Digitalisation for the Future Weather-Driven Energy System

Centre for Net Zero, Febr. 2023

Henrik Madsen
DTU Compute

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

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ebalanceplus
www.h2020-bridge.eu

This initiative is funded by

Some European and International Activities

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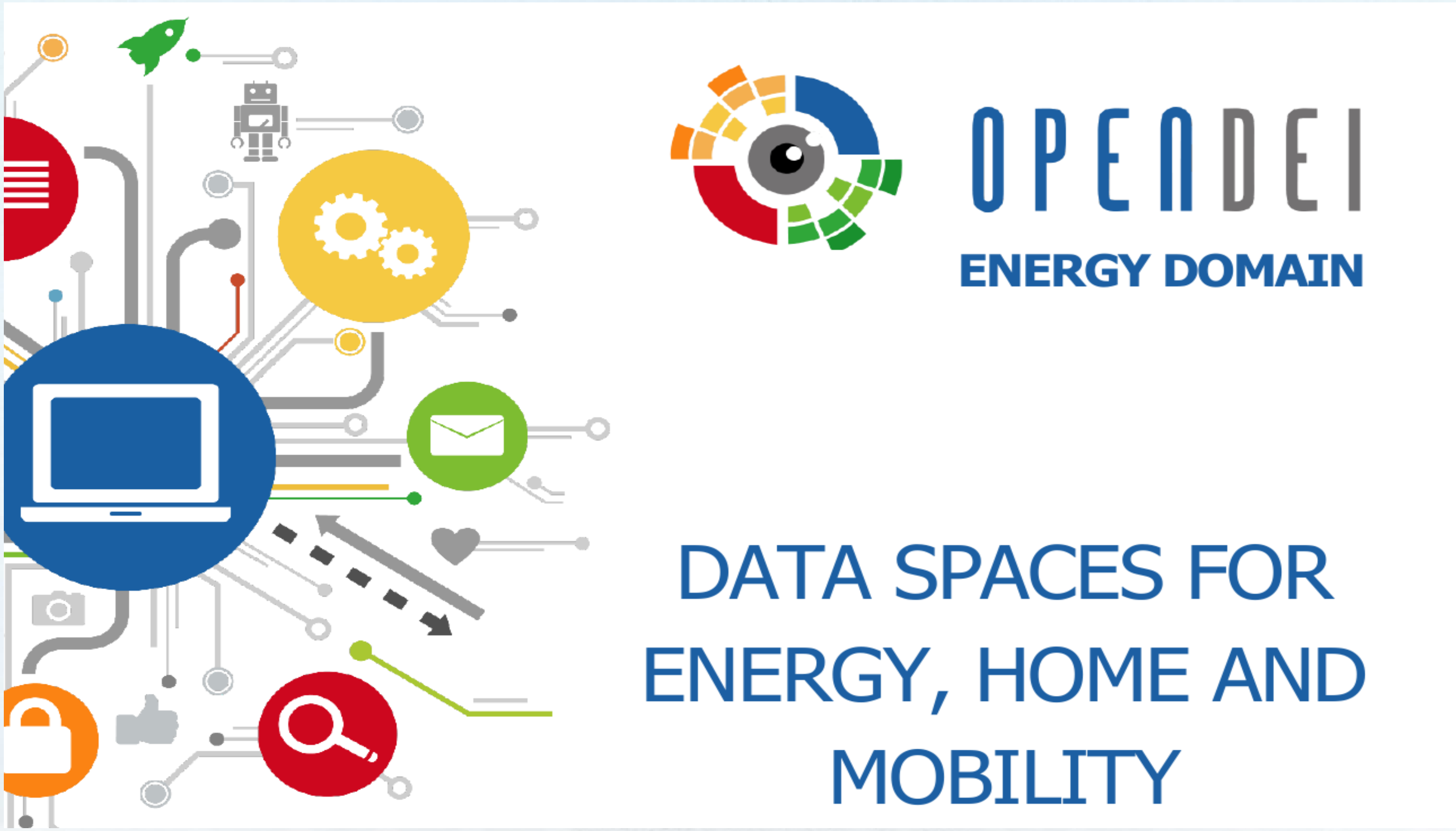
EU Report on Data Spaces

DTU



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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Digital Europe – Data Spaces

Phase 1 (22 Feb 2022) | Phase 2 (Q2 2022) | Phase 3 (Q1 2023) | Phase 4 (Q2 2023)

SMART & SUSTAINABLE CITIES

Go Li.EU
Living-in.EU Governance
CSA (2m€)

DS4SSCC – Data Space for Smart Communities (prep)
CSA (1m€)

EDIH
European Digital Innovation Hubs
CSA (2-4x 5m€)

LDT Toolbox Tech Specs (2m€/3 mo)

Citiverse?

Advancing Digital Transformation in SCC
[Local Digital Twin Toolbox etc.] (24m€)

AI on-demand platform (28m€)

Data Space for Smart Communities
Deployment action (18m€ + 18m€)

CitCom.ai
AI Testing & Experimentation Facility for SCC
Deployment action (20m€ + 20m€)

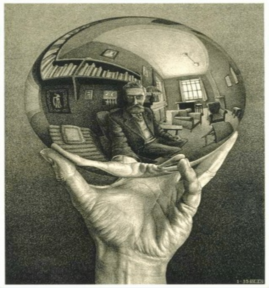
ENER

OMEGA-X
Scoping (2022-24)
HE RIAs (3x 8m€)

Blueprint (2024)
CSA (5m€?)

Large-Scale Pilots (2025-7)
Deployment Action (100-200m€?)

European and International Initiatives on Smart Energy Systems



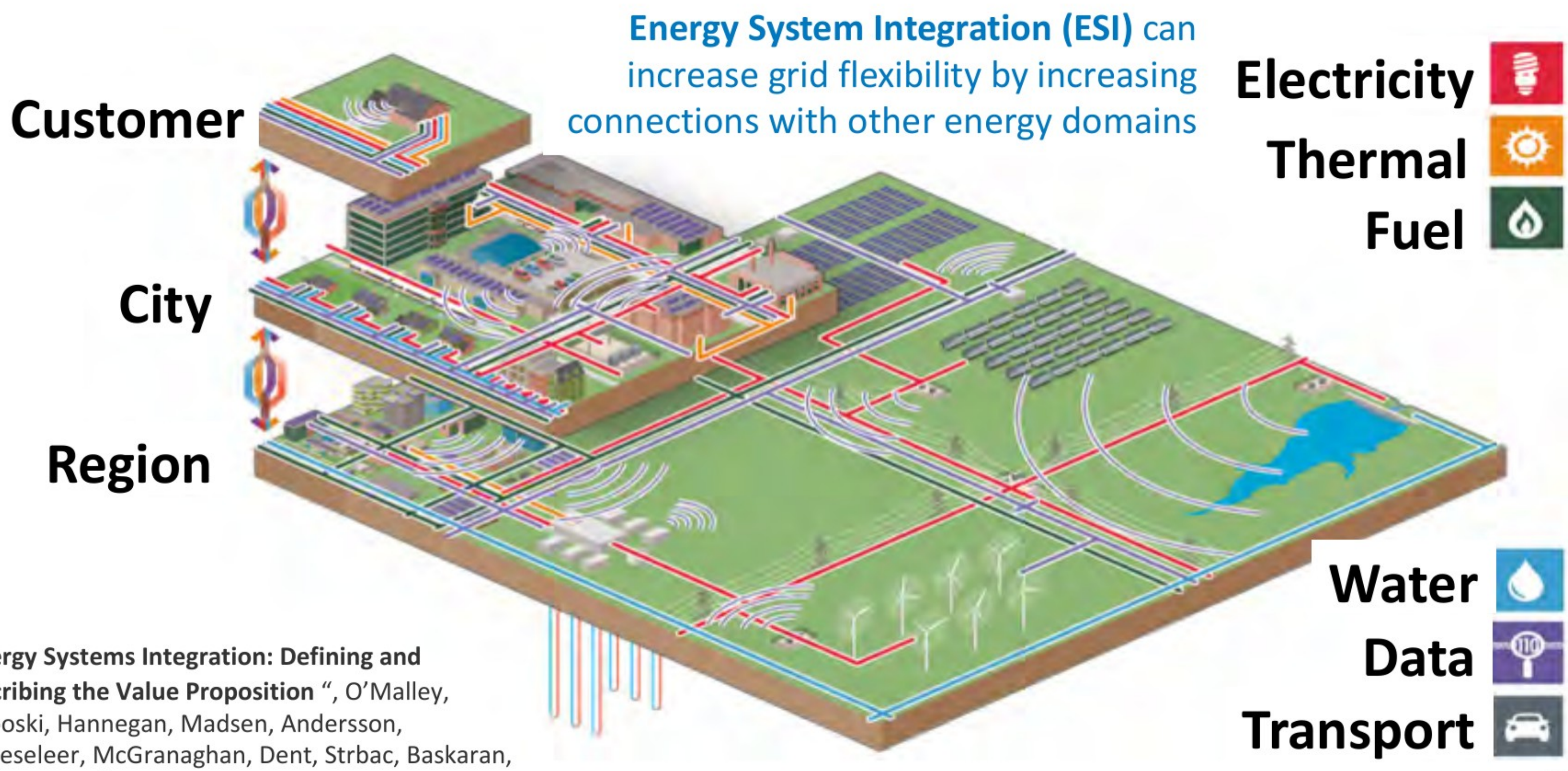
- Digitalisation of Energy Action Plan (DoEAP)
- Data Spaces for Energy Systems
- Digitalisation and DG CNECT
- Key elements mentioned in EU and UN reports:
  - Minimum Interoperability Mechanicsms (MIMs)
  - Some MIMs for energy systems:

    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

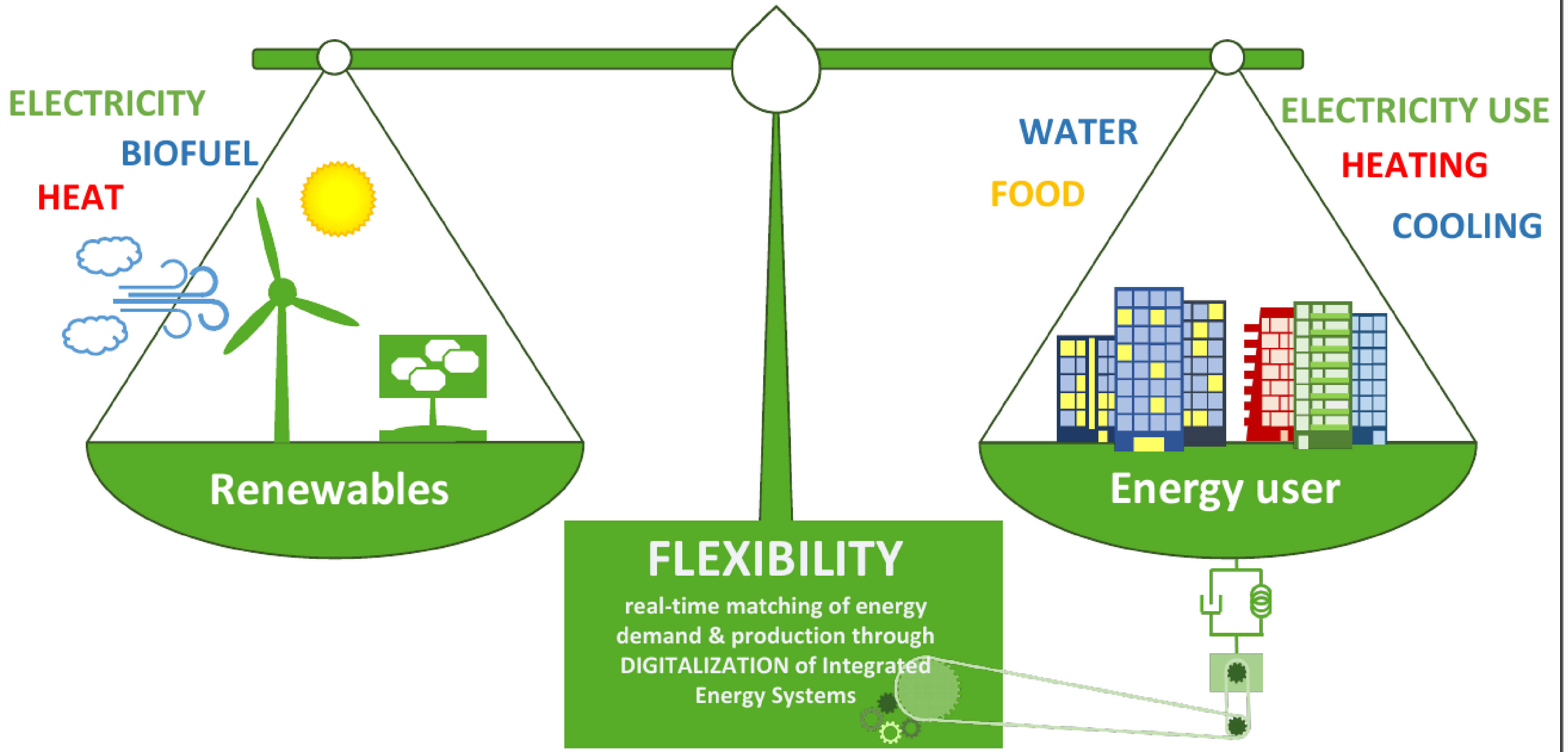
Digitalization and Markets for Energy Systems Integration

Energy Systems Integration



"**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

The Challenge: Denmark Fossil Free 2050



DTU Elektro
3,658 followers
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DIGITAL FOUNDATION OF FUTURE ENERGY NEEDED Read contribution in **Altinget.dk** by **Jacob Østergaard**, Professor, **DTU Elektro** and **Henrik Madsen**, Professor and Head of Department, **DTU Compute**: Research holds the key to the future of green energy systems, but the national focus needs to be on the digital operating system that will connect it all.

Read here: https://lnkd.in/eemjyNfQ

#DTUdk #energysystems #dkgreen #dkenergi #renewableenergy

Digital foundation of future energy needed - DTU
elektro.dtu.dk • 4 min read

Laurent Schmitt • 1st
Head of Utilities & European Developments at dcbel & President at Digital4Grids
9h •

Some interesting reading. The accelerated introduction of #DER - PV, storage, #V2G - across congested grid systems in Europe requires open and transparent #flexibility price discovery where nodal optimisations are without any doubt the most accurate and efficient to use for grid real-time congestion and redispatch management. Looking forward next regulatory developments

Sarah Keay-Bright FEI FRSA MEng • 2nd
Energy policy expert and strategist
9h • Edited •

Just released! - the latest **Energy Systems Catapult** report – "Introducing Nodal Pricing to the GB Power Market to Drive Innovation for Consumers' Benefit: Why now and How?" - lays out the case for nodal pricing in the GB power market as the first-best approach to signalling locational value in a more deeply decarbonised, decentralised, and digitised electricity system. We are calling on **Department for Business, Energy and Industrial Strategy (BEIS)** and **Ofgem** to require **National Grid ESO** to commission a detailed study on the introduction of nodal pricing in the GB power market, encompassing an assessment of the cost benefit case and the implementation and transition practicalities.
See report here: https://lnkd.in/gsHYuyyg

The escalating redispatch costs for the congested GB power system are inefficient and unsustainable. Our view is that the GB market should transition directly to nodal pricing and not via zonal pricing given experience in the US, Australia and Europe. It could be introduced right away at transmission level, providing a more efficient alternative to network charges (TNUoS); over time it can be moved down to lower voltage levels.

