Data-driven Methods for the Future Weather-driven Smart Energy Systems

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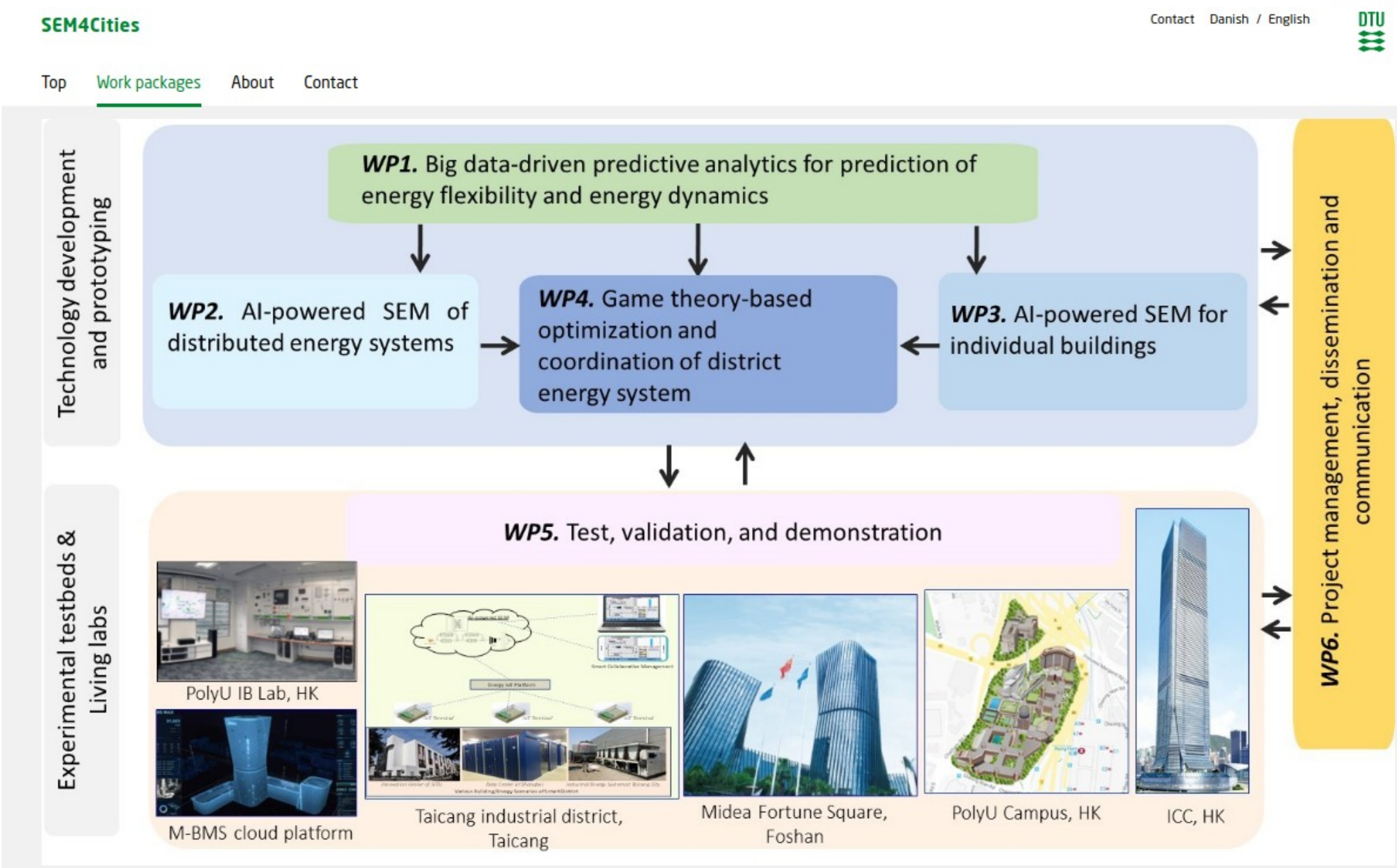
SEM4Cities
Development of Smart Energy Management Technologies for Buildings and Districts in High-Density Cities

Contact Danish / English

Top Work packages About Contact

The SEM4Cities project aims to develop innovative smart energy management technologies and solutions for buildings and districts in smart and sustainable high-density cities by effectively leveraging advanced big data and AI technologies.



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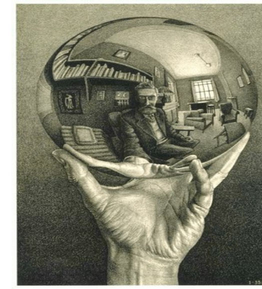
Content

- Challenges
- Digitalized energy systems
- Smart-Energy Operating-System (SE-OS)
- Flexibility – and smart grids
- Peak shaving
- Energy or Emission efficiency?
- Integrated Forecasting and Control of Buildings
- Forecasting using spatial hierachies



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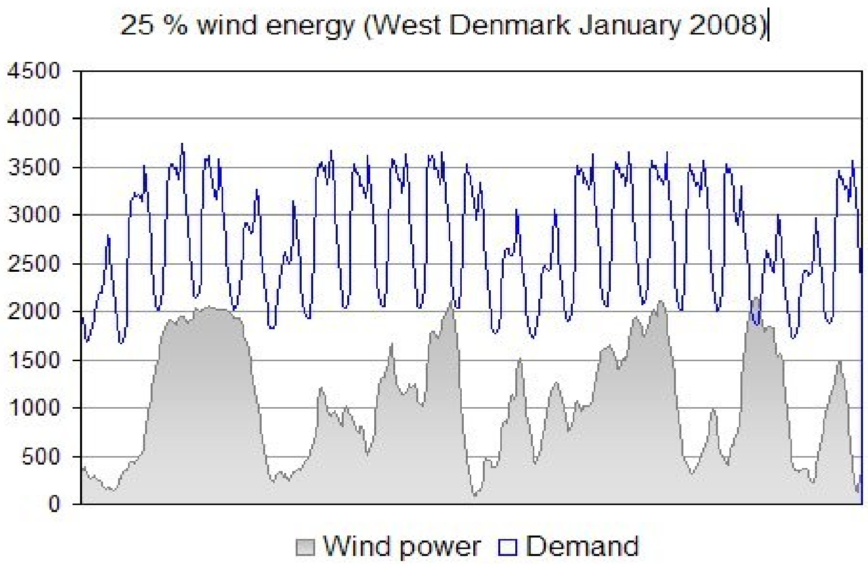
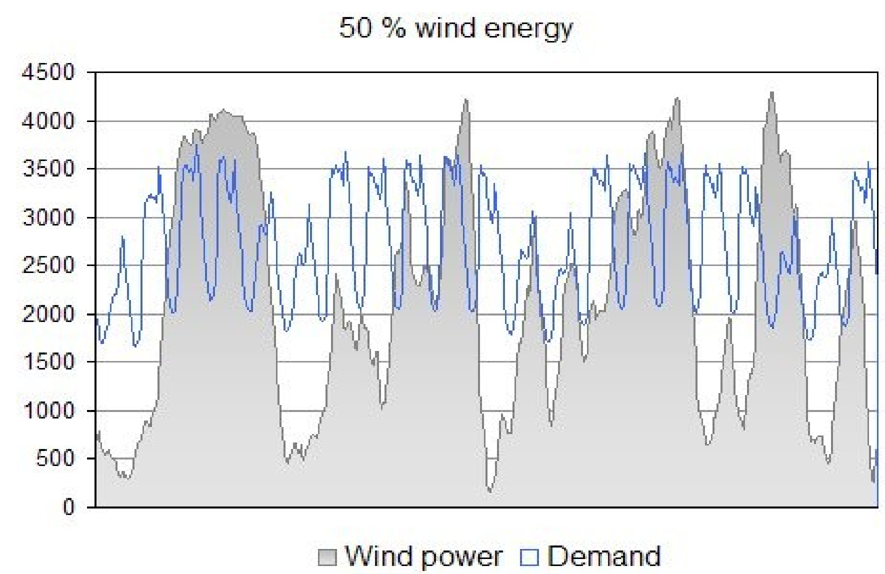
Challenges

The Danish Wind Power Case

.... balancing of the power system





In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

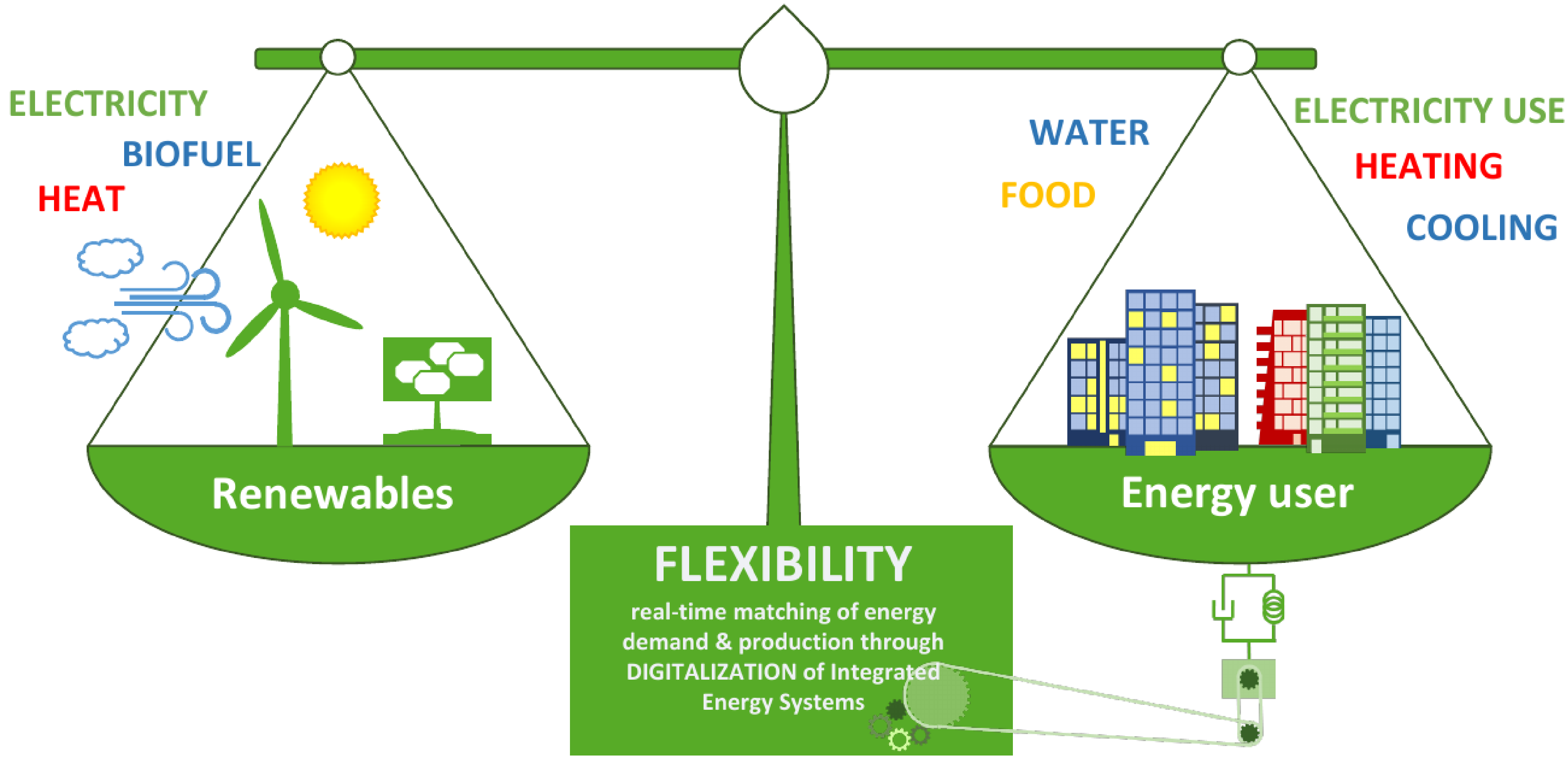
Now flexibility of the load is essential

That's the topic of 'Flexible Energy Denmark'

(For several days the wind power production is more than 100 pct of the power load)

