Methods and Models for Efficient Large-scale Wind and Solar Integration

US-DK Seminar Oct. 2022

Henrik Madsen
DTU Compute

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

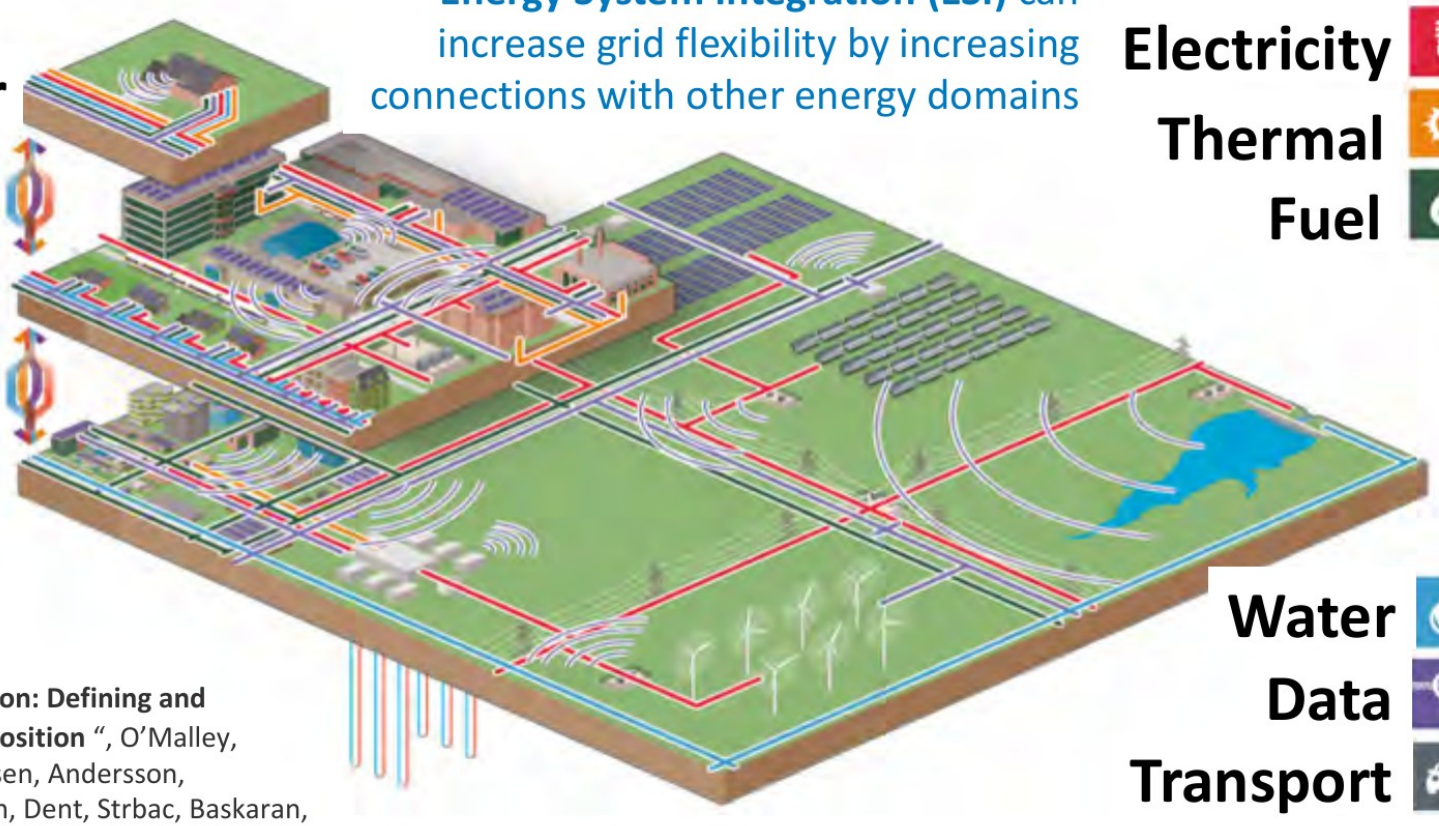
FED FLEXIBLE ENERGY DENMARK

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



"**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

FED FLEXIBLE ENERGY DENMARK

US-DK Seminar, Oct. 2022

EU Report on Data Spaces

OPENDEI

ENERGY DOMAIN

DATA SPACES FOR ENERGY, HOME AND MOBILITY

FEU FLEXIBLE ENERGY DENMARK

US-DK Seminar, Oct. 2022

Space of Solutions

Flexibility

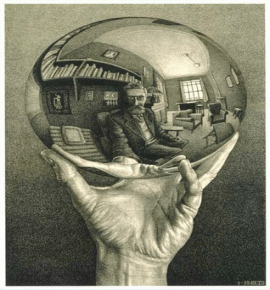
(enabled by **AI, Digital Twins, Communication and IoT**)

