Energy Smart Water

From workshops arranged by Energinet and Center Denmark

Henrik Madsen

Applied Mathematics and Scientific Computing (DTU)

https://www.flexibleenergydenmark.dk/

https://www.smart-cities-centre.org

http://www.henrikmadsen.org

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.

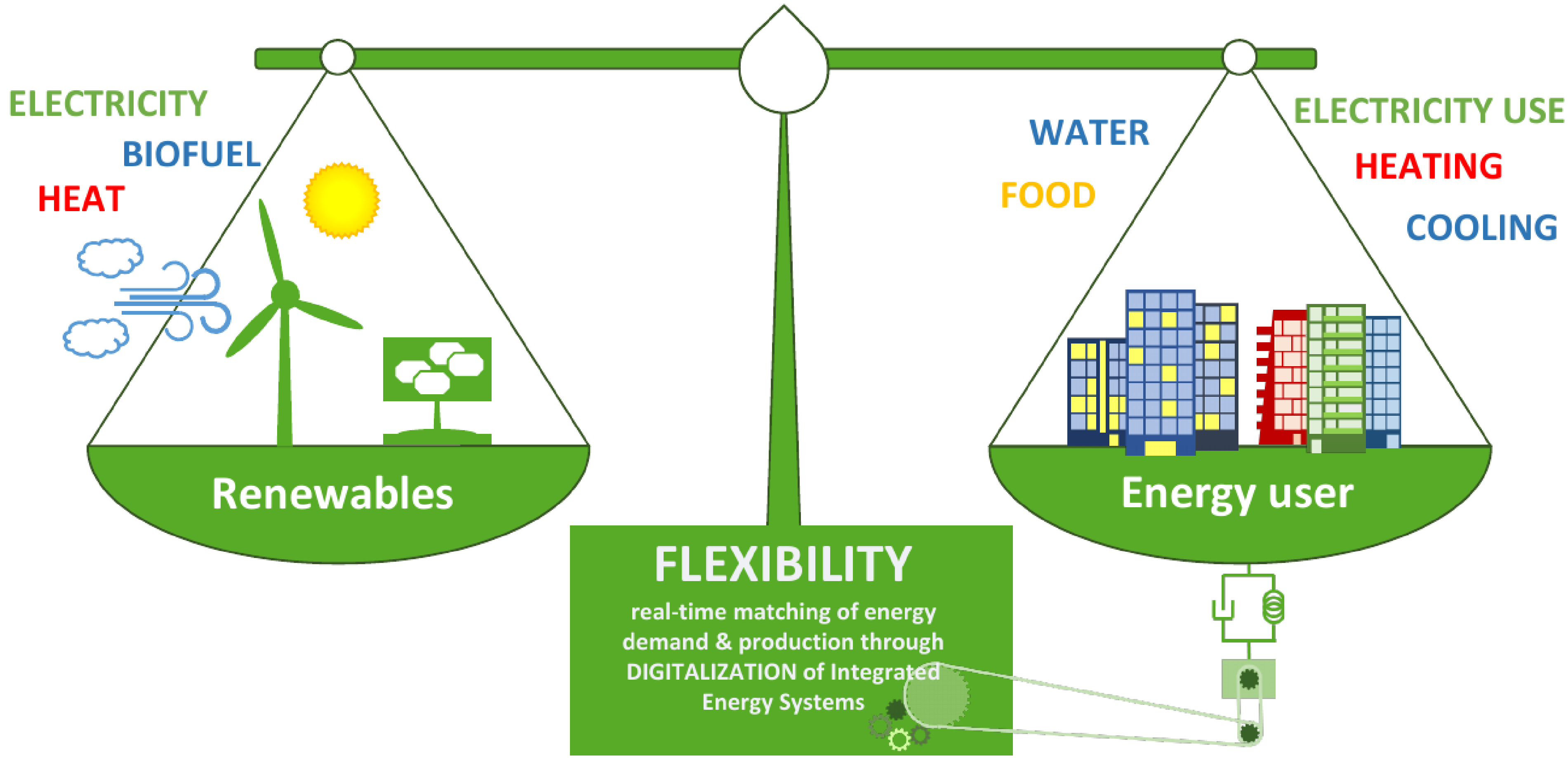
Yes, there will be distributional impacts to manage and some incumbents and consumers may need temporary support during the transition, but the overall net benefits for consumers will likely significantly outweigh the downsides given the

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.

