Exploiting flexibility from batteries across hierarchies in the power system

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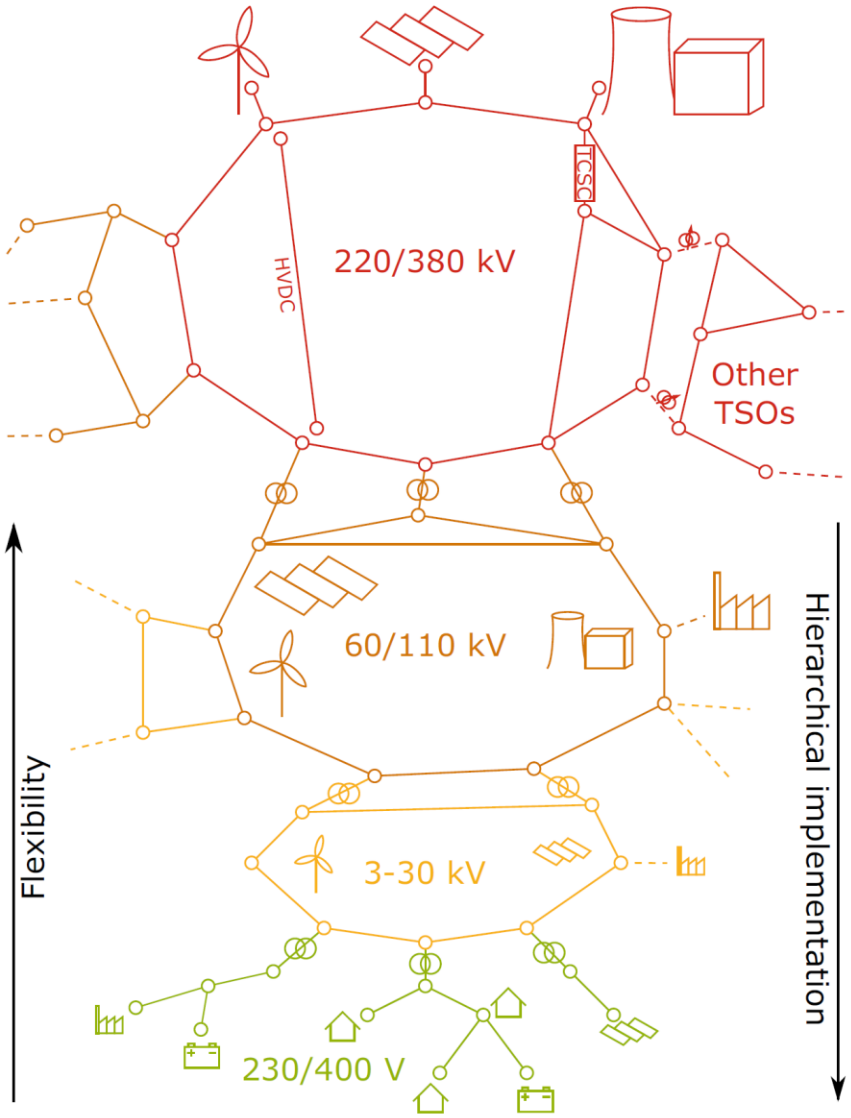
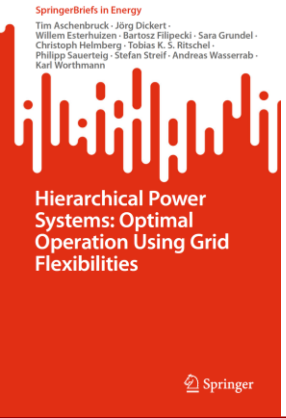
Flexibility across hierarchies

Data-driven model
of demand response

Indirect control of demand

Hierarchical power system





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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