Grids **Batteries**

FED FLEXIBLE ENERGY DENMARK

ebalanceplus

European and International Initiatives on Smart Energy Systems



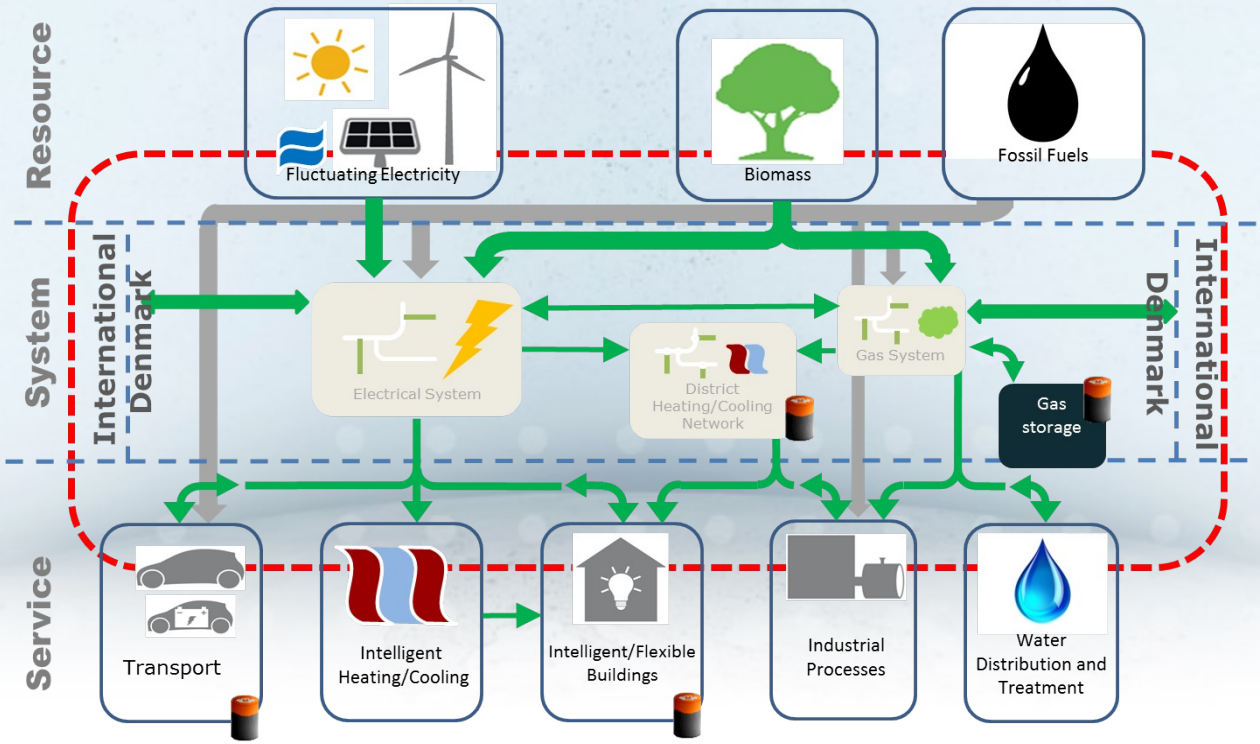
- Data Spaces for Energy Systems
- Digitalization of Energy Systems
- Key elements mentioned in EU and UN reports:
  - Minimum Interoperability Mechanicsms (MIMs)
  - MIMs for energy systems include:

    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

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

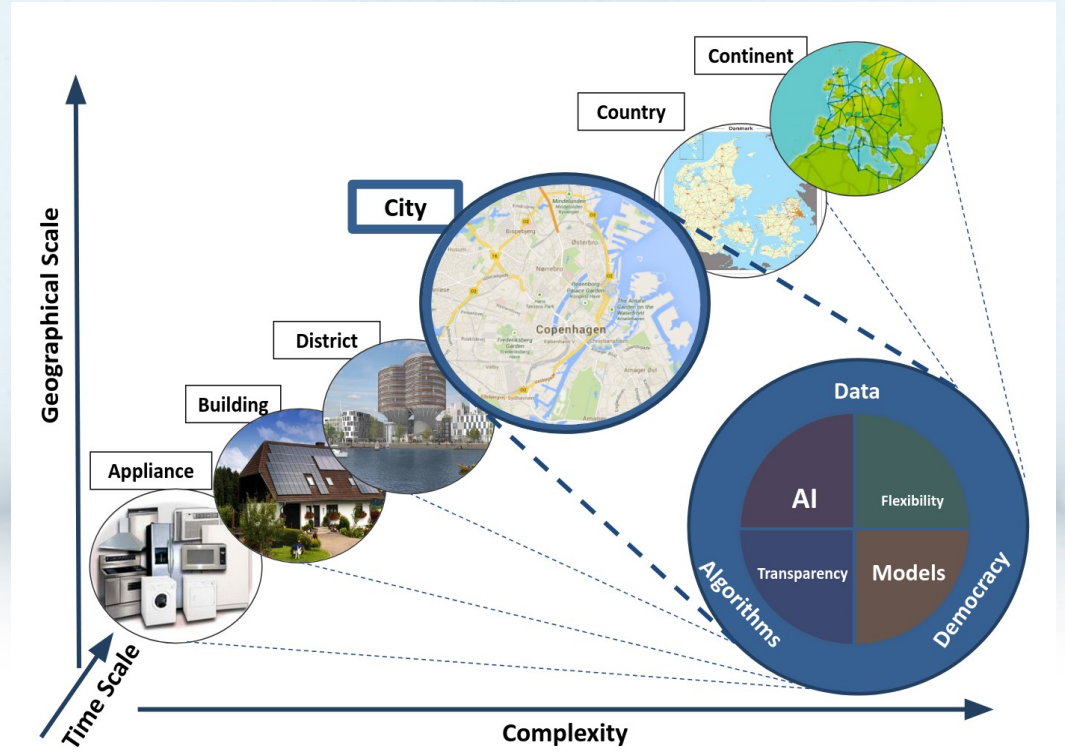


FED FLEXIBLE ENERGY DENMARK

US-DK Seminar, Oct. 2022

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** for large scale wind integration

