Digitalization for the Future Weather-Driven Energy System

Henrik Madsen

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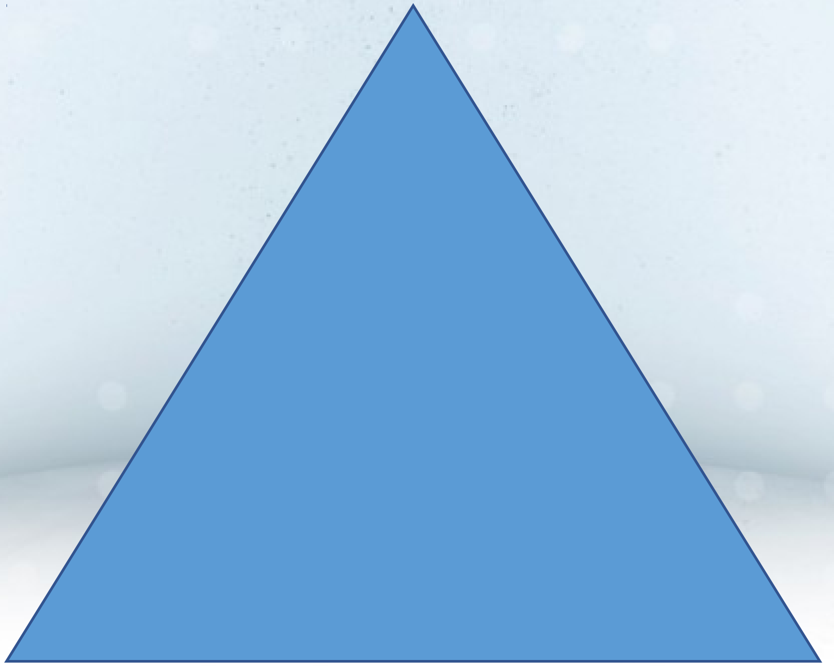
Space of Solutions

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



Grids **Batteries**

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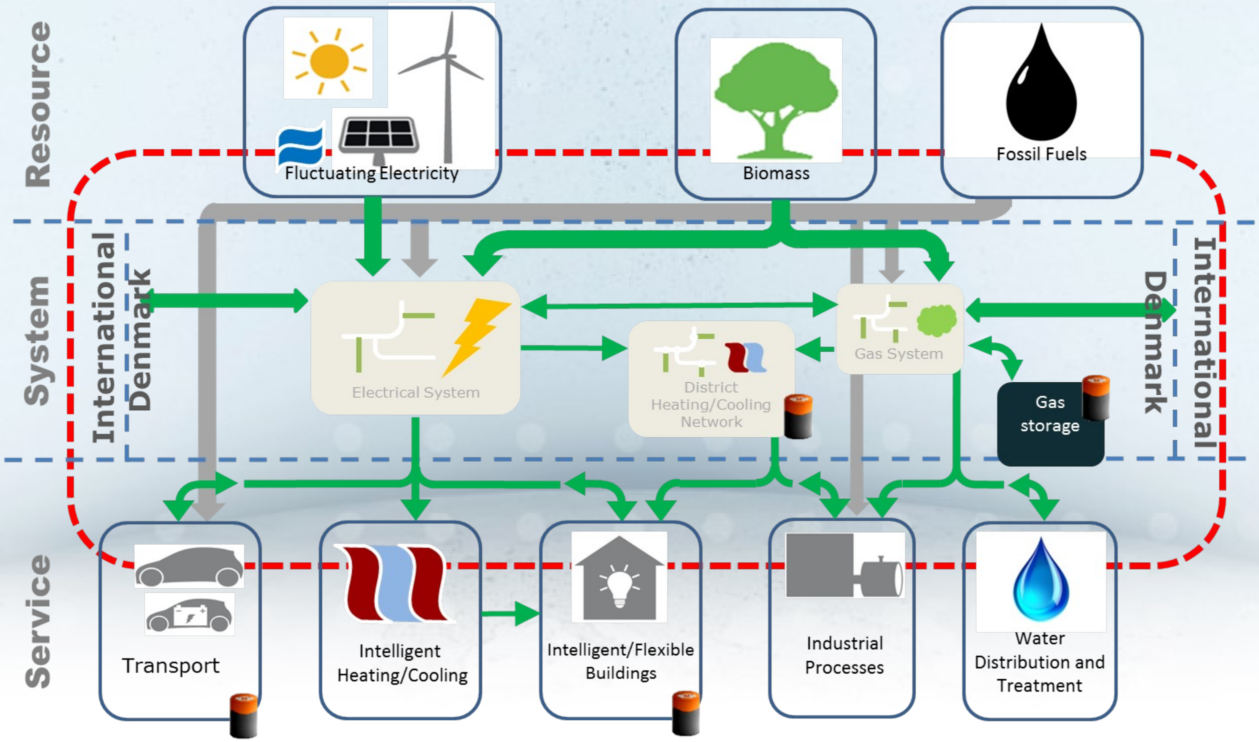
Some FED related questions?

- Where does the physics stop and the markets begin?
- How to unlock flexibility at scale?
- How do we reach customers at scale?
- How to avoid all the sequential markets?
- How to set up markets for sector coupling?
- How to ensure coherency between forecasts and models on all spatial-temporal levels (and e.g. between TSO and DSOs)?
- How do we reduce the silo thinking (also in the regulatory frameworks)?
- How to optimize transparency, democracy, fairness, and trust?
- How to reduce disproportionate technical and administrative requirements, procedures, and charges?
- Would you be able to bid into the existing markets?

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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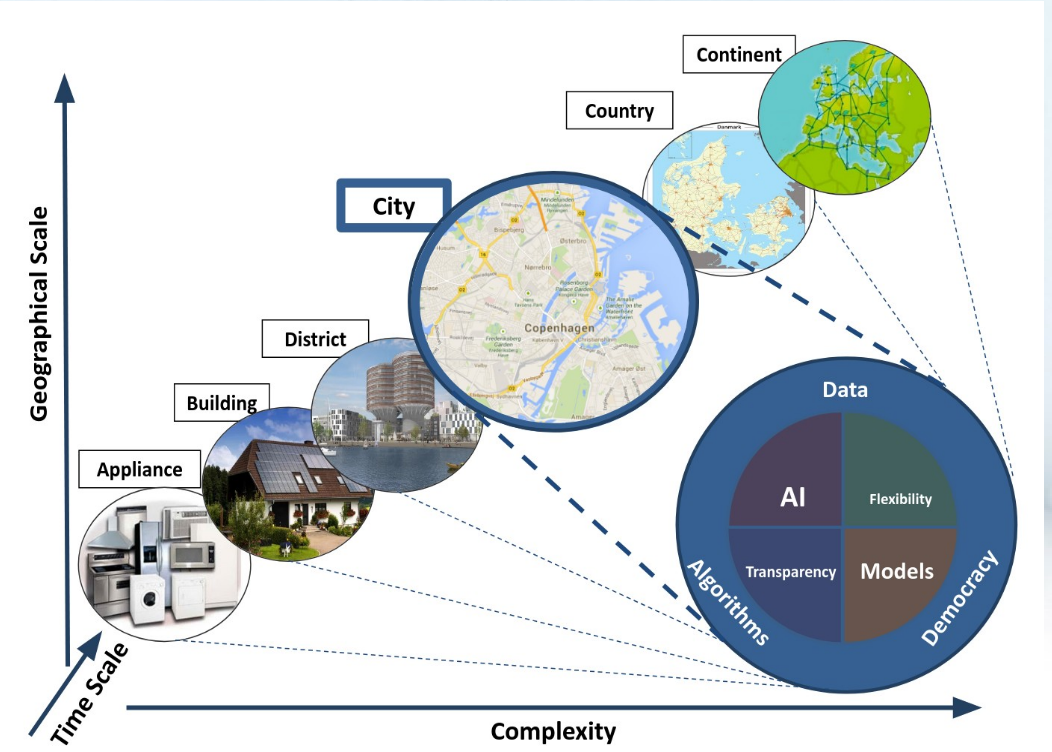
Temporal and Spatial Coherency

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**.