Yes, there will be distributional impacts to manage and some incumbents and consumers may need temporary support during the transition, but the overall net benefits for consumers will likely significantly outweigh the downsides given the

Rethinking Electricity Markets

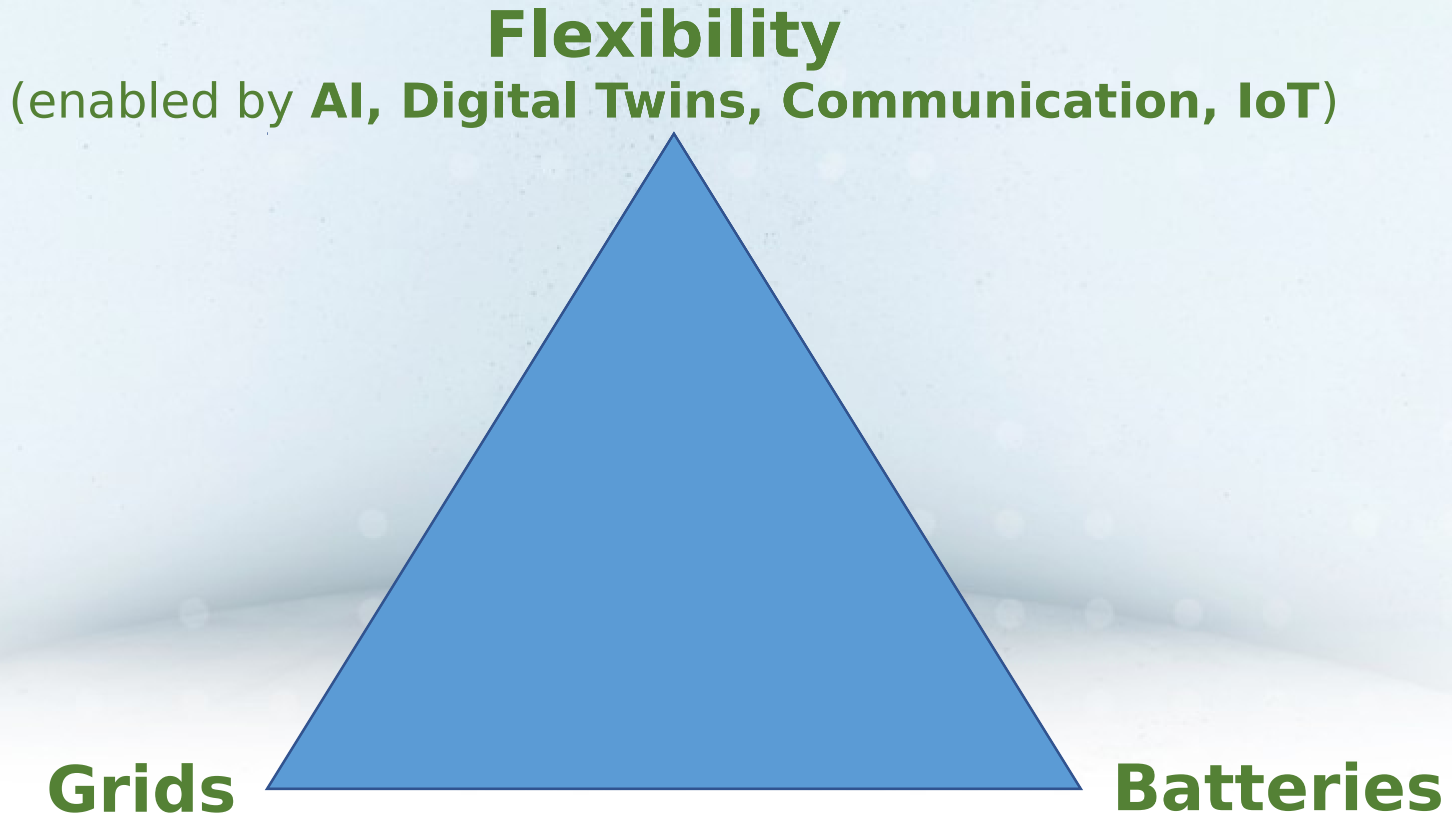
EMR 2.0: a new phase of innovation–friendly and consumer–focused electricity market design reform

Rethinking Electricity Markets is an Energy Systems Catapult initiative to develop proposals to reform electricity markets so that they best enable innovative, efficient, whole energy system decarbonisation.

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**
- Markets for Energy Systems Integration -> **Price-based solution**

Space of Solutions



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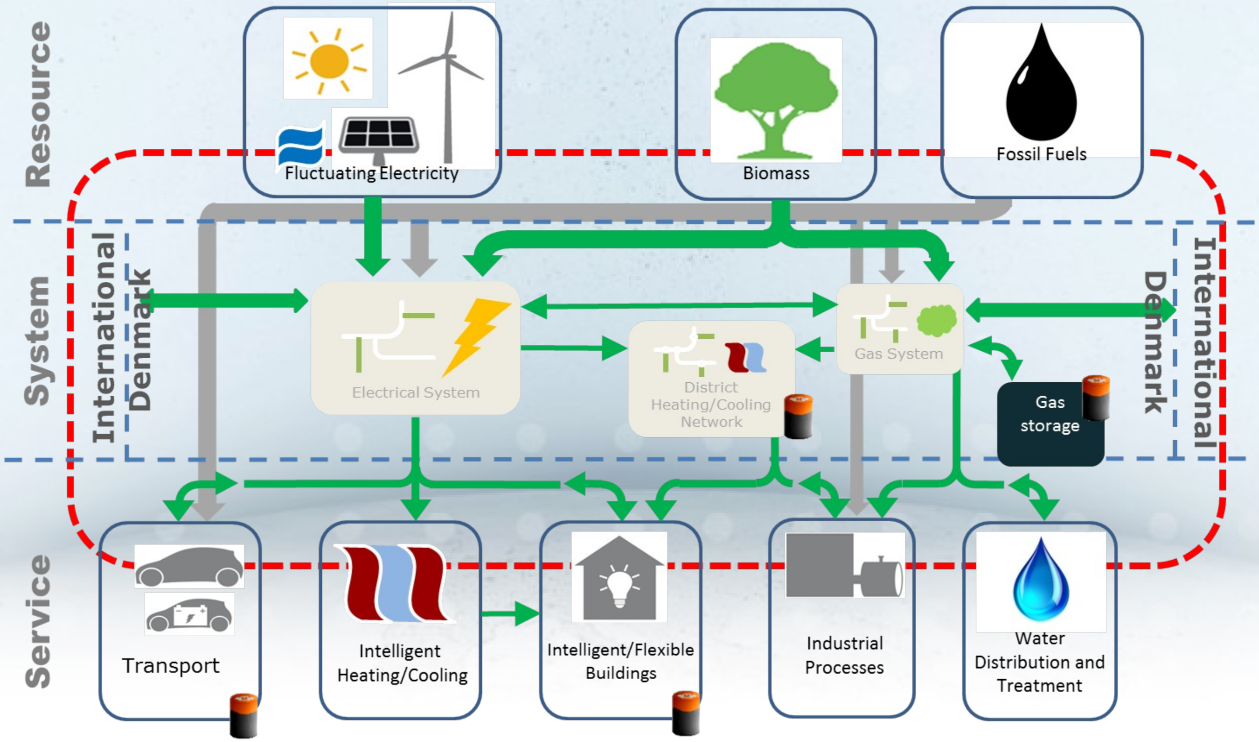
ebalanceplus

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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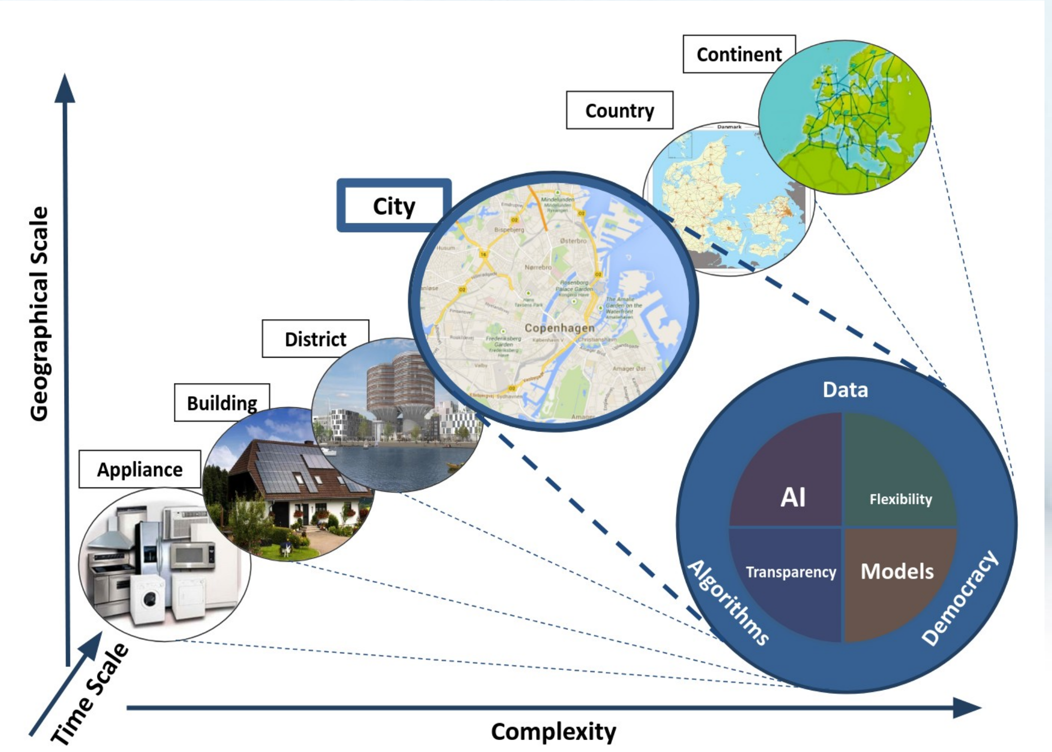
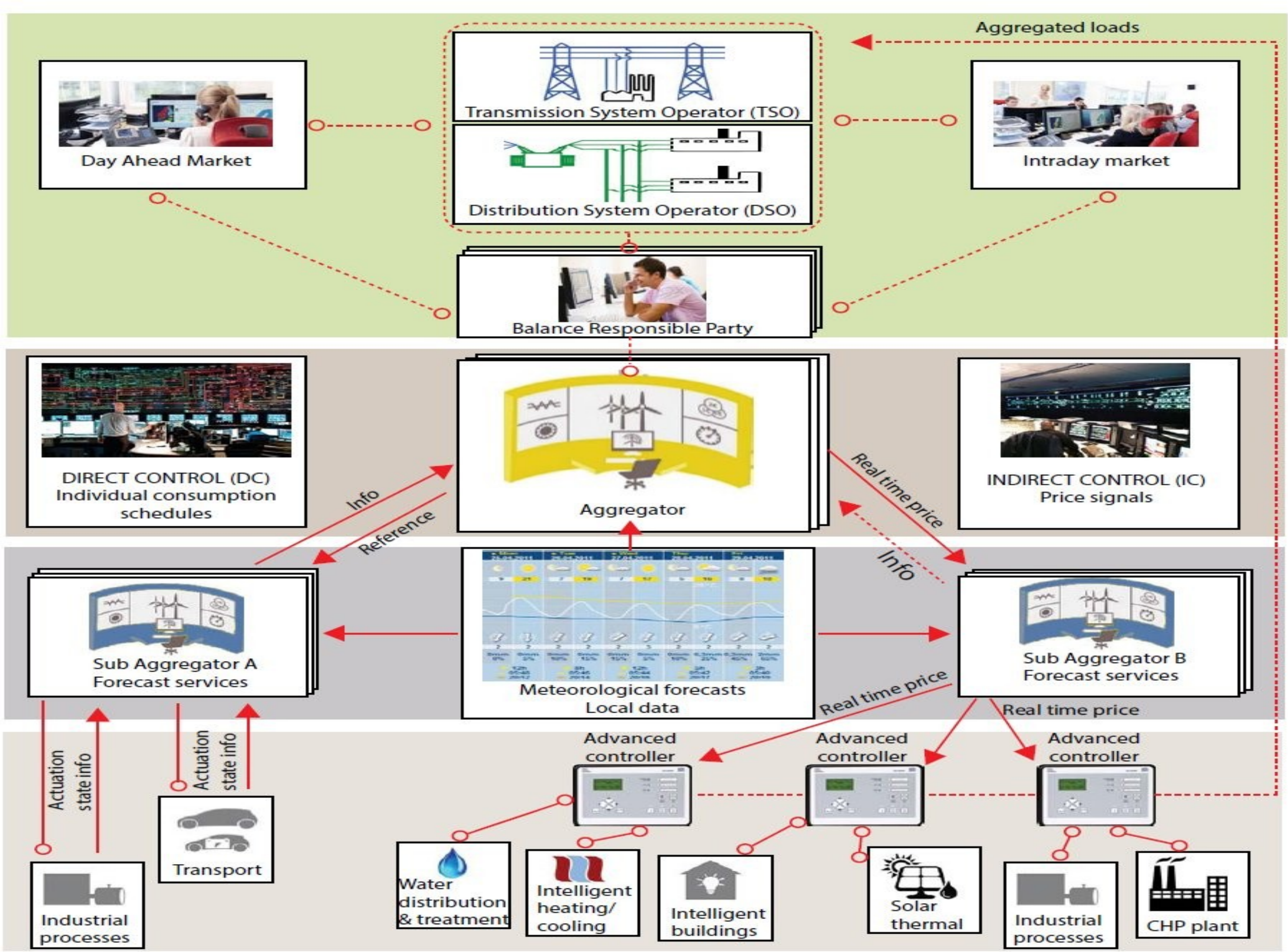
Temporal and Spatial Coherency

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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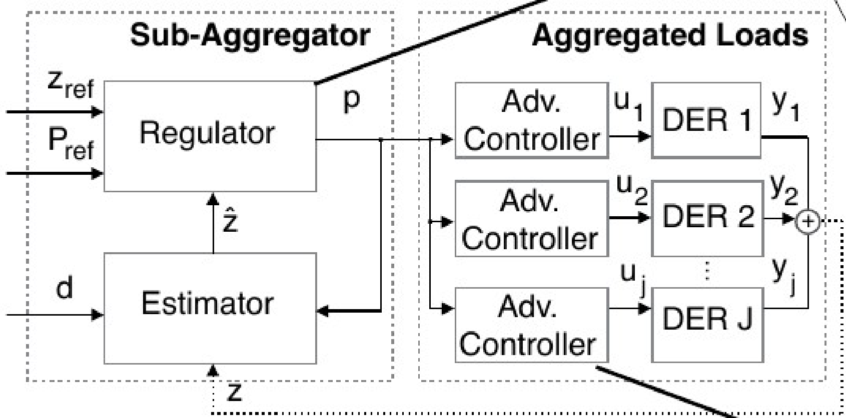
Proposed methodology
Control-based methodology



$$\min_{p} \quad \mathrm{E}[\sum_{k=0}^{N} w_{j,k} ||\hat{z}_k - z_{ref,k}|| + \mu ||p_k - p_{ref,k}||]$$

$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$

$$\min_{u} \quad \mathrm{E}[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)]$$

$$\begin{aligned} \text{s.t.} \quad x_{k+1} &= Ax_k + Bu_k + Ed_k, \\ y_k &= Cx_k, \\ y_k^{min} \leq y_k &\leq y_k^{max}, \\ u_k^{min} \leq u_k &\leq u_k^{max} \end{aligned}$$

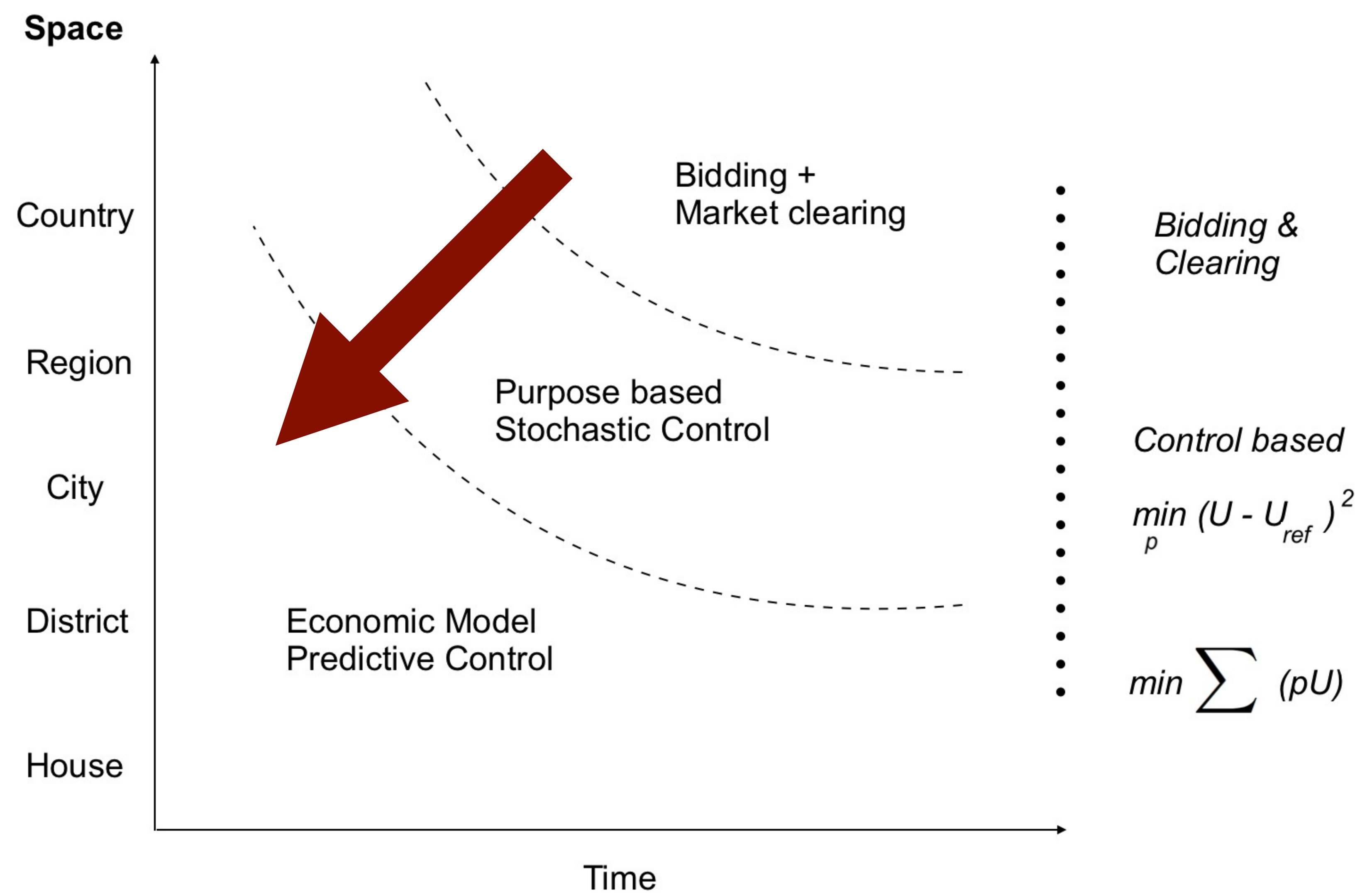
We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

