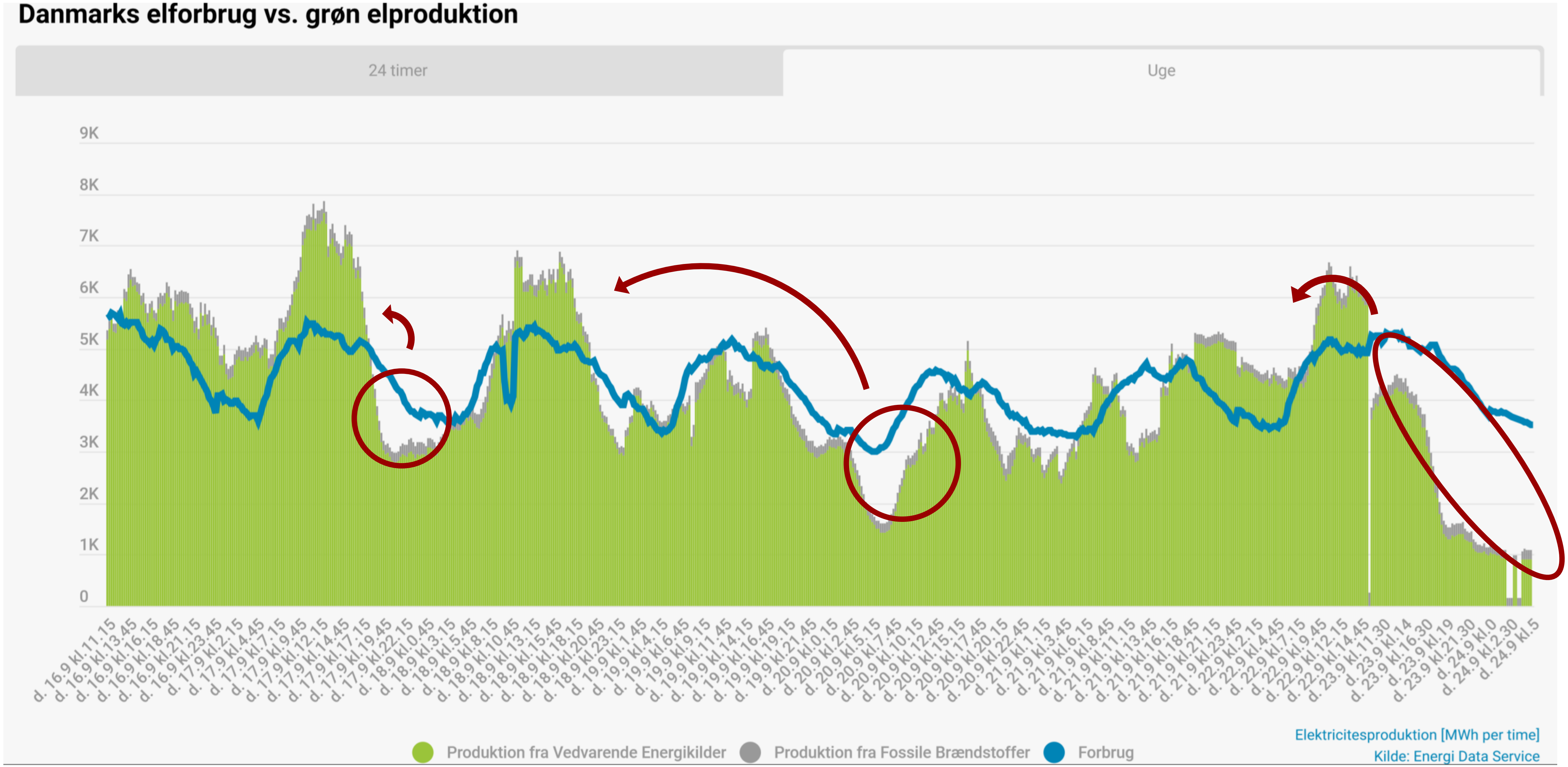
Hierarchical methods for exploiting flexible energy resources

GreenLab Research Community Day
March 11th, 2026
Skive, Denmark

Tobias K. S. Ritschel
Associate Professor
Department of Applied Mathematics and Computer Science
Technical University of Denmark

