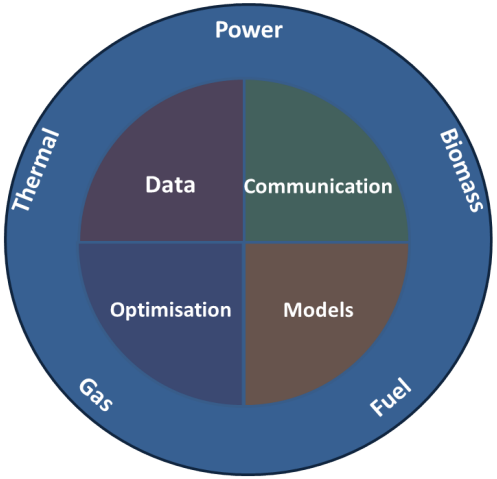
Renewable Energy Integration

CITIES Project

(Center for IT-Intelligent Energy Systems)



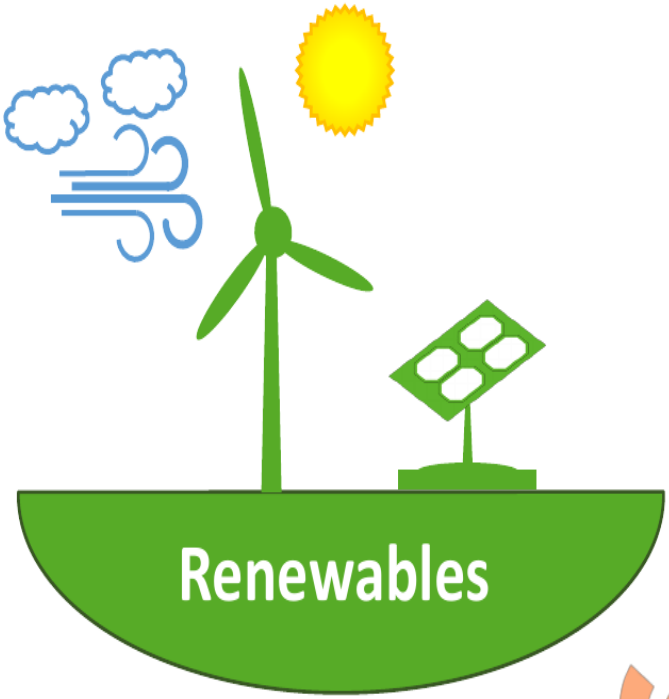
Henrik Madsen

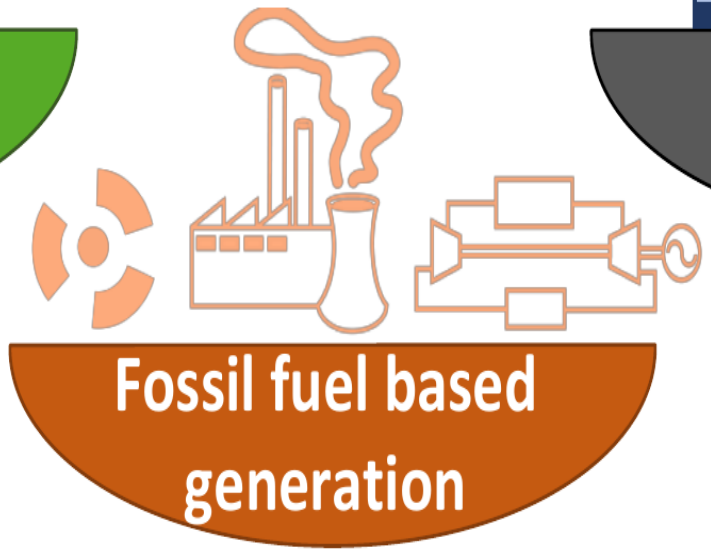
DTU Compute

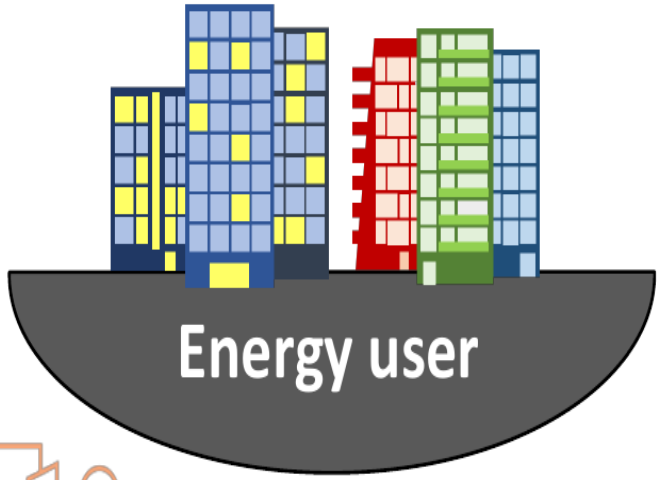
http://www.smart-cities-centre.org

http://www.henrikmadsen.org

The Challenge: Denmark Fossil Free 2050



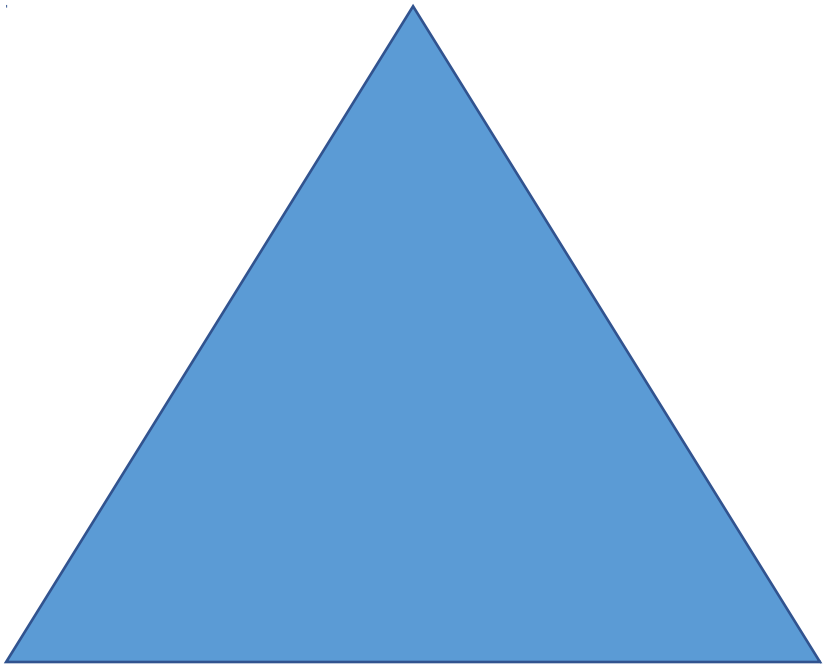




Space of Solutions

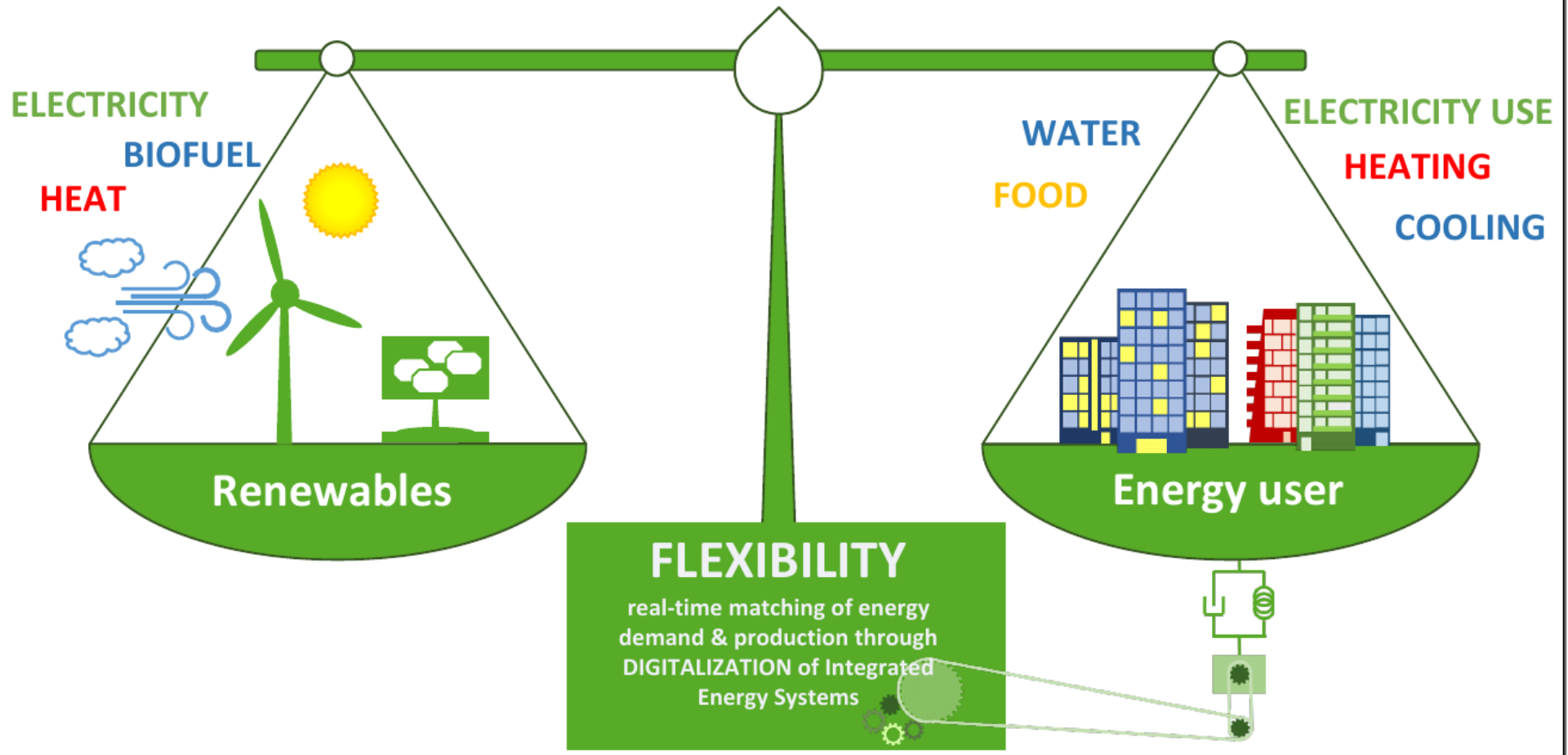
:

Flexibility (eg enabled by AI and Energy Systems Integration)



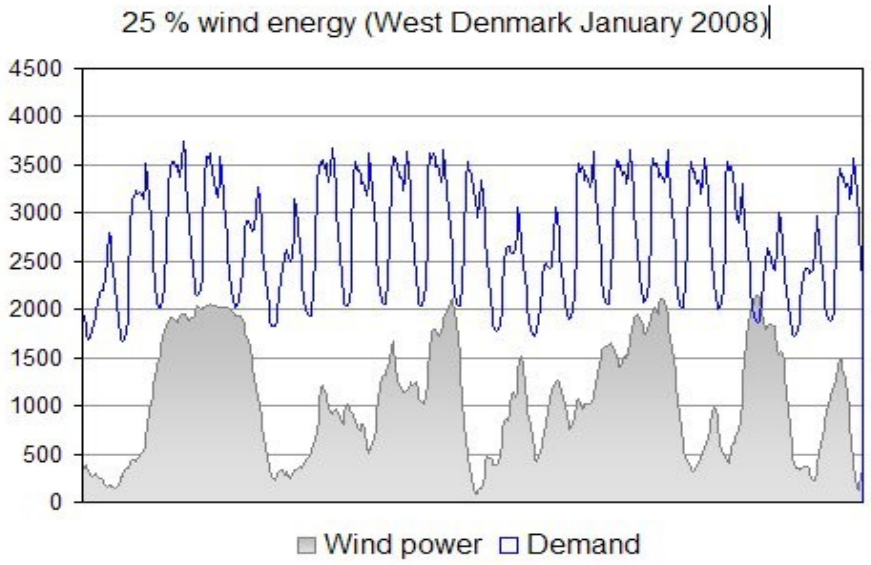
Super Grids **Batteries**

The Challenge: Denmark Fossil Free 2050

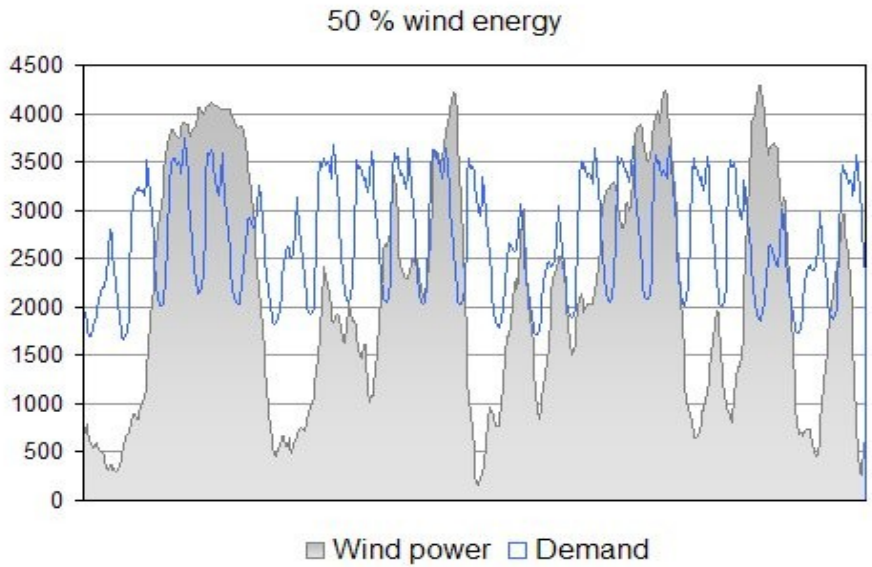


The Danish Wind Power Case

…. balancing of the power system



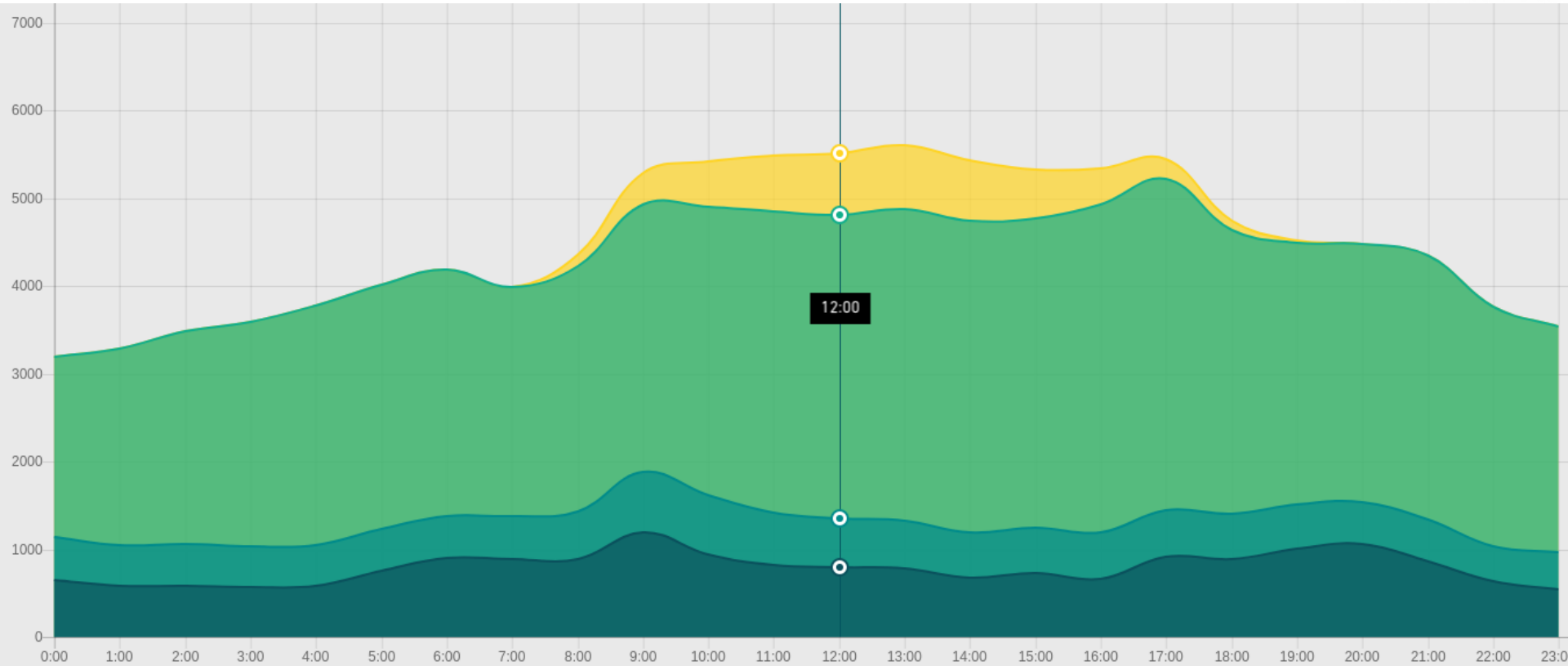
In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)



In the first half of 2017 more than 44 pct of electricity load was covered by wind power.