Direct vs Indirect Control

Level	Direct Control (DC)	Indirect Control (IC)
III	$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$	$\min_{\hat{z},p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$ s.t. $\hat{z}_{k+1} = f(p_k)$
	$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$	
IV	s.t. $x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$	$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$ s.t. $x_{k+1} = f_j(x_k, u_k)$

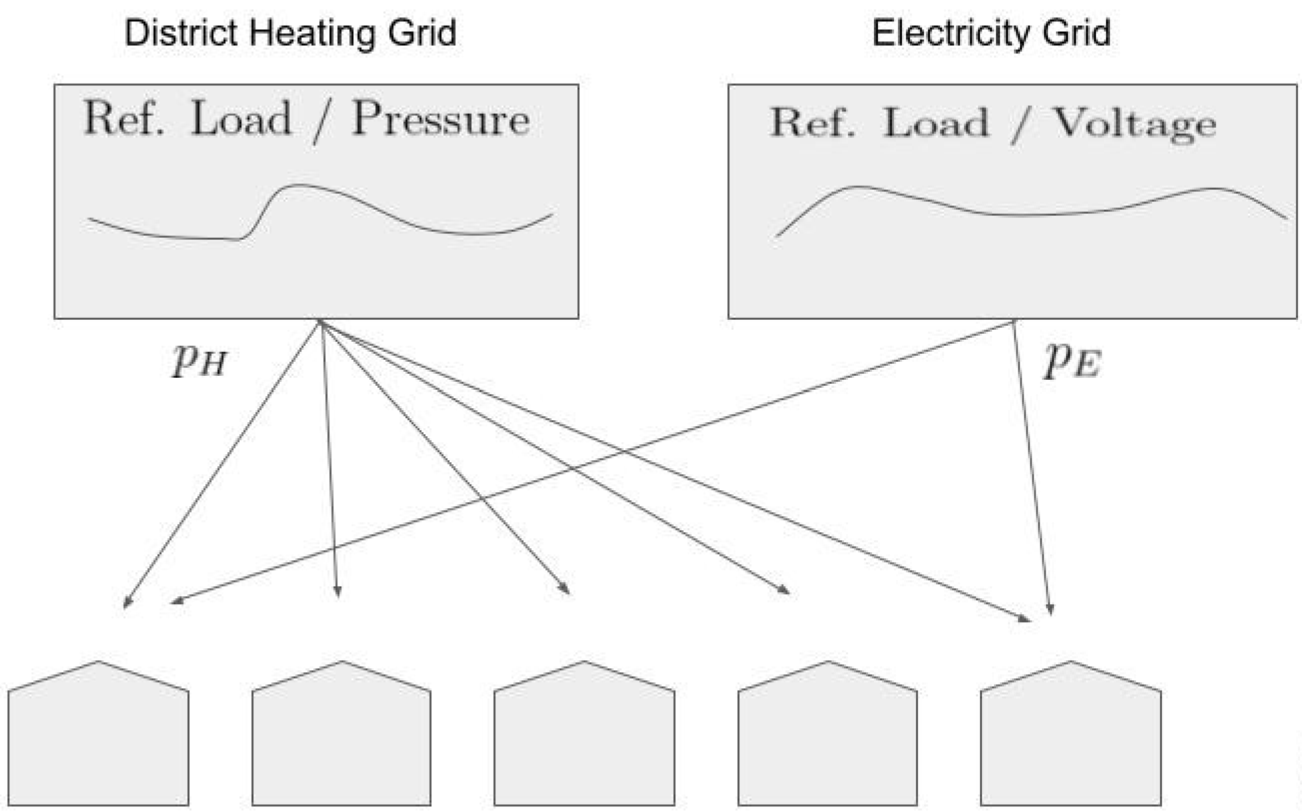
Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals u_j are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes the optimal prices p which are sent to the J-units at level IV. Hence the J DERs optimize their own energy consumption taking into account p as the actual price of energy.

The ‘market’ of tomorrow



Energy Systems Integration

Smart-Energy OS for multi-supply systems (here DH and Electricity)



$$\arg\min_{p}(L(p) - ref_{load}))^2$$

$$\arg\min_{U_H, U_E} \sum_{k=1}^{N} (p_H U_H + p_E U_E)$$

$s.t.$

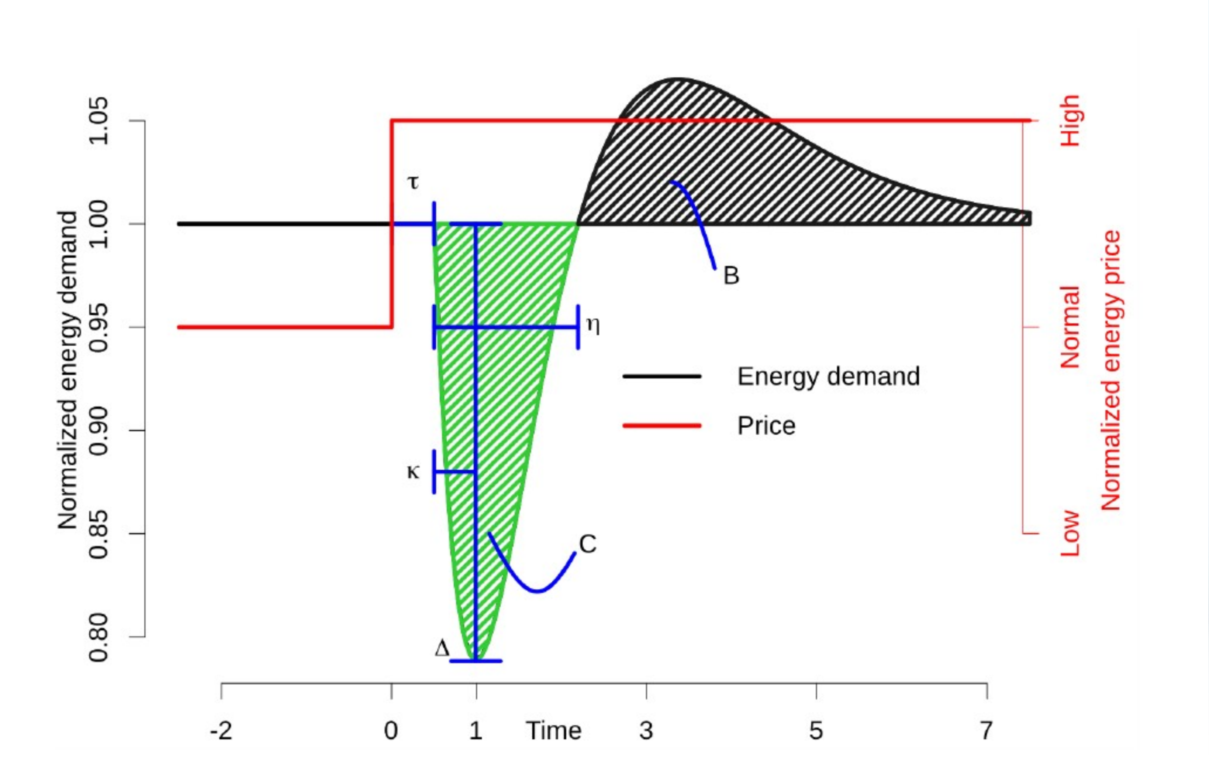
$Temp(U_H, U_E) \in \text{Comfort}$

Case study

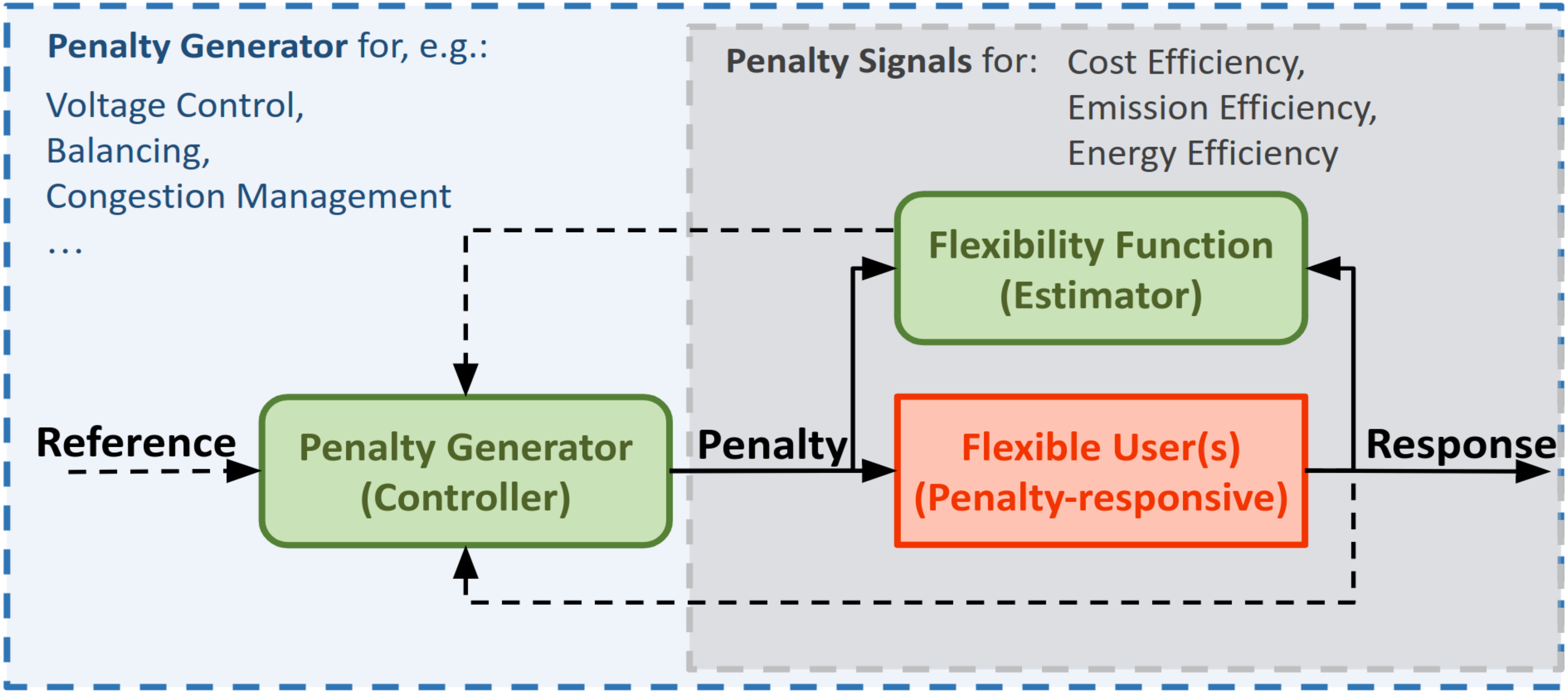
Flexibility Functions as the Fundamental MIM for Linking Markets to the Physics

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 (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*.

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Case study

Price-based Control of Power Consumption (Peak Shaving)

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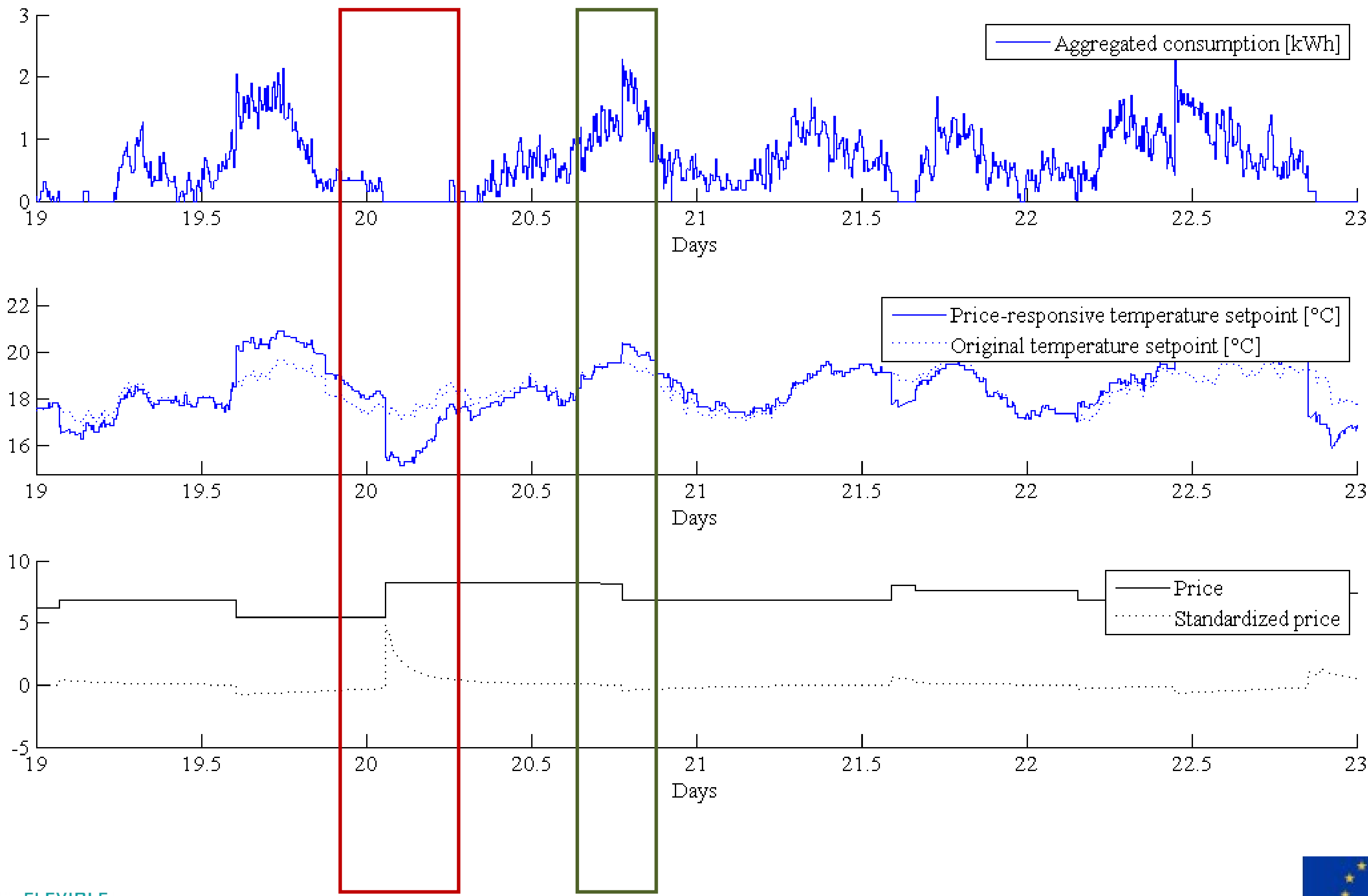
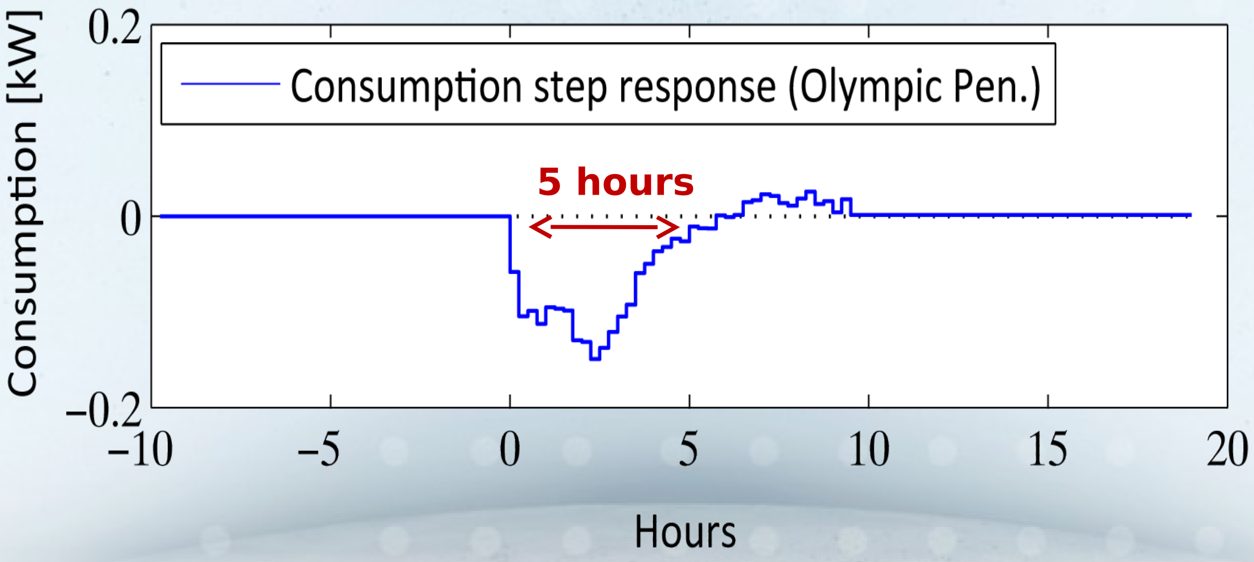
Aggregation (over 20 houses)