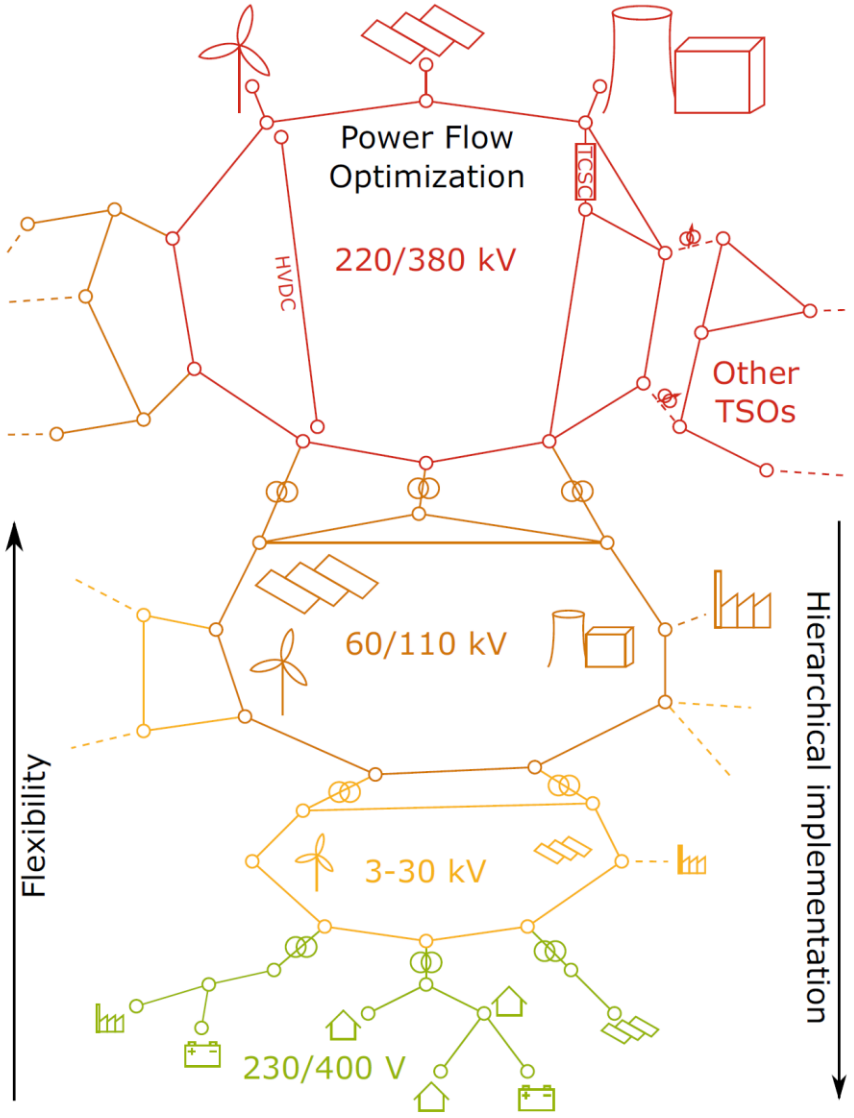
Economic (price-sensitive) control

Fundamental challenges

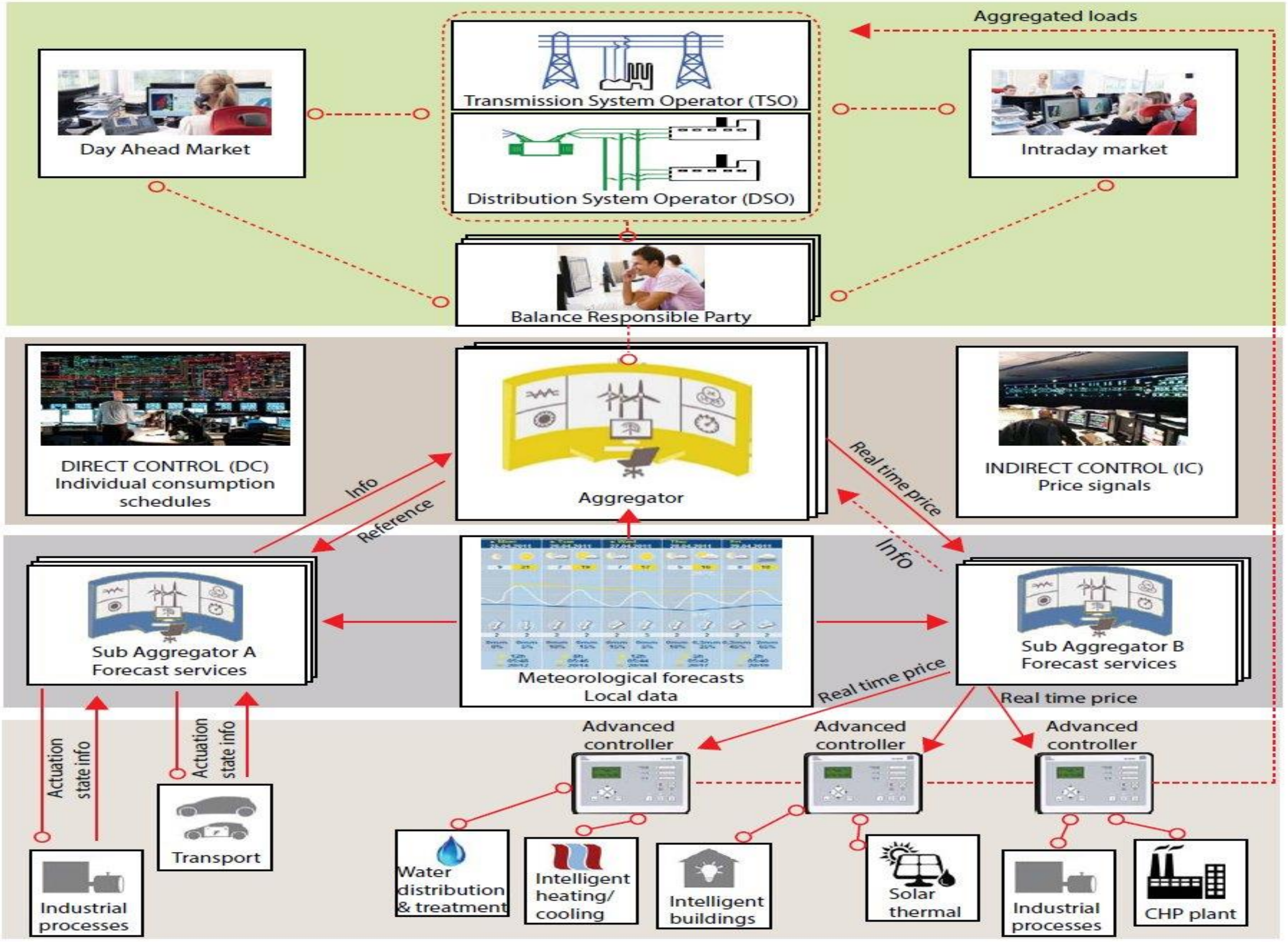
High communication requirements

Direct control of consumer demand

Does not account for finite flexibility



Smart Energy Operating System (SE-OS)



(Static)

Conventional markets

Link markets to physics using MIMs

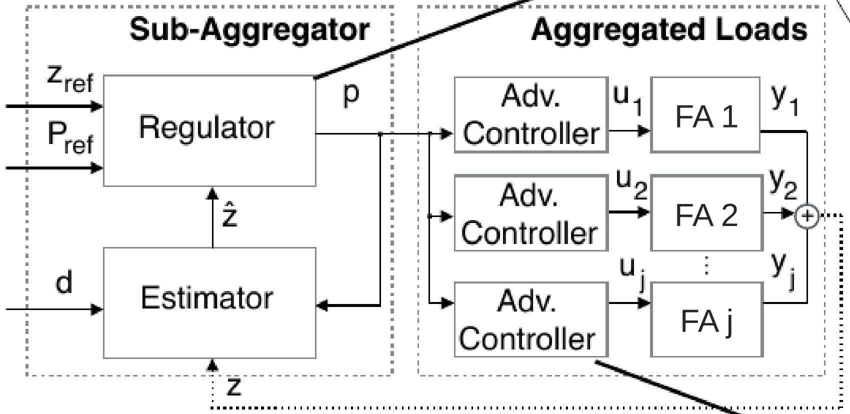
(Flexibility Functions)

(Dynamic)

Local flexibility markets

(Hierarchy of controllers)