Motivation



https://ing.dk/artikel/live-danmarks-elforbrug-og-elproduktion

Motivation

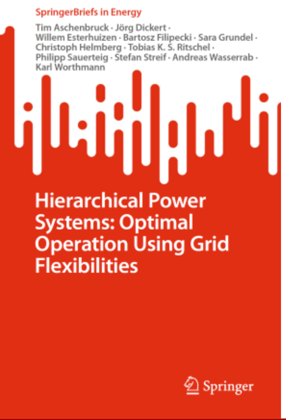
Energy storage systems

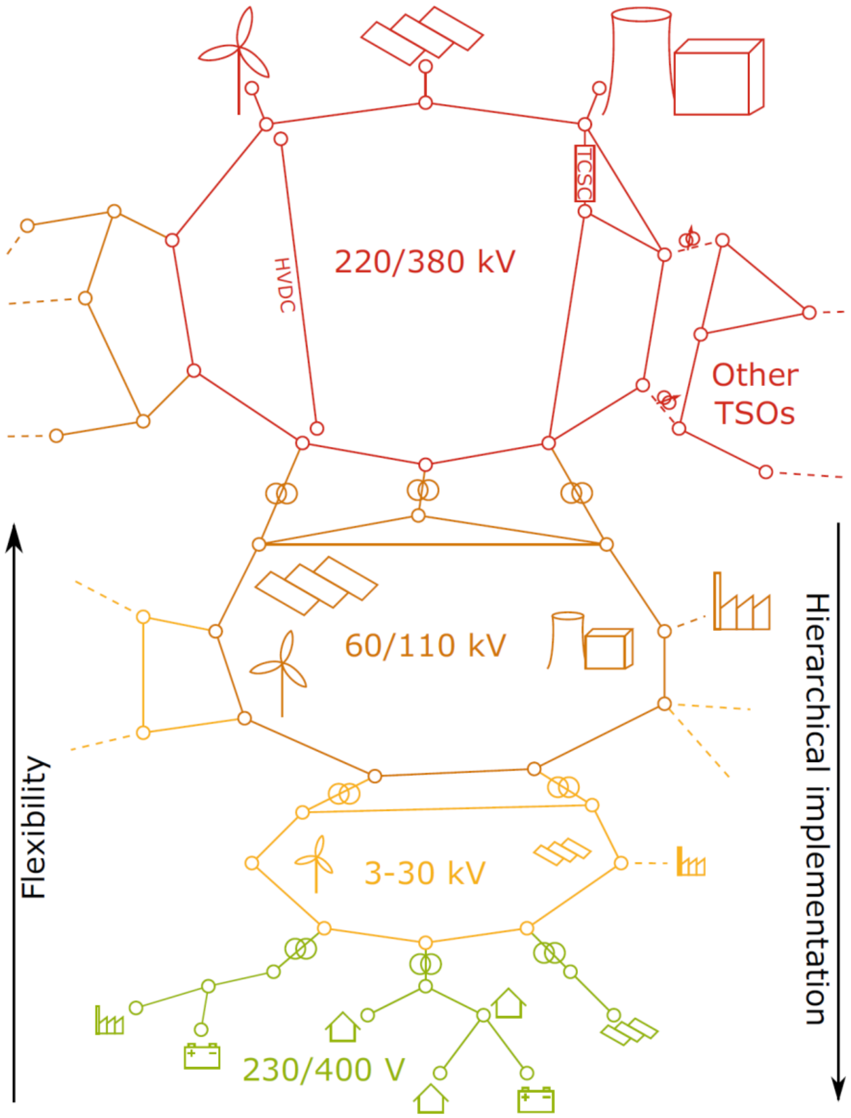
Increase renewable + curtail

Power-to-X

Demand-side flexibility

Hierarchical power systems: Grid flexibilities (2023)





https://doi.org/10.1007/978-3-031-25699-8

Transmission grid

Economic optimal power flow

- Minimize cost
- Security constraints (N-1)
- Transient stability (network Laplacian)
- Demand of flexible nodes are free

Flexible distribution grid

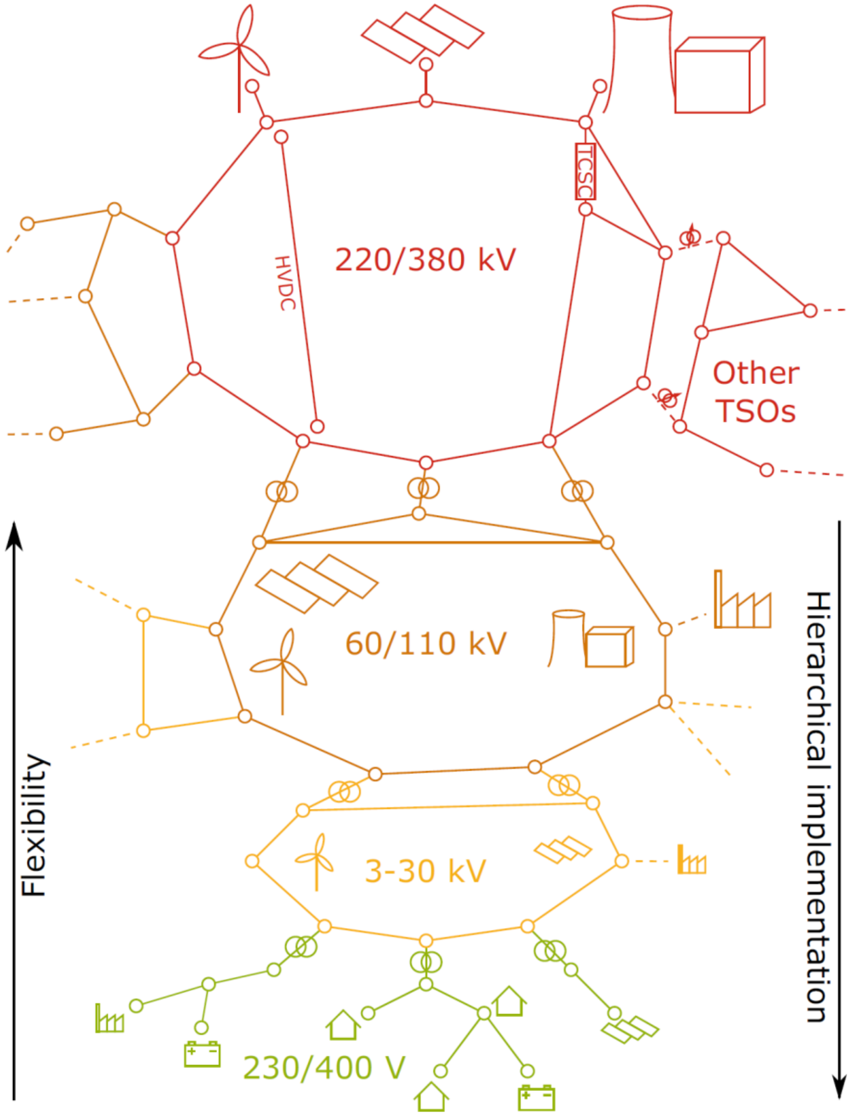
Min/max optimal power flow

- Min/max total energy demand
- Demands of flexible nodes are free

Flexible assets (e.g., microgrids or vertical agriculture)

