A Control-oriented Framework for the Future Weather-driven Energy System

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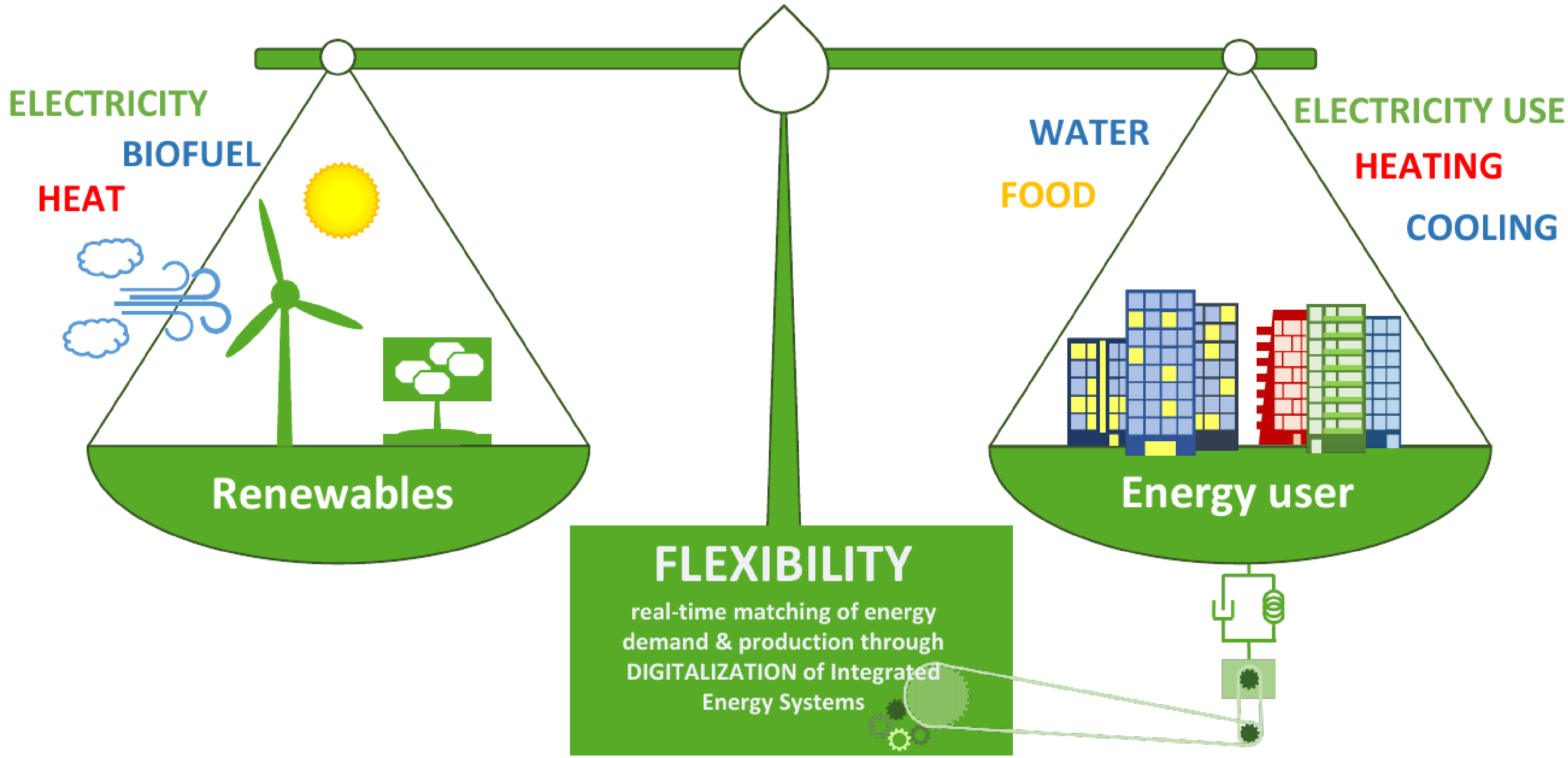
Challenges

The Challenge: Denmark Fossil Free 2050



Challenges

Preparatory study on
Smart Appliances

European Commission

Ecodesign Preparatory Study performed for the European Commission

Welcome | Project summary | Planning & Meetings | Documents | Register for website | Register for meeting | Contact & Consortium

Home > Project summary

Project Summary

The Ecodesign Preparatory Study on Smart Appliances (Lot 33) has analysed the technical, economic, market and societal aspects with a view to a broad introduction of smart appliances and to develop adequate policy approaches supporting such uptake.

The study deals with Task 1 to 7 of the Methodology for Energy related products (MEErP) as follows:

- Scope, standards and legislation (Task 1, Chapter 1);
- Market analysis (Task 2, Chapter 2);
- User analysis (Task 3, Chapter 3);
- Technical analysis (Task 4, Chapter 4);
- Definition of Base Cases (Task 5, Chapter 5);
- Design options (Task 6, Chapter 6);
- Policy and Scenario analysis (Task 7, Chapter 7).

An executive summary of the project results can be downloaded here.

Throughout the study, new relevant aspects have come up which will be covered in a second phase of the Preparatory Study:

- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.

Almost no Flexibility

DTU Elektro
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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.

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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**

Data-Intelligent and Flexible Energy Systems

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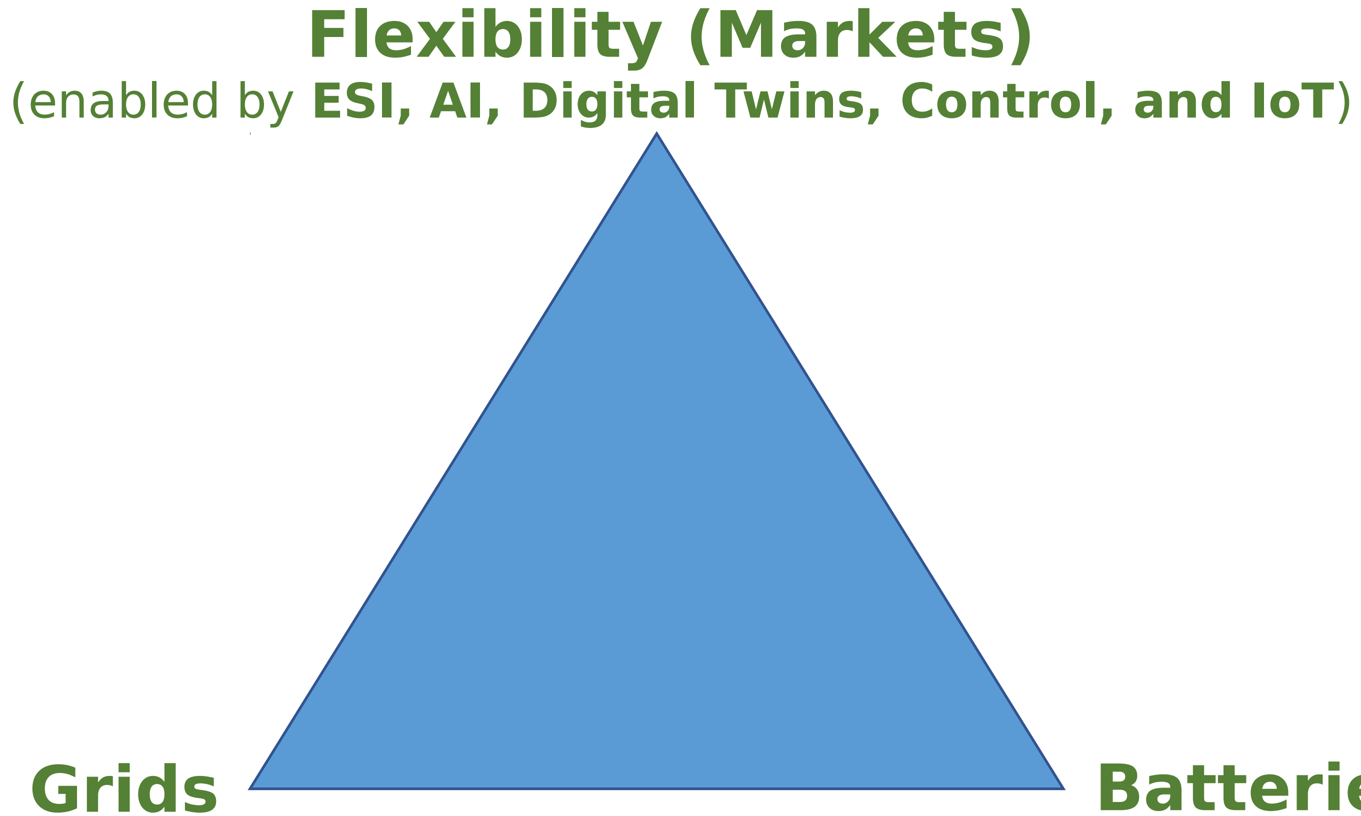
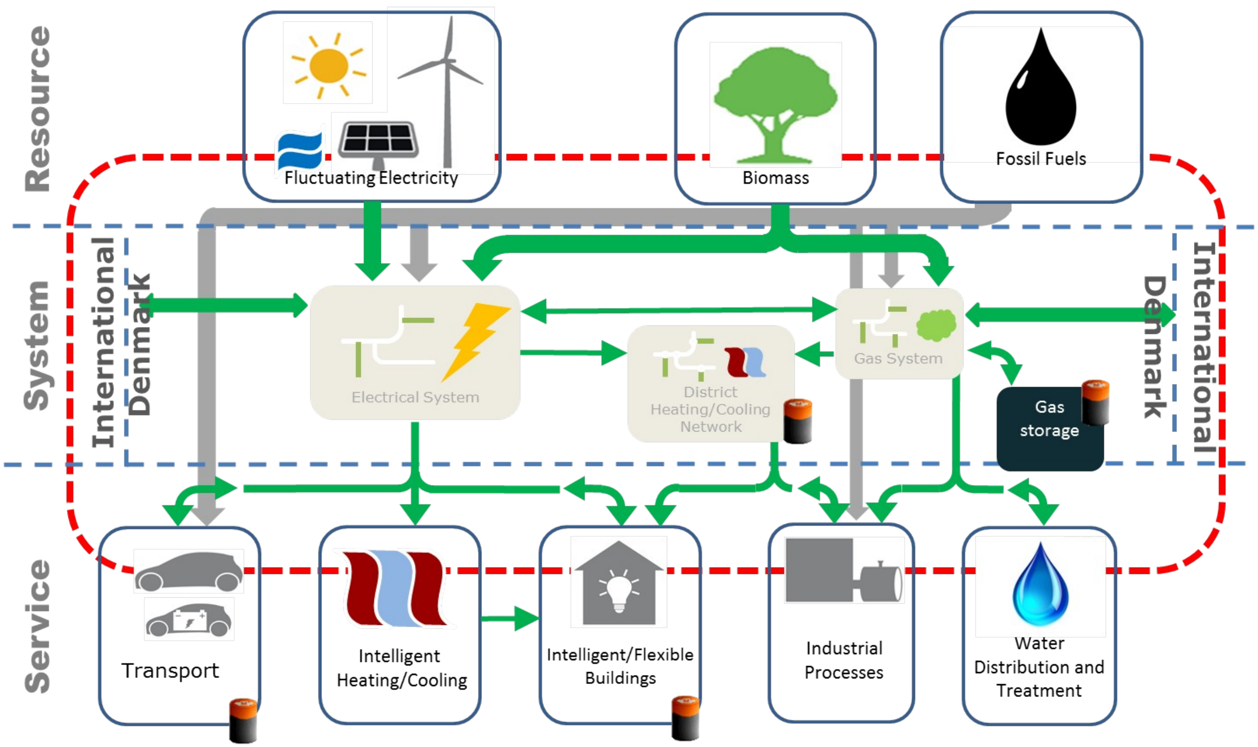
Space of Solutions