Interoperability through indirect control



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

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

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

Interoperability through indirect control

$$\min_{C_u} \left(\mathrm{FF}(C_u) - r_l\right)^2, \qquad \text{Upper level}$$

$$\min_{u_k} \sum_k C_u^{\mathsf{T}} u_k \qquad \text{Lower level}$$

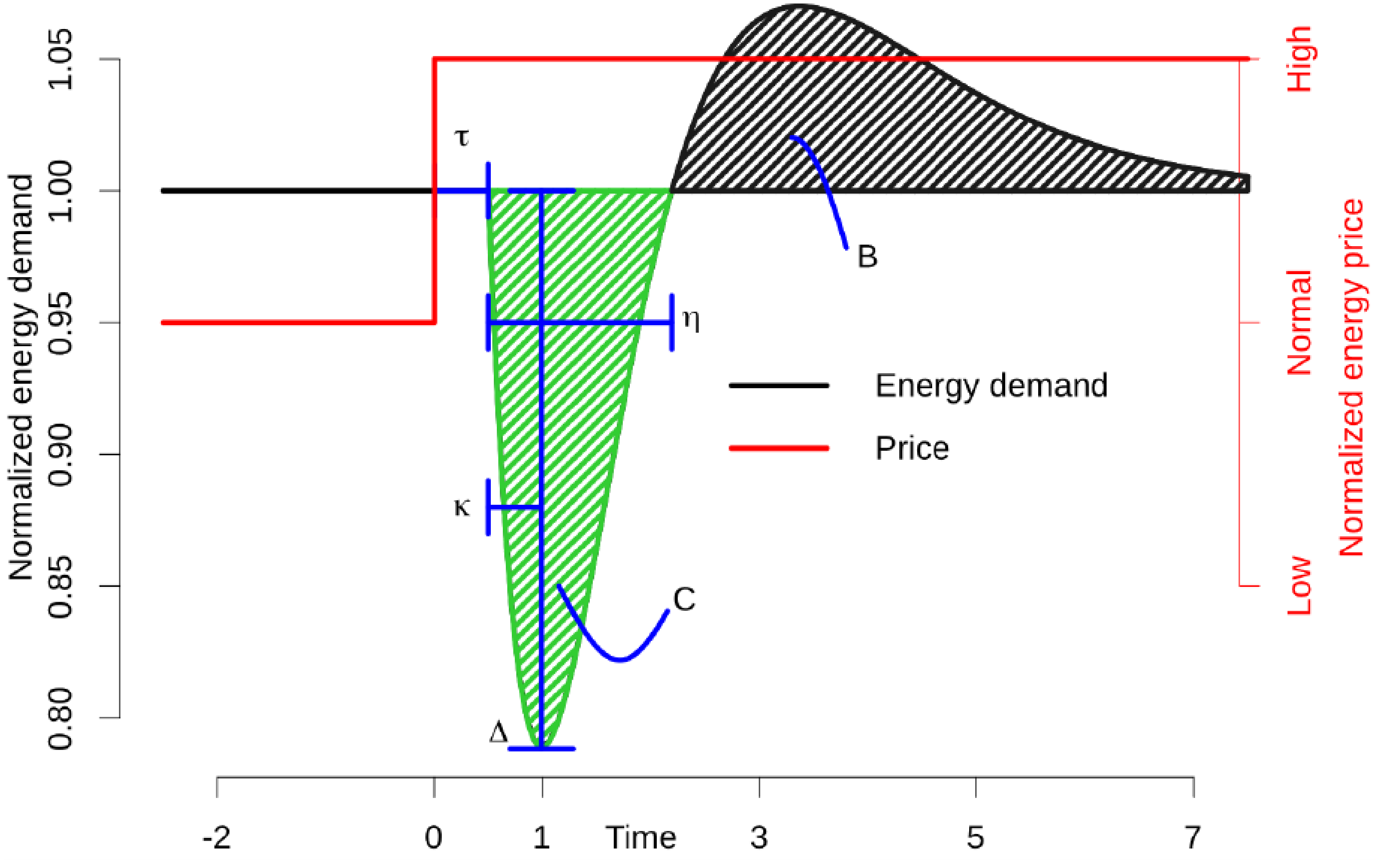
$$\text{s.t.} \quad \mathrm{d}x = f(x, u, d, t)\mathrm{d}t + g(x, u, d, t)\mathrm{d}w,$$