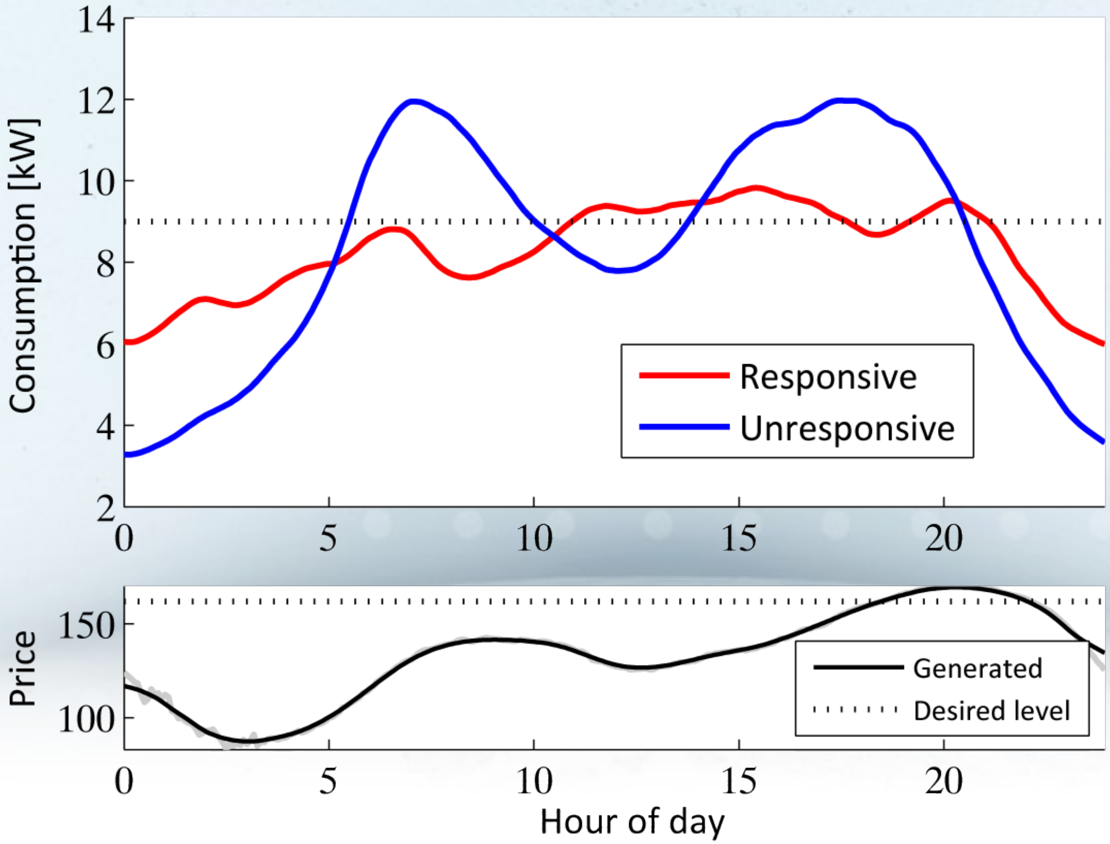


Response on Price Step Change

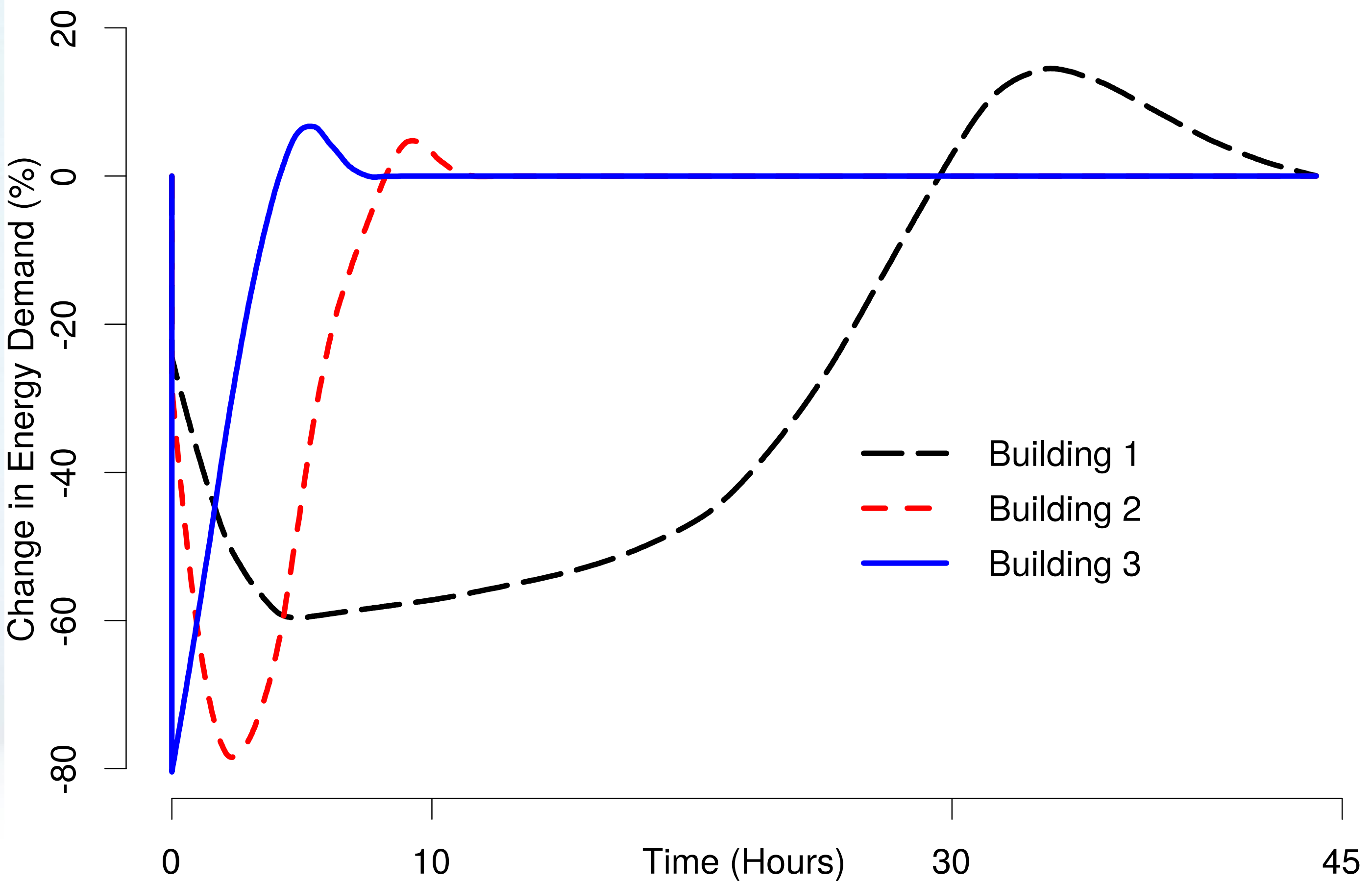


Control performance

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.

$$\mathrm{d}X_t = \frac{1}{C}(D_t - B_t)\mathrm{d}t + X_t(1 - X_t)\sigma_X \mathrm{d}W_t$$

$$\delta_t = f(X_t; \alpha) + g(\lambda_{t-\tau}; \beta)$$

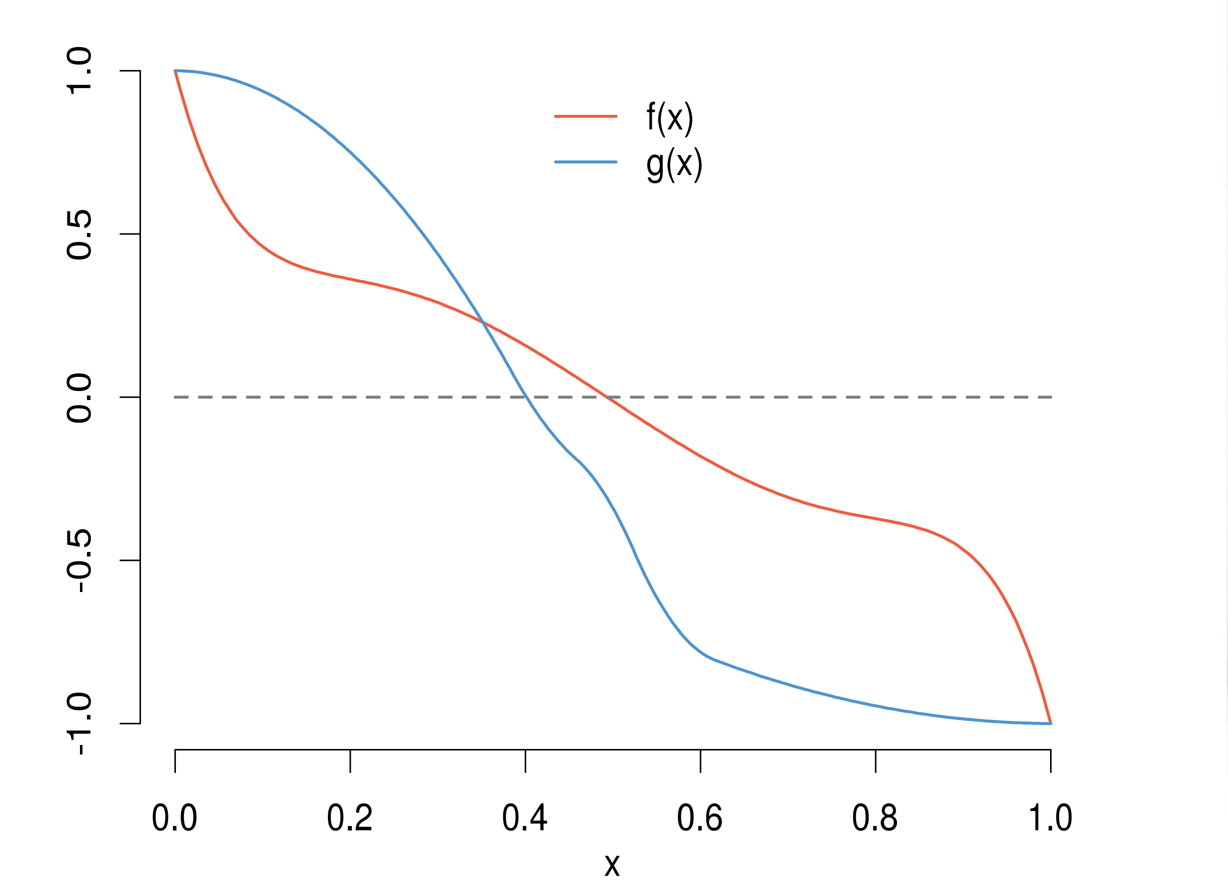
$$D_t = B_t + \delta_t \Delta \left(\mathbb{1}(\delta_t > 0)(1 - B_t) \; + \mathbb{1}(\delta_t < 0) B_t\right)$$

$$Y_t = D_t + \sigma_Y \epsilon_t$$

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



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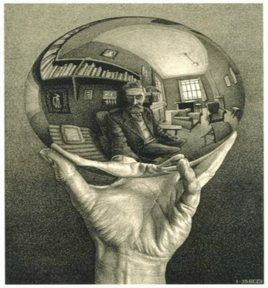
SE-OS Characteristics

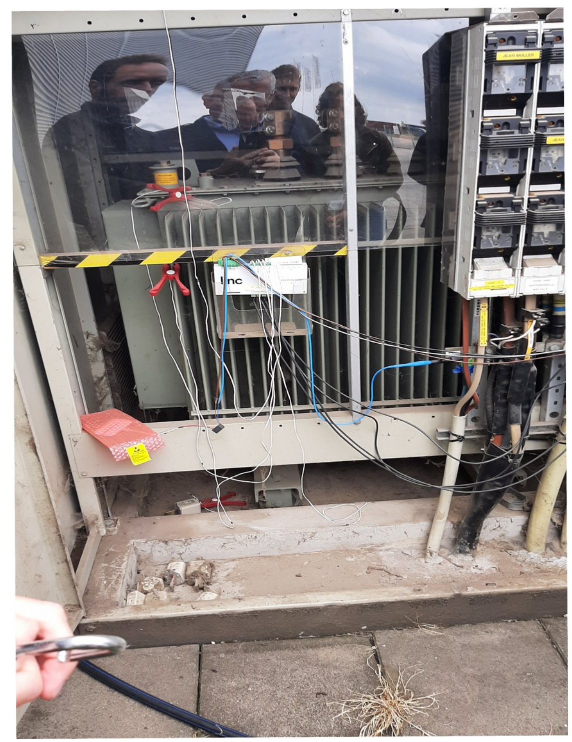
DTU

- 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, ...)



Case Study:

DSO - Smart Grid Intelligence
Models for Dynamic Transformer Rating



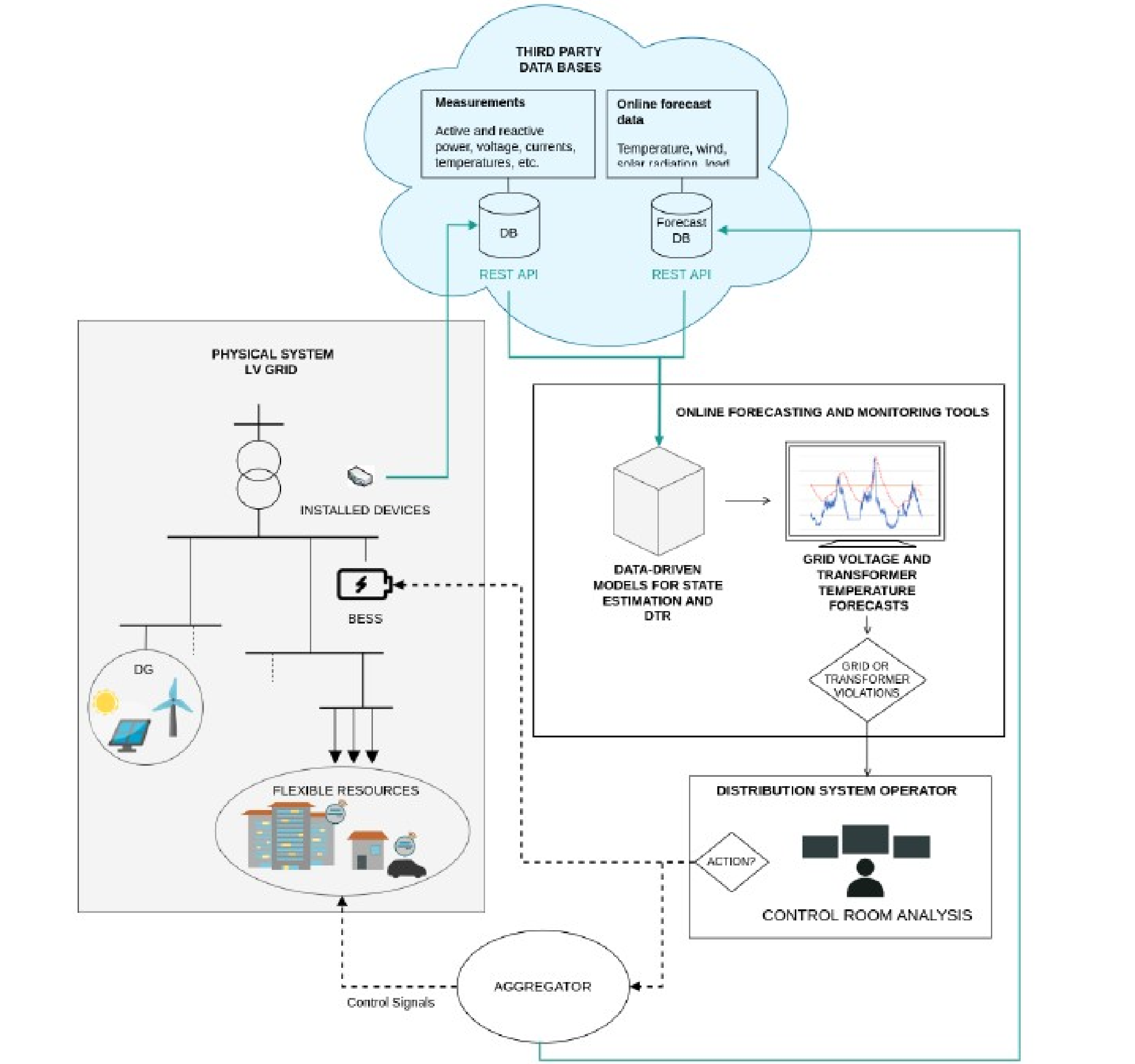


Figure 5.1: Operational framework for adaptive DSO smart grid operation. Turquoise lines indicate data flows and dotted lines indicate communication signals.

