Smart-Energy OS:
A Hierarchy of Controllers and Services for the Future Weather-driven Low-carbon Energy System

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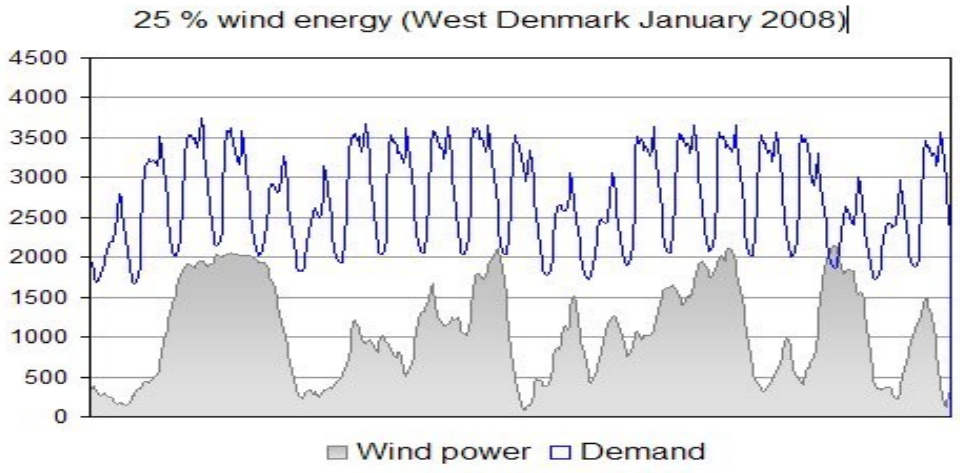
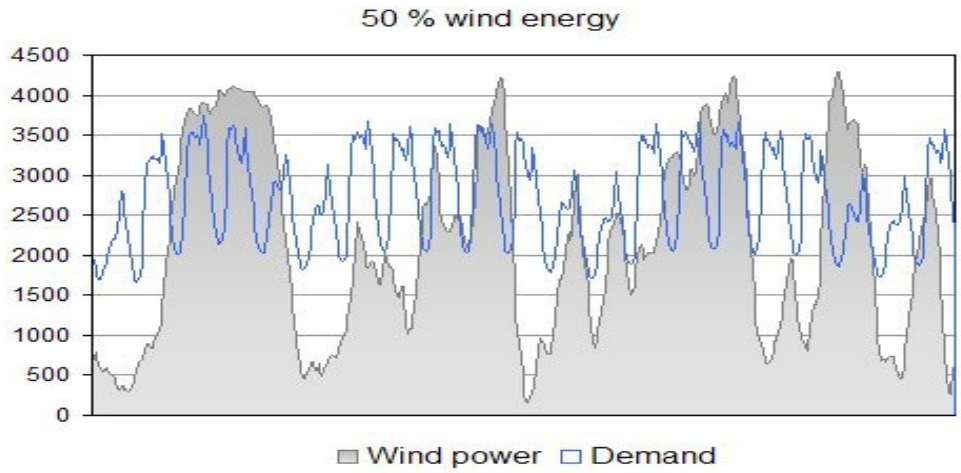
The Danish Wind Power Case

…. balancing of the power system



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



In 2020 Flexibility, IoT and Edge Computing are 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)