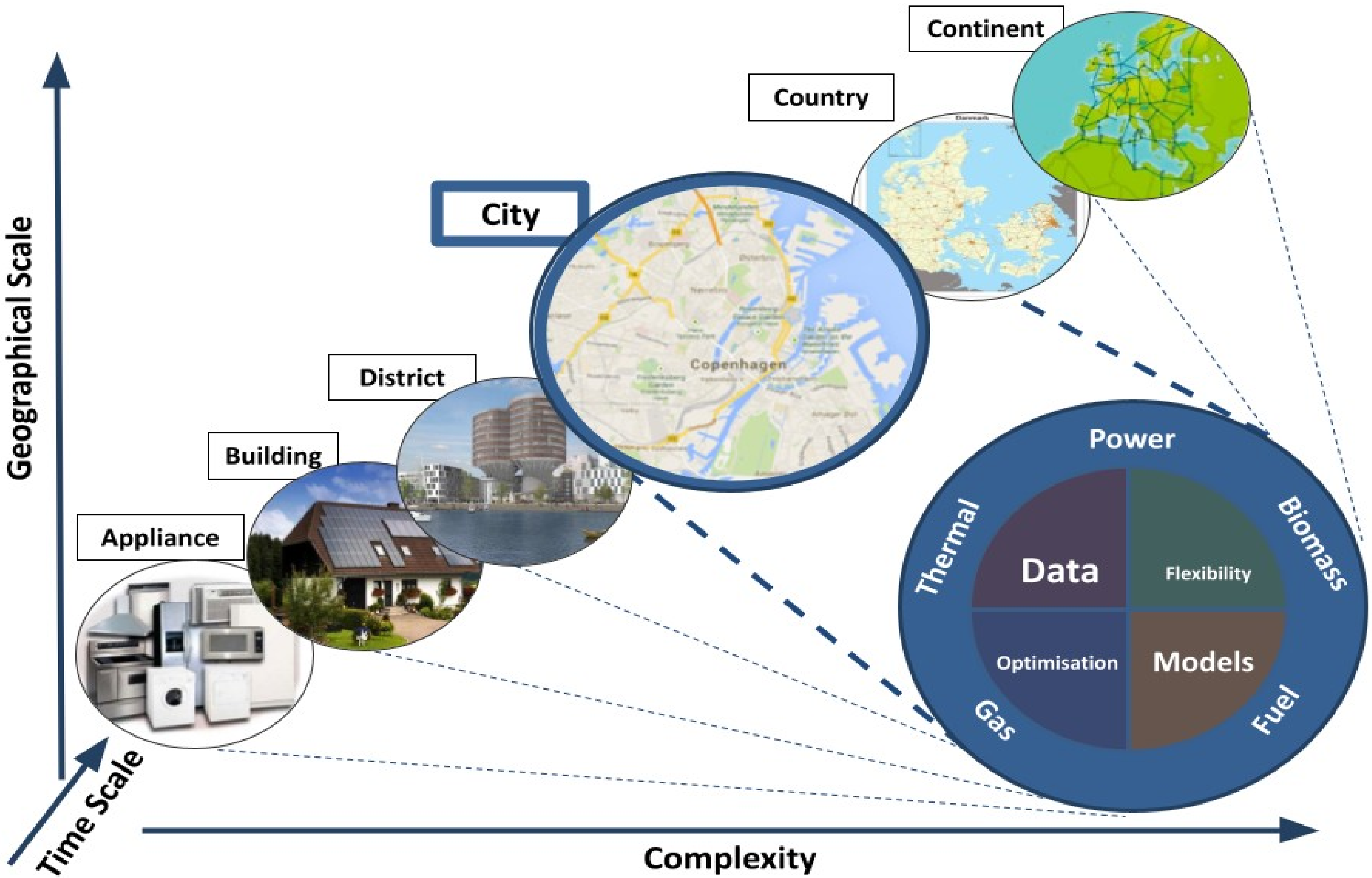
The Challenge: Denmark Fossil Free 2050



Markets – Needed changes

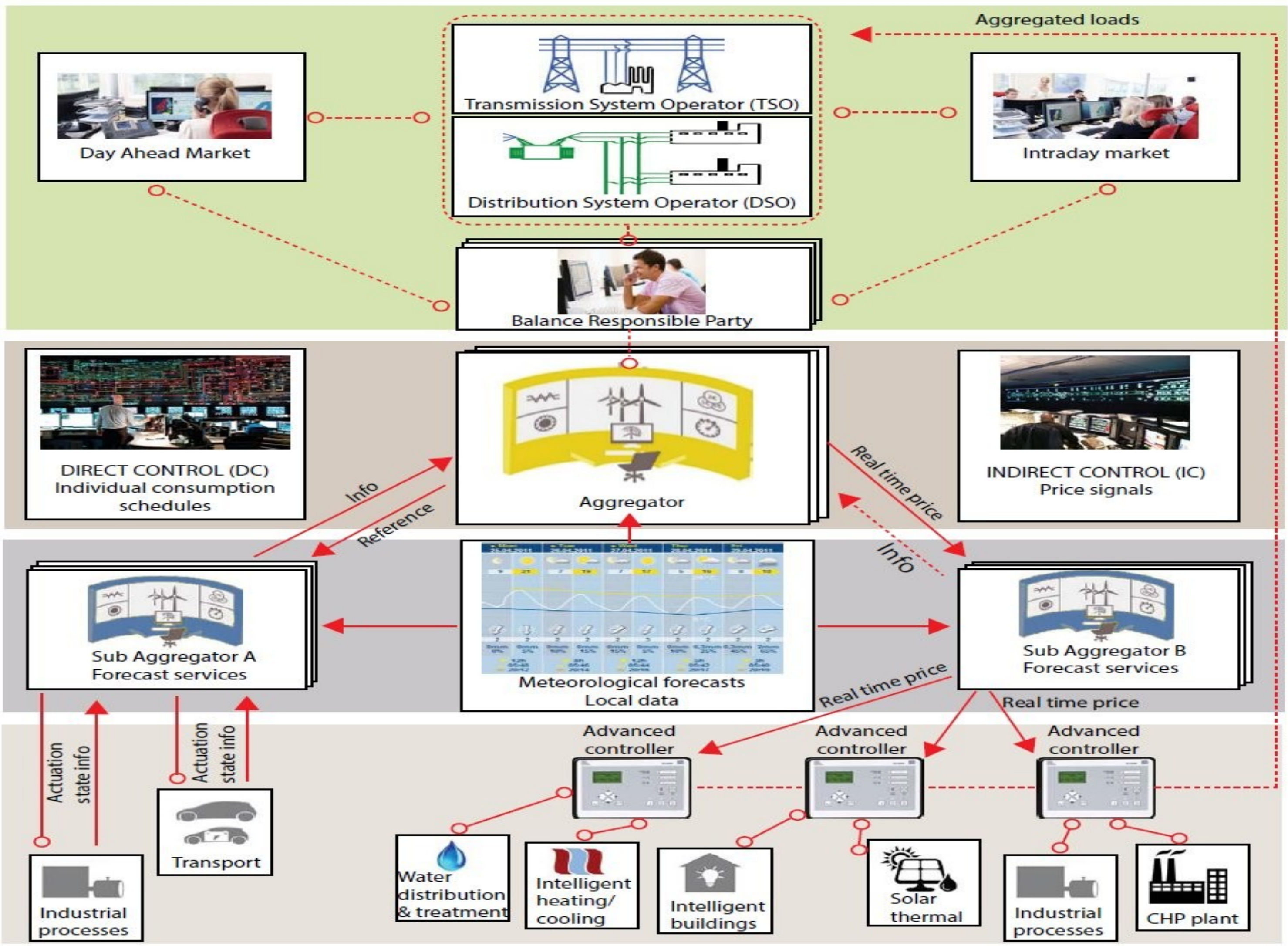
- Static -> **Dynamic**
- Deterministic -> **Stochastic**
- Linear -> **Nonlinear**
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, ...) -> **Coordination + Hierarchy**
- Speed / problem size -> **Decomposition + Control Based Solutions**
- Characterization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

Temporal and Spatial Scales



Smart-Energy OS

The Transformative Power of Digitalisation



(**Static**)

Conventional Markets

Linking Markets to Physics

(Flexibility Functions)

(**Dynamic**)

Local Flexibility Markets

(Hierarchy of controllers)