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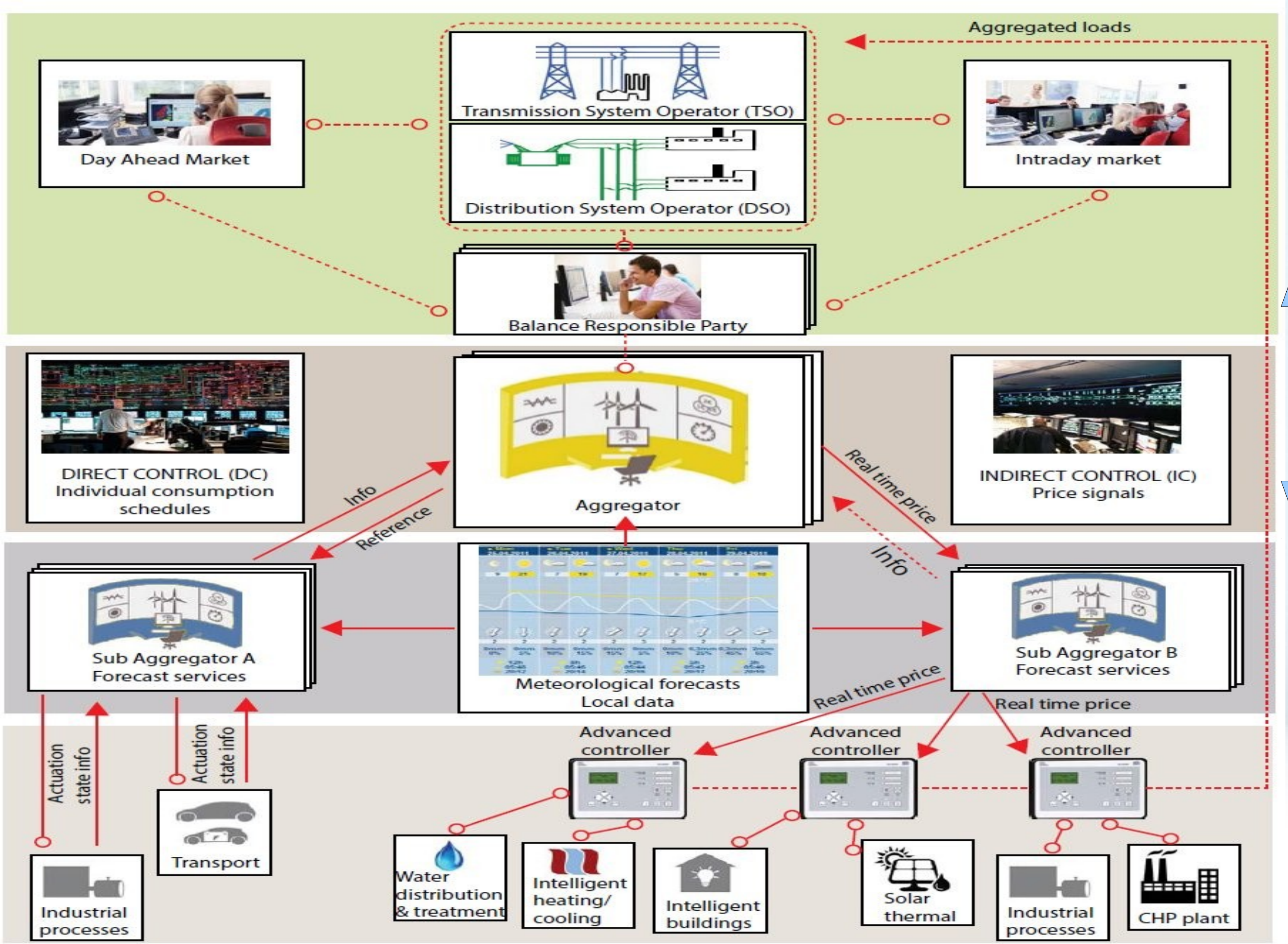
Smart-Energy OS

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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Flexibility Functions
The Fundamental MIMs for Linking Markets to the Physics

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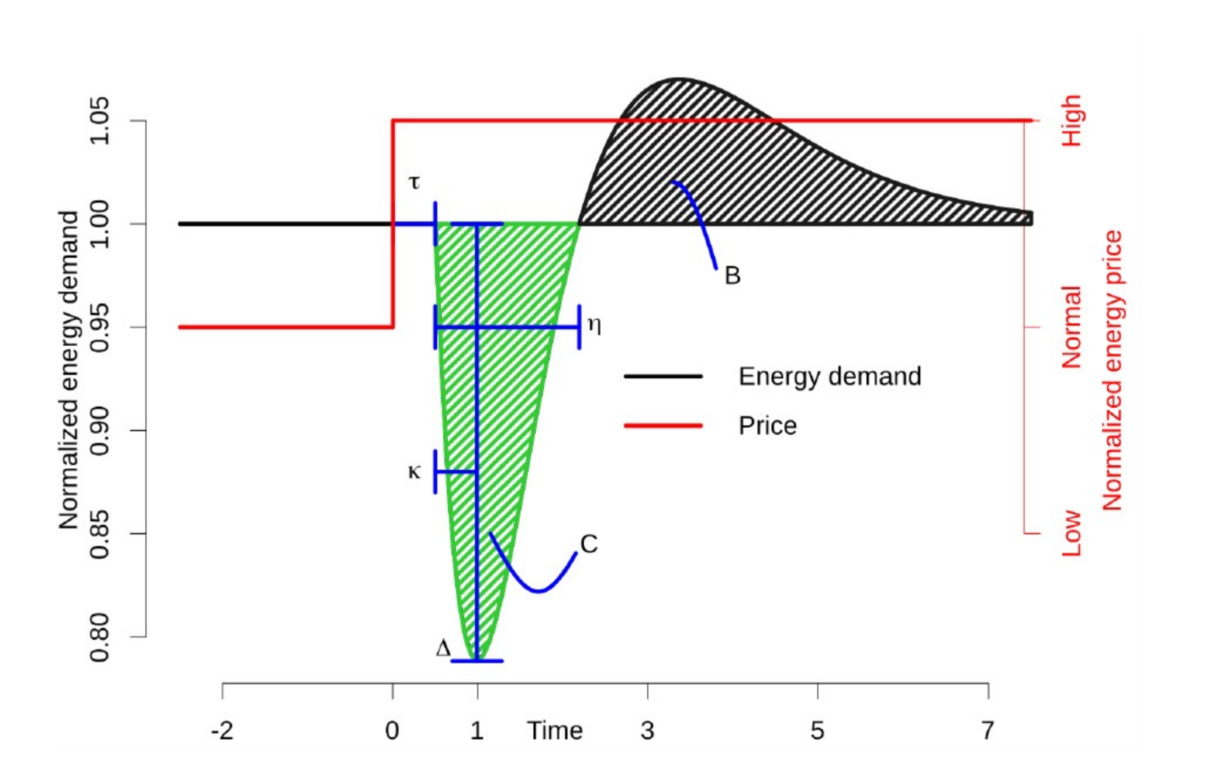
Flexibility Function