$$\Pr(x_{\min} \leq x \leq x_{\max}) \geq 1 - \alpha$$

Indirect control through <u>flexibility functions</u>

Flexibility function: Predict flexible demand as function of

- **Price**
- **State of charge** (aggregate)



Flexibility function

State of charge (SDE)

$$dx_t = \frac{\Delta D_t}{C}\,dt + \sigma_x x_t(1 - x_t)\,dW_t$$

Demand

$$D_t = B_t + \Delta D_t$$

(Dis-)charging rate

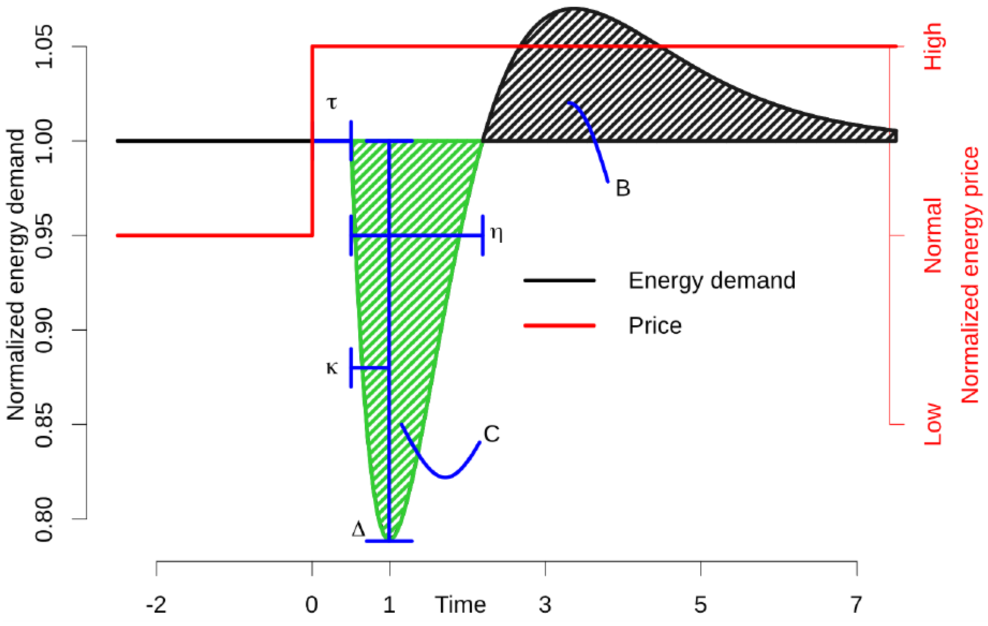
$$\Delta D_t = \varphi(x_t, p_t)$$