Flexibility Function

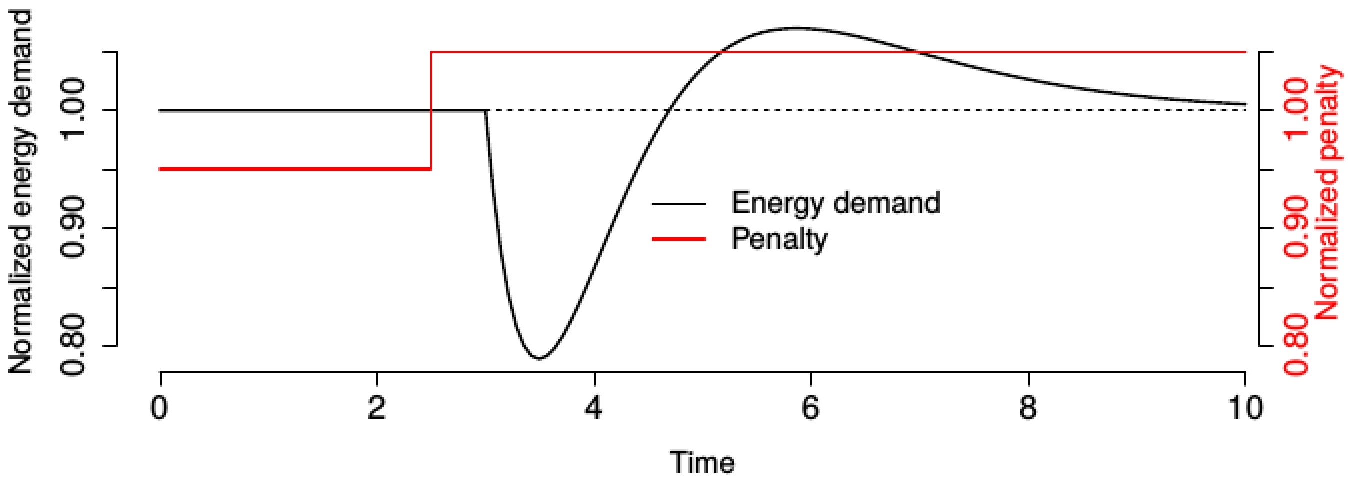


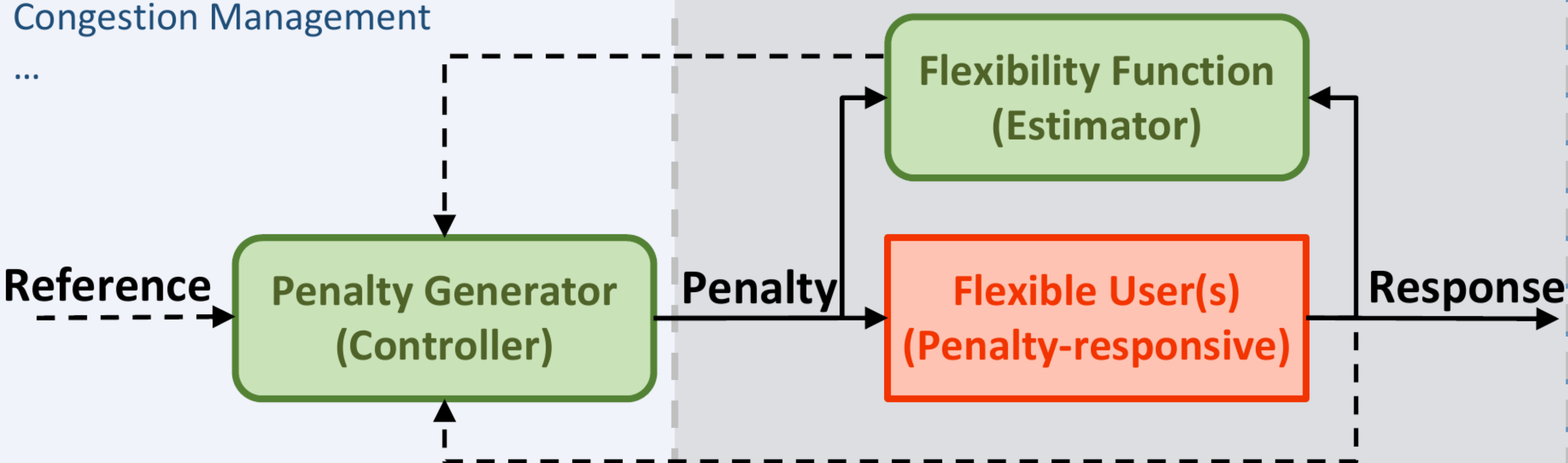
Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

A FED example: Flexible Users and Penalty Signals

Penalty Generator for, e.g.:

Voltage Control,
Balancing,
Congestion Management
…

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



Case study
(using existing markets)

Water Distribution Network
(joint work with Grundfos)

Auto-commissioning and MPC for water distribution networks

Application setup

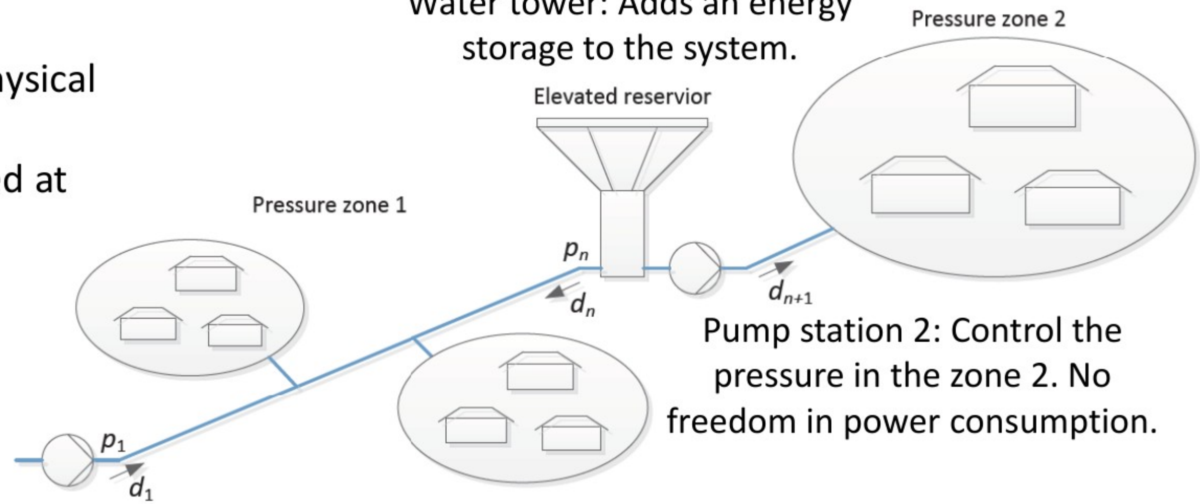
- or CO2 level.

- Control objective: Control the pump station 1 to minimize the energy cost.

- Constraints:
  - The level in the water tower must be maintained within certain limits.
  - The pump flow is limited by the physical constraints of the pumps.
  - Water quality should be maintained at all times (water age).

- Disturbances:
  - Water consumption in zone 1 and zone 2.

Water tower: Adds an energy storage to the system.



Pump station 2: Control the pressure in the zone 2. No freedom in power consumption.

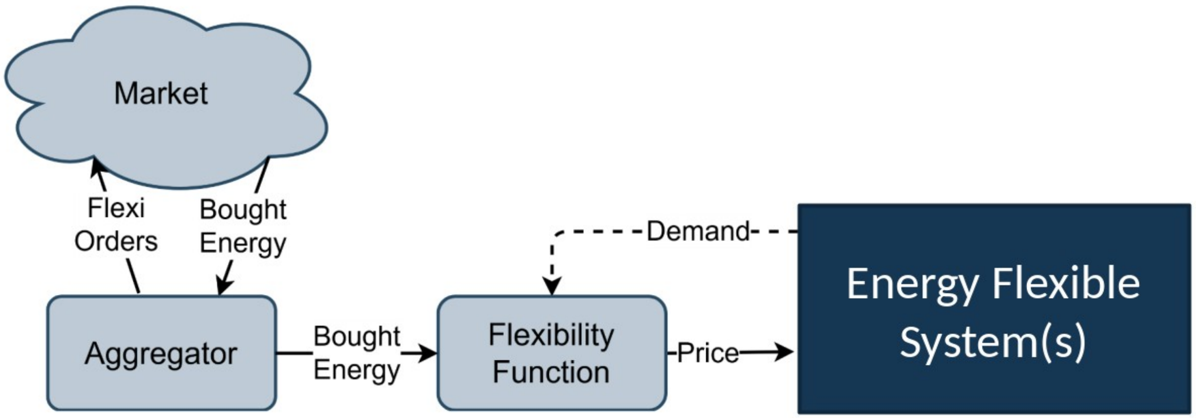
Pump station 1: Supplying zone 1 and the water tower.

Flexibility Function (key concept)