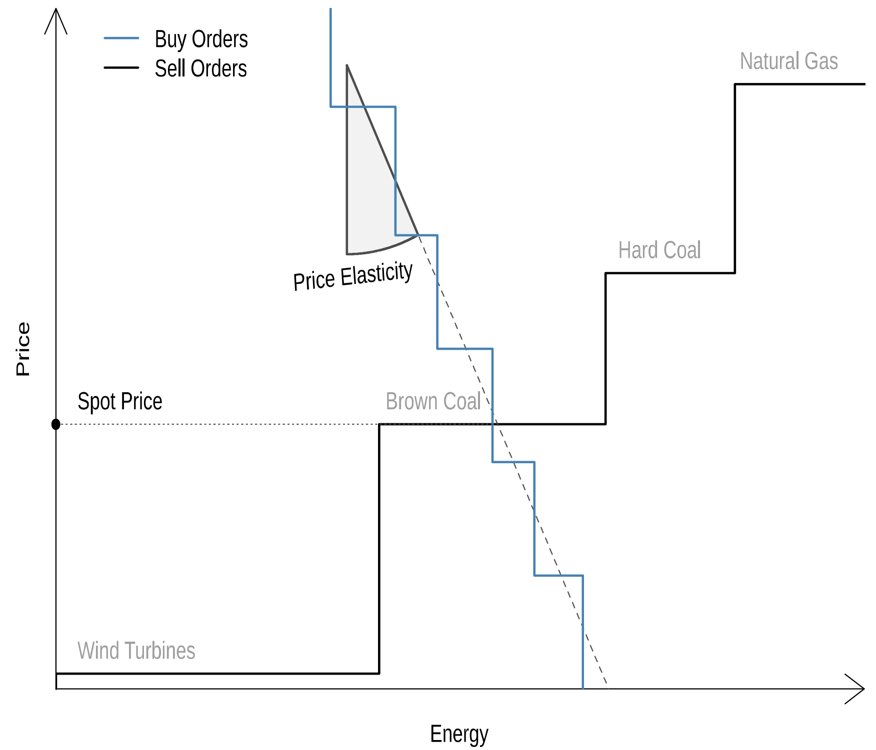
Weather-driven Energy System

The Challenge: Denmark Fossil Free 2050



Characterisation of Energy Flexibility

Today: Static Measures - Price elasticity

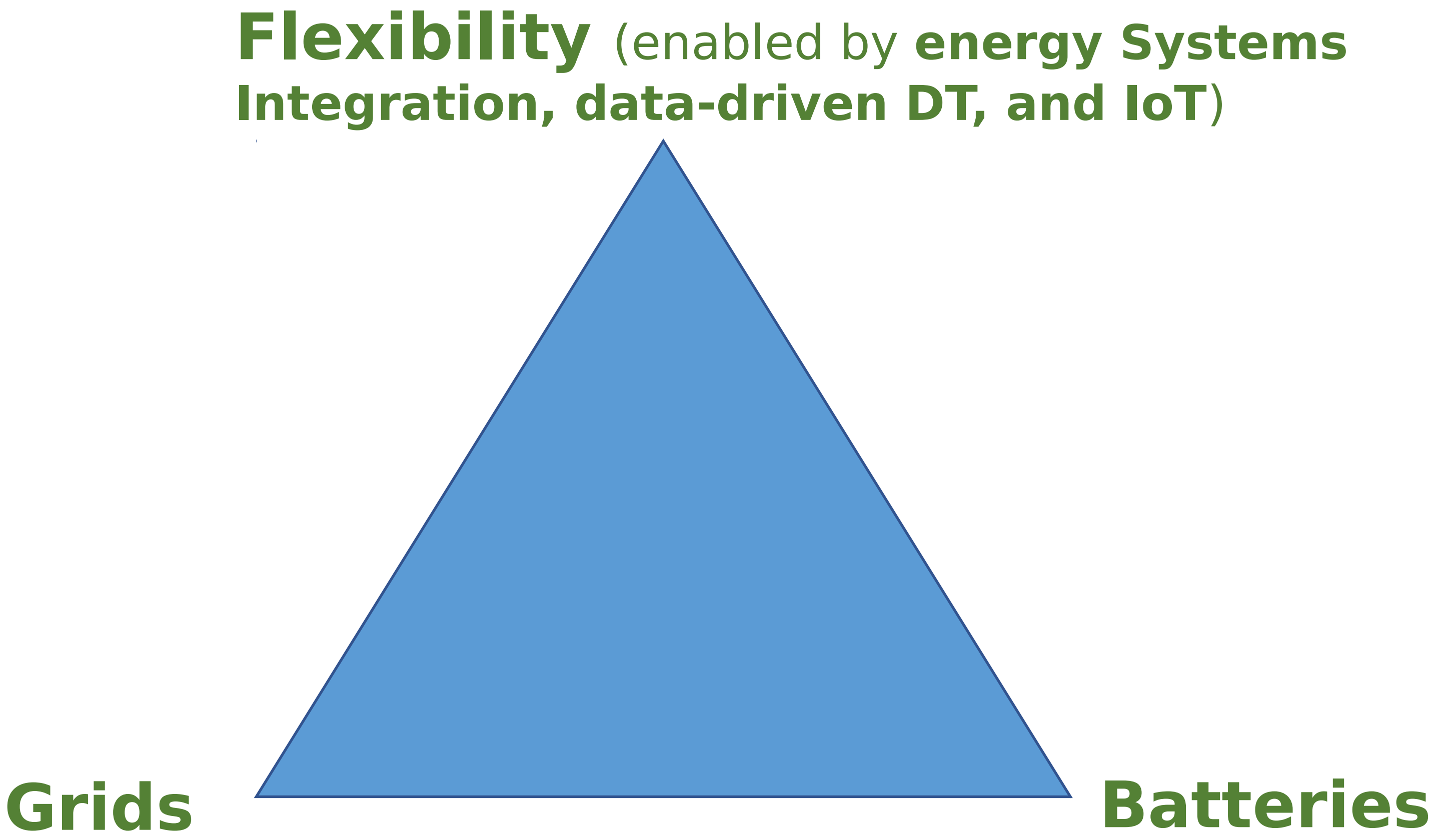


Needed Modifications of Energy Markets

- 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**

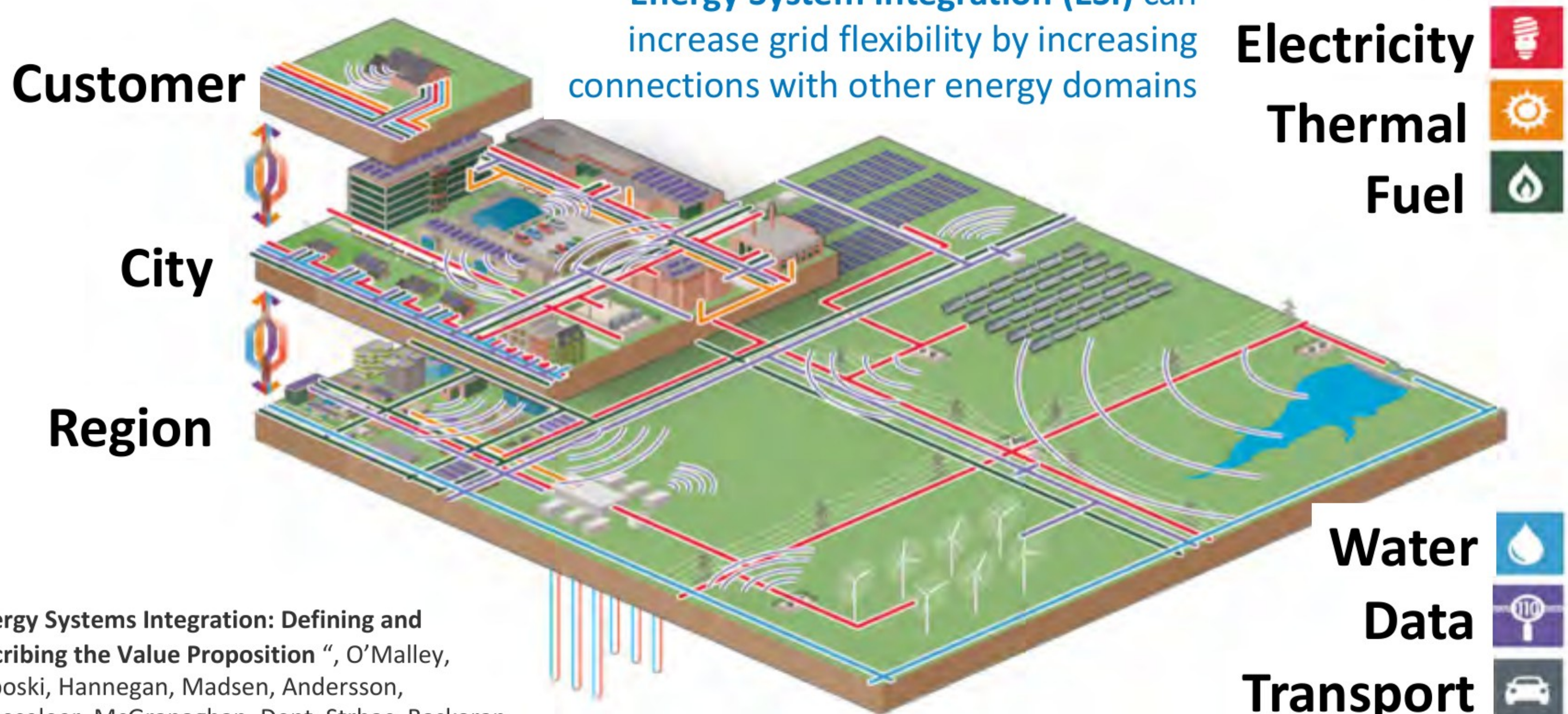
Data-Intelligent and Flexible Energy Systems

Space of Solutions



Energy Systems Integration

Energy System Integration (ESI) can increase grid flexibility by increasing connections with other energy domains

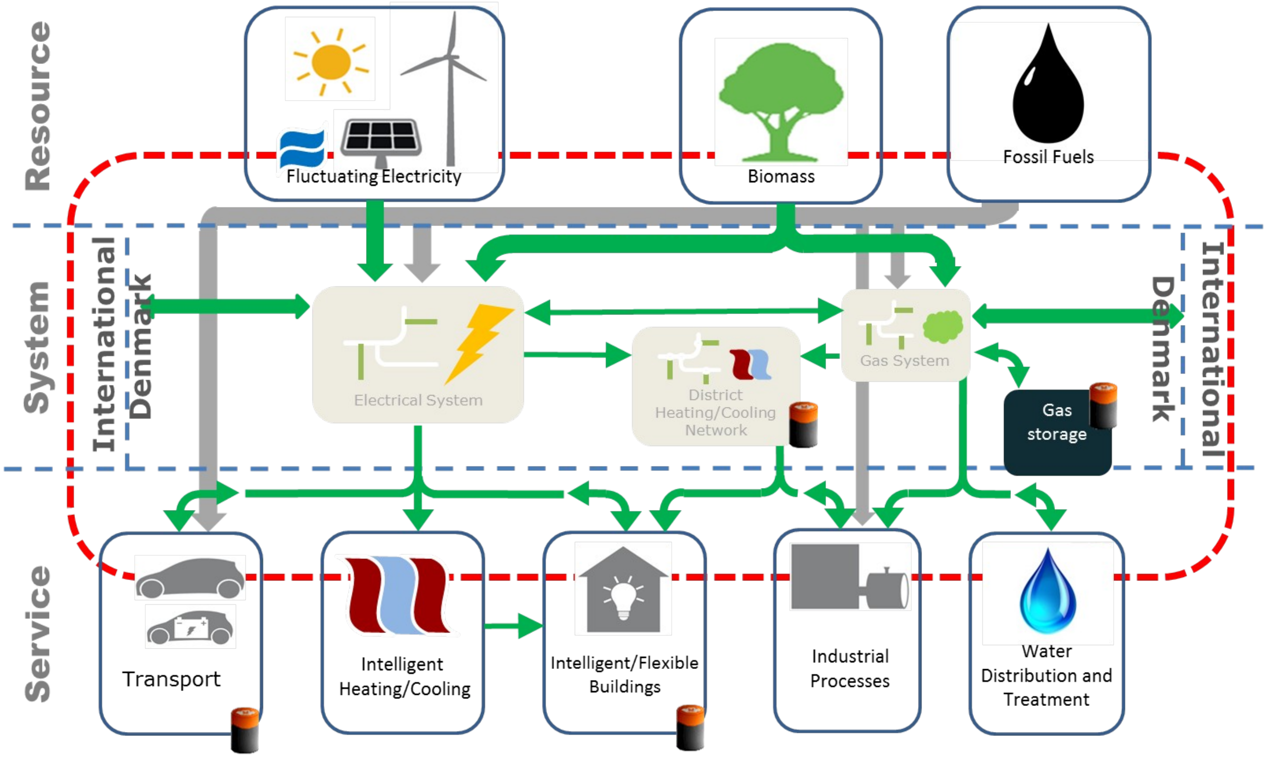


"**Energy Systems Integration: Defining and Describing the Value Proposition** ", O'Malley, Kroposki, Hannegan, Madsen, Andersson, D'haeseleer, McGranaghan, Dent, Strbac, Baskaran, Rinker., NREL/TP-5D00-66616. June 2016