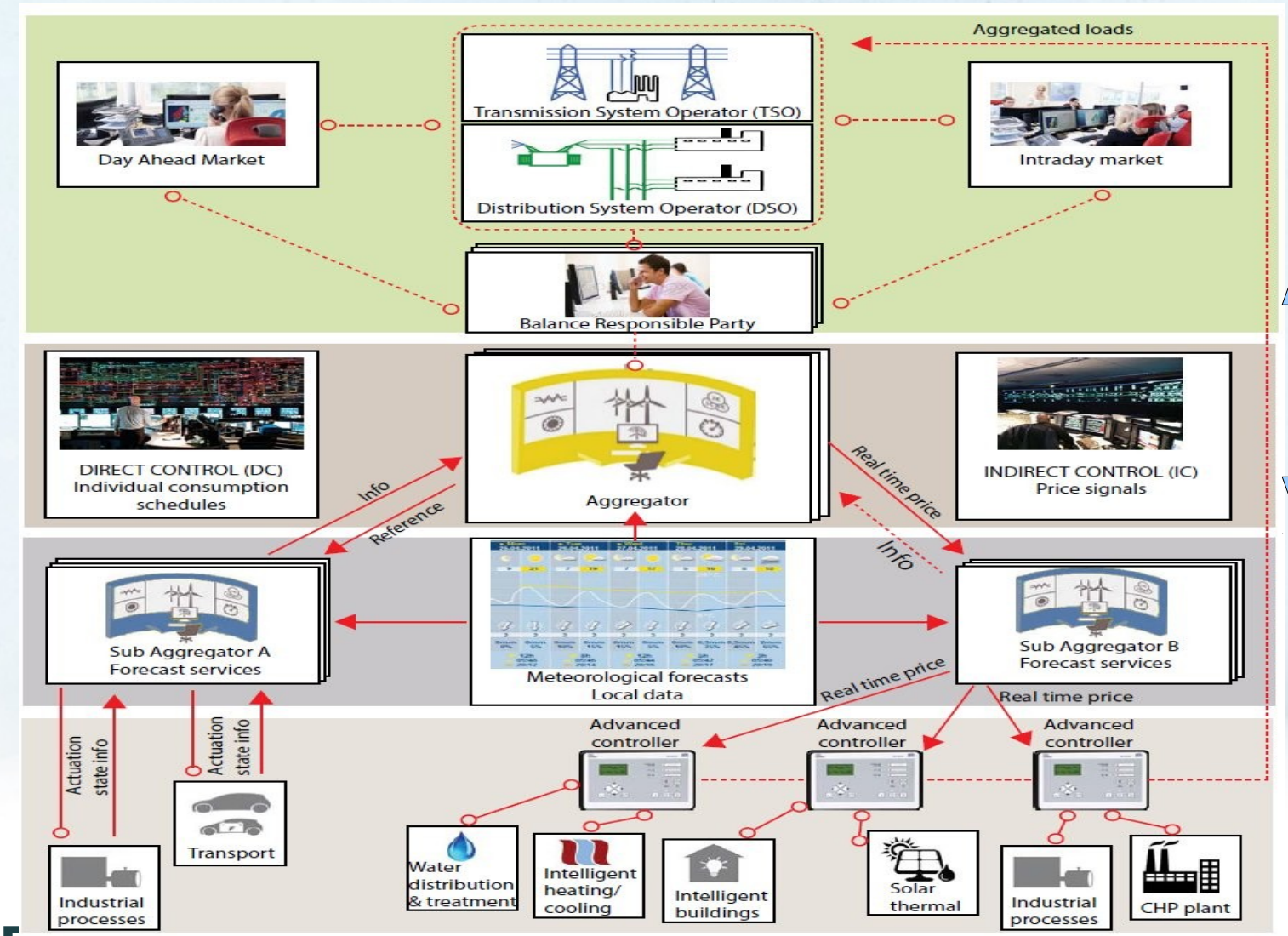


FED FLEXIBLE ENERGY DENMARK

ebalanceplus

EU Report: Smart-Energy OS

The Transformative Power of Digitalization



(**Static**)

Conventional Markets

Linking Markets to Physics using MIMs

(Flexibility Functions)

(**Dynamic**)