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Sensor setup for transformators

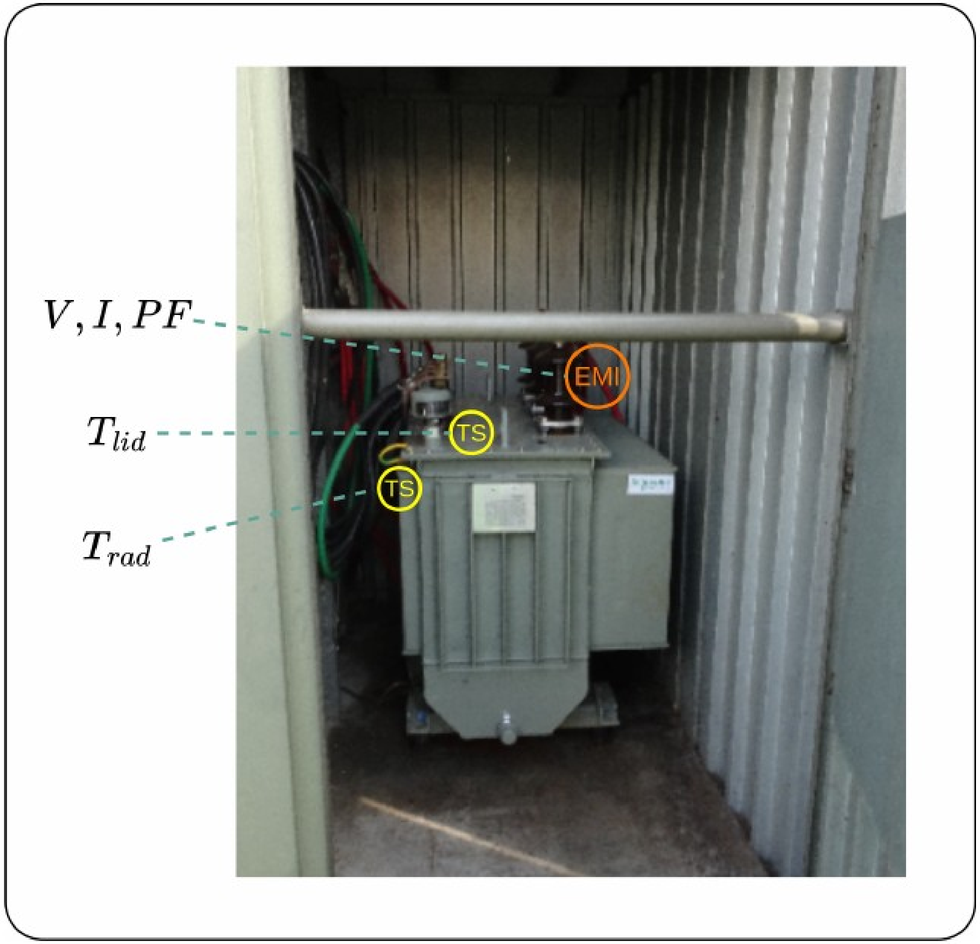


Figure 5.2: Suggested final setup for the transformers, with temperature sensor (TS) and electronic measurement instruments (EMI).

Grey-box model for transformator stations

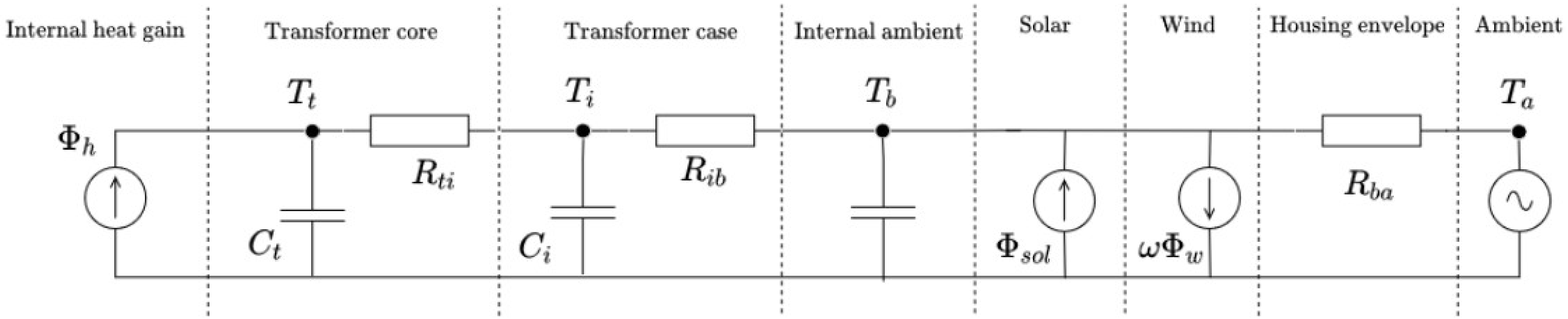


Figure 7: RC circuit of the three state model $TiTtTb$.

Model performance; 6-hour predictions

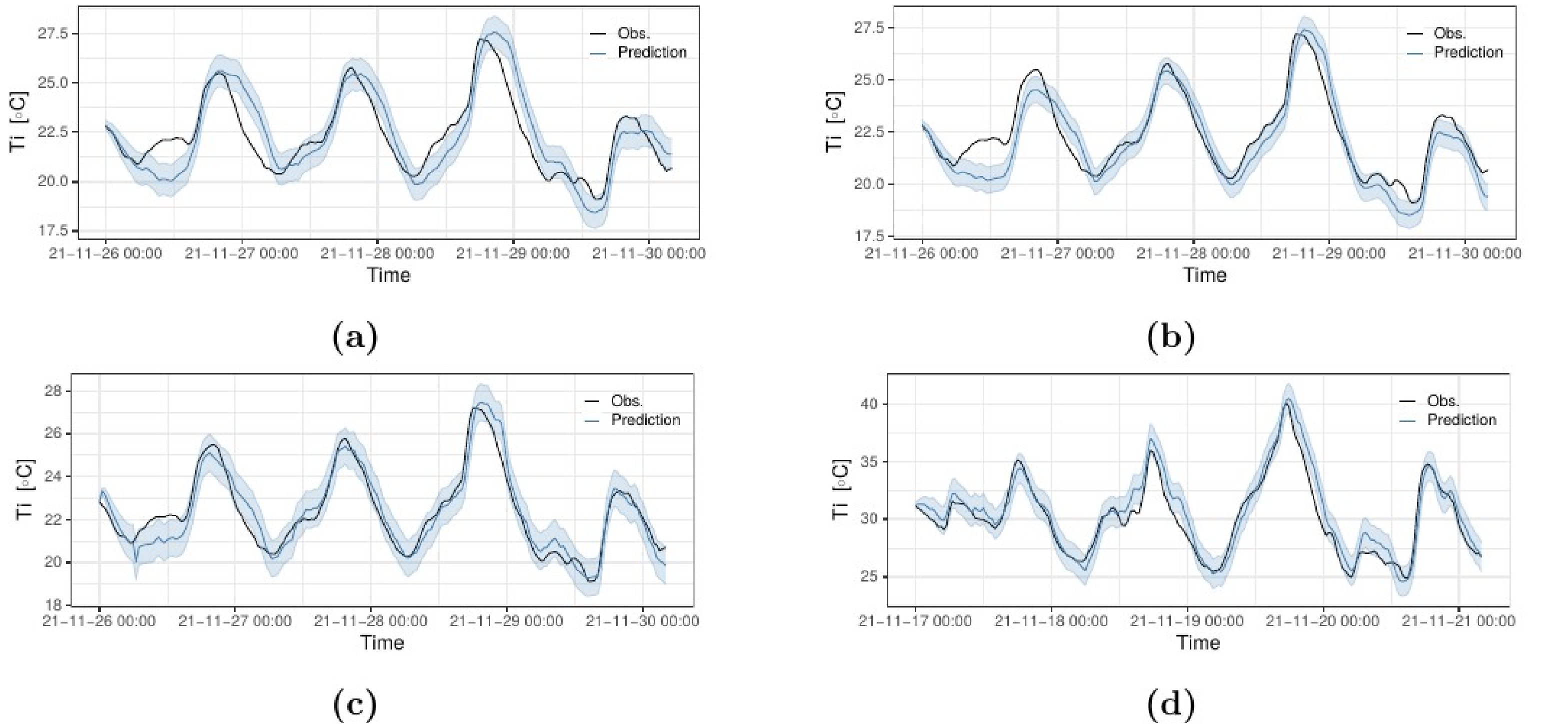
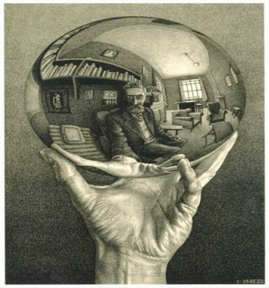


Figure 11: Prediction analysis for 12 step ahead (6 hours) predictions. Subfigures (a)-(c) show predictions for TRF 1 using the one state model (a), extended two state model (b) and the final three state model (c). Subfigure (d) shows predictions for TRF 2 using the final three state model. Black line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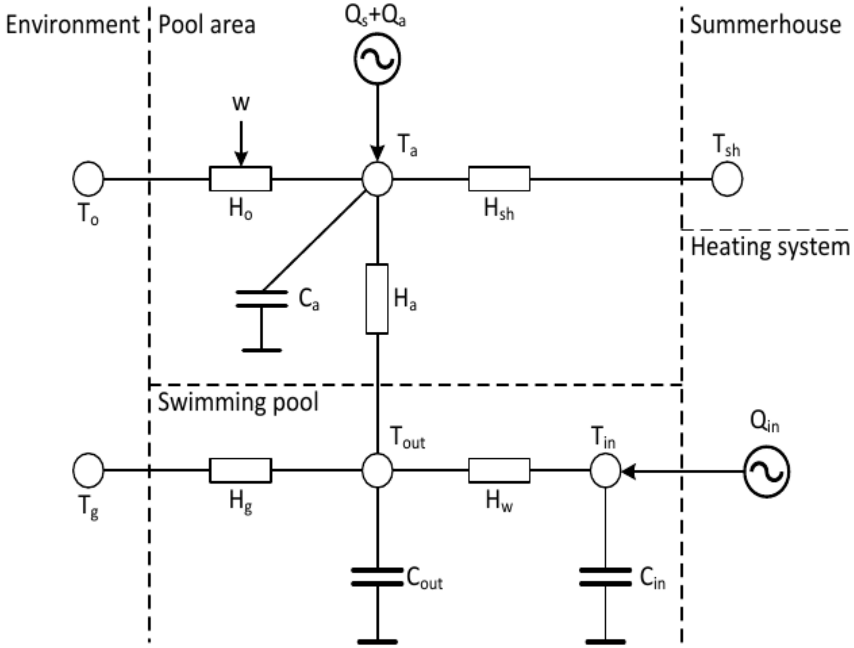
Case Study

Balance Responsible Parties: Summerhouses with a pool

Data-driven models for the buildings
(Using lumped parameter models)



- Based on equivalent thermal parameters model
- Dynamics:

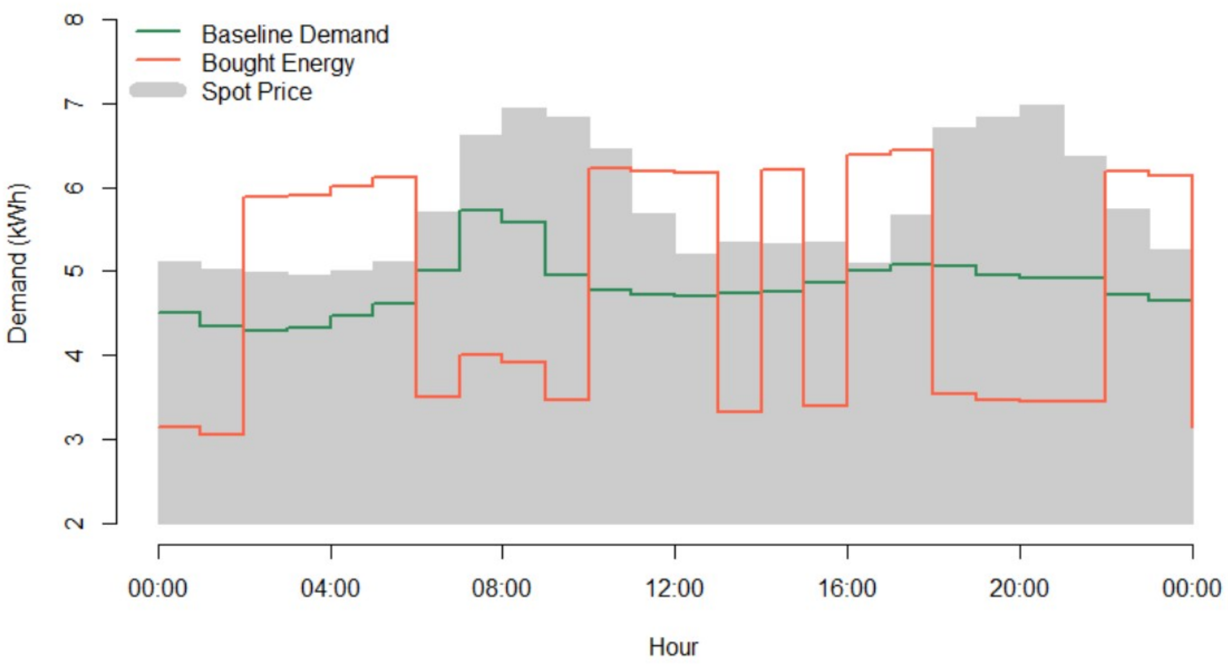
$$\frac{dT_{in}}{dt} = \frac{1}{C_{in}}[H_w(T_{out} - T_{in}) + Q_{in}]$$

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

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

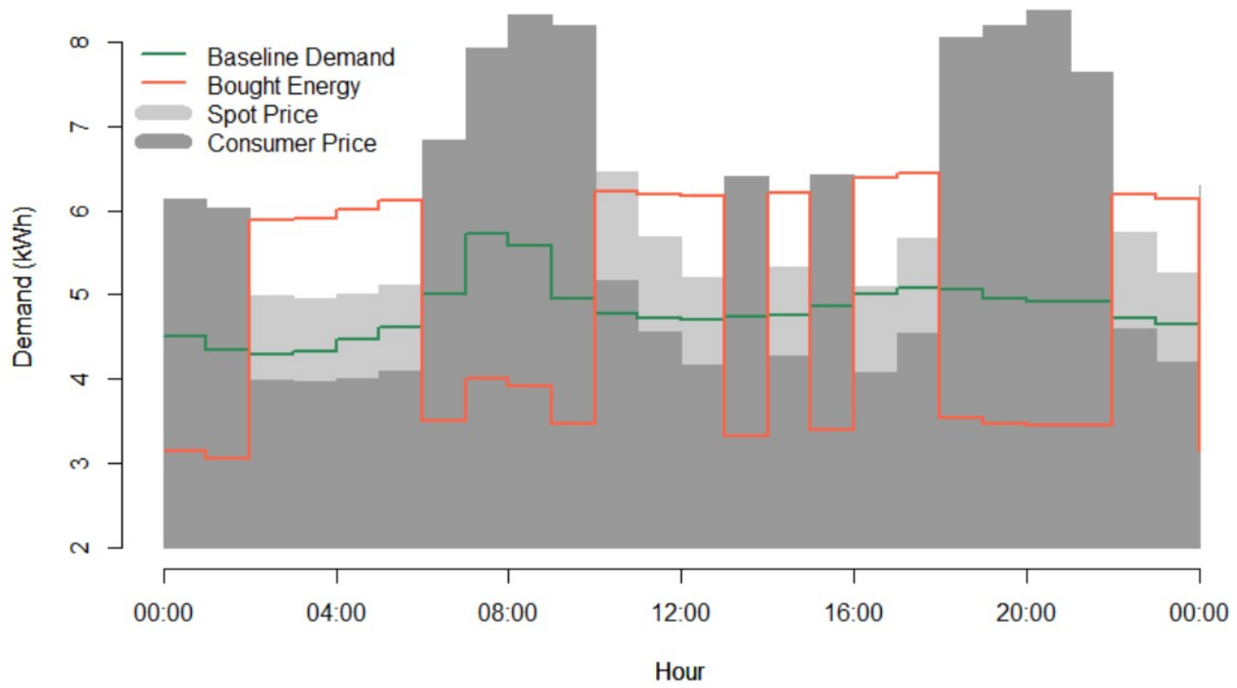
Bidding Flexibility into Markets

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



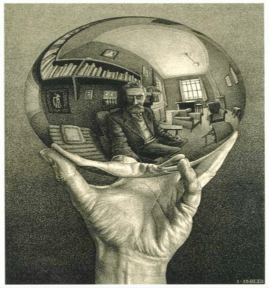
Bidding Flexibility into Markets

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



Example: CO_2-based control (savings 10-30 pct)