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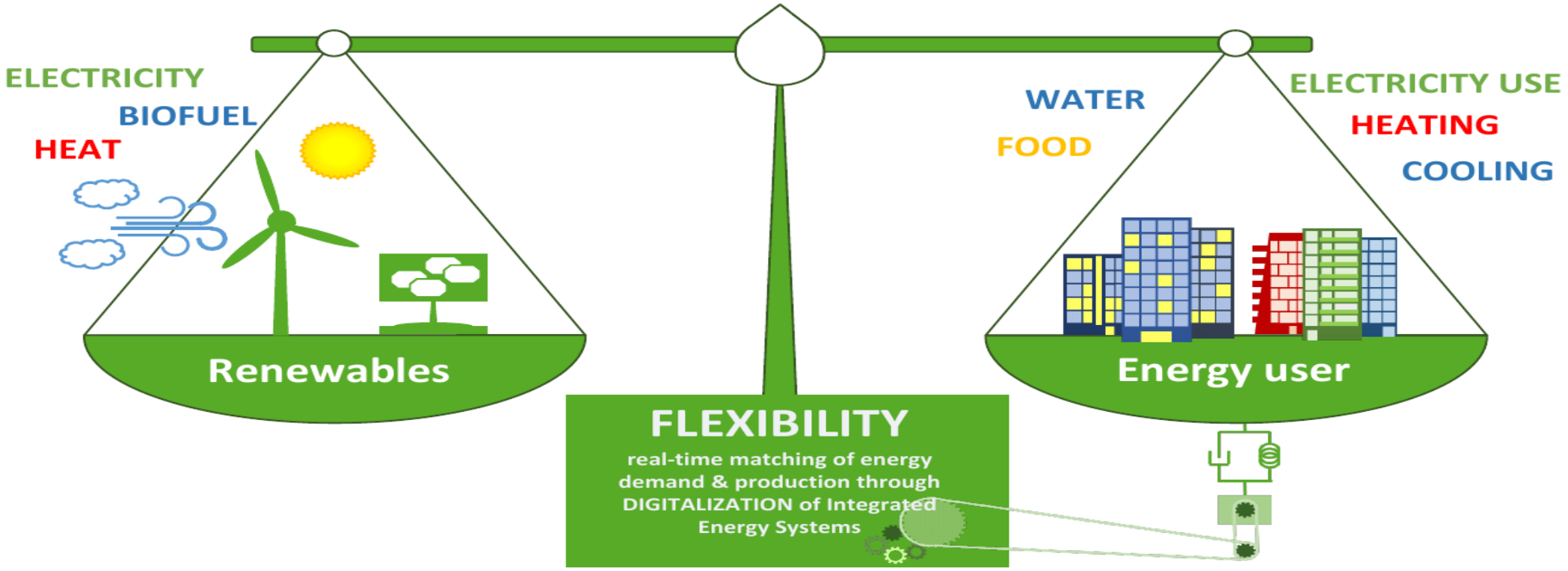
The Challenge: Denmark Fossil Free 2050

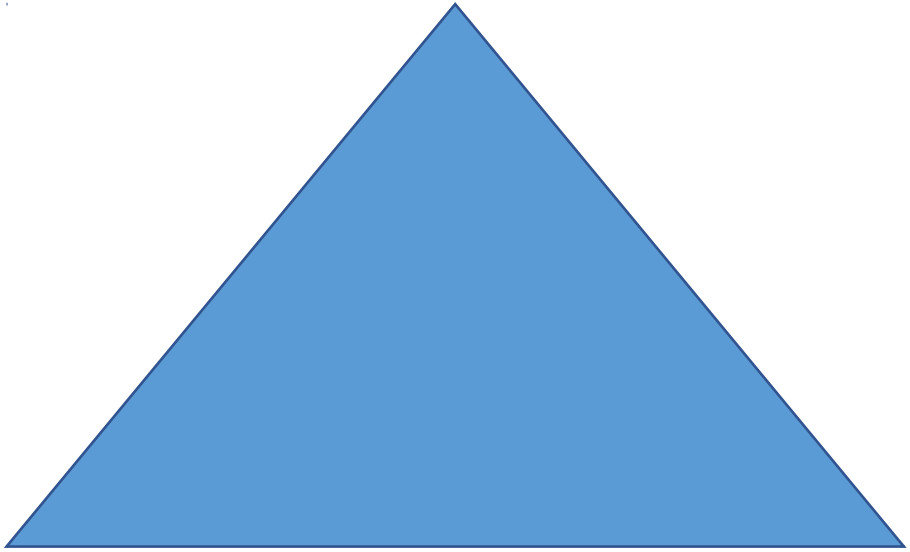


Markets/Services: Needed changes

- 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**

Space of Solutions

Flexibility (enabled by **AI, Energy Systems Integration and IoT**)



