy, Home and Mobility (1.07). Zenodo. https://doi.org/10.5281/zenodo.7193318

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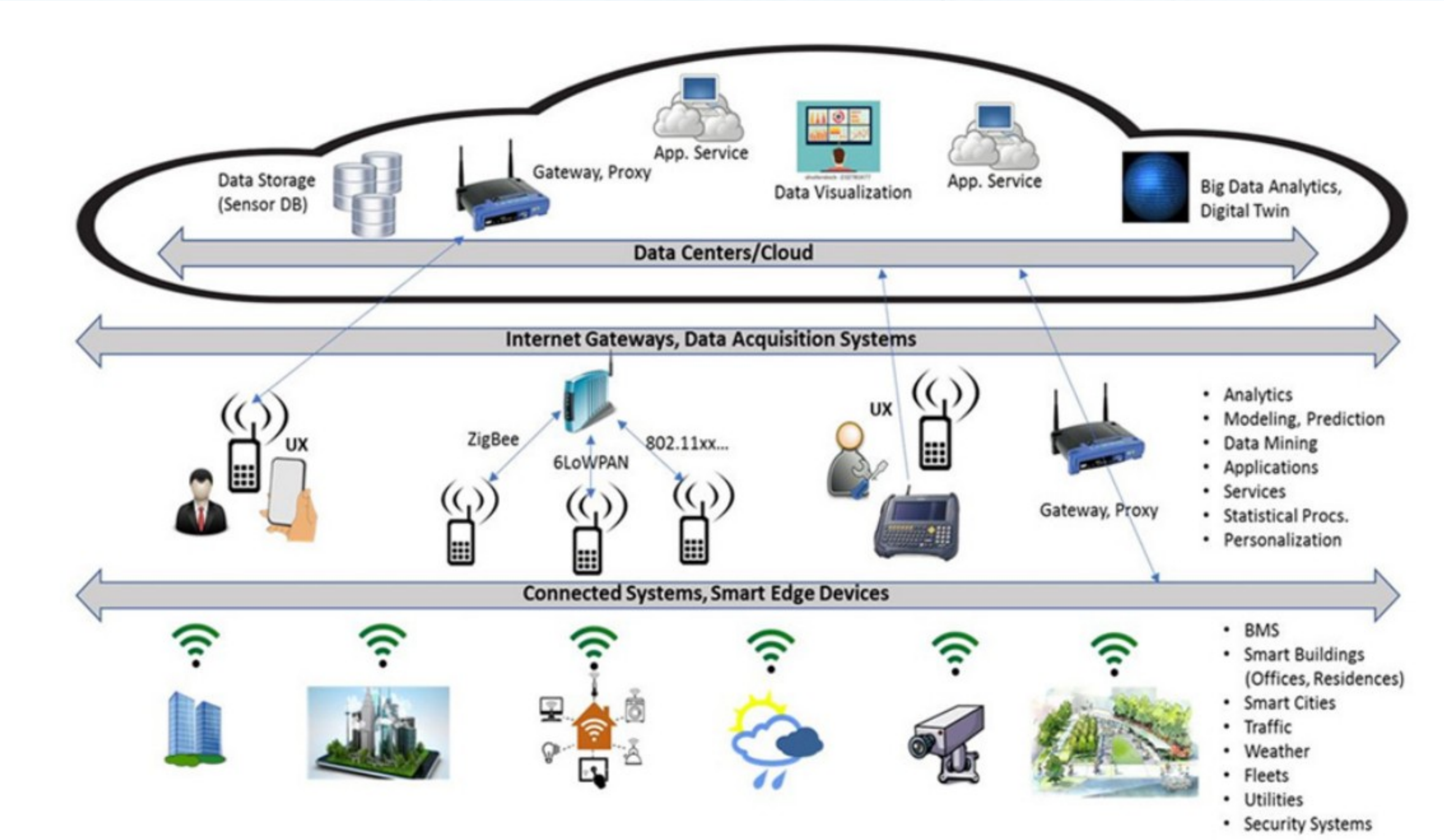
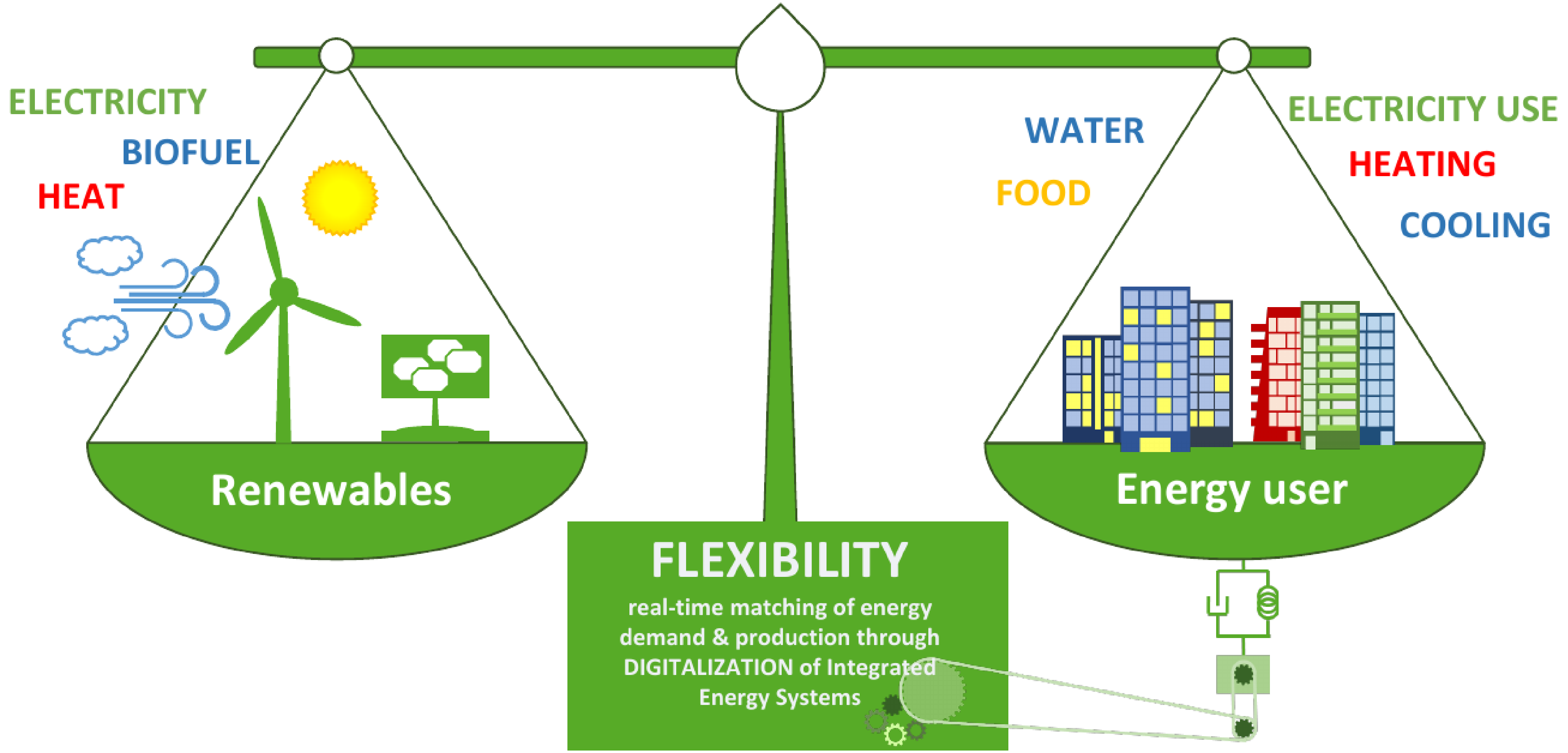
UN Report: IT Architecture for Smart Buildings and Cities



The Challenge: Denmark Fossil Free 2050



ELECTRICITY

BIOFUEL

HEAT

Renewables

WATER

FOOD

ELECTRICITY USE

HEATING

COOLING

Energy user

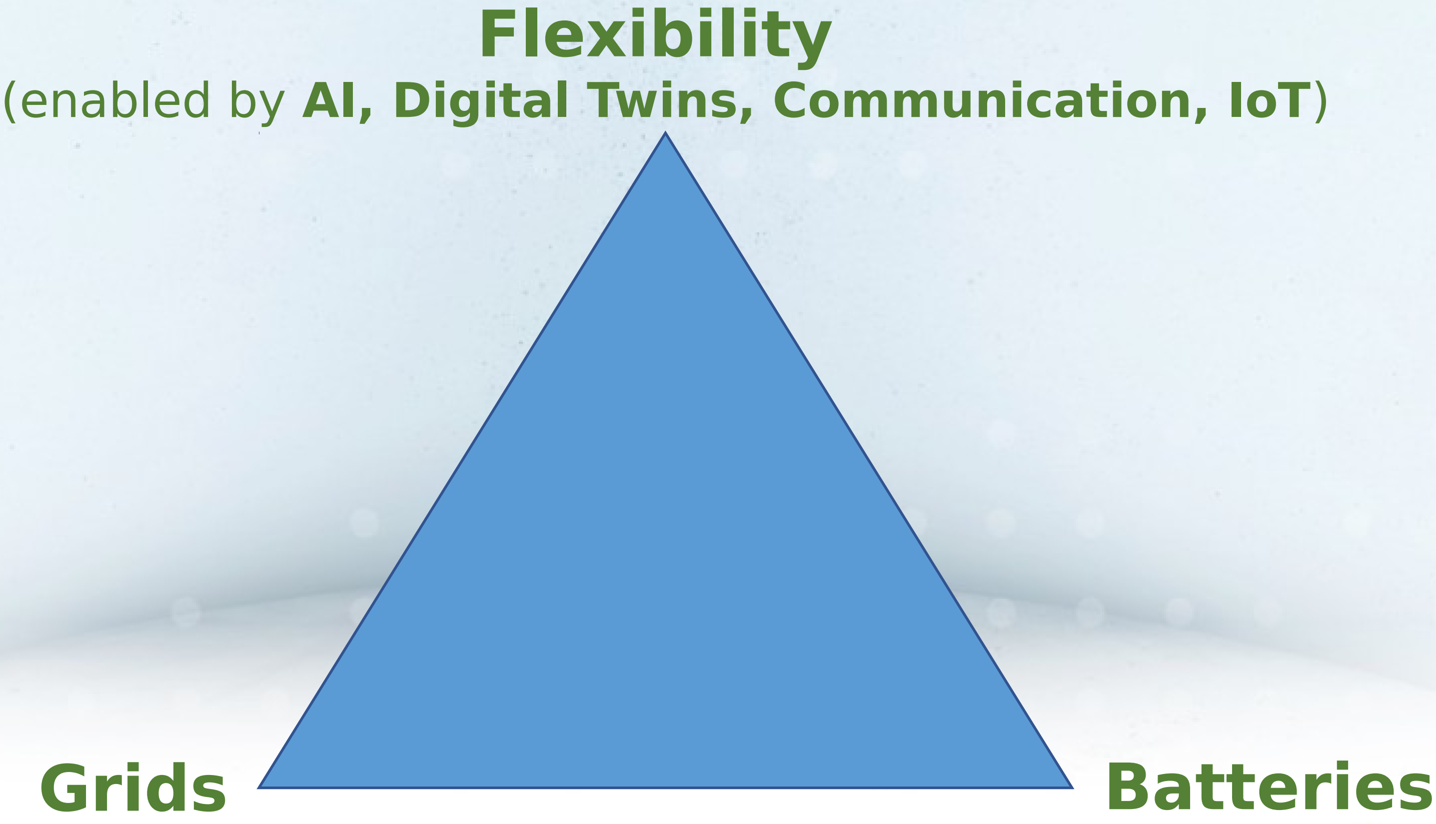
FLEXIBILITY

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

Local Flexibility Markets vs Classical Markets

- Static -> **Dynamic**
- Deterministic -> **Stochastic**
- Linear -> **Nonlinear**
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, ...) -> **Coordination + Hierarchy**
- Speed / problem size -> **Decomposition + Control Based Solutions**
- Characterization of flexibility (bids) -> **Flexibility Functions**
- Requirements on user installations -> **One-way communication**

Space of Solutions



Flexibility

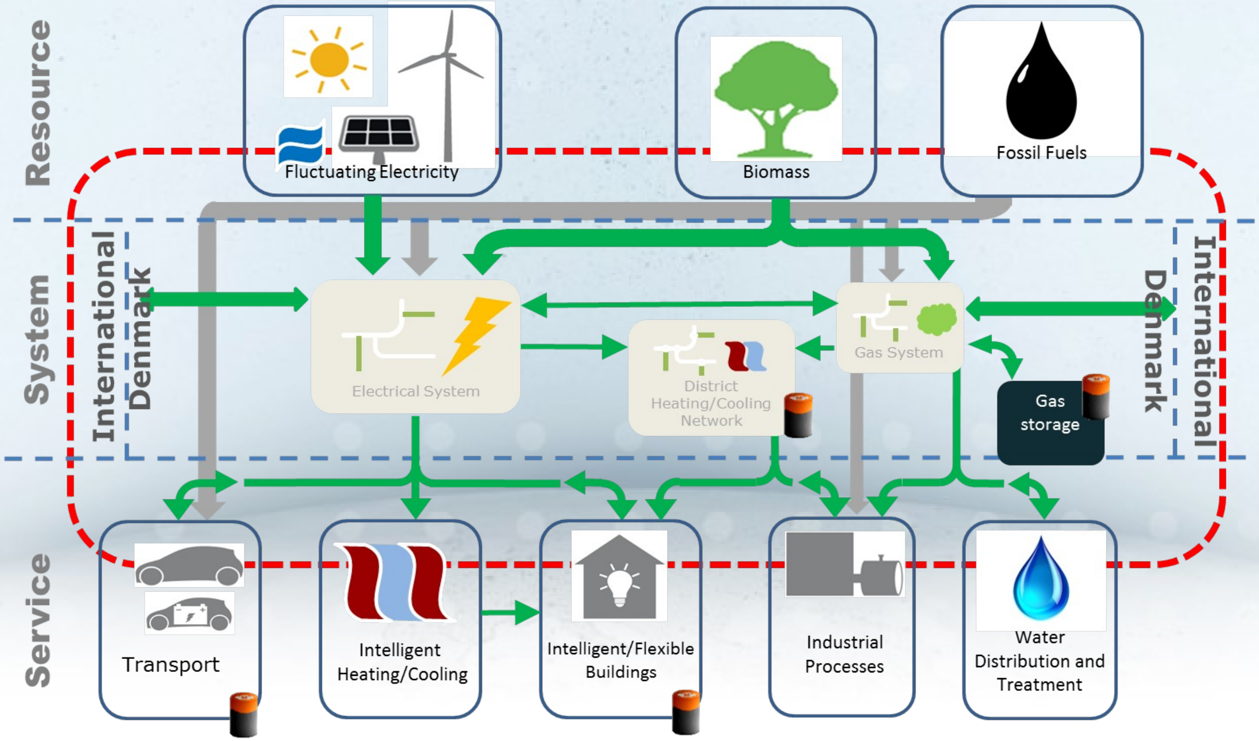
(enabled by **AI, Digital Twins, Communication, IoT**)