Rationality assumptions

$$\varphi(0, p) \geq 0$$
$$\varphi(1, p) \leq 0$$

$$\frac{\partial \varphi}{\partial x}(x, p) < 0$$

$$\frac{\partial \varphi}{\partial p}(x, p) < 0$$



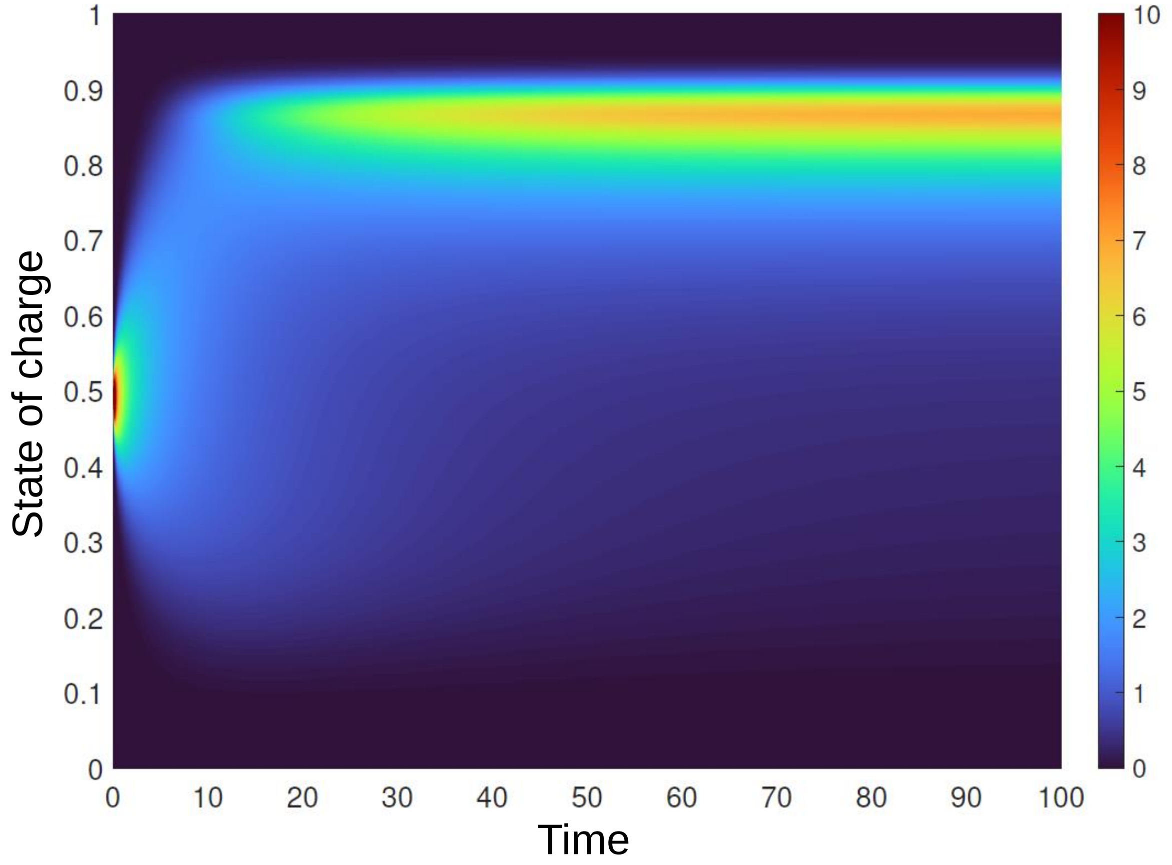
Uncertainty quantification

Fokker-Planck equation (numerical solution)

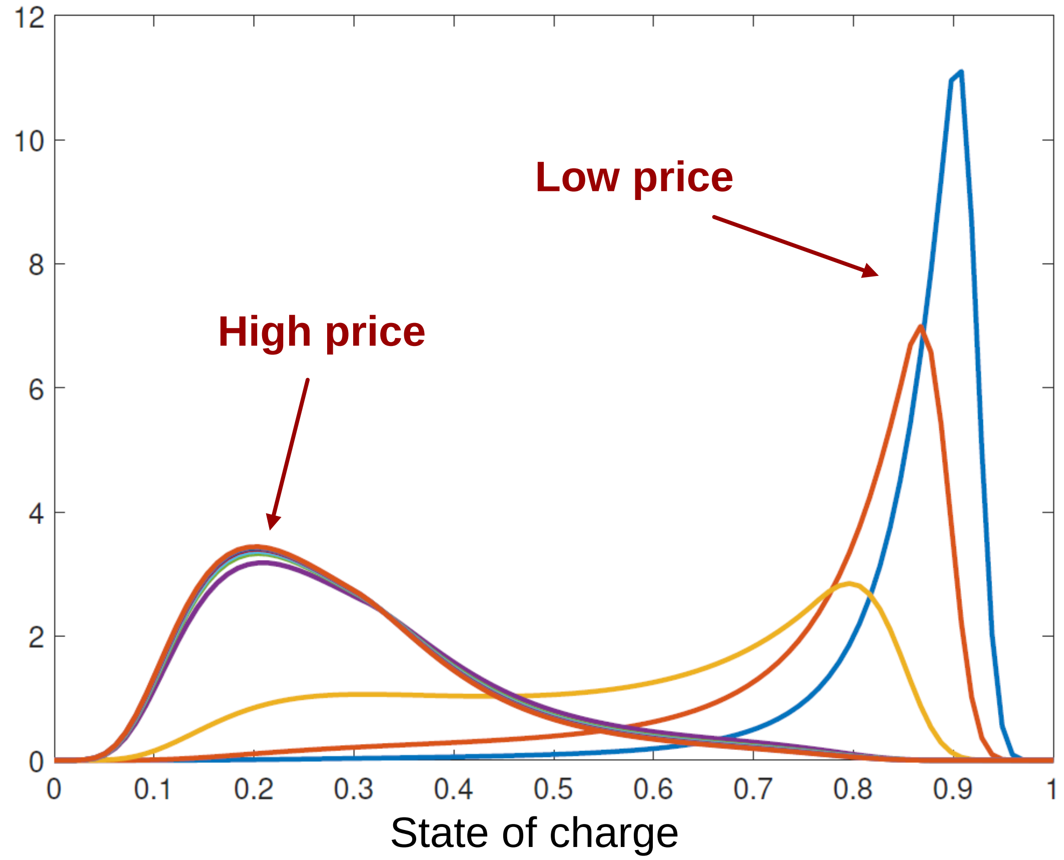
$$\frac{\partial p}{\partial t}(x,t) = -\frac{\partial}{\partial x}\big(f(x,u,t)p(x,t)\big) + \frac{\partial^2}{\partial x^2}\big(\sigma(x,u,t)p(x,t)\big)$$