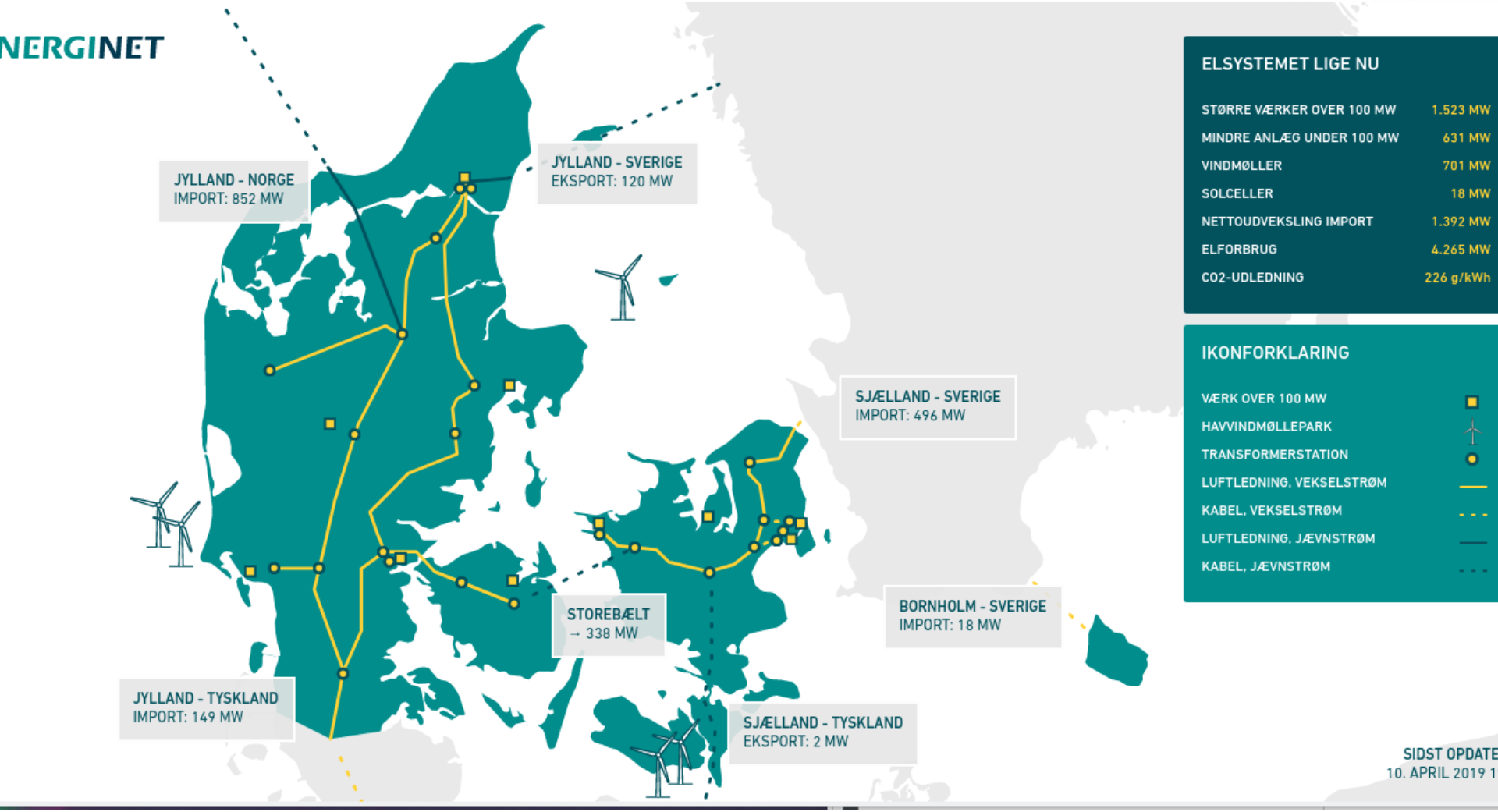
For several days the wind power production was more than 100 pct of the power load.

July 10th, 2015 more than 140 pct of the power load was covered by wind power



STØRRE VÆRKER OVER 100 MW	MINDRE ANLÆG UNDER 100 MW	VINDMØLLER	SOLCELLER
797 MW	558 MW	3.451 MW	712 MW

NETTOUDVEKSLING IMPORT	ELFORBRUG	CO2-UDLEDNING	TOTAL PRODUKTION
-1.456 MW	4.064 MW	69 G/KWH	5518 MW


NERGINET
JYLLAND - NORGE
IMPORT: 852 MW
JYLLAND - SVERIGE
EKSPORT: 120 MW
SJÆLLAND - SVERIGE
IMPORT: 496 MW
STOREBÆLT
→ 338 MW
BORNHOLM - SVERIGE
IMPORT: 18 MW
JYLLAND - TYSKLAND
IMPORT: 149 MW
SJÆLLAND - TYSKLAND
EKSPORT: 2 MW
ELSYSTEMET LIGE NU
STØRRE VÆRKER OVER 100 MW 1.523 MW
MINDRE ANLÆG UNDER 100 MW 631 MW
VINDMØLLER 701 MW
SOLCELLER 18 MW
NETTOUDVEKSLING IMPORT 1.392 MW
ELFORBRUG 4.265 MW
CO2-UDLEDNING 226 g/kWh
IKONFORKLARING
VÆRK OVER 100 MW
HAVVINDMØLLEPARK
TRANSFORMERSTATION
LUFTLEDNING, VEKSELSTRØM
KABEL, VEKSELSTRØM
LUFTLEDNING, JÆVNSTRØM
KABEL, JÆVNSTRØM
SIDST OPDATE
10. APRIL 2019 1

Challenges

Preparatory study on Smart Appliances

European Commission

Ecodesign Preparatory Study performed for the European Commission

Welcome | Project summary | Planning & Meetings | Documents | Register for website | Register for meeting | Contact & Consortium

Home > Project summary

Project Summary

The Ecodesign Preparatory Study on Smart Appliances (Lot 33) has analysed the technical, economic, market and environmental aspects with a view to a broad introduction of smart appliances and to develop adequate policy approaches supporting such uptake.

The study deals with Task 1 to 7 of the Methodology for Energy related products (MEErP) as follows:

- Scope, standards and legislation (Task 1, Chapter 1);
- Market analysis (Task 2, Chapter 2);
- User analysis (Task 3, Chapter 3);
- Technical analysis (Task 4, Chapter 4);
- Definition of Base Cases (Task 5, Chapter 5);
- Design options (Task 6, Chapter 6);
- Policy and Scenario analysis (Task 7, Chapter 7).

An executive summary of the project results can be downloaded here.

Throughout the study, new relevant aspects have come up which will be covered in a second phase of the Preparatory Study:

- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.

Almost no Flexibility

Existing Markets - Challenges

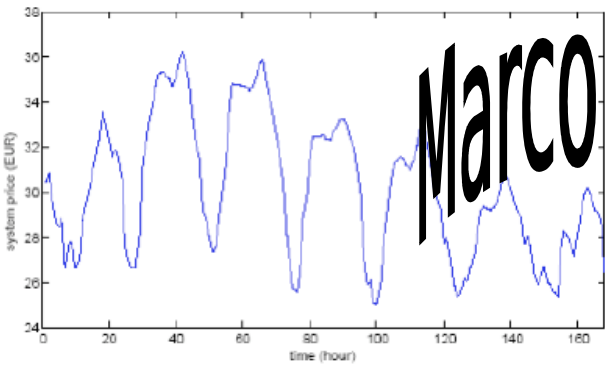
- Dynamics
- Stochasticity
- Nonlinearities
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, …)
- Speed / problem size
- Characterization of flexibility
- Requirements on user installations

COMPETITIVE BIDDING AND STABILITY ANALYSIS IN ELECTRICITY MARKETS USING CONTROL THEORY

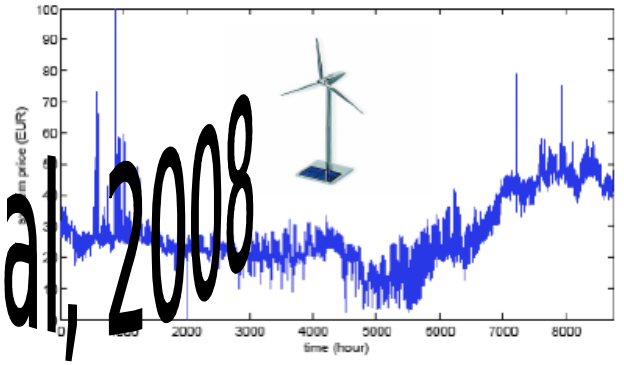
Main idea: **applying control theory to the study of power markets**

Advantages in handling effectively

Dynamics



Uncertainty



Marco Zugno et.al, 2008

control theory provides ways of modeling the dynamics which is intrinsic in energy markets

↓

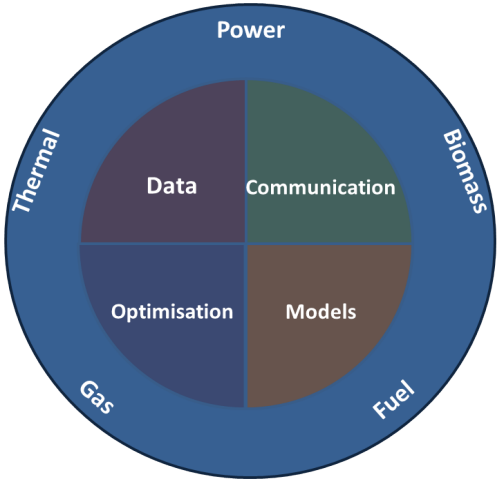
it is possible to develop advanced bidding strategies which exploit the inclusion of the dynamics in the model

stochastic control theory allows for taking into account different sources of uncertainty (wind, ...)

↓

it is possible to develop bidding strategies which are optimal with respect to the stochastic characteristics of the market

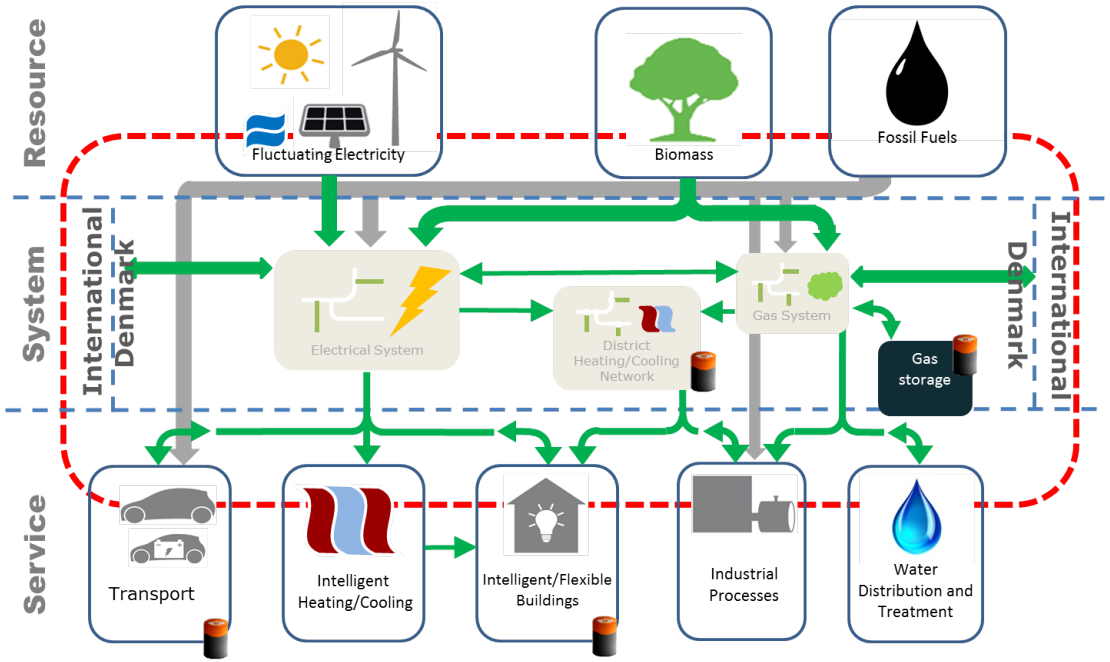
Hypothesis



The **central hypothesis** is that by **intelligently integrating** currently distinct **energy** (heat, power, gas and biomass) and **water** components using **ICT solutions** we can **balance** very large shares of renewables, and consequently obtain substantial reductions in CO2 emissions.