Grids

Batteries

Data-driven Digital Twins for Real Time Applications

Grey-box models are simplified Digital Twin models facilitating system integration and use of sensor data in real-time



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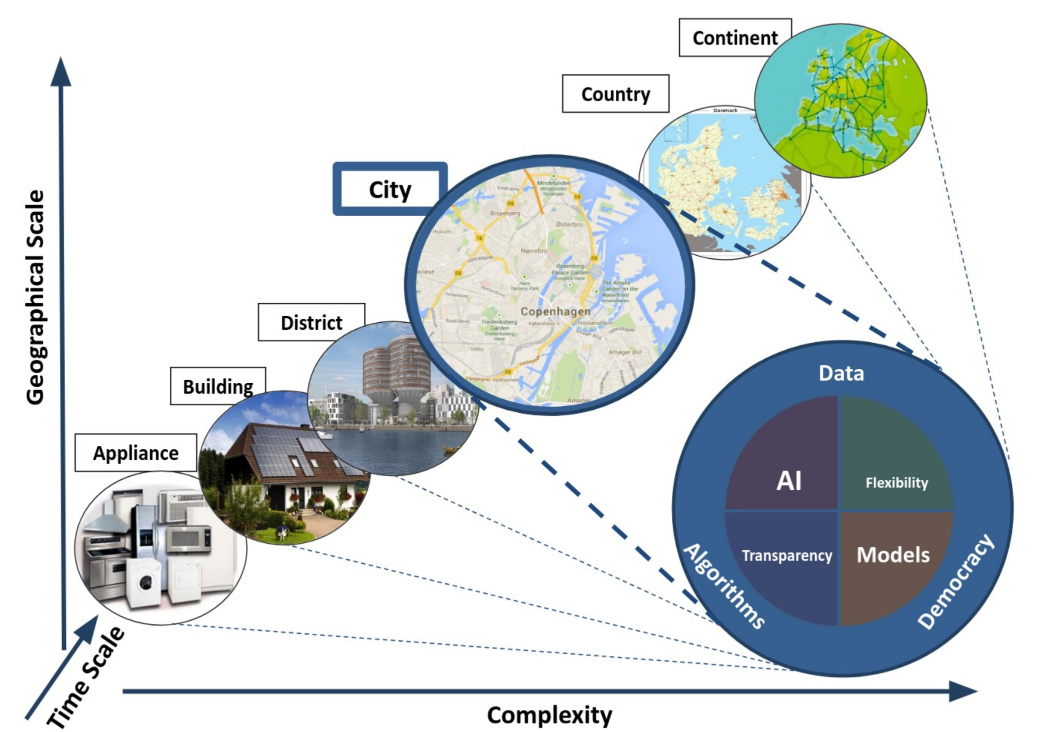
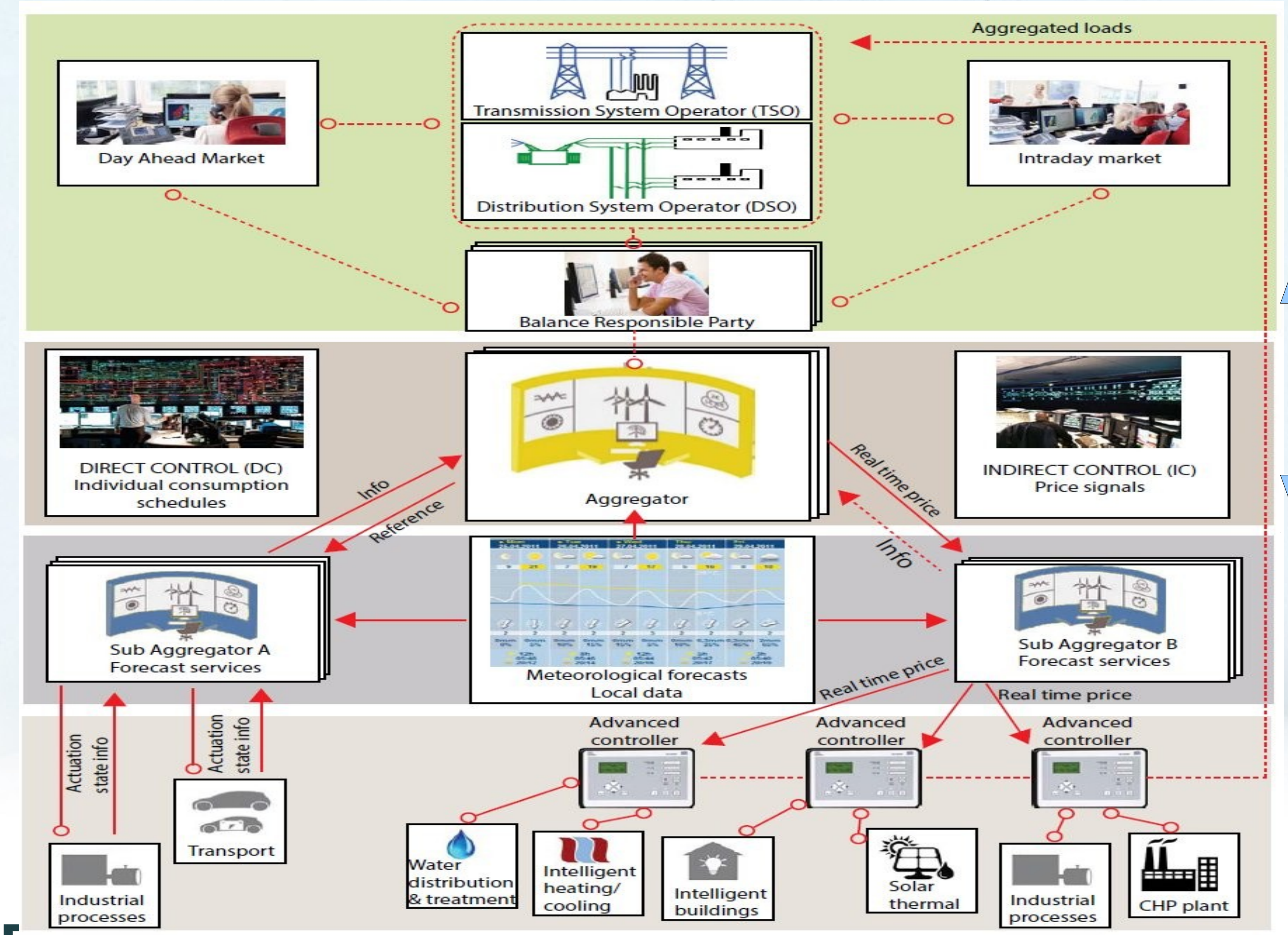
Temporal and Spatial Coherency

A so-called ***Smart-Energy Operating-System (SE-OS)*** is developed in order to develop, implement and test solutions (layers: data, models, optimization, control, communication) for ***operating flexible electrical energy systems*** at **all scales**.



EU Report: Smart-Energy OS

The Transformative Power of Digitalization



(**Static**)

Conventional
Markets

***Linking
Markets to
Physics
using MIMs***

***(Flexibility
Functions)***

(**Dynamic**)

Local Flexibility
Markets

(Hierarchy of
controllers)

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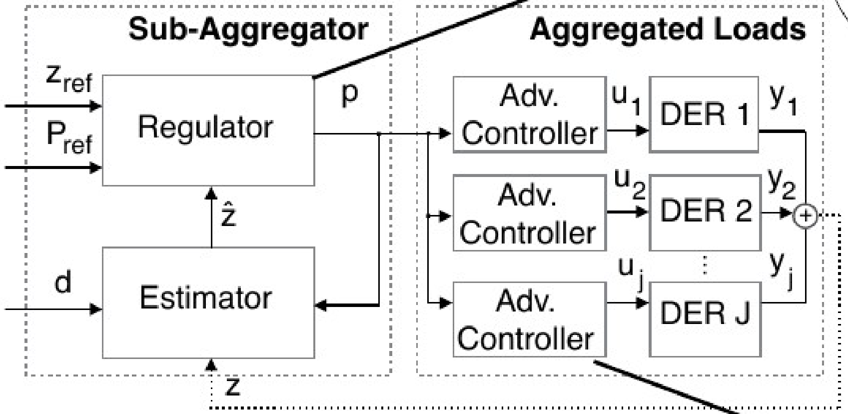
Proposed methodology
Control-based methodology



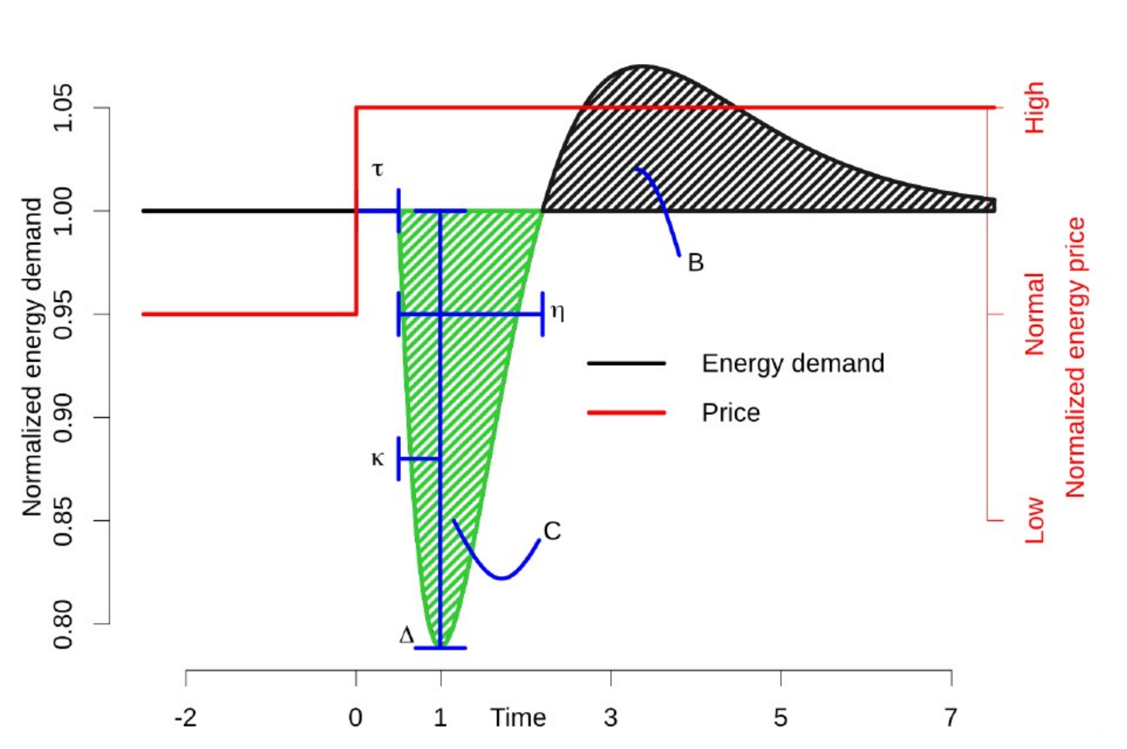
$$\begin{aligned} \min_{p} \quad & \mathrm{E}[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||] \\ \text{s.t.} \quad & \hat{z}_{k+1} = f(p_k) \end{aligned}$$

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

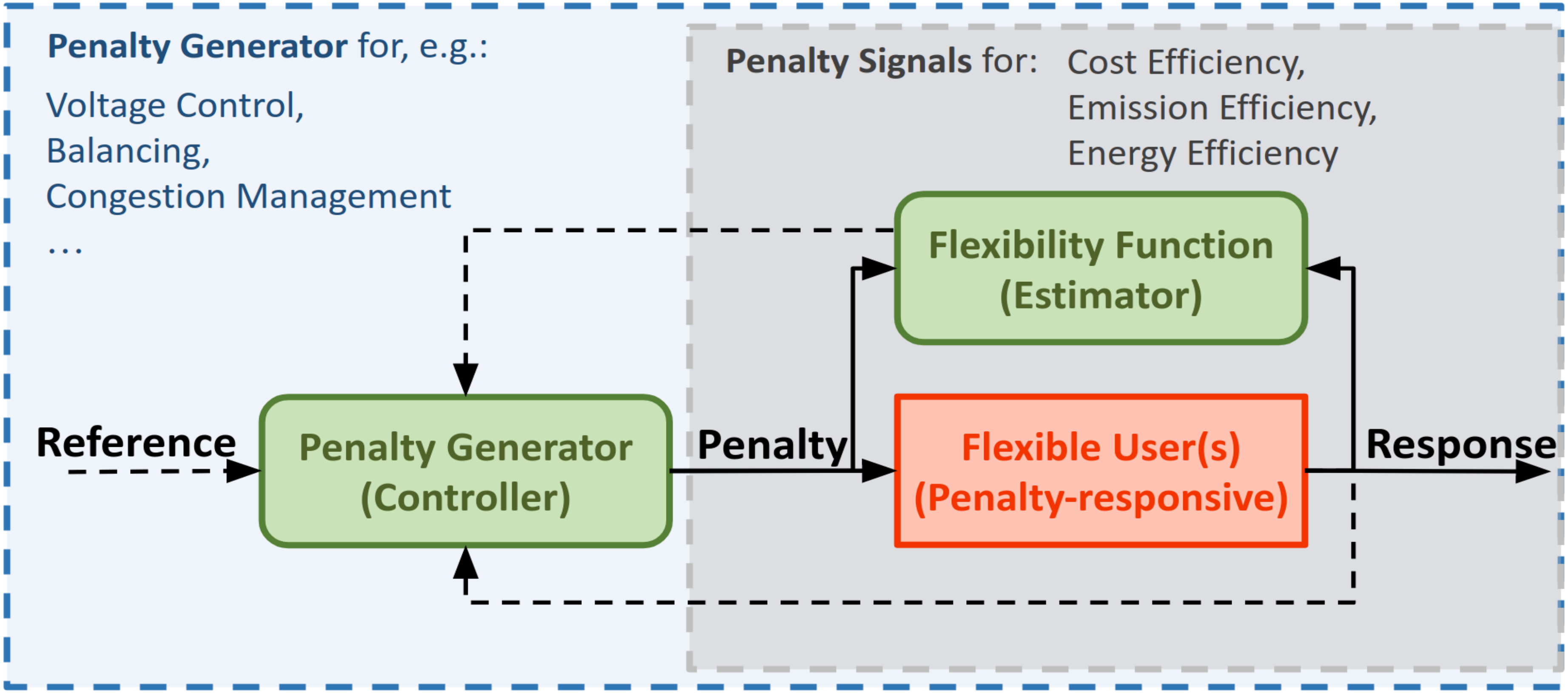
We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

Flexibility Function

The ***Flexibility Function (FF)*** is a **MIMs for energy systems** used to characterize flexibility and providing an interface between local and high-level markets



Flexible Users and Penalty Signals



Penalty Generator for, e.g.:

Voltage Control,
Balancing,
Congestion Management
...

