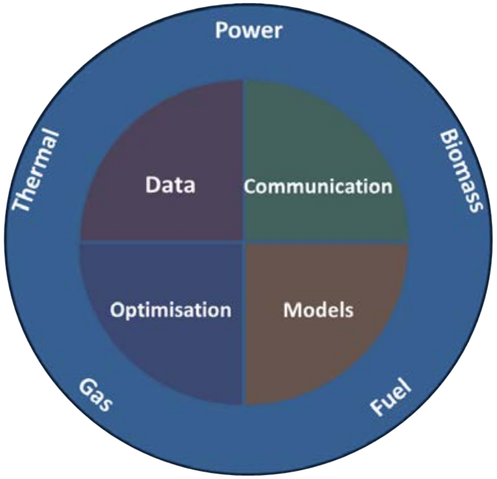
Accelerating the Green Transition Using Energy Systems Integration and Data-Intelligence



Henrik Madsen (DTU) + many others

https://www.flexibleenergydenmark.dk/

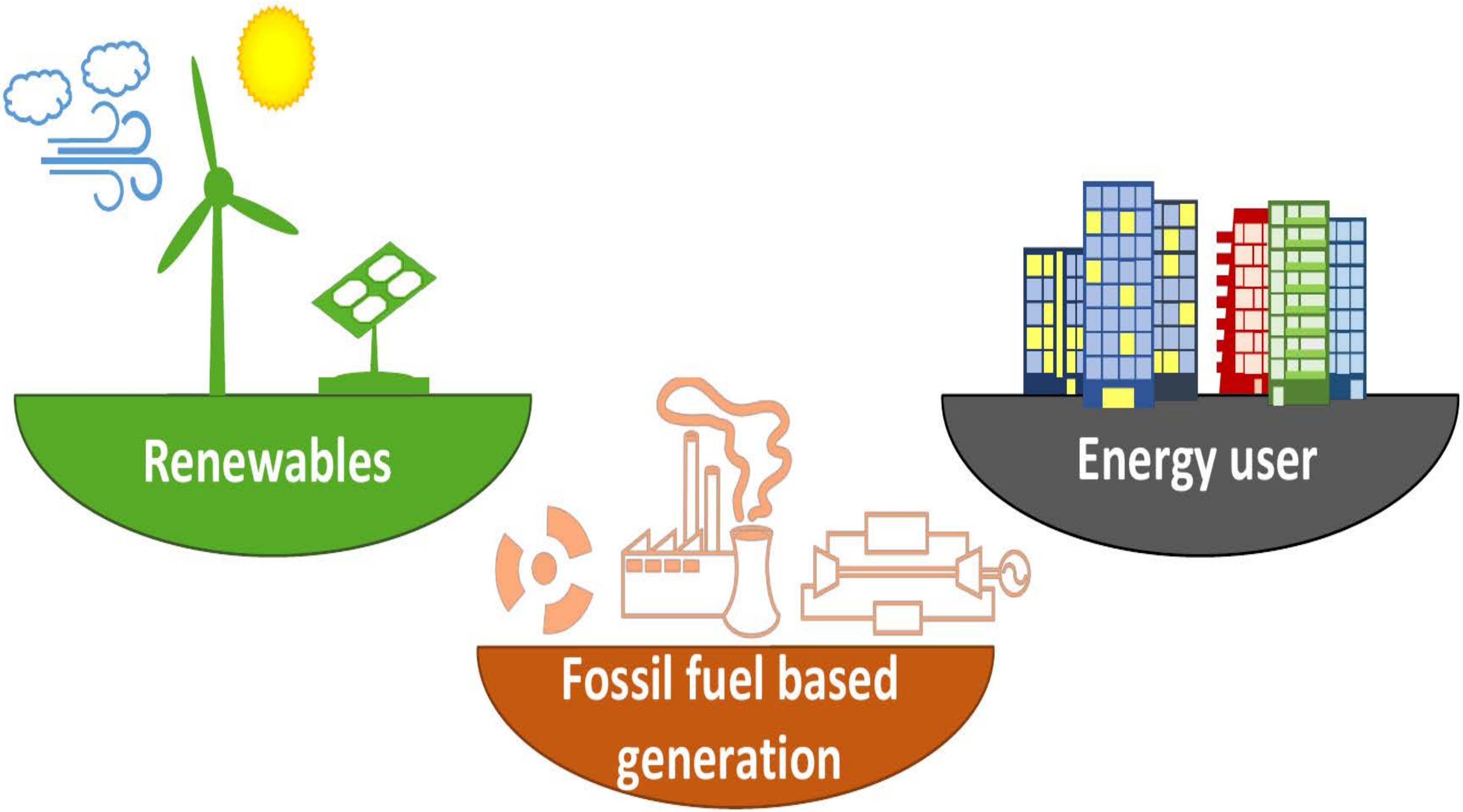
http://www.smart-cities-centre.org

http://www.henrikmadsen.org

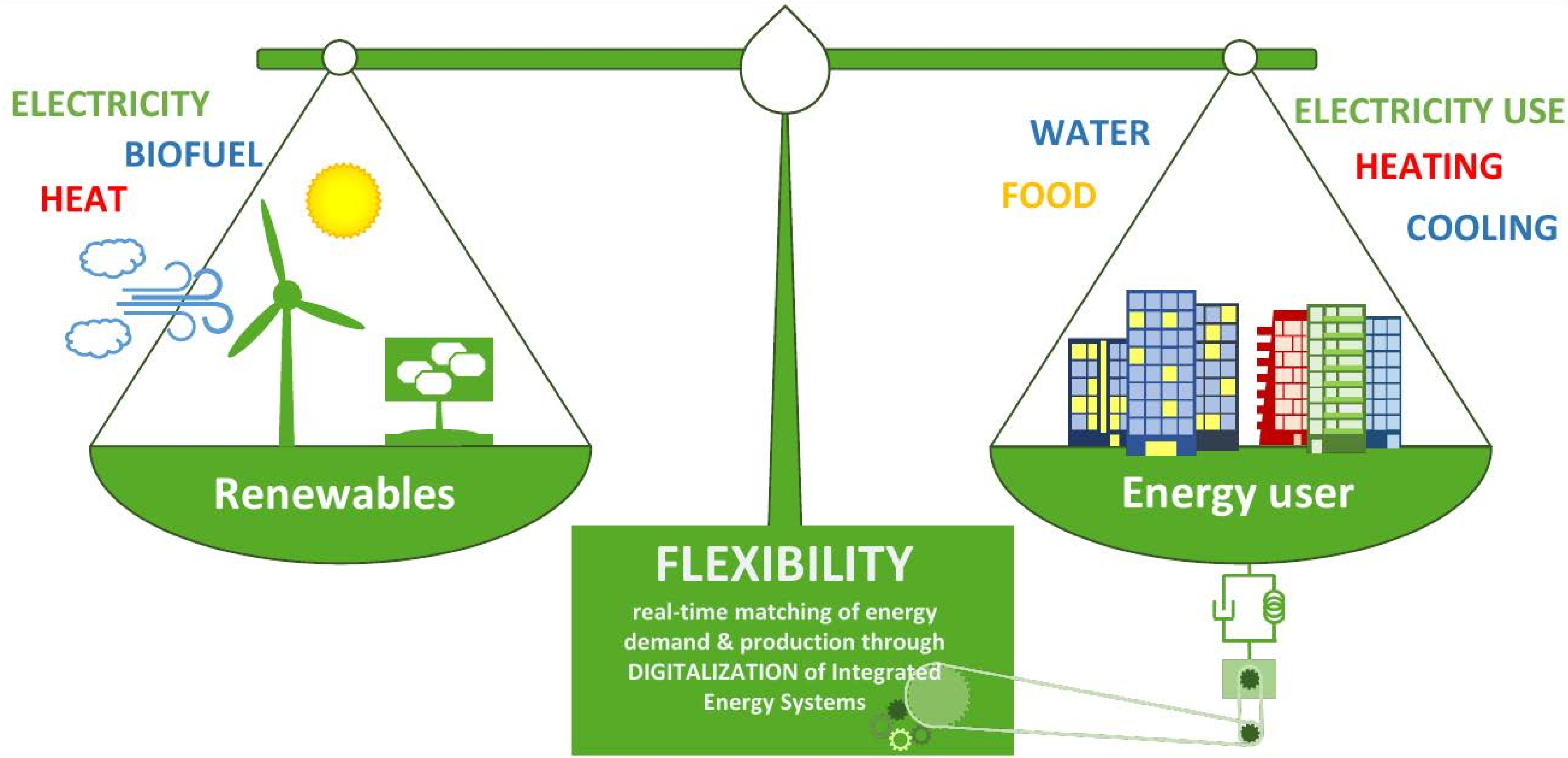
CITIES Centre for IT Intelligent Energy Systems