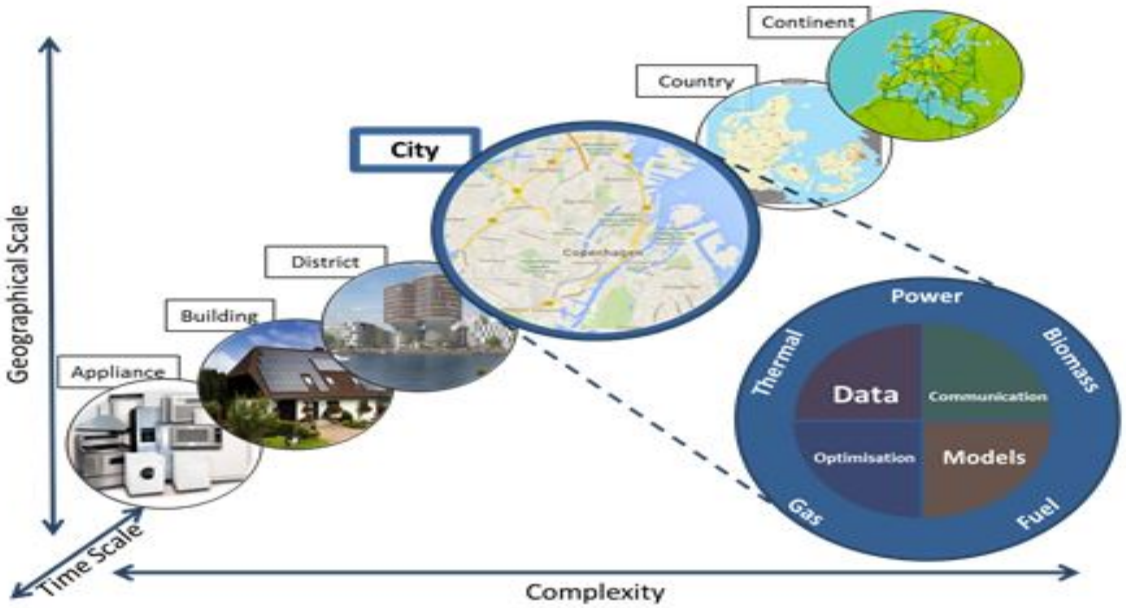
Concepts

Integration based on **ICT solutions** (Data Analytics, Grey-Box Models, Forecasting, Control, IoT, IoS, AI, automated learning, ..) leading to methods for **operation** and **planning** of future energy systems

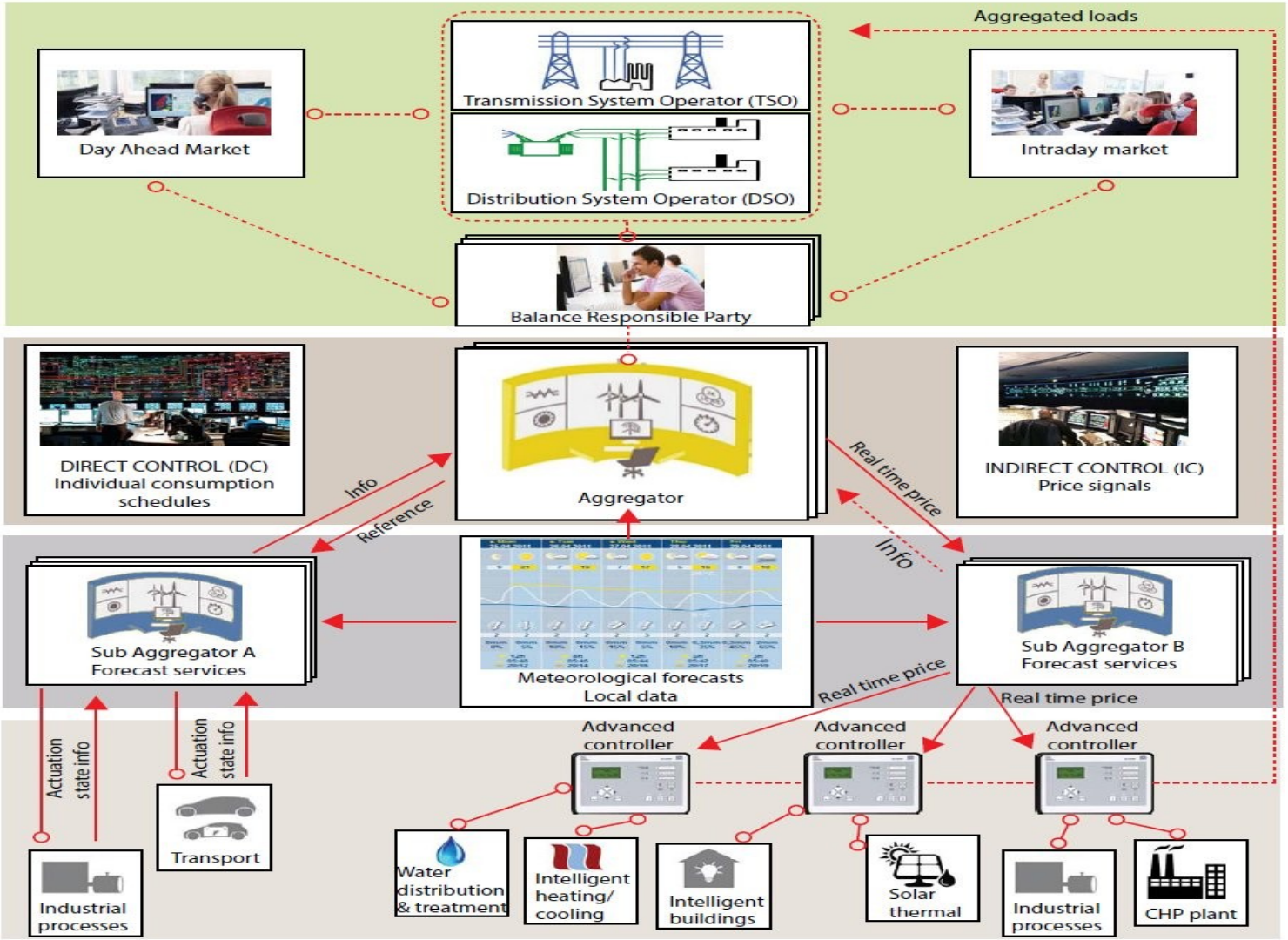


Temporal and Spatial Scales

The ***Smart-Energy Operating-System (SE-OS)*** is used 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

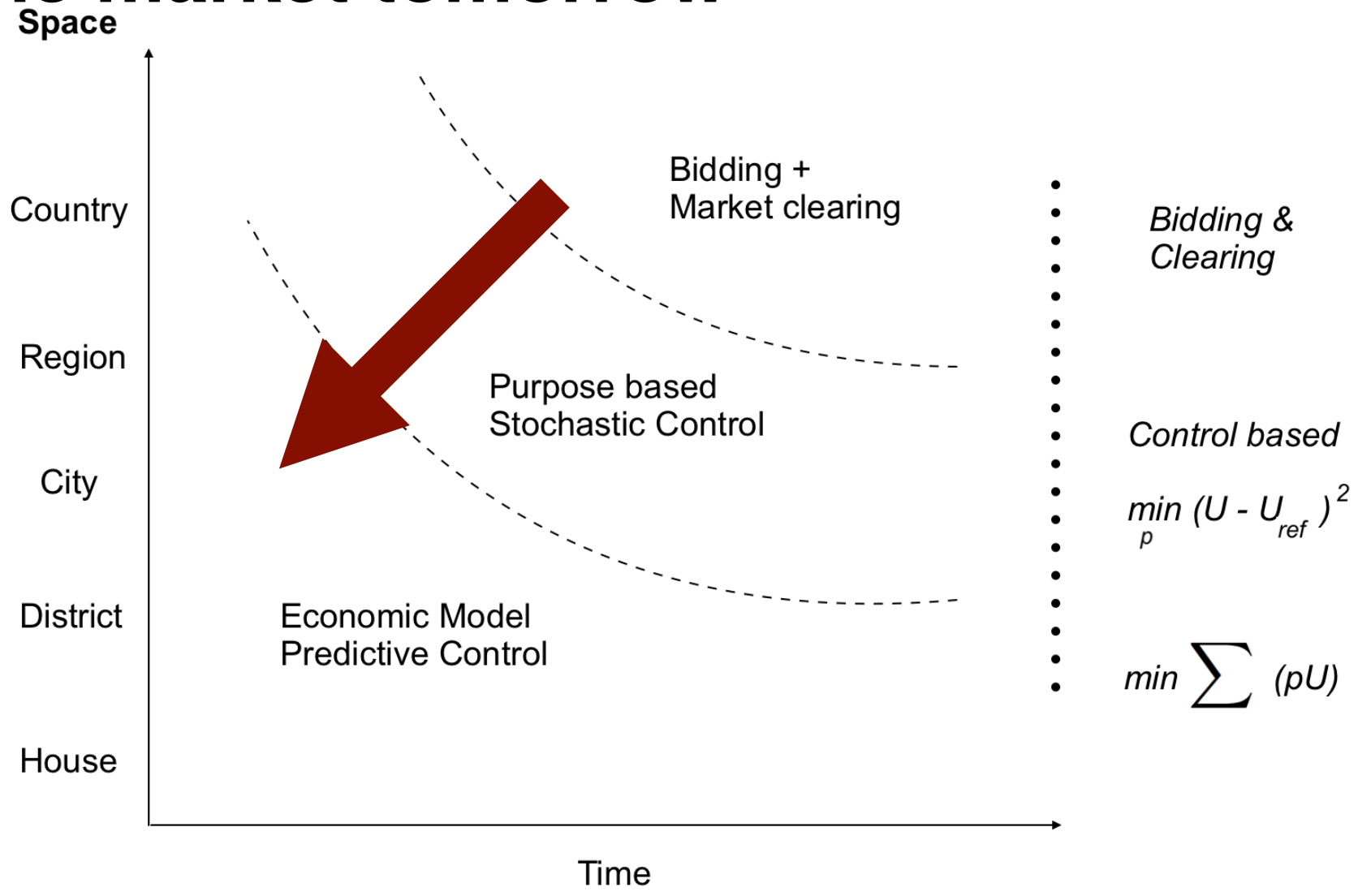


Direct vs Indirect Control

Level	Direct Control (DC)	Indirect Control (IC)
III	$\min_{x,u} \sum_{k=0}^{N} \sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k})$	$\min_{\hat{z},p} \sum_{k=0}^{N} \phi(\hat{z}_k, p_k)$ s.t. $\hat{z}_{k+1} = f(p_k)$
IV	$\downarrow u_1 \cdots \downarrow u_J \quad \uparrow x_1 \cdots \uparrow x_J$ s.t. $x_{j,k+1} = f_j(x_{j,k}, u_{j,k}) \quad \forall j \in J$	$\min_u \sum_{k=0}^{N} \phi_j(p_k, u_k) \quad \forall j \in J$ s.t. $x_{k+1} = f_j(x_k, u_k)$

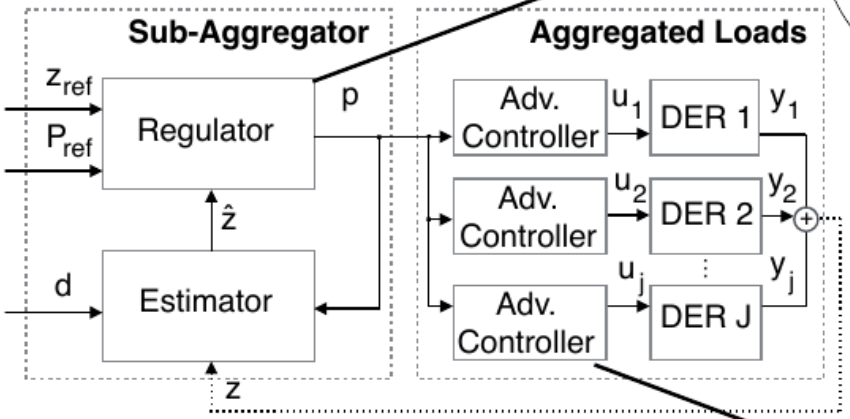
Table 1: Comparison between direct (DC) and indirect (IC) control methods. (DC) In direct control the optimization is globally solved at level III. Consequently the optimal control signals u_j are sent to all the J DER units at level IV. (IC) In indirect control the optimization at level III computes the optimal prices p which are sent to the J-units at level IV. Hence the J DERs optimize their own energy consumption taking into account p as the actual price of energy.

The market tomorrow



Proposed methodology
Control-based methodology

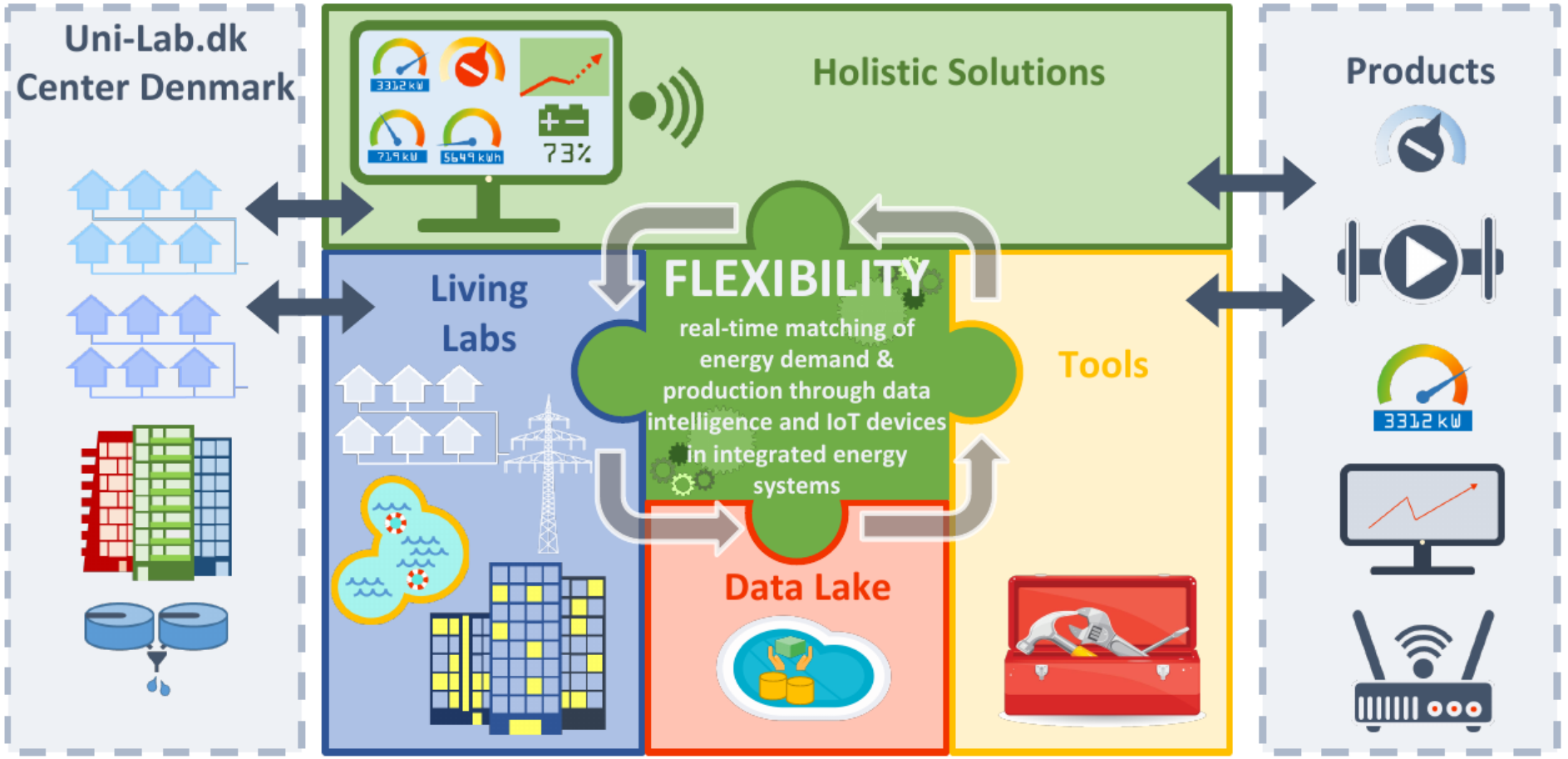
$$\min_{p} \quad \mathrm{E}[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||]$$
$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$



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

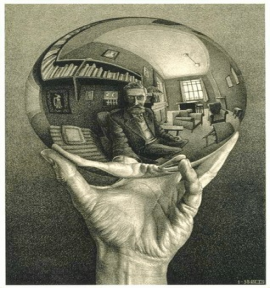
$$\min_{u} \quad \mathrm{E}[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)]$$
$$\text{s.t.} \quad x_{k+1} = Ax_k + Bu_k + Ed_k,$$
$$y_k = Cx_k,$$
$$y_k^{min} \leq y_k \leq y_k^{max},$$
$$u_k^{min} \leq u_k \leq u_k^{max}$$