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

Reference

Penalty Generator (Controller)

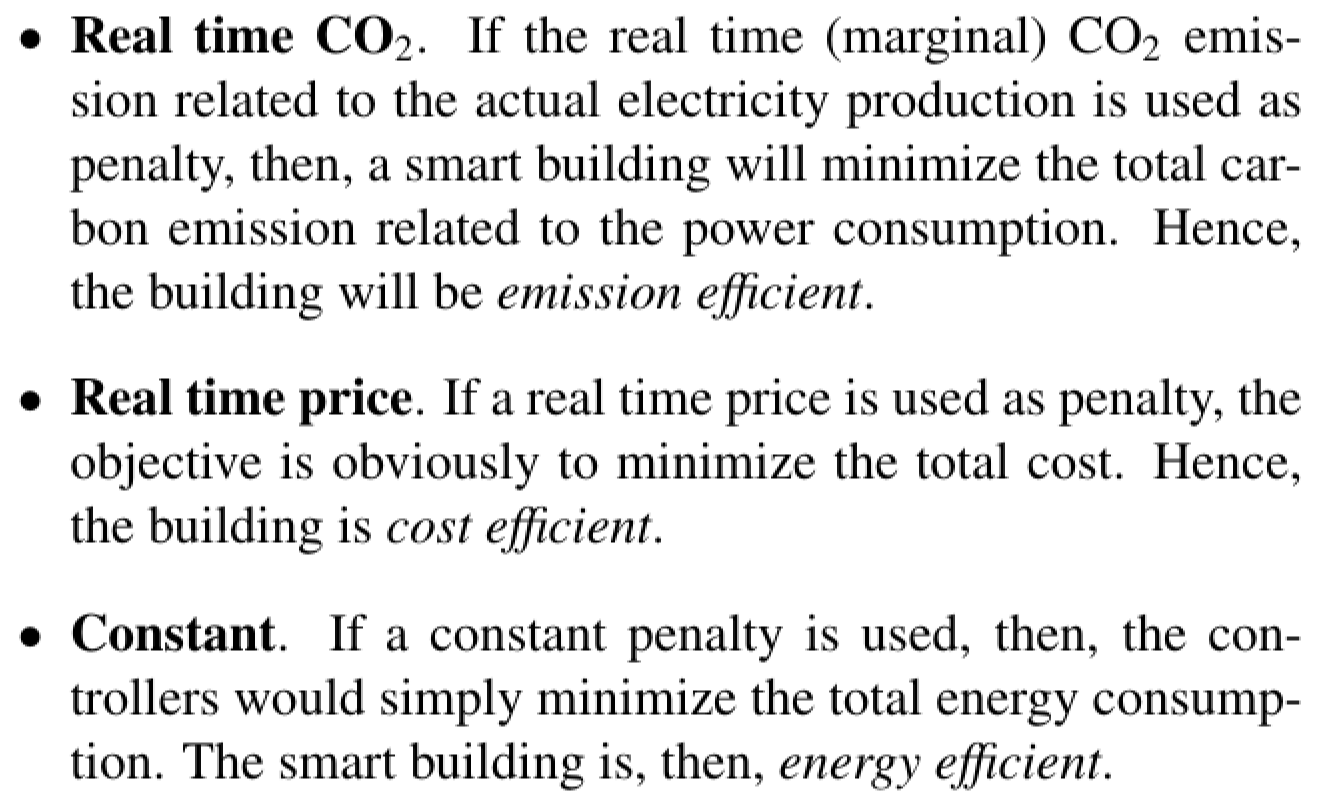
Penalty

Flexibility Function (Estimator)

Flexible User(s) (Penalty-responsive)

Response

Penalty (examples)



- **Real time CO_2**. If the real time (marginal) CO_2 emission related to the actual electricity production is used as penalty, then, a smart building will minimize the total carbon emission related to the power consumption. Hence, the building will be *emission efficient*.
- **Real time price**. If a real time price is used as penalty, the objective is obviously to minimize the total cost. Hence, the building is *cost efficient*.
- **Constant**. If a constant penalty is used, then, the controllers would simply minimize the total energy consumption. The smart building is, then, *energy efficient*.

Case study

Price-based Control of Power Consumption (Peak Shaving)

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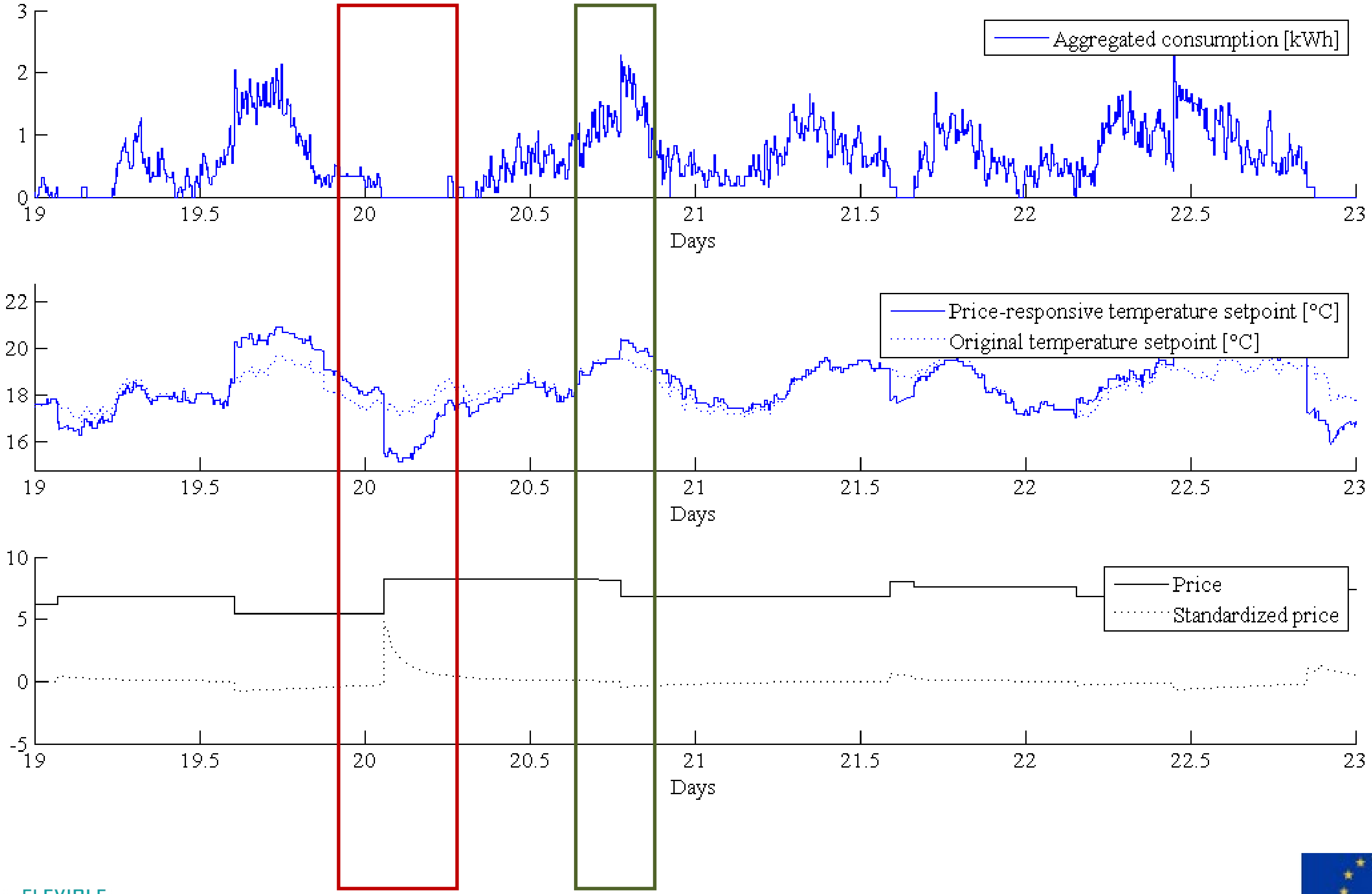
Aggregation (over 20 houses)



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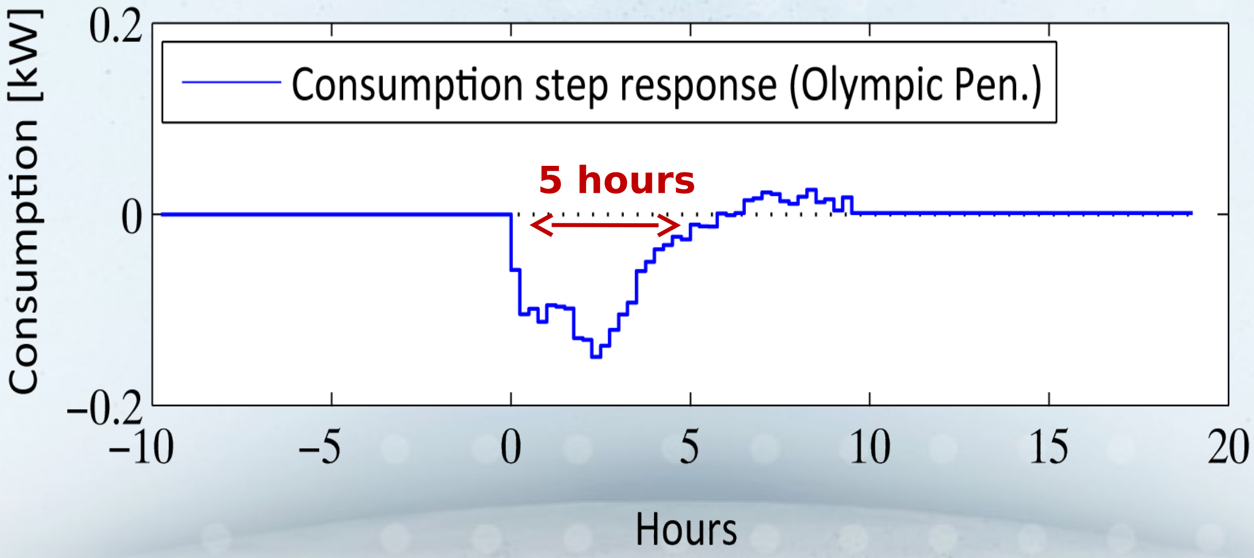
Response on Price Step Change



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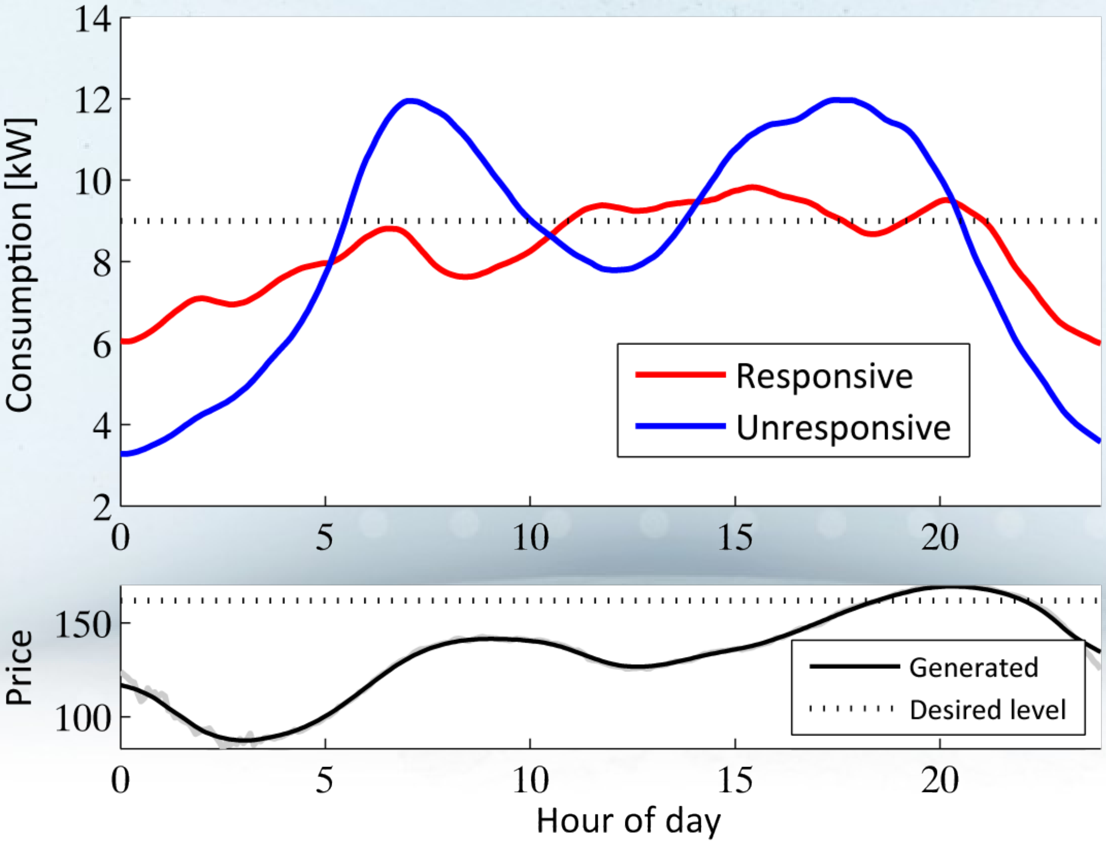
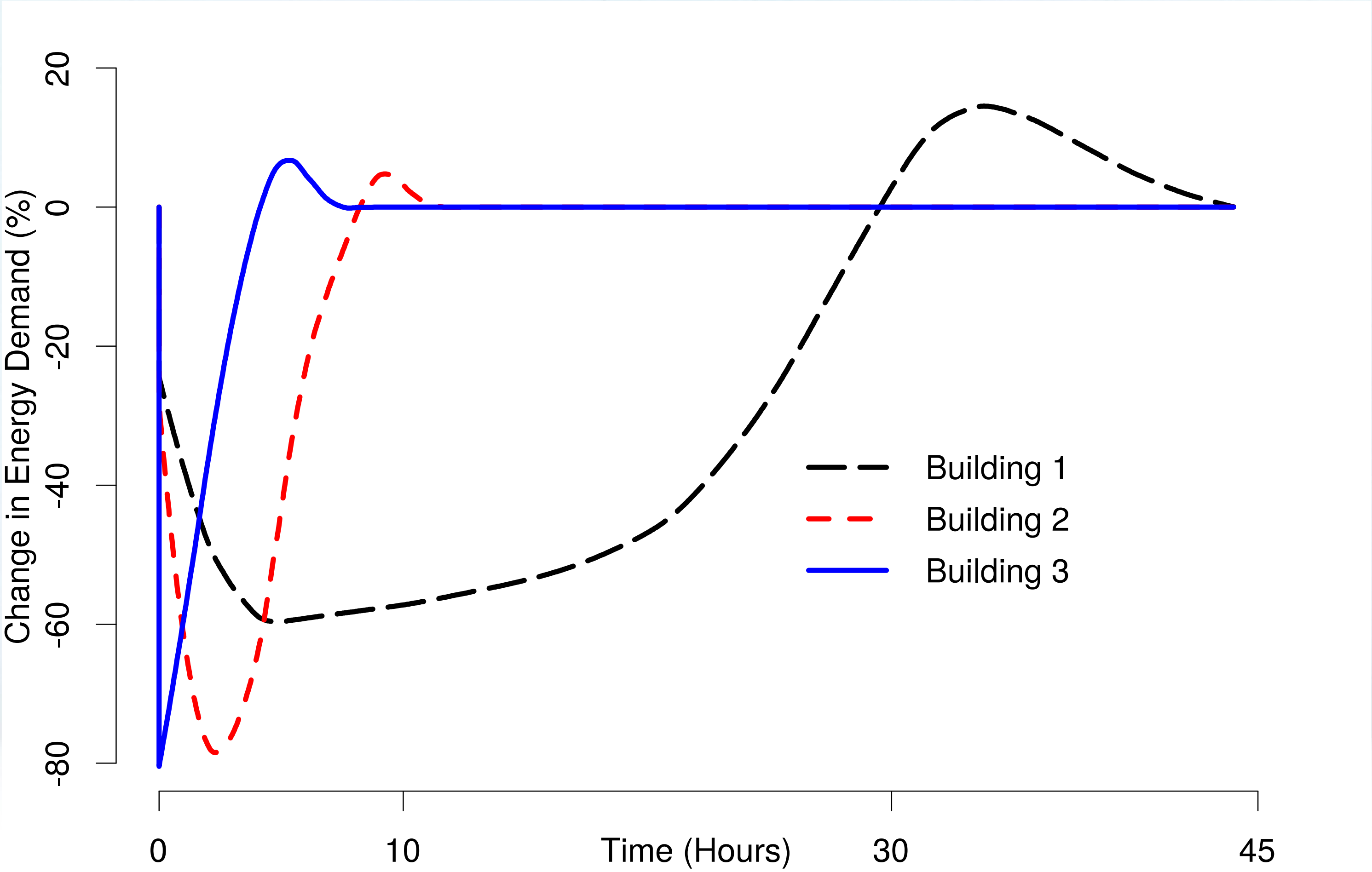
Control performance