FED FLEXIBLE ENERGY DENMARK

The Challenge: Denmark Fossil Free 2050

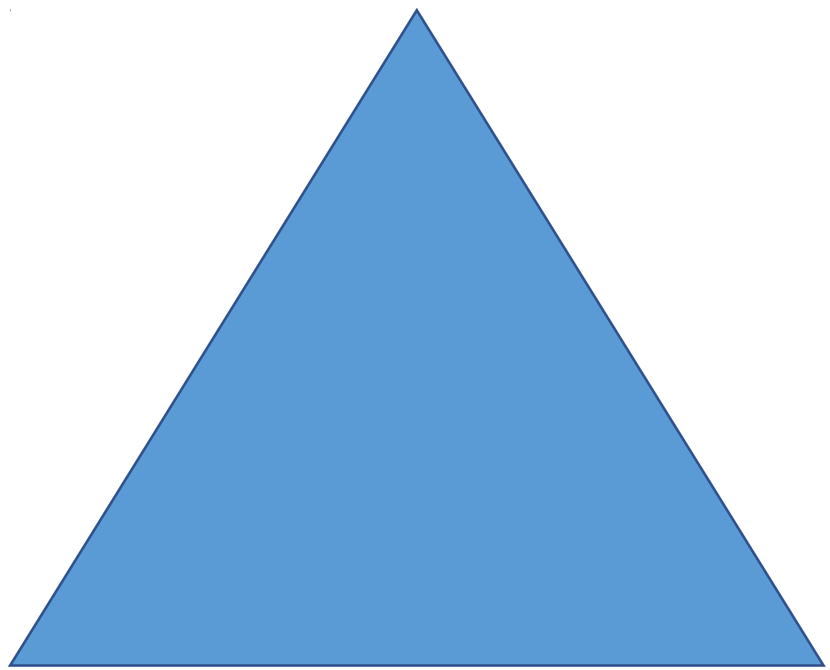


The Challenge: Denmark Fossil Free 2050



Space of Solutions

Flexibility (eg enabled by AI and Energy Systems Integration)