A Danish Path to a Fossil Free Society



SE-OS Characteristics

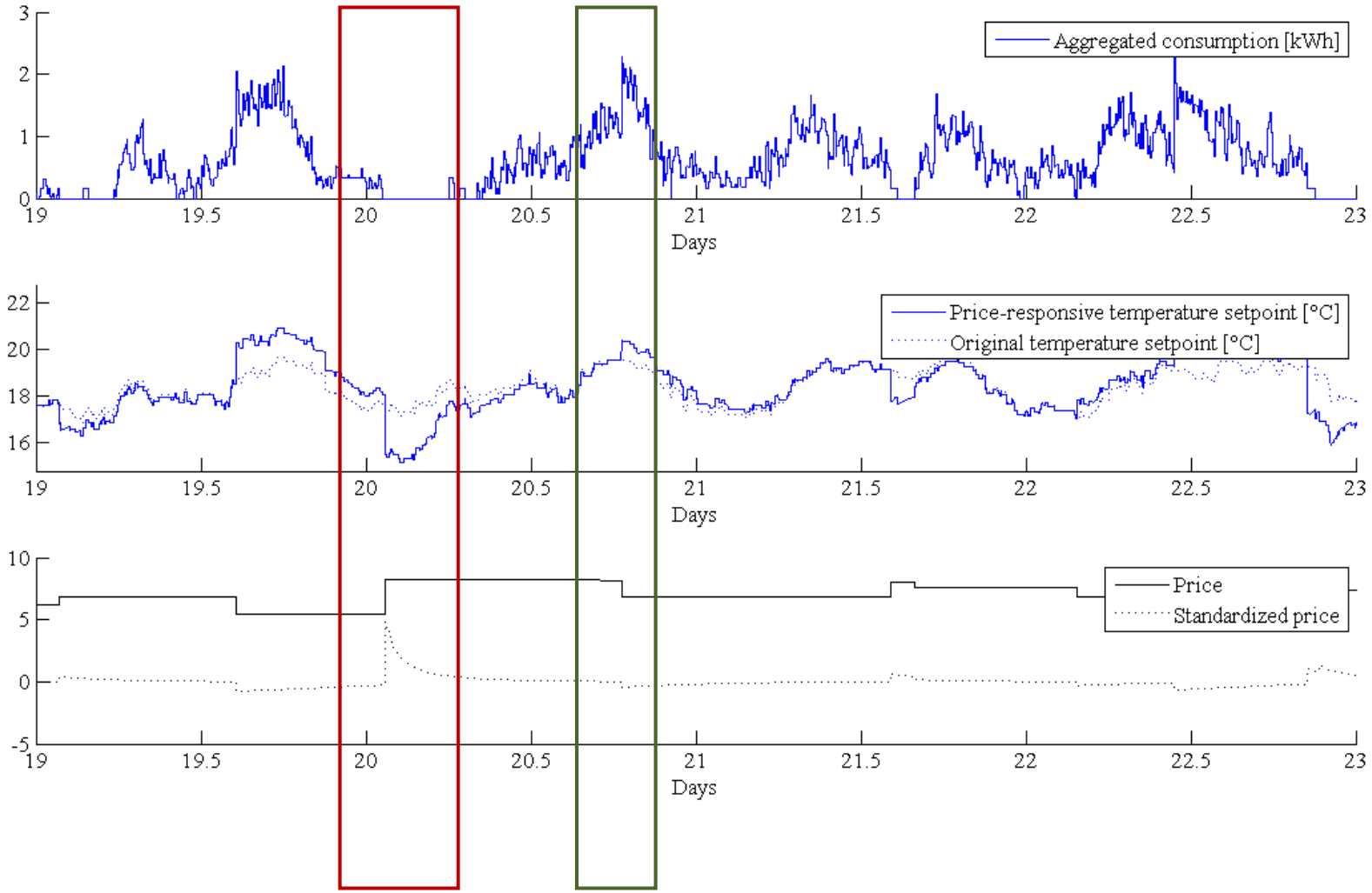
- 'Bidding – clearing – activation' at higher levels
- Nested sequence of systems – systems of systems
- Hierarchy of optimization (or control) problems
- Control principles at higher spatial/temporal resolutions
- Cloud or Fog (IoT, IoS) based solutions – eg. for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, …)
- Allow for new players (specialized aggregators)
- Simple setup for the communication and contracts
- Provides a solution for all ancillary services
- Harvest flexibility at all levels -> max. Virtual storage



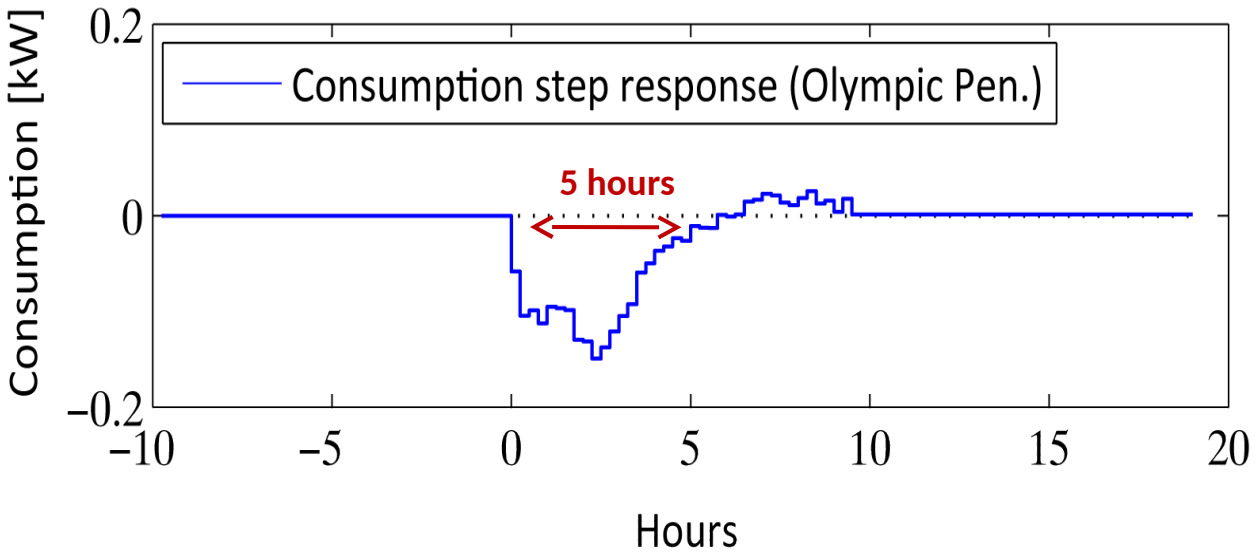
Case study (Level III)

Price-based Control of Power Consumption

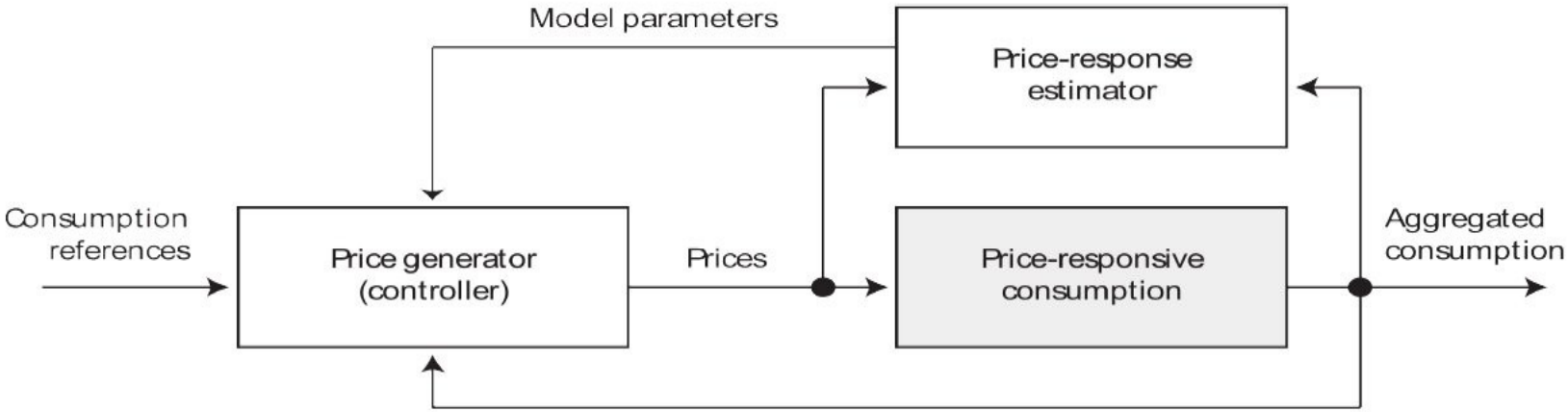
Aggregation (over 20 houses)



Response on Price Step Change

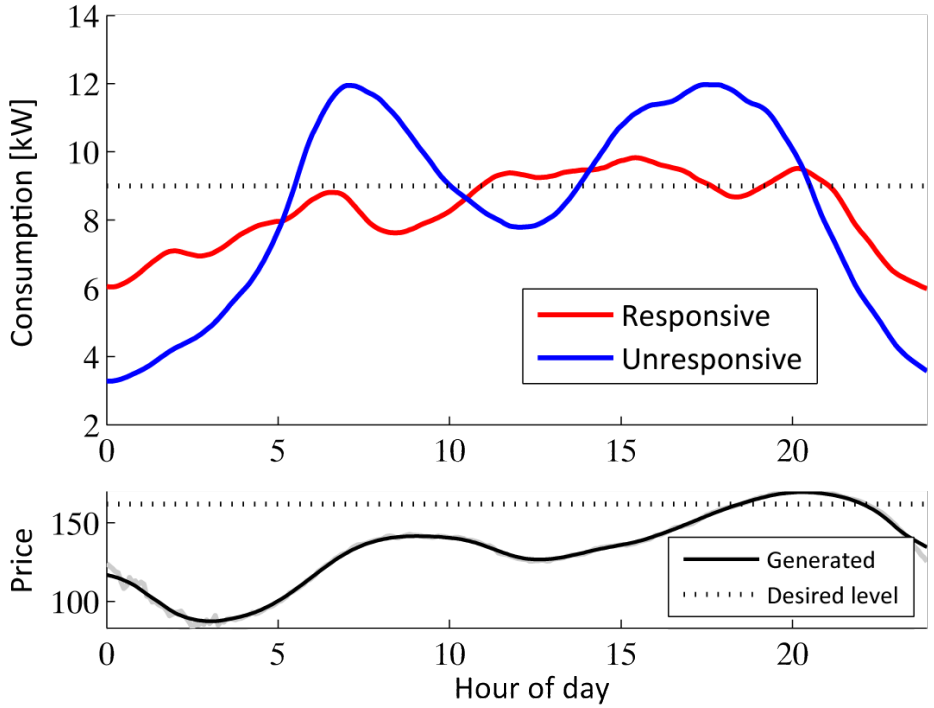


Control of Power Consumption



Control performance

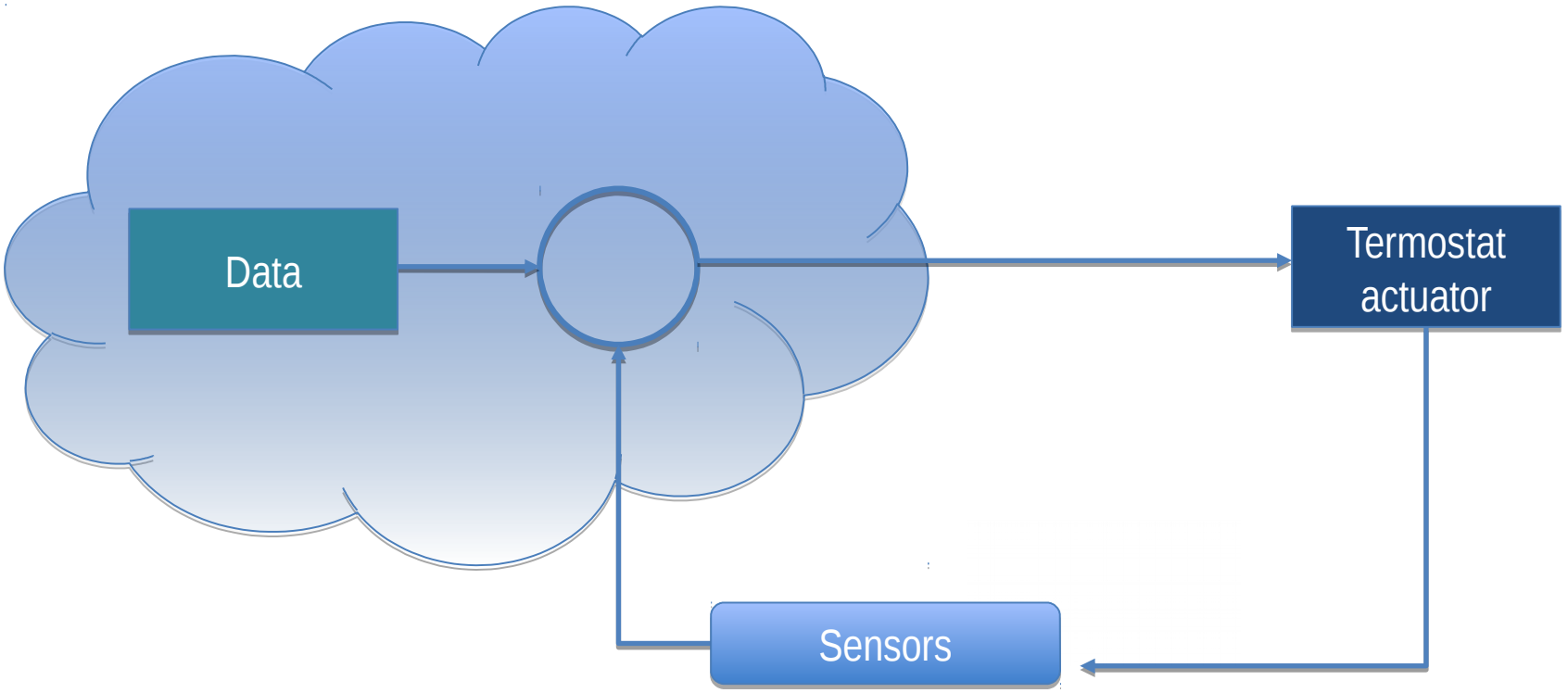
Considerable **reduction in peak consumption**



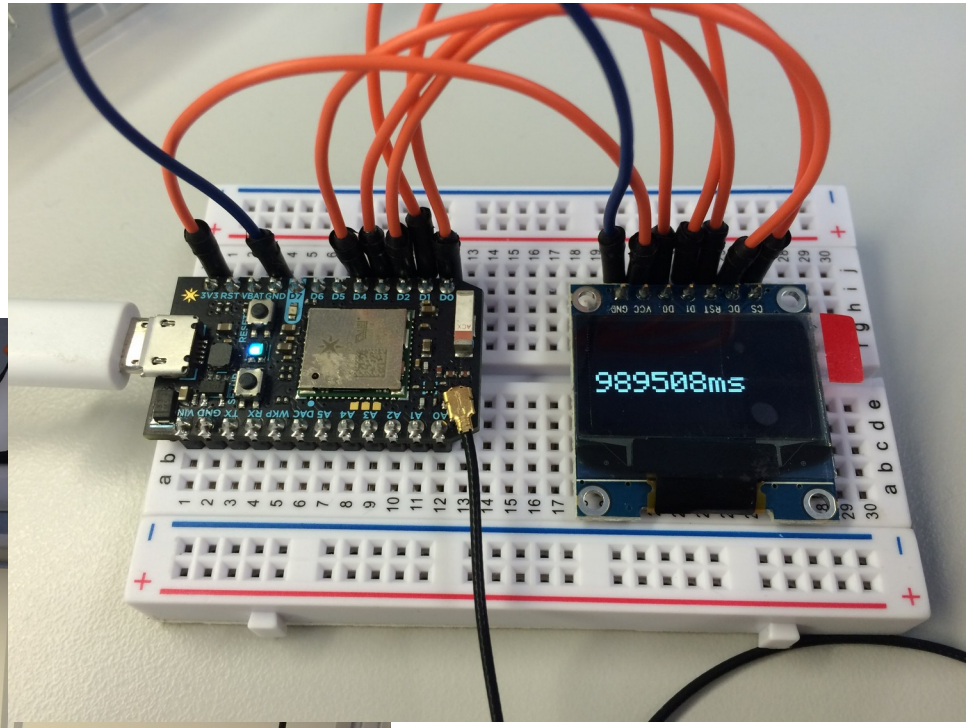
Case study
(Level IV – Indirect Control)