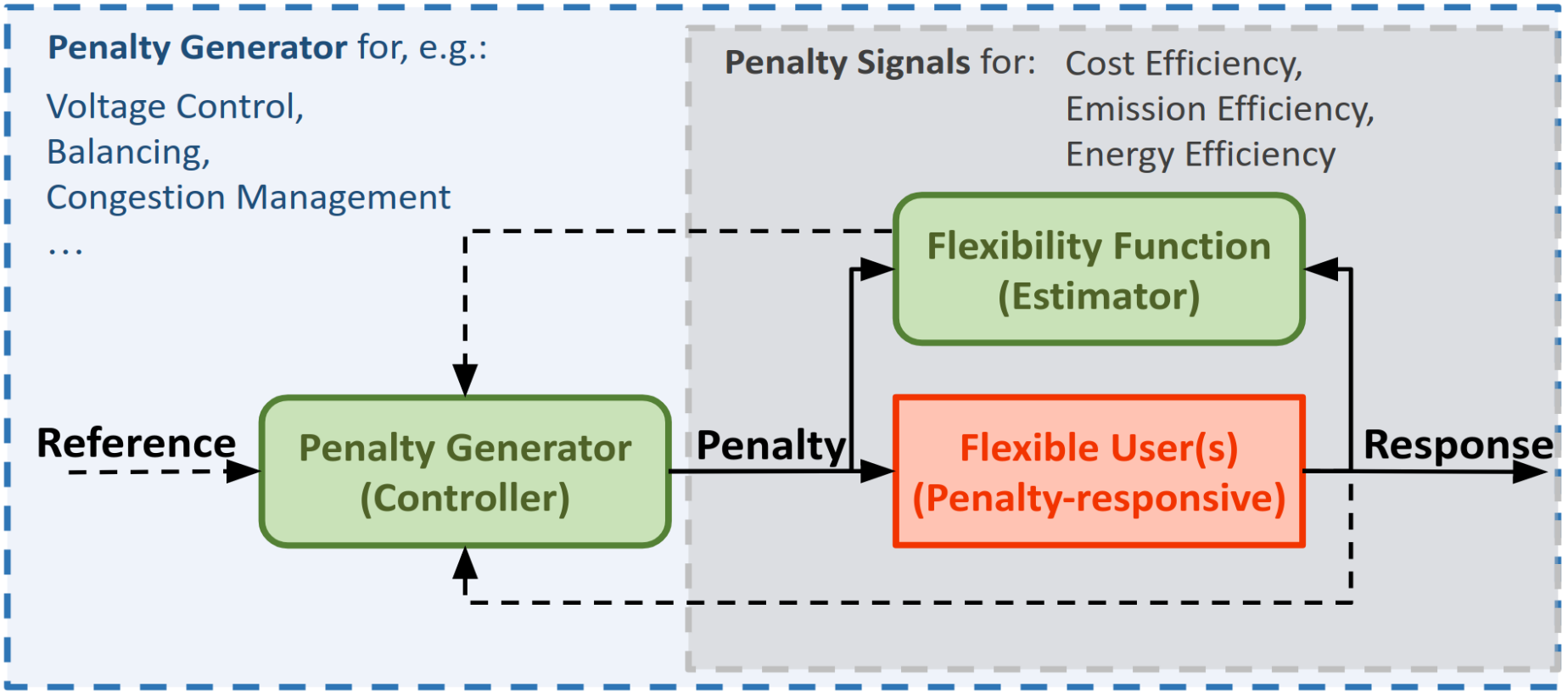
Local Flexibility Markets

(Hierarchy of controllers)

FLEXIBLE ENERGY DENMARK

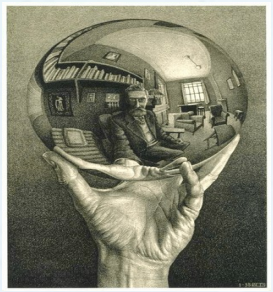
US-DK Seminar, Oct. 2022

Flexible Users and Penalty Signals



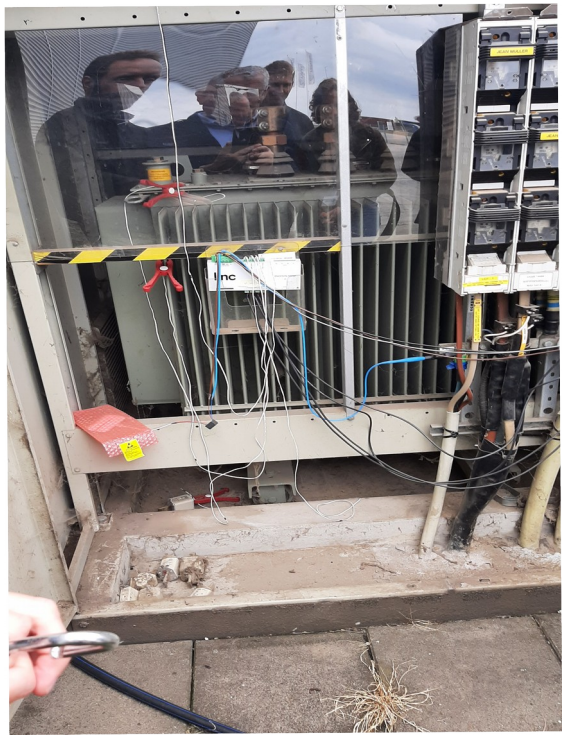
SE-OS Characteristics

- 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
- Creates a 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 Operations:
Models for Dynamic Transformer Rating