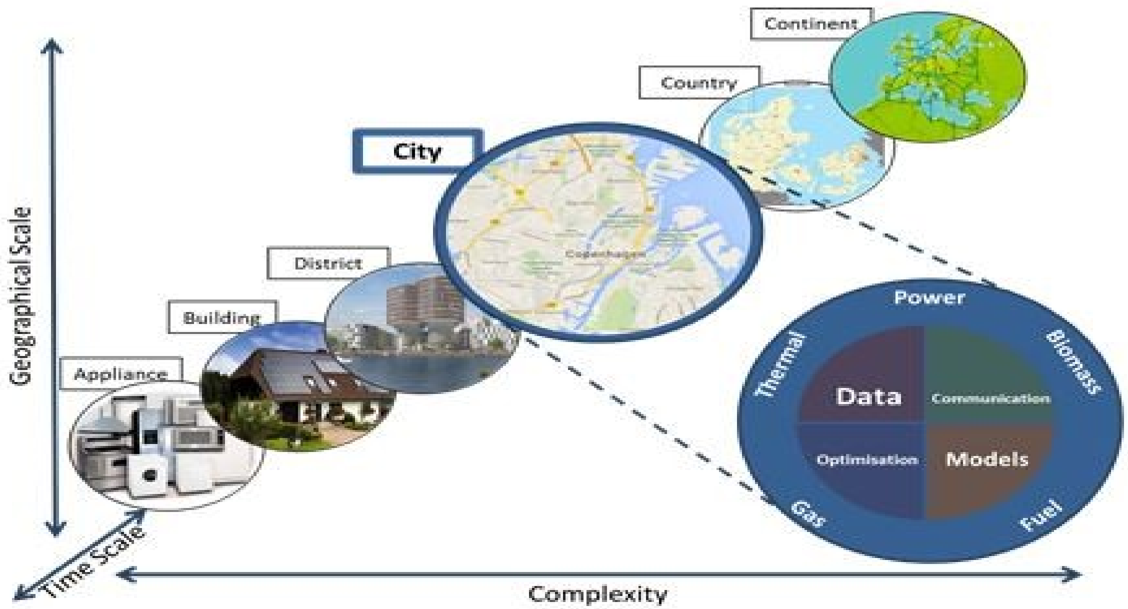
Data-driven Digital Twins for Real Time Applications

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

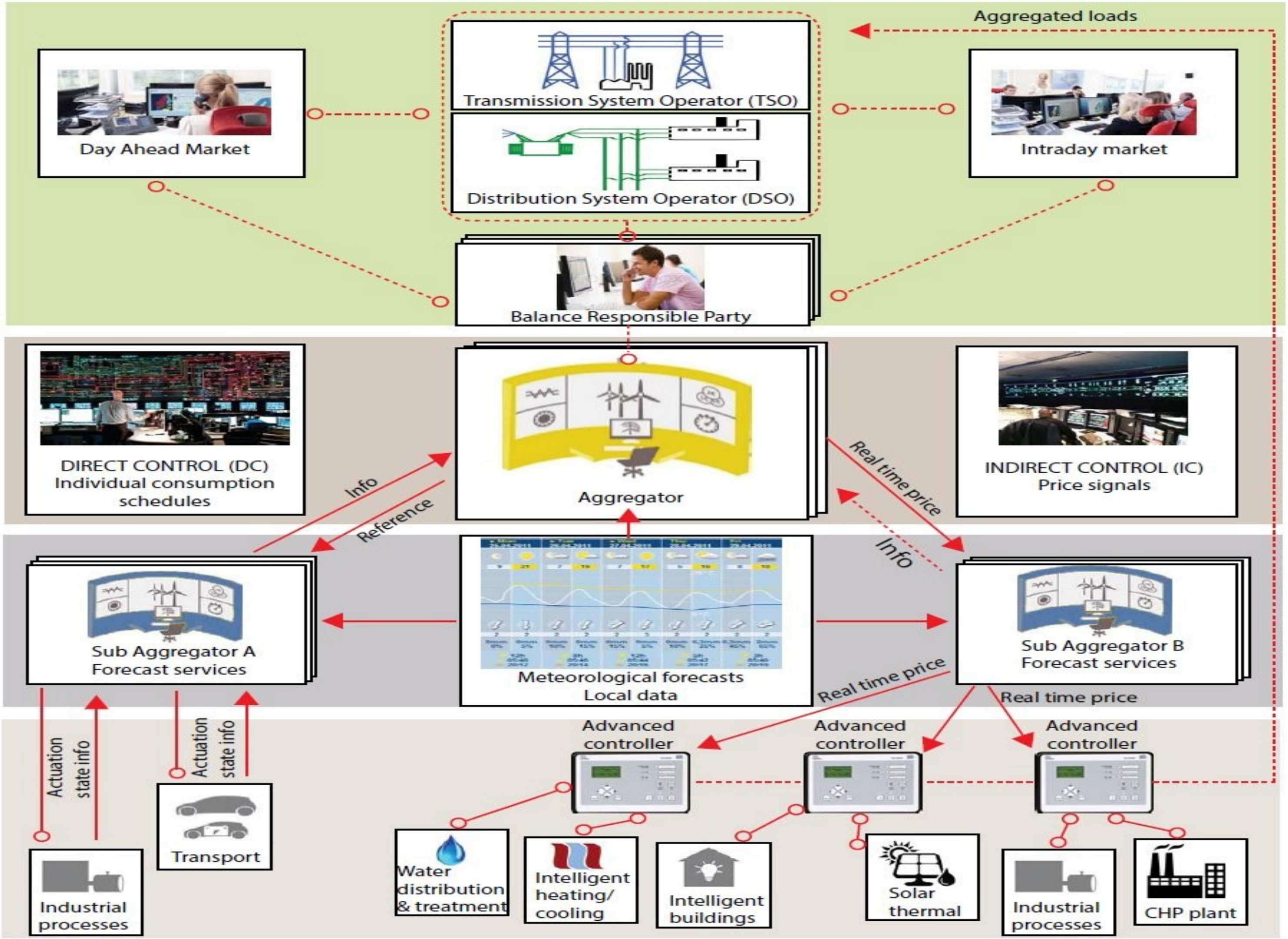


Temporal and Spatial Scales

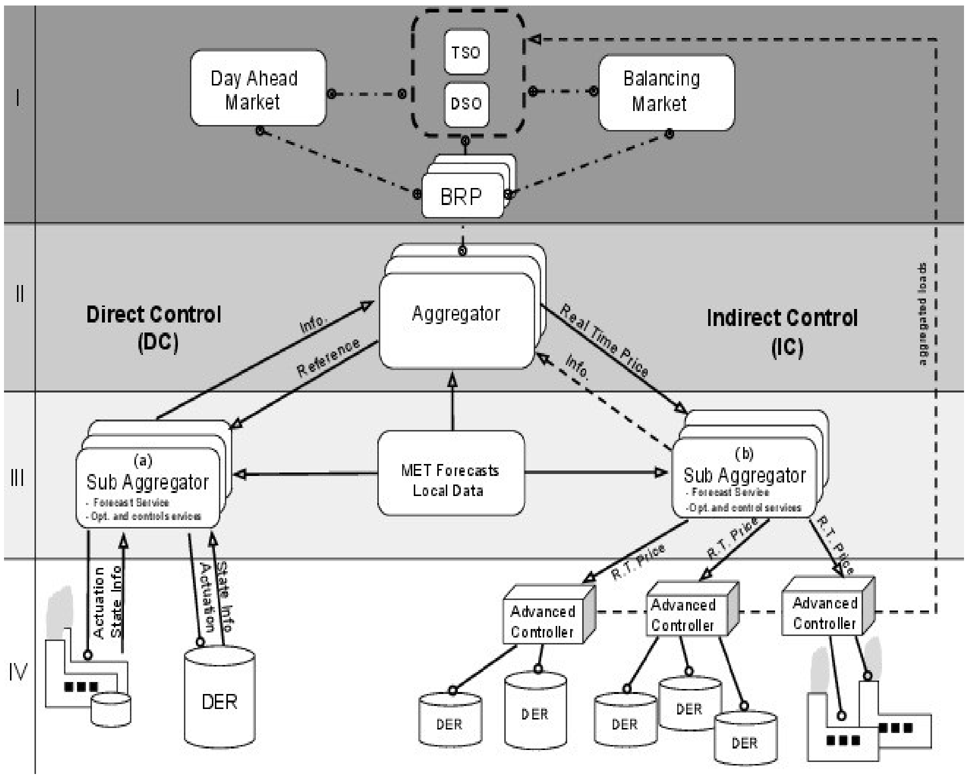
A so-called ***Smart-Energy Operating-System (SE-OS)*** is suggested to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for ***operating flexible electrical energy systems*** at **all scales**.



Smart-Energy OS
The Transformative Power of Digitalization



Control and Optimization in SE-OS



In Wiley Book: Control of Electric Loads in Future Electric Energy Systems, 2016

Day Ahead:

Stoch. Programming based on eg. Scenarios

Cost: Related to the market (one or two levels)

Direct Control:

Actuator: **Power**

Two-way communication

Models for DERs are needed

Constraints for the DERs (calls for state est.)