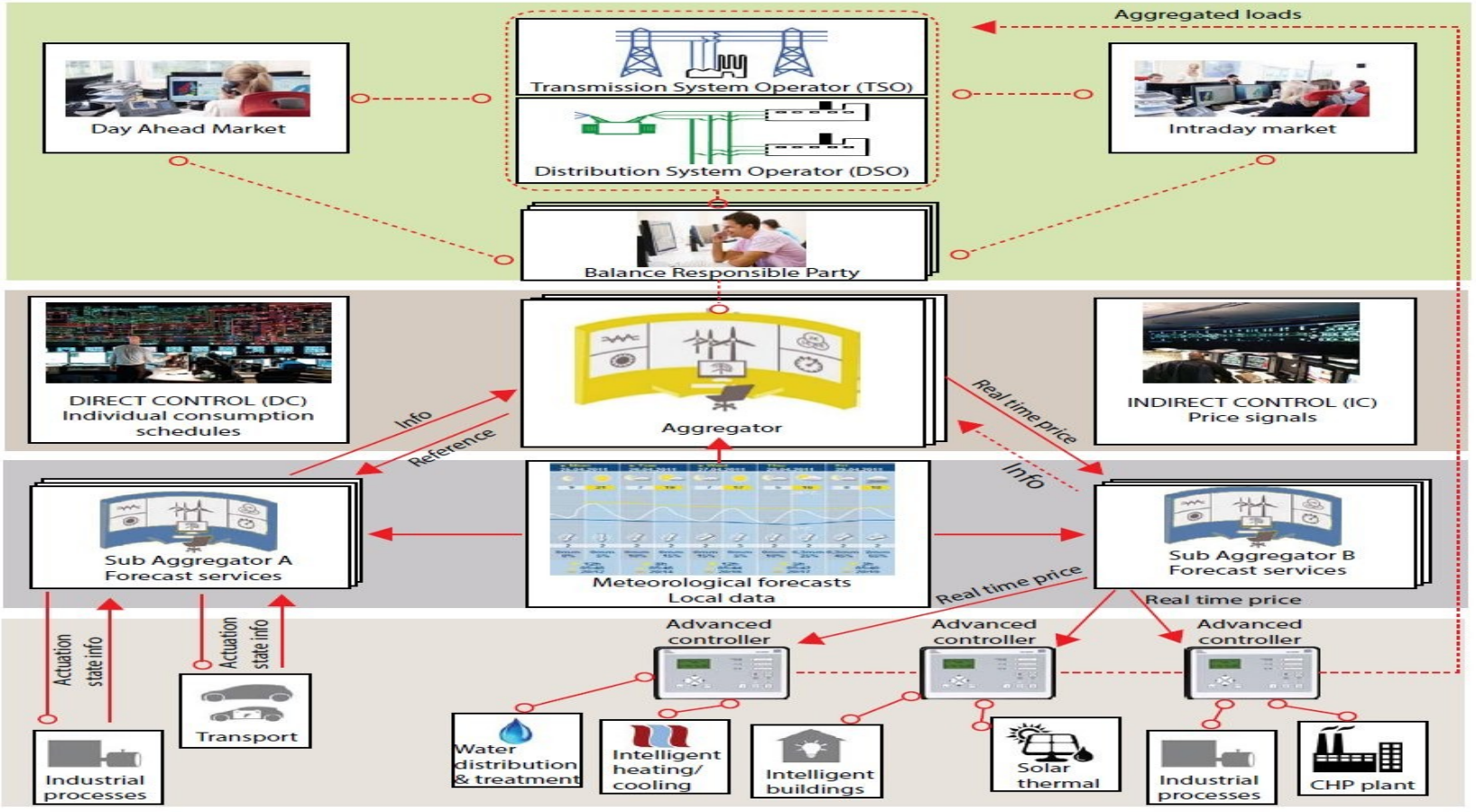
(Super) Grids

Batteries

Temporal and Spatial Scales

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

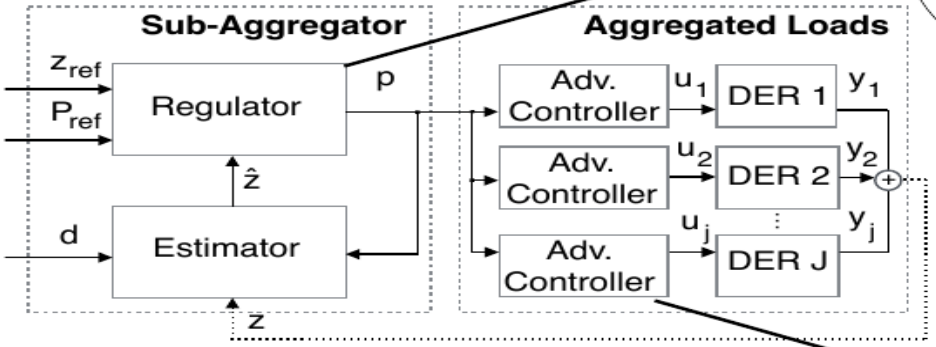
Smart-Energy OS



```
38  # slow approach, but we are sure things get do
39  # Try to parallelize anyway
40  require(multicore)
41  numcores<-multicore:::detectCores()
42  mclapply(
43  ··1:N,·
44  ··function(i,data)·{
45  ····print(paste(i,·"/",·N))
46
47  ····#·Find·the·indices·of·rows·corresponding·to·
48  ····j·<-·which(data$dt_agg·%in%·aggdata$dt[i])
49
50  ····#·Filter·out·those·who·are·NA
51  ····j·<-·j[!is.na(data$last_one_min_power[j])]
52
53  ····#·Count·number·of·readings
54  ····aggdata$num_readings[i]·<-·length(j)
```