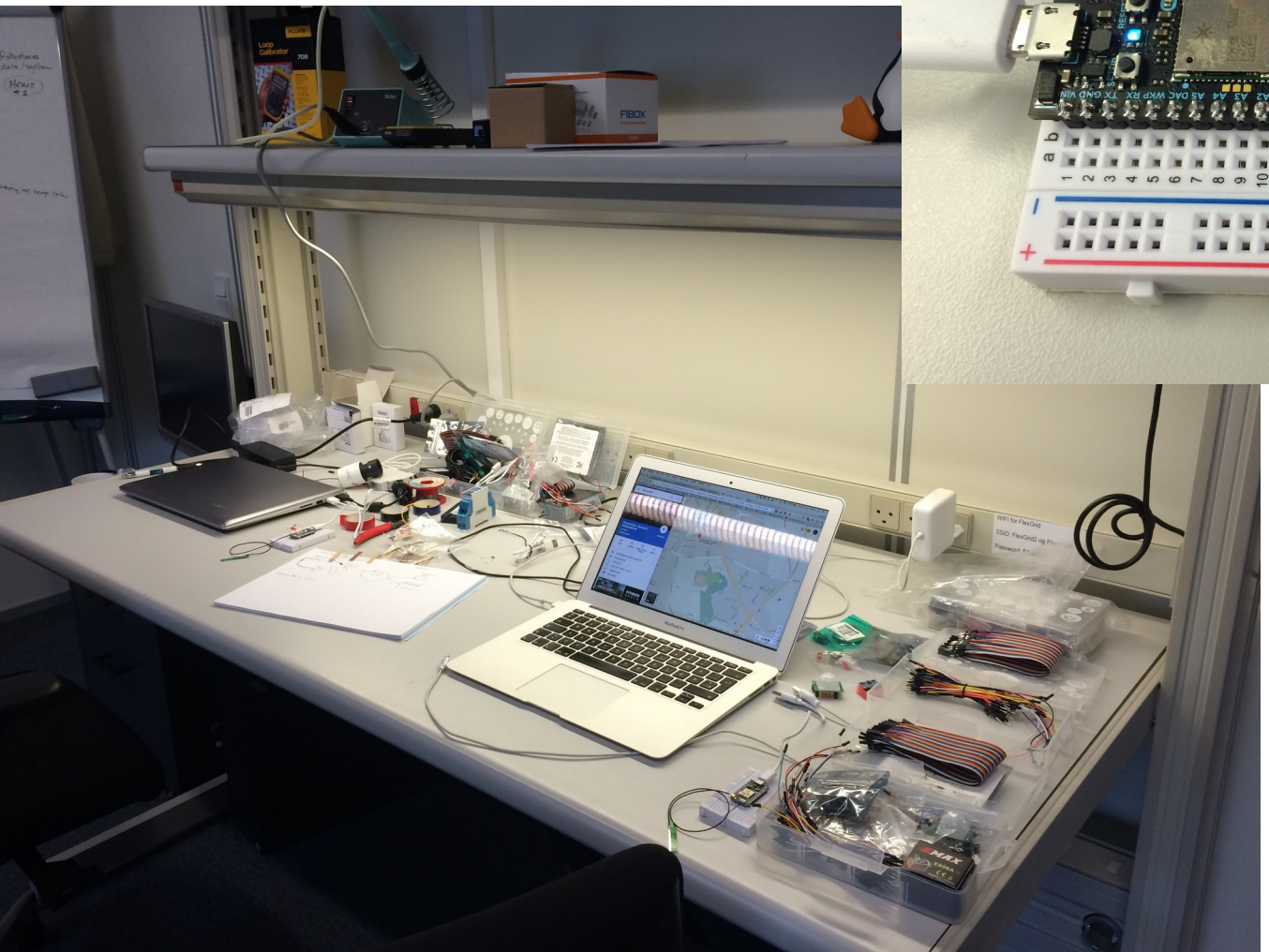
Control of HVAC Systems
(based on varying prices from Level III)

SE-OS – Low level controllers
Control loop design – **logical drawing**

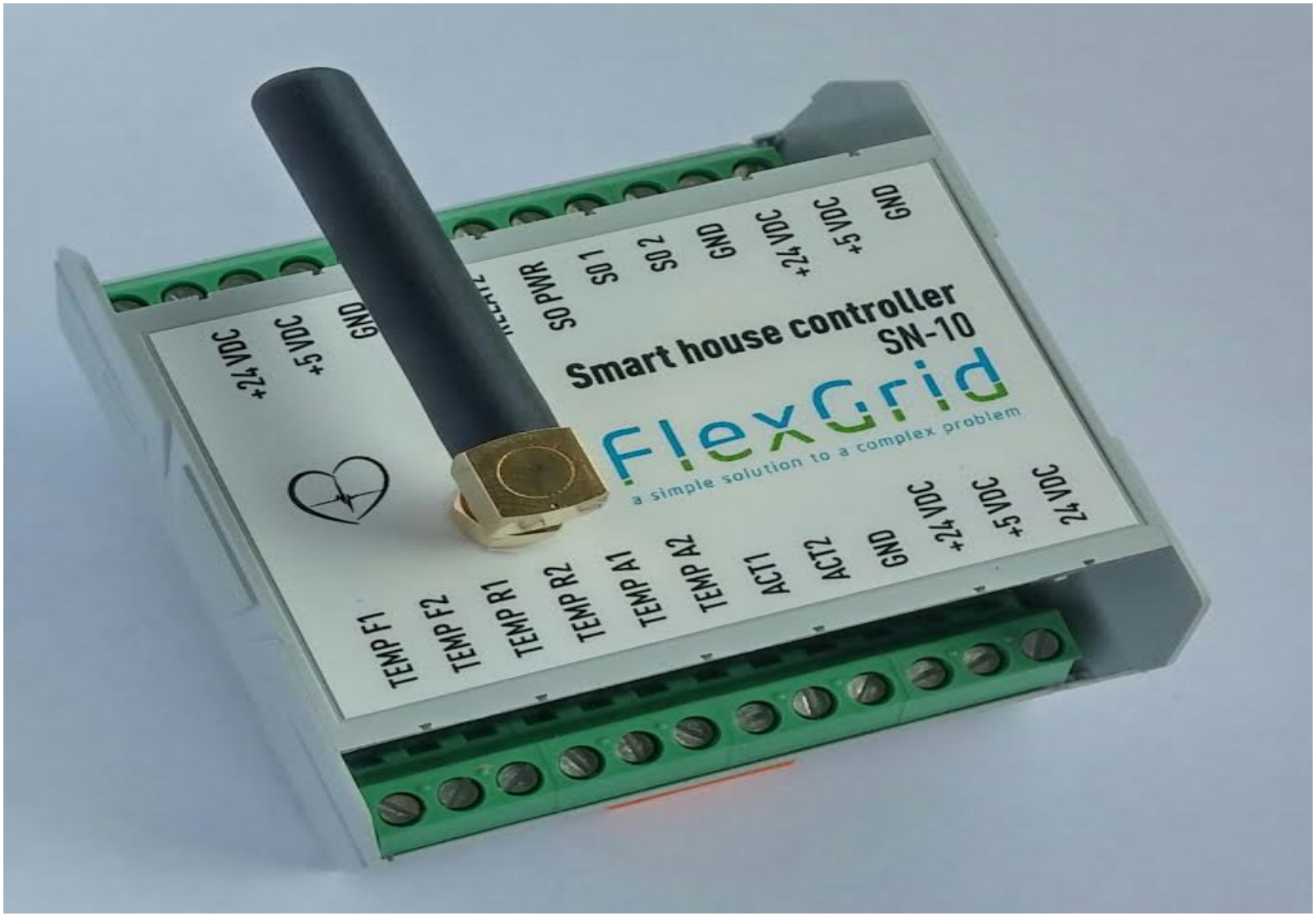


Lab testing ….

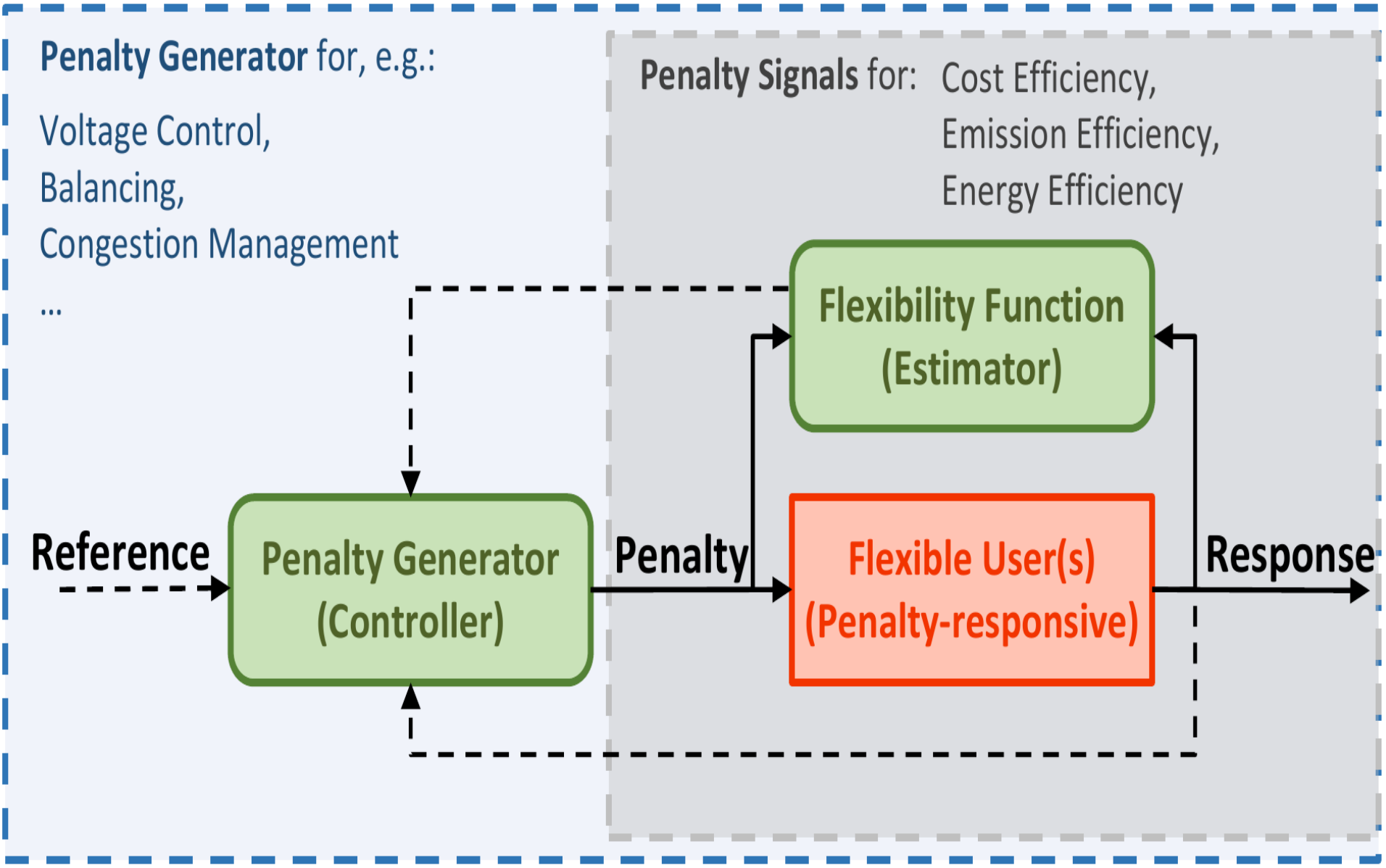




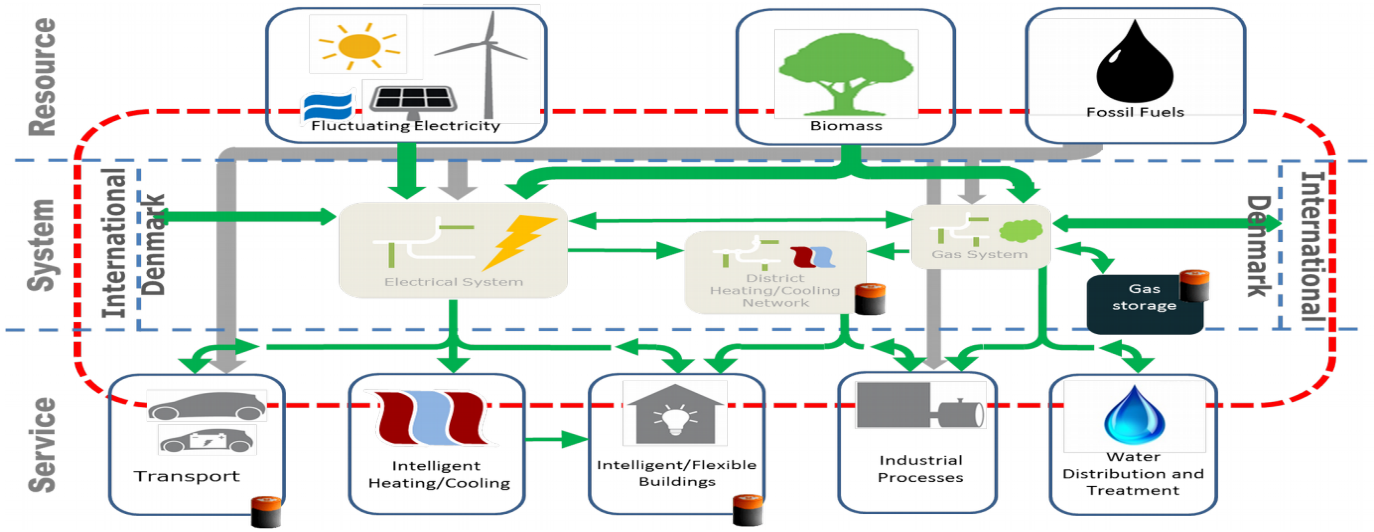
SN-10 Smart House Prototype



A FED example: Flexible Users and Penalty Signals



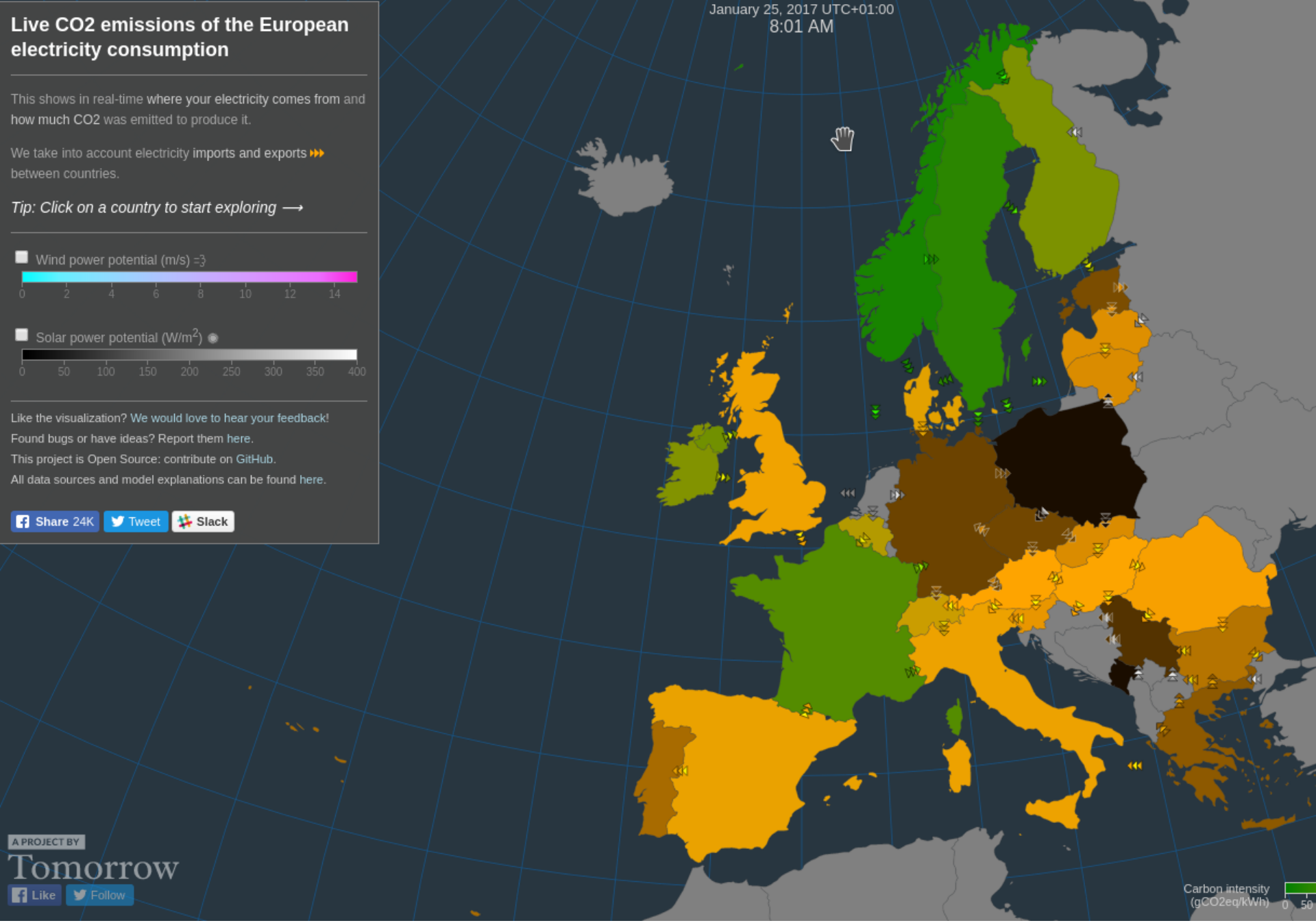
(Virtual) Storage Solutions



- **Flexibility (or virtual storage) characteristics:**
  - Supermarket refrigeration can provide storage 0.5-2 hours ahead
  - Buildings thermal capacity can provide storage up to, say, 2-10 hours ahead
  - Buildings with local water storage can provide storage up to, say, 2-18 hours ahead
  - District heating/cooling systems can provide storage up to 1-3 days ahead
  - DH systems with thermal solar collectors can often provide seasonal storage solutions
  - Gas systems can provide seasonal/long term storage solutions