Contracts are complicated

Indirect Control:

Actuator: **Price**

Cost: E-MPC at **low (DER) level**, One-way communication

Models for DERs are not needed

Simple 'contracts'

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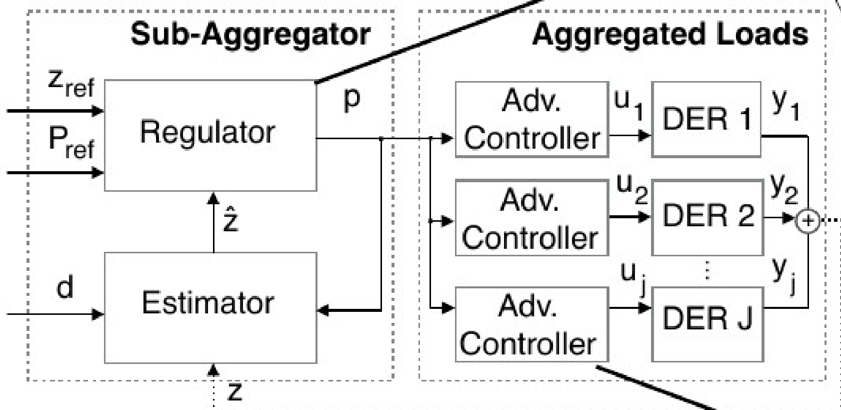
Proposed methodology
Control-based methodology



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

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

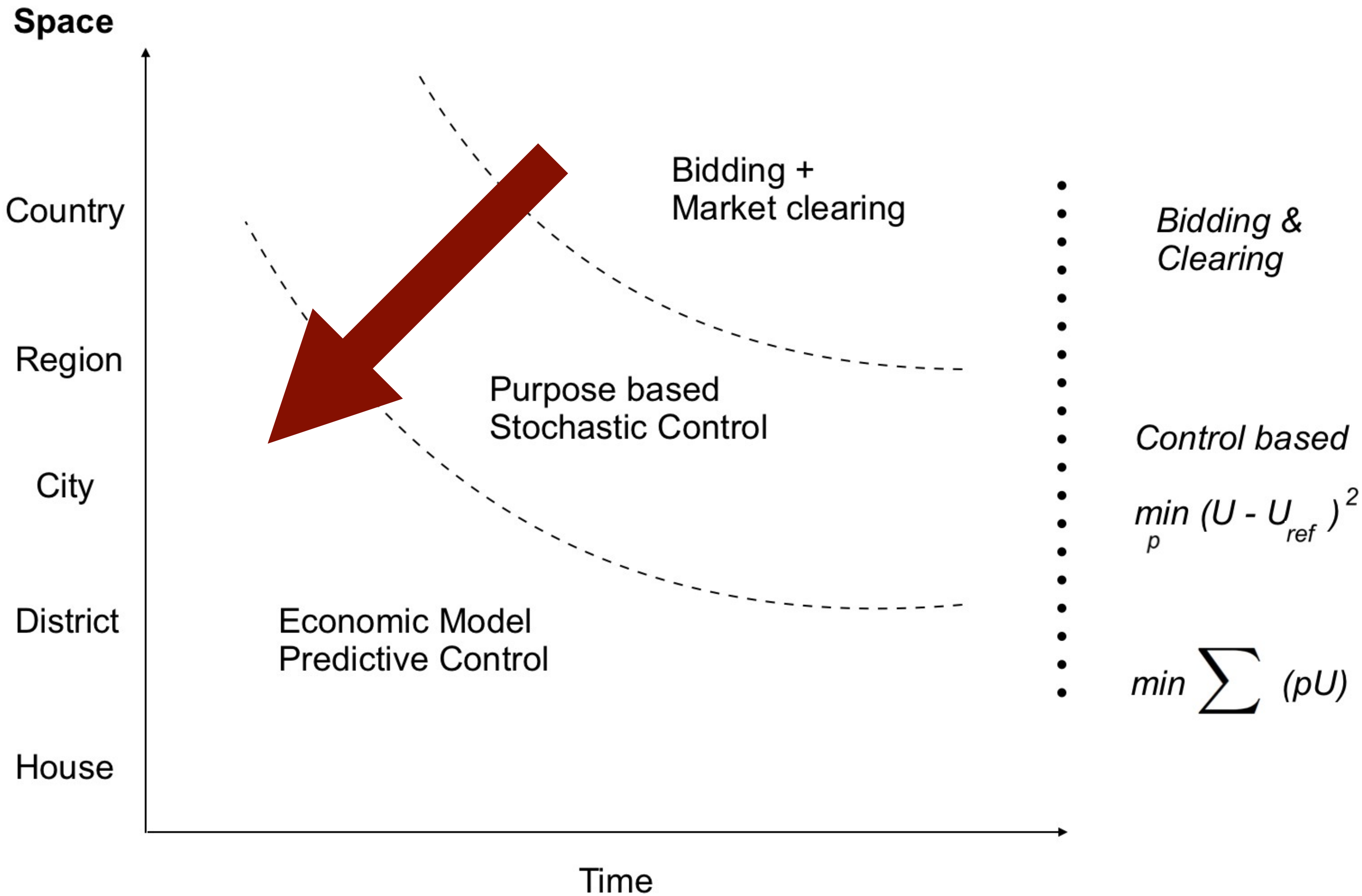
We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

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. $\hat{z}_{k+1} = f(p_k)$
IV	$\downarrow_{u_1} \cdots \downarrow_{u_J} \quad \uparrow_{x_1} \cdots \uparrow_{x_J}$ 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. $x_{k+1} = f_j(x_k, u_k)$

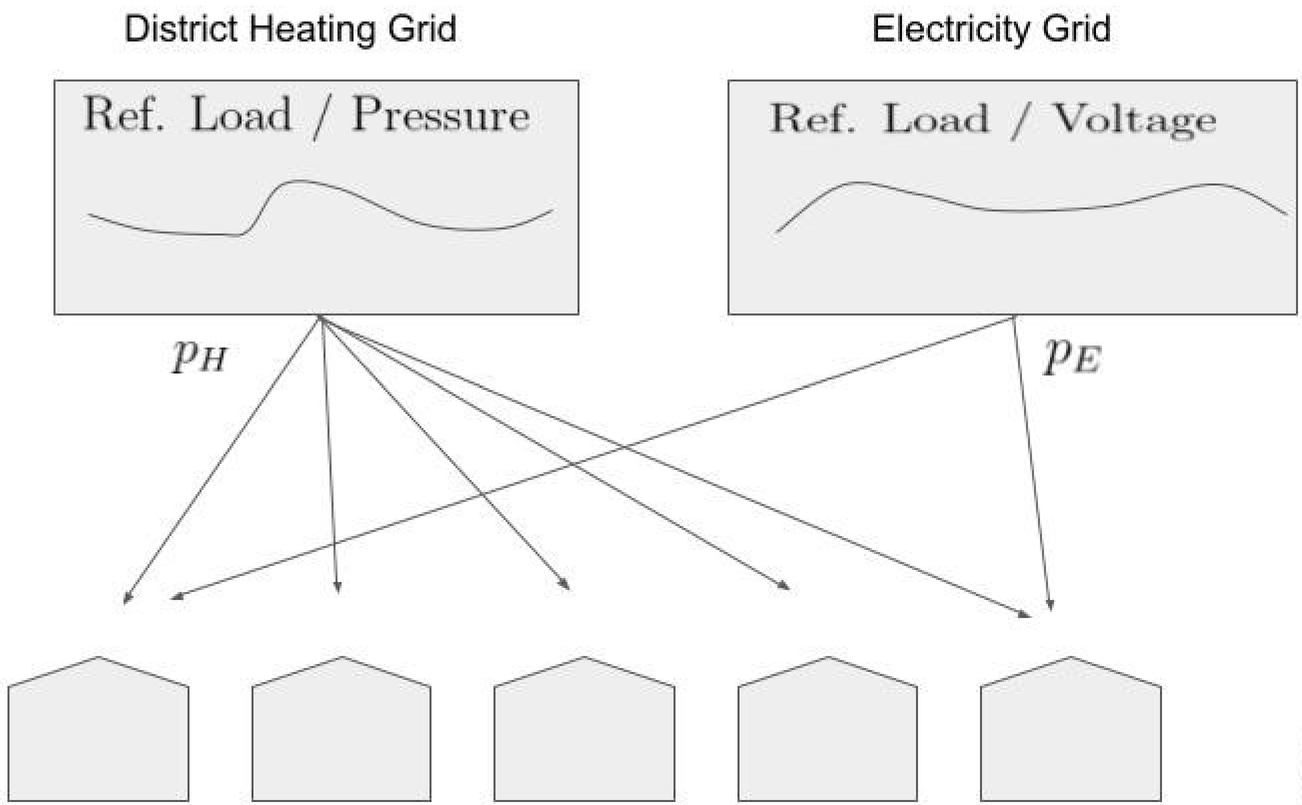
Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals u_j are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes 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