Considerable **reduction in peak consumption**



Flexibility Function Examples



Flexibility Function Model

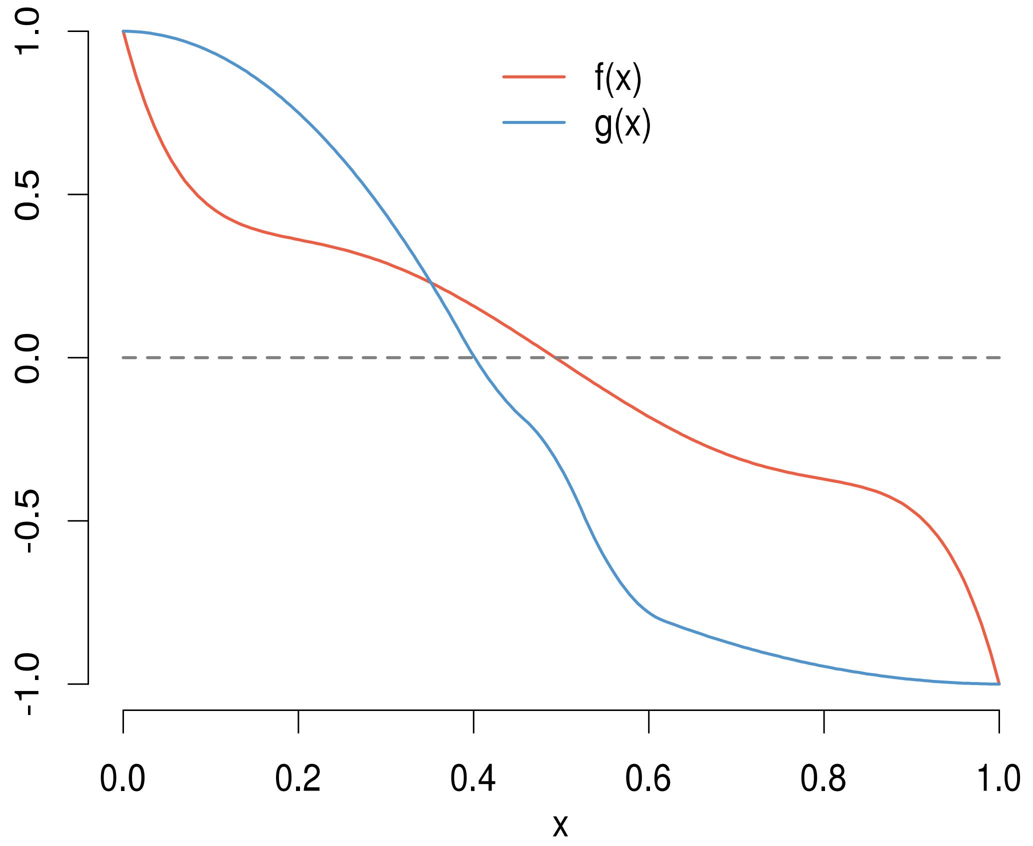
Flexibility Function Model (nonlinear version) describes the energy demand of a price-responsive systems as function of price and state of charge.

$$
\begin{aligned}
\mathrm{d}X_t &= \frac{1}{C}(D_t - B_t)\mathrm{d}t + X_t(1 - X_t)\sigma_X \mathrm{d}W_t \\
\delta_t &= f(X_t; \alpha) + g(\lambda_{t-\tau}; \beta) \\
D_t &= B_t + \delta_t \Delta \left(\mathbb{1}(\delta_t > 0)(1 - B_t) \; + \mathbb{1}(\delta_t < 0) B_t\right) \\
Y_t &= D_t + \sigma_Y \epsilon_t
\end{aligned}
$$

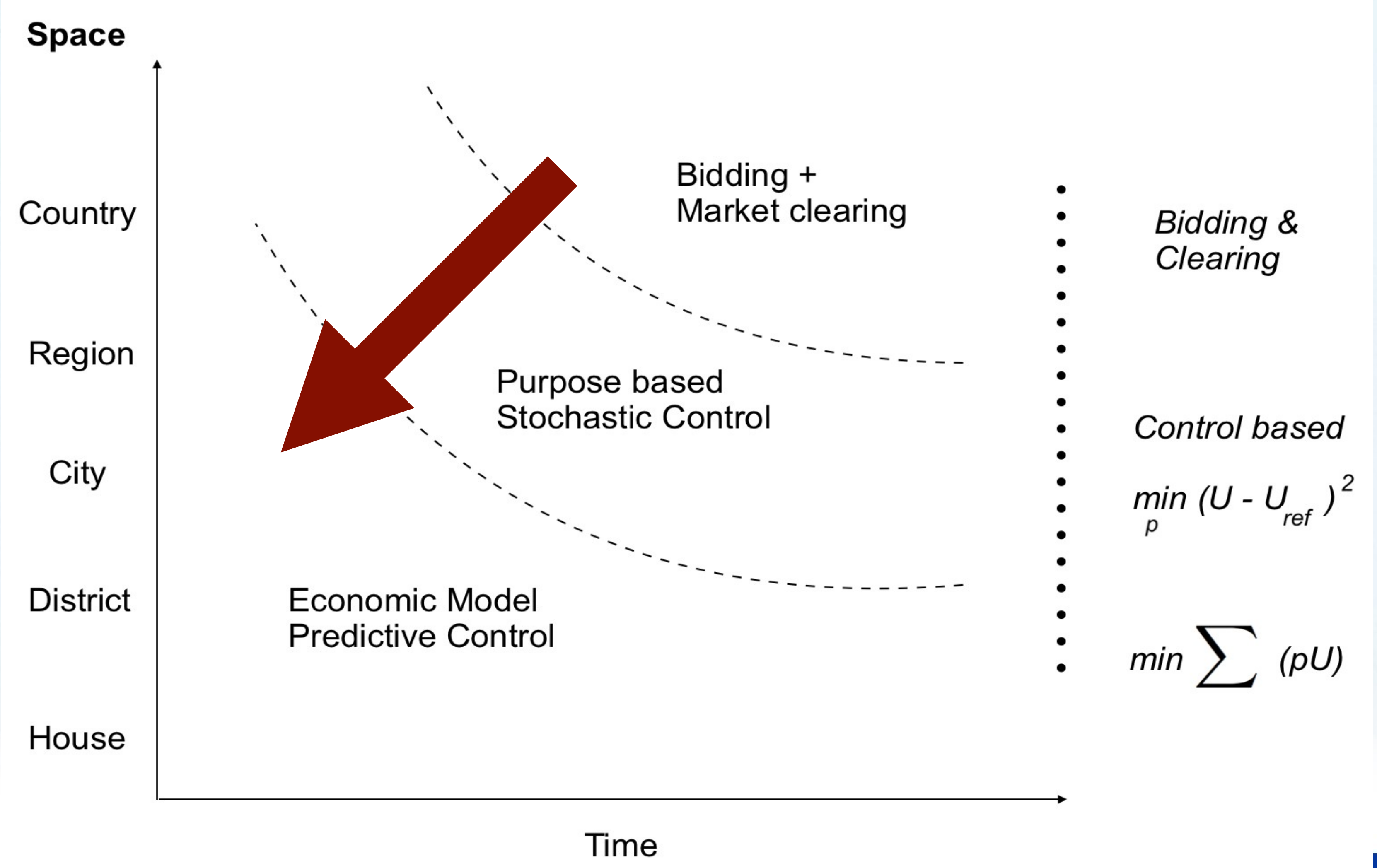
X = state of charge
B = demand (at constant price) / baseline
f(*) = Demand-SoC relationship
g(*) = Demand-Price relationship

Characterisation of Energy Flexibility

Non-linear Flexibility Function using SDE’s



The ‘market’ of tomorrow



Space

Country

Region

City

District

House

Time

Bidding +
Market clearing

Purpose based
Stochastic Control

Economic Model
Predictive Control

*Bidding &
Clearing*

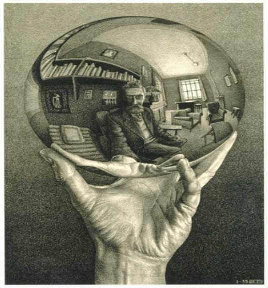
Control based

$$\min_{p} (U - U_{ref})^2$$

$$\min \sum (pU)$$

SE-OS Characteristics

- Relies on the Minimal Interoperability Mechanisms (MIMs) roadmap for a digital transformation of energy systems
- Flexibility Functions are used (as MIMs) to unlock flexibility at all scales
- Security and Privacy by design
- Data-driven digital twins
- Hierarchy of optimization and control problems
- Provides link between markets and the physics
- Combined Cloud, Fog, Edge based solutions
- Simple setup for the communication and contracts
- Facilitates energy systems integration (power, gas, thermal, ...)



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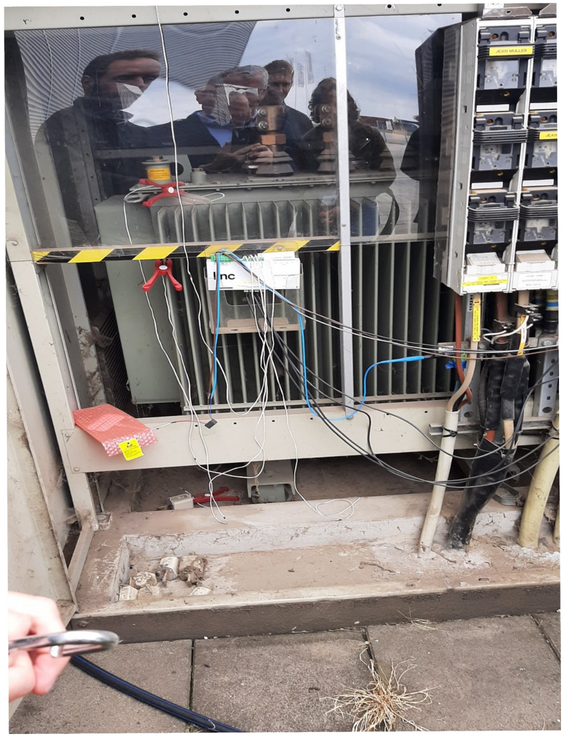
Case Study:

DSO - Smart Grid Intelligence

Models for Dynamic Transformer Rating



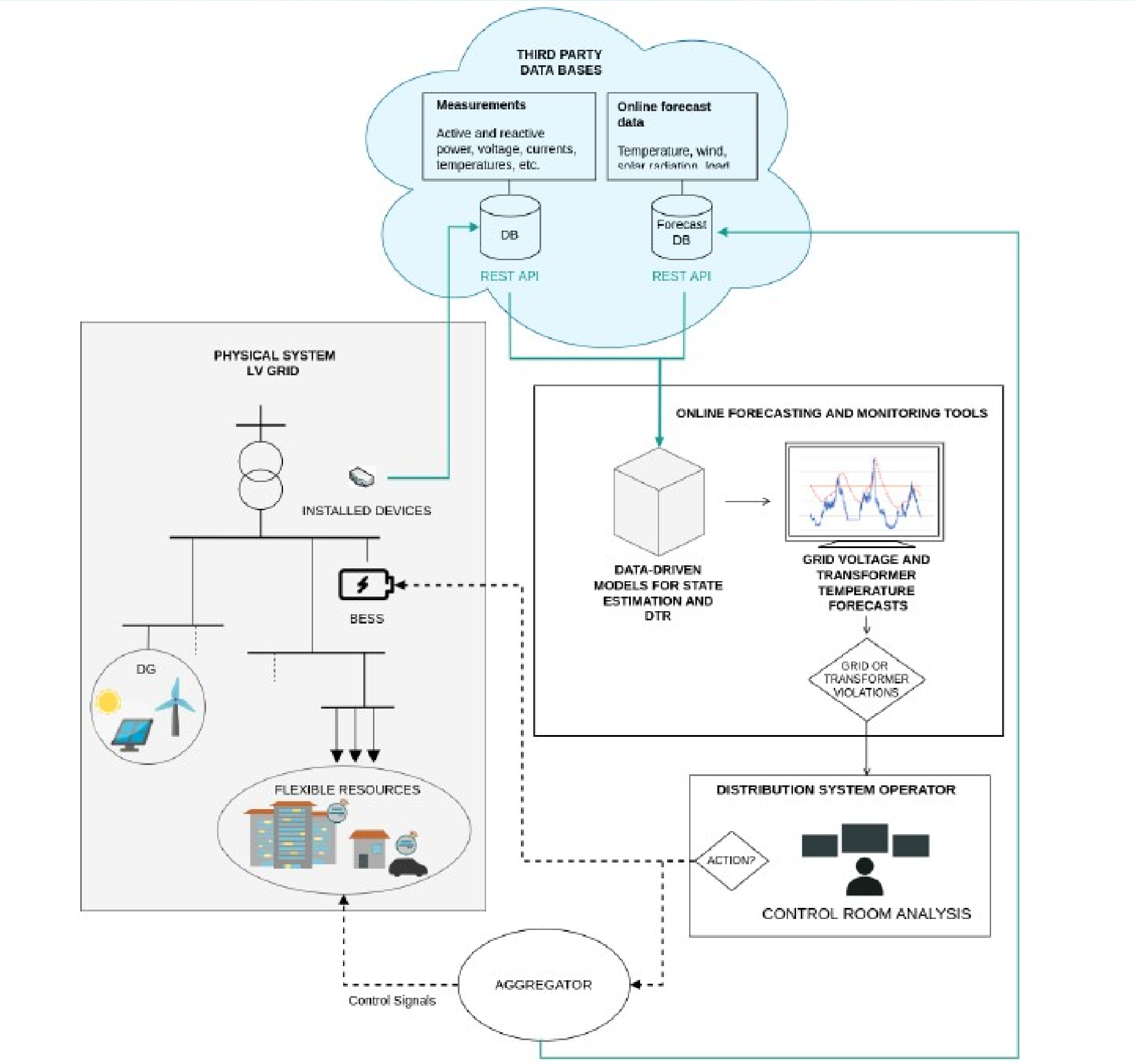


Figure 5.1: Operational framework for adaptive DSO smart grid operation. Turquoise lines indicate data flows and dotted lines indicate communication signals.