Wind Power Forecasting for DSOs and TSO using Spatial Hierarchies

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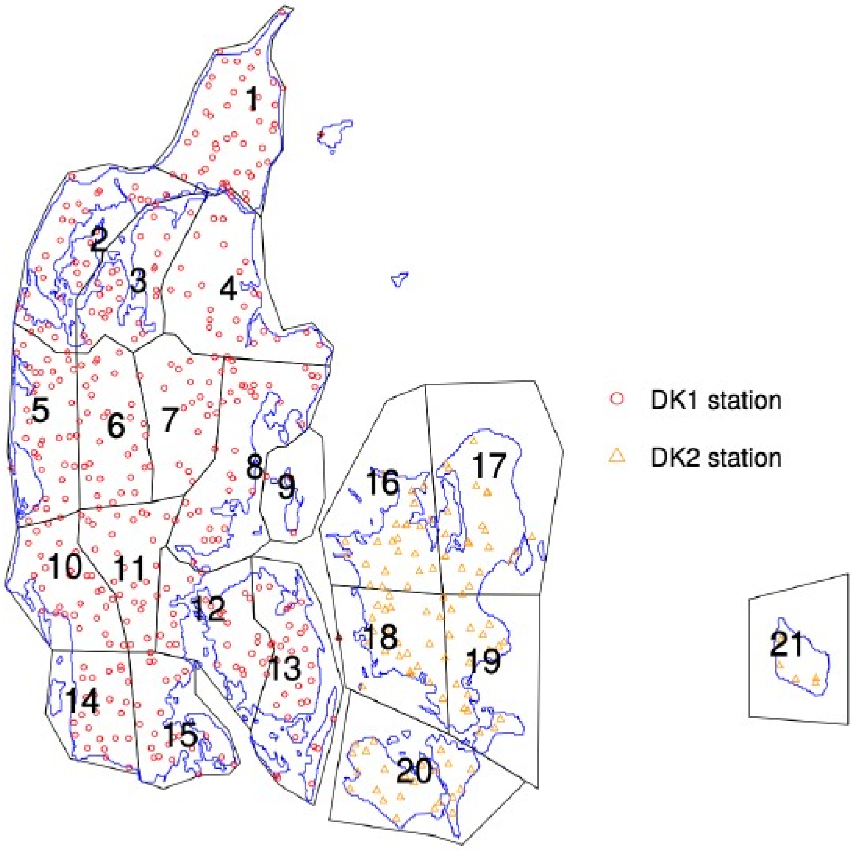
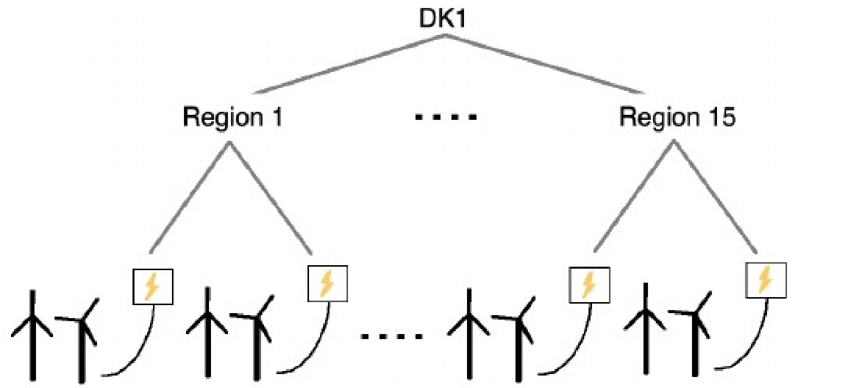
Digitalisation for Weather-Driven Energy Systems, February 2023

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.

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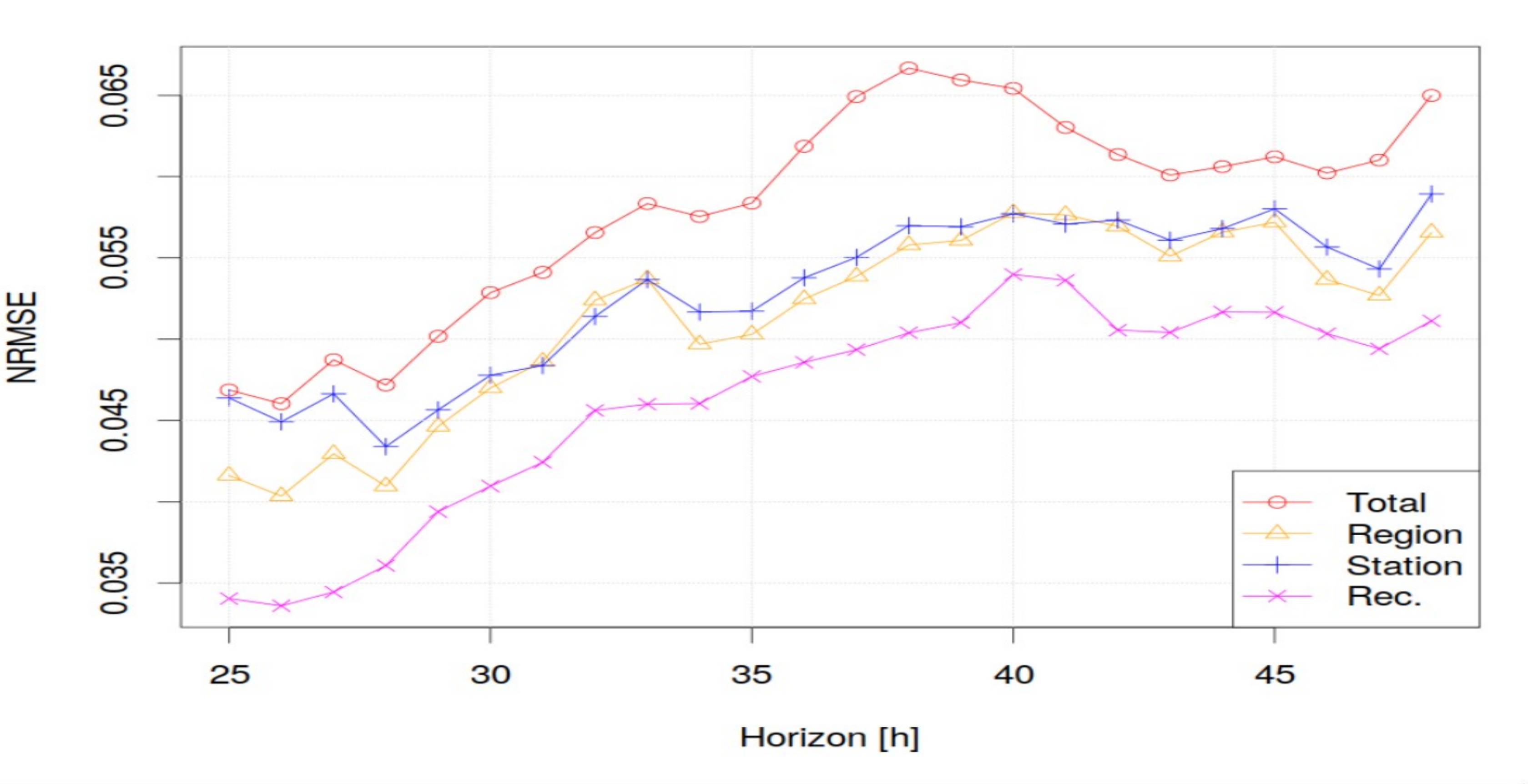
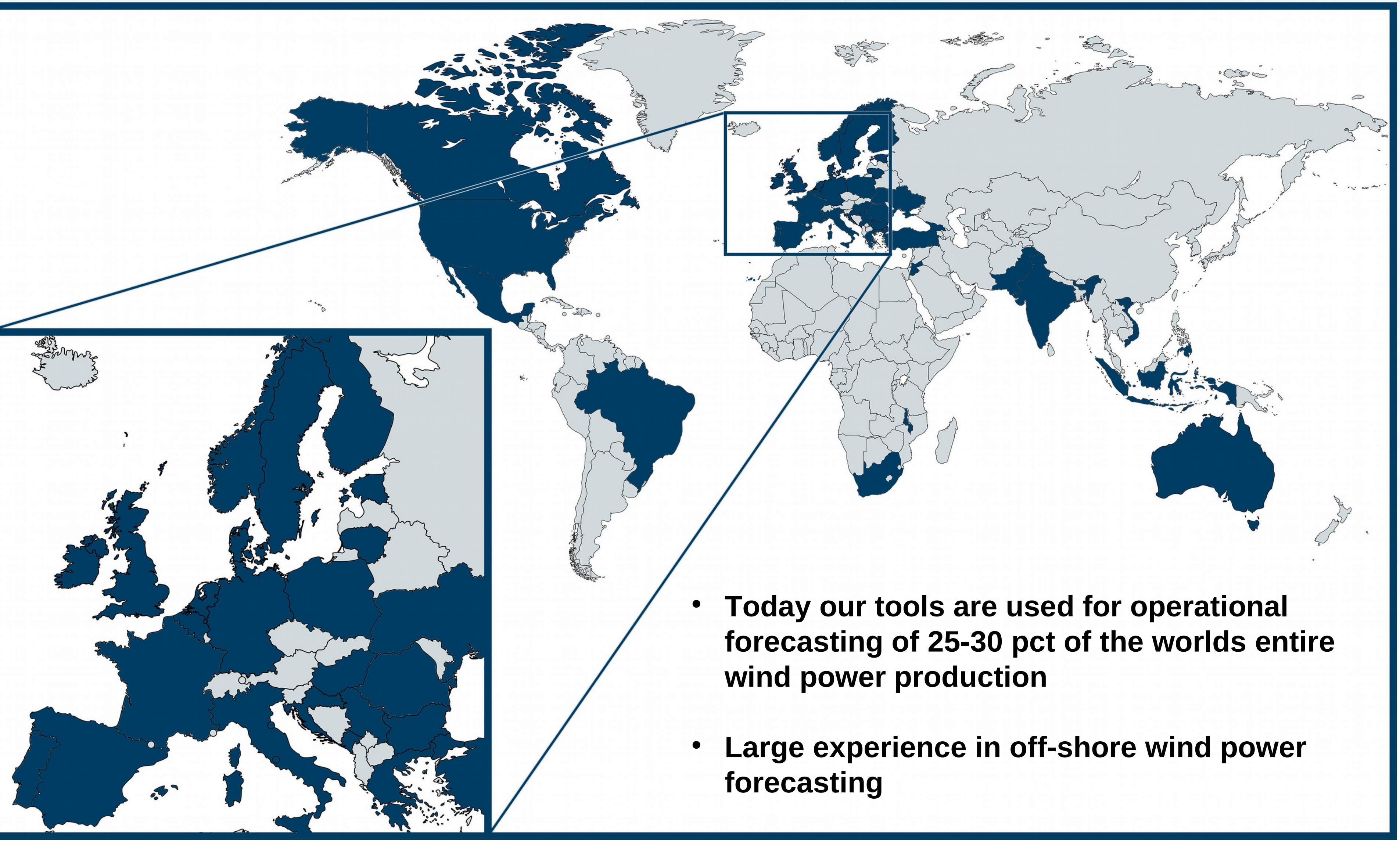
Wind Power Forecasting in DK1 (improvements 20 pct)



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**

Case study

Wastewater Treatment
(Joint work with Krüger/Veolia)

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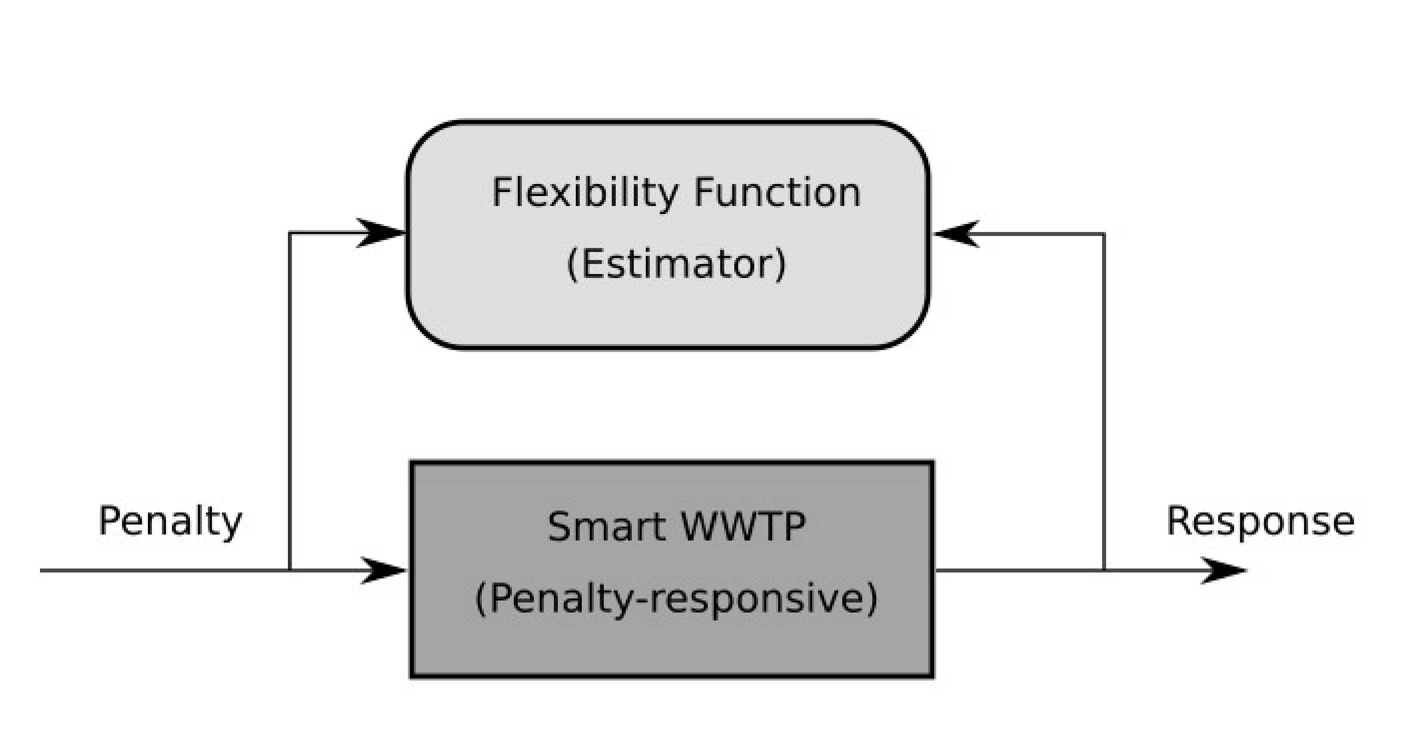
Flexibility Function