Proposed methodology
Control-based methodology

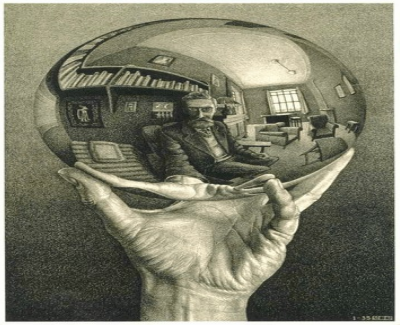
$$\min_{p} \quad \mathrm{E}[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||]$$
$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$



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

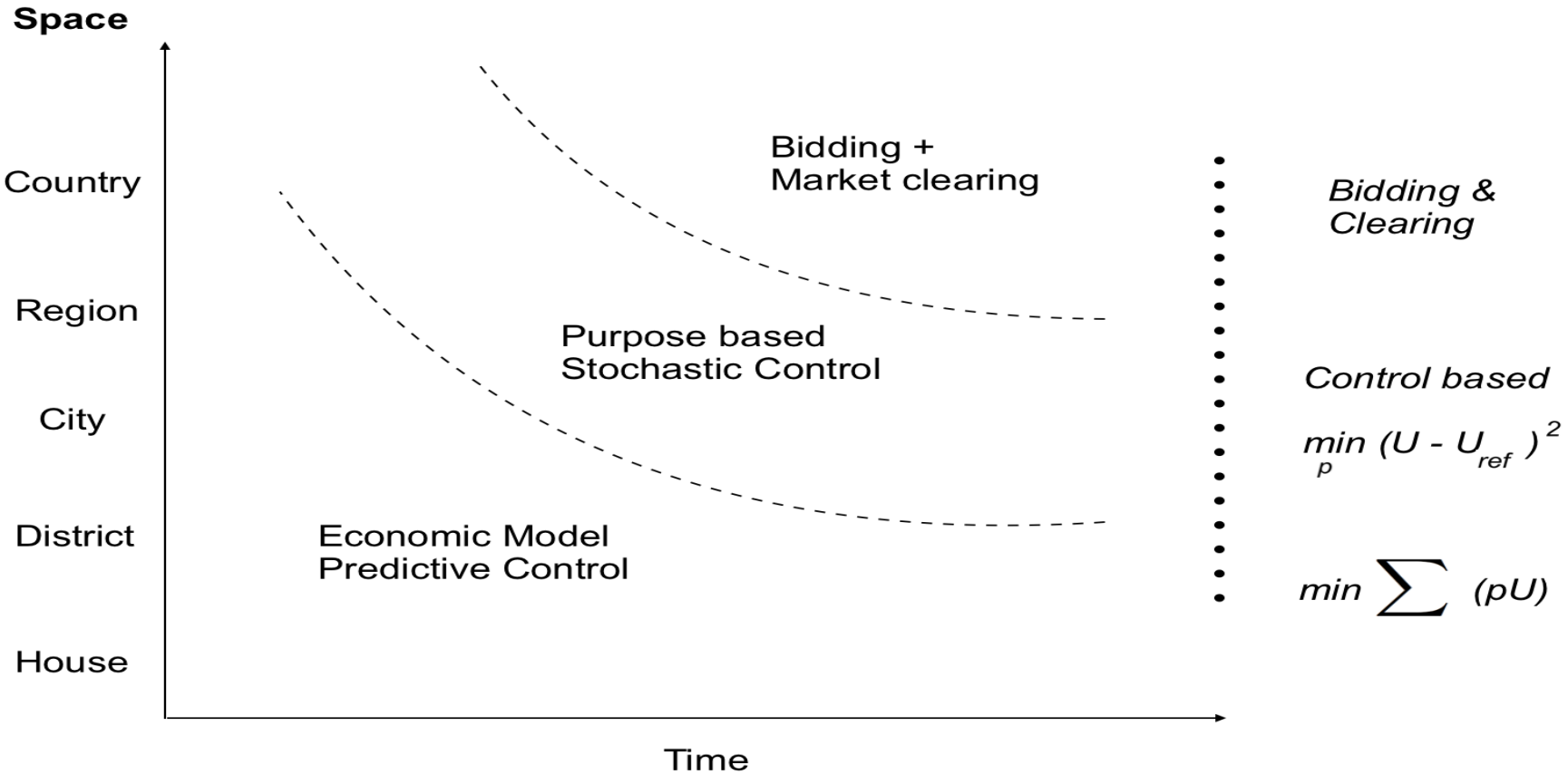
$$\min_{u} \quad \mathrm{E}[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)]$$
$$\text{s.t.} \quad x_{k+1} = Ax_k + Bu_k + Ed_k,$$
$$y_k = Cx_k,$$
$$y_k^{min} \le y_k \le y_k^{max},$$
$$u_k^{min} \le u_k \le u_k^{max}$$