Sensor setup for transformators

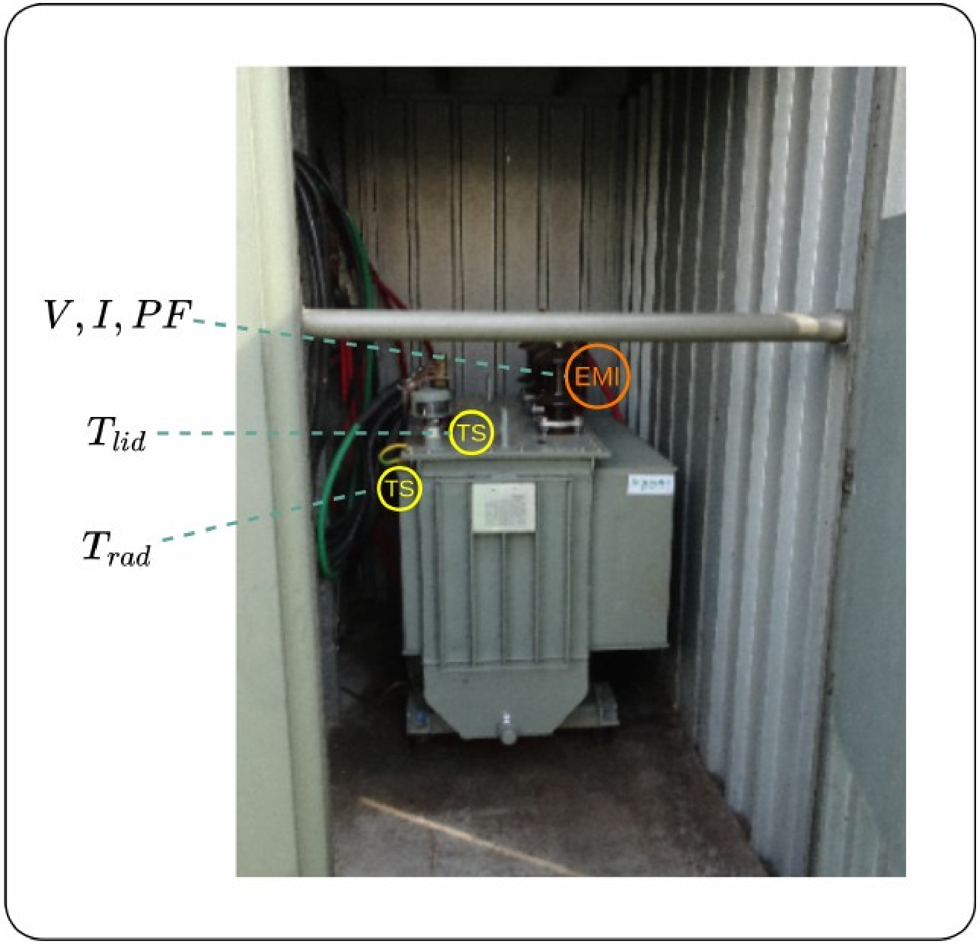


Figure 5.2: Suggested final setup for the transformers, with temperature sensor (TS) and electronic measurement instruments (EMI).

Grey-box model for transformator stations

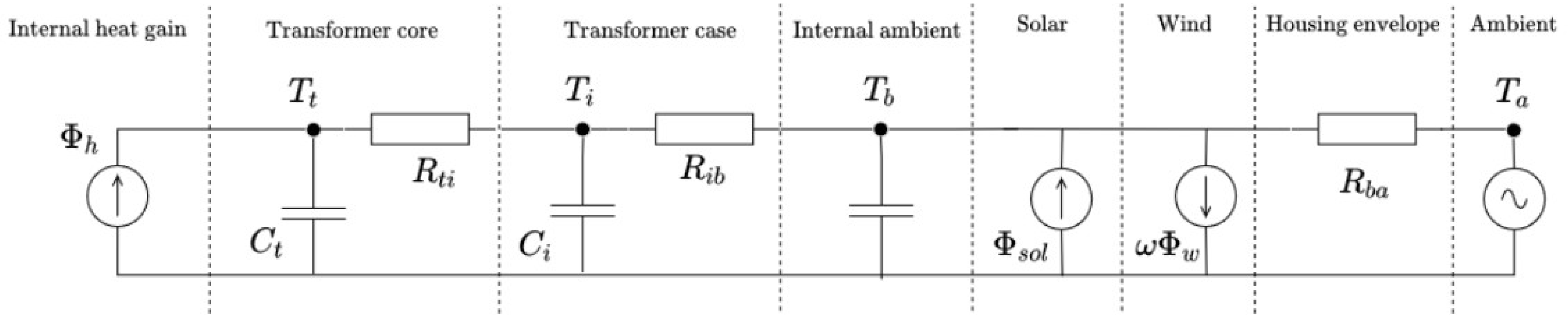


Figure 7: RC circuit of the three state model $TiTtTb$.

Model performance; 6-hour predictions

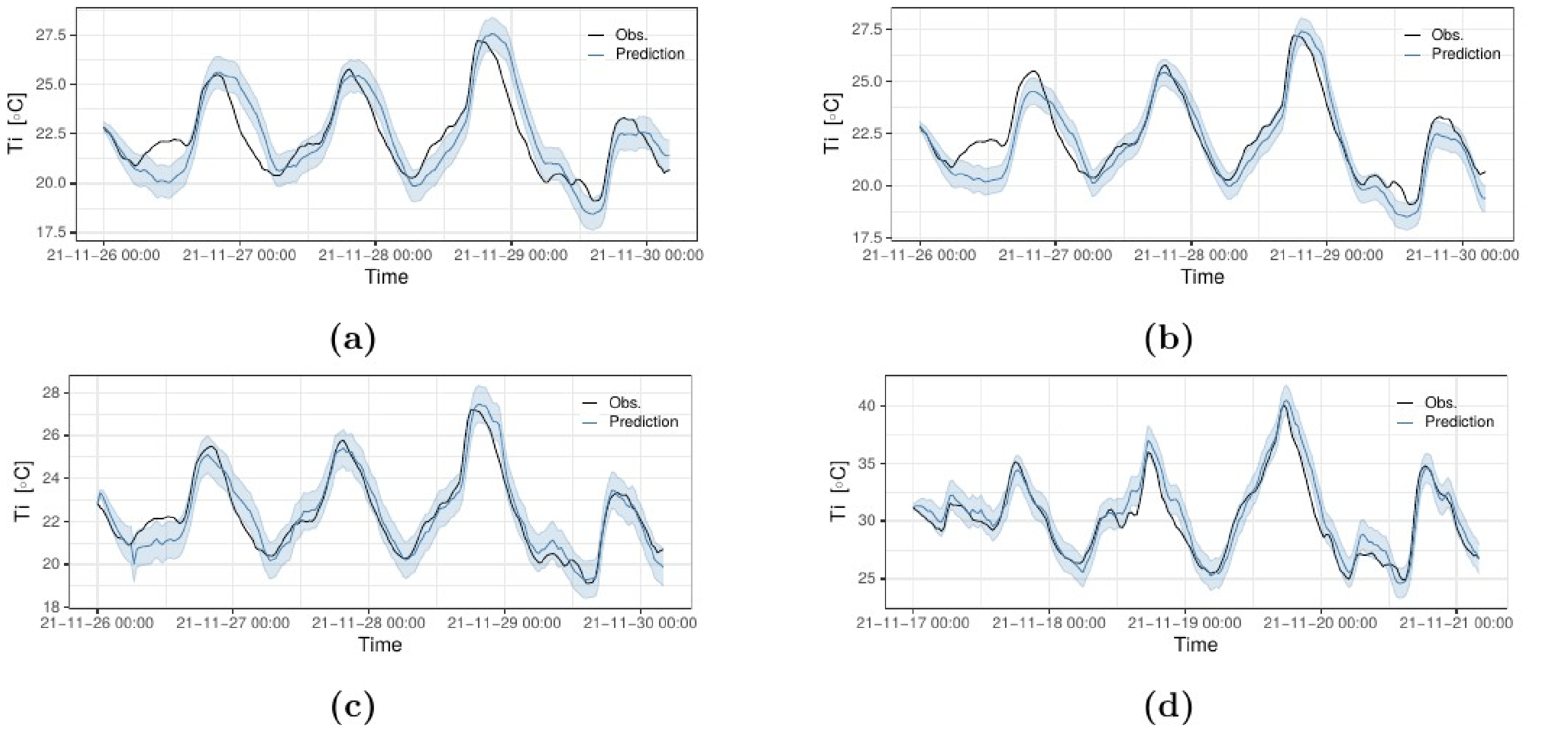
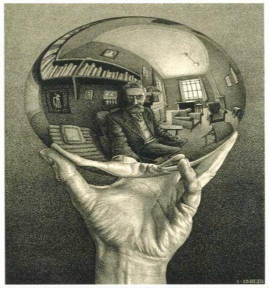


Figure 11: Prediction analysis for 12 step ahead (6 hours) predictions. Subfigures (a)-(c) show predictions for TRF 1 using the one state model (a), extended two state model (b) and the final three state model (c). Subfigure (d) shows predictions for TRF 2 using the final three state model. Black line – observations, Blue line – predictions, Light blue area – 95% PI.

Dynamic Transformer Rating

- Relies on data-driven Digital Twins of the Transformer stations
- Gives good predictions of the hidden states (e.g., oil temperatures) more than 6h ahead
- DTR can reduce the risk of overloading
- The models can be used to predict failures of transformators
- Experiences show that transformers often can be overloaded (up to 120 pct) without any problem
- **Wind farms can be expanded up to 60 pct** without problems (since wind speed and wind power generation are highly correlated)



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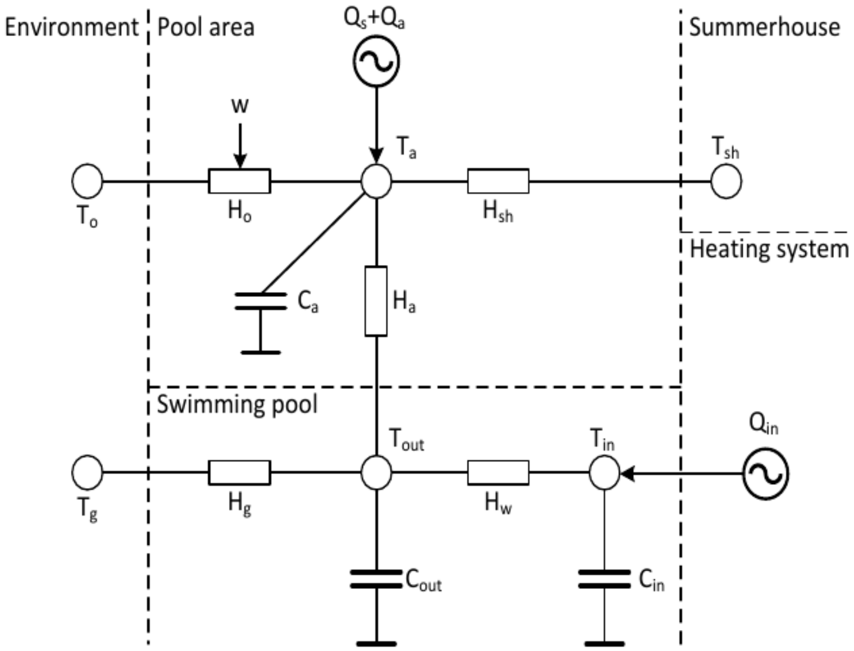
Case Study

Balance Responsible Parties: Summerhouses with a pool

Data-driven models for the buildings

(Using lumped parameter models)



- Based on equivalent thermal parameters model
- Dynamics:

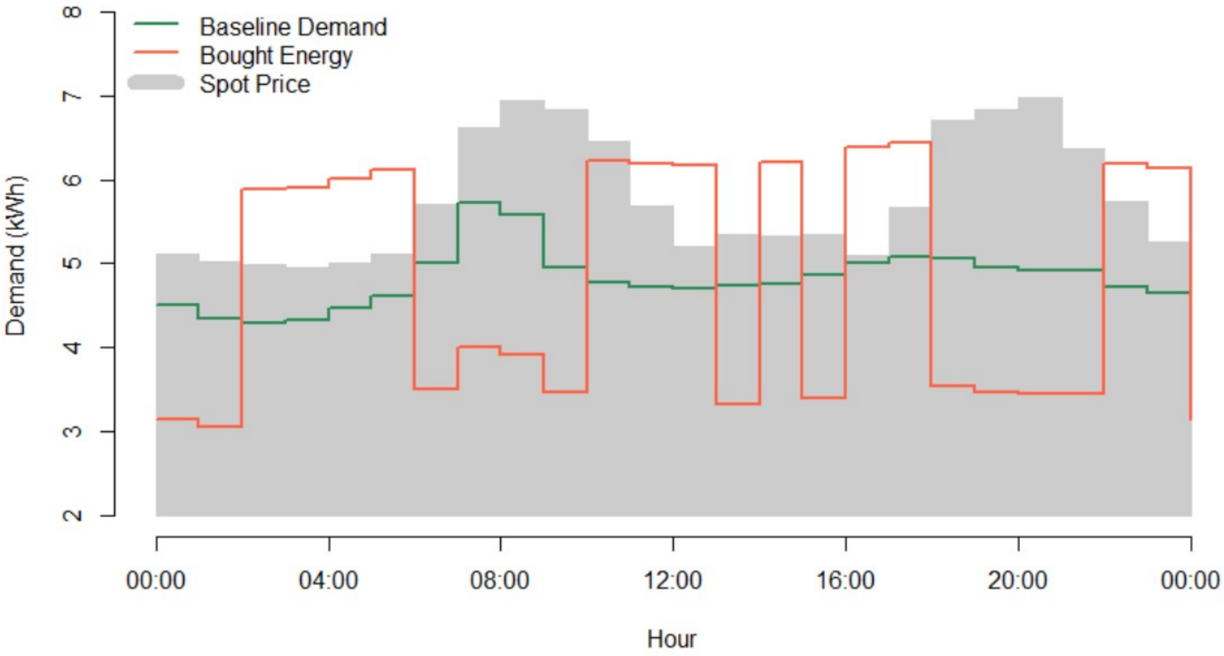
$$\frac{dT_{in}}{dt} = \frac{1}{C_{in}}[H_w(T_{out} - T_{in}) + Q_{in}]$$