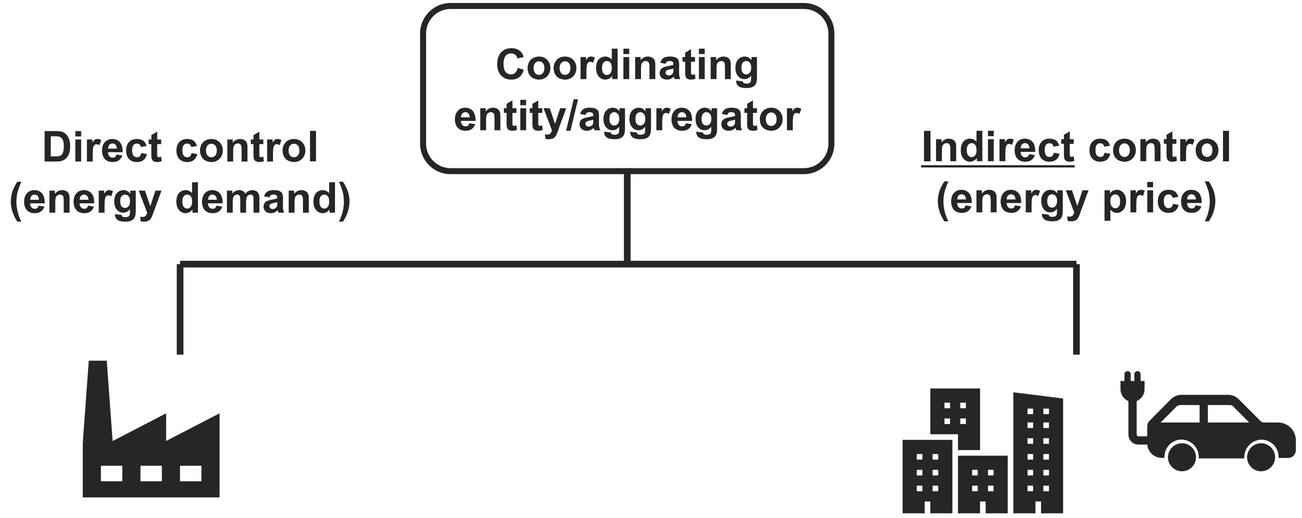
Economic (price-sensitive) control

Remaining challenges



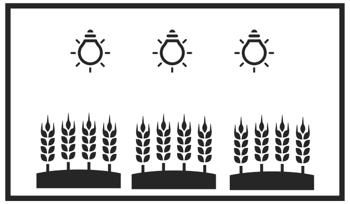
- Demand response depends on “state of charge”
- Flexibility may be finite
- Requires full control of energy demand

Direct vs. indirect control (incentivization)