SE-OS Characteristics



- AI and Grey-Box models for data-intelligence
- Nested sequence of systems – Systems of Systems
- Hierarchy of optimization (or control) problems
- Control principles at higher spatial/temporal resolutions
- Cloud, Fog, Edge based (IoT, IoS) solutions – eg. for forecasting and control
- Integrated modelling, forecasting, control and optimization
- Simple setup for the communication and contracts
- Facilitates energy systems integration (power, gas, thermal, …)

SE-OS: Hierarchy of Optimatization and Control Problems



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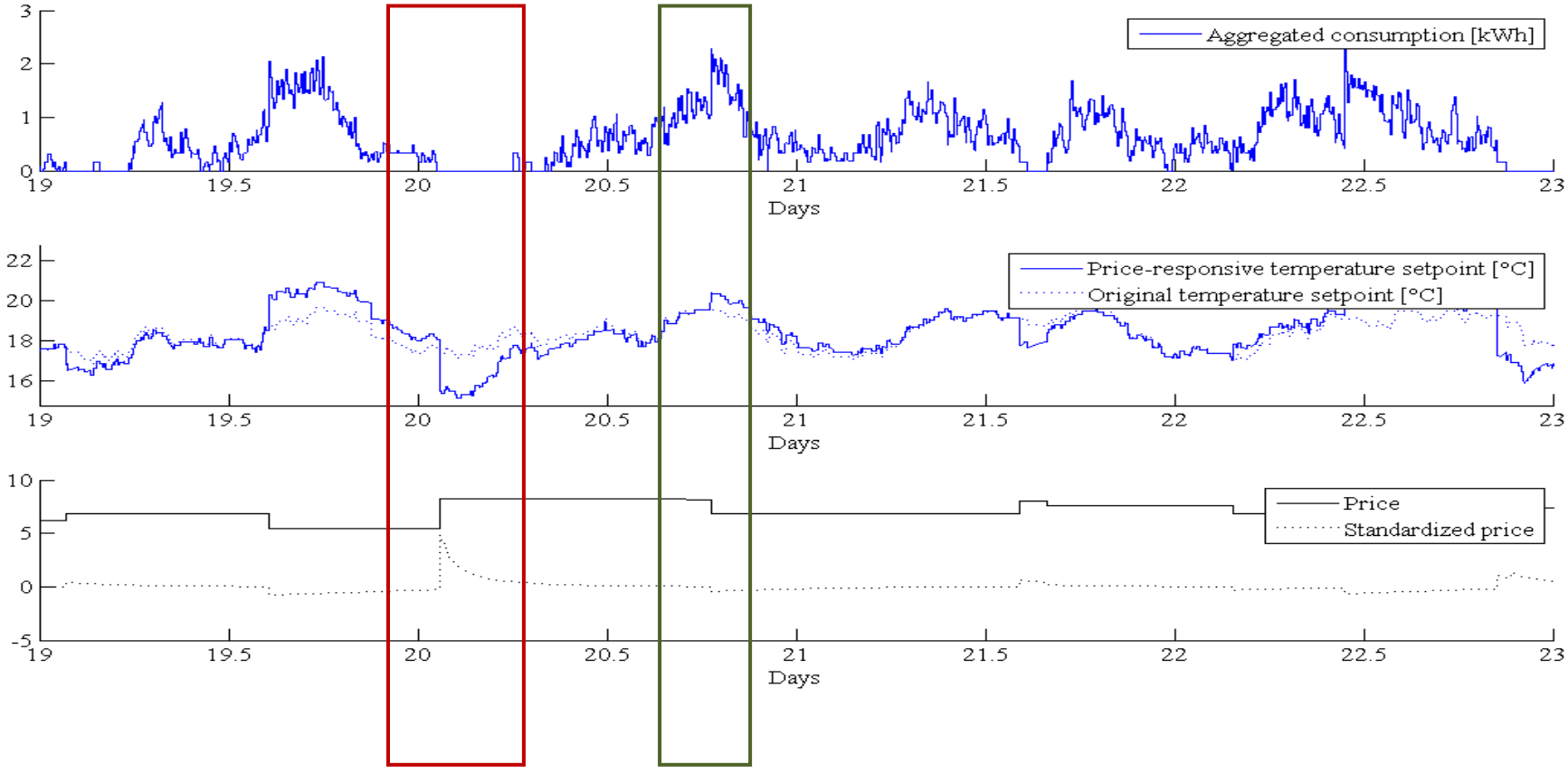
Case study