NREL | 17

Energy System Digital Twins for Real Time Applications and Data Assimilation

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



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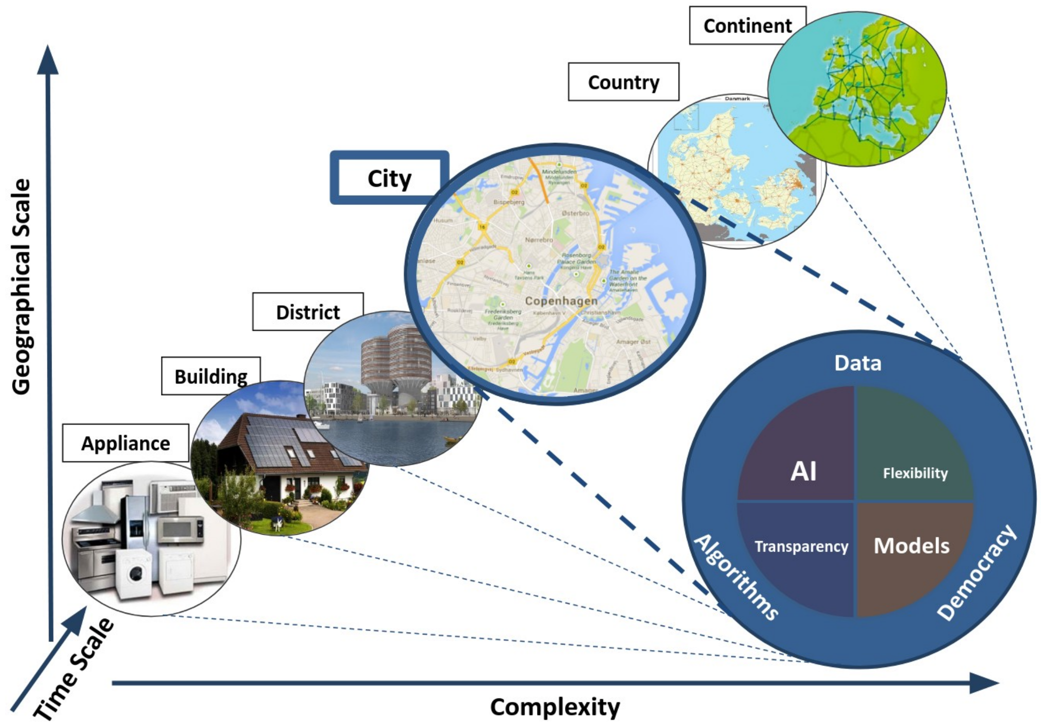
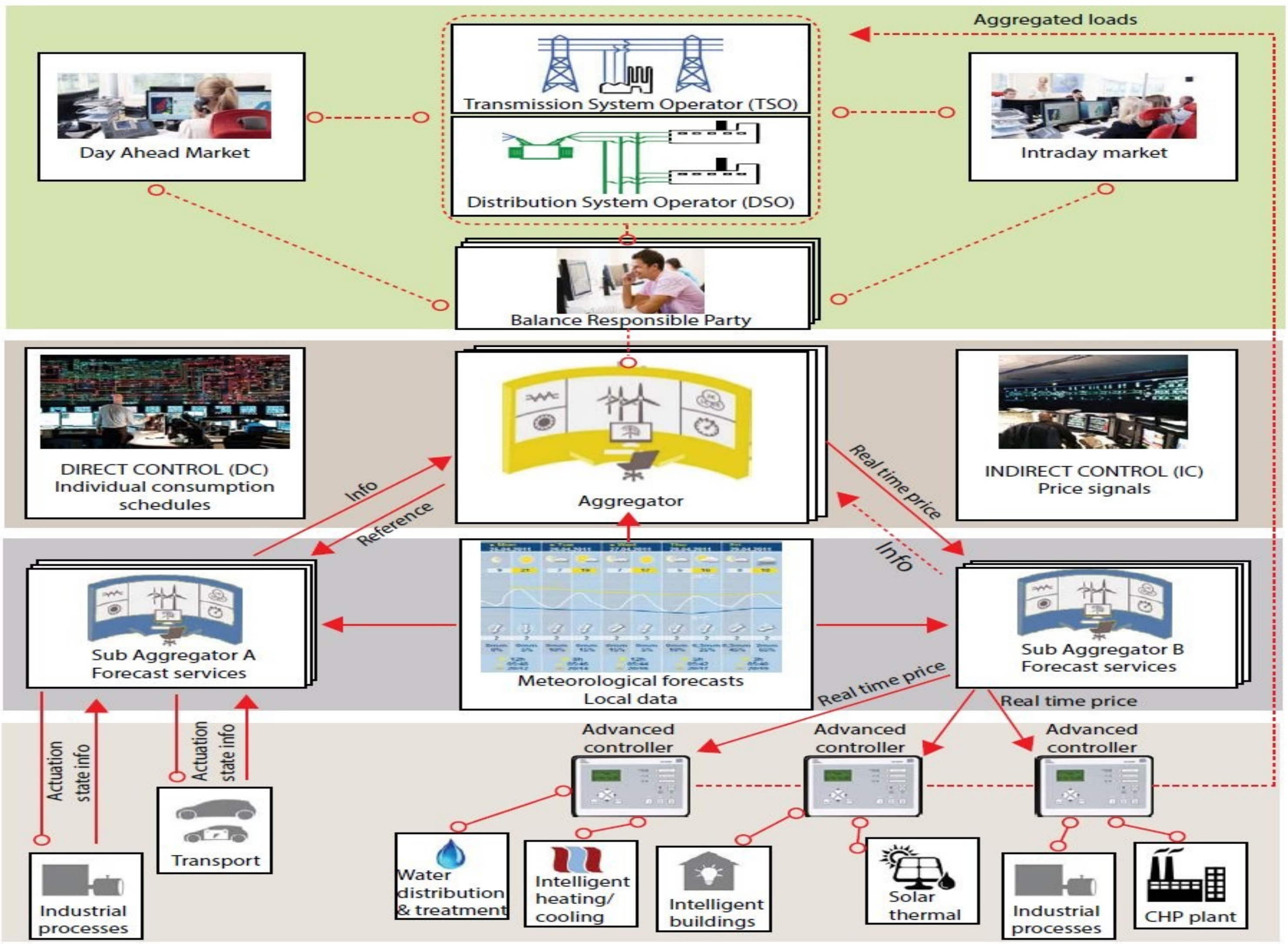
Temporal and Spatial Scales

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**.



Smart-Energy OS
The Transformative Power of Digitalization



(**Static**)

Conventional Markets

Linking Markets to Physics

(Flexibility Functions)

(**Dynamic**)

Local Flexibility at the Edge

(Hierarchy of controllers)

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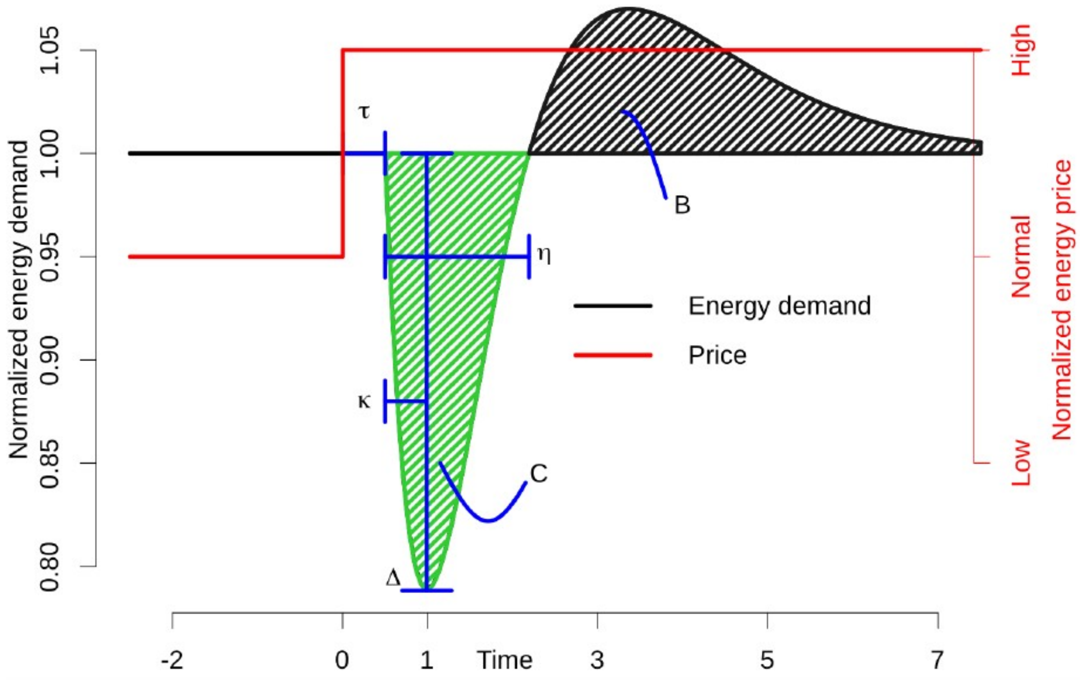
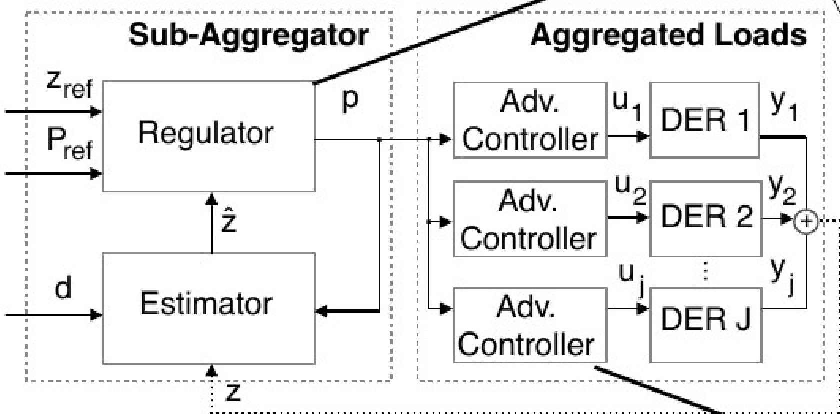
Flexibility Function

The ***Flexibility Function (FF)*** is one of the **MIMs (Minimum Interoperability Mechanisms) for energy systems** used to characterizing flexibility and providing interface between local flexibility and high-level markets



Proposed methodology
Control-based methodology



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

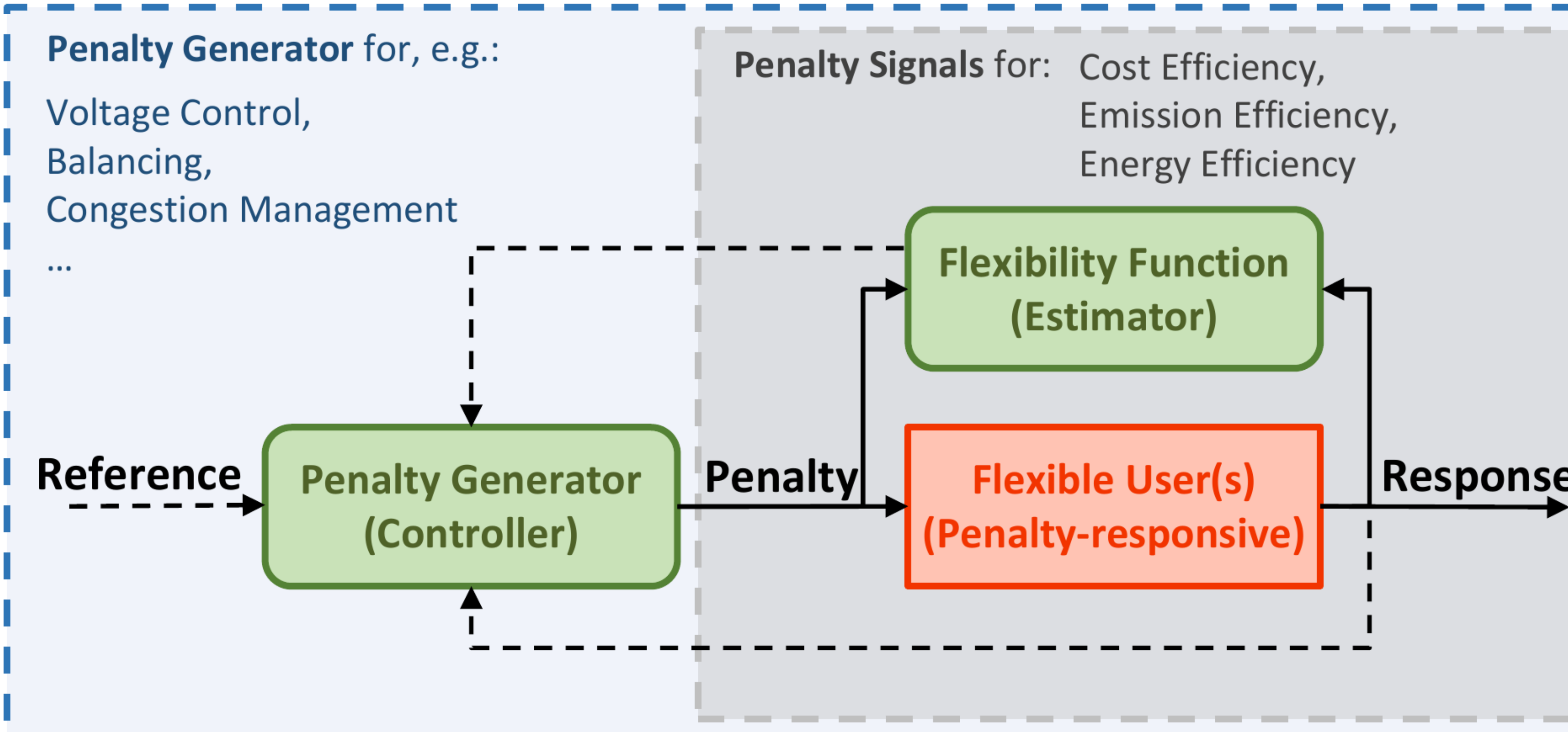
$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$

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

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

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

A FED example: Flexible Users and Penalty Signals



Penalty (examples)

- **Real time CO_2.** If the real time (marginal) CO_2 emission related to the actual electricity production is used as penalty, then, a smart building will minimize the total carbon emission related to the power consumption. Hence, the building will be *emission efficient*.