Sector coupling

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



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

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

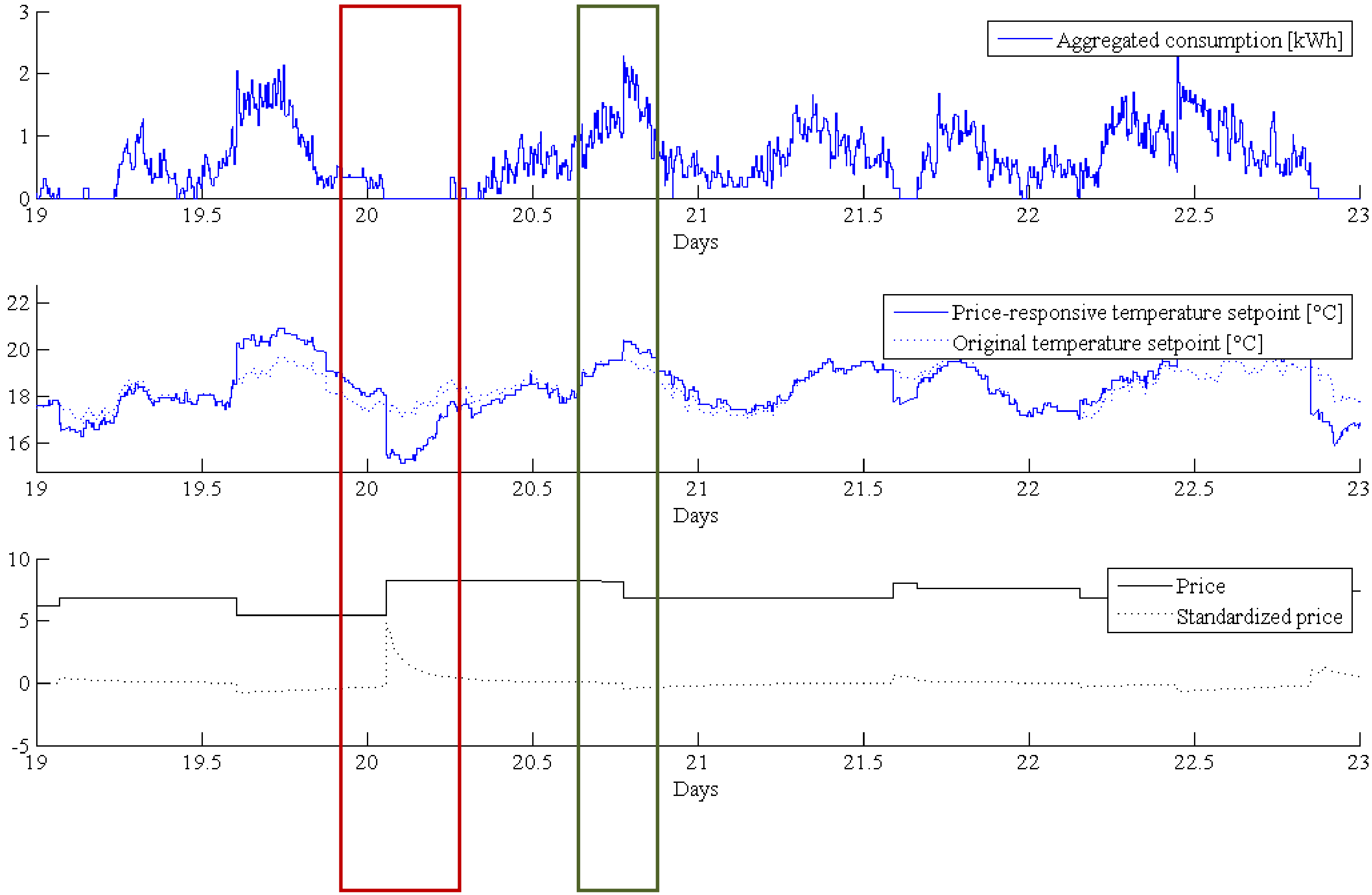
$$s.t.$$

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

Case study (Level III)

Price-based Control of Power Consumption (Peak Shaving)

Aggregation (over 20 houses)



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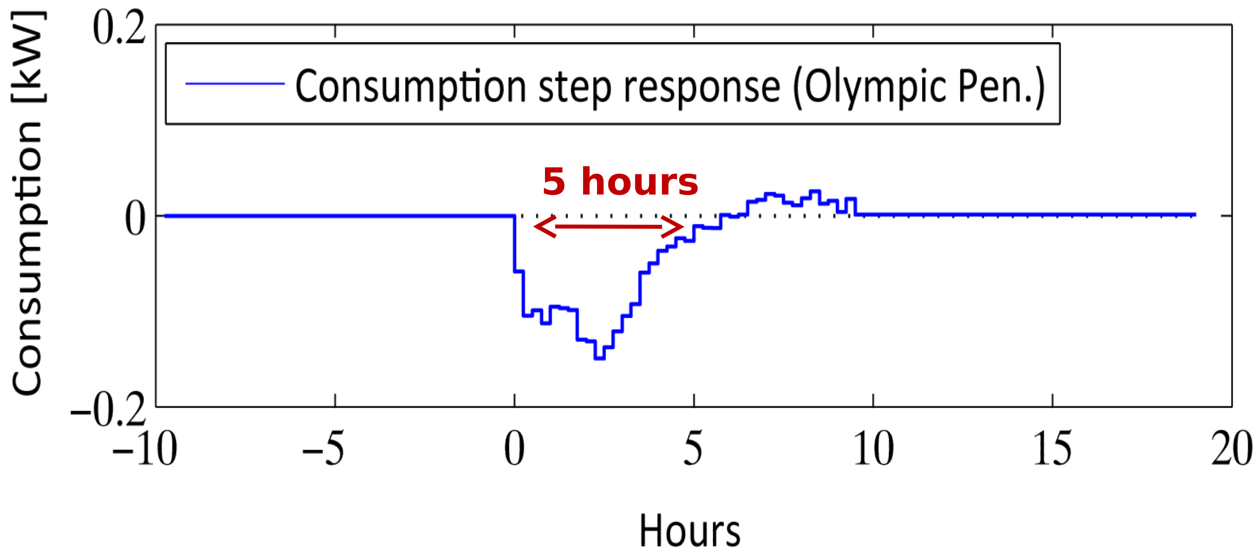
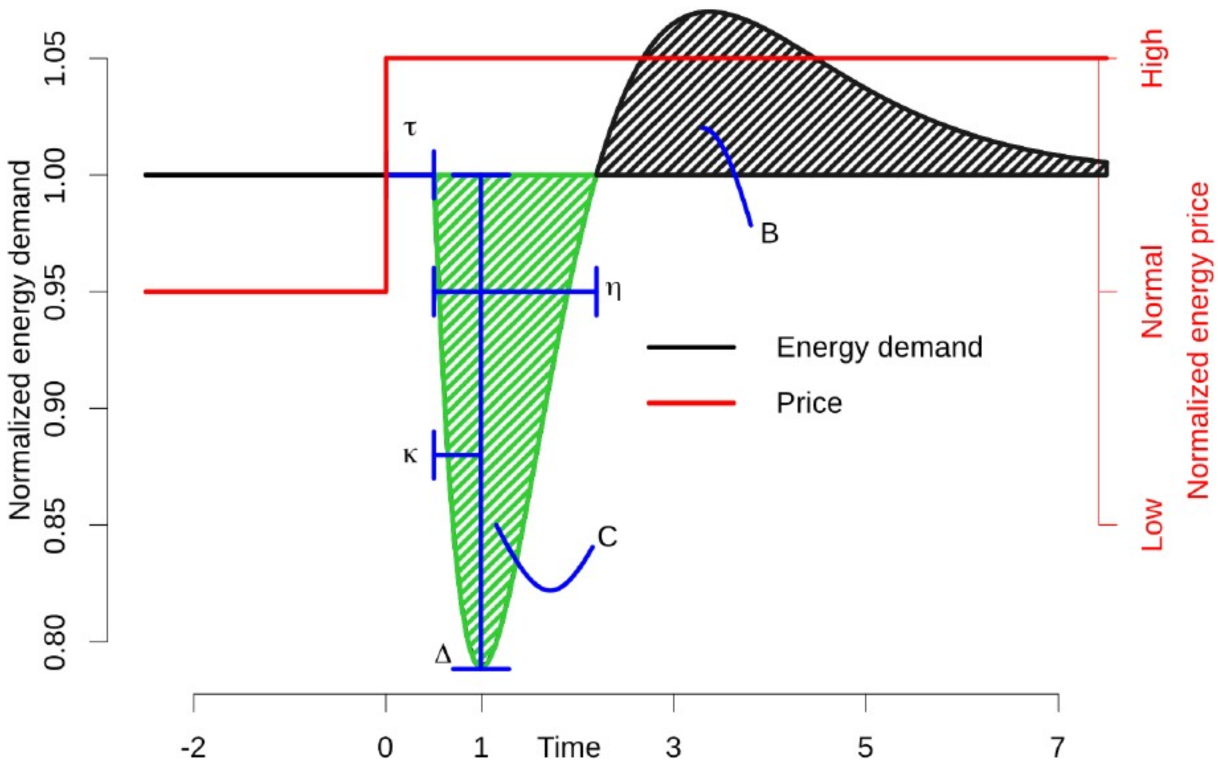
Response on Price Step Change

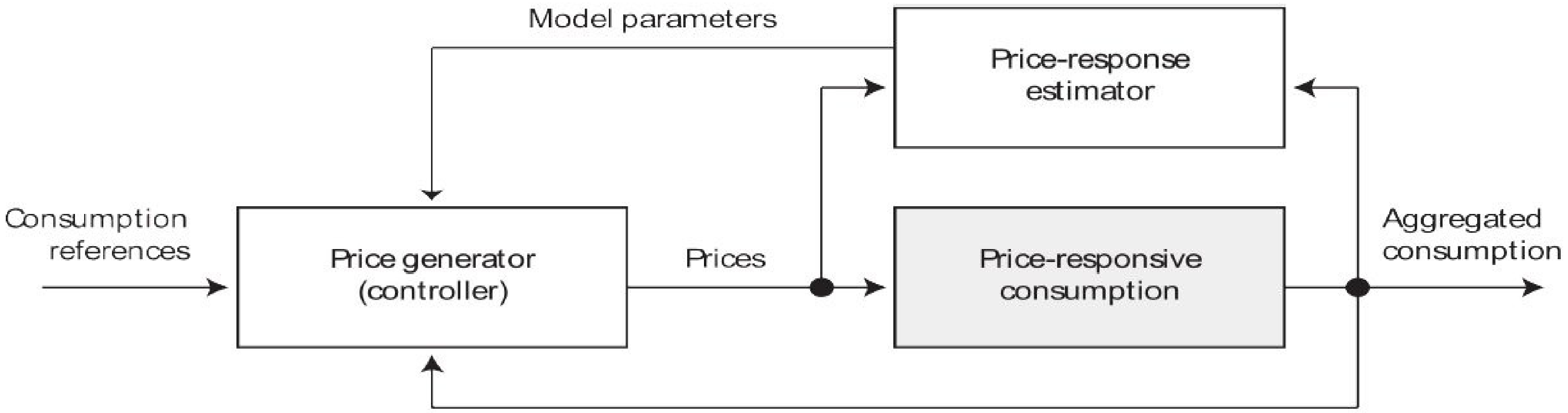


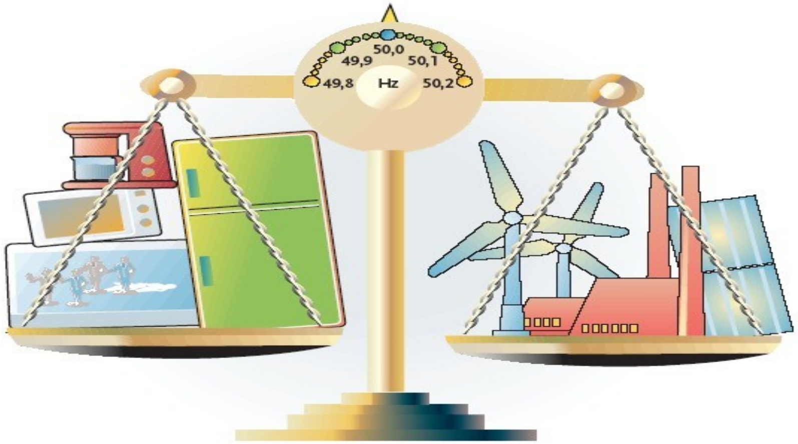
Flexibility Function

The ***Flexibility Function (FF)*** is used to characterize and control the flexibility at **all scales (incl all aggregation levels)**.