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



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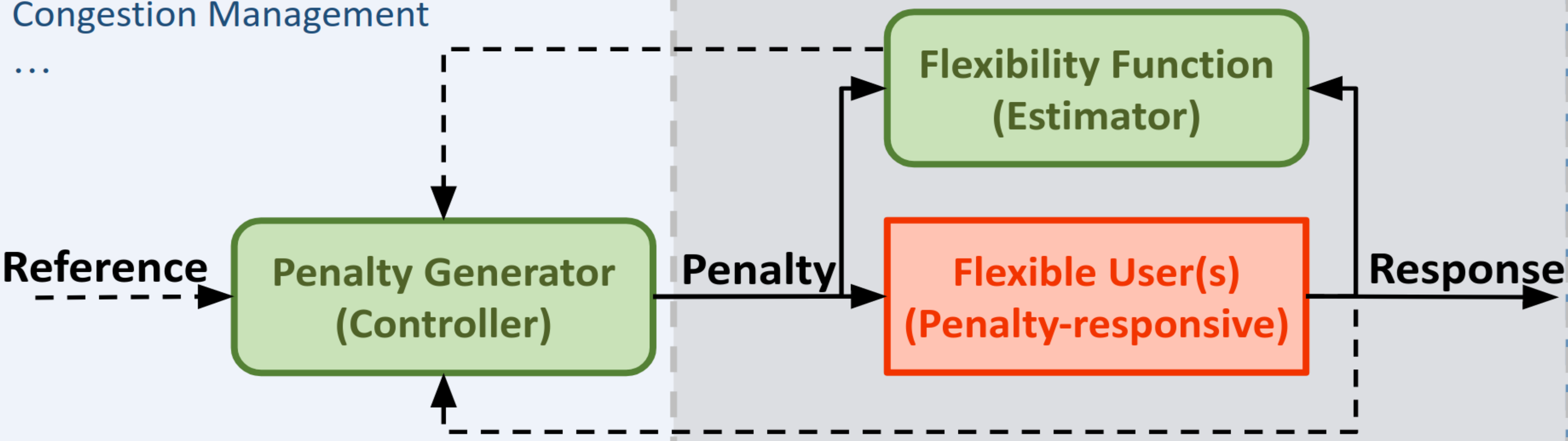
Flexible Users and Penalty Signals

Penalty Generator for, e.g.:

Voltage Control,
Balancing,
Congestion Management
...

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



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Case Study:

DSO - Smart Grid Intelligence
TREFOR Living Lab
Dynamic Transformer Rating

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Grey-box model for transformator stations

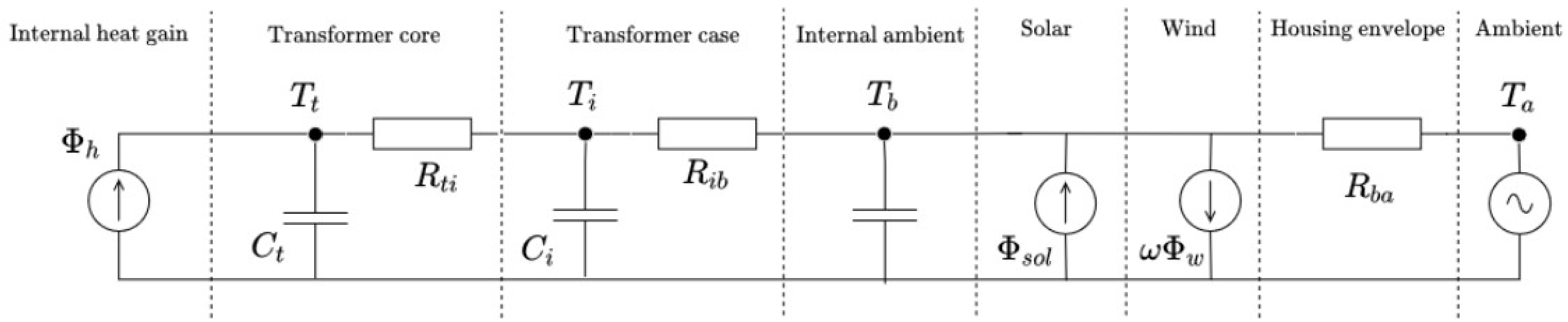


Figure 7: RC circuit of the three state model $TiTtTb$.

Model performance; 6-hour predictions

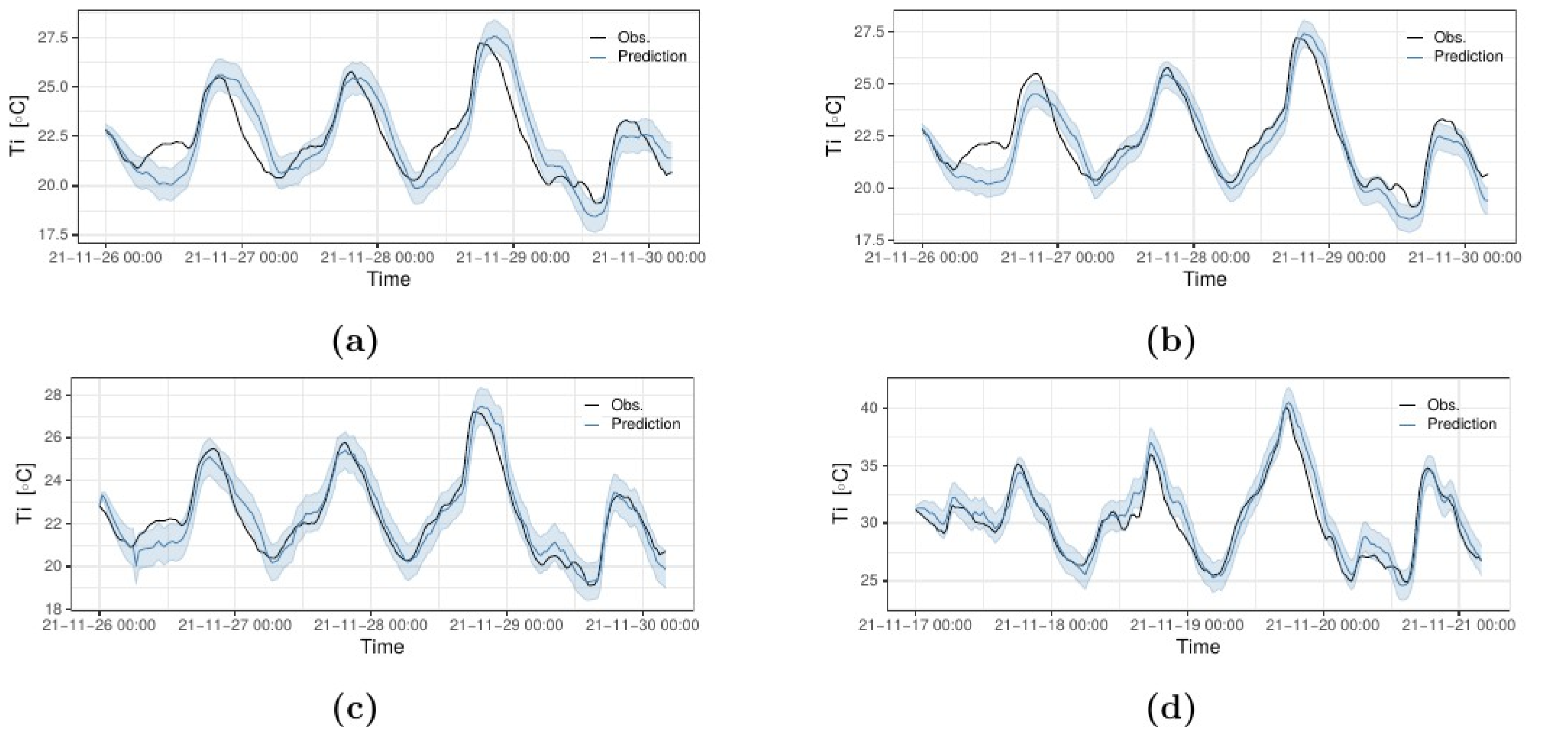
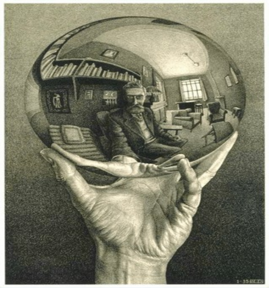