- **Real time price**. If a real time price is used as penalty, the objective is obviously to minimize the total cost. Hence, the building is *cost efficient*.

- **Constant**. If a constant penalty is used, then, the controllers would simply minimize the total energy consumption. The smart building is, then, *energy efficient*.

Flexibility Function Model

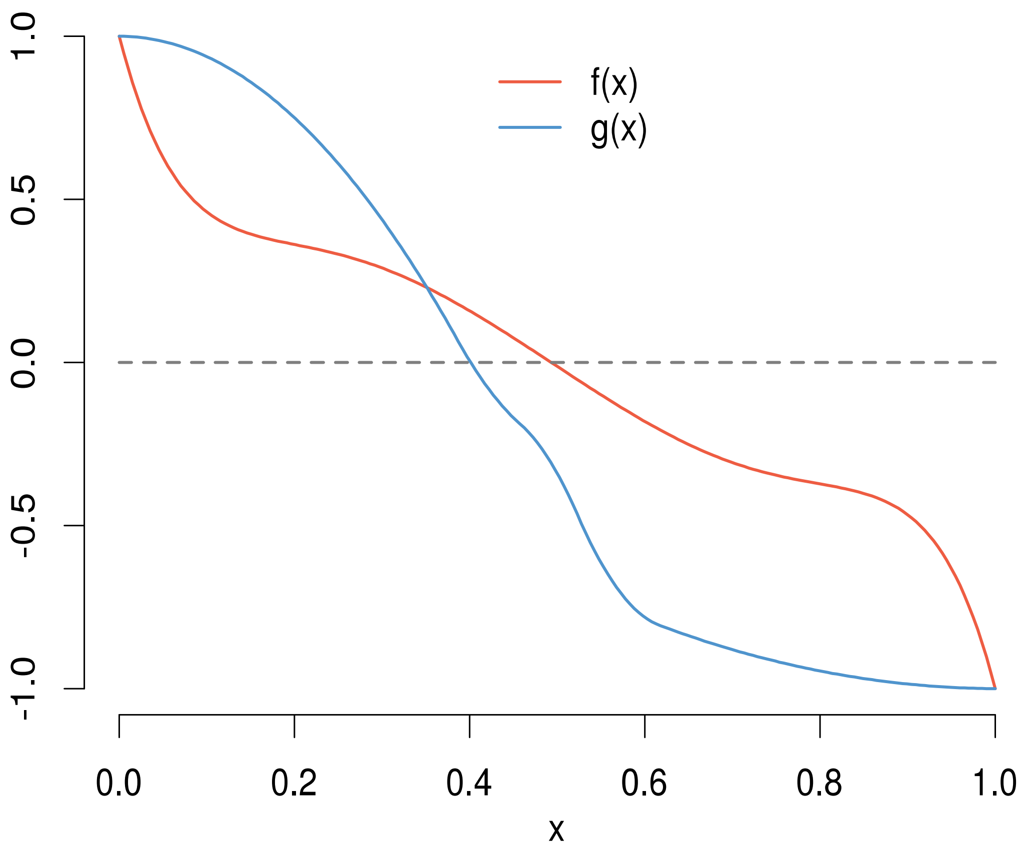
Flexibility Function Model describes the energy demand of a price-responsive systems as function of price and state of charge.

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

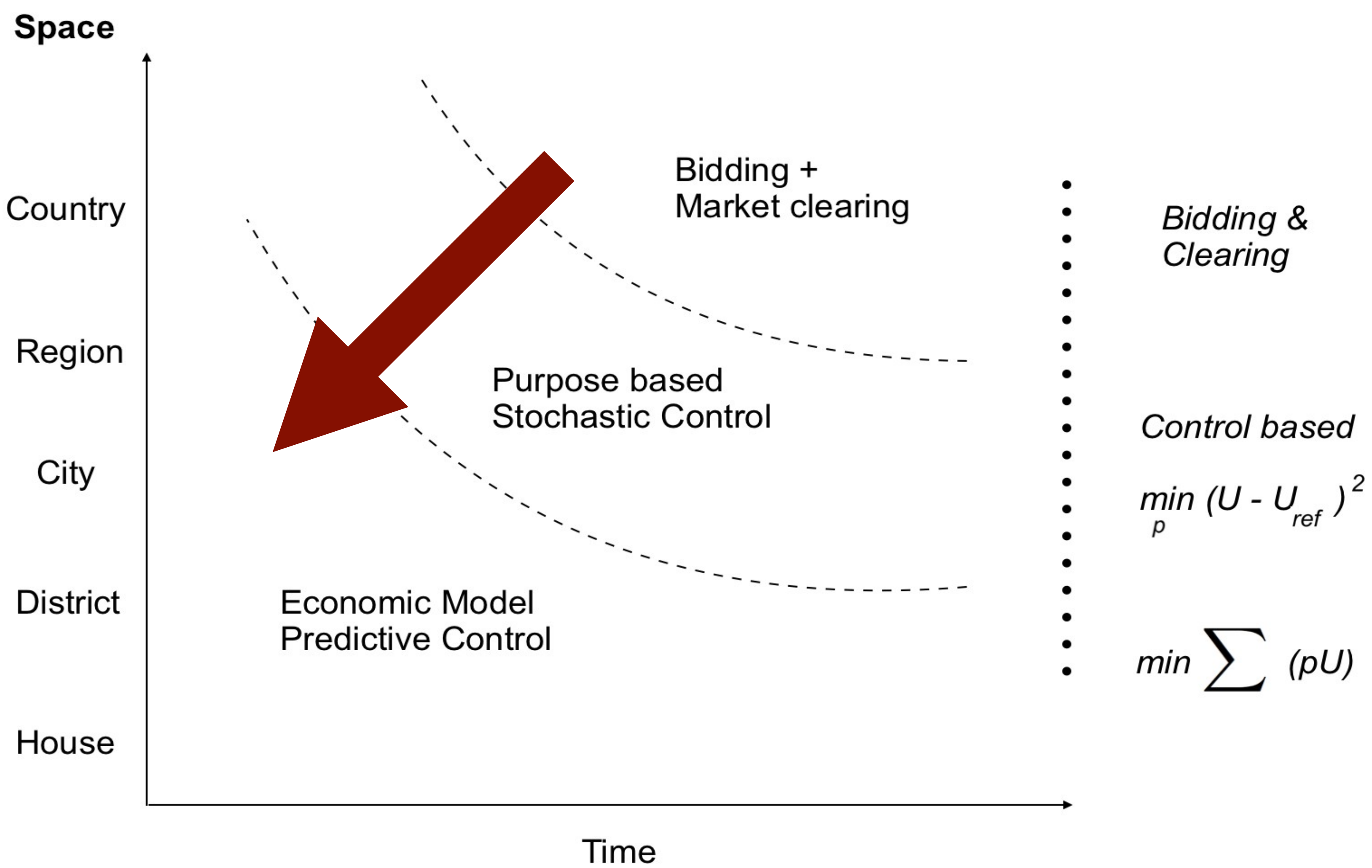
X = state of charge
B = demand (at constant price) / baseline
f(*) = Demand-SoC relationship
g(*) = Demand-Price relationship

Characterisation of Energy Flexibility

Non-linear Flexibility Function using SDE's



The ‘market’ of tomorrow



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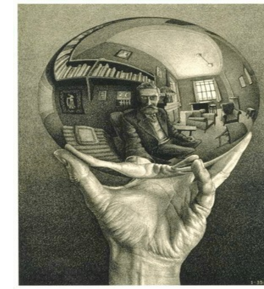
SE-OS Characteristics

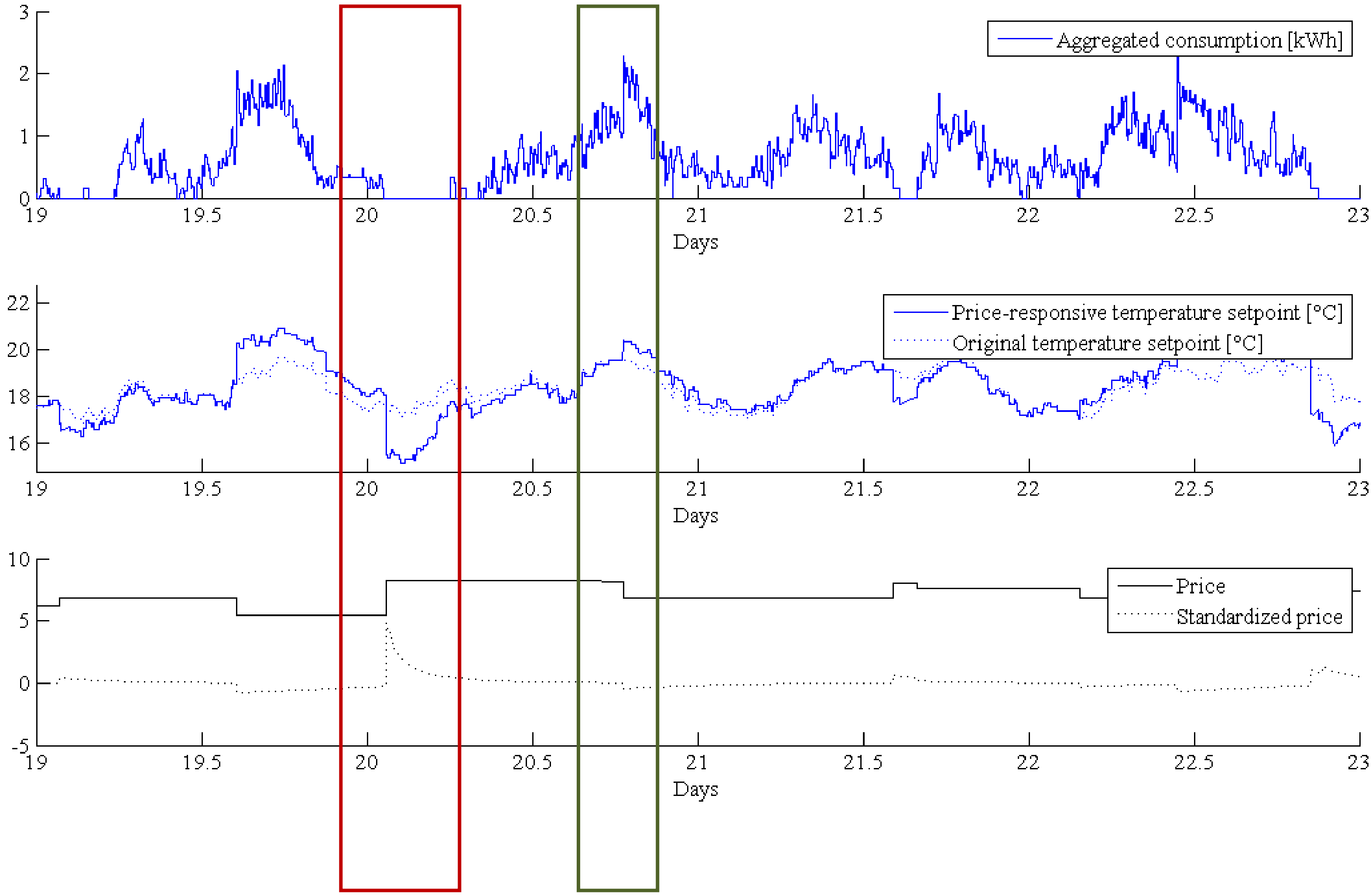


- Security and Privacy by design
- Democracy and Transparency prioritized
- Able to unlock flexibility at end-users
- Embedded TSO-DSO coordination
- AI and Grey-Box models for data-intelligence
- Hierarchy of optimization (or control) problems
- Creates a link between markets and the physics
- Cloud, 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, ...)