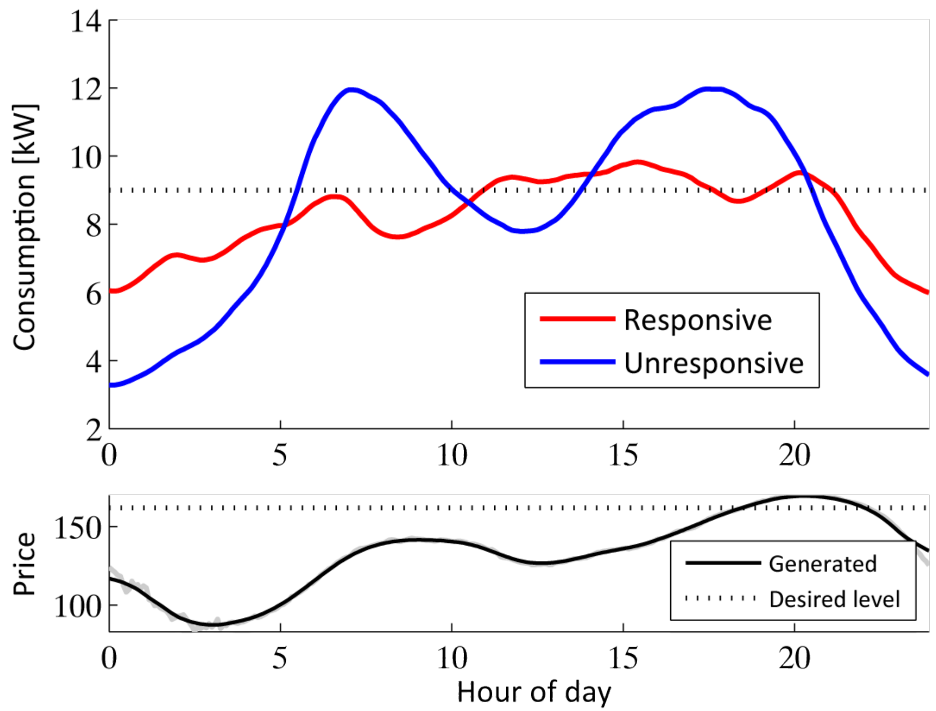
Control of Power Consumption



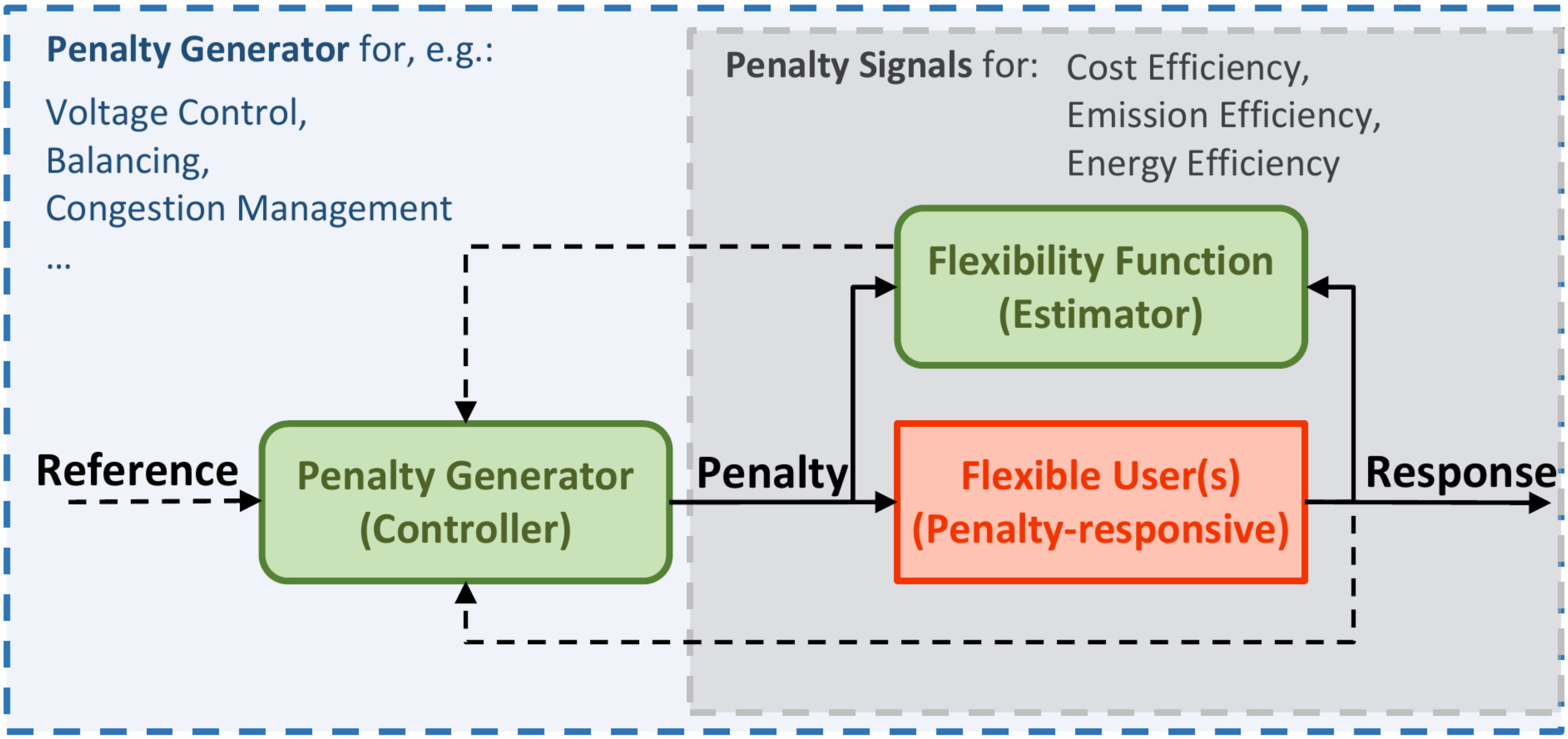


Control performance

Considerable **reduction in peak consumption**



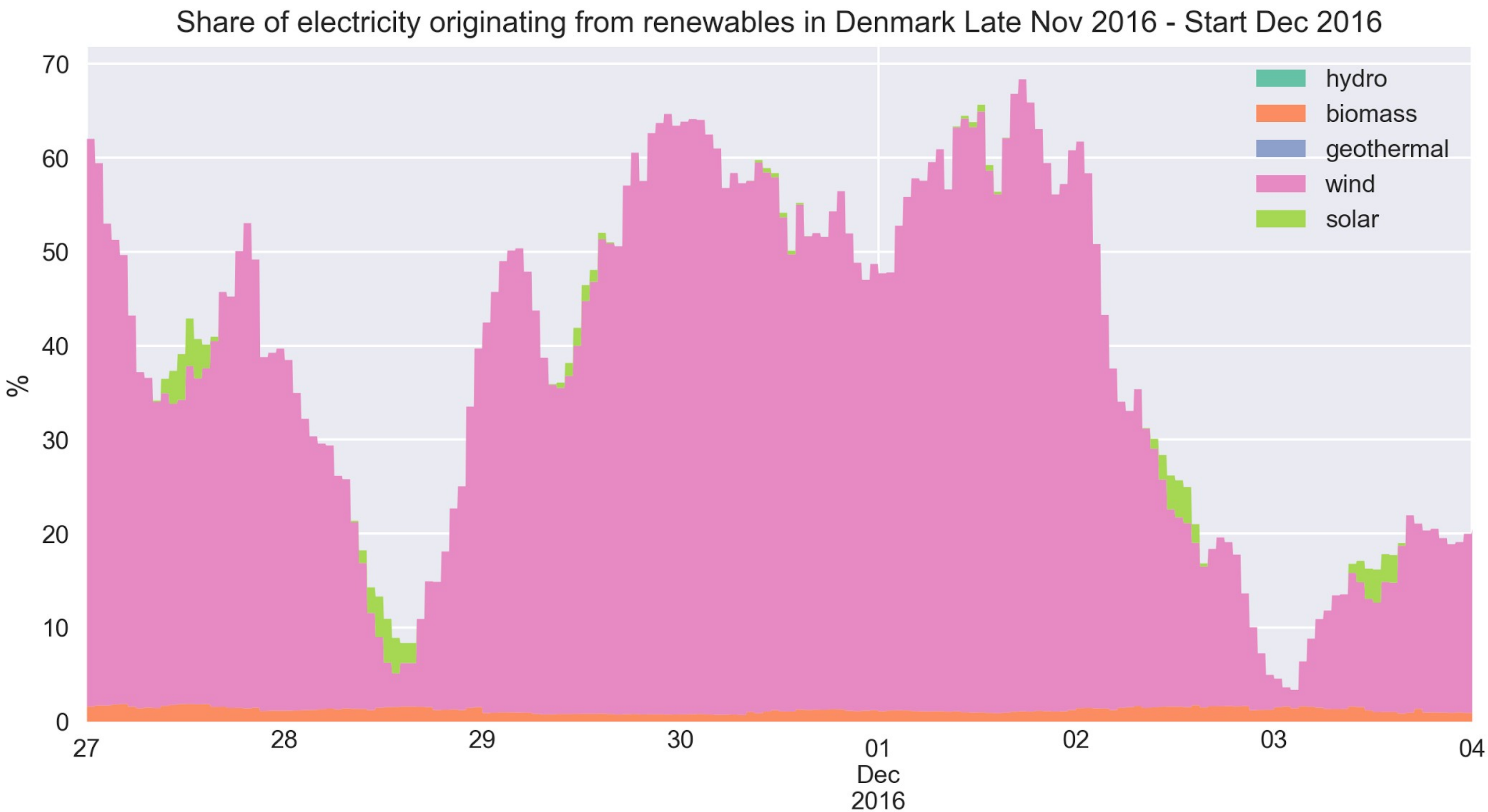
A FED example: Flexible Users and Penalty Signals



Case study (level IV)

Control of heat pumps for buildings with a pool

(Price/CO2-based control)