$$0 = -\frac{\partial}{\partial x}\big(f(x,u,t)p(x,t)\big) + \frac{\partial^2}{\partial x^2}\big(\sigma(x,u,t)p(x,t)\big)$$

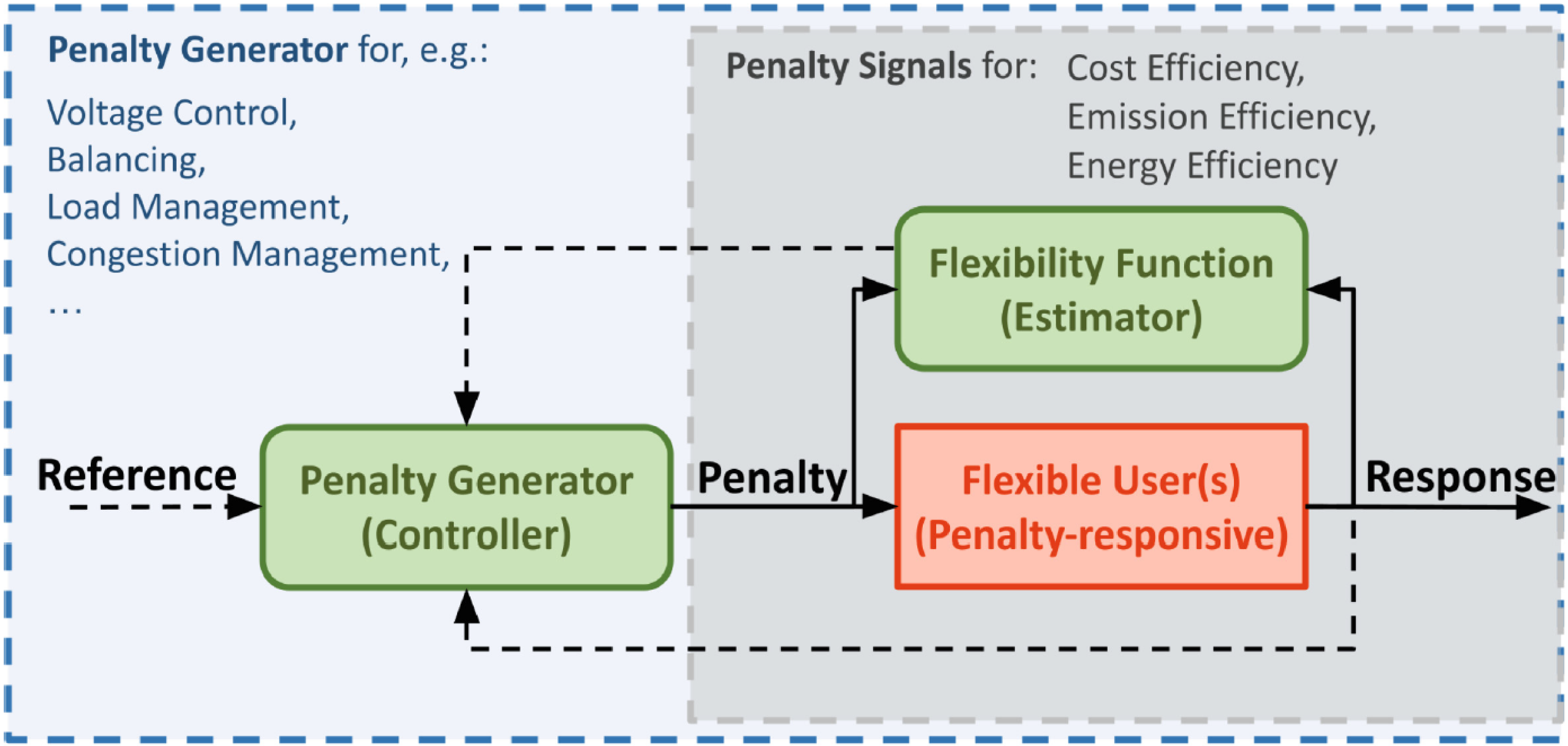
Probability density function



Stationary density



Price signal generation



Price signal generation

Predictive open-loop control
(day-ahead prices, setpoint tracking)

$$\min_{\{\bar{u}_k\}_{k=0}^{N-1}} \quad \phi^{OL}\left([z_t, \bar{z}_t]_{t_0}^{t_f}\right),$$

s.t.