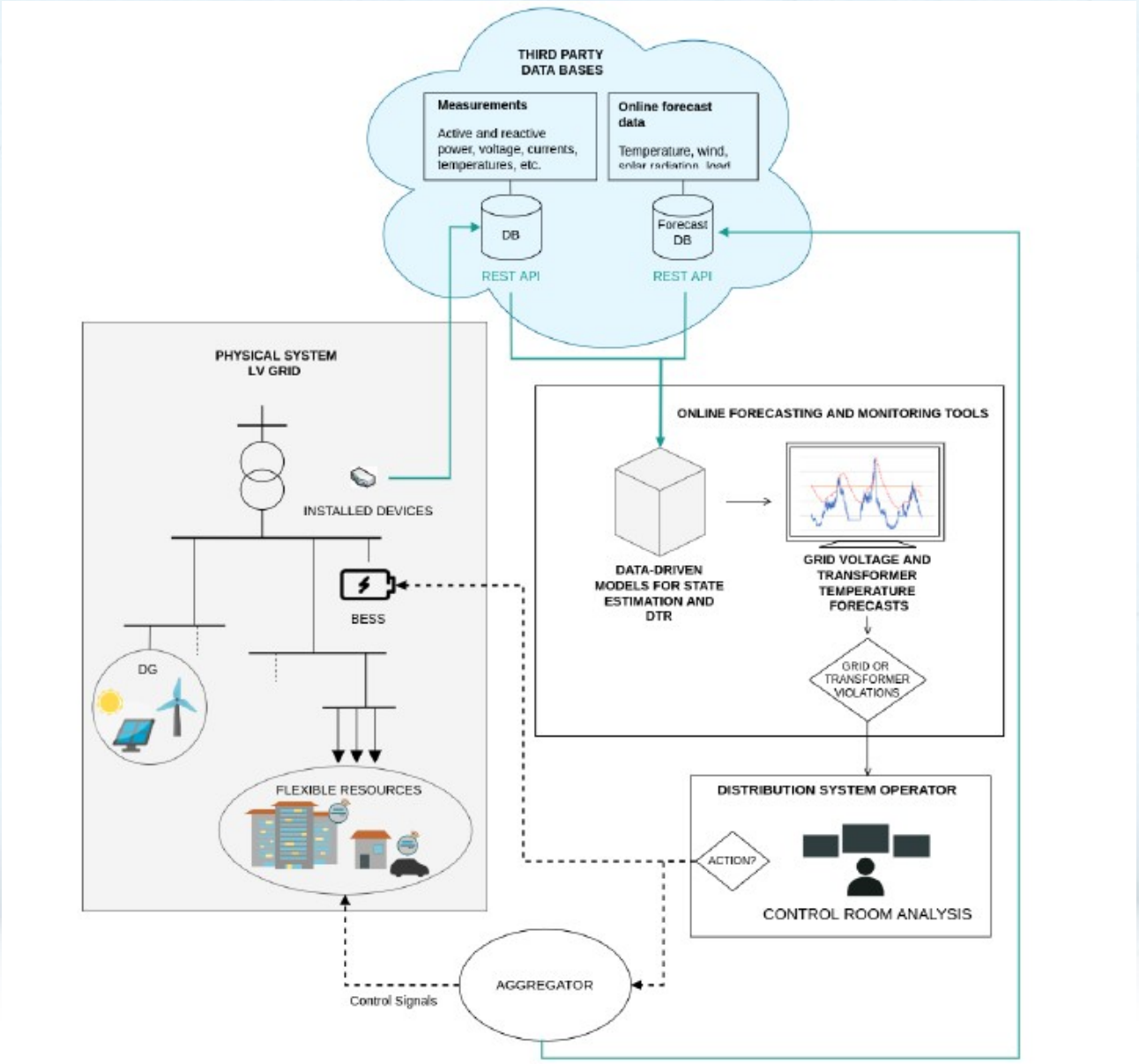


Figure 5.1: Operational framework for adaptive DSO smart grid operation. Turquoise lines indicate data flows and dotted lines indicate communication signals.

Sensor setup for transformators

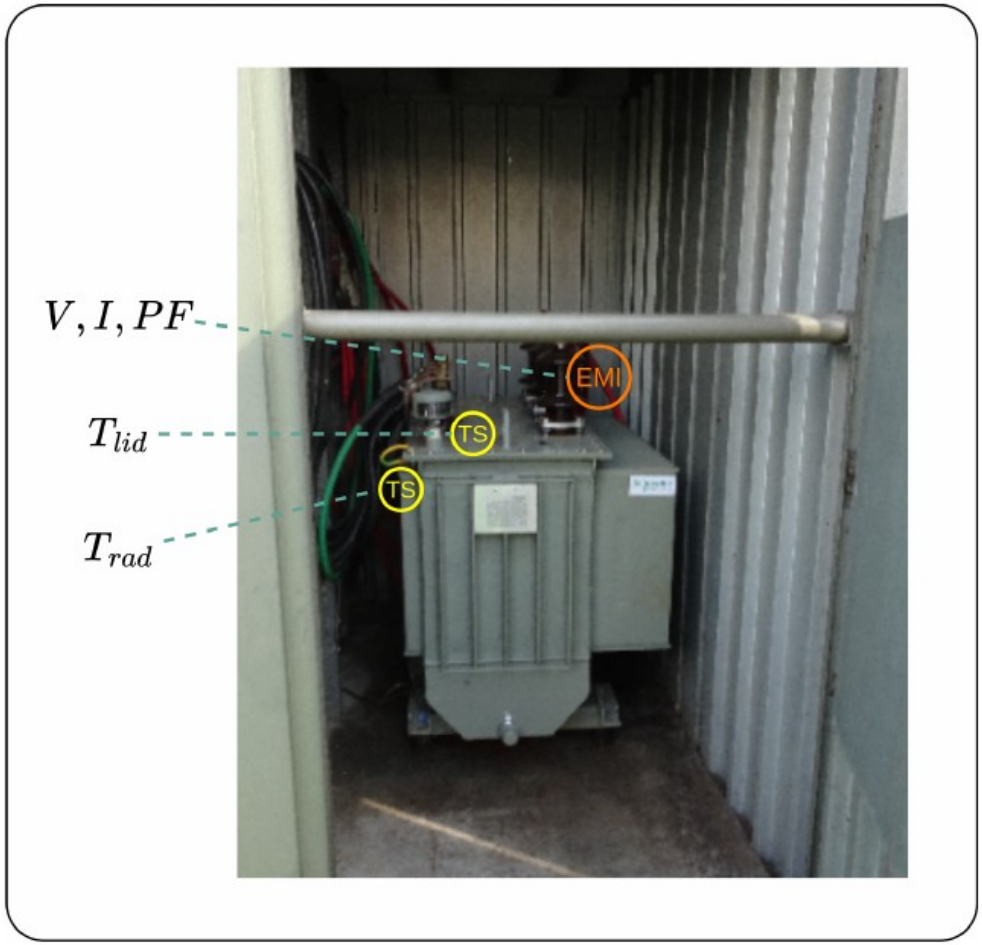


Figure 5.2: Suggested final setup for the transformers, with temperature sensor (TS) and electronic measurement instruments (EMI).

Grey-box model for transformator stations

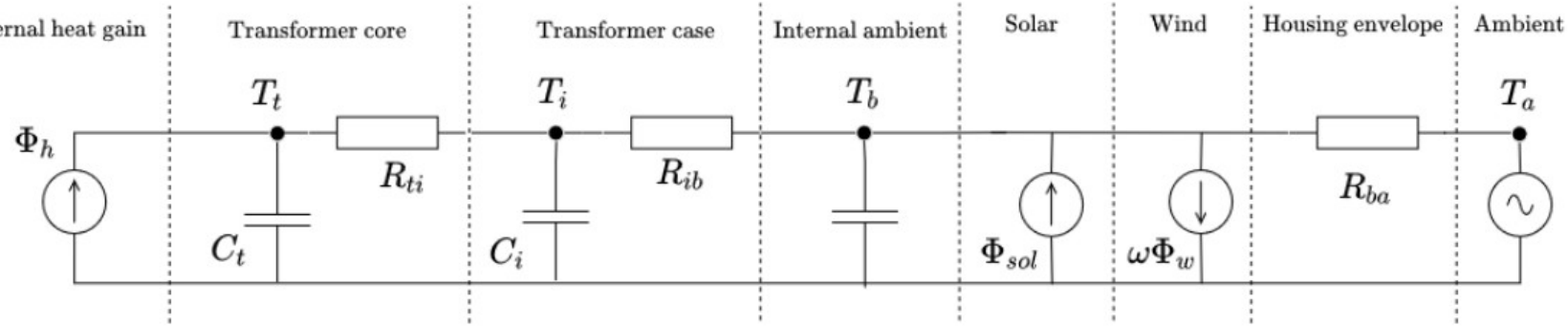


Figure 7: RC circuit of the three state model $TiTtTb$.