Source: pro.electicitymap.org

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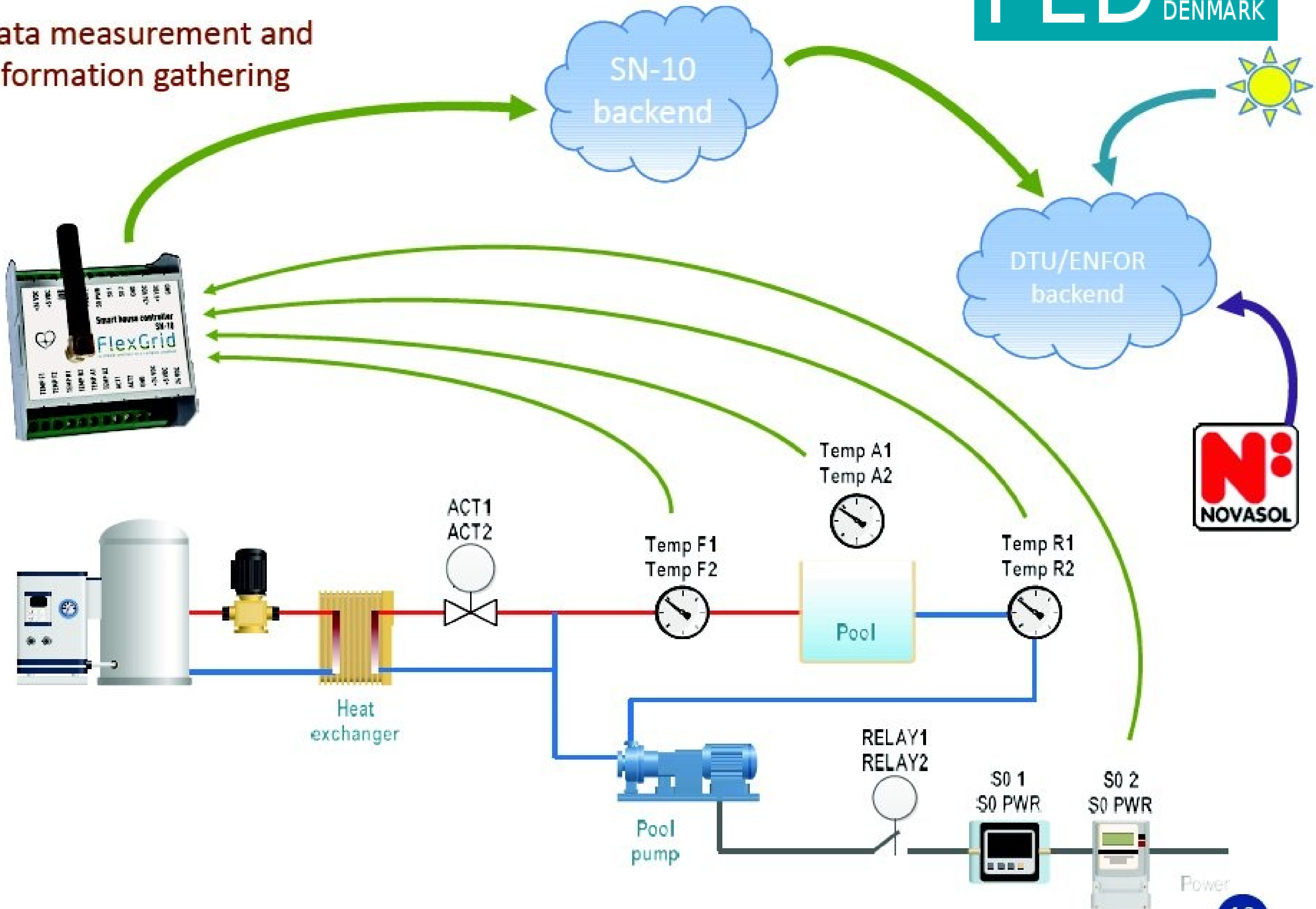
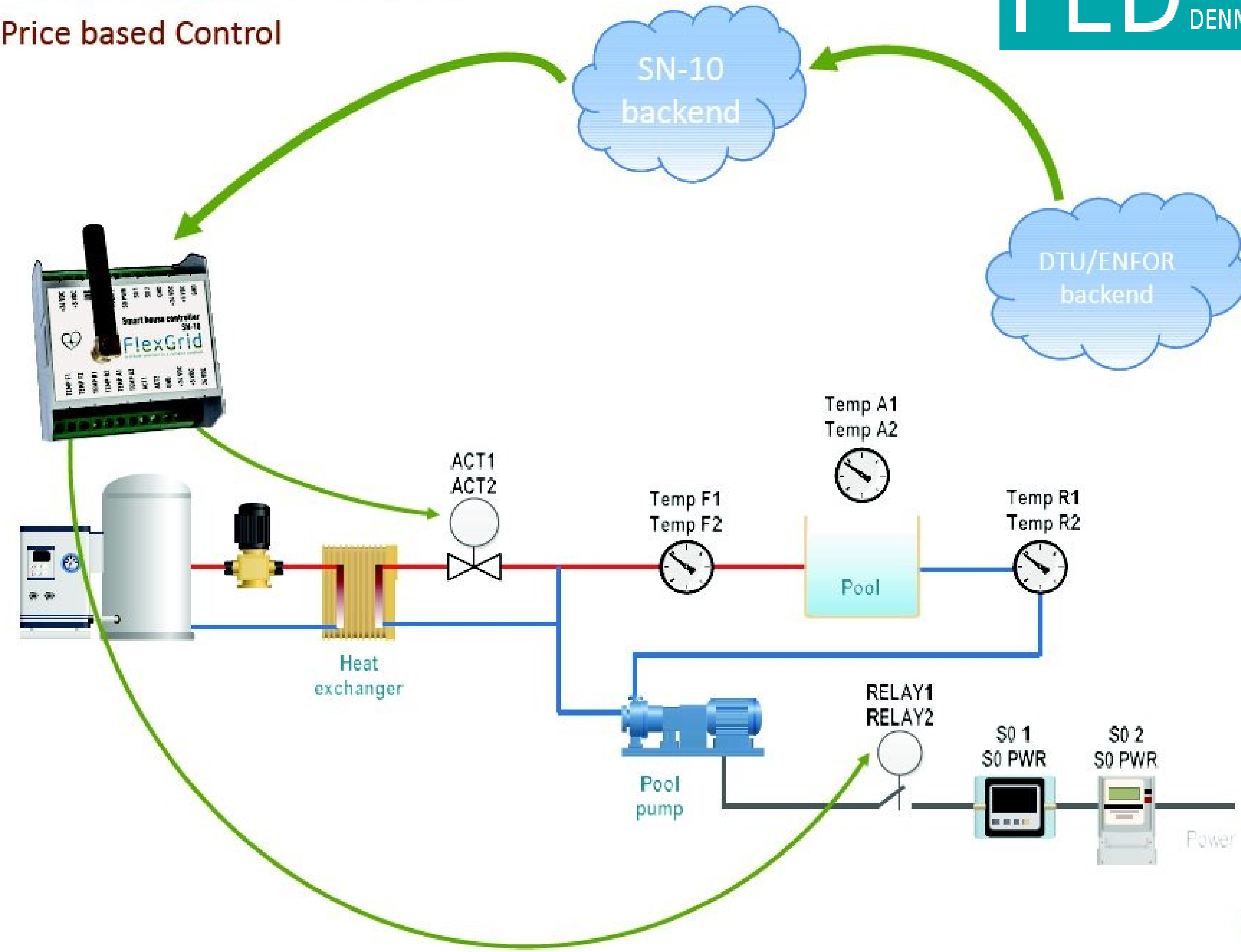
How does it work?

Data measurement and information gathering



How does it work?

Price based Control



Example: Price-based control

Example: CO2-based control (savings 10-30 pct)

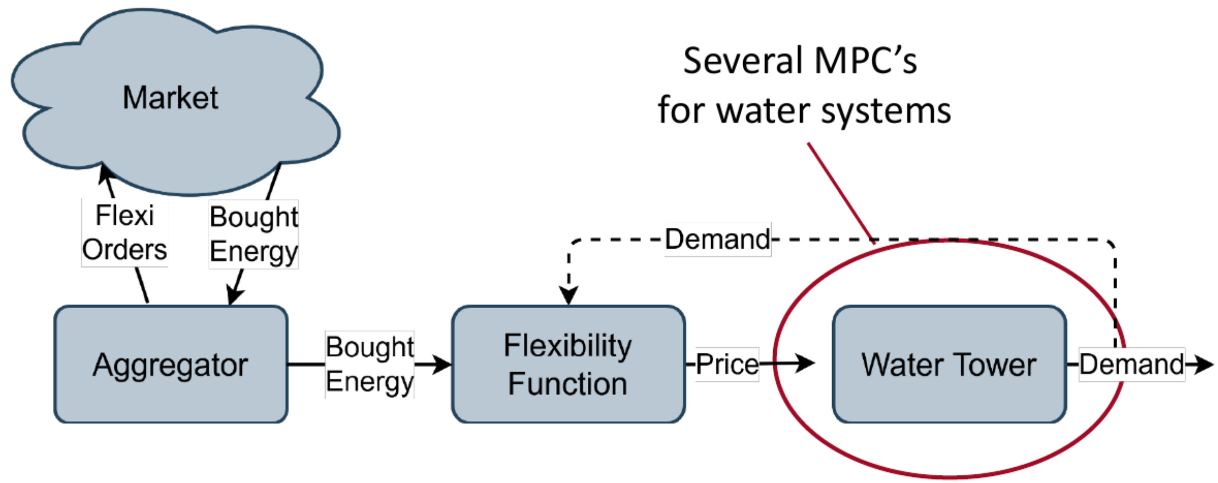
SE-OS Characteristics

- Security and Privacy by design
- Democracy and Transparency prioritized
- Able to unlock flexibility in LV grids
- Embedded TSO-DSO coordination
- AI and Grey-Box models for data-intelligence
- Hierarchy of optimization (or control) problems
- Creates a link between markets and the physics
- Cloud, Fog, Edge based (IoT, IoS) solutions – eg. for forecasting and control
- Simple setup for the communication and contracts
- Allow for special (technical) aggregators
- Facilitates energy systems integration (power, gas, thermal, ...)

Case study
(using existing markets)
Water Distribution Network
(joint work with Grundfos)

Price prediction

- We can control the system, handling the concerns of the water utilities.
- We can optimize the operation to a known price profile 24h forward in time.
- Unfortunately, the actual electrical price is decided on the fly.
- Makes it possible to for small energy user to be part of stabilizing the power grid.
- How to handle price setting towards the market is the topic of the remain of this talk.



Grid balancing trough the power marked is handled globally.