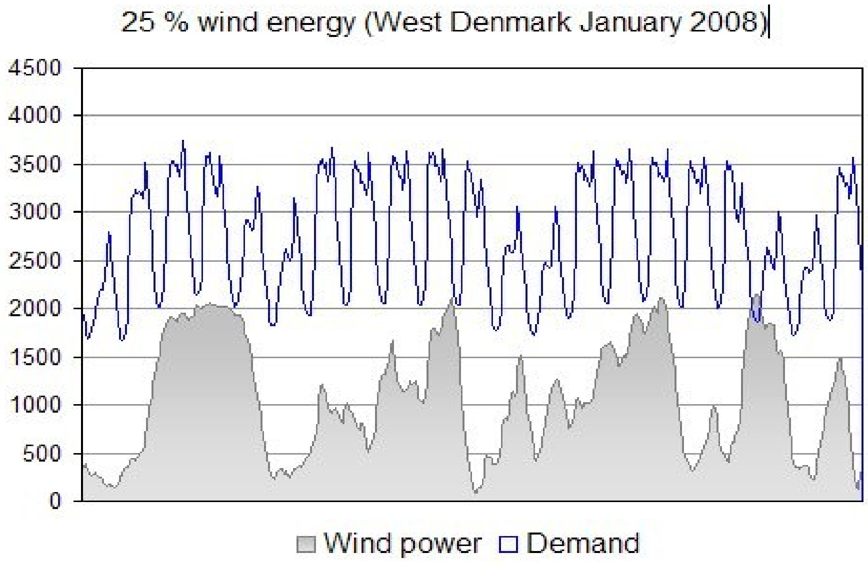


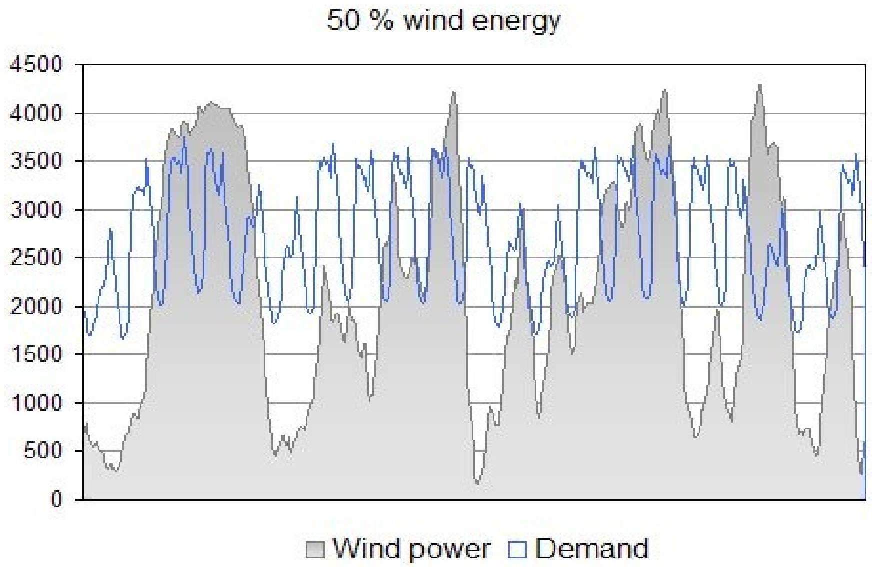
Super Grids

Batteries

The Danish Wind Power Case

.... balancing of the power system