$$\begin{aligned}
x_{t_0} &\sim \mathcal{N}(\hat{x}_0, P_0), \\
dx_t &= f(t, x_t, u_t)\, dt + g(x_t)\, dW_t, \quad t \in [t_0, t_f], \\
z_t &= h(t, x_t, u_t), \quad t \in [t_0, t_f], \\
u_t &= \bar{u}_k, \quad t \in [t_k,\ t_{k+1}[, \quad k = 0, \ldots, N-1, \\
u_{min} &\leq \bar{u}_k \leq u_{max}, \quad k = 0, \ldots, N-1,
\end{aligned}$$

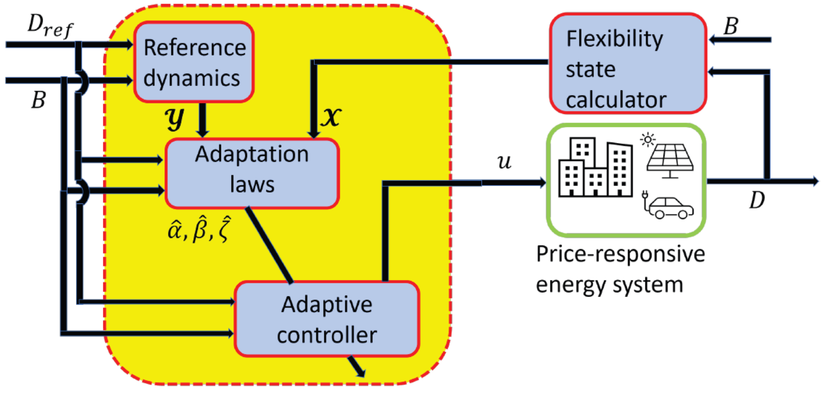
Feedback control
(real-time prices, follow setpoint)

$$\min_{\mu} \quad \phi^{CL}(\mu),$$

s.t.

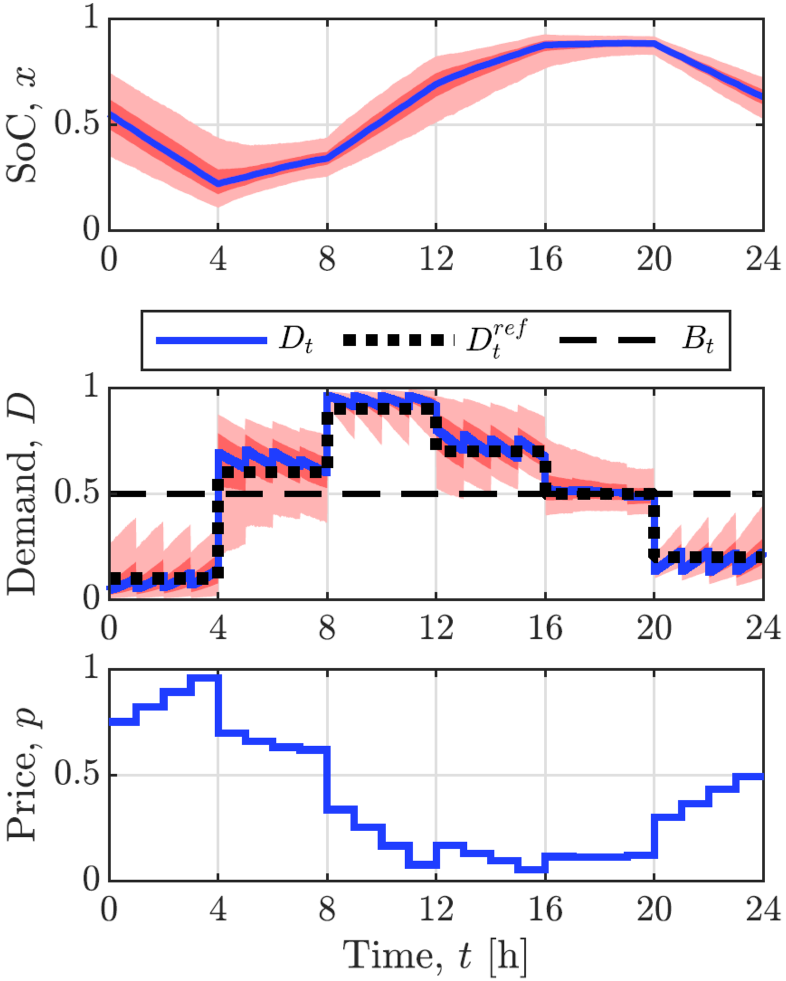
$$\begin{aligned}
x_{t_0} &= \mathcal{N}(\hat{x}_0, P_0), \\
dx_t &= (f_0(t) + f_1 u_t)\, dt + g(x_t)\, dW_t, \quad t \in [t_0, t_f], \\
u_t &= \mu(t, x_t), \quad t \in [t_0, t_f], \\
u_{min}(t, x_t) &\leq u_t \leq u_{max}(t, x_t), \quad t \in [t_0, t_f],
\end{aligned}$$