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

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

Bidding Flexibility into Markets

- 4 hours intervals consisting of 30% of consumption with durations of 2 hours:



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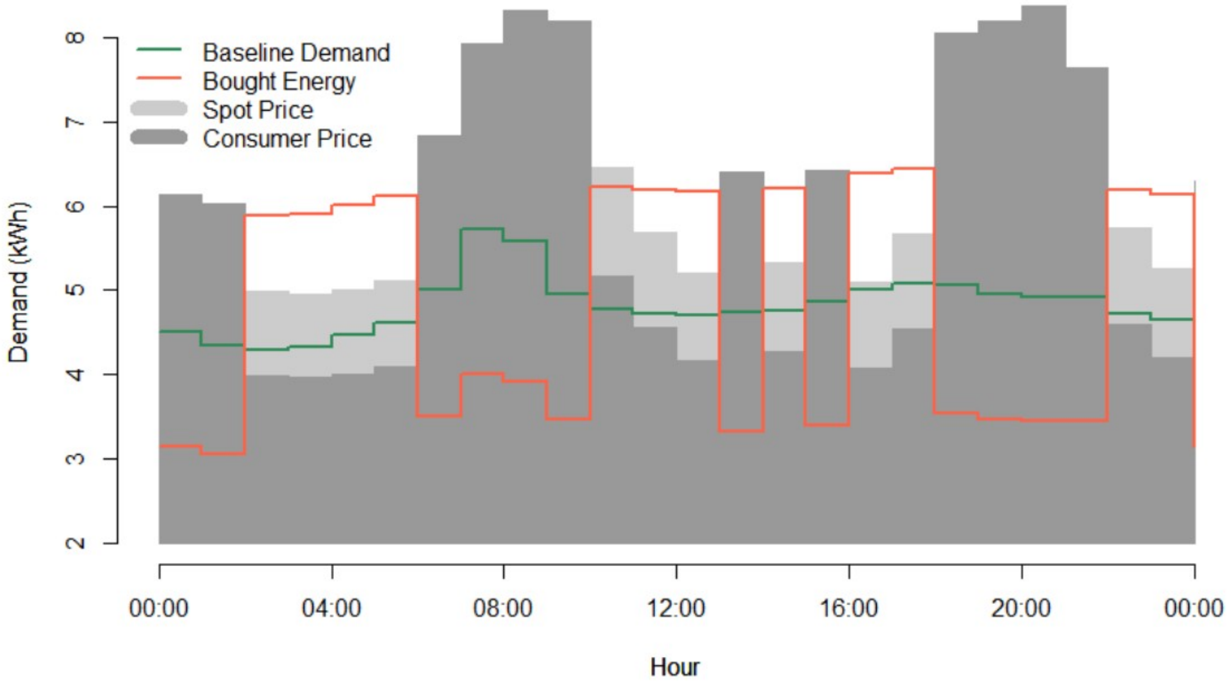
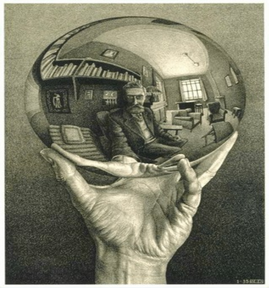
Bidding Flexibility into Markets

Solve FF(Price)=Bought Energy:



Summer house smart control: DSO-TSO Perspectives

- Considered BRP-case which lead to savings: approx. 30 pct
- Built-in DSO-TSO coordination in solving grid challenges
- Price signals important in balancing the distribution grids
- New dynamic and geographical tariffs can solve many of the issues in summer house areas
- New tariffs can take care of local energy systems
- We can use inverters as voltage stabilizing devices
- Automatic solutions targeting also small units



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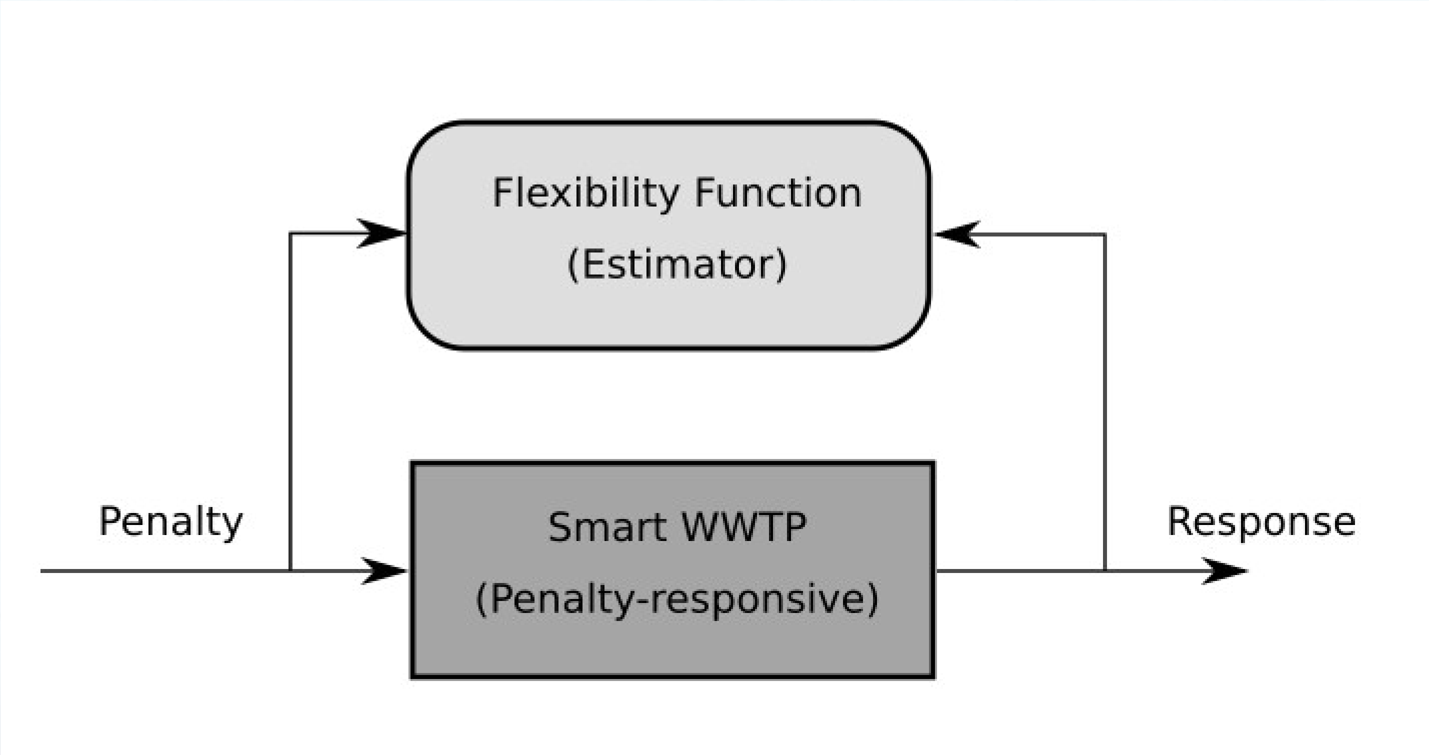
Case study

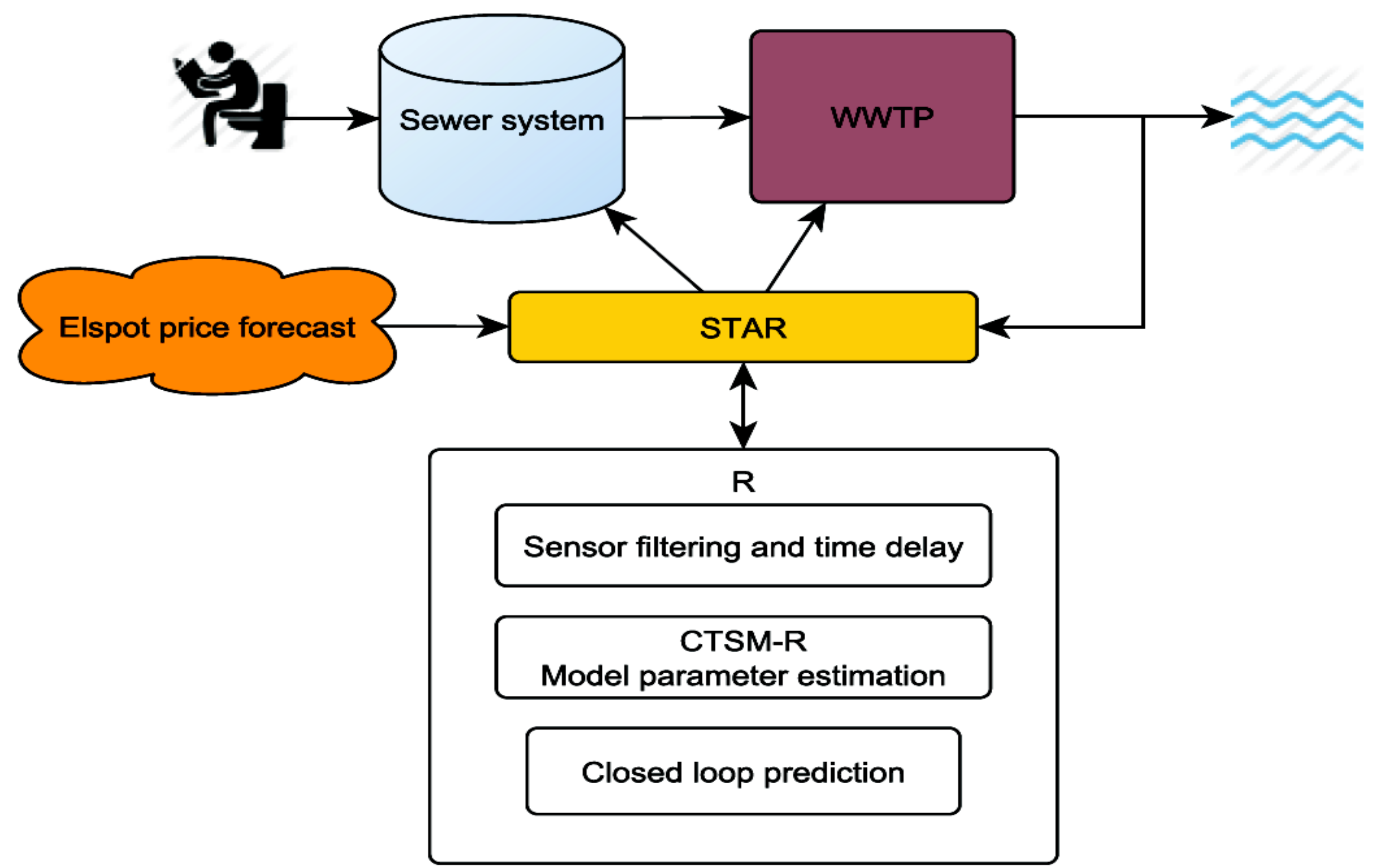
Wastewater Treatment

(Joint work with Kruger)