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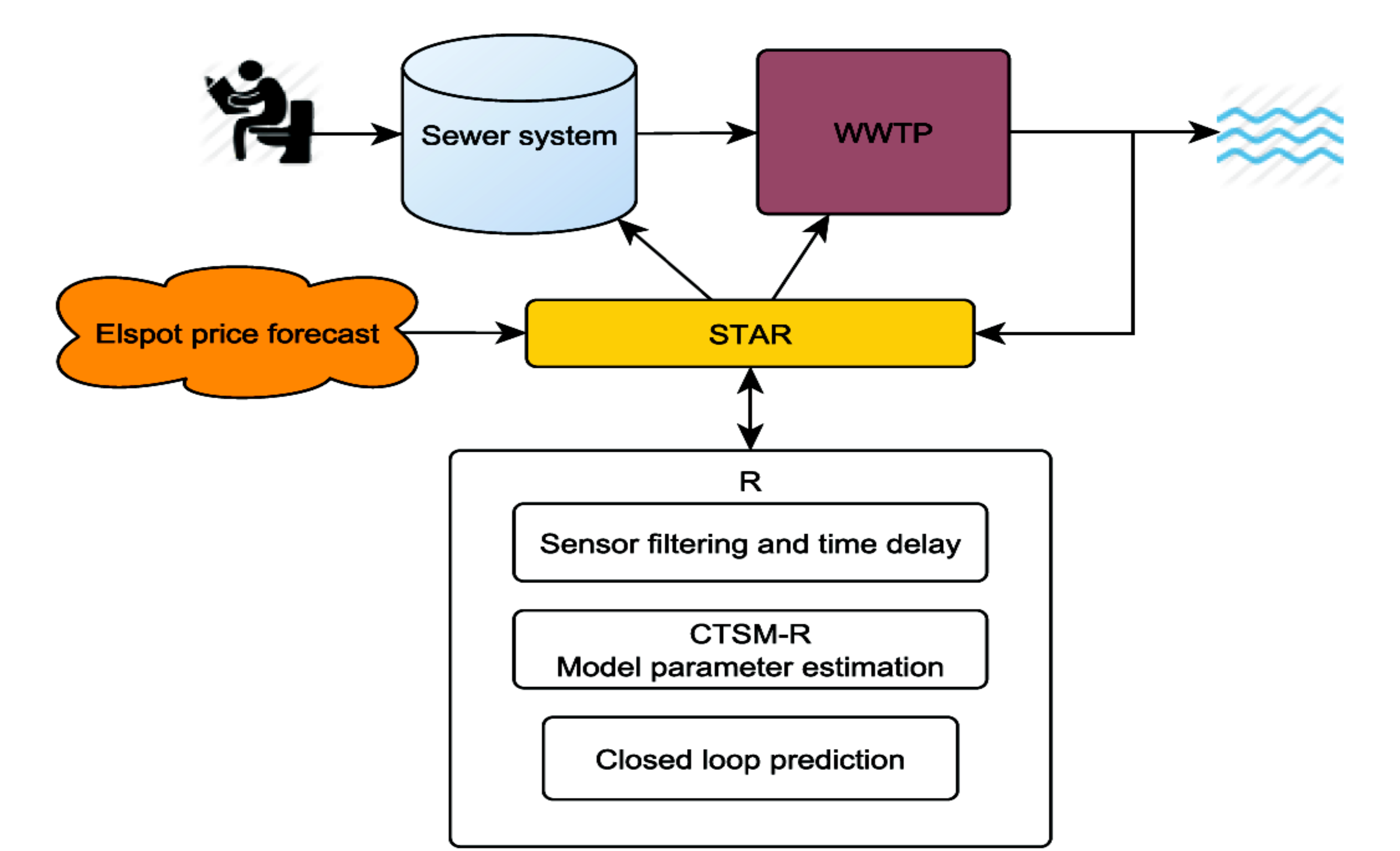
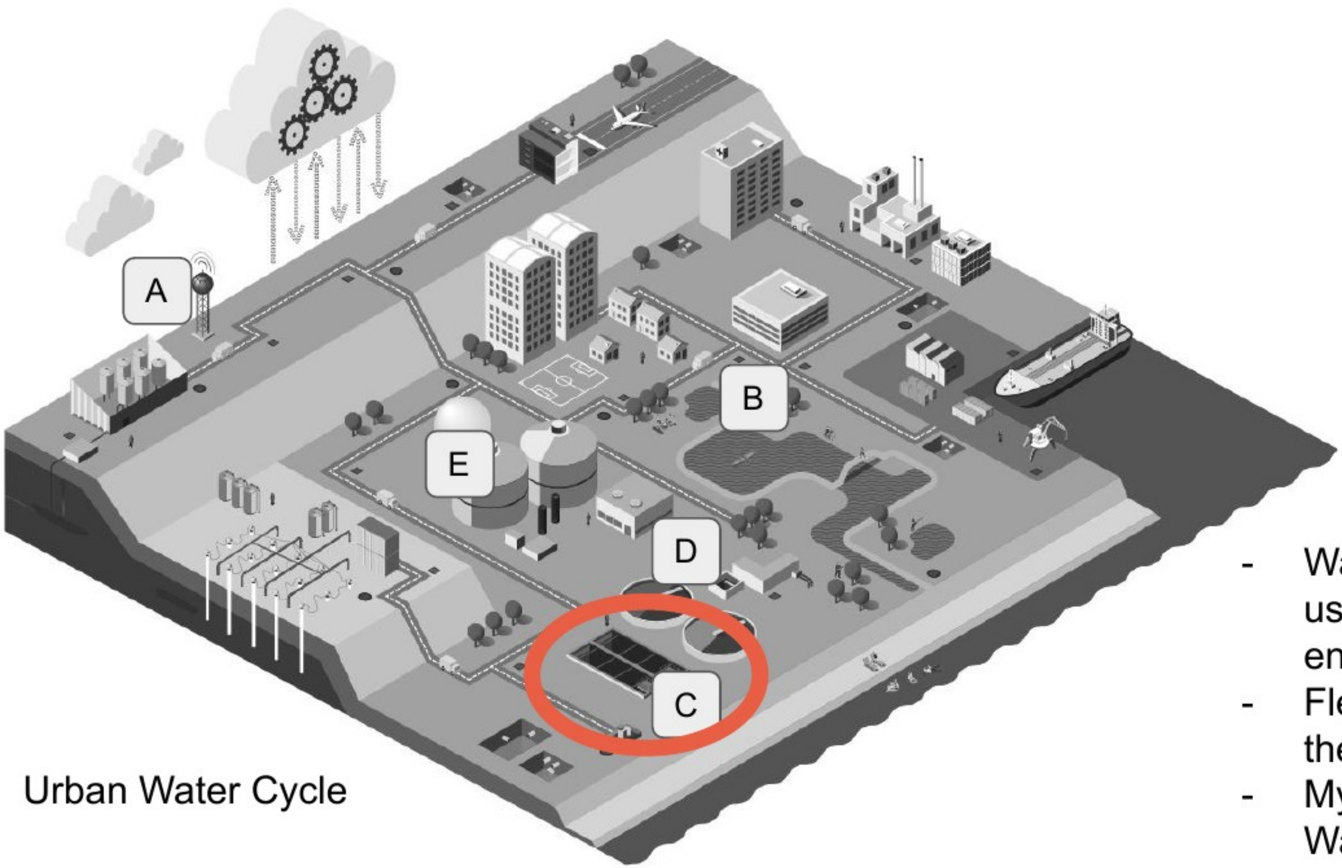
Energy Flexibility in Wastewater Treatment



Urban Water Cycle

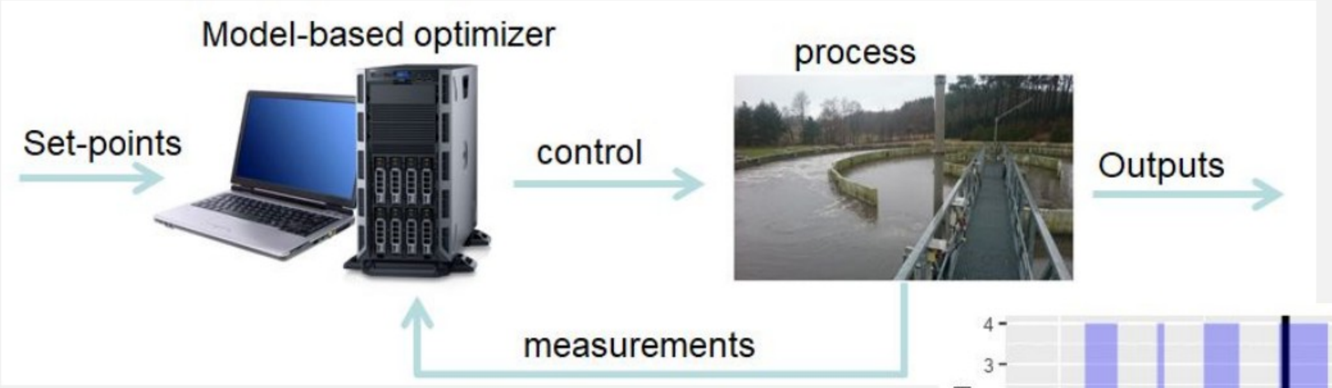


Urban Water Cycle

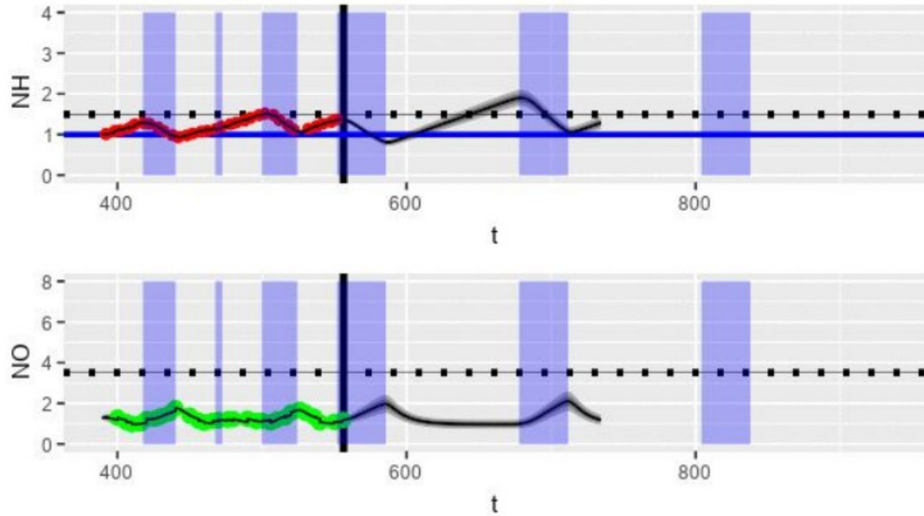
- Water & Wastewater sector uses 1-5% of total electrical energy of a country
- Flexibility is found in all parts of the urban water cycle
- My focus has been on Wastewater treatment aeration (C)

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

Implementation:
Data Space for
Spatial and Temporal Data

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

Center Denmark, some employees and board members

Center Denmark, Vision

centerdenmark
intelligent energy

Vision: Center Denmark will **accelerate the green transition towards 100 % renewable energy** in DK through **digitalization** and **sector coupling** and thereby unlocking flexibilities and utilize digital opportunities at all levels across energy systems

Mission

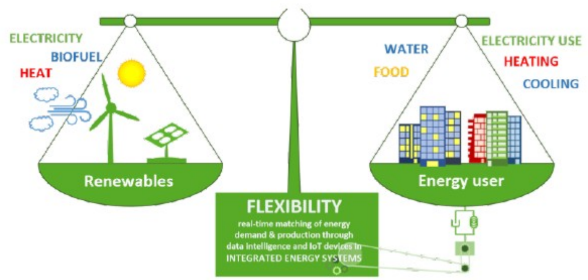
A. Utilize RE production capacity in full by demand response and avoid down-regulation of production

B. Save investments in infrastructure / avoid bottlenecks in the grids by peak shaving

C. Bring continuity into research and provide access for commercial use and market implementation

D. Strengthen digital competences within energy industry supporting new digital business models

Sector Coupling
+
Digitalization



Energy effectiveness vs. System efficiency

Services

1. Trusted Data Sharing platform with 24/7 access to energy related data and digital tools – Bi-directional.

2. Test and demonstration in representative and scalable settings

3. Digital Innovation Hub (DIH) for knowledge transfer services *(Access point for commercial services)*

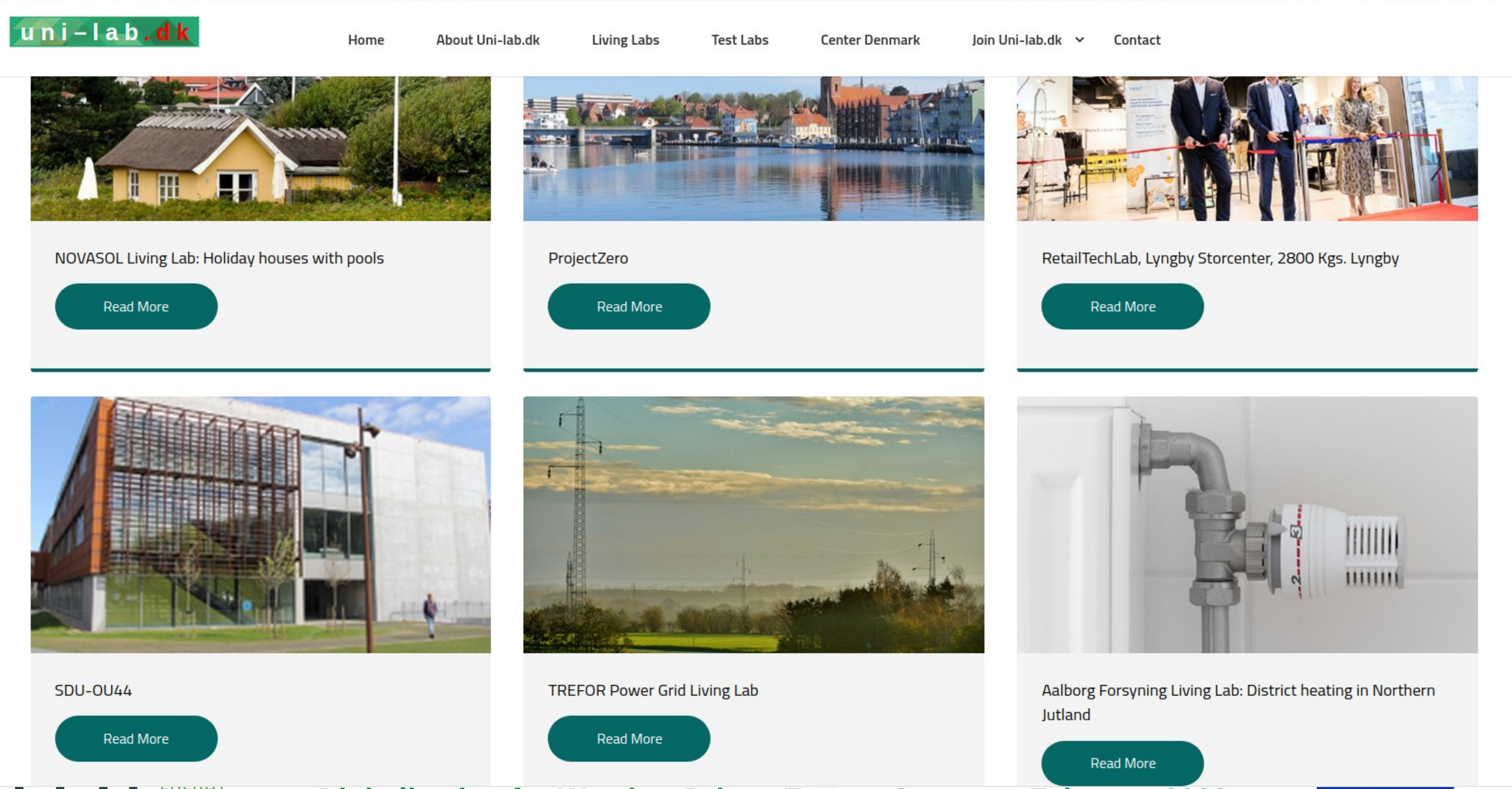
4. Inkubator for digital business models aimed at new data driven services for the energy sector