Price-based Control of Power Consumption (Peak Shaving)

Aggregation (over 20 houses)



Flexibility Function

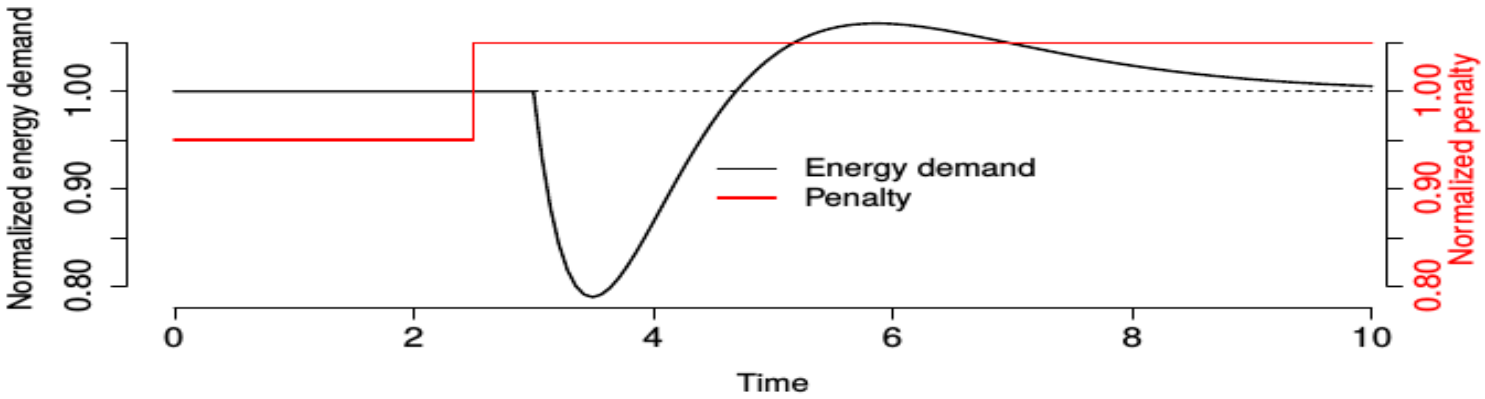
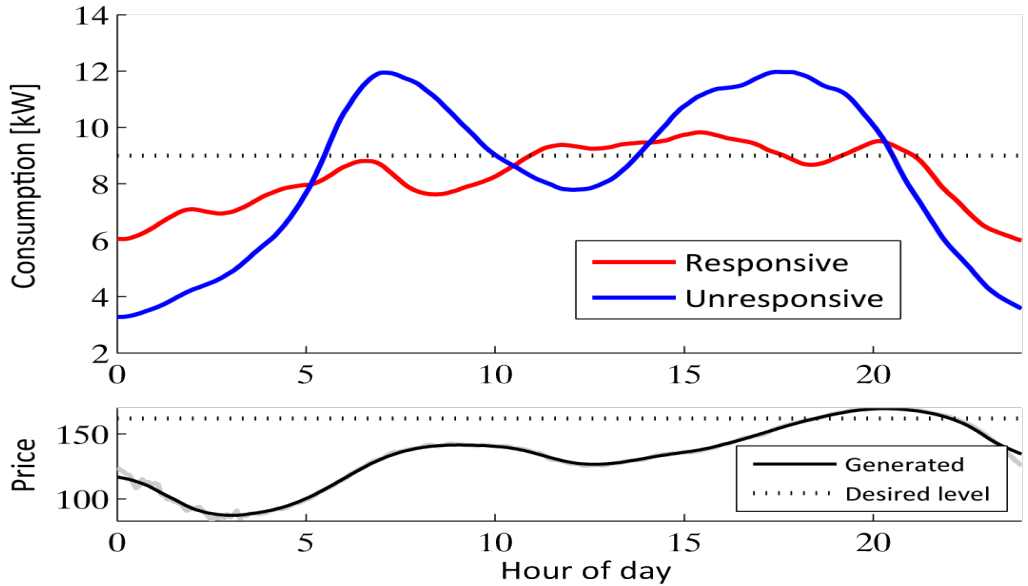