Flexibility Function



Energy Flexibility in Wastewater Treatment



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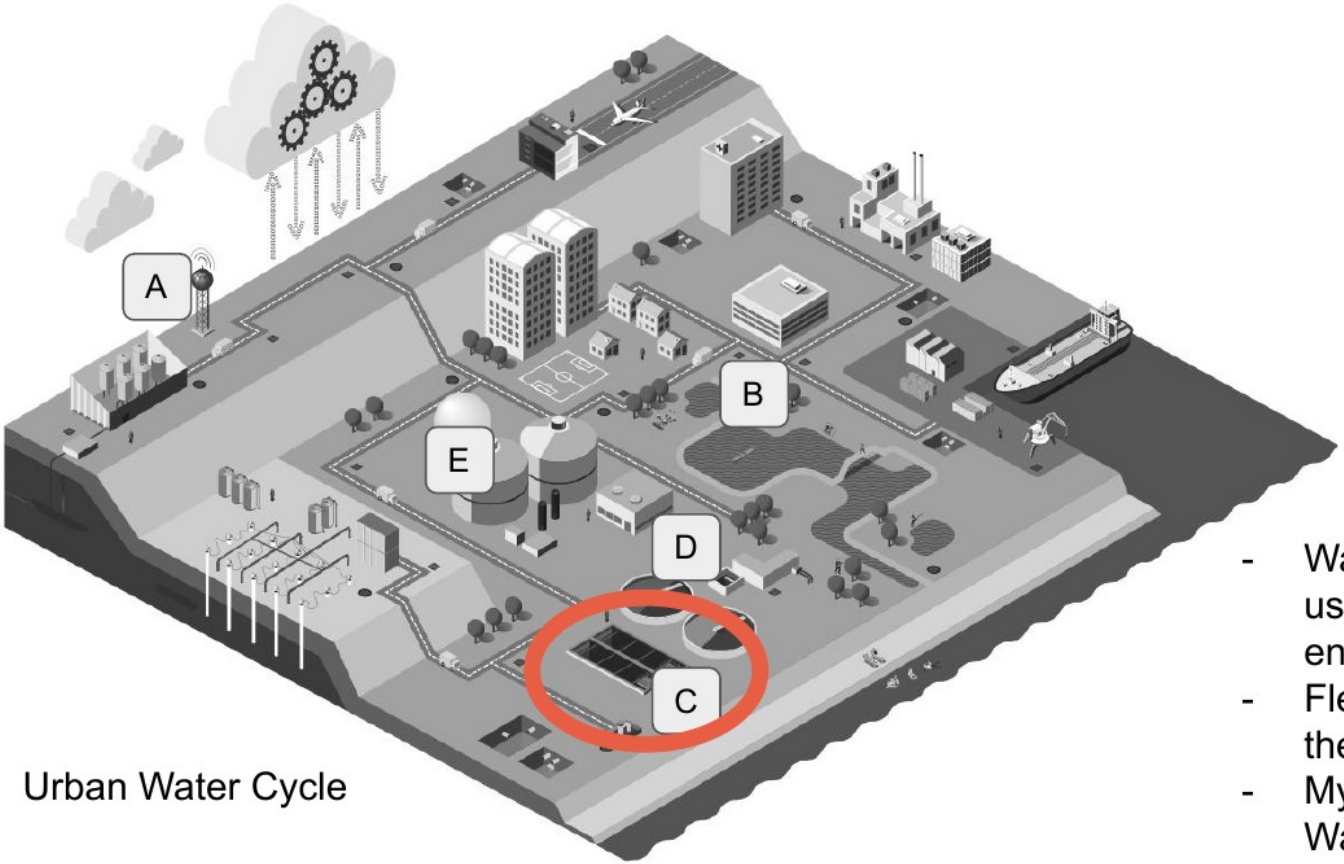
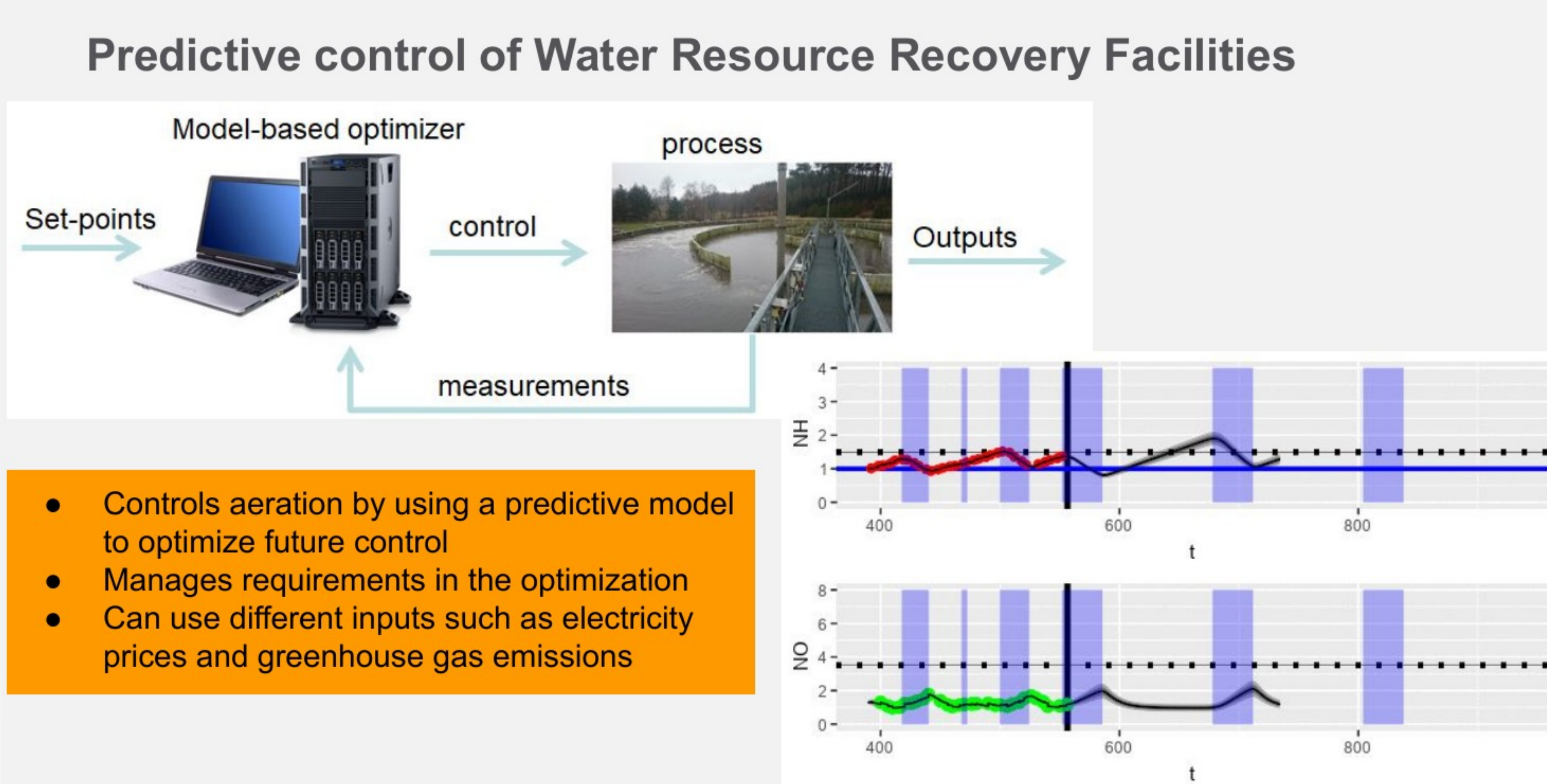
Urban Water Cycle



Urban Water Cycle

- Water & Wastewater sector uses 1-5% of total electrical energy of a country
- Flexibility is found in all parts of the urban water cycle
- My focus has been on Wastewater treatment aeration (C)

Wastewater Treatment Plant



Predictive control of Water Resource Recovery Facilities

- Controls aeration by using a predictive model to optimize future control
- Manages requirements in the optimization
- Can use different inputs such as electricity prices and greenhouse gas emissions

Potential savings (Wastewater Treatment Plants)

Environment	• Reduce GHG emissions related to electricity use and process by 50% • Improve effluent concentration by 10-20%
Costs	• Reduce electricity and taxation costs by 20% • Reduce need for investments in grid and tuning of controls
Usability	• Operators will be trained and will seamlessly adapt to the new solutions • Easy to adapt to new requirements

Wind Power Forecasting for DSOs and TSO using Spatial Hierarchies

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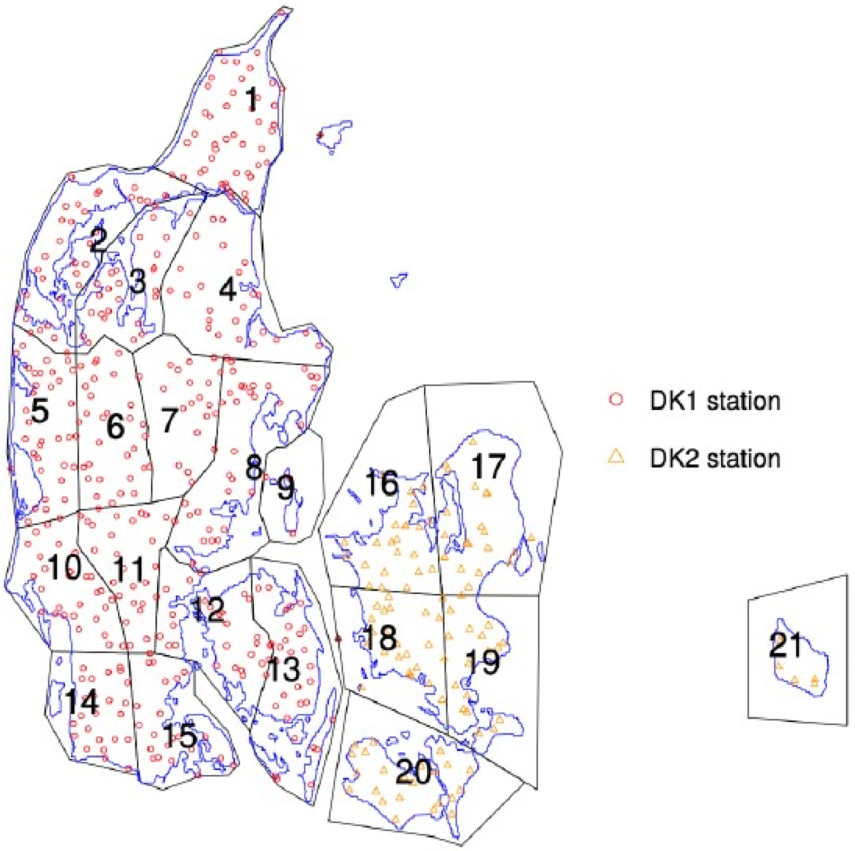
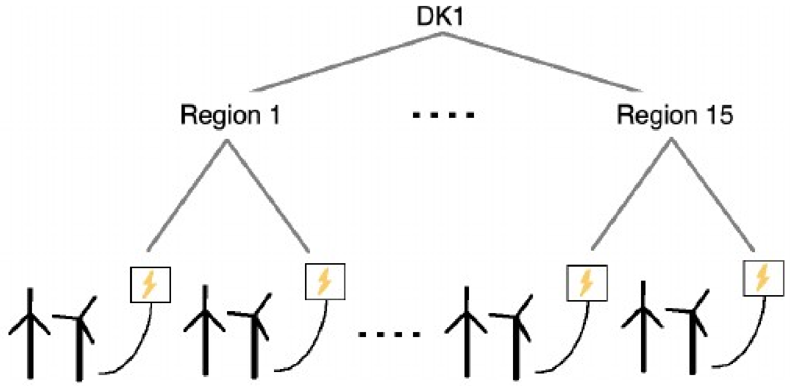
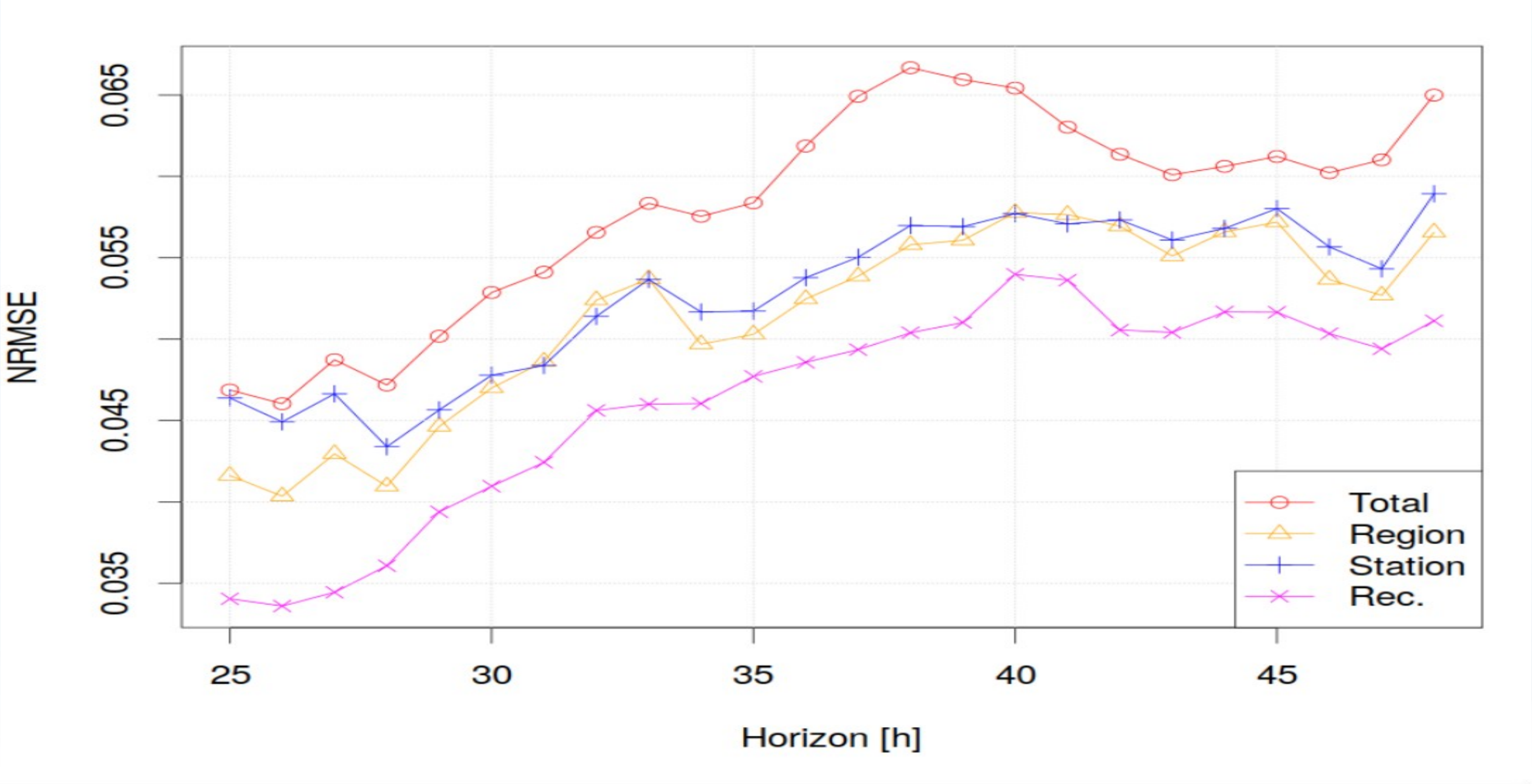
Wind Power Forecasting





(b) Illustration of the spatial hierarchy for DK1 with 407 individual conversion stations at the bottom level, 15 regions at the middle level, and the total of Western Denmark at the top.