- Input: Price
- Output: Demand

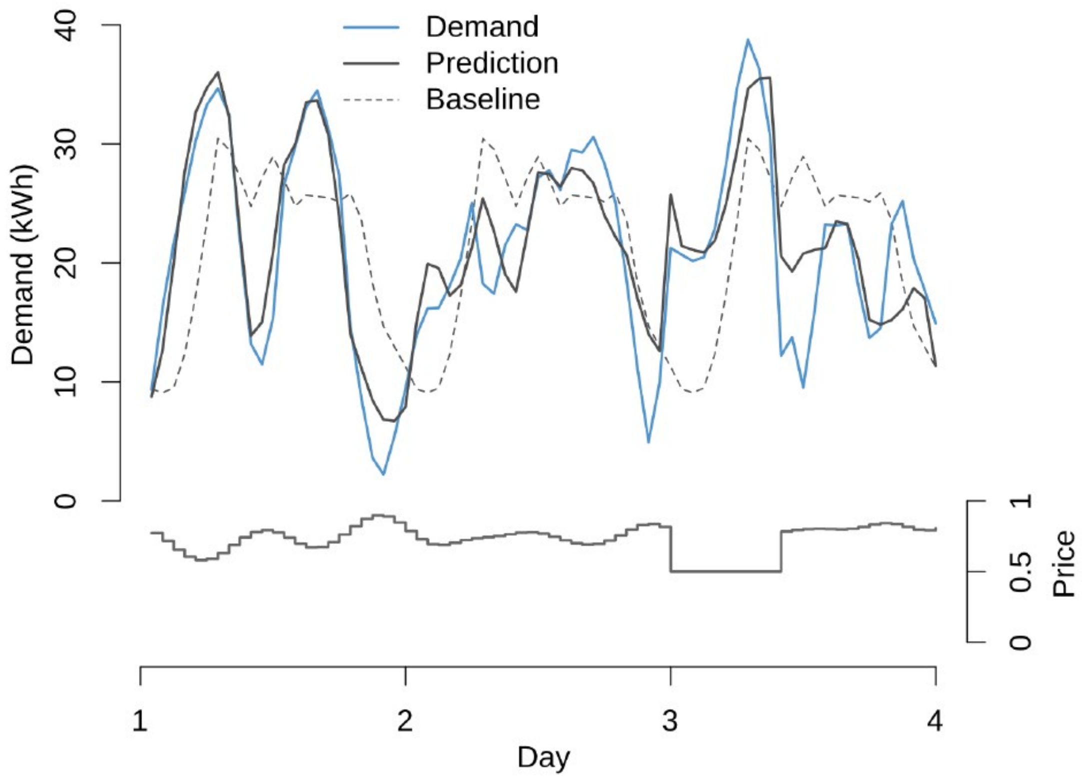
- Estimate relation: Flexibility Function!

- Use Flexibility Function to design price signals.



Flexibility Function: Accuracy

- Accurate several days ahead.
- We need only 24 hour predictions.

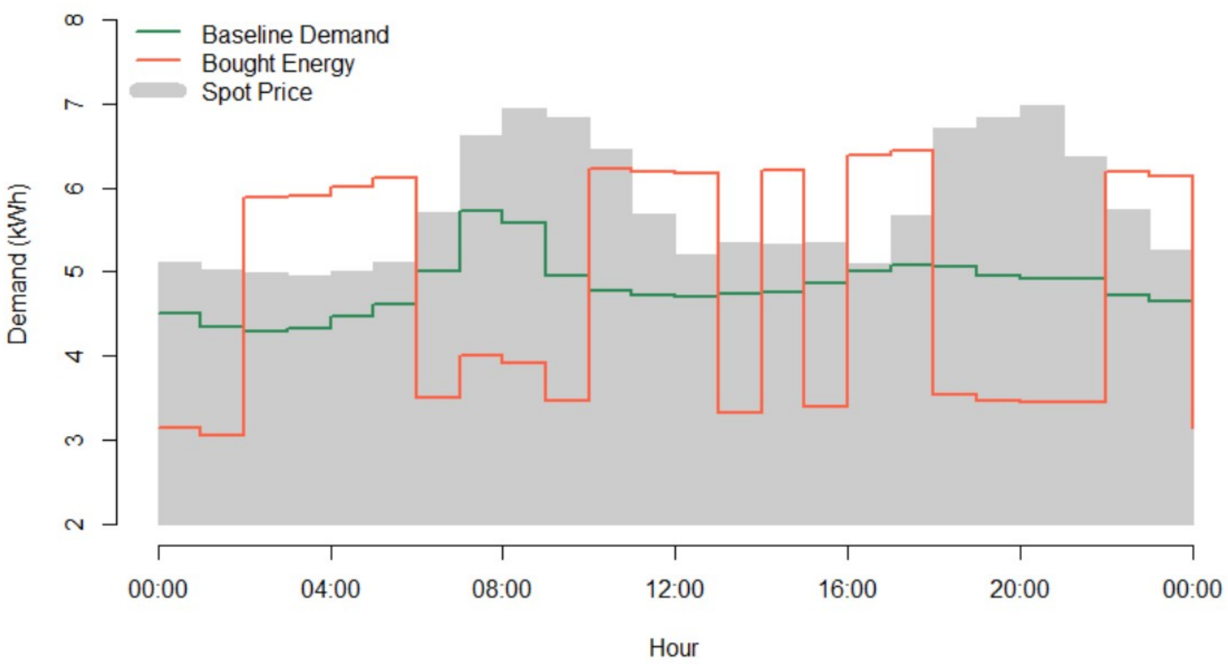


Bidding Flexibility into Markets

- 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

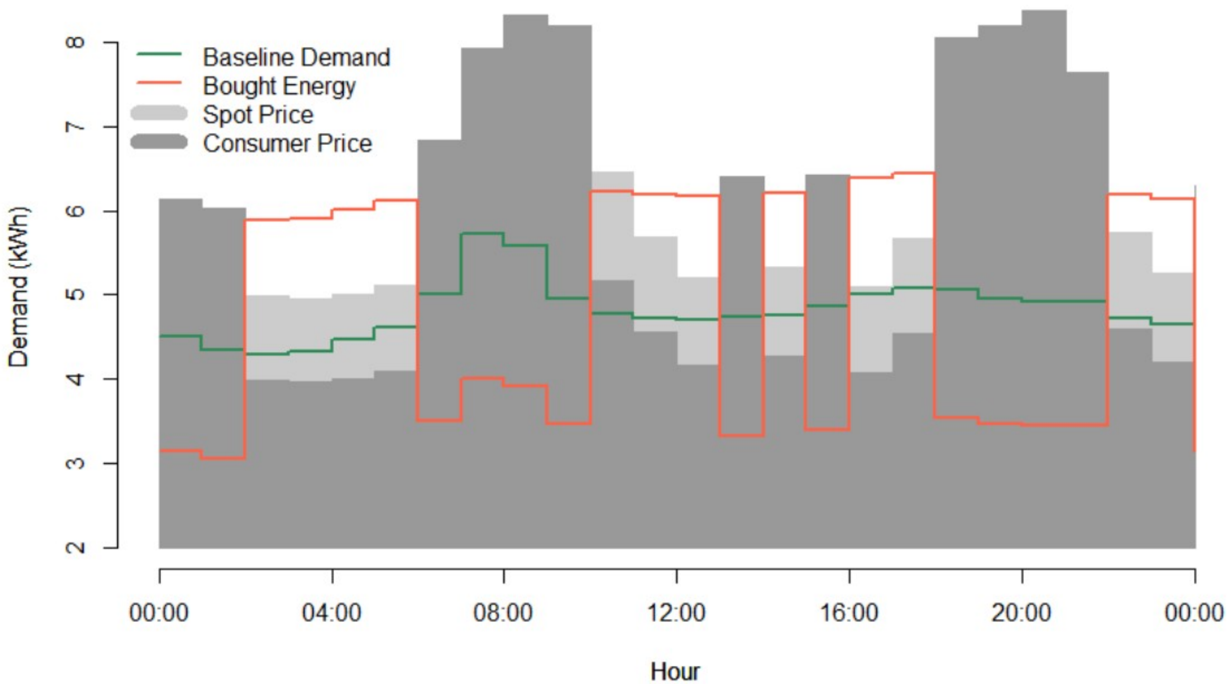
Bidding Flexibility into Markets

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



Bidding Flexibility into Markets

Solve FF(Price)=Bought Energy:



Results

- For one year of current market conditions 4.1% of the costs can be saved.
- With perfect foresight of spot prices and demand 5.4% could be saved – often assumed by other researchers.