Center Denmark
Integrated Energy Systems
Control Room and Data Space

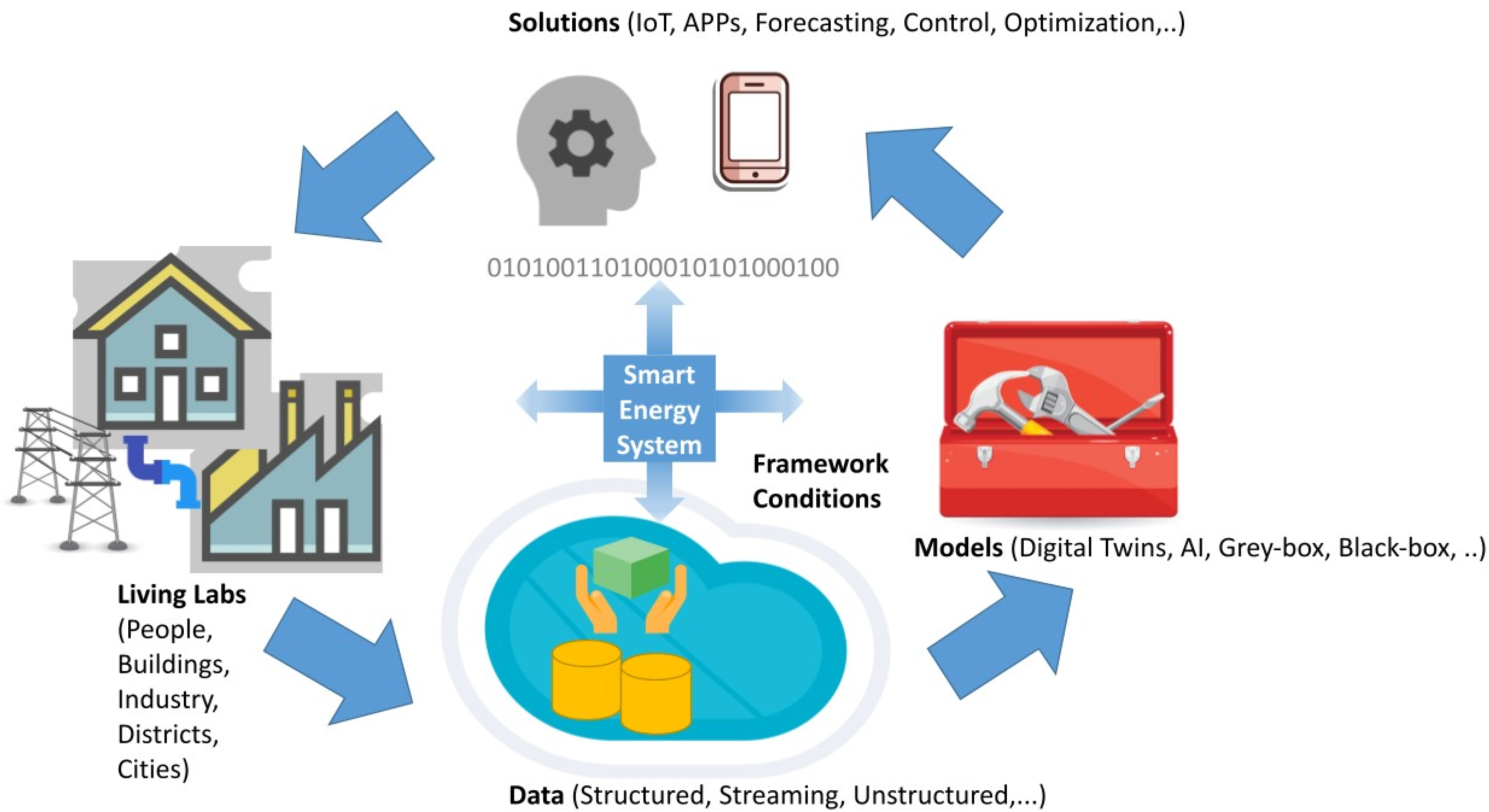
Center Denmark aims at facilitating a trusted data space which put priorities in cyber security and in empowering the partners such that they are able to provide Digitalized and Efficient Solutions for People and Industry without being subject to disproportionate technical requirements, administrative requirements, procedures and charges

Uni-Lab.dk

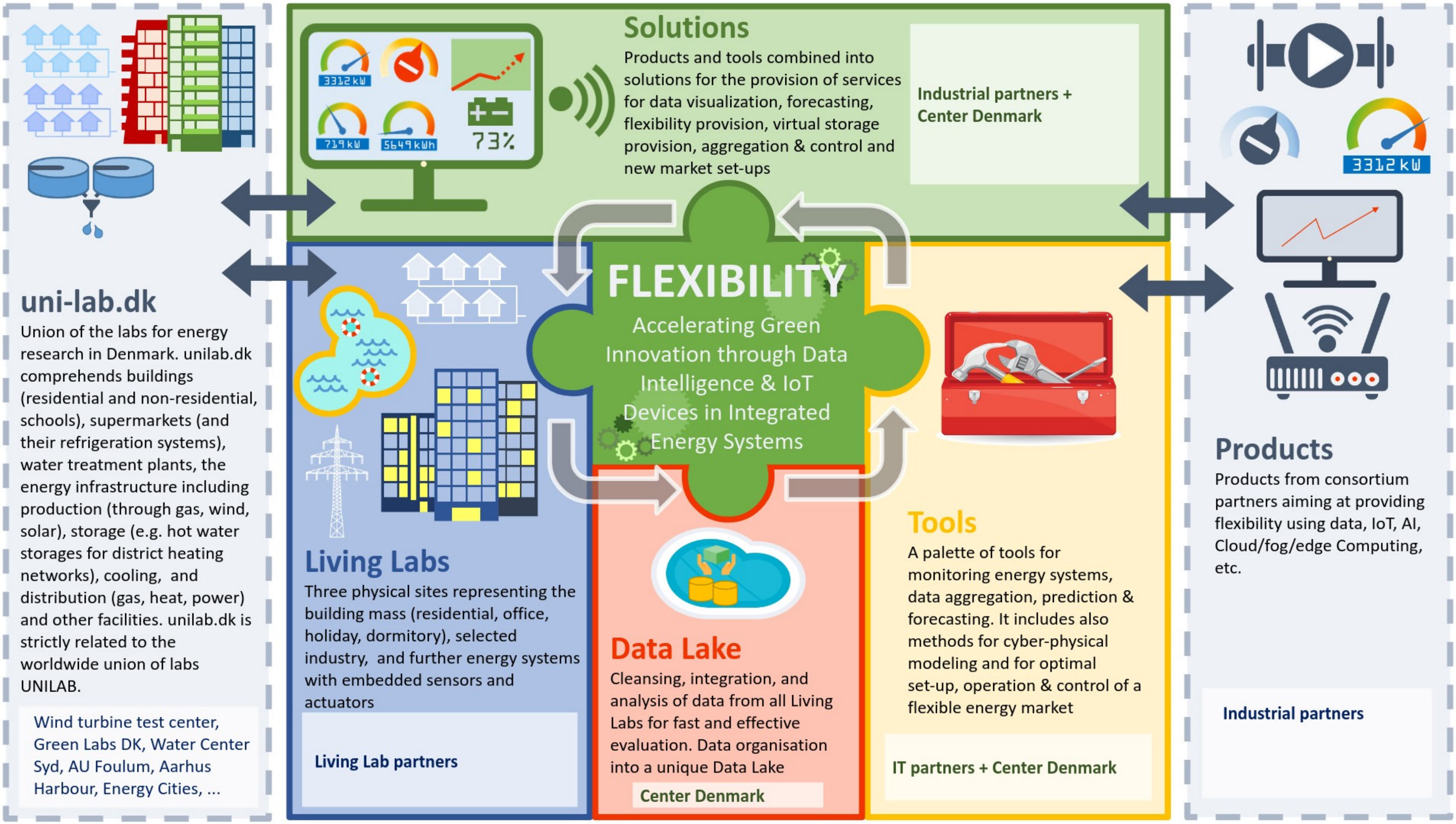
Living Labs, Test Labs, ESI Pilots



Innovation Cycle
Living Labs, Data, Models, Solutions

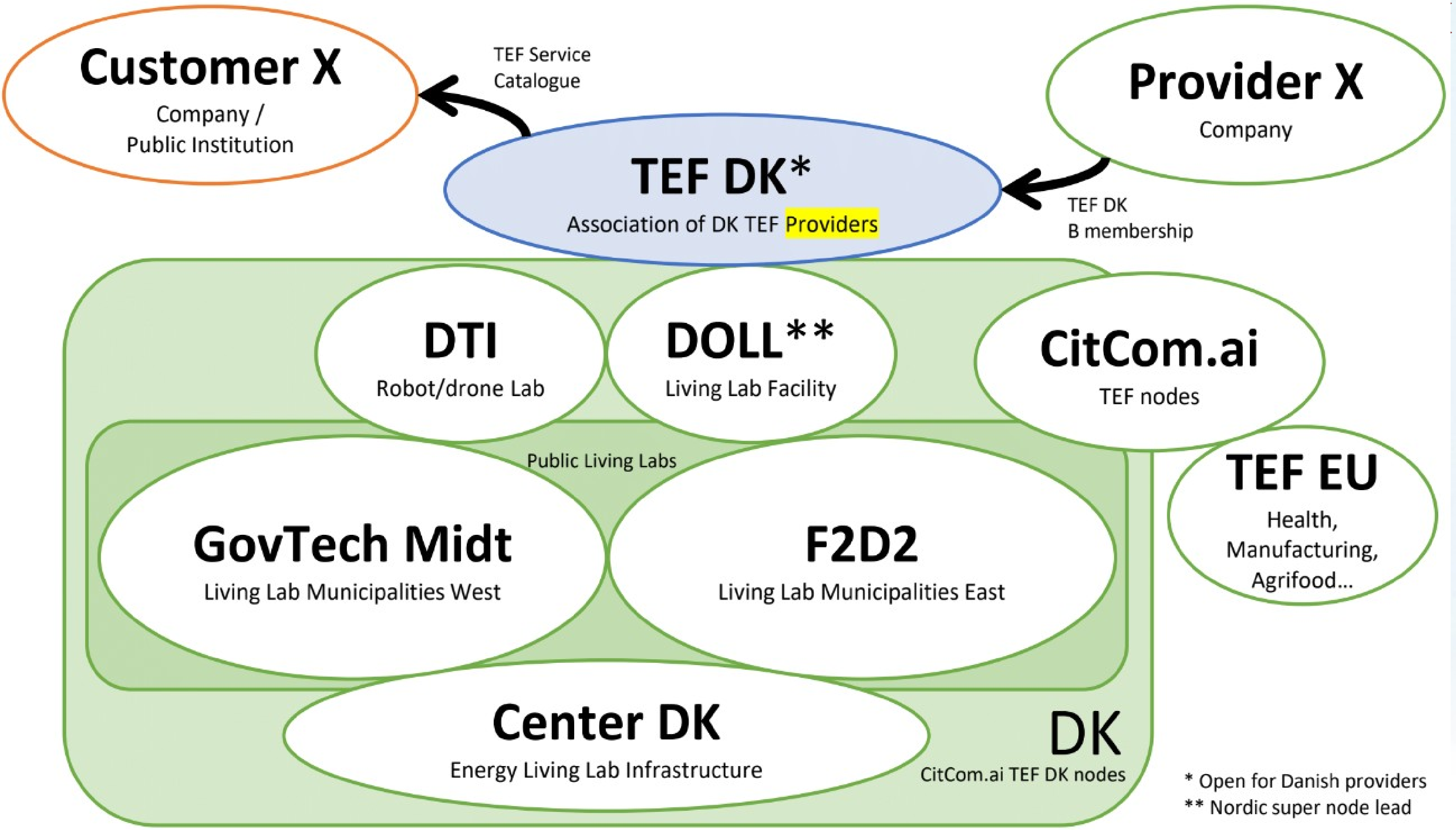


Business Ecosystem



Digital Energy Hub, Center Denmark

EU-TEF Power, Mobility and Communication



Energy Taxes for the Future

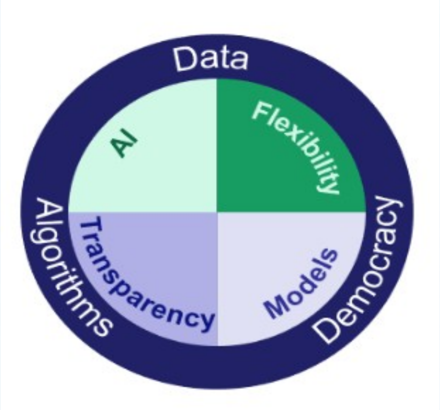
- Taxes should be linked to physics
- Taxes should be linked to the actual CO_2 emission (locally – temporal and spatial)
- Taxes should be the same for all energy sources
- Taxes should be the same for all types of consumption
- Taxes should hinder carbon leakage
- Taxes most contain a fixed part (energy efficiency) and a part proportional with the CO_2 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

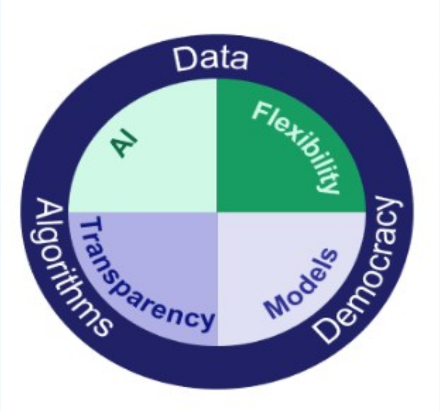
Summary

- 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 – 30 pct



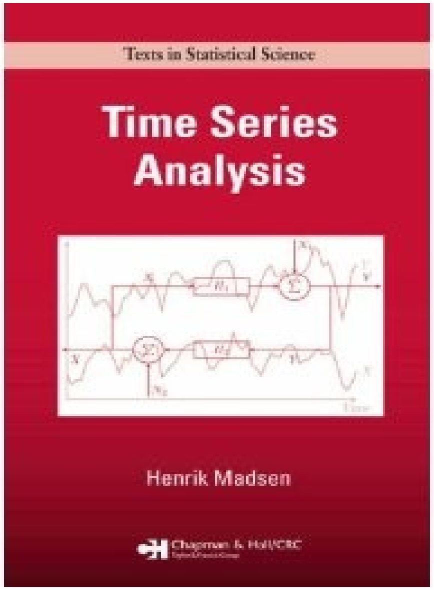
Summary

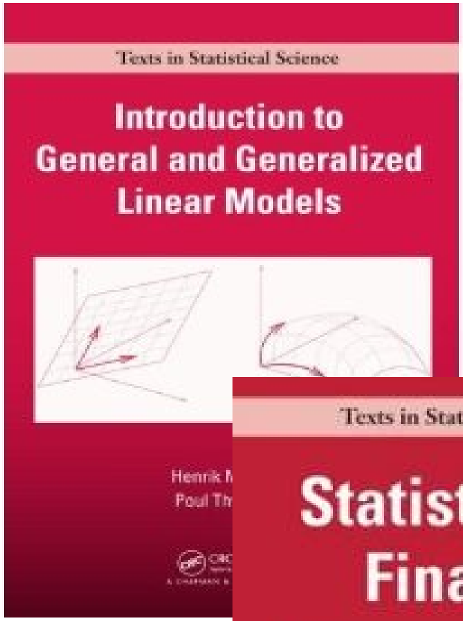
- We have described digitalisation for **unlocking flexibility everywhere**
- We need **dynamic (temporal and spatial) tariffs** (and **taxes**)
- We need **data hubs** for energy related **streaming data** (like Center Denmark)
- We need a Business Ecosystem with **Trusted Data Sharing** in a ecosystem with ESI Pilots 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 Digitalisation Hub, Center Denmark**

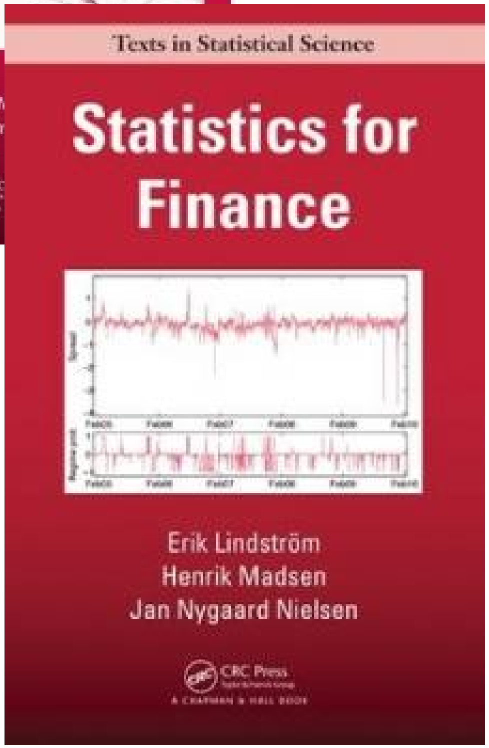


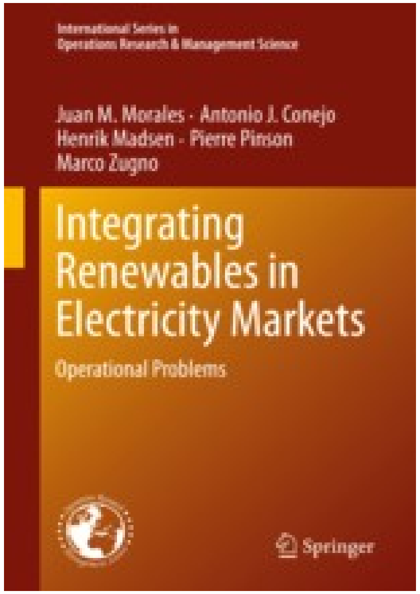
Thanks for your attention!

Some 'randomly picked' books on modeling, finance, markets and renewable integration ....









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