Wind Power Forecasting in DK1 (improvements 20 pct)



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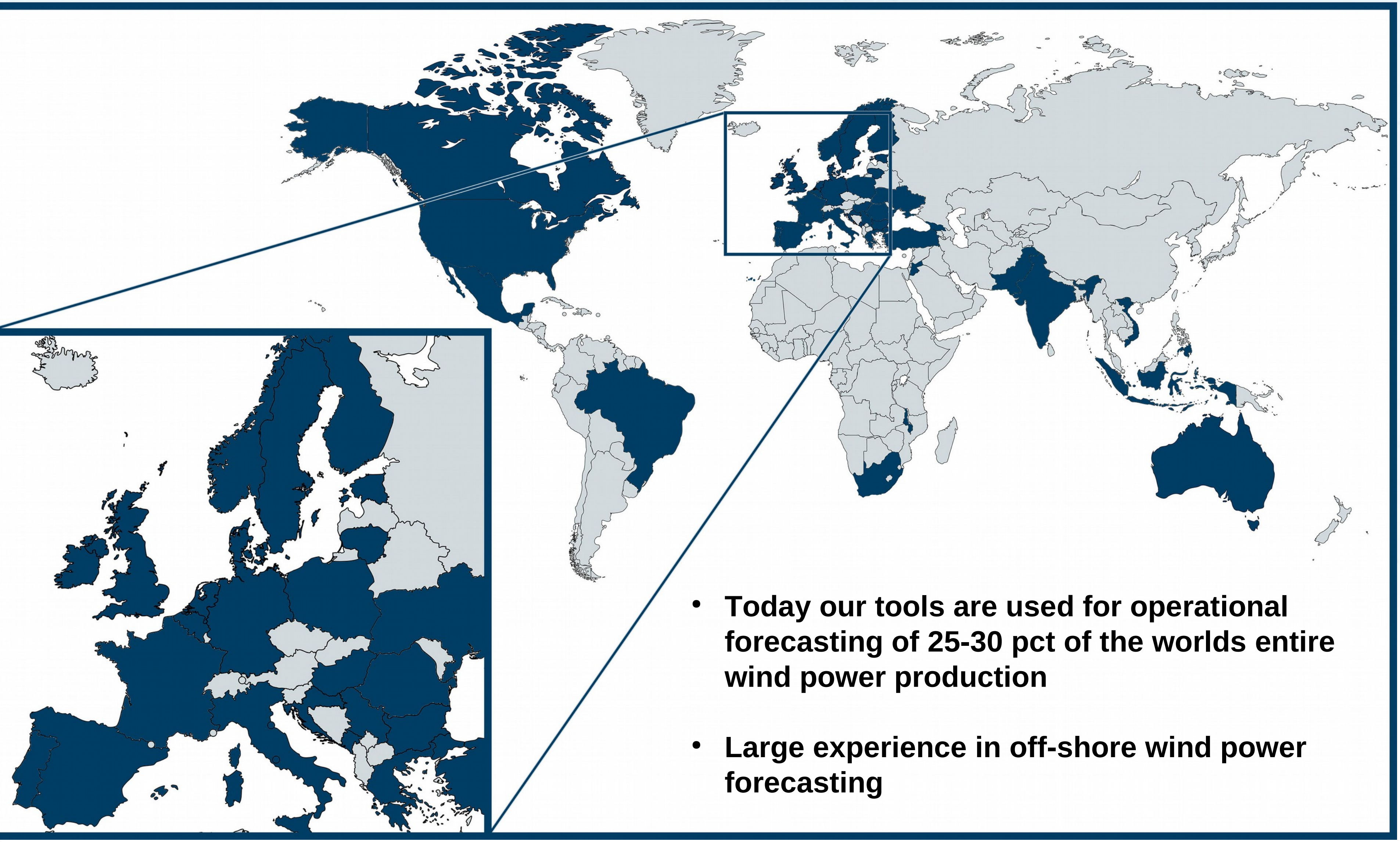
Wind Power Forecasting
Using API's developed at DTU



- **Today our tools are used for operational forecasting of 25-30 pct of the worlds entire wind power production**

- **Large experience in off-shore wind power forecasting**

Implementation: National Data Hub for Spatial and Temporal Data

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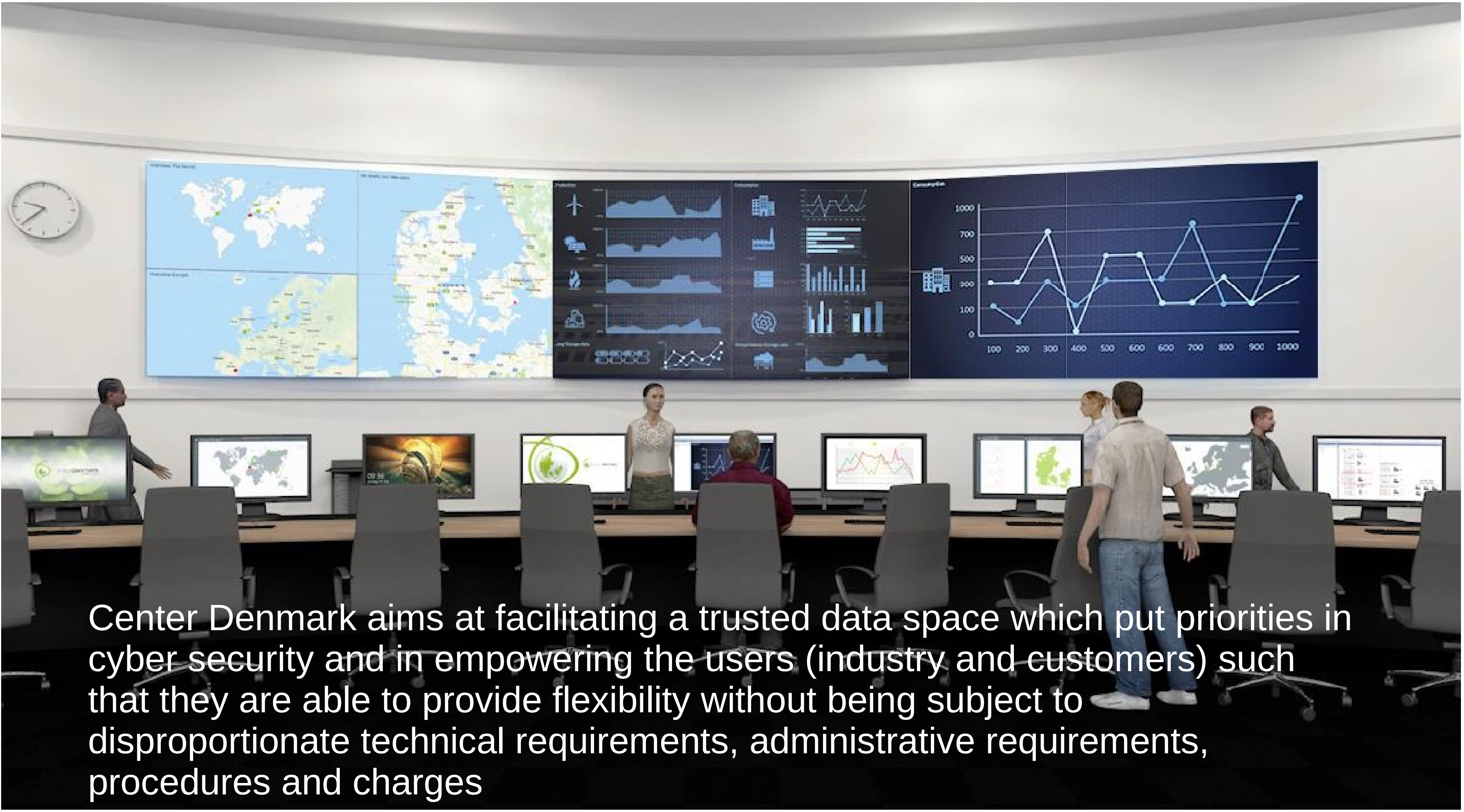
Center Denmark
Control Room and Data Space
Spatial–Temporal thinking and coherency



Center Denmark aims at facilitating a trusted data space which put priorities in cyber security and in empowering the users (industry and customers) such that they are able to provide flexibility without being subject to disproportionate technical requirements, administrative requirements, procedures and charges

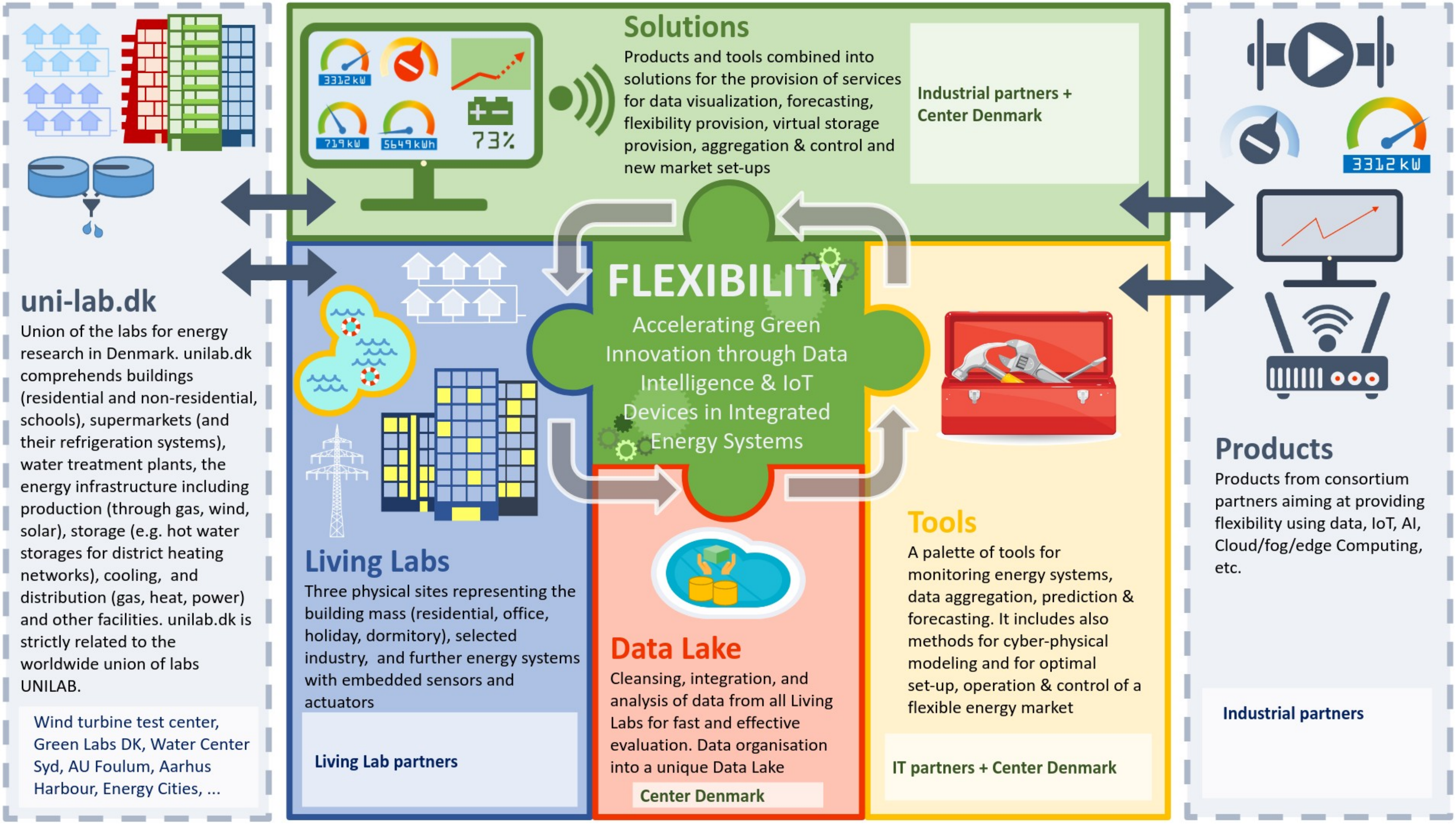
Trusted Data Sharing Platform

Data Exchange Facilities Market provide neutral (infrastructure and rules) mechanisms in the background for controlled, trusted and secure data transactions.

Participants accepting the market rules benefit from the exchange mechanisms and shape together an open market for data.

This is how we work together

Business Ecosystem



uni-lab.dk

Union of the labs for energy research in Denmark. unilab.dk comprehends buildings (residential and non-residential, schools), supermarkets (and their refrigeration systems), water treatment plants, the energy infrastructure including production (through gas, wind, solar), storage (e.g. hot water storages for district heating networks), cooling, and distribution (gas, heat, power) and other facilities. unilab.dk is strictly related to the worldwide union of labs UNILAB.

Wind turbine test center, Green Labs DK, Water Center Syd, AU Foulum, Aarhus Harbour, Energy Cities, ...

Solutions

Products and tools combined into solutions for the provision of services for data visualization, forecasting, flexibility provision, virtual storage provision, aggregation & control and new market set-ups

Industrial partners + Center Denmark

FLEXIBILITY

Accelerating Green Innovation through Data Intelligence & IoT Devices in Integrated Energy Systems

Living Labs

Three physical sites representing the building mass (residential, office, holiday, dormitory), selected industry, and further energy systems with embedded sensors and actuators

Living Lab partners

Data Lake

Cleansing, integration, and analysis of data from all Living Labs for fast and effective evaluation. Data organisation into a unique Data Lake

Center Denmark

Tools

A palette of tools for monitoring energy systems, data aggregation, prediction & forecasting. It includes also methods for cyber-physical modeling and for optimal set-up, operation & control of a flexible energy market

IT partners + Center Denmark

Products

Products from consortium partners aiming at providing flexibility using data, IoT, AI, Cloud/fog/edge Computing, etc.

Industrial partners

Expected Drivers for the Transition

- More green (and fluctuating) energy production
- Increased use of electricity everywhere
- Increased deployment of district heating/cooling and green gas
- Sector coupling and P2X
- Digitalization
- Flexibility everywhere (also at the Edge)
- Energy savings

Energy Taxes for the Future

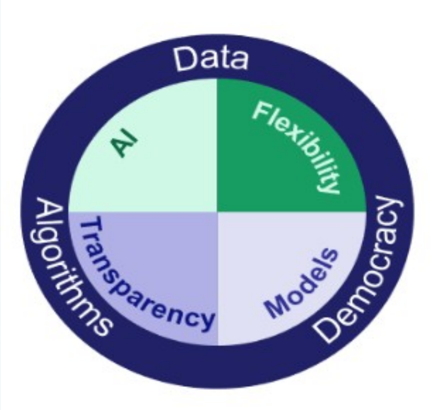
- Taxes should be linked to physics
- Taxes should be linked to the actual CO2 emission (locally – temporal and spatial)
- Taxes should be the same for all energy sources
- Taxes should be the same for all types of consumption
- Taxes should hinder carbon leakage
- Taxes most contain a fixed part (energy efficiency) and a part proportional with the CO2 emission (flexibility)
- The total revenue can be maintained (it is a political decision)

Net Tariffs for the Future

- We need dynamic tariffs (spatial – temporal)
- Must be fair, transparent, safe and democratic
- Should be instrumental in solving net related issues
- Must be linked to physics
- Stability issues are extremely important
- Zero mean cost or non-zero mean cost depending on the issue

Summary

- An efficient implementation of the **future weather-driven** energy system calls for **data-driven Smart Energy Systems**
- We need **digitalization and IoT solutions for enabling low-level flexibility markets**
- **Minimum Interoperability Mechanisms (MIMs) are building blocks** for sector coupling and for implementing IoT solutions
- We need **transparent**, **safe, fair** and **democratic** solutions
- We have proposed to use **control-based methods for activating local flexibility (Smart-Energy OS)**
- **Savings:** Wastewater treatment 40 – 50 pct; summer houses: 20 – 35 pct



FED FLEXIBLE ENERGY DENMARK

Summary

- We have described methods to **unlock flexibility everywhere**
- We need **dynamic (temporal and spatial) tariffs** (and **taxes**)
- We need **data hubs** for energy related **streaming data** (like Center Denmark)
- We need a Business Ecosystem with **Trusted Data Sharing** and Living Labs (like TEF CitCom.ai)
- We need **transparent**, **safe, fair** and **democratic** solutions
- **It must be easy**. Industry and house owners should be able to participate in **flexibility markets** without being subject to disproportionate technical requirements, procedures and charges
- We have indicated how to use **control-based methods for all type of grid services**
- Implemented at the **National Digitalization Hub, Center Denmark**