Model-reference adaptive control
(real-time prices)

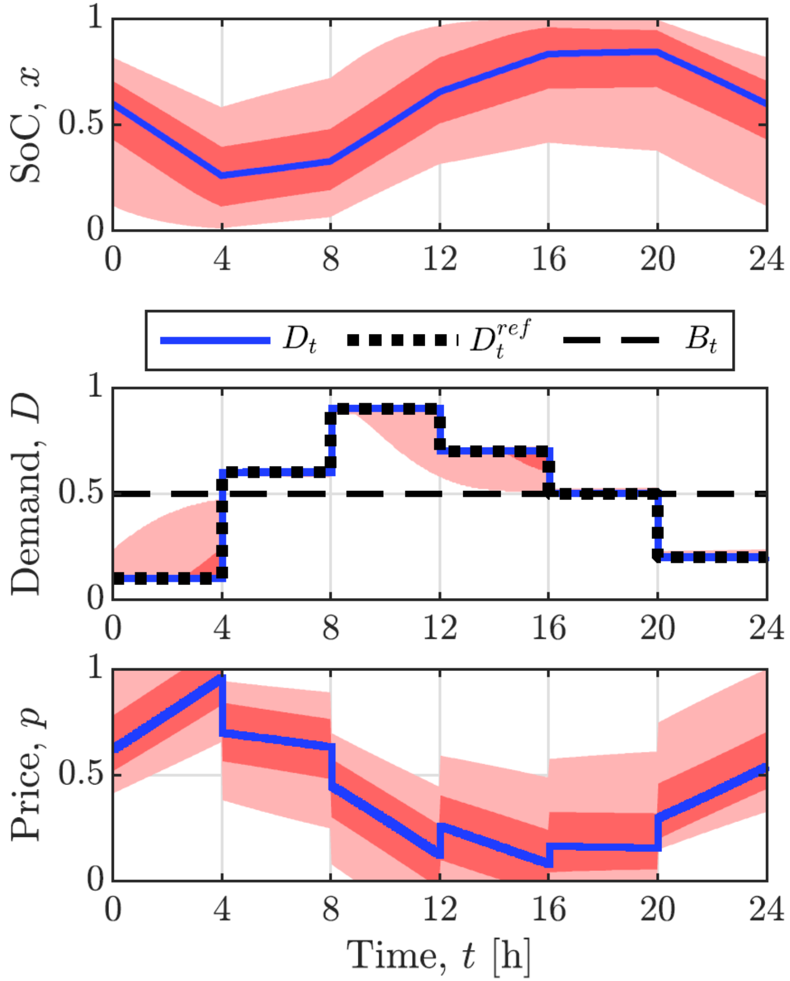


Generated price signals

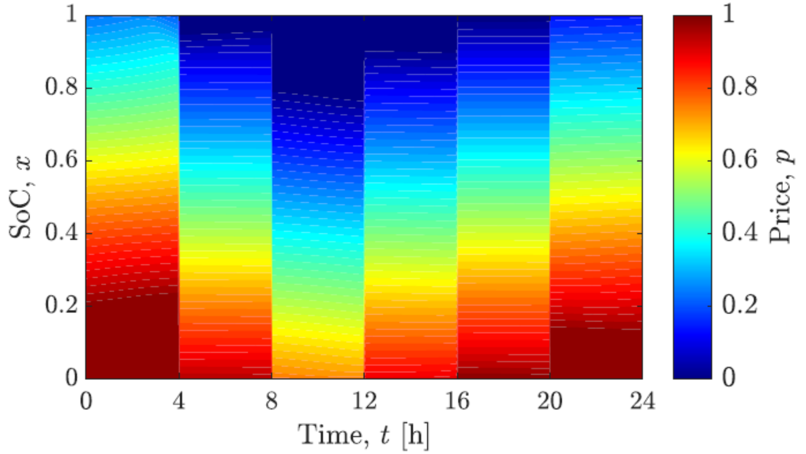
Day-ahead prices
(open-loop)



Real-time prices
(closed-loop, HJB)



Optimal feedback policy



Flexibility across hierarchies

- Indirect control
- Time-varying flexibility

Data-driven model
of demand response

- Flexibility function
- SDE
- Real-time identification

Indirect control of demand

- Day-ahead (open-loop)
- Real-time prices (closed-loop)

Thank you