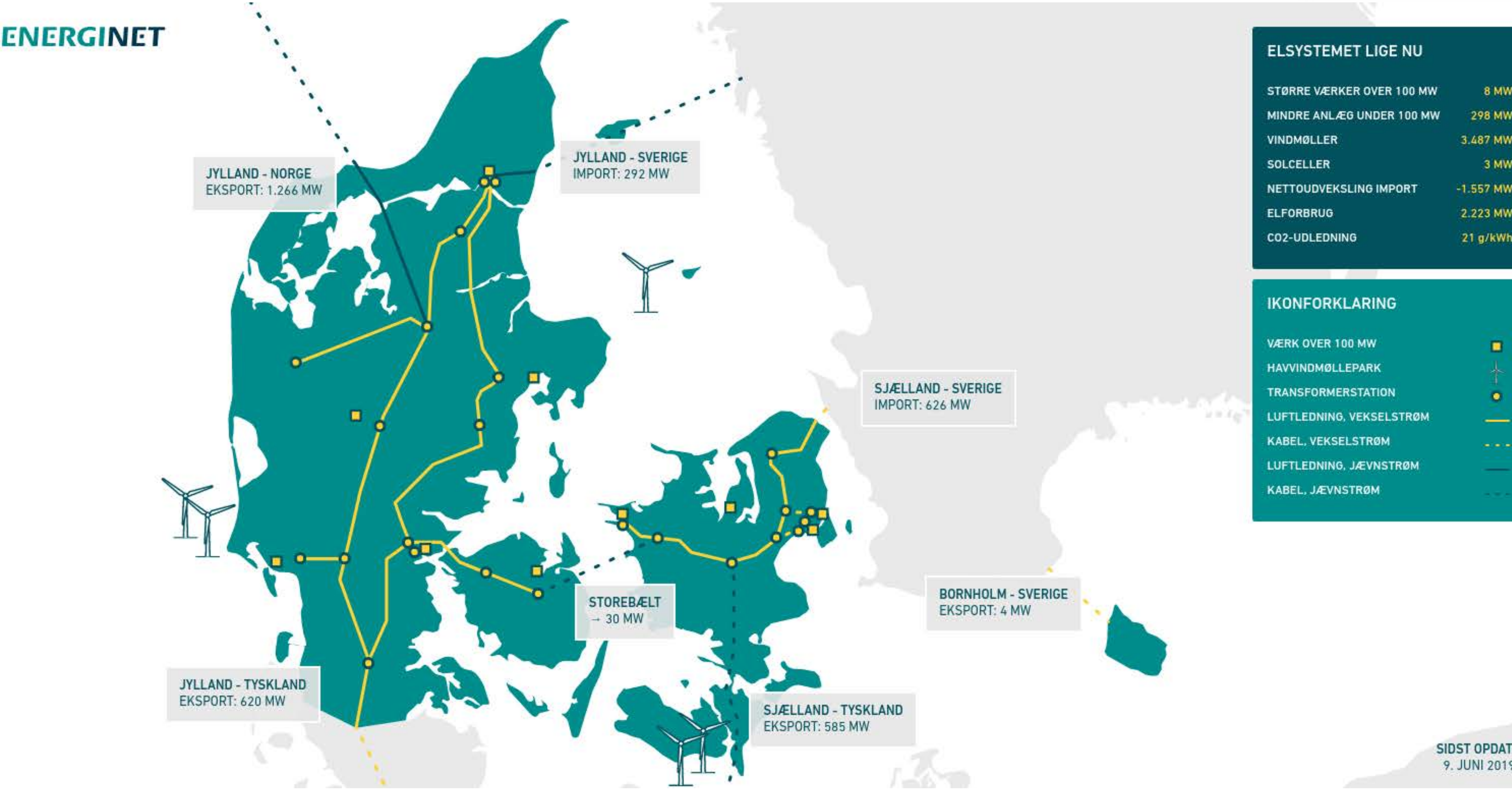




In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

In 2019 more than 50 pct of electricity load was covered by wind and solar power.