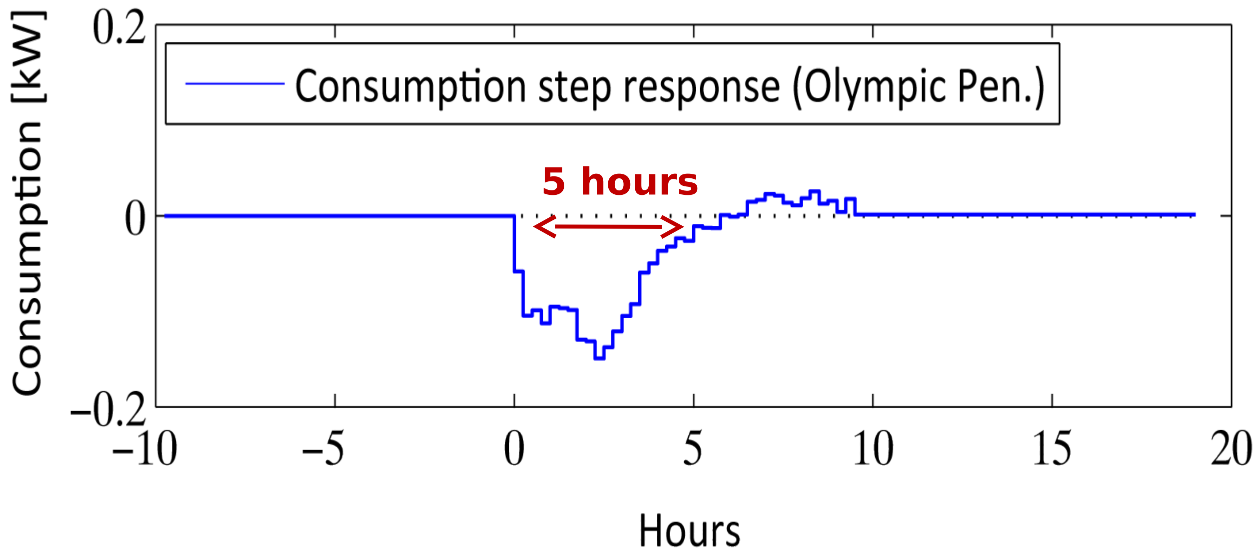
Case study

Price-based Control of Power Consumption (Peak Shaving)

Aggregation (over 20 houses)

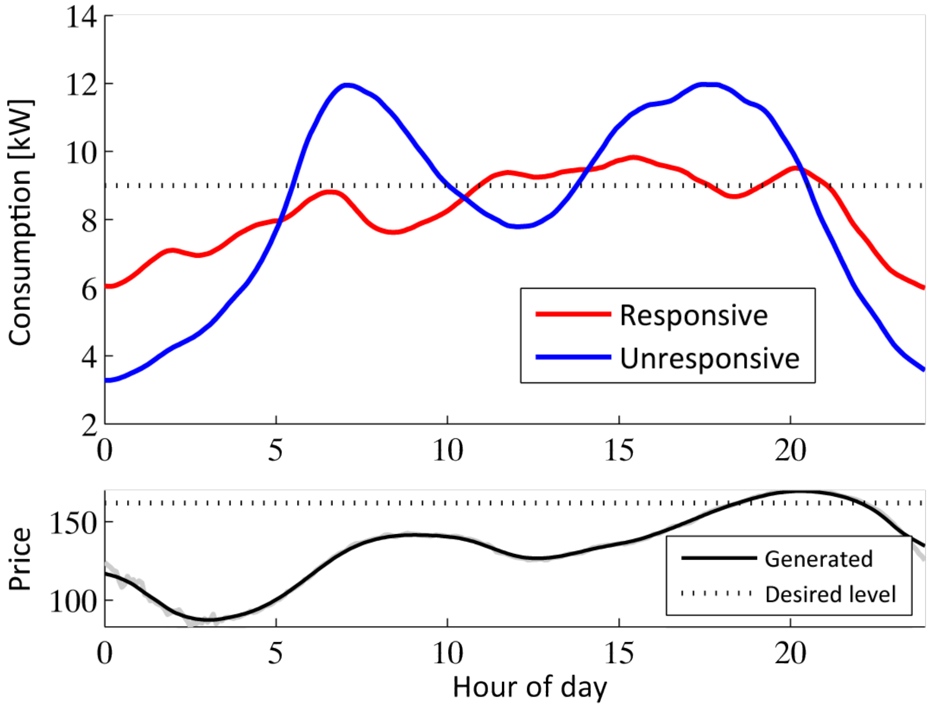


Response on Price Step Change

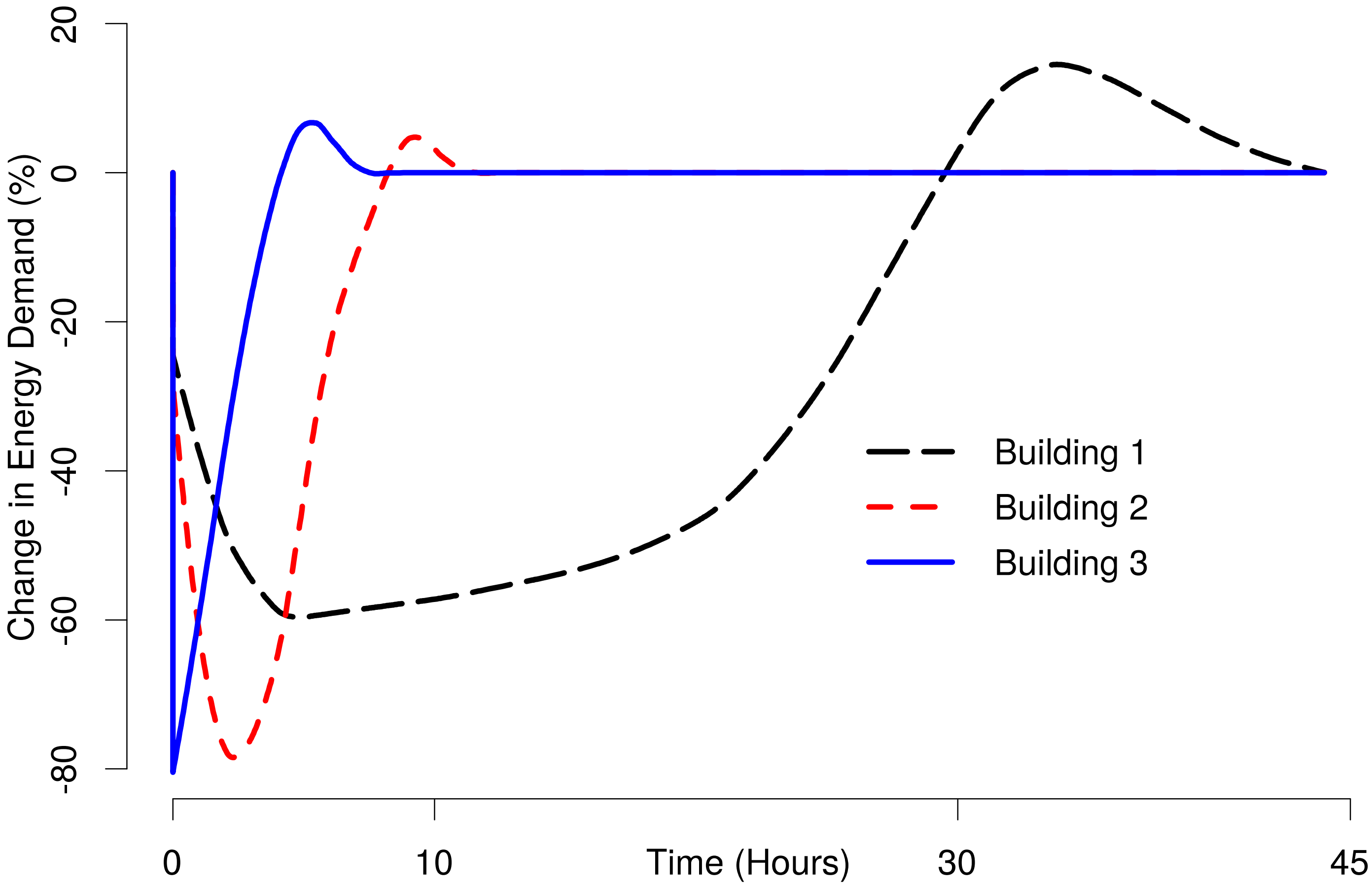


Control performance

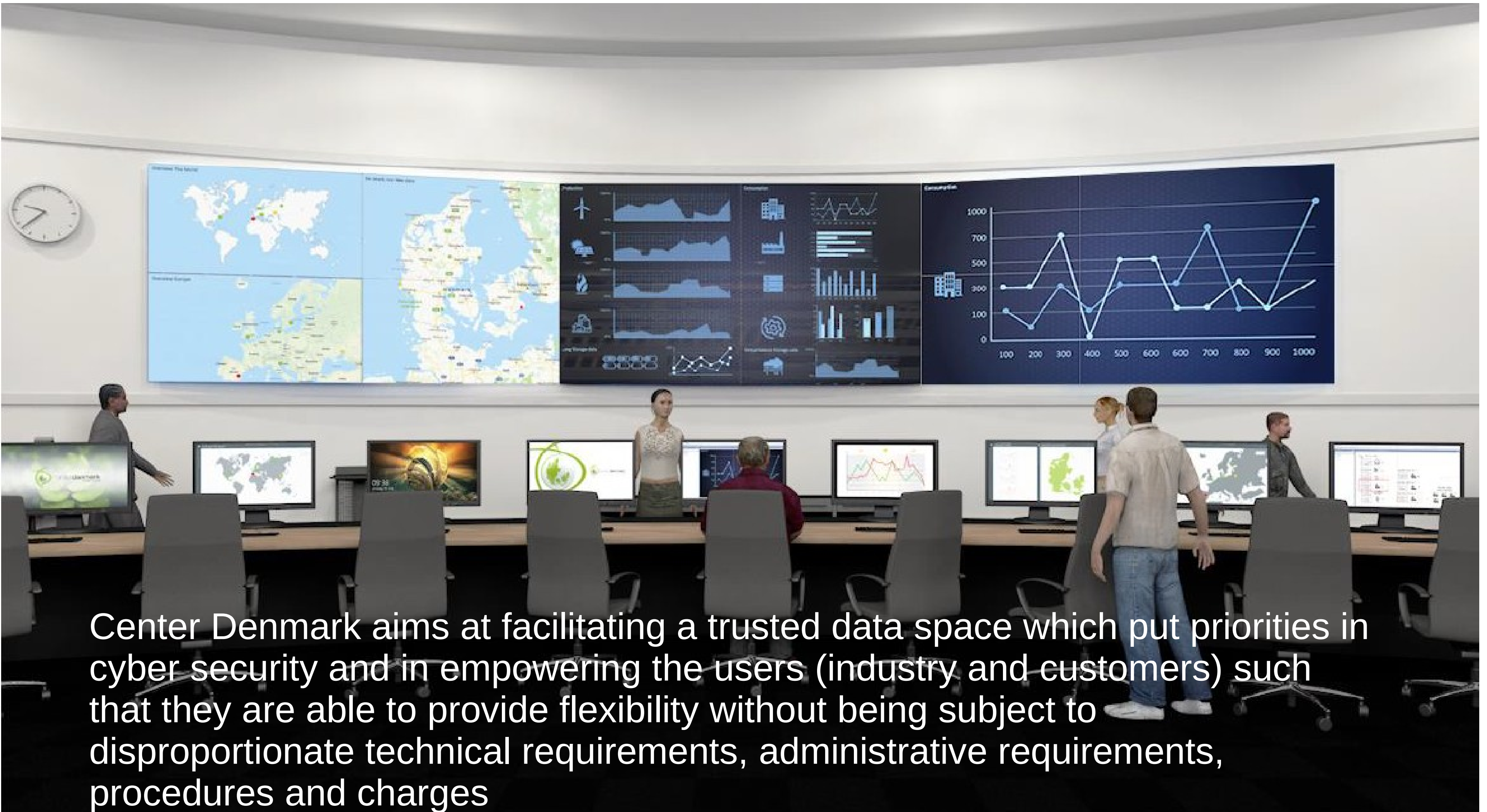
Considerable **reduction in peak consumption**