Model performance; 6-hour predictions

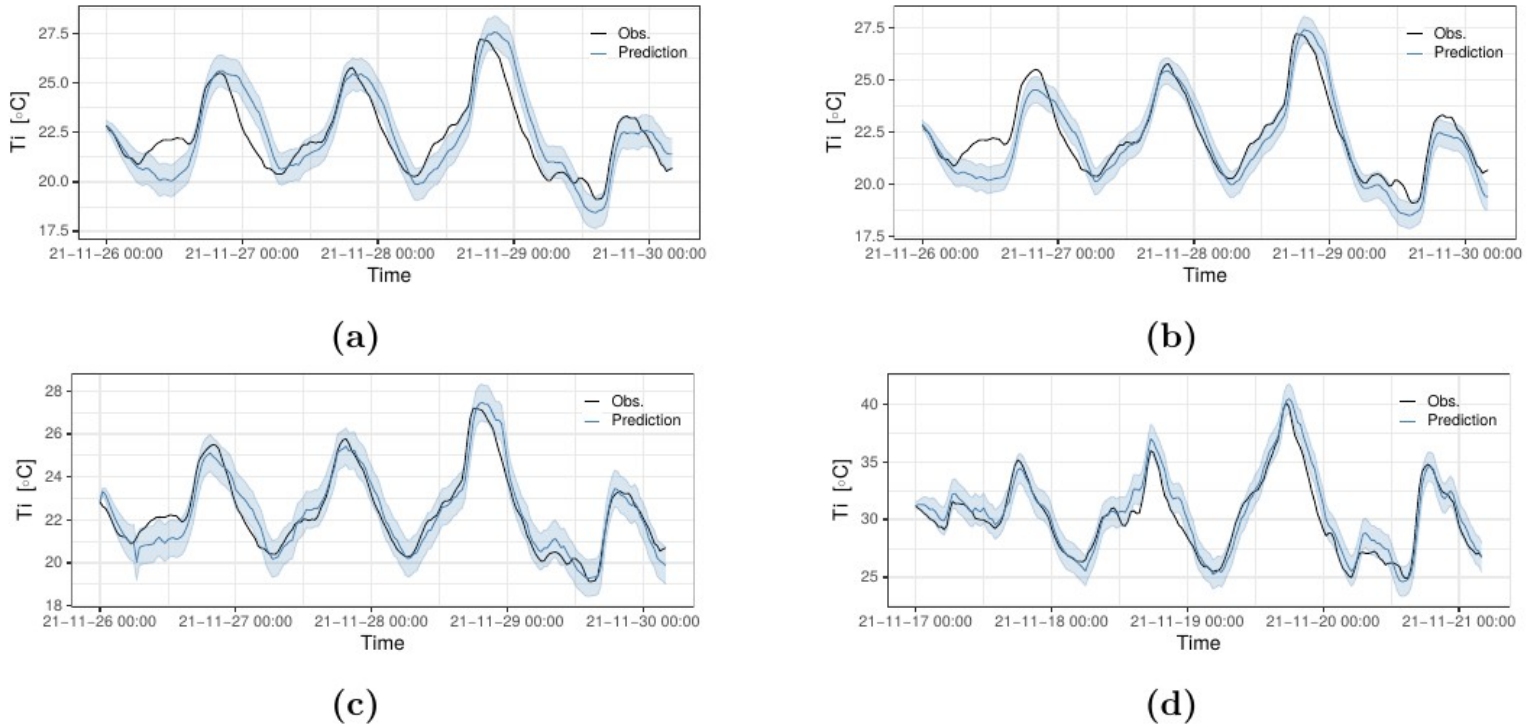
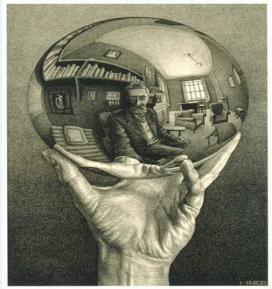


Figure 11: Prediction analysis for 12 step ahead (6 hours) predictions. Subfigures (a)-(c) show predictions for TRF 1 using the one state model (a), extended two state model (b) and the final three state model (c). Subfigure (d) shows predictions for TRF 2 using the final three state model. Black line – 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
- With DTR we can reduce the risk of overloading
- The models can be used to predict some failures of transformators
- Experiences show that transformers 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)