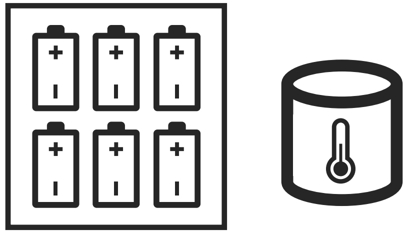


Types of flexible assets

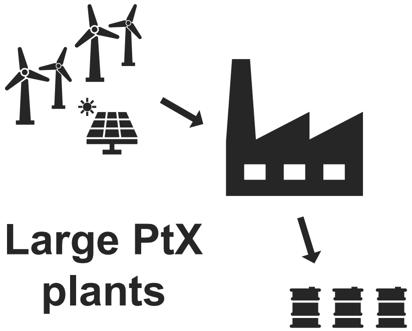
Large and intensive



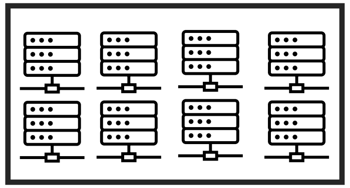
Greenhouses



Energy storage facilities

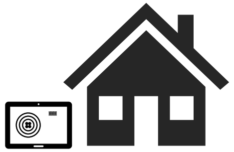


Large PtX plants

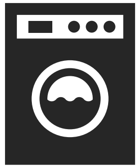


Data centers

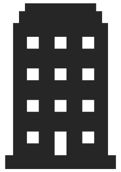
Small but widespread



Heat pumps



Smart appliances

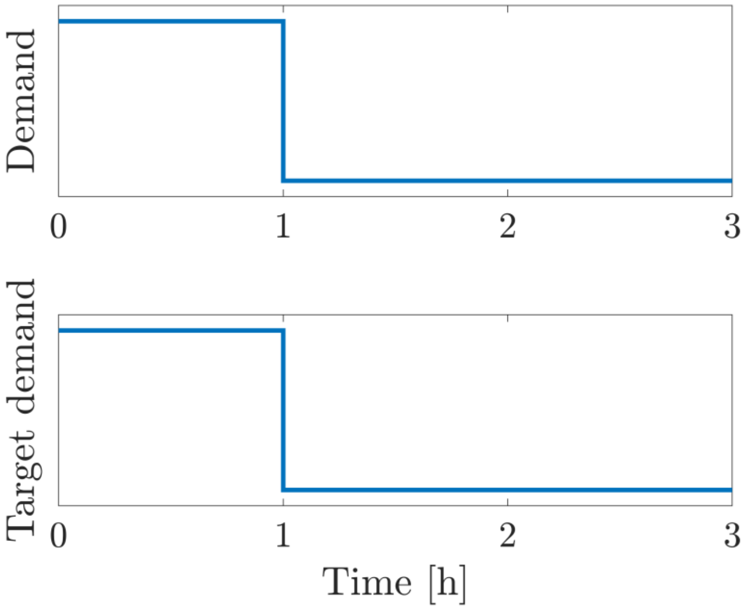


Household heating

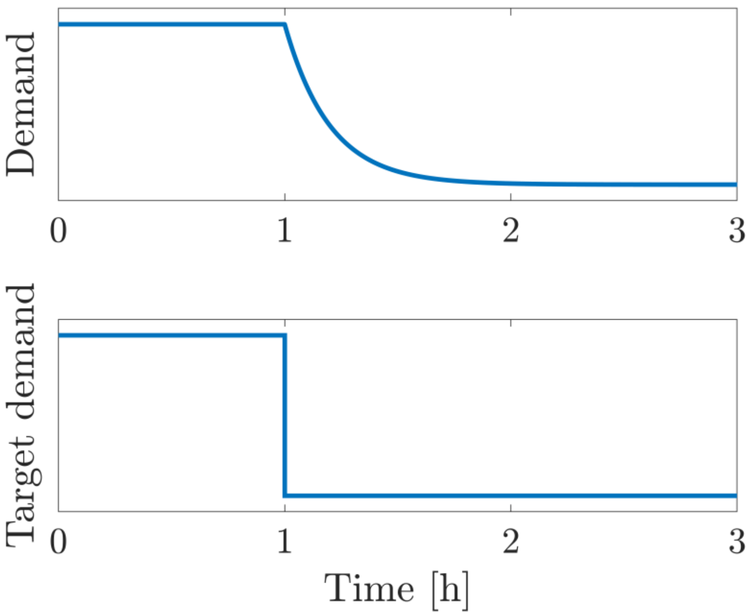
Electric vehicle charging

Types of flexibility

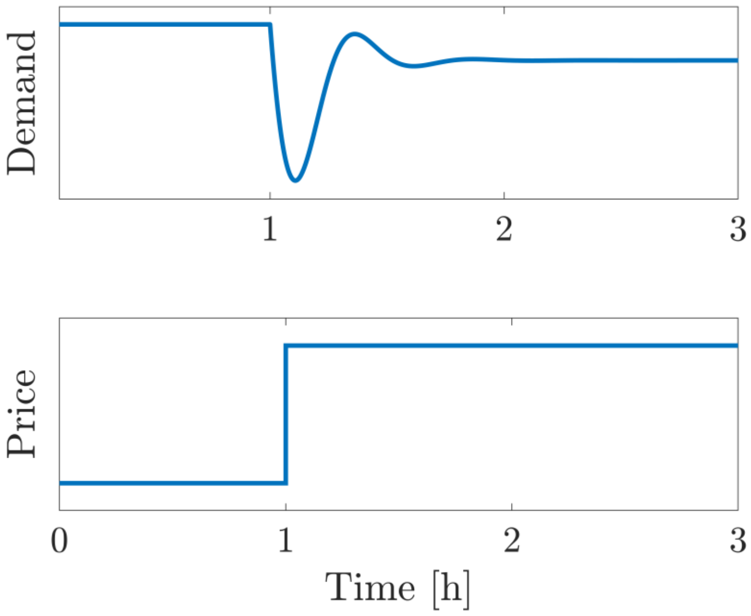
Flexible and fast



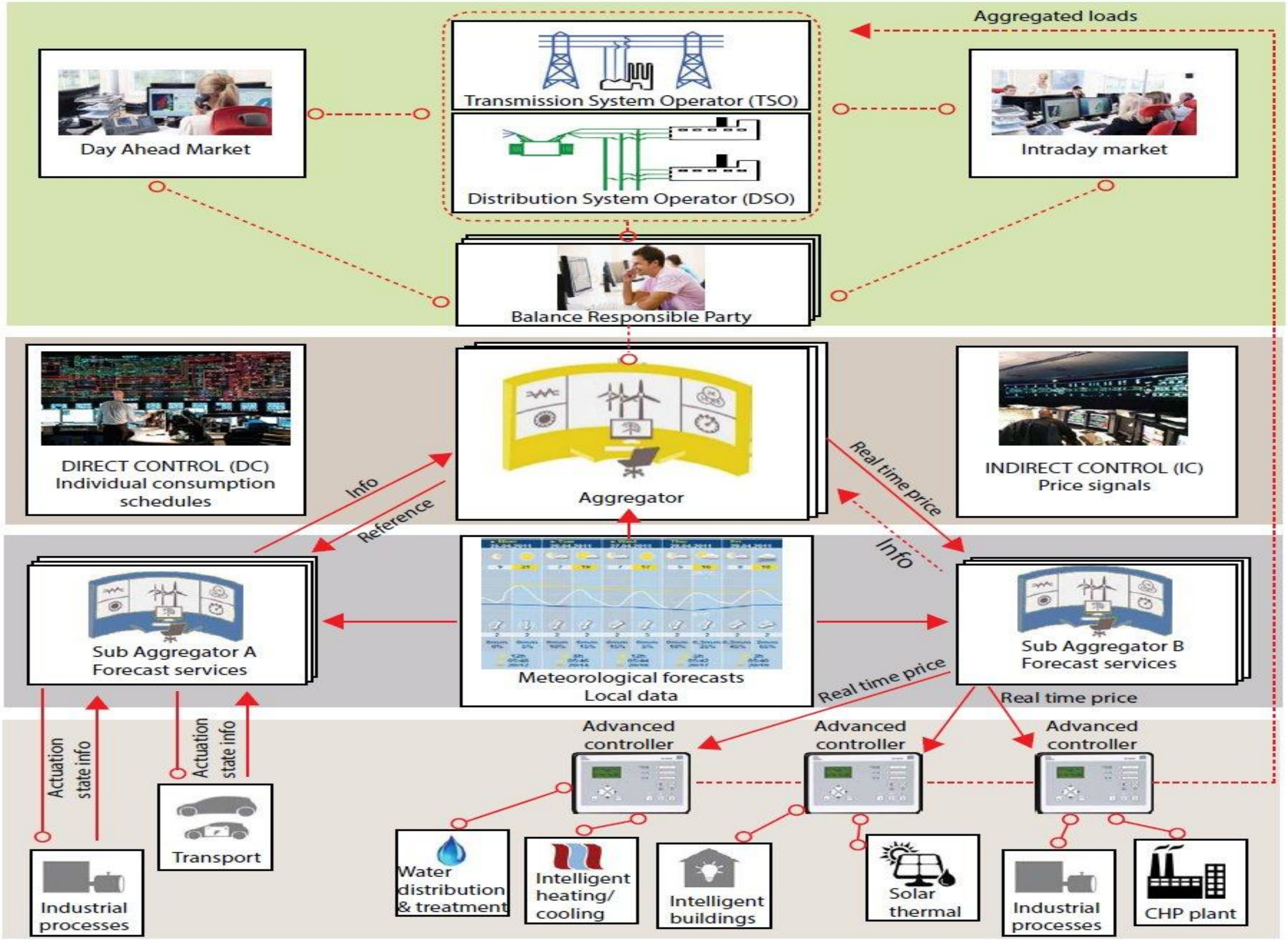
Flexible but slow



Complex



Smart Energy Operating System (SE-OS)



(Static)

Conventional markets

Link markets to physics using MIMs

(Flexibility Functions)

(Dynamic)