Flexibility Function Examples



Center Denmark
Control Room and Data Space
Spatial–Temporal thinking



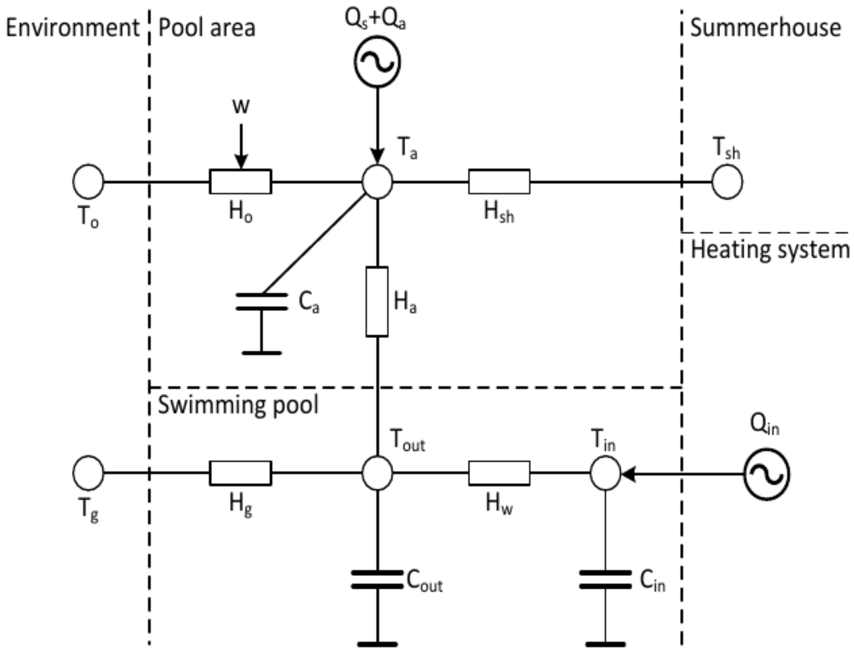
Center Denmark aims at facilitating a trusted data space which put priorities in cyber security and in empowering the users (industry and customers) such that they are able to provide flexibility without being subject to disproportionate technical requirements, administrative requirements, procedures and charges

Case study

Summerhouses with a pool

Data-driven models for the buildings

(Using lumped parameter models)



- Based on equivalent thermal parameters model

- Dynamics:

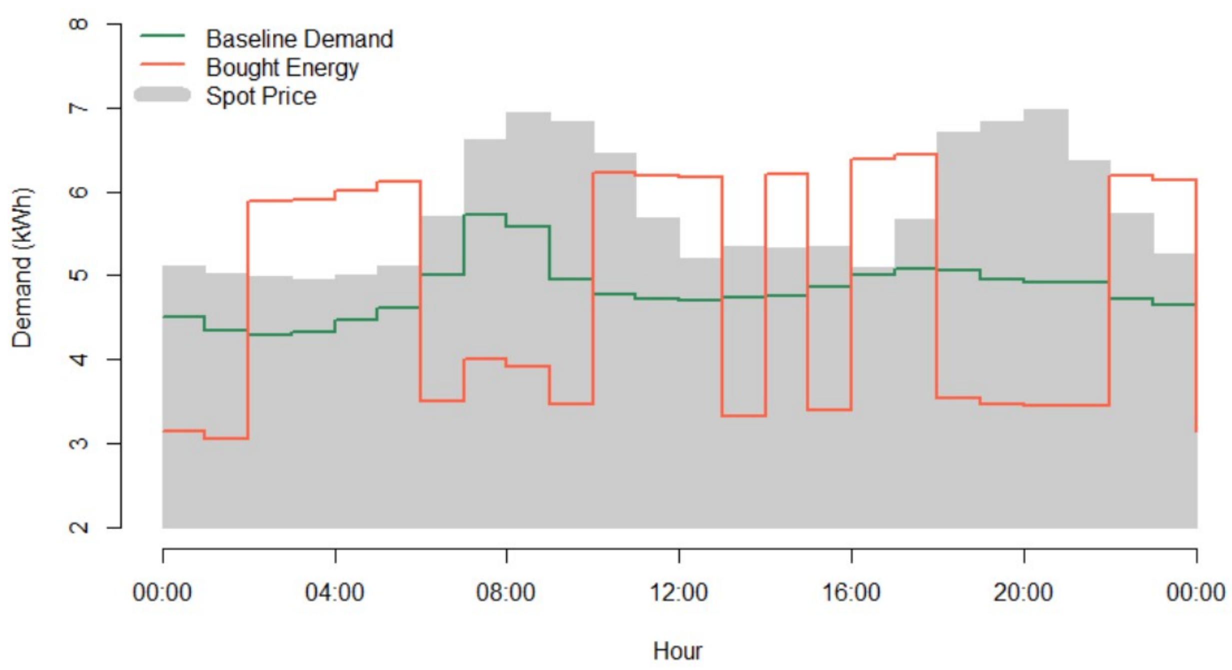
$$\frac{dT_{in}}{dt} = \frac{1}{C_{in}}[H_w(T_{out} - T_{in}) + Q_{in}]$$

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

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

Bidding Flexibility into Markets

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



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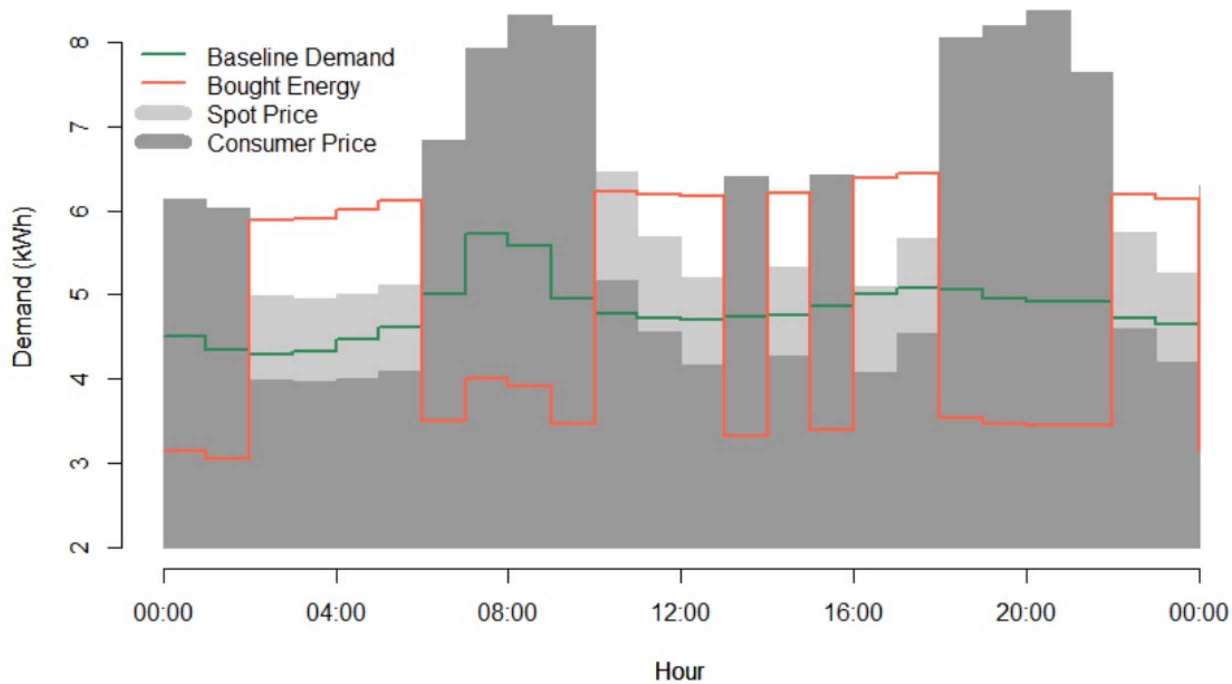
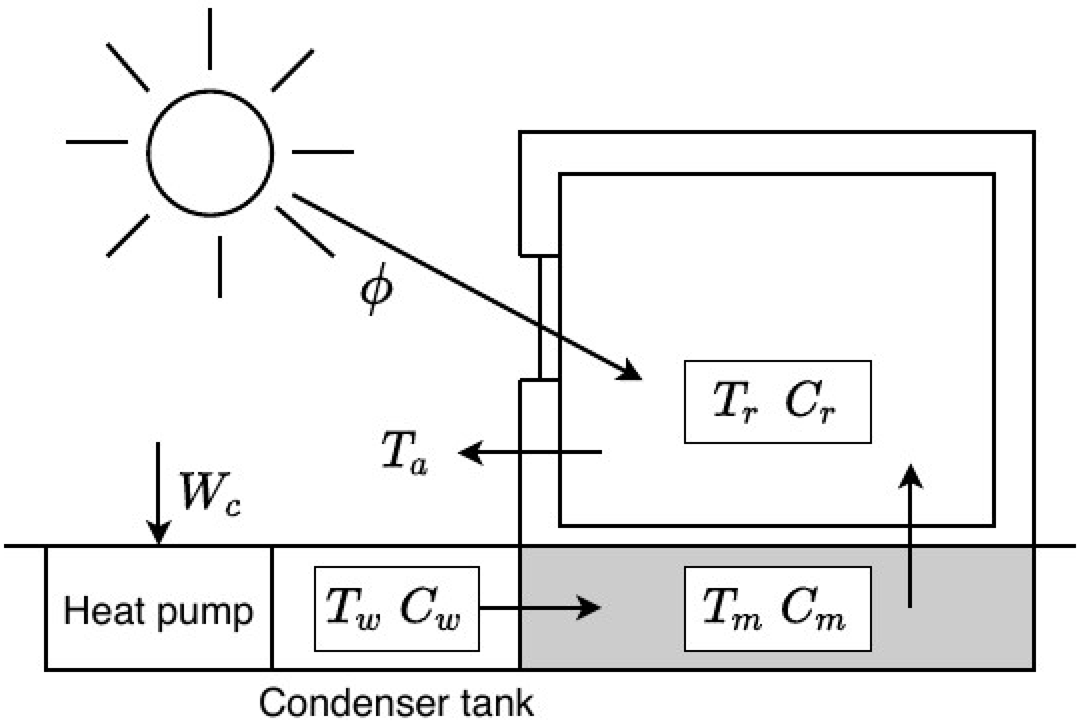
Bidding Flexibility into Markets

Solve FF(Price)=Bought Energy:



Integrated Forecasting and Control for Smart Buildings

Grey-box Model for a Smart Building



Grey-box Model for Forecasting

(Cloud cover, solar radiation, ambient air temperature)

$$
\text{Disturbance model}\begin{cases}
\mathrm{d}Z_\kappa = f_\psi(Z_\kappa)\mathrm{d}t + \sigma_\psi \mathrm{d}\omega_\kappa \\
\kappa = \psi^{-1}(Z_\kappa) \\
\phi = I_N(\kappa, t) + I_D(\kappa, t) \\
R_n = R_n(\kappa, \phi, t) \\
\mathrm{d}T_s = f_{T_s}(T_l, T_s)\mathrm{d}t + \sigma_s \mathrm{d}\omega_s \\
\mathrm{d}T_l = f_{T_l}(T_l, T_s, R_n)\mathrm{d}t + \sigma_l \mathrm{d}\omega_a \\
\boldsymbol{d} = [T_a, \phi]^T
\end{cases}
$$

$$
\text{Observation equation}\begin{cases}
d_\phi = \phi + v_\phi, \quad v_\phi \sim N_{iid}(0, R_\phi) \\
d_{T_a} = T_l + v_{T_a}, \quad v_{T_a} \sim N_{iid}(0, R_{T_a}) \\
\boldsymbol{y}_d = [d_{T_a}, d_\phi]^T,
\end{cases} \qquad (13)
$$