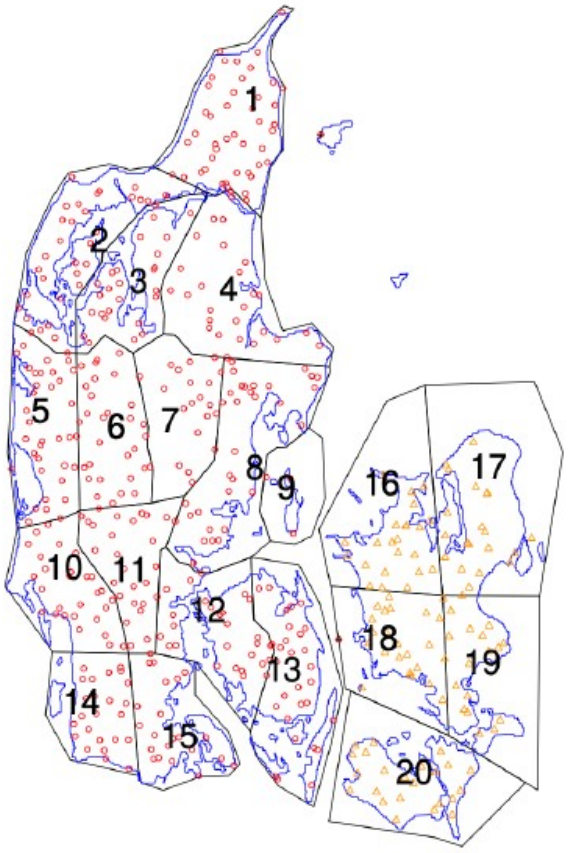


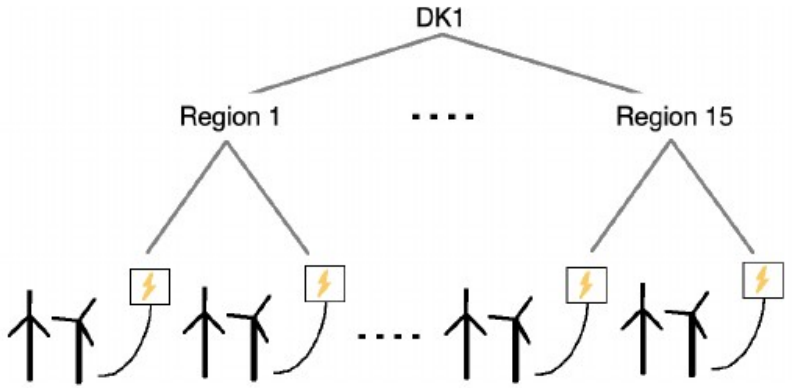
Wind Power Forecasting using Spatial Hierarchies