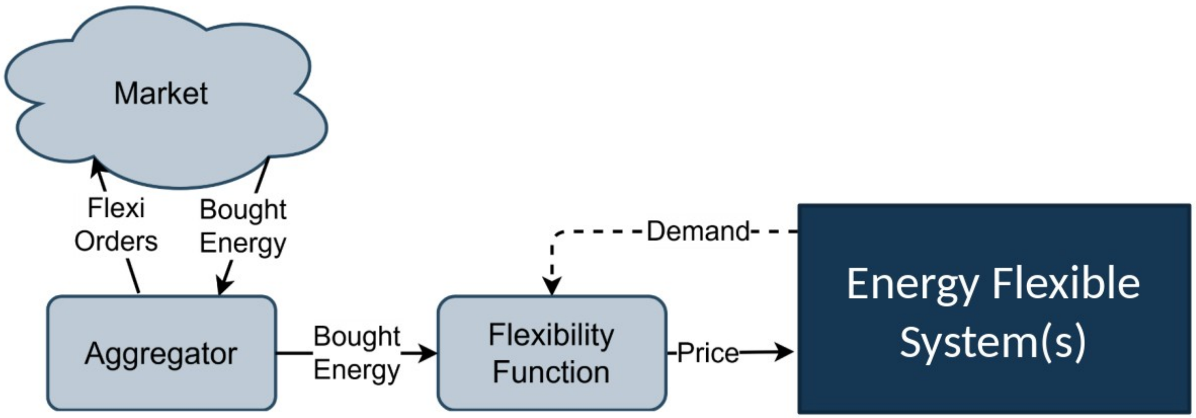
Local control is handled locally.

Flexibility Function (key concept)

- Input: Price
- Output: Demand

- Estimate relation: Flexibility Function!

- Use Flexibility Function to design price signals.

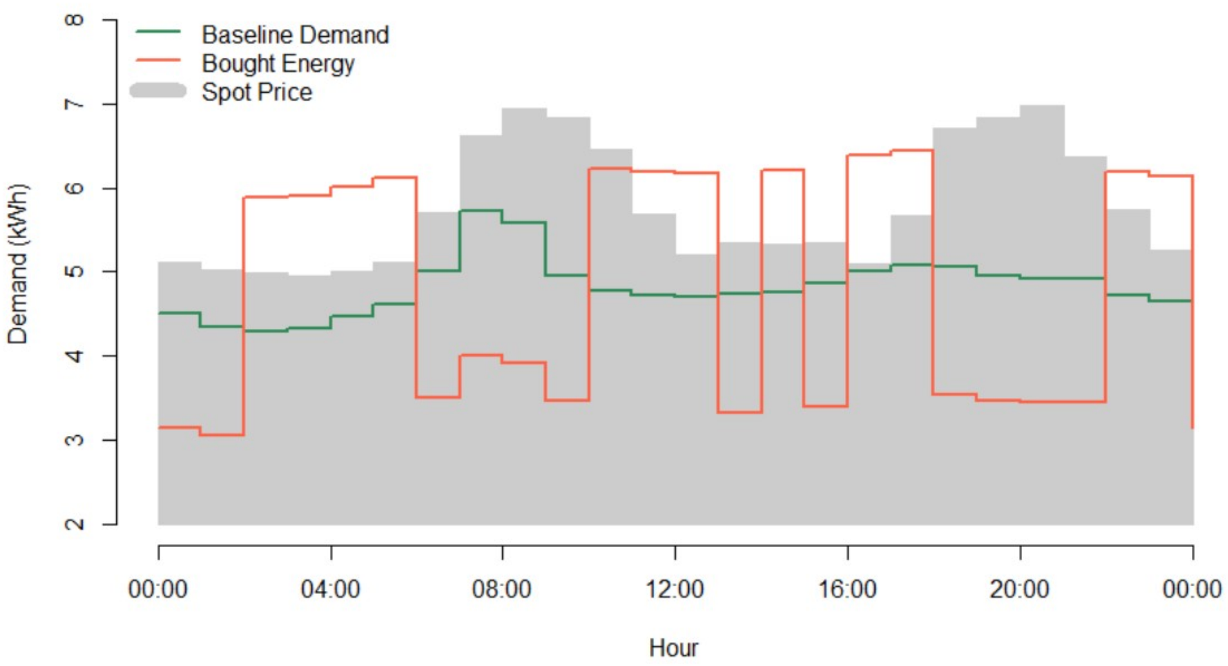


Bidding Flexibility into Markets

- Flexi orders consists of an **interval**, an amount of **energy**, and a **duration**.
- For example, **interval**: 08:00 – 12:00, **energy**: 1 MWh, **duration**: 2 hours.
- Result: 1 MWh bought in the 2 cheapest hours between 08:00 and 12:00.
- Can be combined with regular spot market bids to obtain part flexibility

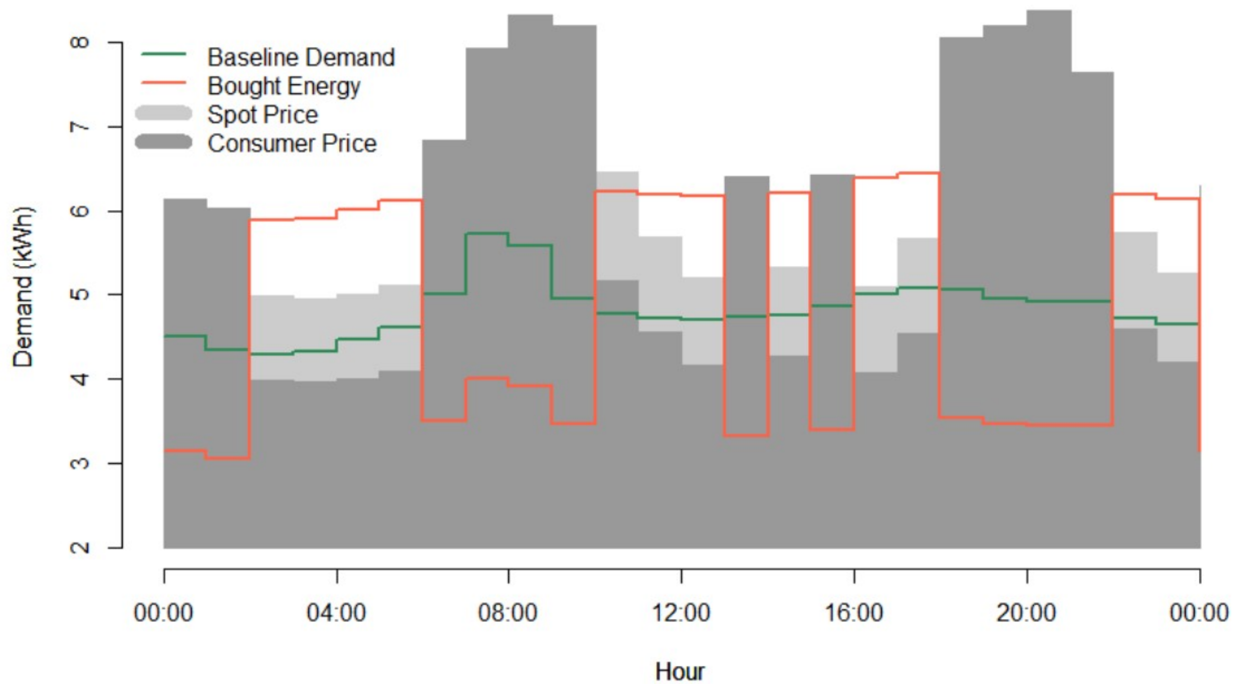
Bidding Flexibility into Markets

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



Bidding Flexibility into Markets

Solve FF(Price)=Bought Energy:

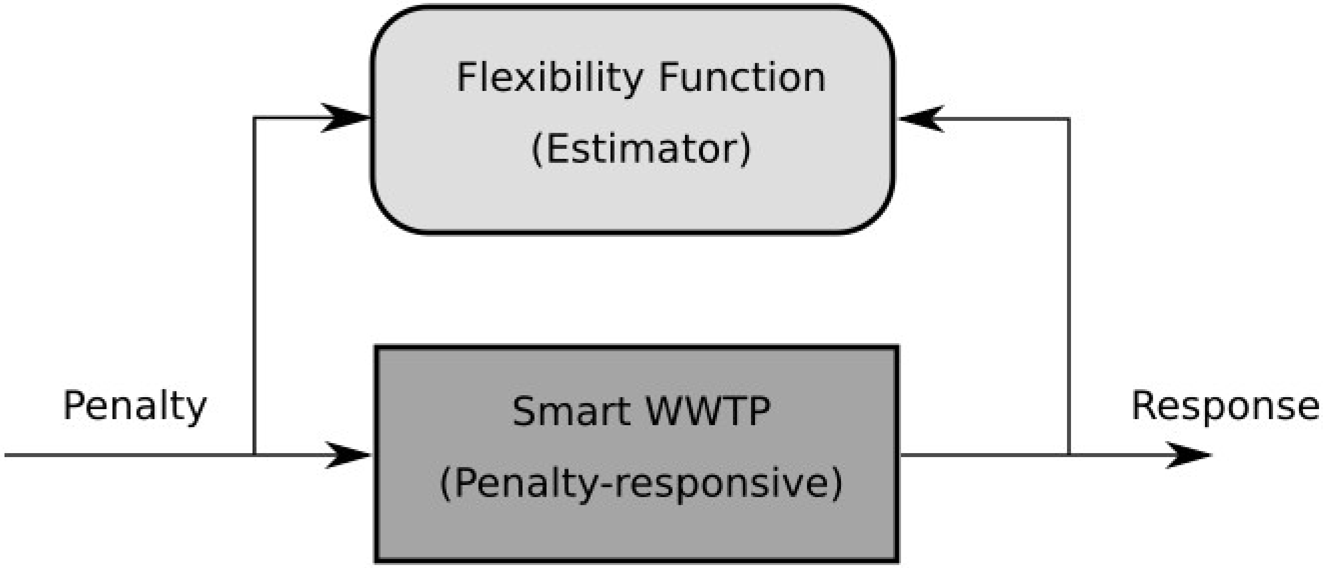


Case study

Wastewater Treatment

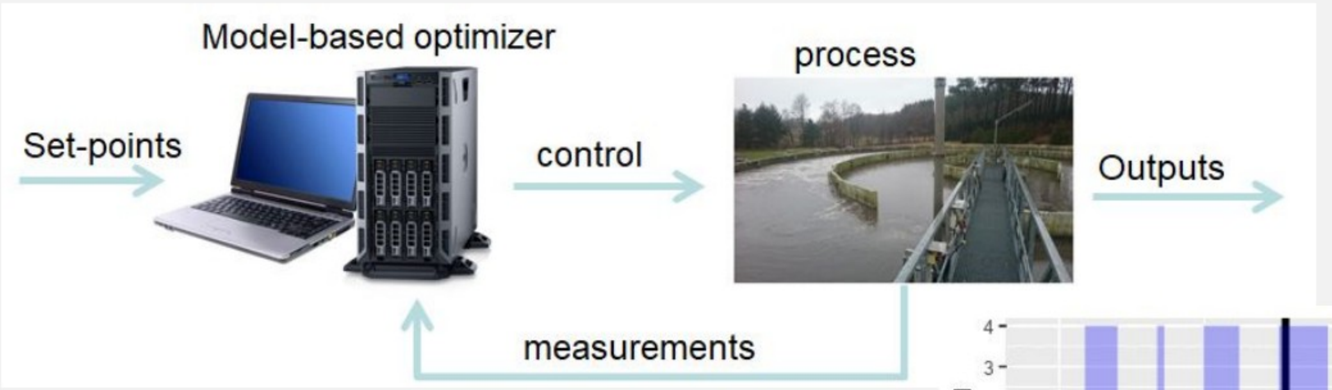
(Collaboration with Krüger/Veolia)