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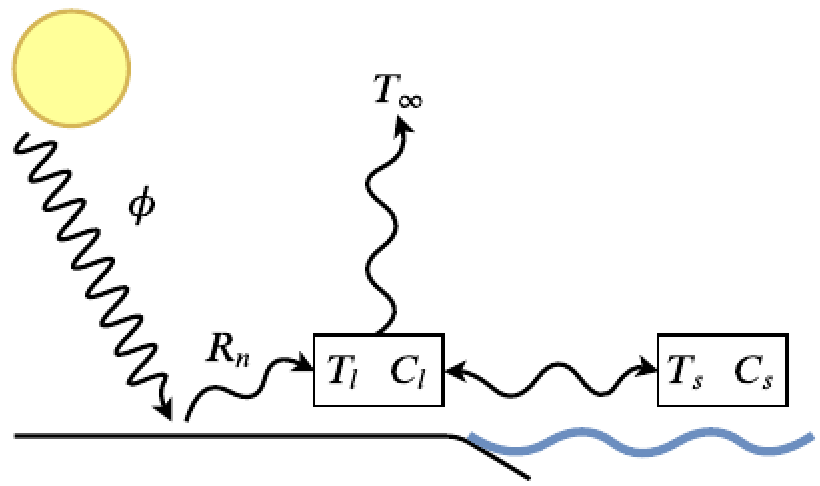
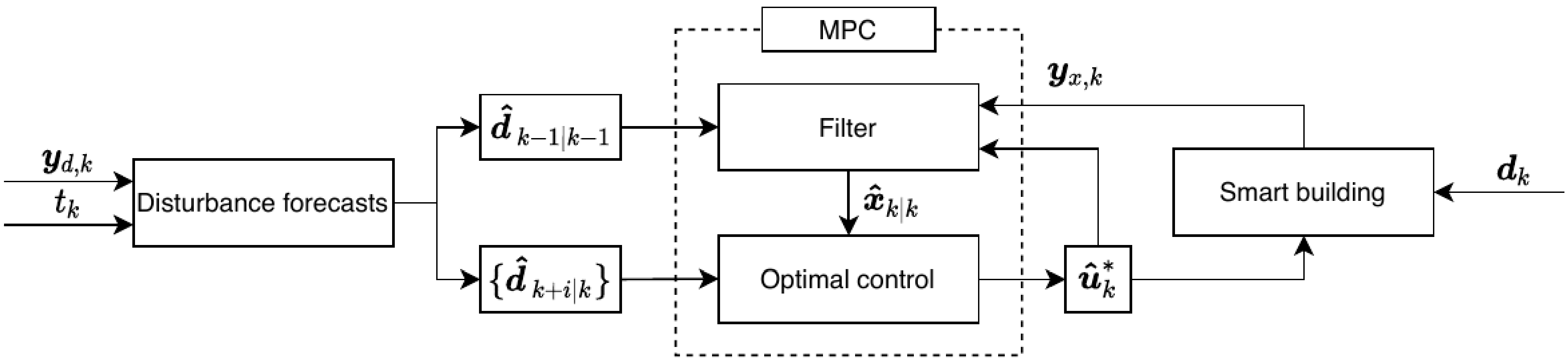
Grey-box model for Ambient Air Temperature



Integrated Forecasting and Control

The MPC framework for smart house control and how distrubance forecasts are incorporated



$$\begin{aligned} \mathrm{d}\boldsymbol{x}(t) &= f_s(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t))\mathrm{d}t \\ &\quad + g_s(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t))\mathrm{d}\boldsymbol{\omega}_s(t)\,, \end{aligned} \tag{1a}$$

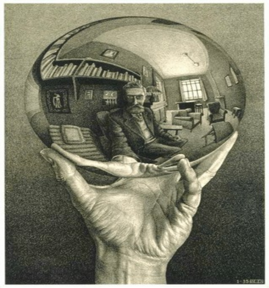
$$\mathrm{d}\boldsymbol{d}(t) = f_d(\boldsymbol{d}(t))\mathrm{d}t + g_d(\boldsymbol{d}(t))\mathrm{d}\boldsymbol{\omega}_d(t)\,, \tag{1b}$$

$$\boldsymbol{y}_s(t_k) = h_s(\boldsymbol{x}(t_k)) + \boldsymbol{v}_{s,k}\,, \tag{1c}$$

$$\boldsymbol{y}_d(t_k) = h_d(\boldsymbol{d}(t_k)) + \boldsymbol{v}_{d,k}\,, \tag{1d}$$

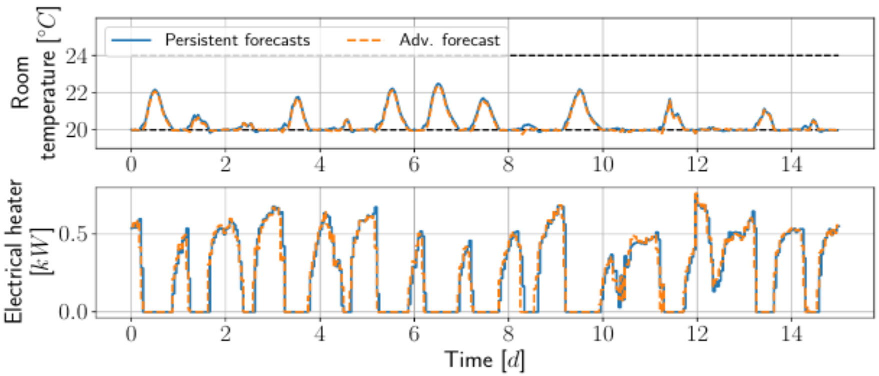
Heating strategies

- Strategy No. 1: Electrical heaters
- Strategy No. 2: Heat pump
- Strategy No. 3: Heat pump and electrical heaters
- Strategy No. 4: Heat pump plus electrical heaters and cooling

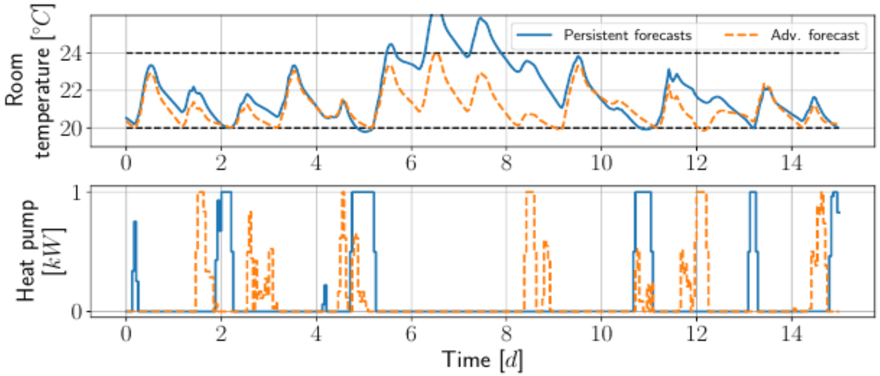


15 days out of 7 months simulation

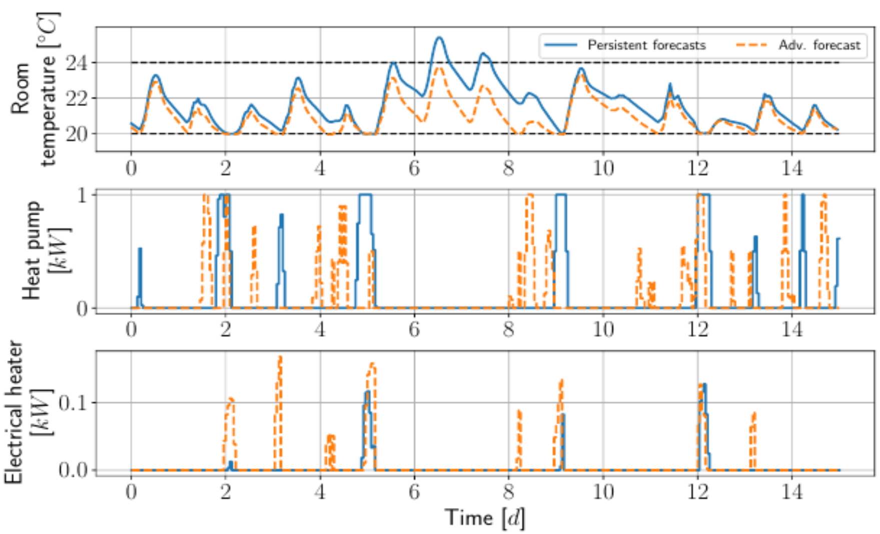
Strategy 1: Electrical Heaters



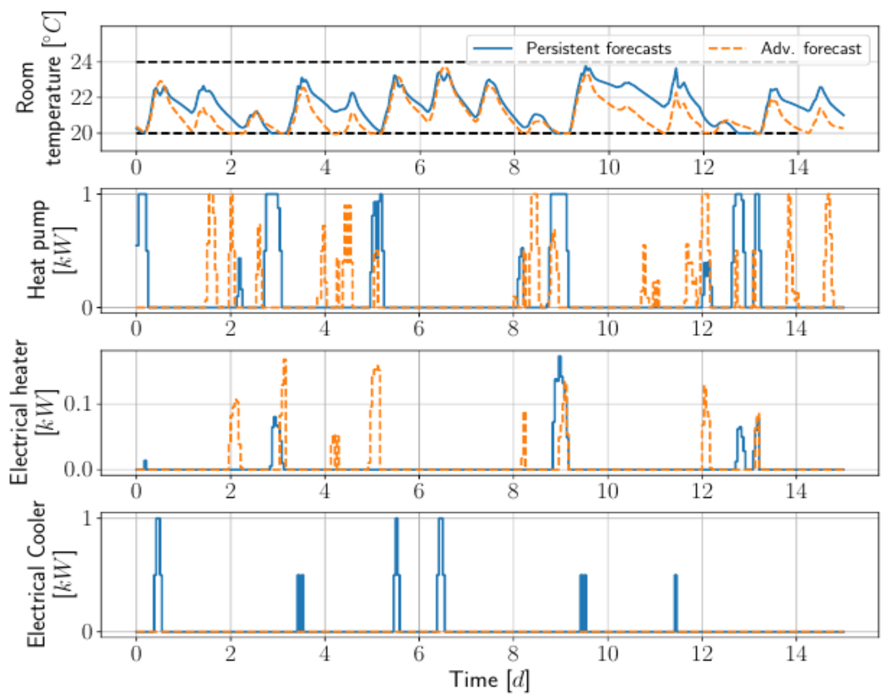
Strategy 2: Heat Pump



Strategy 3: Heat Pump & Electrical Heaters



Strategy 4: Heat Pump & Electrical Heaters & Coolers



Electricity cost in EUR

Electricity cost of the simulations			
Heating strategy	Persistent	Advanced forecasts	Perfect
Electrical heaters, u_1	303.2	302.2	302.0
Heat pump, u_2	117.3	110.4	107.7
Heat pump plus electrical heaters, $\boldsymbol{u}_3$	113.0	108.2	107.5
Heat pump plus electrical heaters and coolers, $\boldsymbol{u}_4$	117.9	108.3	107.5

Constraint violations

Constraint violation of the control simulations			
Heating strategy	Persistent	Advanced forecasts	Perfect
Electrical heaters, u_1	48.5	39.6	25.1
Heat pump, u_2	157.9	12.3	1.7
Heat pump plus electrical heaters, $\boldsymbol{u}_3$	48.0	6.7	1.2
Heat pump plus electrical heaters and coolers, $\boldsymbol{u}_4$	4.4	2.4	0