Strategy	Costs $\left(\frac{\text{EUR}}{\text{year}}\right)$	Price $\left(\frac{\text{EUR}}{\text{MWh}}\right)$	Energy $\left(\frac{\text{MWh}}{\text{year}}\right)$
Baseline	44457	65.2	682
Flexible	42627 (-4.1%)	62.0 (-4.8%)	687 (+0.75 %)
Potential	42070 (-5.4%)	61.6 (-5.4%)	683 (+0.05%)

Larger savings with optimized market conditions – i.e. the Smart-Energy OS

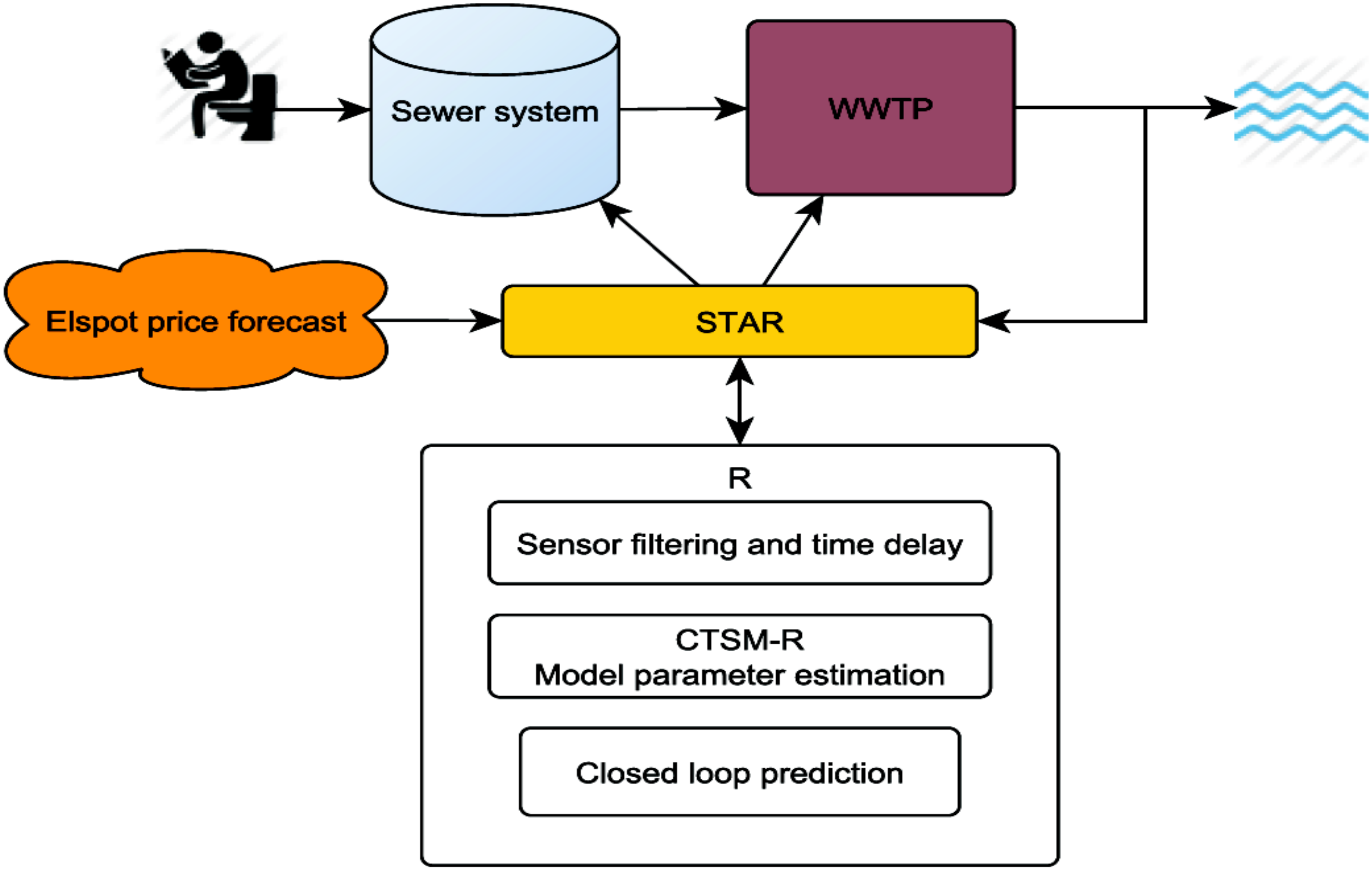
For more information:

Junker, R. G., Kallesøe, C. S., Real, J. P., Howard, B., Lopes, R. A., & Madsen, H. (2020). Stochastic nonlinear modelling and application of price-based energy flexibility. Applied Energy, 275(1), 115096. https://doi.org/10.1016/j.apenergy.2020.115096

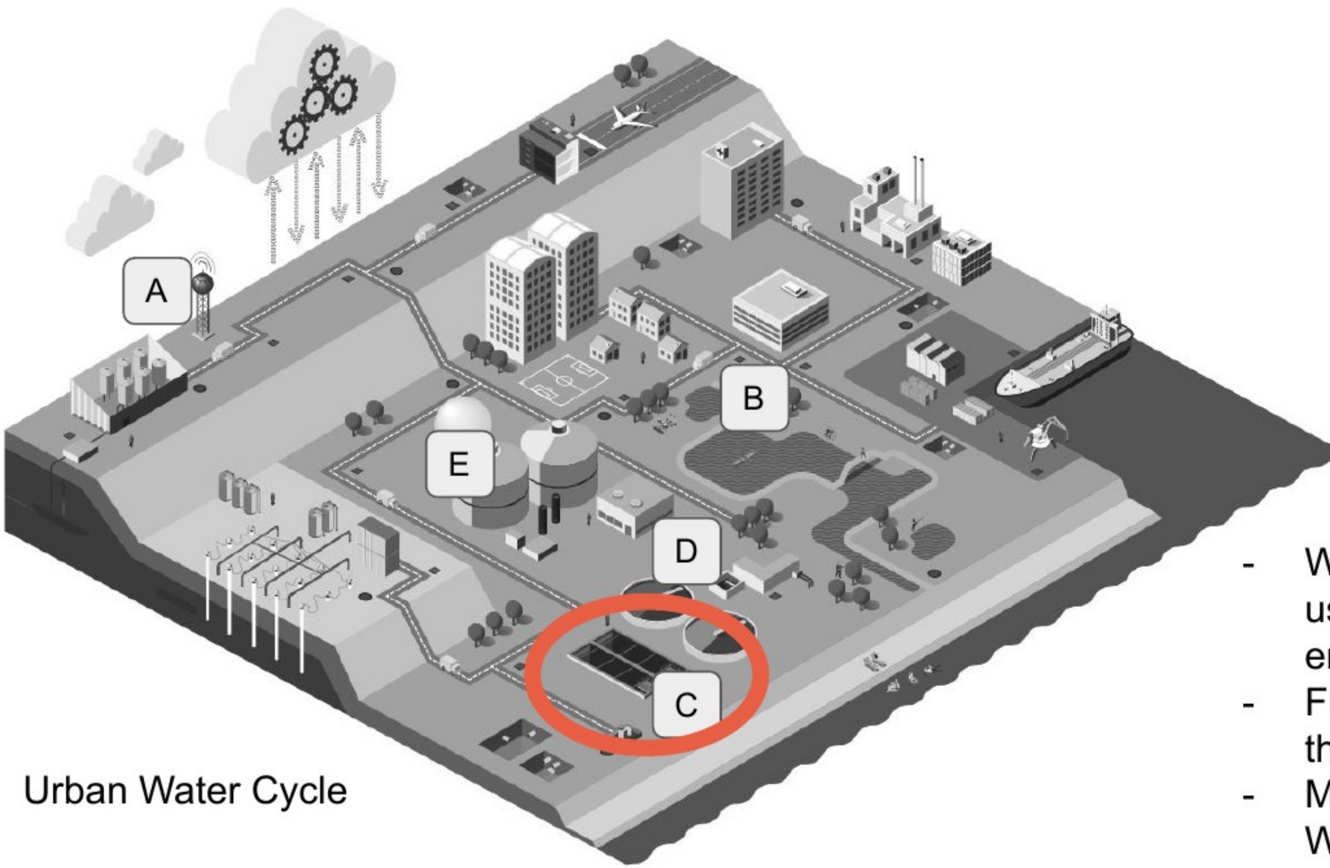
Case study

Wastewater Treatment
(Joint work with Kruger)