Figure 11: Prediction analysis for 12 step ahead (6 hours) predictions. Subfigures (a)-(c) show predictions for TRF 1 using the one state model (a), extended two state model (b) and the final three state model (c). Subfigure (d) shows predictions for TRF 2 using the final three state model. Black line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

Konstant Living Lab
Flexibility in Freezing Houses

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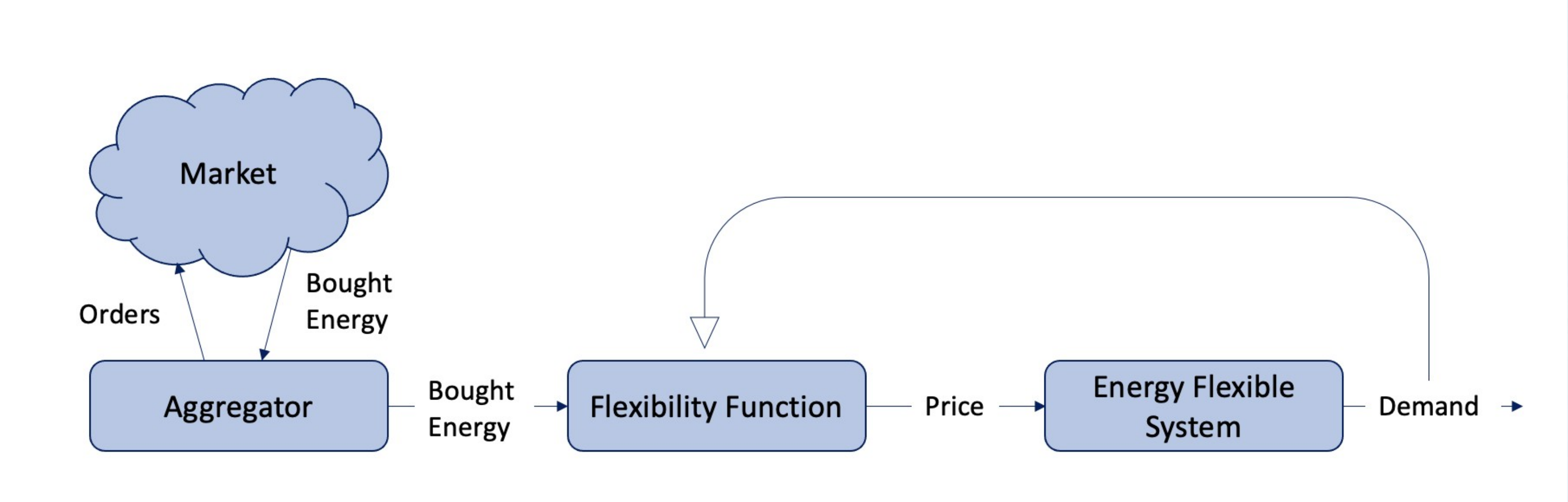