Case study

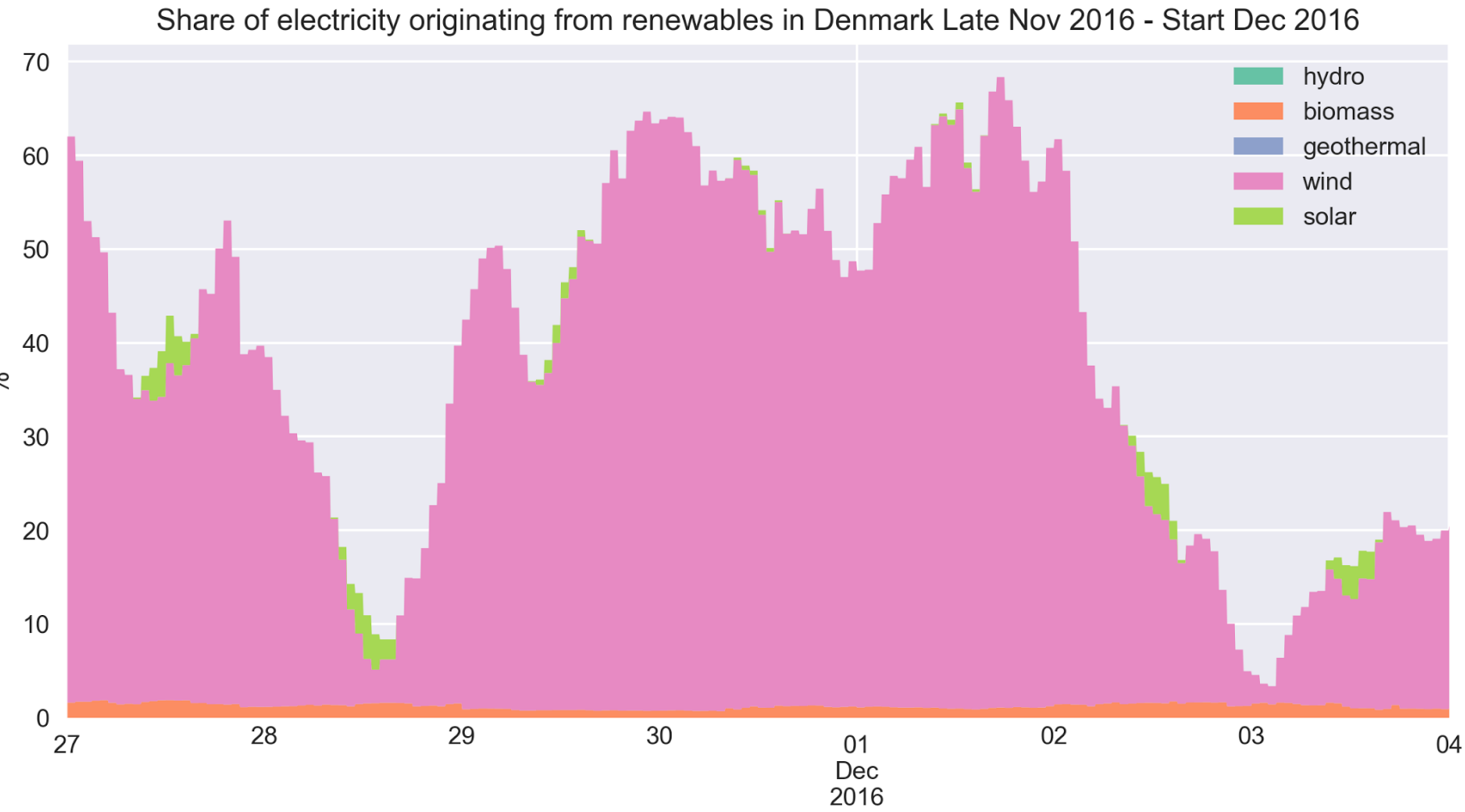
Control of heat pumps
(Energy or/and CO2 efficient control)



CITIES
Centre for IT Intelligent Energy Systems

Annex 71 and Dynasty Symposium, Bilbao, April 2019

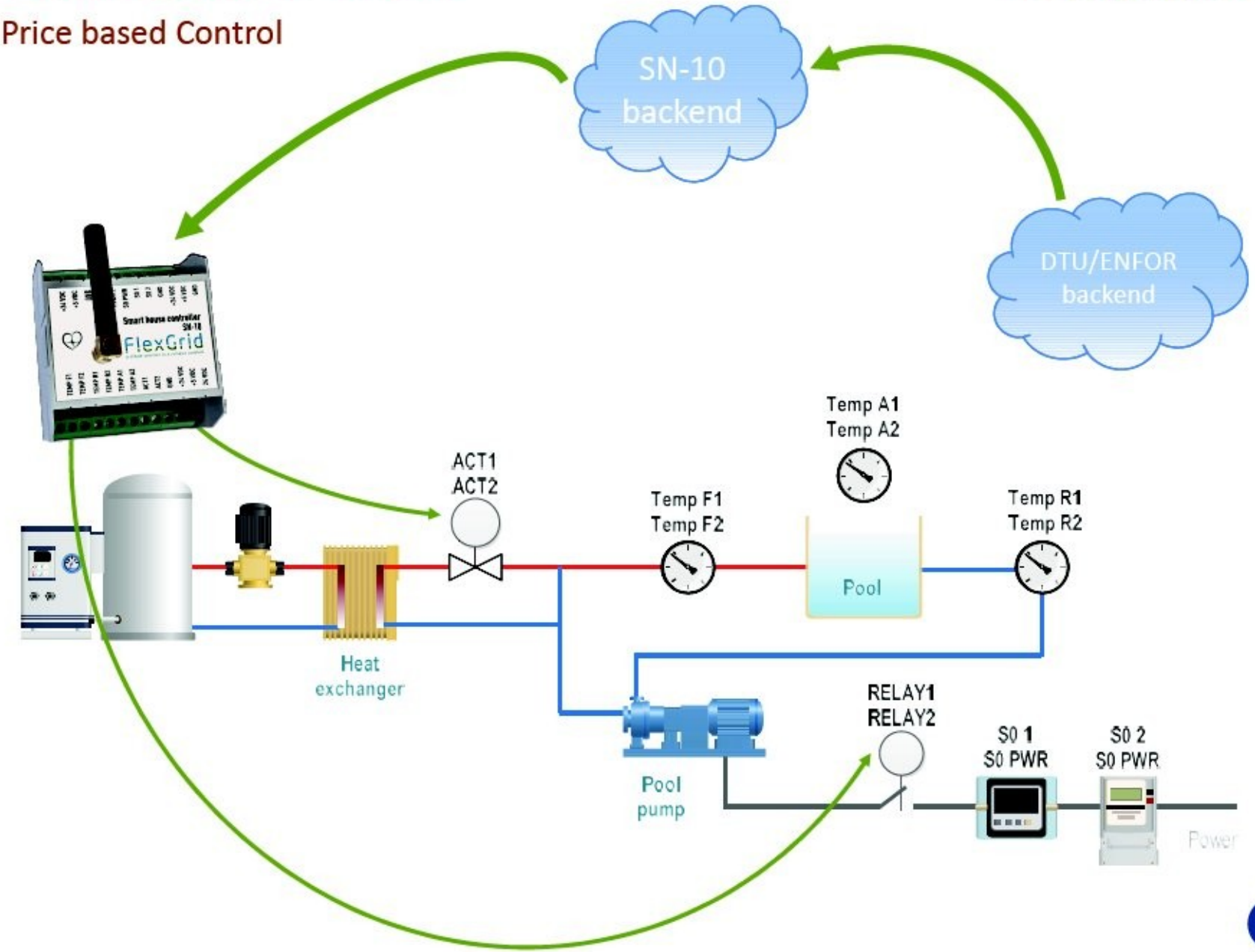
Innovation Fund Denmark



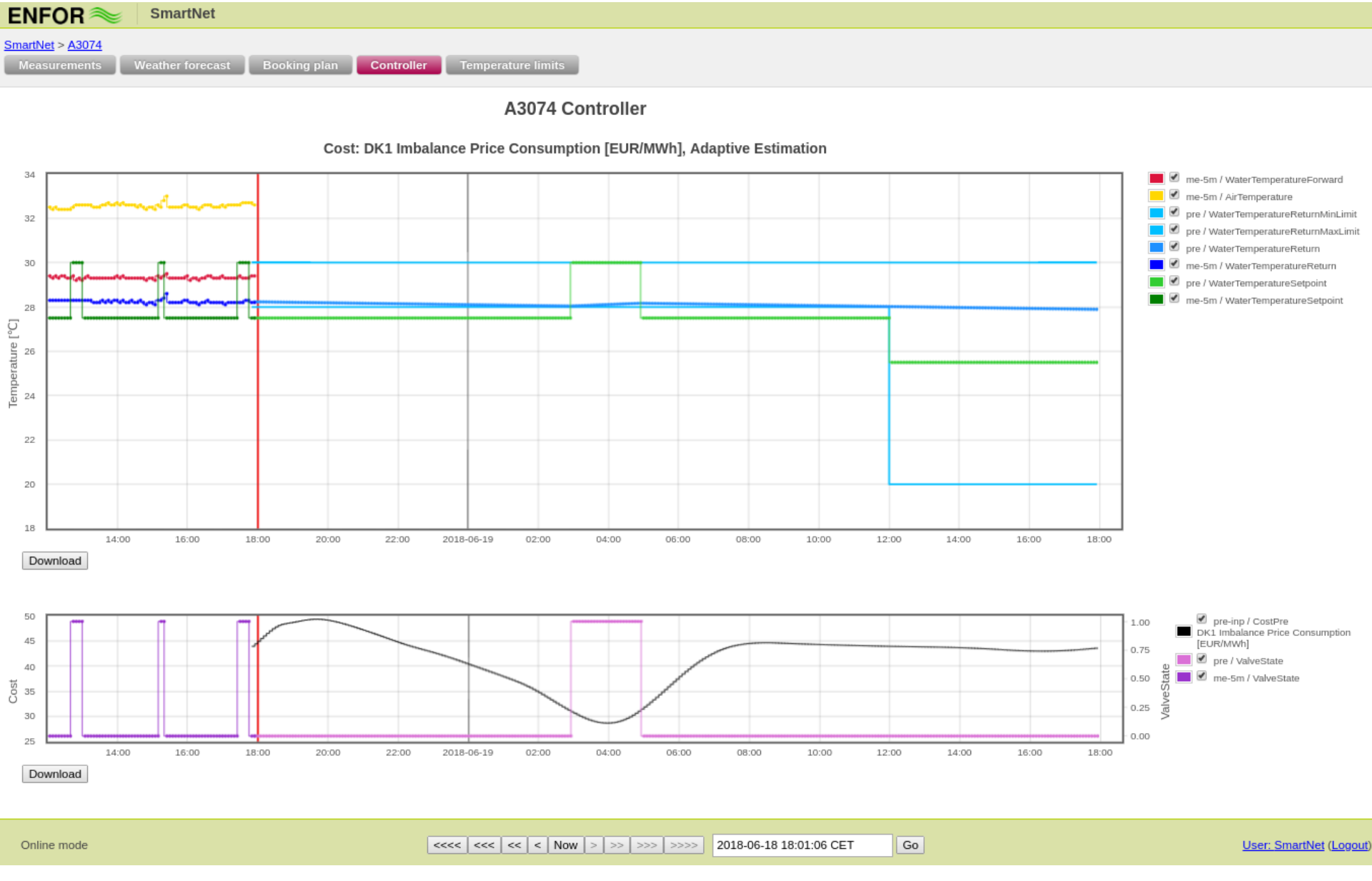
Source: pro.electicitymap.

How does it work?