Energy Flexibility in Wastewater Treatment



Urban Water Cycle

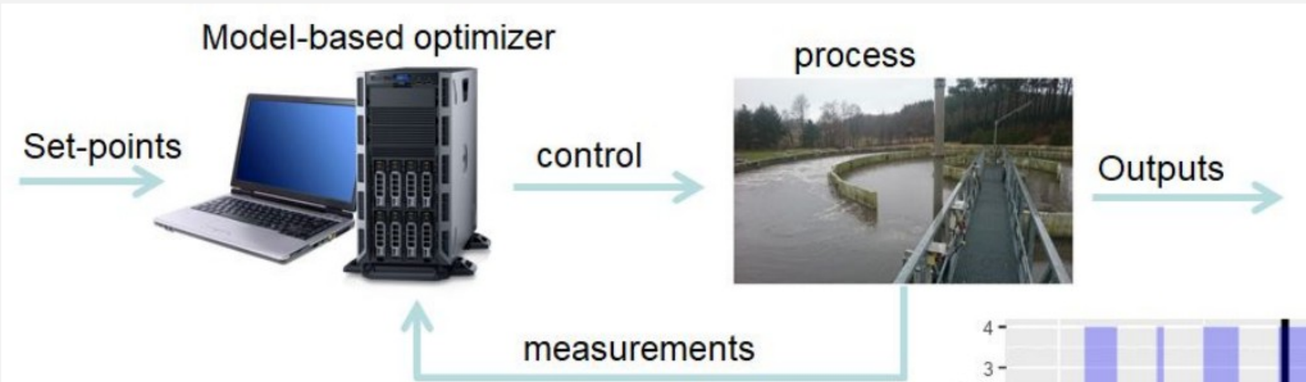


Urban Water Cycle

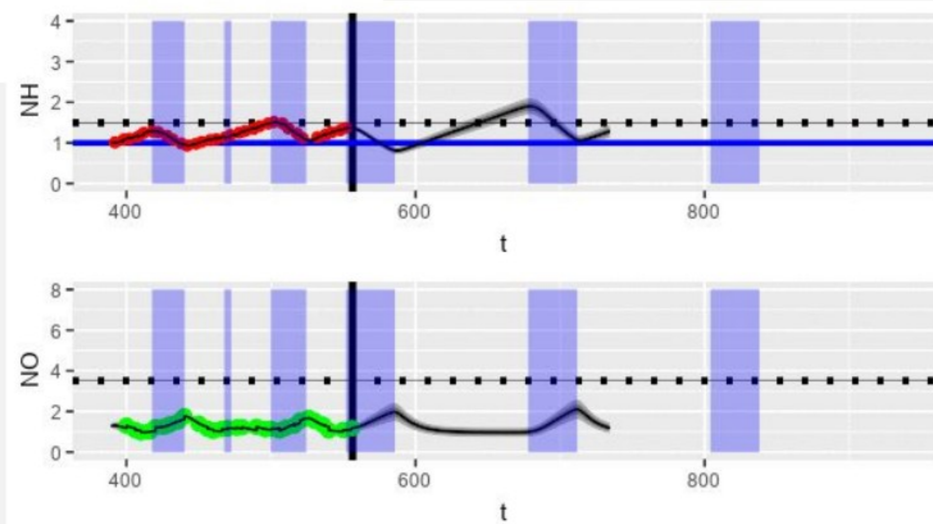
- Water & Wastewater sector uses 1-5% of total electrical energy of a country
- Flexibility is found in all parts of the urban water cycle
- My focus has been on Wastewater treatment aeration (C)

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
(Wastewater Treatment Plant)

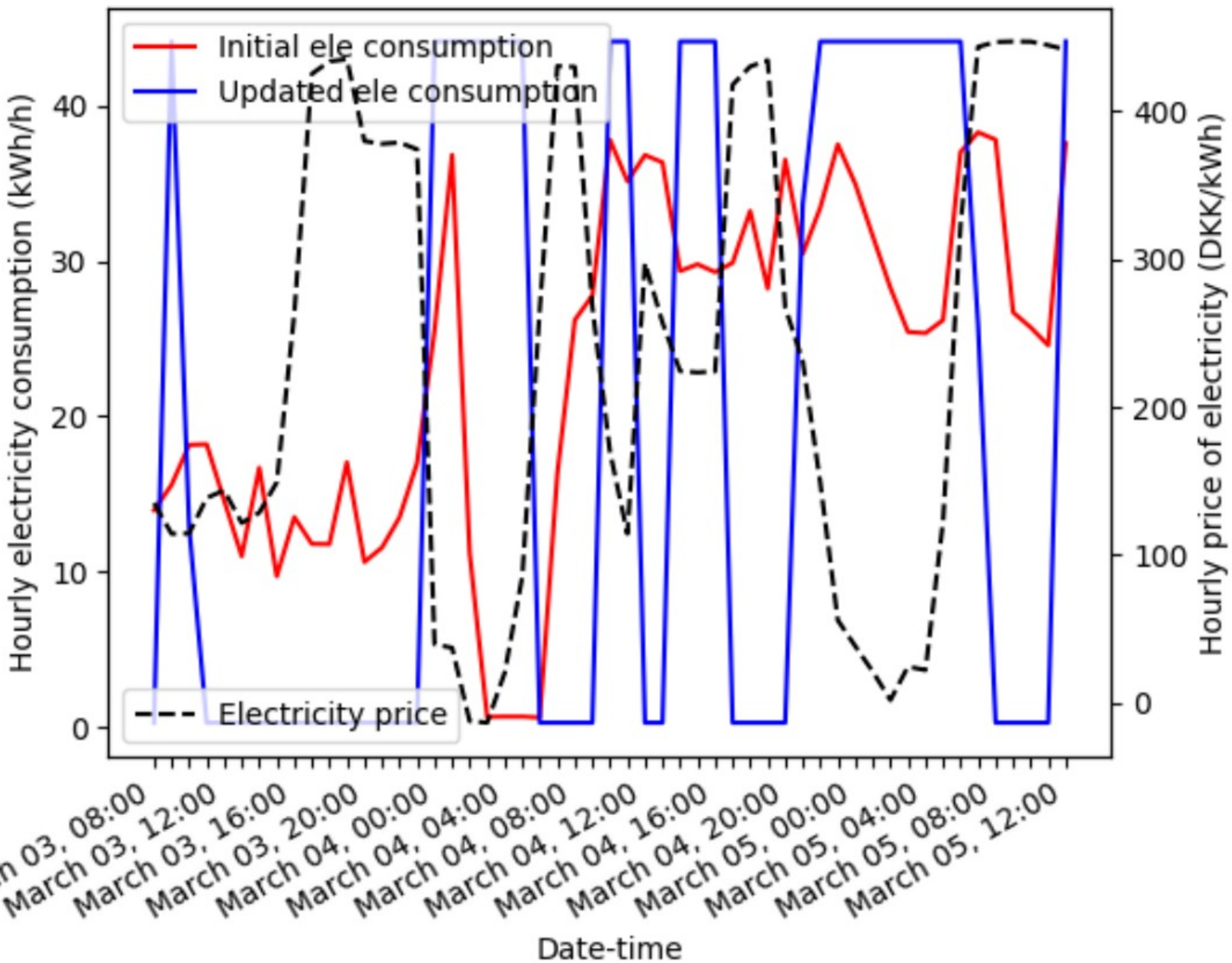
Environment	• Reduce GHG emissions related to electricity use and process by 50% • Improve effluent concentration by 10-20%
Costs	• Reduce electricity and taxation costs by 20% • Reduce need for investments in grid and tuning of controls
Usability	• Operators will be trained and will seamlessly adapt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