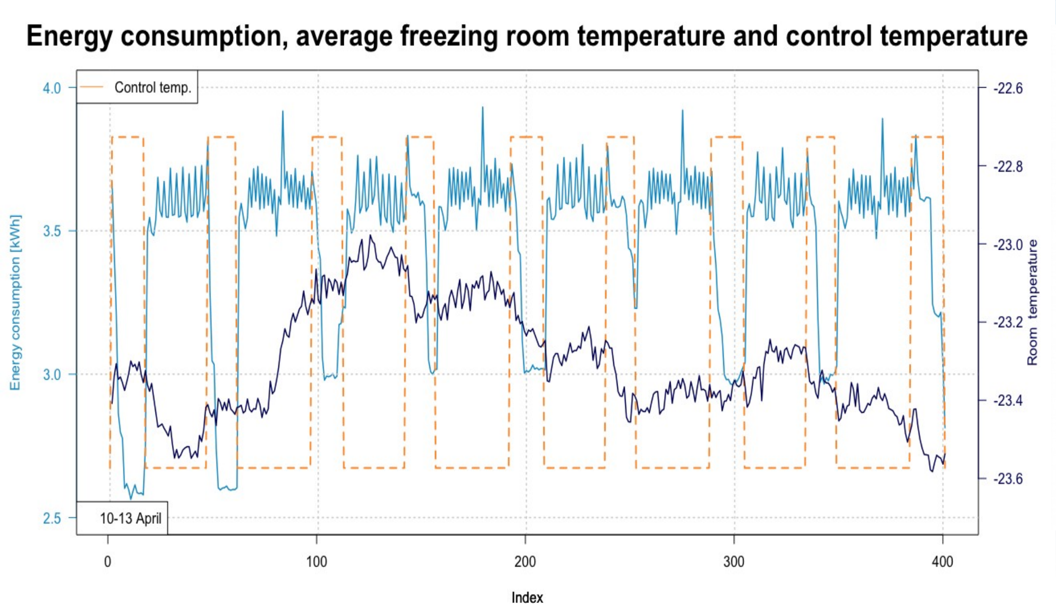

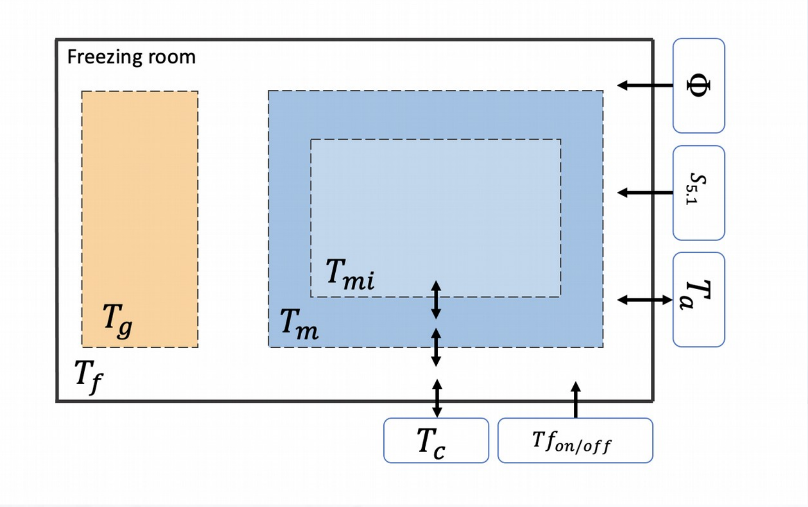

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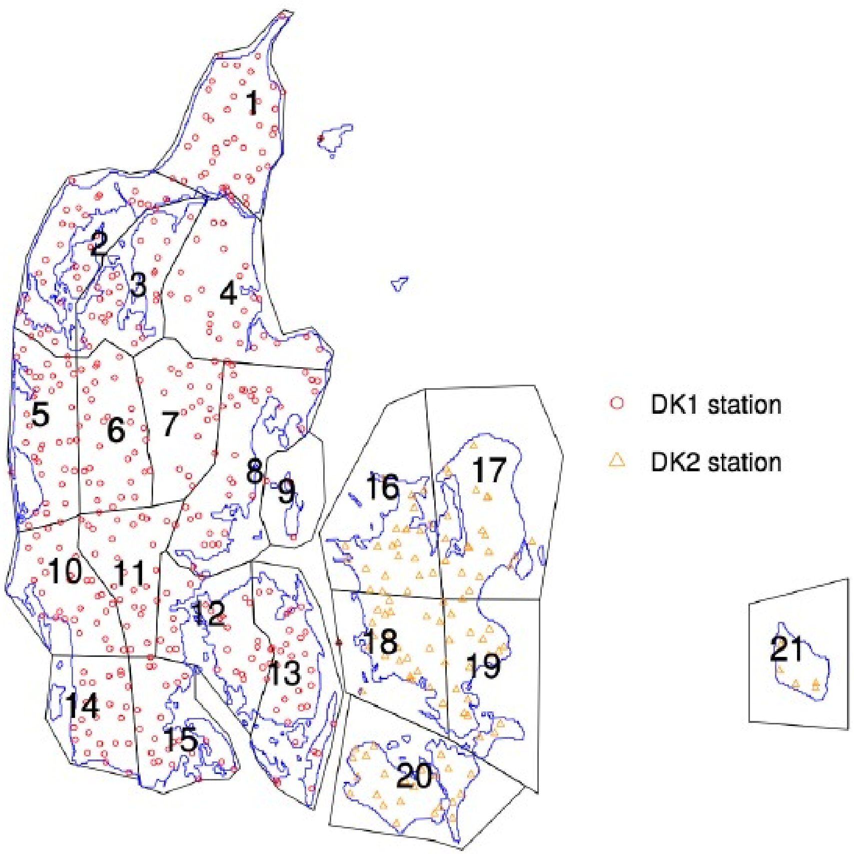
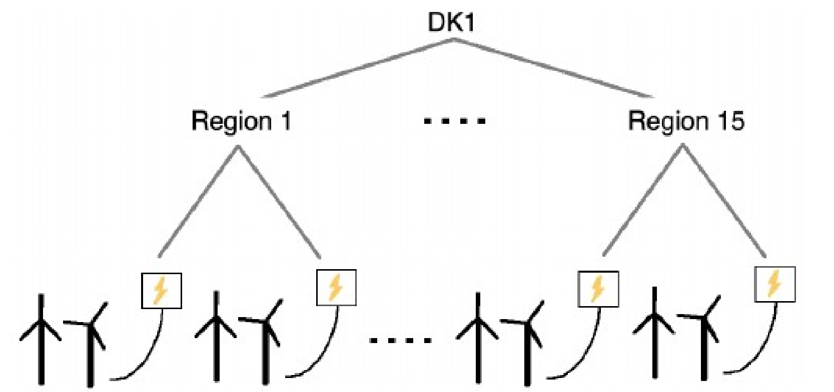
Coherent Forecasting for all Grid Levels (DSOs+TSO) using Spatial Hierarchies

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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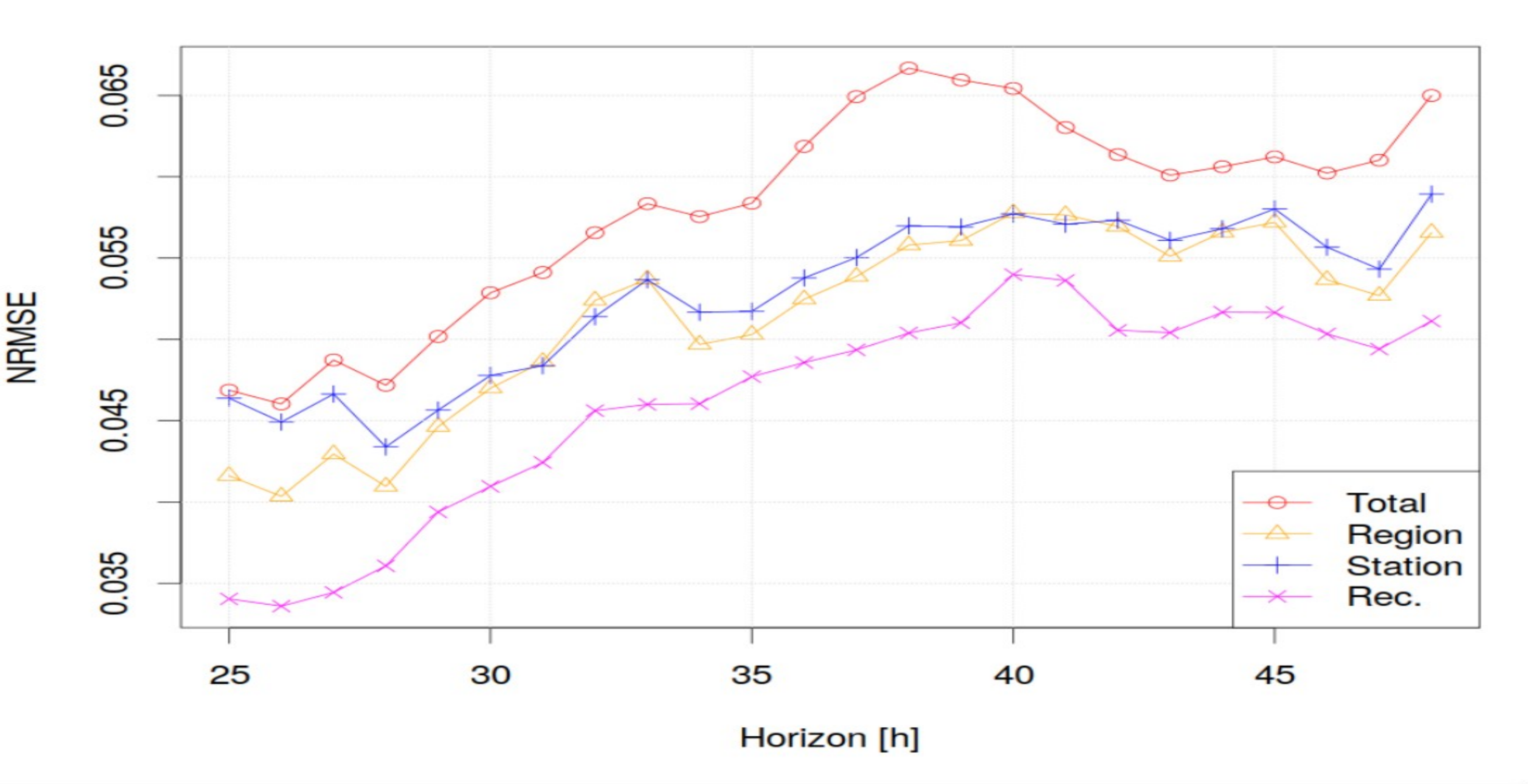
Wind Power Forecasting in DK1 (improvements 20 pct)