Price based Control

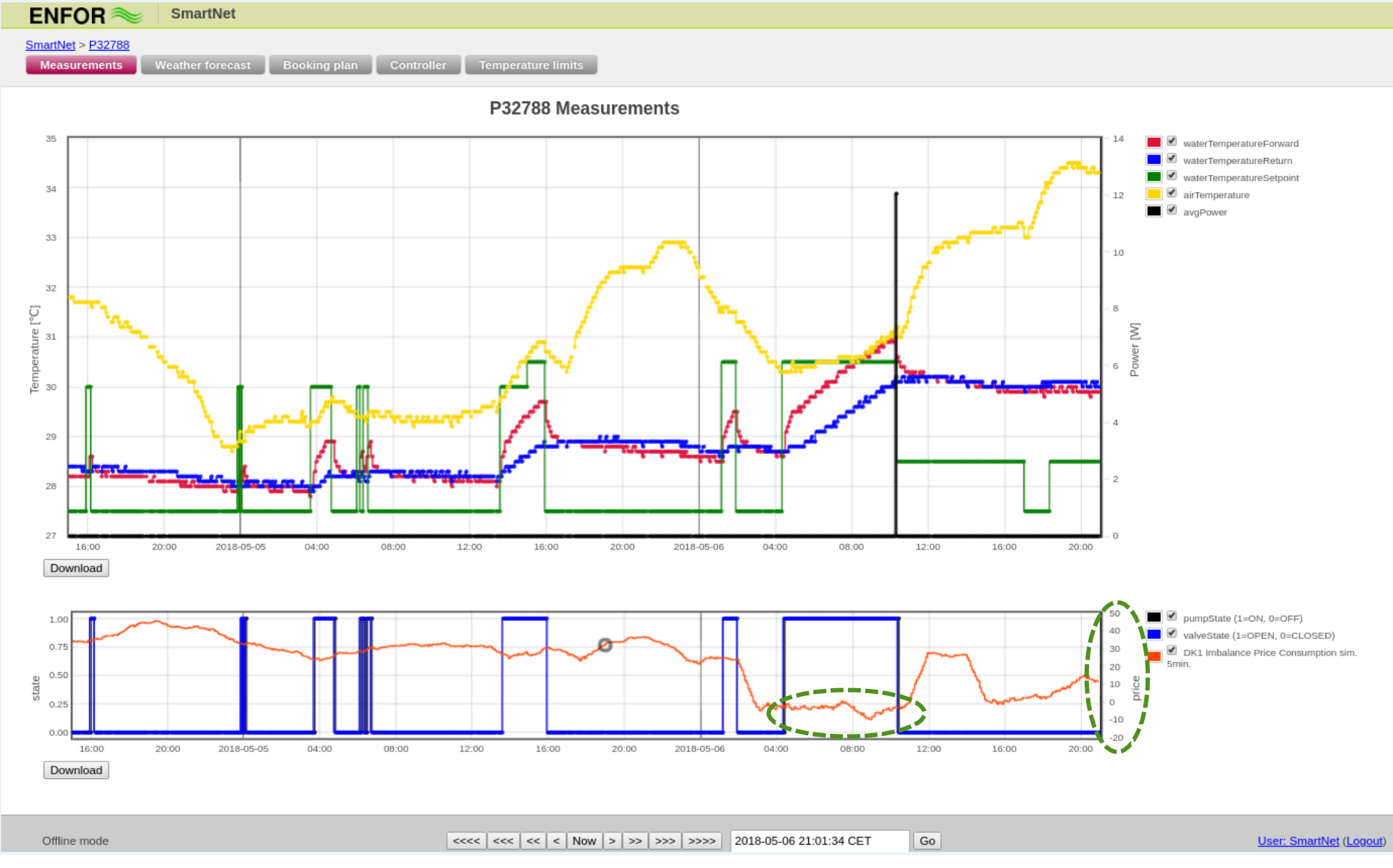


Example: Price-based control



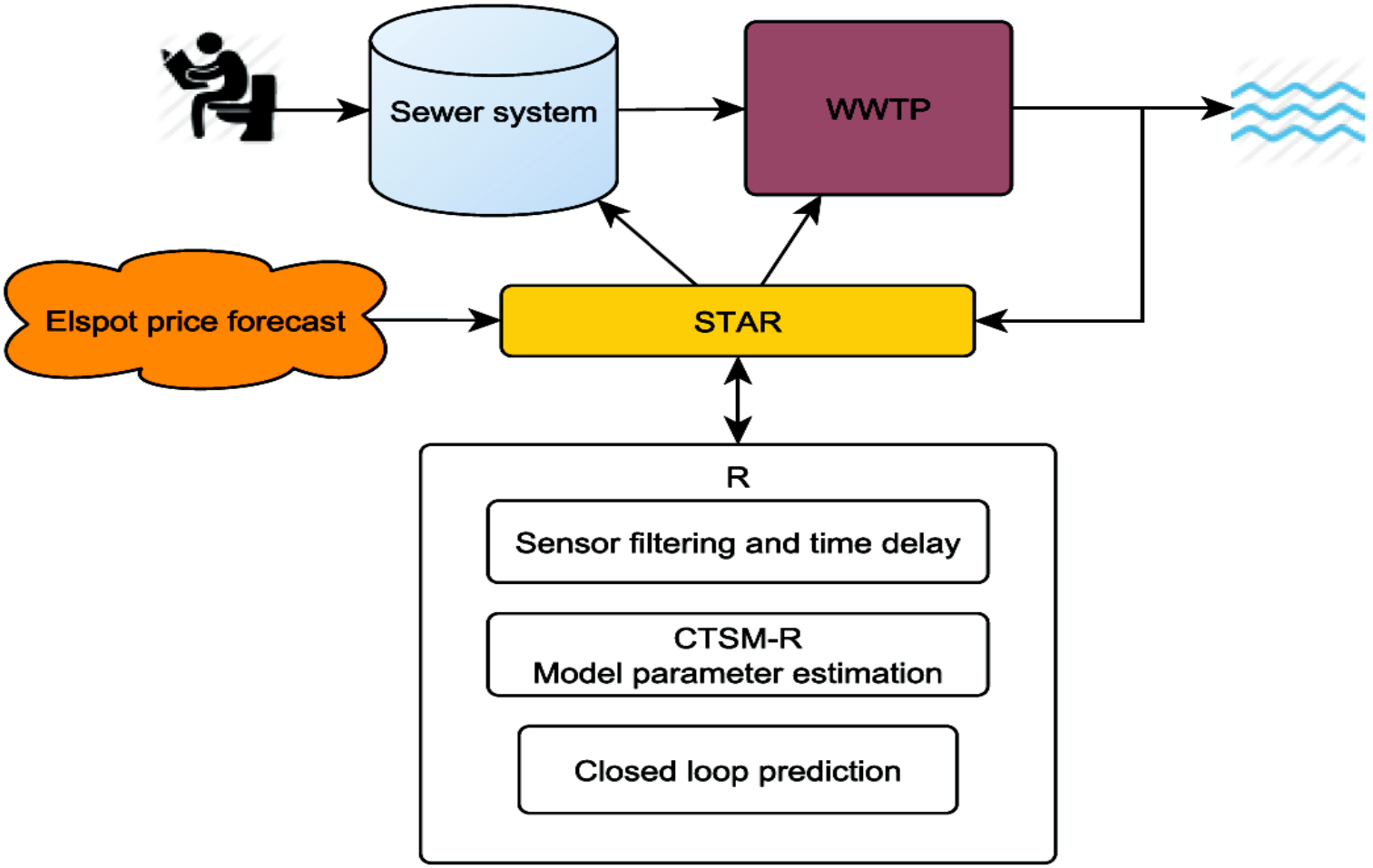
Example: CO2-based control (10 pct savings in CO2 e.)

Example with negative power prices

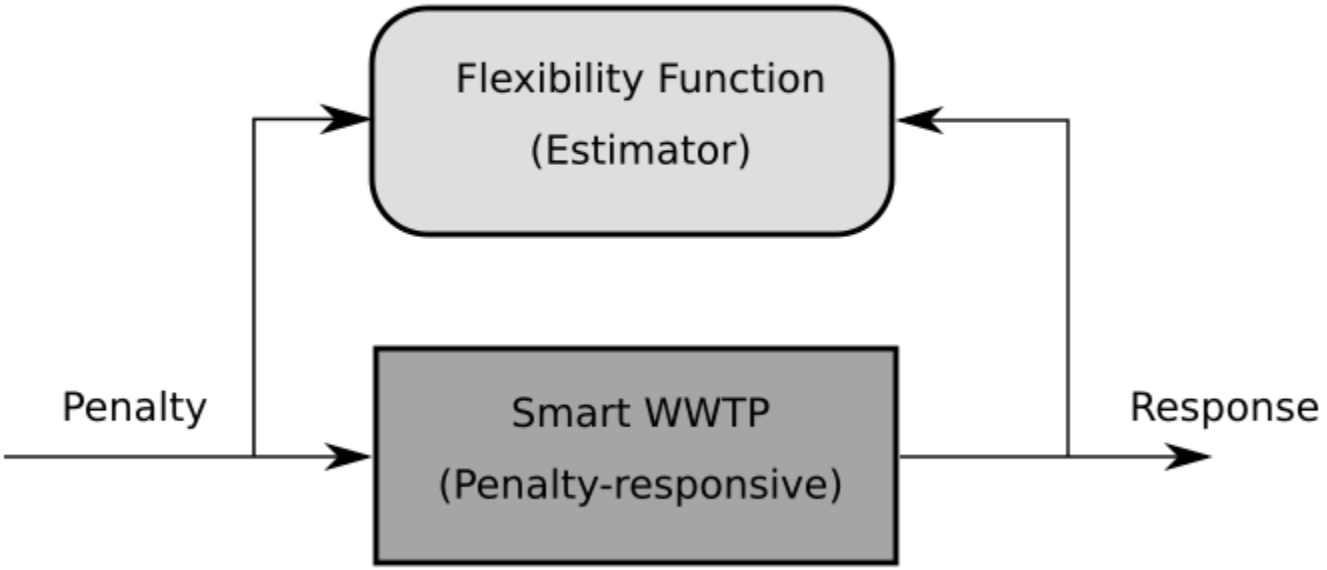


CITIES Solutions

Energy Flexibility in Wastewater Treatment



Flexibility Function



CITIES INNOVATION CENTER

Integrated energy systems powered by intelligent data

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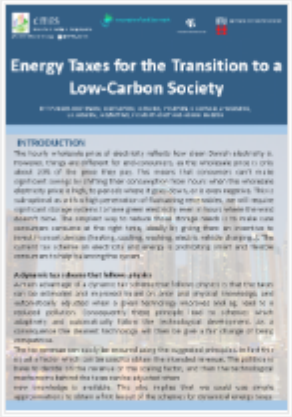
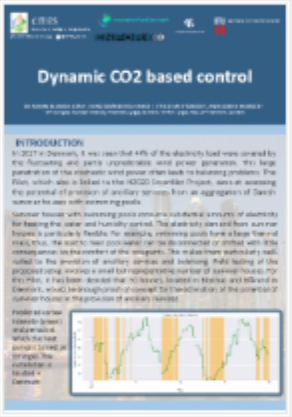
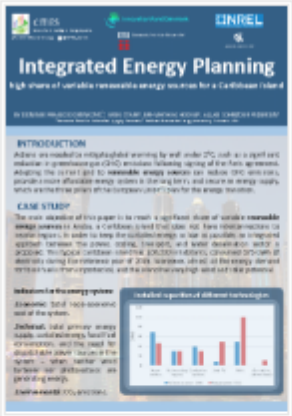


Energy taxes for the transition to a low-carbon society



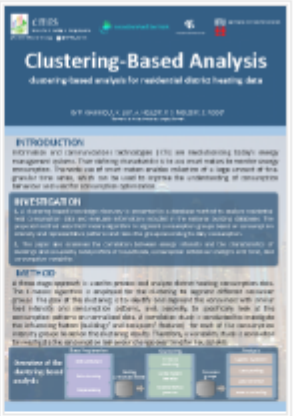
Dynamic CO2 based control

Stability of electricity smart meter clusters



Integrated energy planning for a carribean island

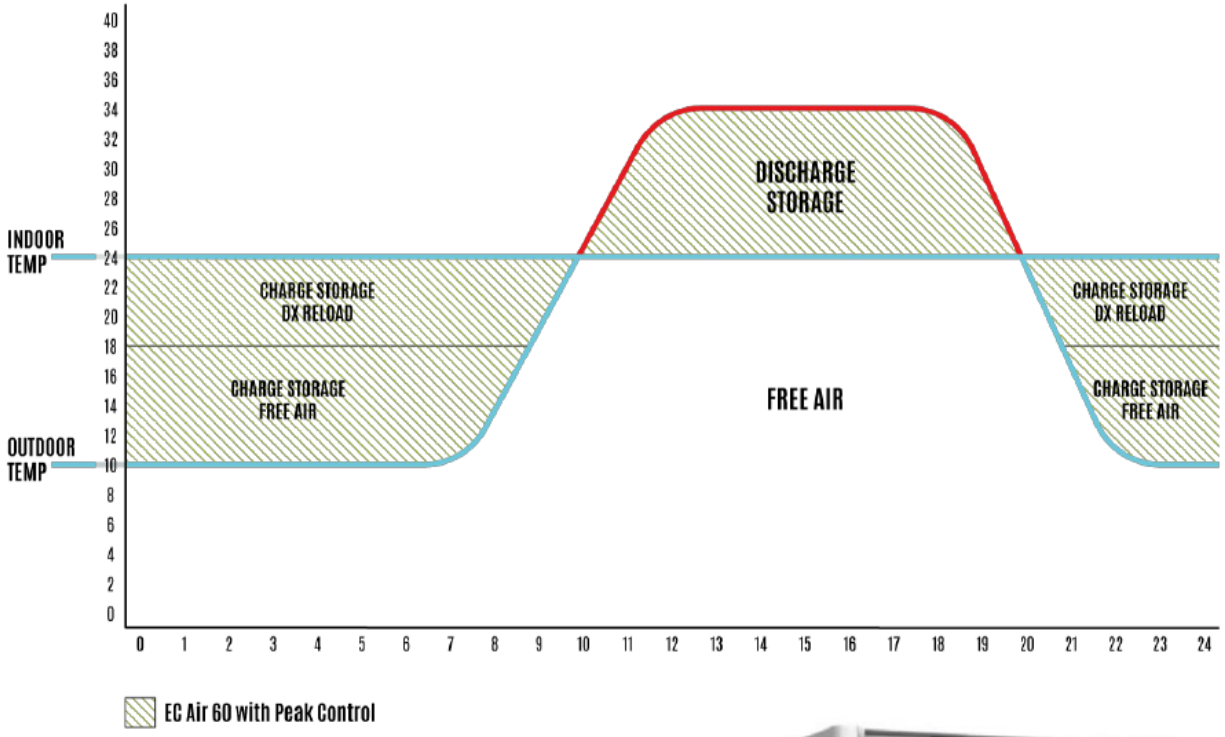
Potential of district cooling



Clustering based analysis of residential district heating data

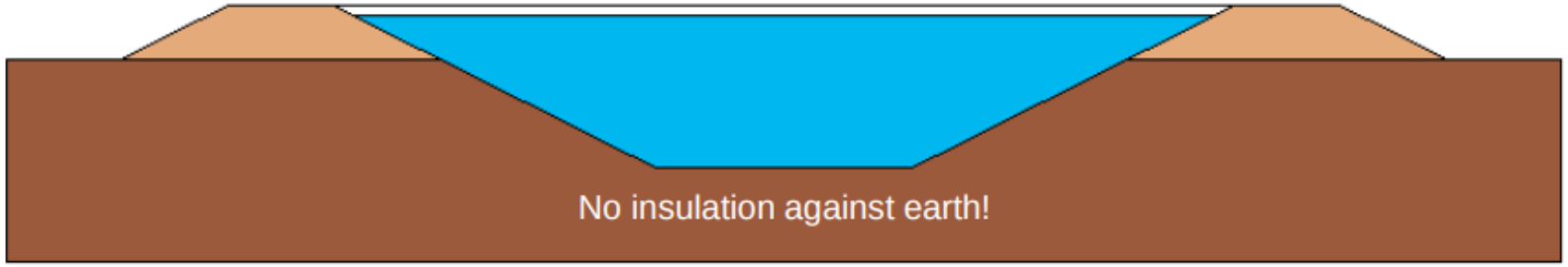
Data Centers

Large savings (90-95 pct) related to cooling of data centers using PCM (from Center Denmark)

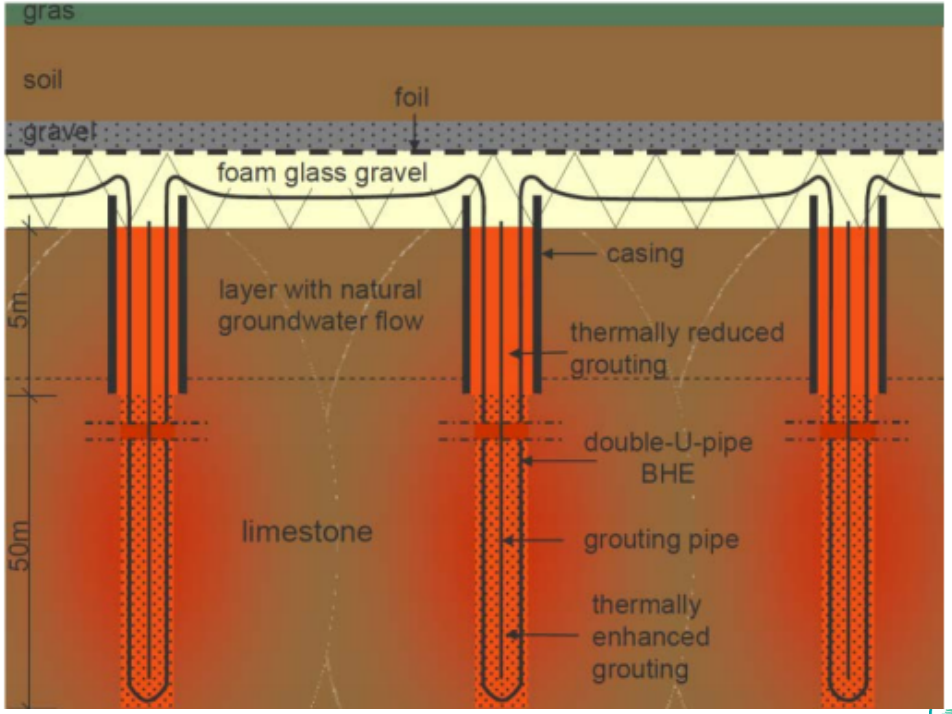


Seasonal Storage - District Heating
(from Simon Furbo, DTU Byg)