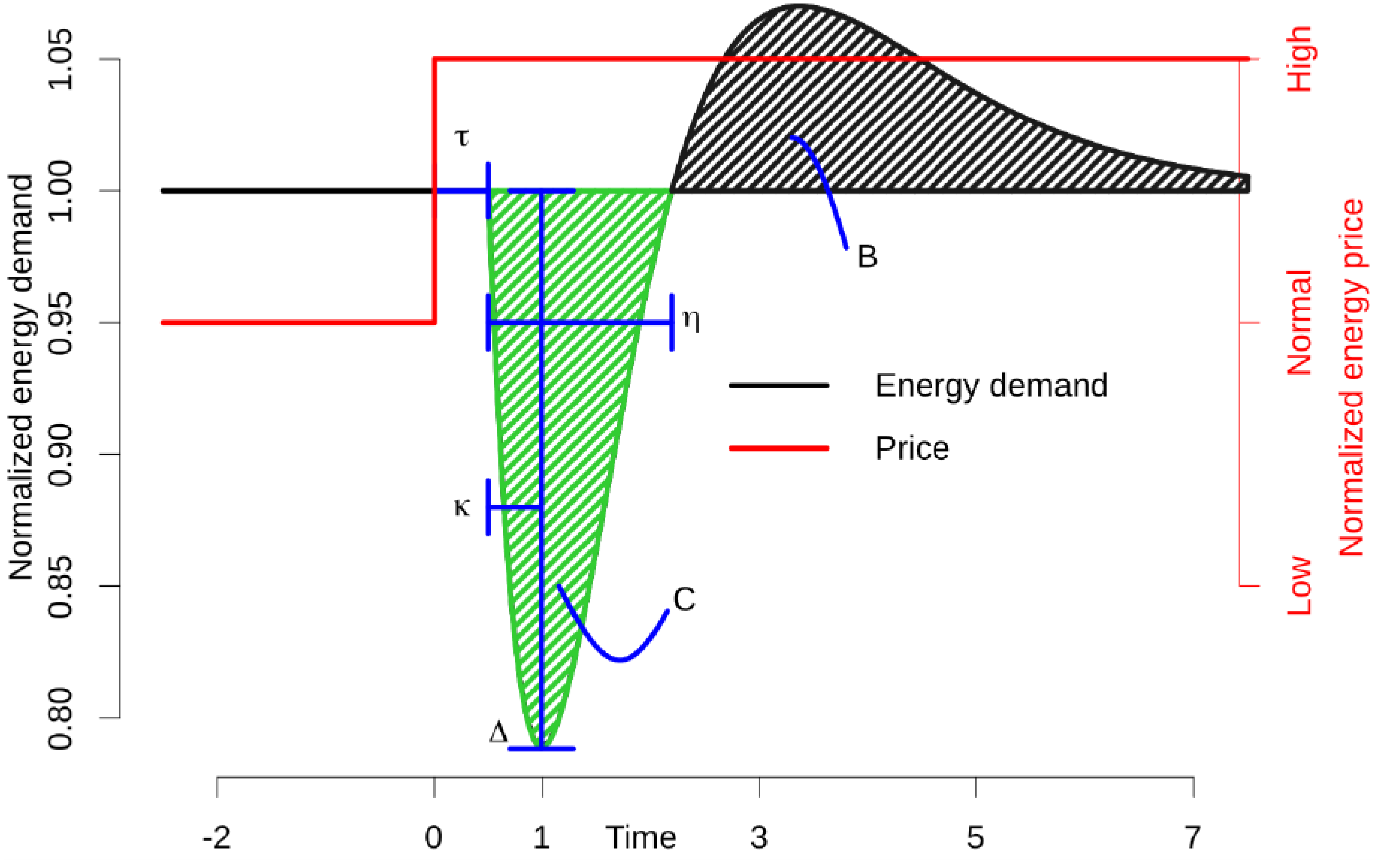
Local incentive-based flexibility exploitation

(Hierarchy of controllers)

Minimal demand response models: <u>Flexibility functions</u>

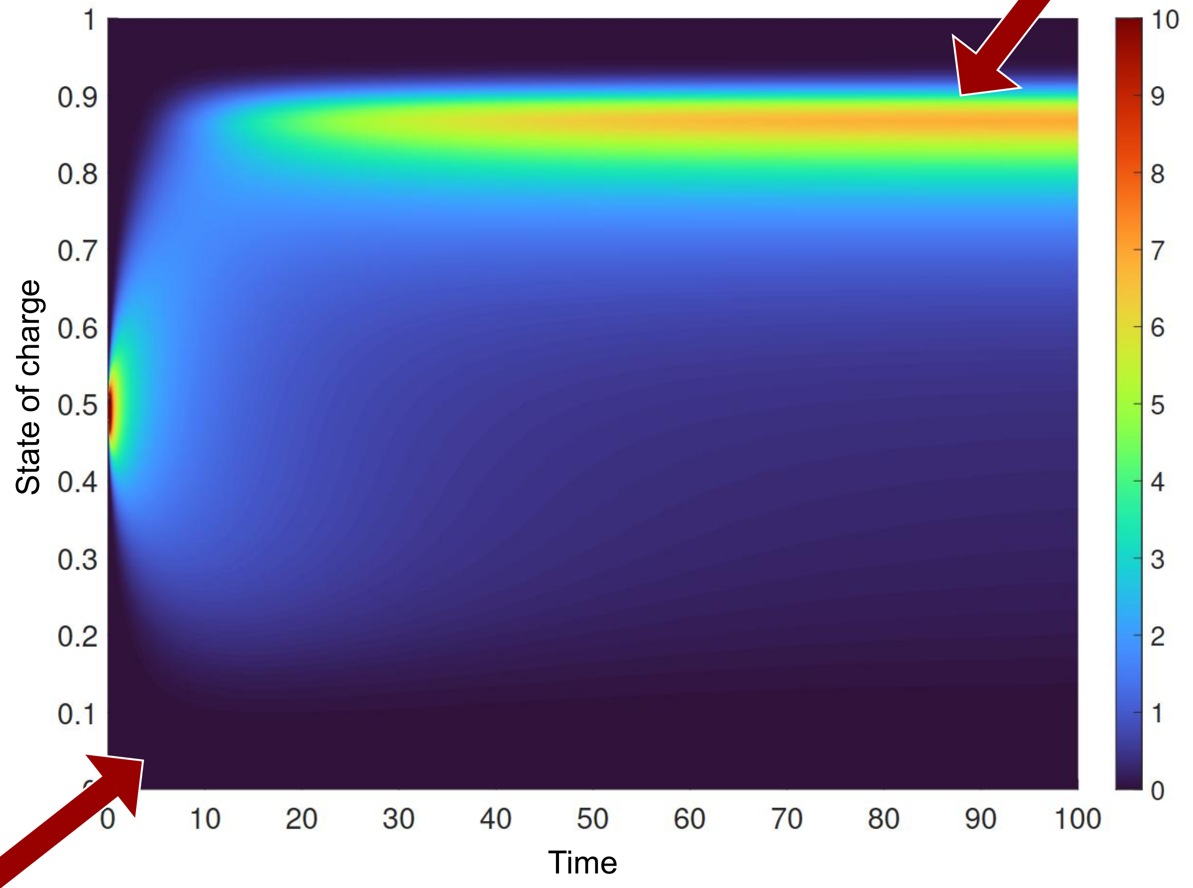
Flexibility function: Predict flexible demand as function of