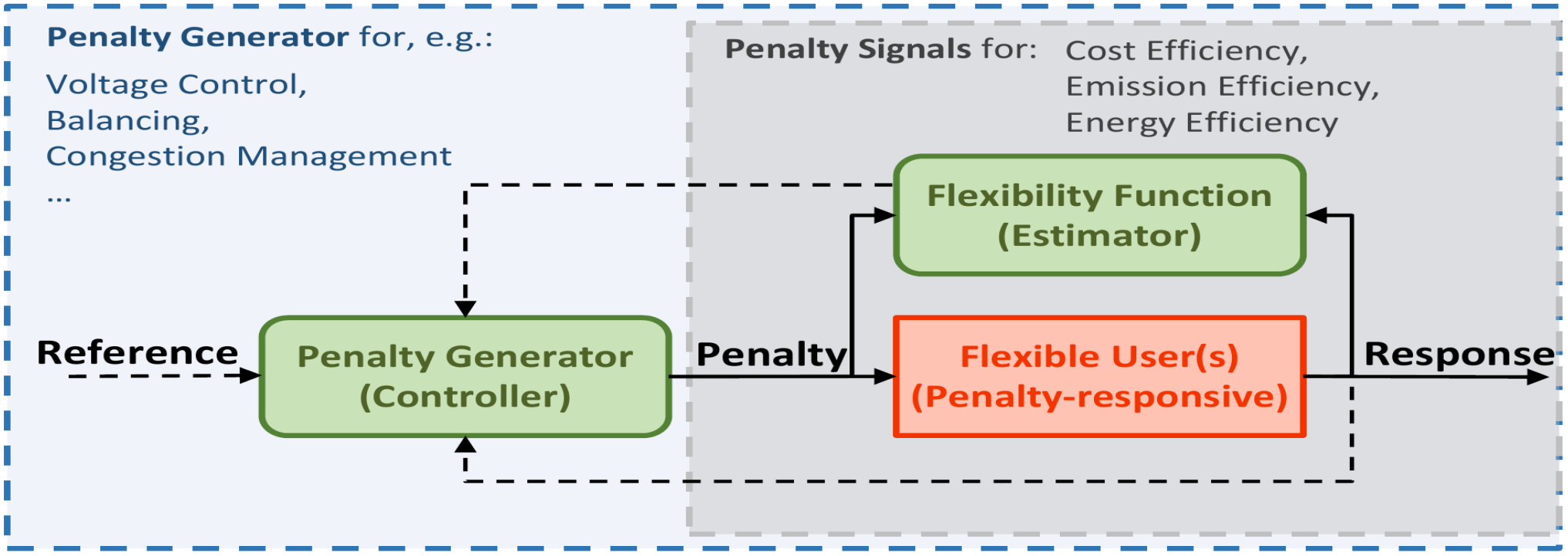
Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

Control performance

Considerable **reduction in peak consumption**



A FED example: Flexible Users and Penalty Signals



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Center Denmark

Digitalization Hub for Smart Energy Systems

Center Denmark – Control Room

(Spatio-Temporal thinking)

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

Summary

- A Smart-Energy Operating-System is suggested for the future weather-driven low-carbon energy systems
- Facilitates a link between conventional markets and the low level power system (the physics)
- Many power related services (voltage, frequency, congestion, ramping, balancing, capacity, ..)
- Flexibility is described by a Flexibility Function
- Simple contracts and no requirements on user installations
- A national data hub, Center Denmark, for providing services (also for low voltage areas) is established