Water pit



Borehole storage



Measurements

	Borehole storage, Brædstrup	Water pit storage, Marstal	Water pit storage,Dronninglund	Water pit storage, Gram
Size	19000 m^3 soil, corresponding to about 12000 m^3 water	75000 m^3 water	62000 m^3 water	110000 m^3 water
Maximum storage temperature	50°C	90°C	90°C	90°C
Heat recovered from heat storage during first year	44%	18%	78%	55%
Heat recovered from heat storage during second year	38%	65%	90%	
Heat recovered from heat storage during third year	102%	62%	91%	
Heat recovered from heat storage during fourth year	46%	Problems with measurements		

Center Denmark

Green transition paved by green innovation

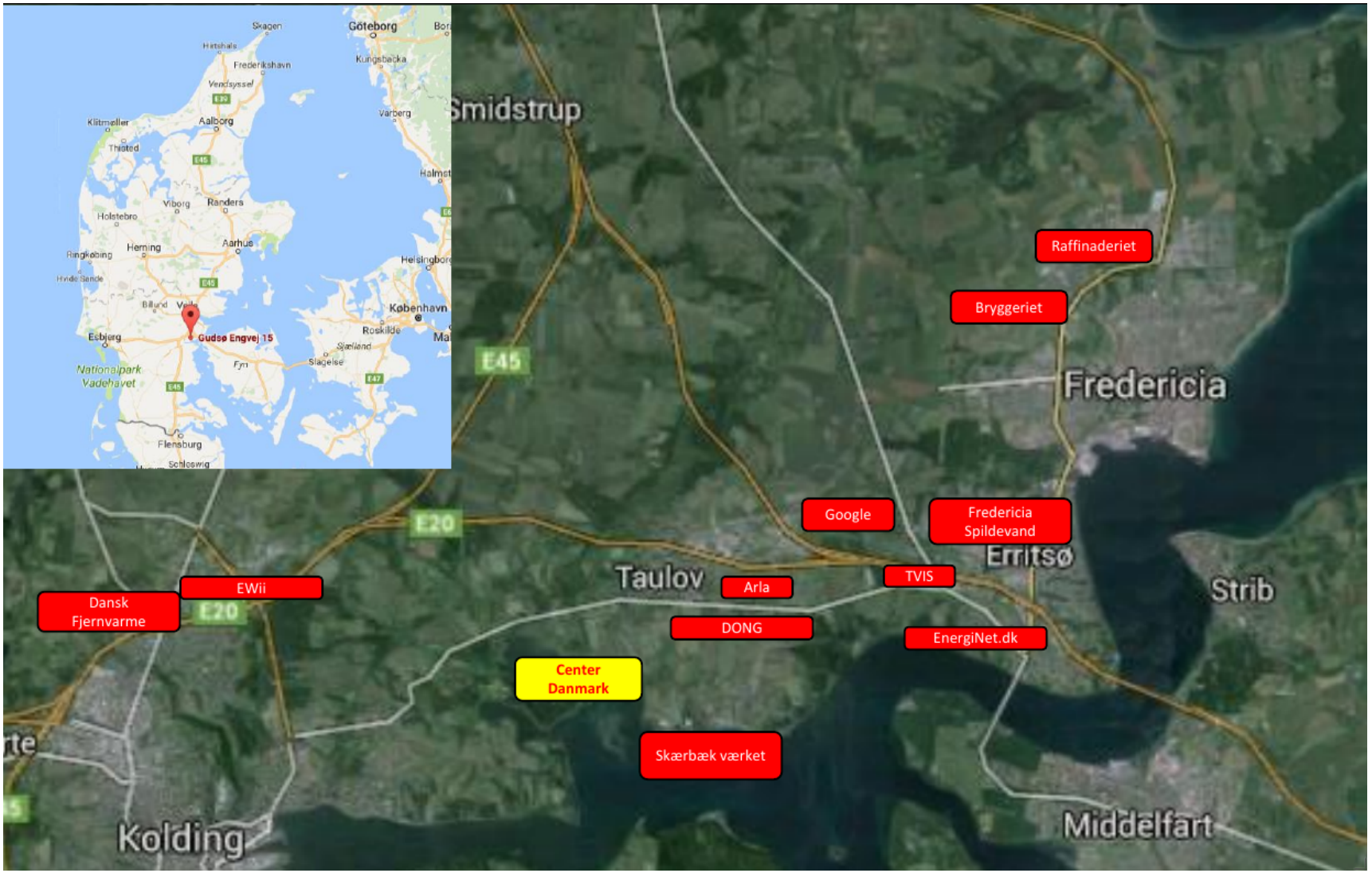
CENTER DENMARK

Connect networks and data for a green world

Danmarks nationale Center

Fremme den grønne omstilling.
Samle og bygge bro, mellem forskning, teknologi, natur og formidling, på tværs af interesseorganisationer, virksomheder, skoler og universiteter.

Center Danmark
Test Center for Intelligent and Integrated Energy Systems



Center Denmark, Living Labs, Partnerships

UNILAB consortium

Cardiff University

Danmarks Tekniske Universitet (DTU), Denmark

Royal Institute of Technology (KTH), Sweden

German Technical and Scientific Association for Gas and Water (DVGW), Germany

Imperial College, United Kingdom

Tianjing University, P.R. China

TNO - Netherlands

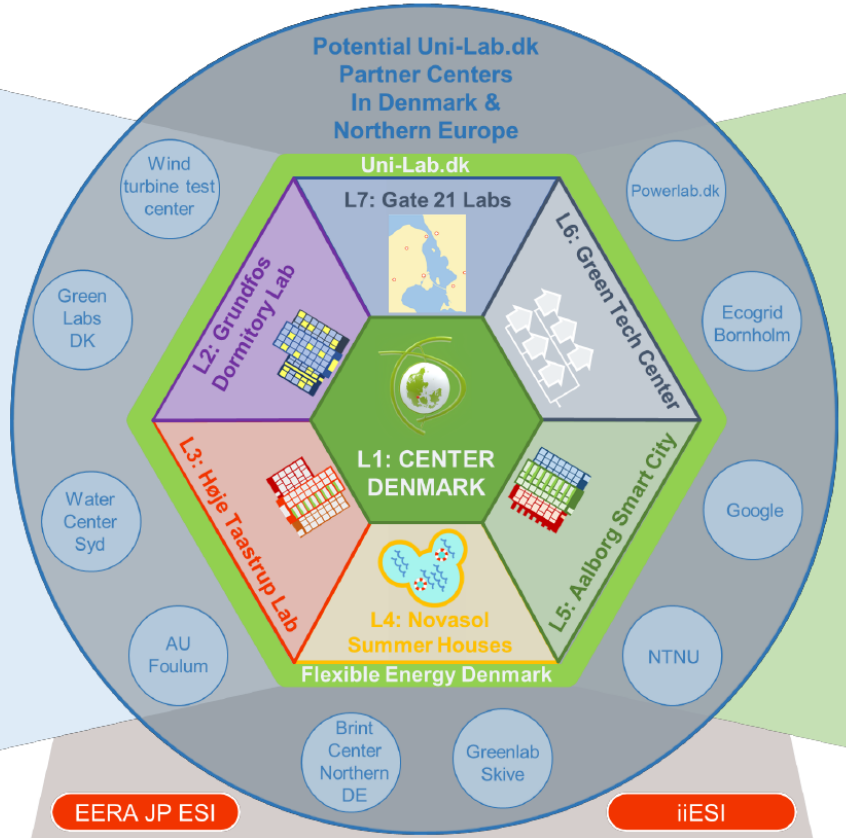
Toshiba Research Laboratory (TRL), UK

Tsinghua University - P.R. of China

Katholieke Universiteit Leuven (KUL), Belgium

Malardalen University, Sweden

University of Pisa (UP), Italy



International Cooperating labs

NREL (US)

CESI (UK)

ZEN (NORWAY)

Berkeley (US)

Argonne (US)

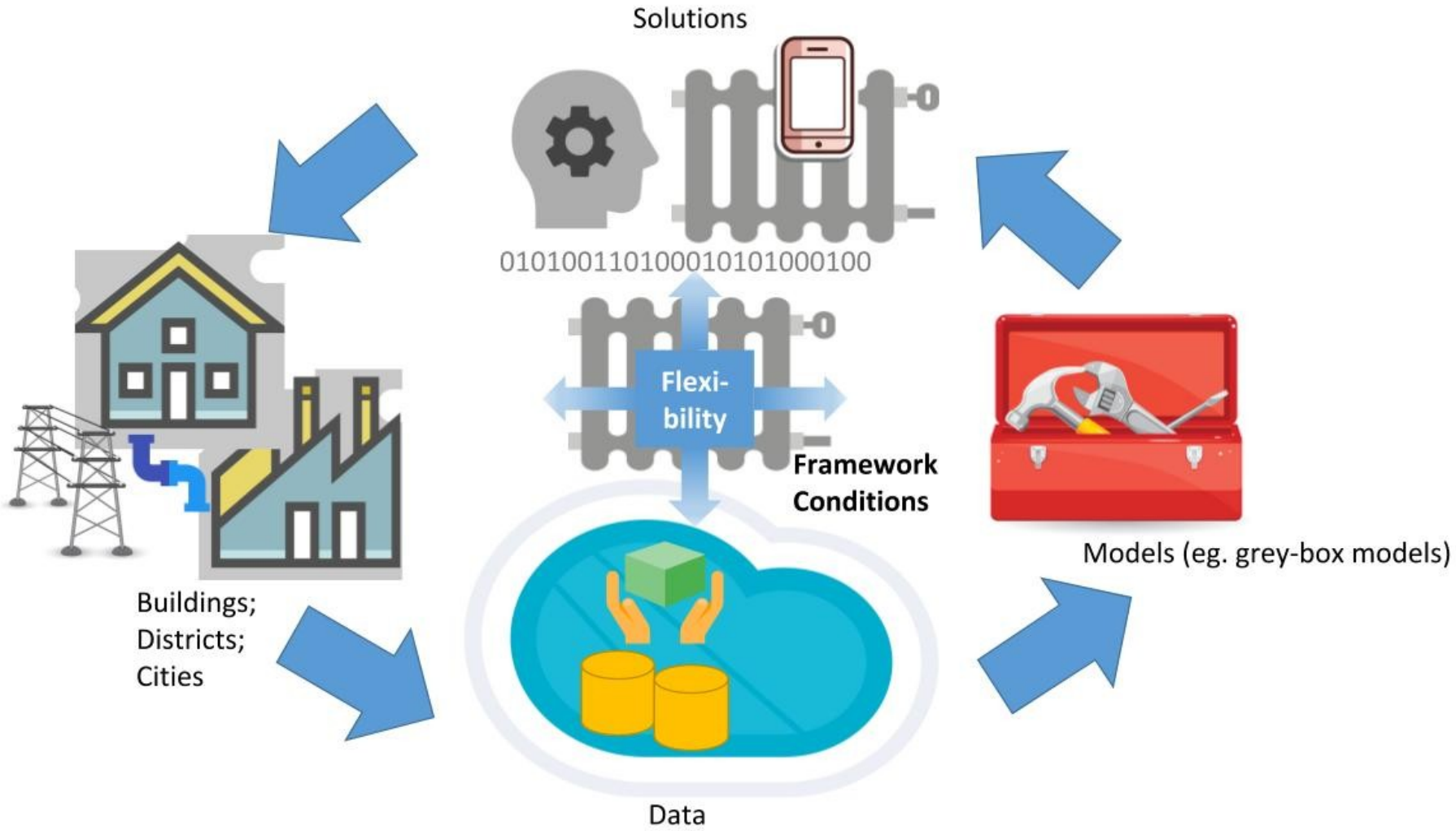
KIER (KOREA)

ESIPP (IRELAND

PSA (SPAIN)

KUBIK (SPAIN)

Flexibility enabled using data intelligence (AI)



Summary

- We have demonstrated a large potential in unlocking the flexibility / Demand Response. Automatic solutions are important
- We need new digitalized markets (based on grey-box modelling and control)
- Controllers developed in CITIES can focus on
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency
- We see large problems with tax and tariff structures in many countries (eg. Denmark)
- Center Denmark is established as a National Digitalization Hub for Smart Energy and Water systems. Main purpose to unlock the flexibility needed for the green transition

Summary (2)

- Flexibility can be unlocked by big data analytic, AI, grey-box modelling, control, forecasting and IoT technologies
- District Heating plays provides a lot of flexibility – and hence DH is very important for integration of fluctuating renewable energy production
- Flexibility has to be described dynamically (Flexibility Function – Annex 67)
- The Flexibility Index gives an Annex 67 / 71 evindence based measure of the smartness of a building or a district
- Energy communities and eg. District heating are important in order to establish the best solutions for the society
- We can design a building such that it's optimal for a given climatic zone (using the Flexibility Index)
- We should calculate/find the optimal mix of insulation and thermal mass
- I don't think that a zero energy building the optimal solution for a society (LCA, source-sink, ...)

For more information …

See for instance

www.smart-cities-centre.org

…or contact

- Henrik Madsen (DTU Compute)

  hmad@dtu.dk

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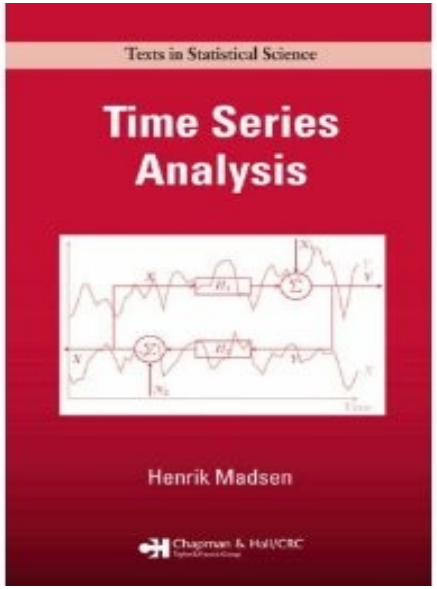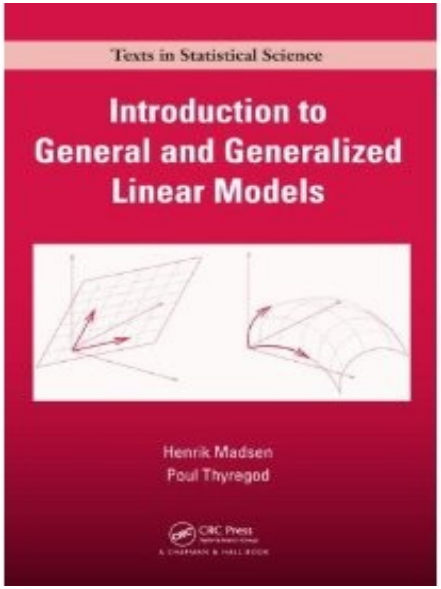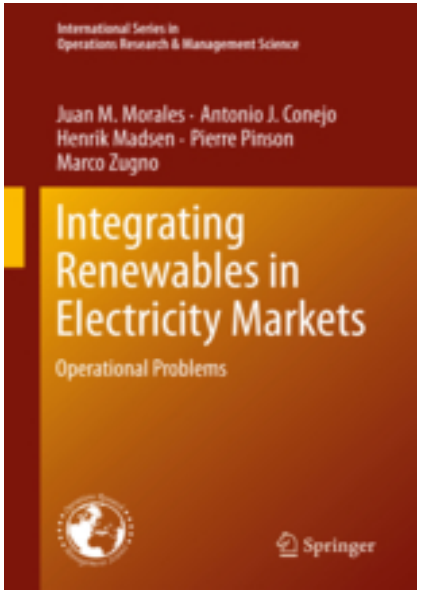
Some 'randomly picked' books on modeling and renewable integration ....