Pump storage operation – 2 days



SE-OS control of pumps

Optimization of CO_2 emissions

- The goal to minimize the CO_2 emissions – not caring about the economic costs
- Pumps (Jan-Dec 2019) PS145:

	CO_2 emissions		Costs (DKK)
Starting emissions	21 t		50.82 tDKK
Demand response (day ahead)	16 t	-23.6 %	46.76 tDKK

Center Denmark

Digitalisation Hub for Accelerating the Green Transition

Trusted Data Sharing Platform

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

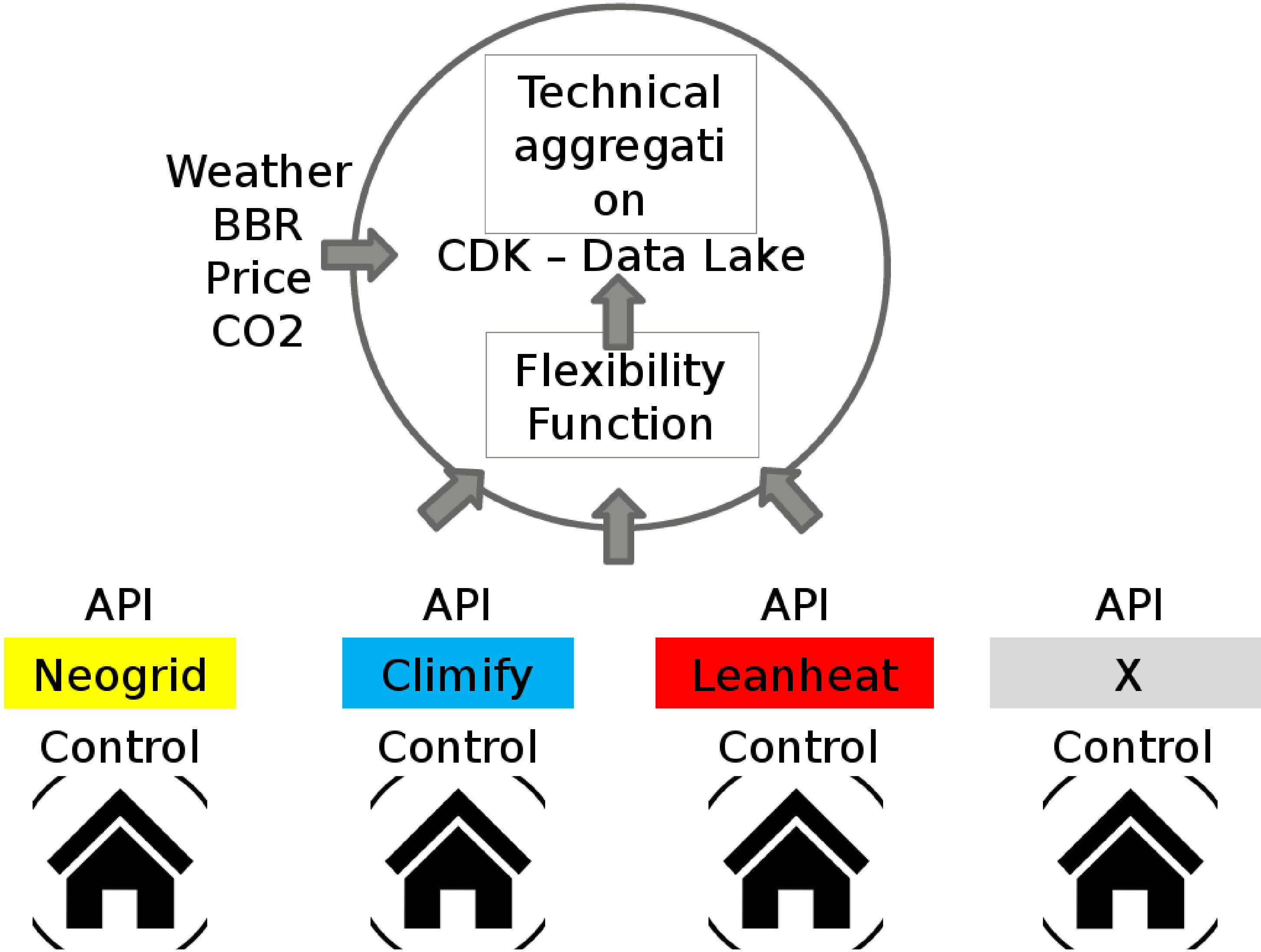
Participants accepting the market rules benefit from the exchange mechanisms and shape together an open market for data.

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

SE-OS at Center Denmark Control Hierarchies



Some highlights

The ***Technical Aggregator*** and ***Data Spaces*** at Center Denmark are designed such that we can shift between any external ’penalty signal’.

Control-based methods for linking high-level markets with the (low-level) physics

New possibilities for BRPs in bidding in flexibility - also on existing markets

We are able to shift to any ‘penalty signal’ with a very short notice. It can be **energy efficient, price efficient** or **emission efficient**.

It will be a **Cloud/Fog/Edge based contro**l of smart buildings/water systems/ .... – and in such a way that they can support the future smart grid (eg. voltage control and congestion management)

GDPR and privacy compliant by design (no online feedback)

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

Perspectives / Next Steps

- Ongoing work with Danish Energy Agency on digitalization for DSO and the future business model
- Ongoing workshops with Energinet and Center Denmark on how to onlock flexibility in water handling
- Several meetings with DG ENER, DG CNECT, ...
- Input on the upcoming Digitalisation of Energy Action Plan
- G-PST initiative (US-DK)
- DK-US Seminar 'Modeling and Optimal Design of Our Future Digital Energy Systems, June 2022, Boston
- Keynote lecture on FED Project at upcoming Conference: Frontiers in Autonomous Systems 24-25 Nov.

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

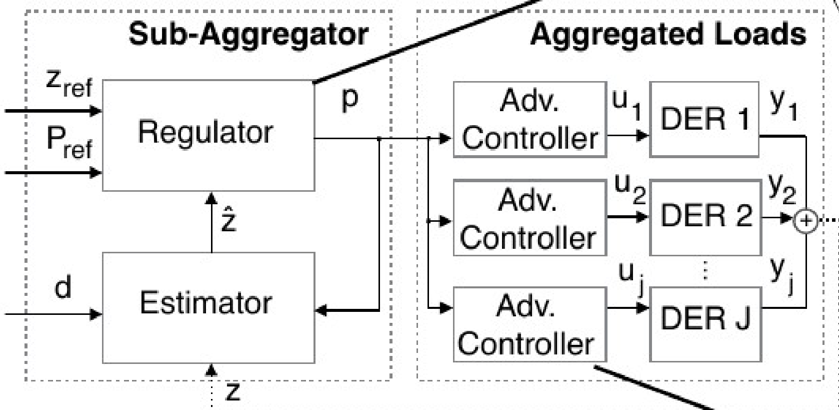
- The future is trusted data sharing environments (exactly like Center Denmark)
- The most important single factor is ‘trust’!
- Next to that is reasonable data sharing aggrements (Data spaces)
- It is very important to be able to combine data from many different sources
- We need to develop by test-and-evaluation (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

Per Bruun Brockhoff • 1st
Head of Department and Professor in Statistics, DTU Compute - DTU - T...
1mo •