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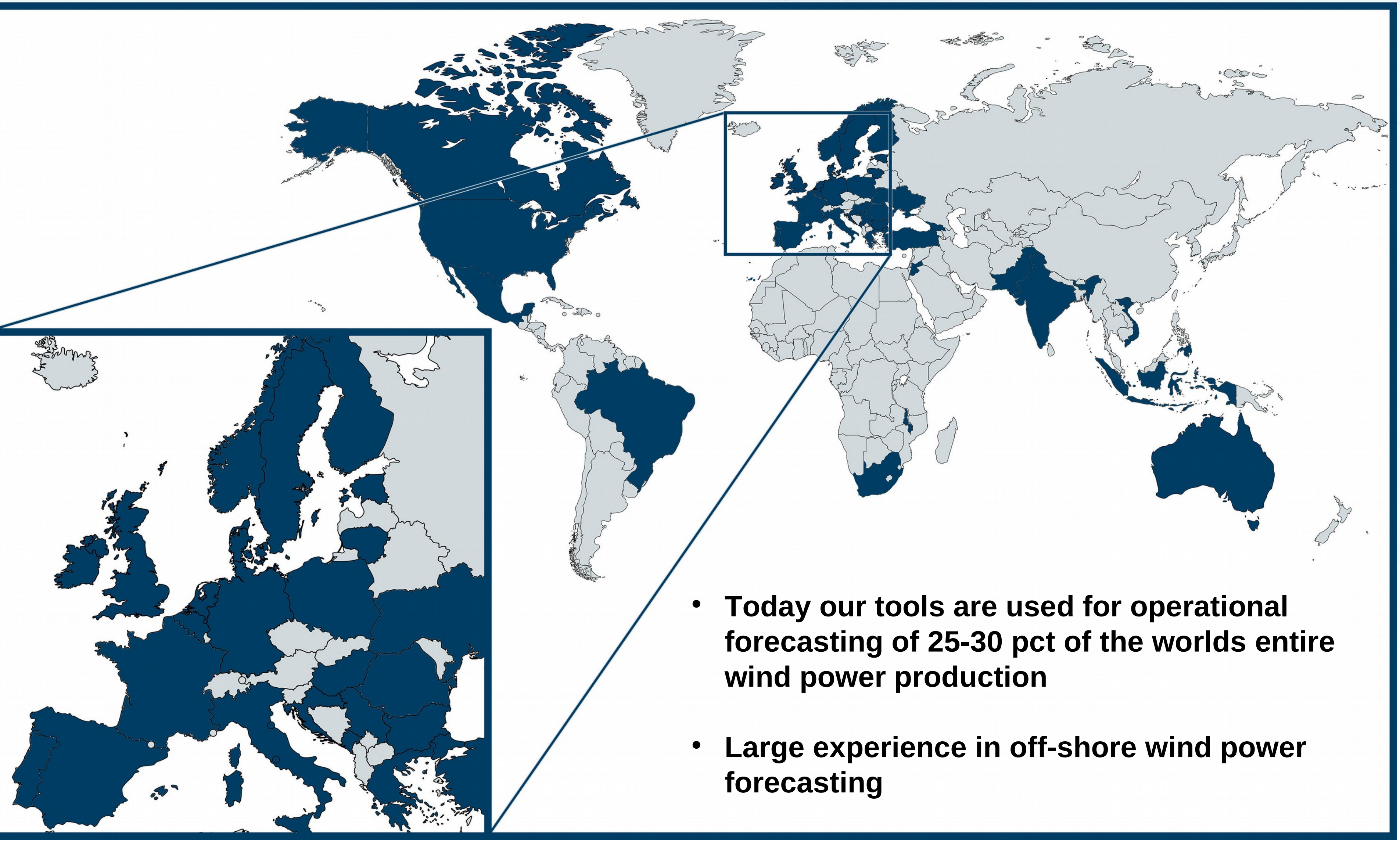
Wind Power Forecasting
Using API's developed at DTU+ENFOR



- **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

Novasol Living Lab
Summerhouses with a pool

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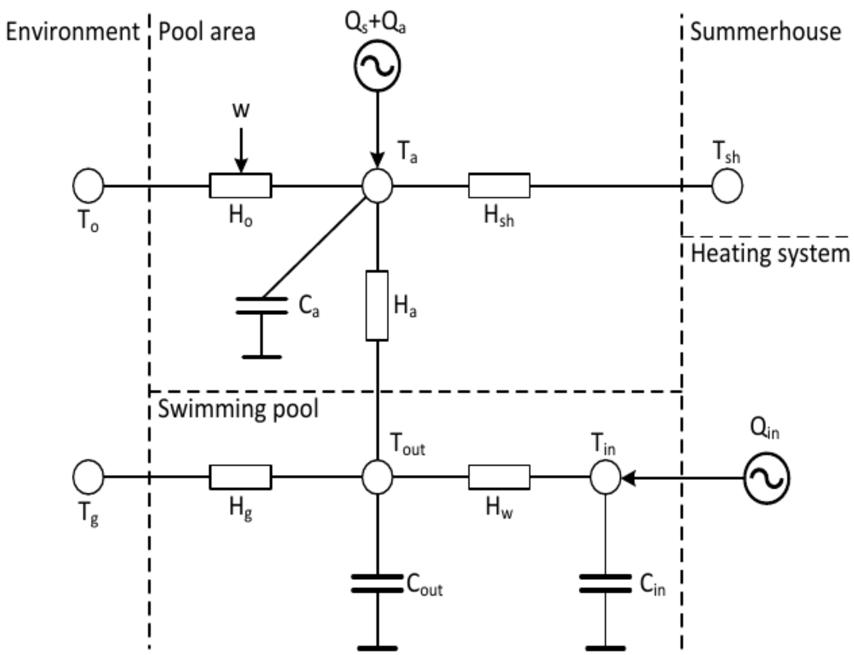
Data-driven models for the buildings

(Using lumped parameter models)



- Based on equivalent thermal parameters model

- Dynamics:

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

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

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

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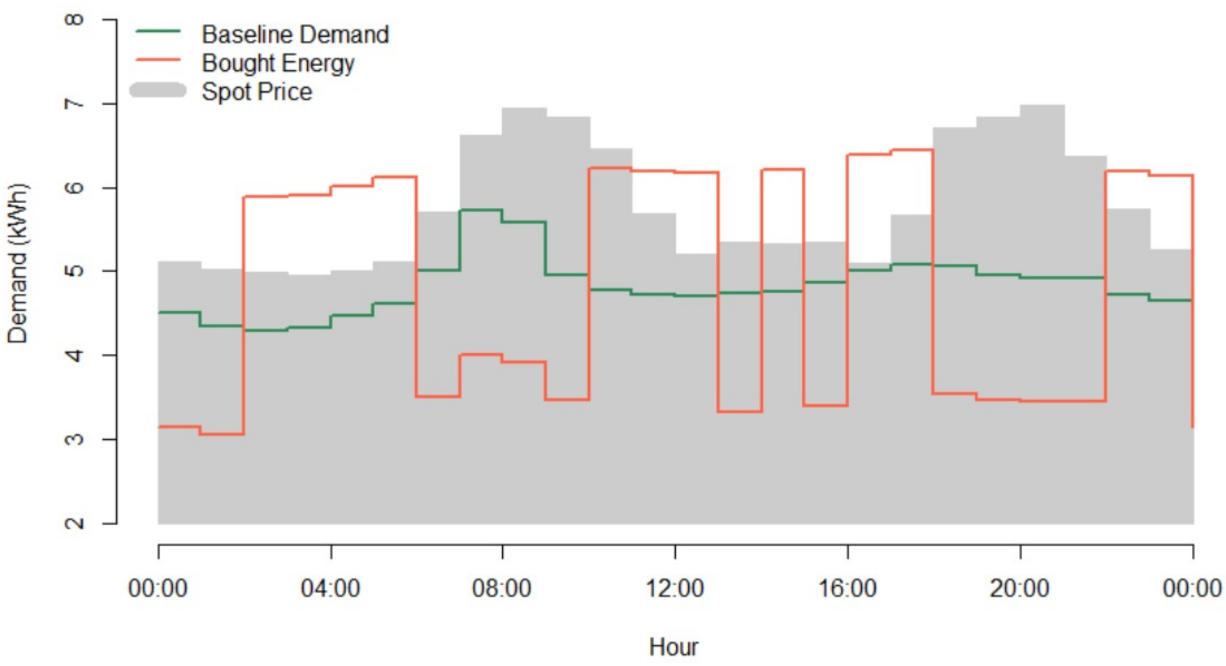
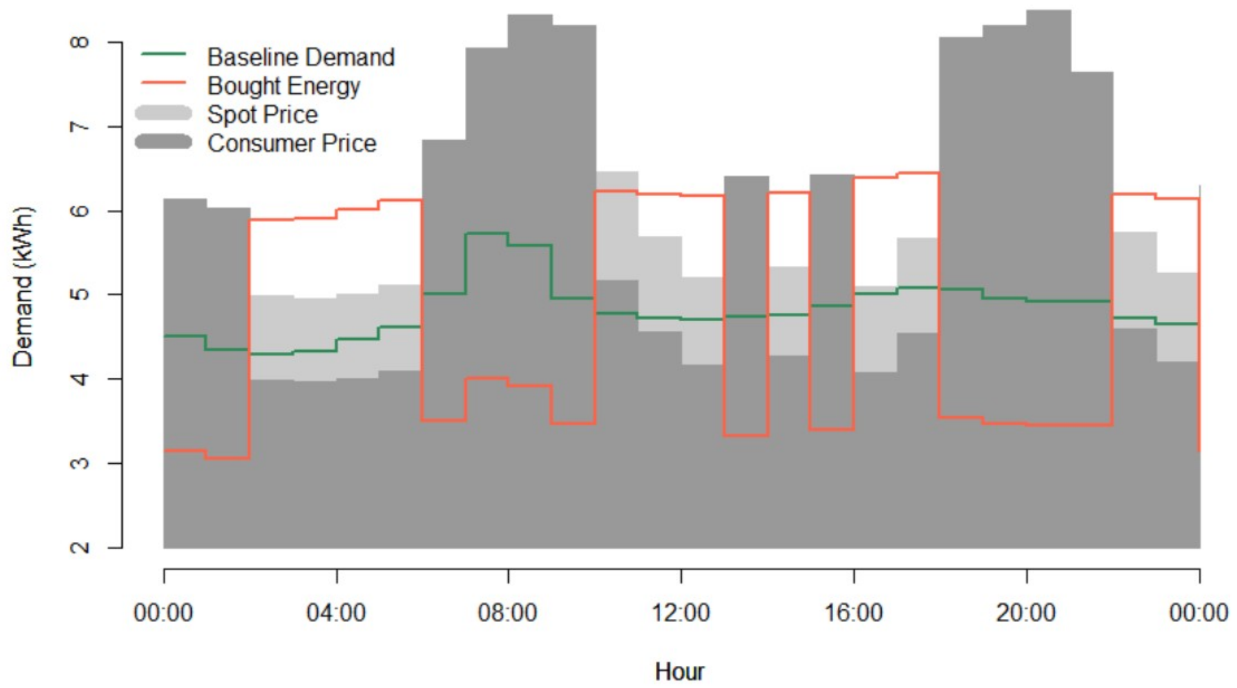
Bidding Flexibility into Markets

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



Bidding Flexibility into Markets

Solve FF(Price)=Bought Energy:



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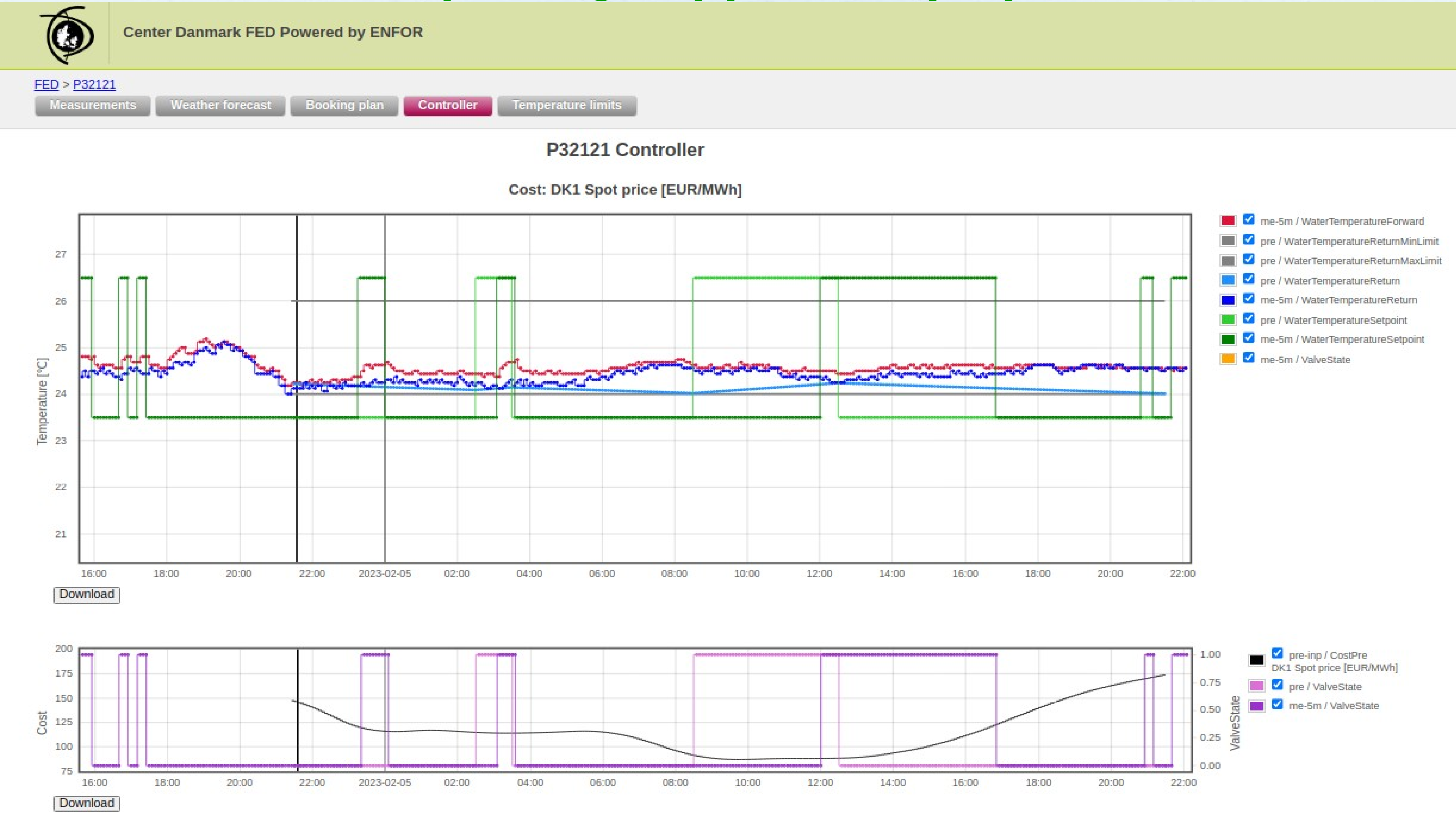
Example: Price-based control (savings approx 30 pct)



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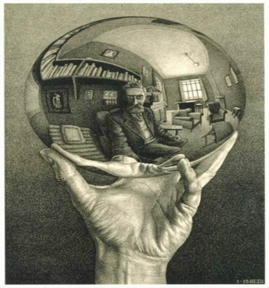
Summer house smart control

- Savings approx. 30 pct using local flexibility
- Built-in DSO-TSO coordination in solving grid challenges
- Price signals important in balancing the distribution grids
- New dynamic and geographical tariffs can solve DSO issues in summer house areas
- New dynamic tariffs can take care of local energy systems (energy communities, etc.)
- Automatic solutions targeting also small units