- **Price**
- **“State of charge”**



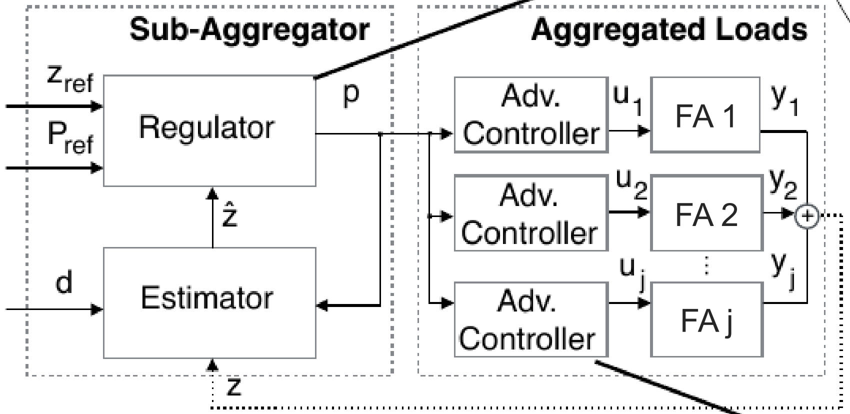
Account for uncertainty

Very likely!



Very <u>un</u>likely!