Flexibility Function

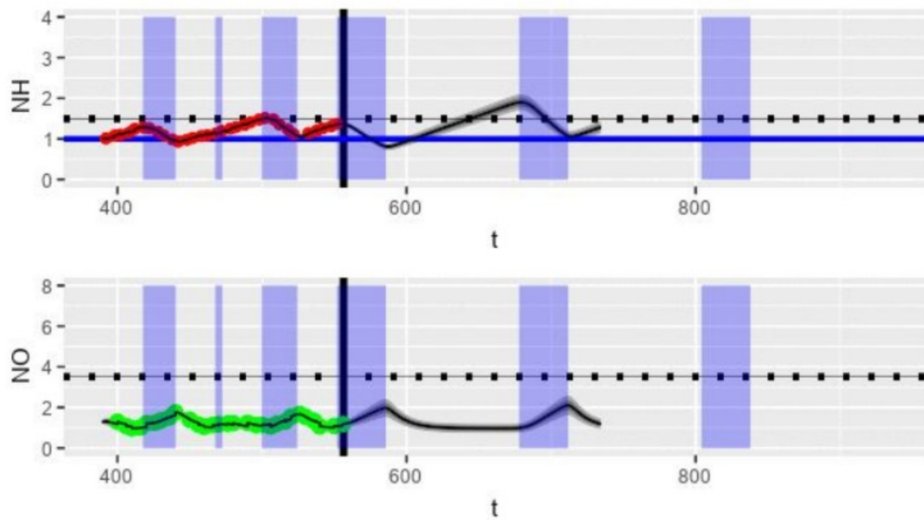


Wastewater Treatment Plant

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 (Wastewater Treatment Plant)

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

Example: Control of Wastewater Treatment Plant (Nørre Snede)

Objective (minimize)	Cost [DKK/day]	GHG emissisions [kg-CO2-eq/day]
Effluent concentrations	409.6	269.9
Electricity consumption	298.3	406.5
Operational costs	288.5	395.7
GHG emissions	352.5	232.3
Current control	317.5	358.4

- Optimizing operational costs – 9.2 pct savings compared to currently implemented control
- Optimizing (minimizing) GHG emissions – 40.9 pct lower emission compared to optimizing for costs

Center Denmark

Digitalization Hub for Accelerating the Green Transition

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Trusted Data Sharing Platform

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

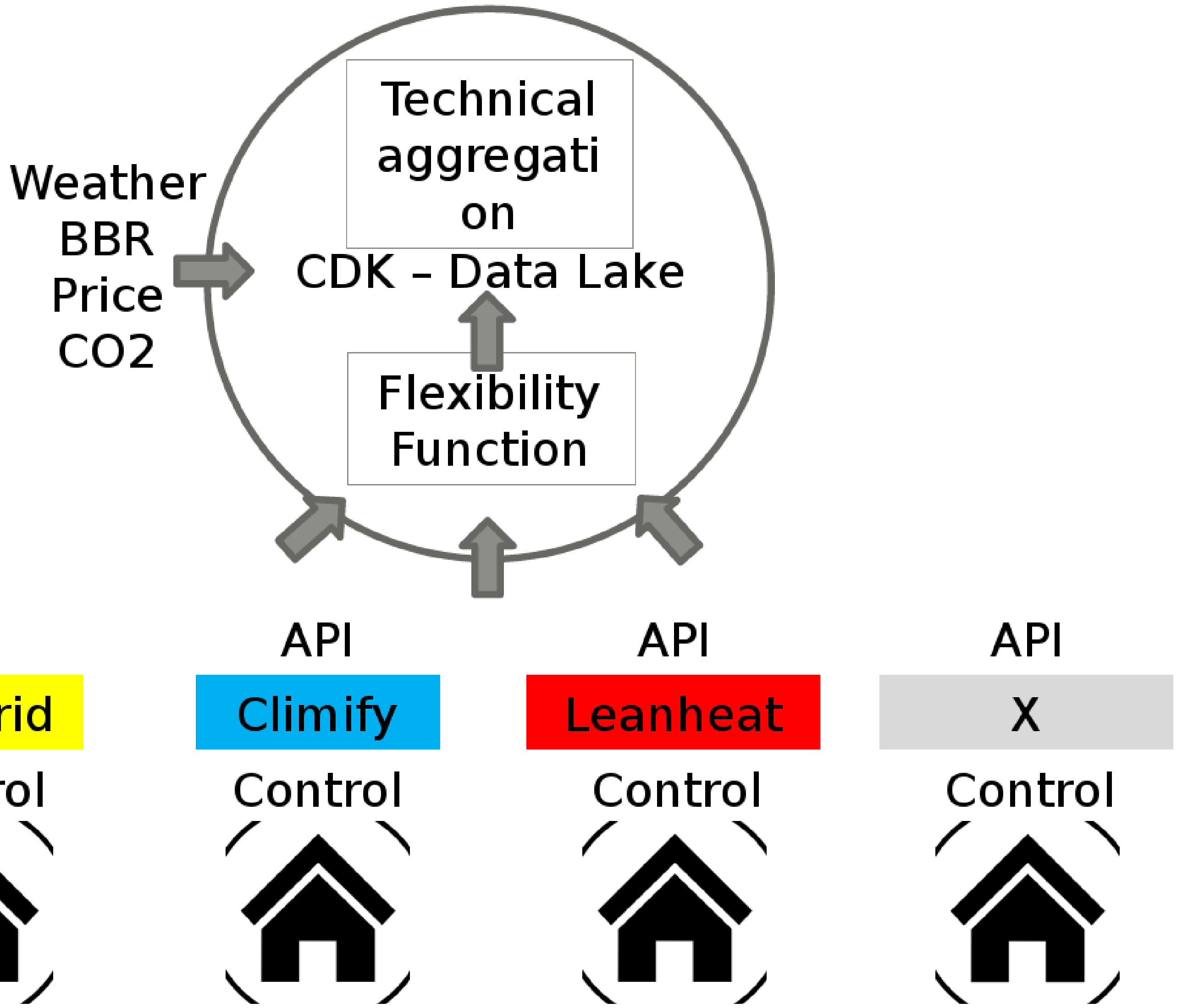
Participants accepting the market rules benefit from the exchange mechanisms and shape together an open market for data.

This is how we work together

Center Denmark
Control Room and Data Space
Spatial–Temporal thinking

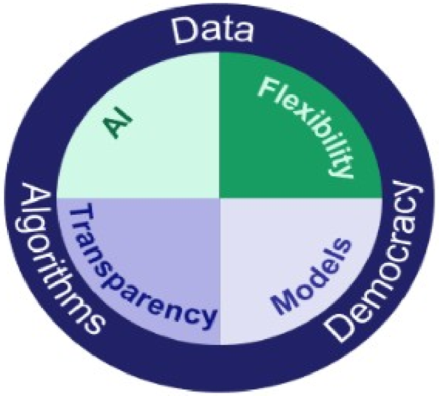
Center Denmark aims at enstablishing a trusted data-sharing data space which put priorities in cyber security and in enpowering the customers such that they are able to provide flexibility without being subject to disproportionate technical requirements, administrative requirements, procedures and charges

Technical Aggregator at Center Denmark
Control Hierarchies



Summary

- The future weather-driven energy system calls for disruptions. We need **a deep digitalisation** (AI, IoT, Cloud/Fog/Edge Computing, **Hierarchy of Controllers**, etc.)
- Consequently we need **an operating system** for the future smart energy system
- We need **transparent**, **safe** and **democratic** solutions
- We need **data hubs** for energy related streaming data (like **Center Denmark**)
- We are looking forward to EU's upcoming 'Digitalisation of Energy Action Plan'



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DSO Perspectives

- Well designed price signals important in balancing of the distribution grid
- New tariff models to support price signals
- Local tariffs are possible
- Real-time tariffs linked to the actual challenges in the grid
- New tariff that can take care of local energy system – which is ‘off grid’
- Better support for (local) energy communitives
- Better power quality at LV level
- Users (incl industry) can contribute with their flexibility
- Possibility for multi-supply systems (eg. district heating and electricity for heating)
- Privacy by design
- Better (active) use of transformators
- New ways to integrate battery systems into the power grid
- Use the inverters as voltage stabilizing devices in the grid
- Can facilitate energy systems integration / sector coupling

TSO perspectives

- Automated solutions targeting also small units
- External control of specific units
- Allow for specialized aggregators (eg. wastewater)
- DSO-TSO combined optimization/coordination
- Maximize flexibility potential
- Reduced number of specialized markets (eg related to flexibility)
- Smart integration of large-scale P2X facilities
- Facilitate energy systems integration

Meetings with Margrethe Vestager (main conclusions)

DTU

- The future is trusted data sharing environments (exactly like Center Denmark)
- The most important single factor is 'trust'!
- Next to that is reasonable data sharing aggrements (Data spaces)
- It is very important to be able to combine data from many different sources
- We need to develop by test-and-evaluation (it's not possible to design the solution before test) – we need to focus more on sandboxing.
- We need to focus on energy and data cooperatives (in Danish - Andelstanken)
- We need disruptions (conventional solutions might not be solutions for the future)
- We must ensure privacy, democracy, transparency, fairness, GDPR, ...
- Contracts must be simple and easy to understand

Flexibility Function Model

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

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

Business Ecosystem