Margrethe Vestager and her cabinet hears about energy flexibility (demand-response) from Professor Henrik Madsen and Green AI from Professor Jan Madsen, both DTU Compute and about the import ...see more

161 • 2 comments

Proposed methodology
Control-based methodology



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

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

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

Flexibility Function Model

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

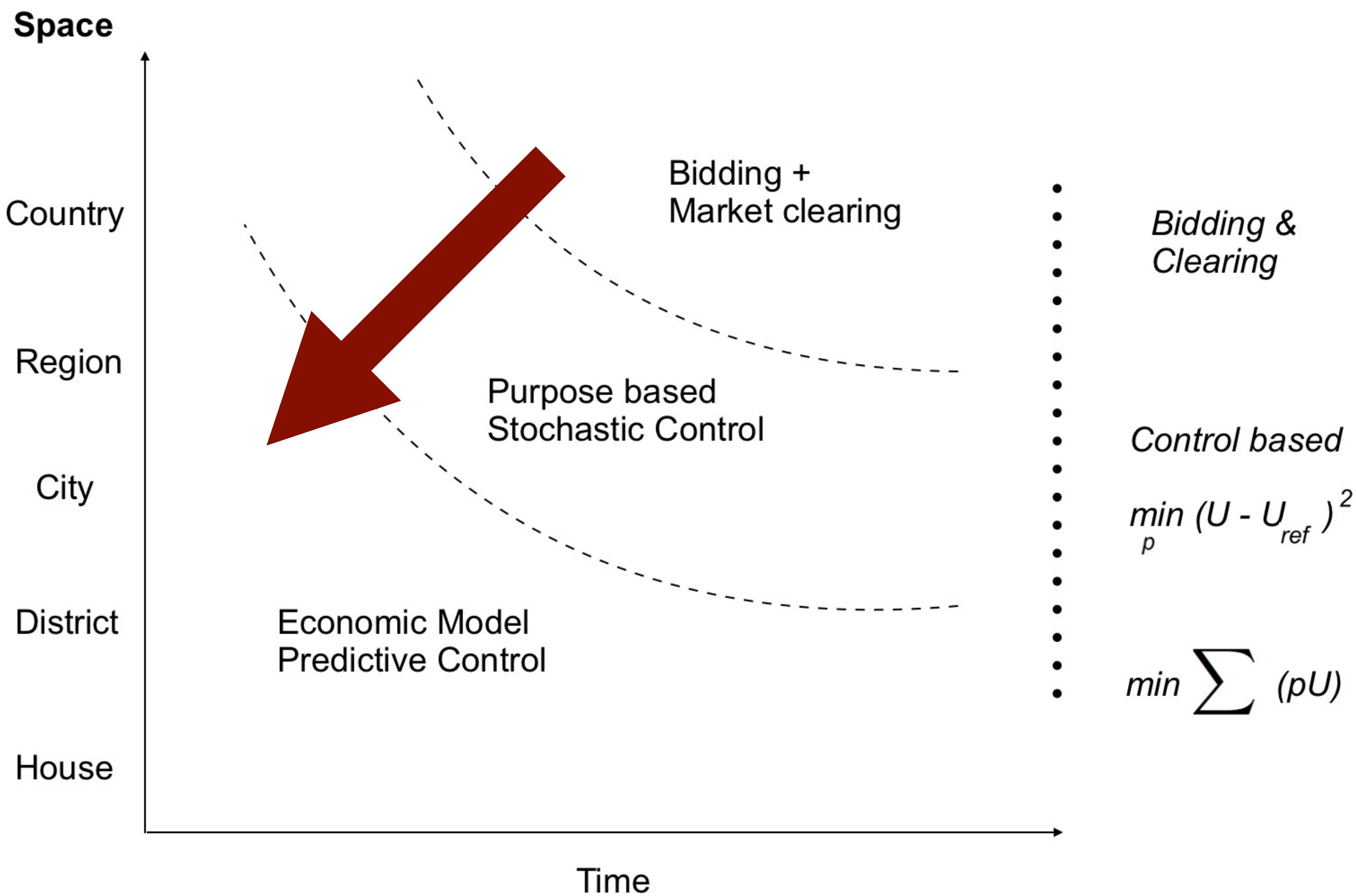
$$\mathrm{d}X_t = \frac{1}{C}(D_t - B_t)\mathrm{d}t + X_t(1 - X_t)\sigma_X \mathrm{d}W_t$$

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

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

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

The ‘market’ of tomorrow

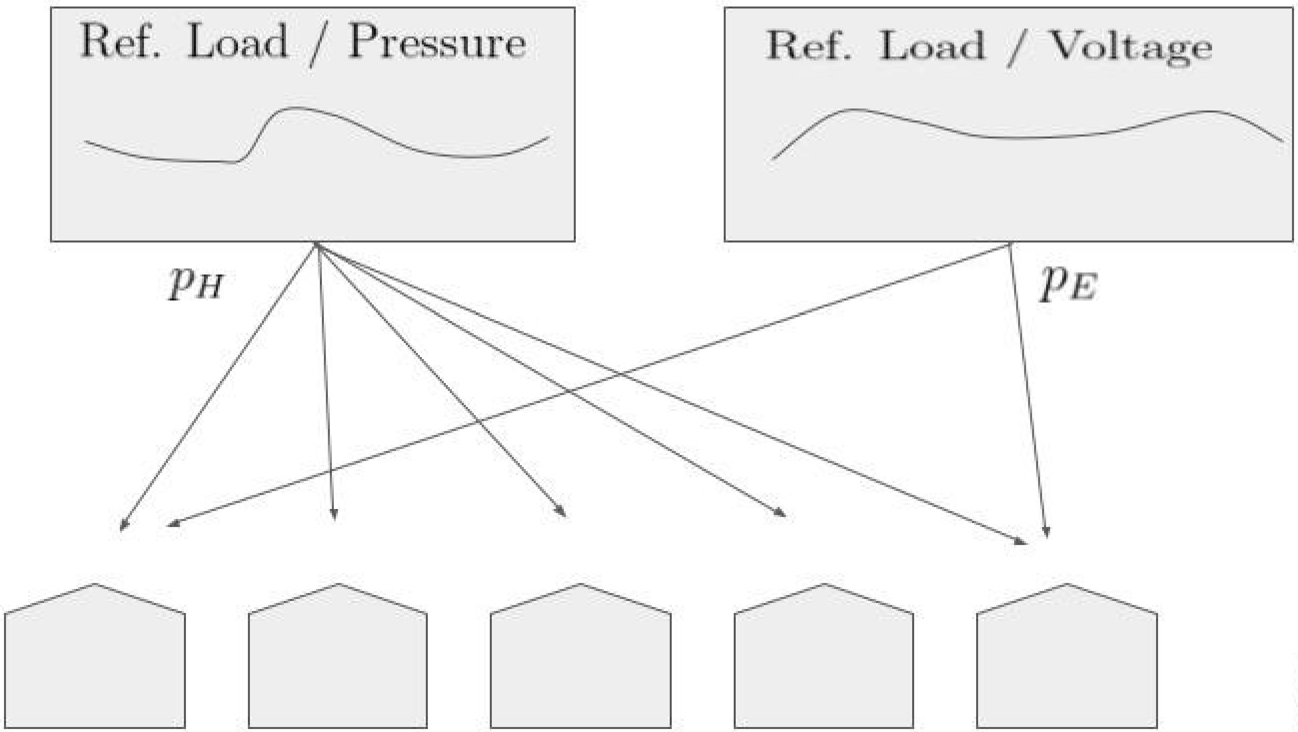


Sector coupling

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

District Heating Grid

Electricity Grid



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

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

$s.t.$

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