Interoperability through incentivization



Price signal generator

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

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

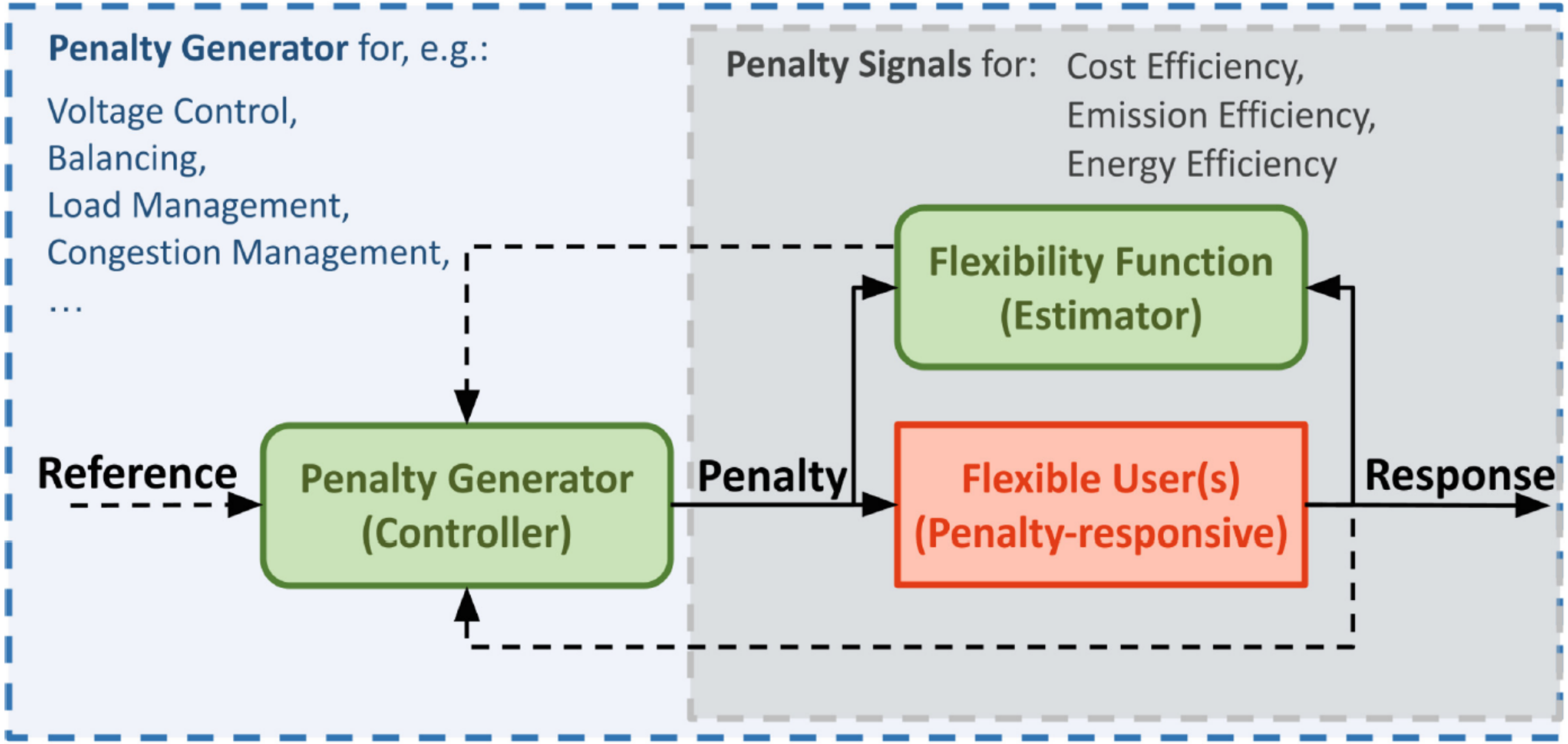
Price-sensitive control system

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

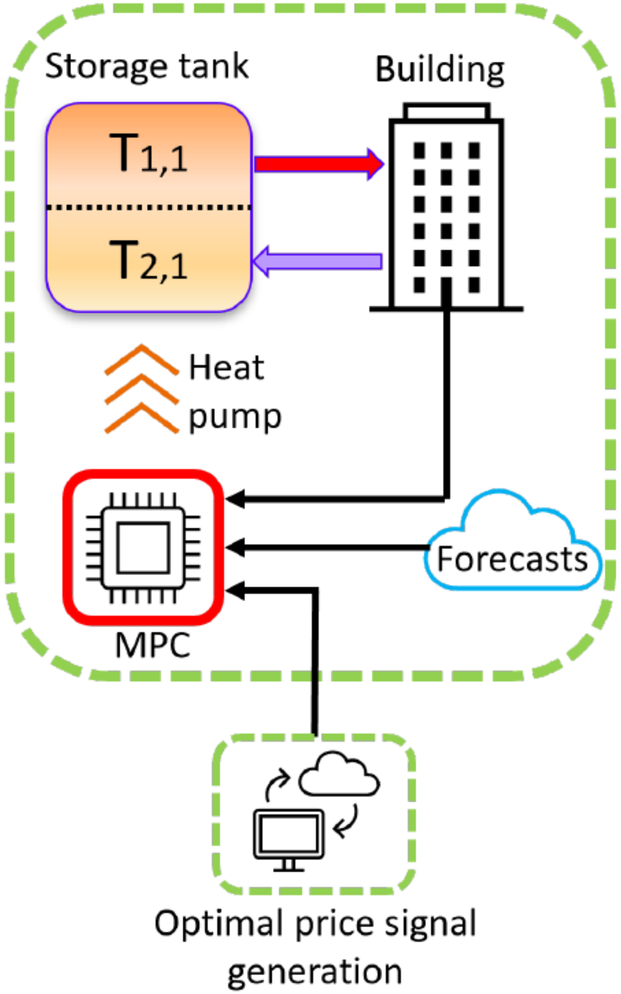
$$\begin{aligned} \text{s.t.} \quad x_{k+1} &= Ax_k + Bu_k + Ed_k, \\ y_k &= Cx_k, \\ y_k^{min} \leq y_k &\leq y_k^{max}, \\ u_k^{min} \leq u_k &\leq u_k^{max} \end{aligned}$$

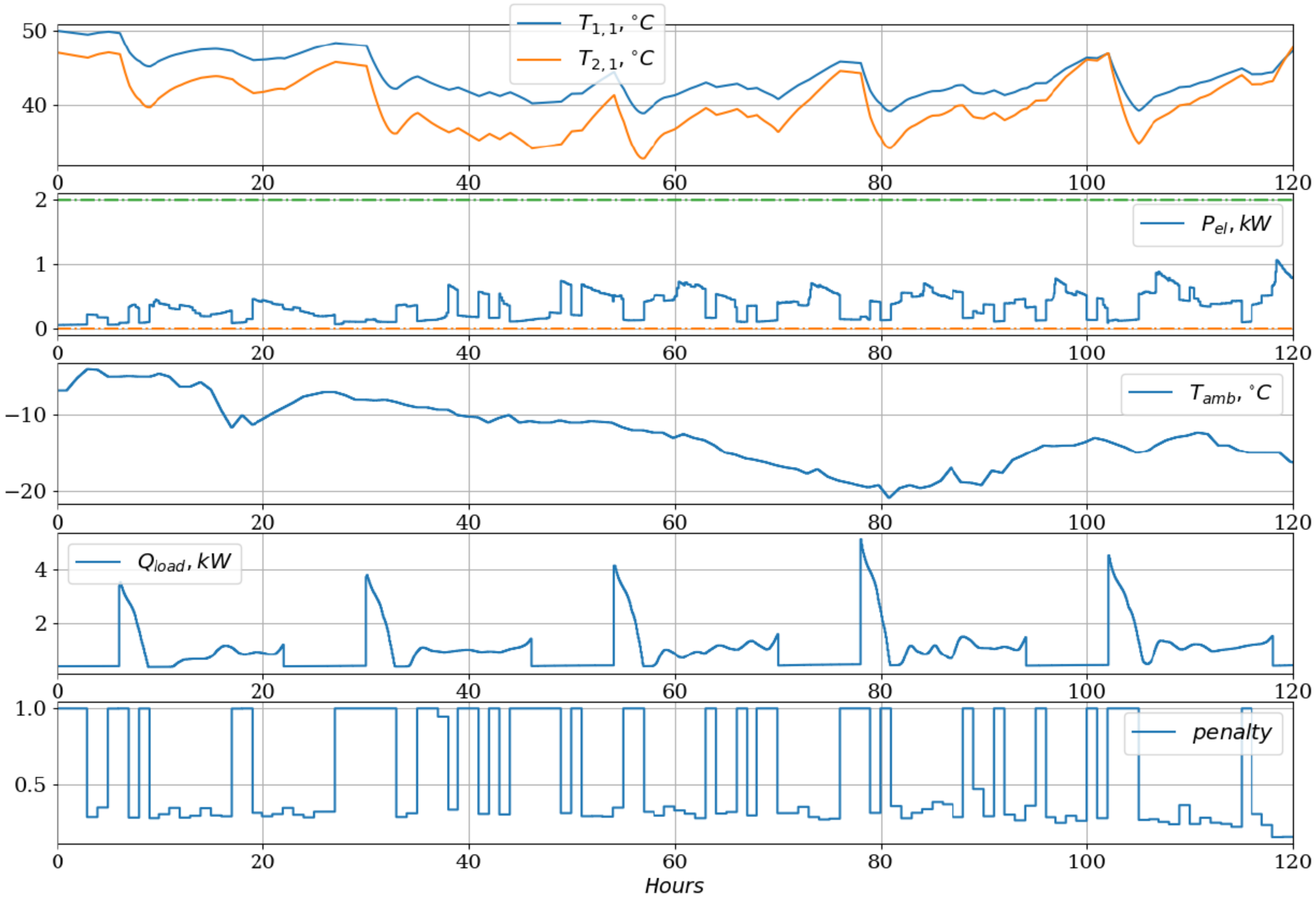
We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

Dynamic price signal generation



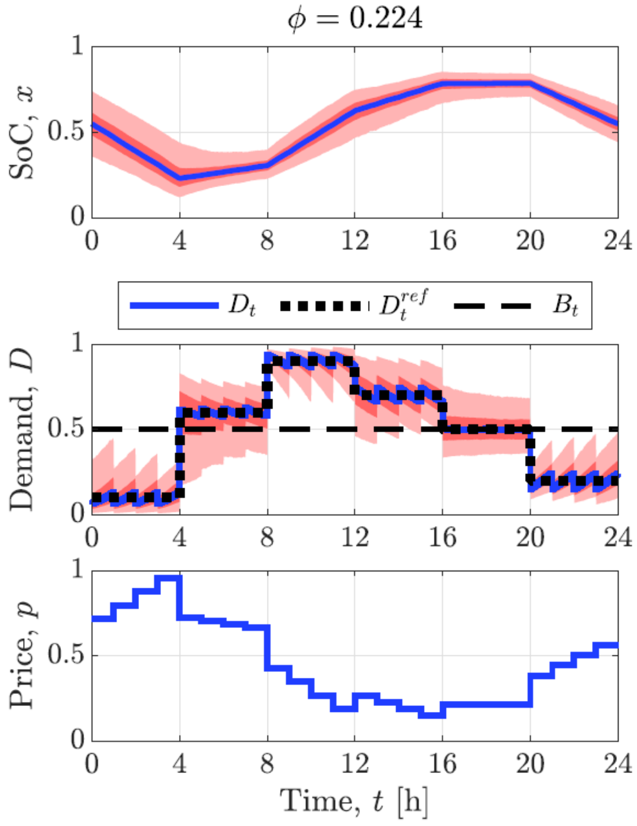
Example: Flexible building energy management system