FED FLEXIBLE ENERGY DENMARK

US-DK Seminar, Oct. 2022

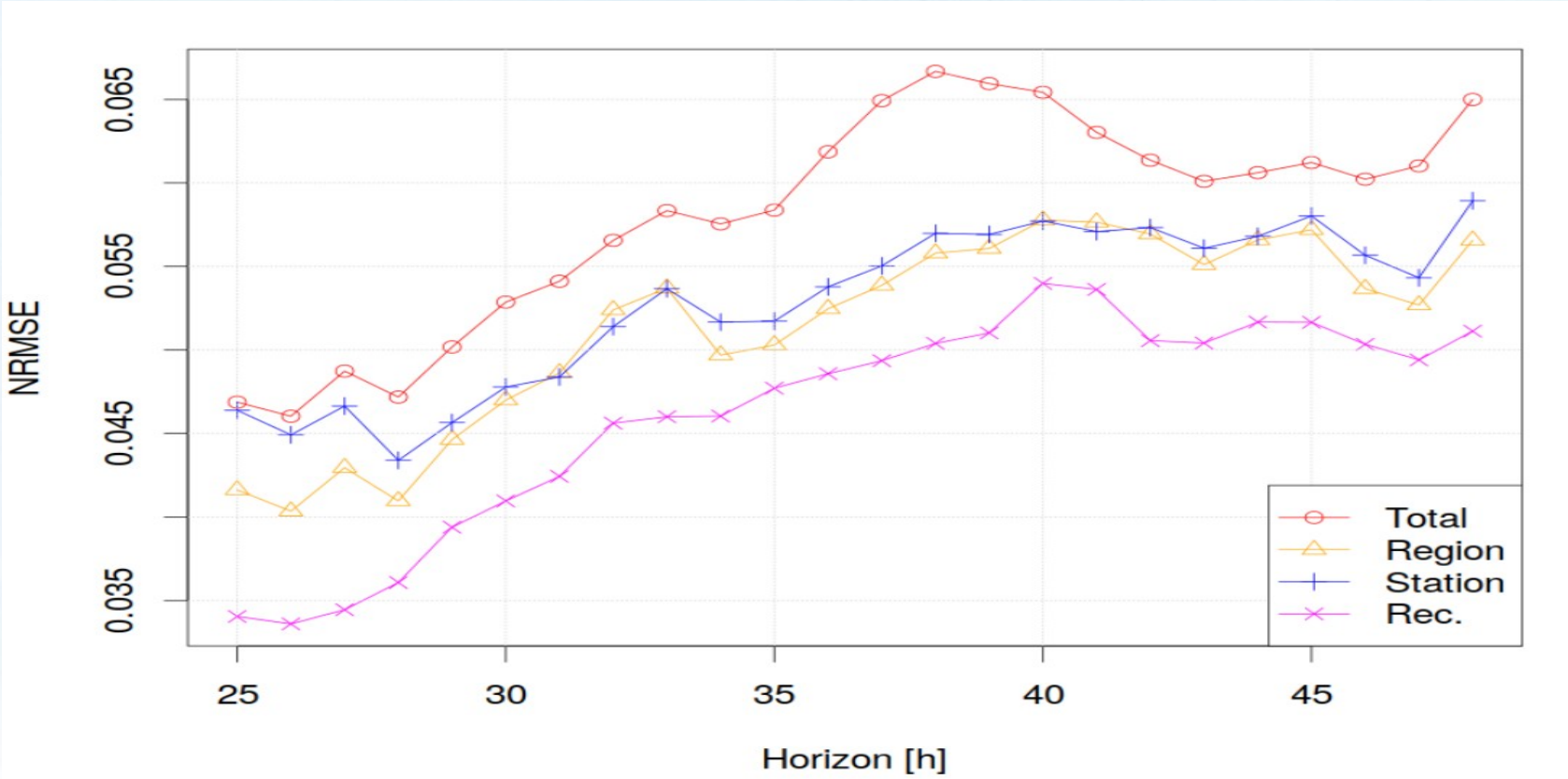
Wind Power Forecasting



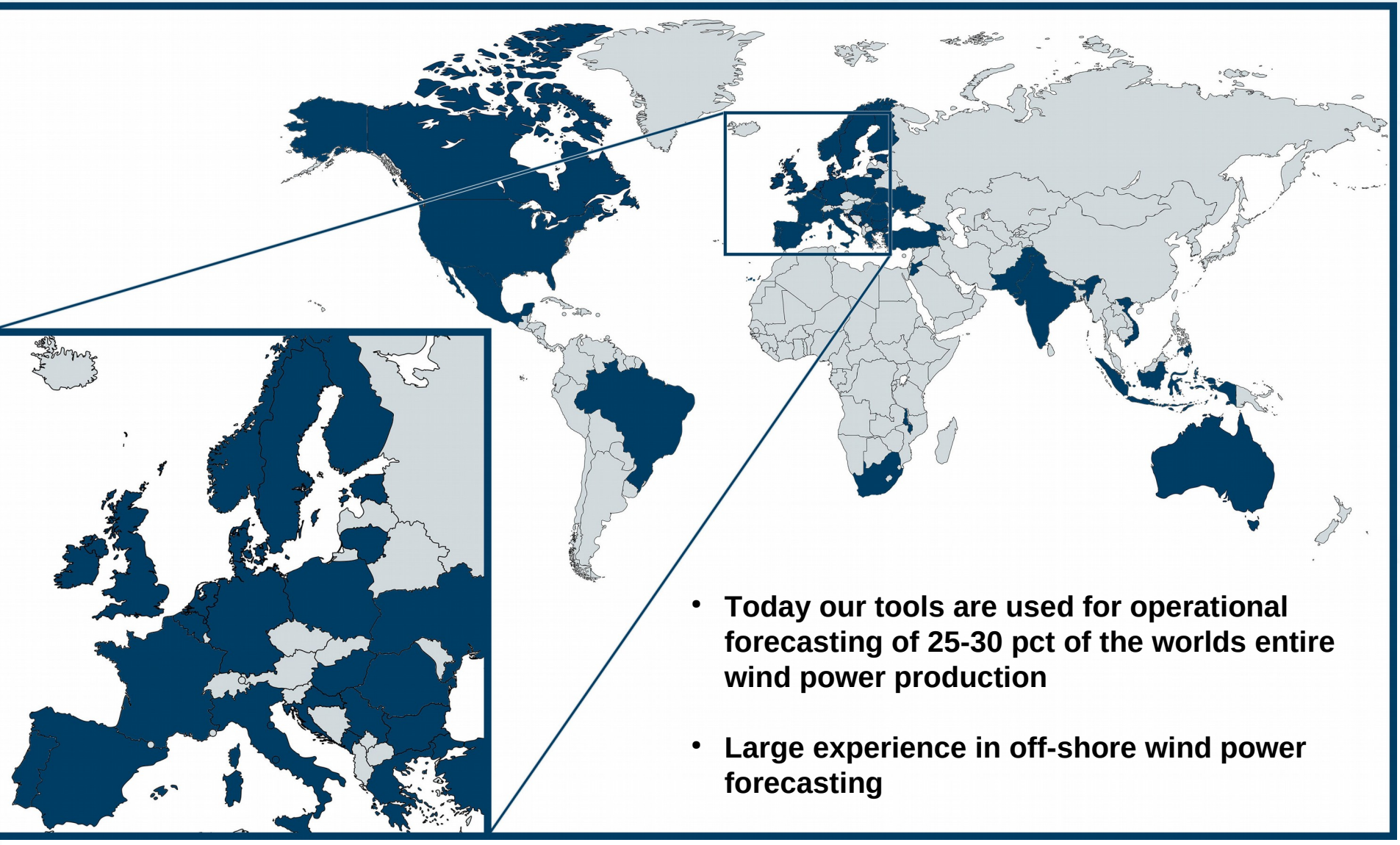


(b) Illustration of the spatial hierarchy for DK1 with 407 individual conversion stations at the bottom level, 15 regions at the middle level, and the total of Western Denmark at the top.

Wind Power Forecasting in DK1 (improvements 20 pct)



Wind Power Forecasting
Using API's developed at DTU



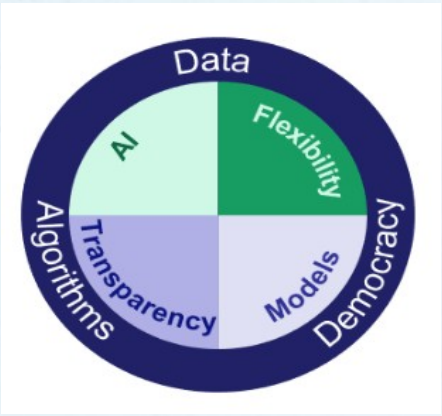
- **Today our tools are used for operational forecasting of 25-30 pct of the worlds entire wind power production**
- **Large experience in off-shore wind power forecasting**

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 for large-scale solar and wind power integration without being subject to disproportionate technical requirements, administrative requirements, procedures and charges

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
- **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 proposed to use **control-based methods for activating local flexibility (Smart-Energy OS)**
- We have indicated how to use **control-based methods for all type of grid services**
- Implemented at the **National Digitalization Hub, Center Denmark**
- **Savings:** Wastewater treatment 40 – 50 pct; summer houses: 20 – 35 pct



Thank you !

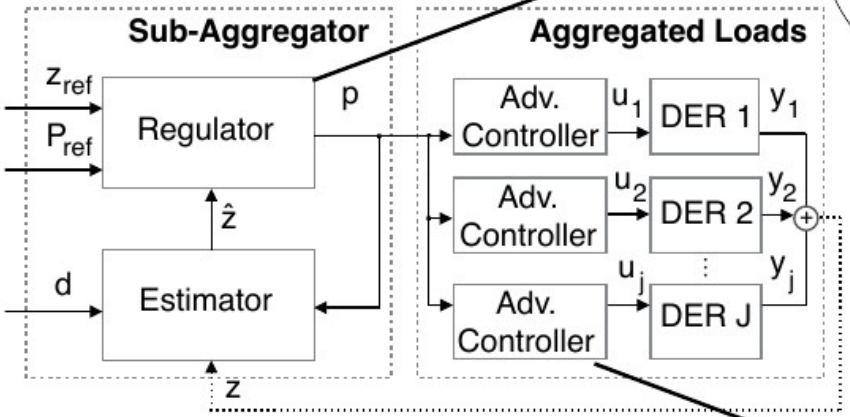
Connect – Share – Innovate

contact data:
Henrik Madsen hmad@dtu.dk

This initiative is funded by

Proposed methodology
Control-based methodology

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



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

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

FED FLEXIBLE ENERGY DENMARK