Case Study

Fredericia District Heating Living Lab
Digitalization and Flexibility

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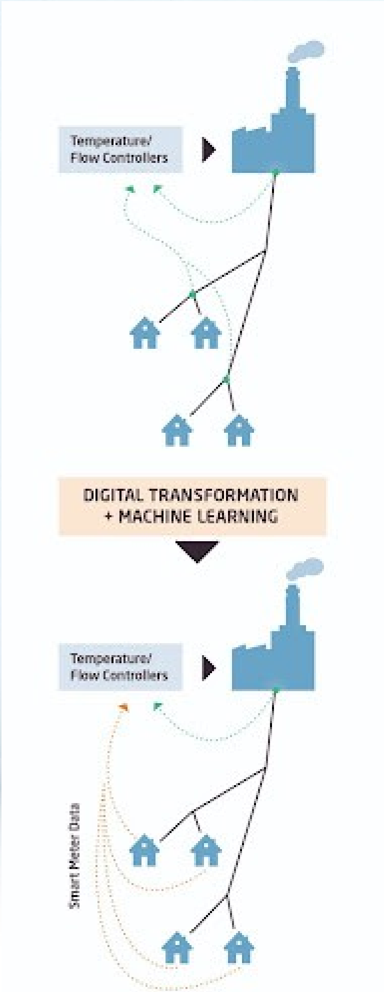
Digitalization of District Heating

- Spatio-temporal heat load forecasting (10 – 40 pct improvements)
- Data-driven methods for temperature optimization (Large savings – up to about 900 mill dkk annually in Denmark)
- New methods for direct use of meter data – gives extra savings and possibilities
- The temperatures are reduced with 3 – 12 degrees; implies reduction of heat loss and better HP integration. Better use of excess heat from supermarkets and industry.
- DH systems give excellent options for storage of energy 1-3 days using net and accumulator tank, seasonal storage using PTES
- Flexibility in DH is excellent for energy systems with large scale integration of solar and wind
- Methods for automated peak shaving and demand response



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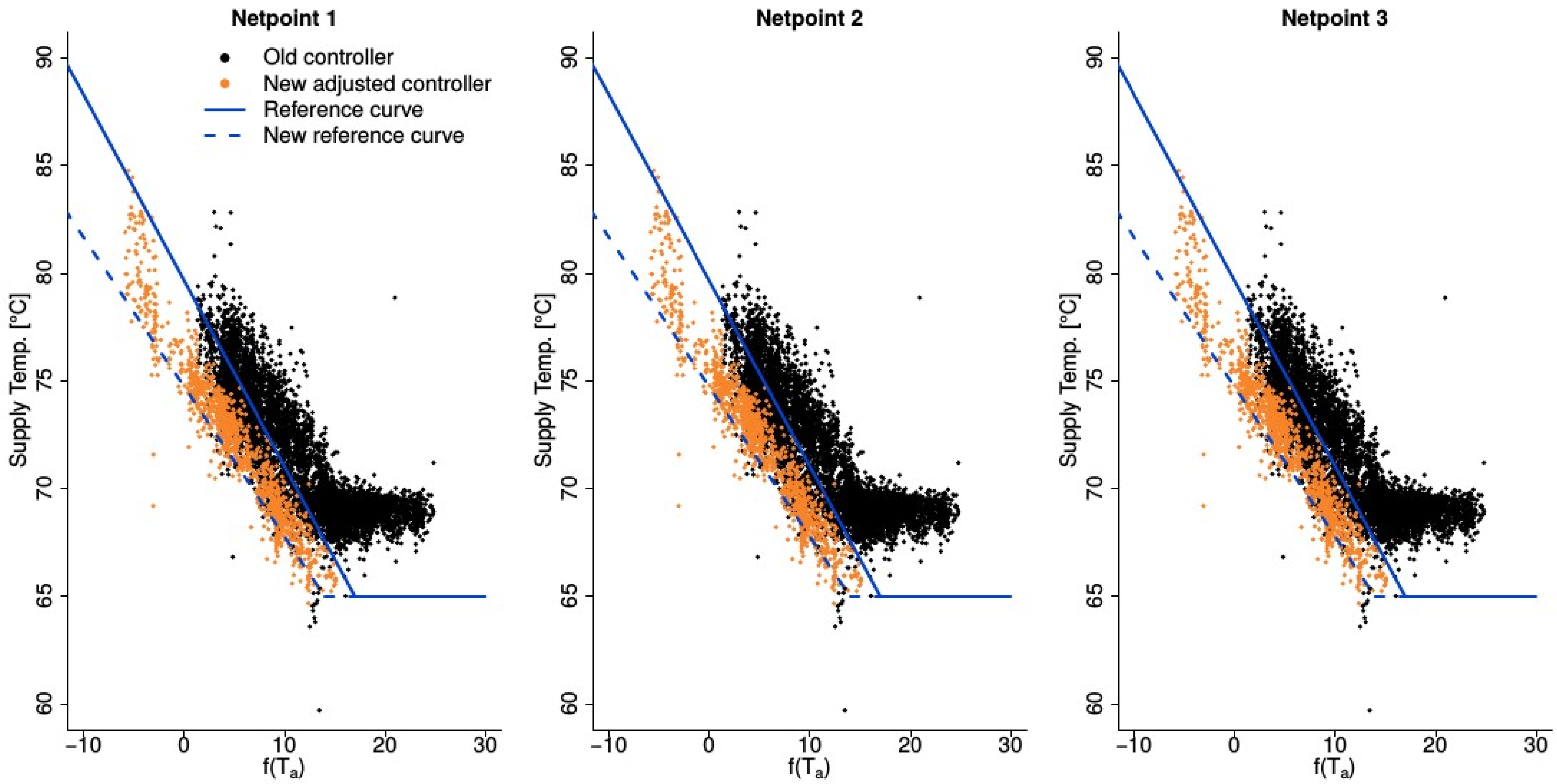
Temperature at end-users (Tingbjerg)
Higher precision = 5 C temp. reduction



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Simulation-Based vs Data-Driven Temperature Optimization

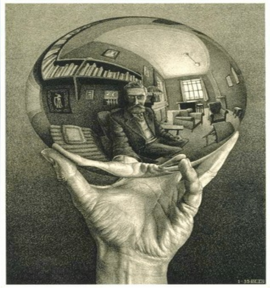
	Simulation-based TO	Data-driven TO
Approach	• Deductive (simulation/theoretical values)	• Inductive (data-driven, self learning)
Optimal usage	• Simulation of new operational scenarios (where no data exists)	• Control of temperature and flow, reduction of heat loss, real time data
Temperature profile	• Temperature calculated using theoretical values for pipes, insulation, soil, etc.	• Temperature estimated using real life data and statistical/AI-based learning
Distribution net	- Does NOT take into account: • Dirtiness, • Soil properties (temperature, humidity, ...) • Leakage, • Wet or damaged insulation, • Deviations from design values / drawings	+ Take into account: • Dirtiness, • Soil properties (temperature, humidity, ...) • Leakage, • Wet or damaged insulation, • Deviations from design values / drawings
Characteristics	- Constant parameters • Require recalibration, which can be difficult and time-consuming	+ Self calibrating / automated learning • Automatic recalibration for instance due to new costumers, heavy rainfall, damaged insulation, etc.
Production facilities	• New production facilities call for recalibration	• New production facilities call for recalibration

Center Denmark
Control Room and Data Space
Spatio-Temporal Thinking

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

Some results

- Digitalization of electricity and heat grids
- The Smart Energy OS for digitalized operations
- Data-driven Digital Twins
- Coherent forecasting on all spatial (grid levels) and temporal scales
- Flexibility Functions as fundamental MIMs for energy systems
- FF gives an operational link between markets and physics
- We are able unlock flexibility at scale
- Security and Privacy by design
- Large savings ($CO2$ / Costs) observed



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