Multivariate Forecasting using Spatial Hierarchies

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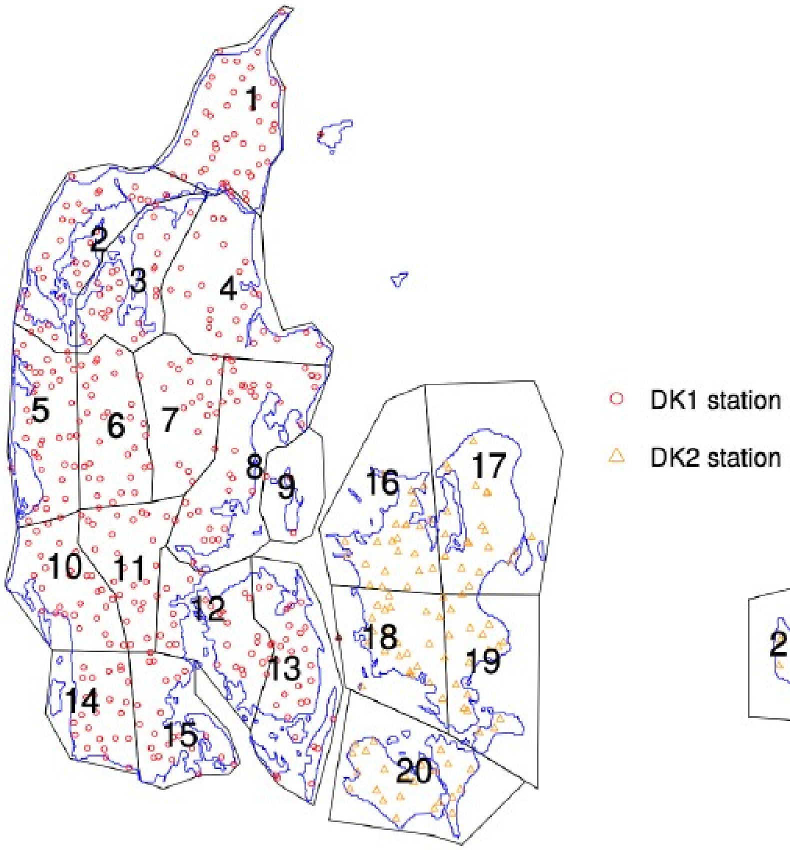
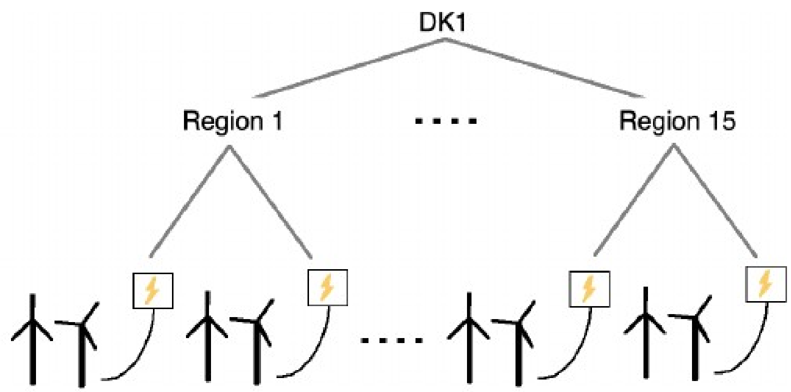
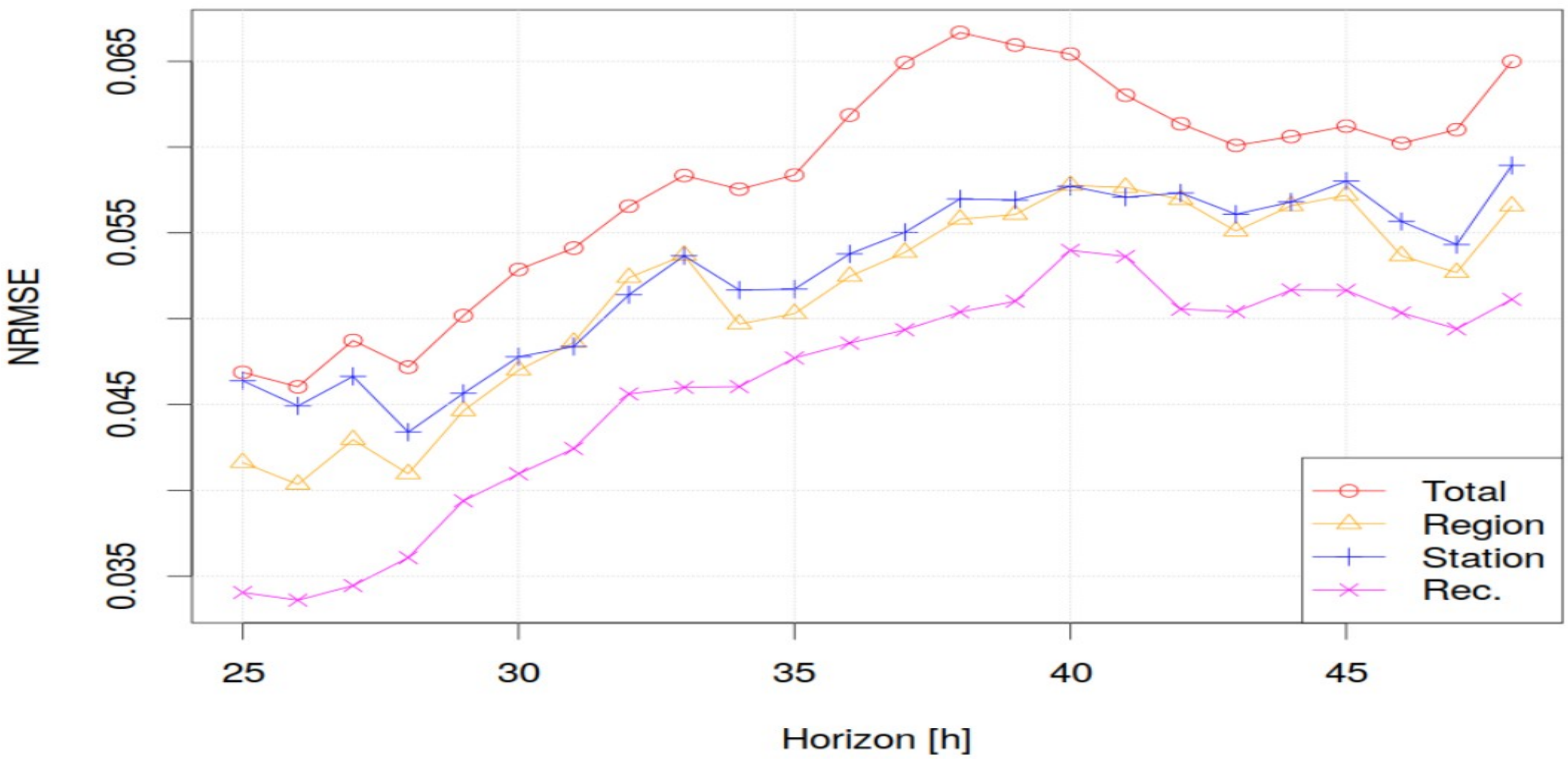
Wind Power Forecasting



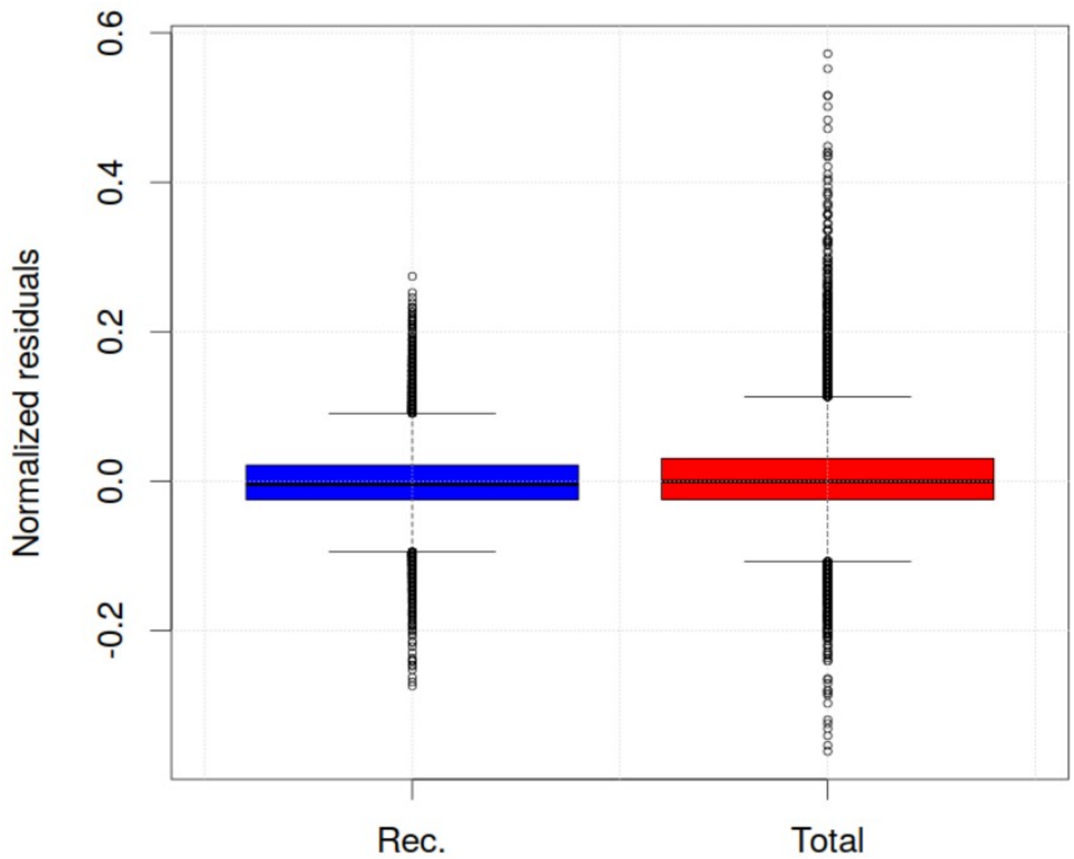


(b) Illustration of the spatial hierarchy for DK1 with 407 individual conversion stations at the bottom level, 15 regions at the middle level, and the total of Western Denmark at the top.

Total Forecasts (DK1) Forecasting (improvements 20 pct)



Box Plot of Forecast Errors



(b) Box plot of the residuals of the reconciled total forecast and the residuals of the base total forecast.

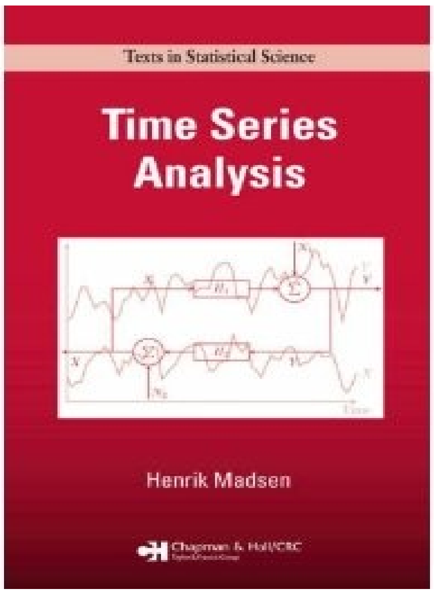
Summary

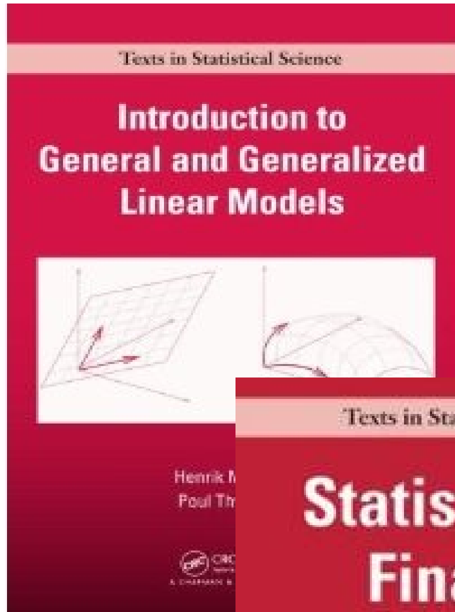
- Data-driven Methods are important for unlocking the needed flexibility for an efficient large scale integration of wind and solar energy
- We have demonstrated how to use Grey-box Modelling for as data-driven digital twins for integrated forecasting and control
- We have suggested the use of Flexibility Functions
- We have adopted a Spatio-Temporal thinking
- We have described the Smart-Energy OS, which is hierarchy of tools for aggregation, modelling, forecasting, optimization, and control
- The Smart-Energy OS can focus on
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency

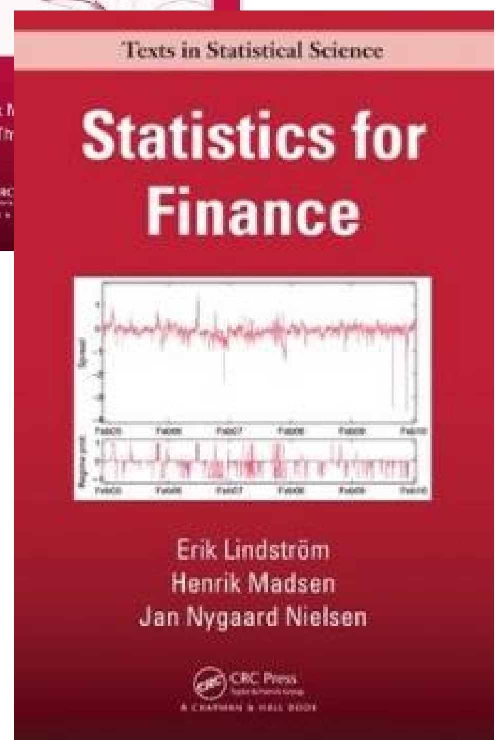
DTU

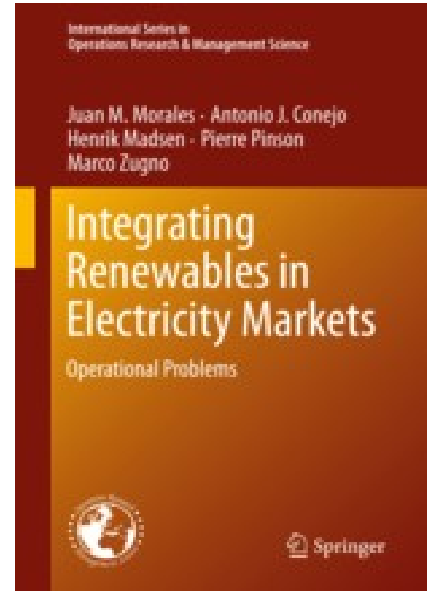
Thanks for your attention!

Some 'randomly picked' books on modeling, finance, markets and renewable integration ....









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