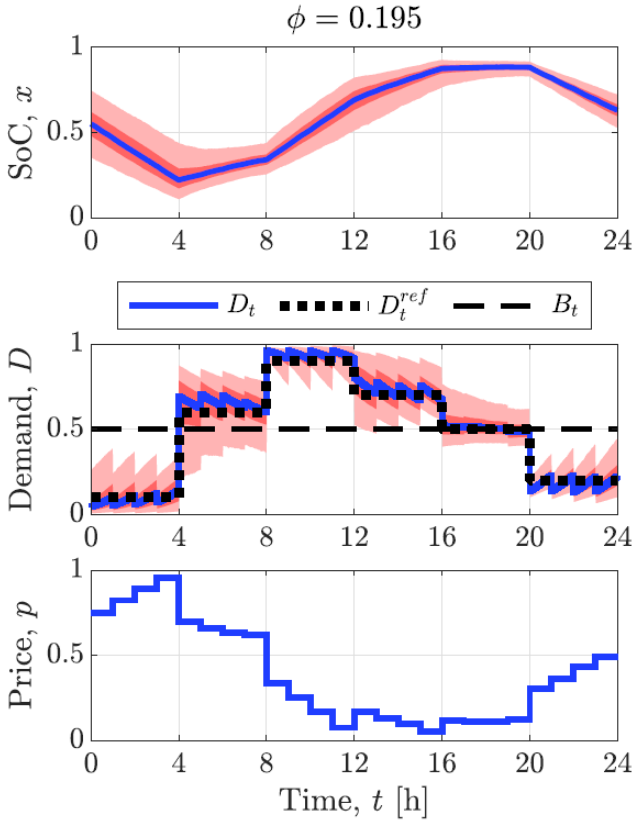
Comparison of price signal generation strategies

Day-ahead (no uncertainty)



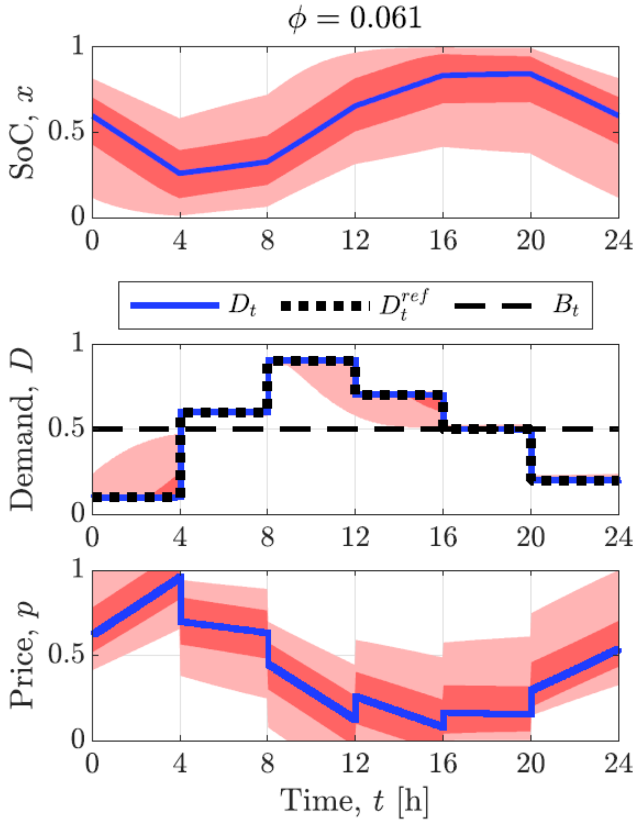
(a) Deterministic open-loop solution, hourly price update

Day-ahead (uncertainty)



(b) Stochastic open-loop solution, hourly price update

Real-time update of prices



(c) Stochastic closed-loop solution, continuous-time price update

Key questions: Flexible operation of data centers

How can data centers operate in response to energy price signals?

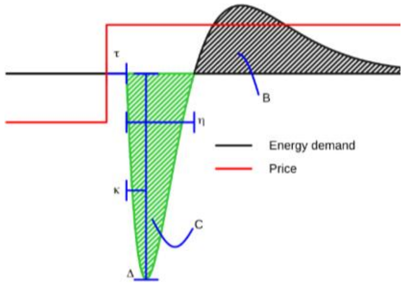
- Power/heat/bio prices?
- Business case?

Can sector coupling increase the flexibility of data centers

- District heating/cooling
- Multiple energy prices

What is the flexibility profile (demand response)

- Response time
- Ramping time
- Duration
- Compensation period/magnitude



Selected research activities

AI·EFFECT

- Horizon Europe
- Flexible operation of district heating grids
- Demand-side flexibility exploitation in district heating

OPTIFLEX

- EUREKA Eurostars
- Demand-side flexibility exploitation
- Integrated market bidding

INNO-CCUS Carbon capture, utilisation, and storage

MISSION GREEN FUELS

energy Cluster Denmark

1. **GreenTwins:** Flexible operation of carbon capture units
2. **PtX Markets:** Demand-side flexibility exploitation
3. **CANSI:** Flexibility of electrolyzers
4. **PtX Sector Coupling and LCA:** Flexible operation of plastic waste to methanol
5. **PWtM-Flex:** Flexible operation of plastic waste to methanol
6. **PtX Risø project** w. SemperCycle**:** Flexible operation of plastic waste to methanol

Flexibility across hierarchies

- Load shift incentivization
- Hierarchies of aggregators

Demand response model

- Flexibility functions
- Time-varying (flexibility is finite)
- Real-time data assimilation

Dynamic energy prices

- Day-ahead prices
- Real-time price adjustments

Thank you