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


ENERGINET
JYLLAND - NORGE
EKSPORT: 1.266 MW
JYLLAND - SVERIGE
IMPORT: 292 MW
SJÆLLAND - SVERIGE
IMPORT: 626 MW
STOREBÆLT
→ 30 MW
BORNHOLM - SVERIGE
EKSPORT: 4 MW
JYLLAND - TYSKLAND
EKSPORT: 620 MW
SJÆLLAND - TYSKLAND
EKSPORT: 585 MW
ELSYSTEMET LIGE NU
STØRRE VÆRKER OVER 100 MW 8 MW
MINDRE ANLÆG UNDER 100 MW 298 MW
VINDMØLLER 3.487 MW
SOLCELLER 3 MW
NETTOUDVEKSLING IMPORT -1.557 MW
ELFORBRUG 2.223 MW
CO2-UDLEDNING 21 g/kWh
IKONFORKLARING
VÆRK OVER 100 MW
HAVVINDMØLLEPARK
TRANSFORMERSTATION
LUFTLEDNING, VEKSELSTRØM
KABEL, VEKSELSTRØM
LUFTLEDNING, JÆVNSTRØM
KABEL, JÆVNSTRØM
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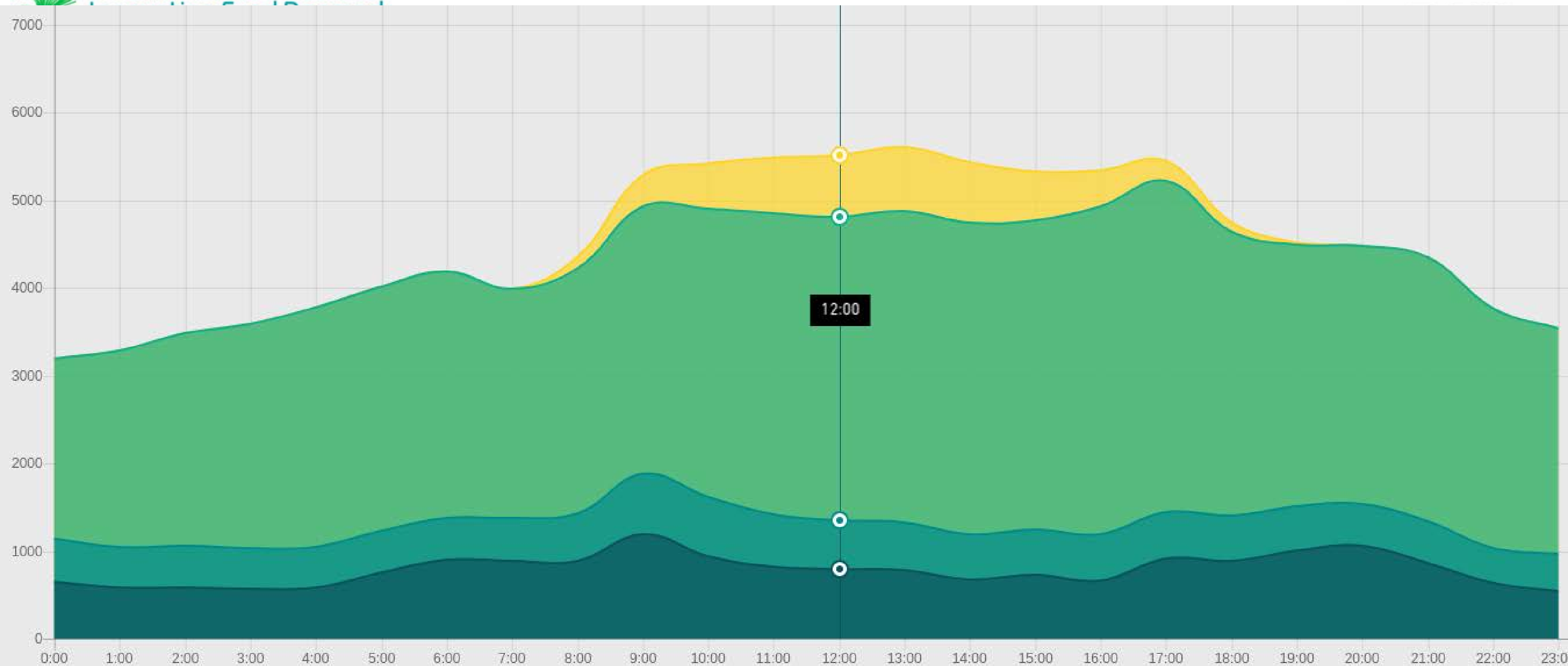


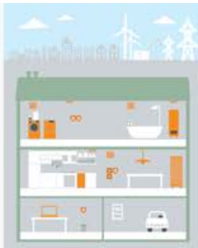
STØRRE VÆRKER OVER 100 MW	MINDRE ANLÆG UNDER 100 MW	VINDMØLLER	SOLCELLER
797 MW	558 MW	3.451 MW	712 MW

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

Innovation Fund Denmark

DTU

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 societal 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

- Static
- Deterministic
- Linear
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, ...)
- Speed / problem size
- Characterization of flexibility (bids)
- Requirements on user installations

Markets – Needed changes

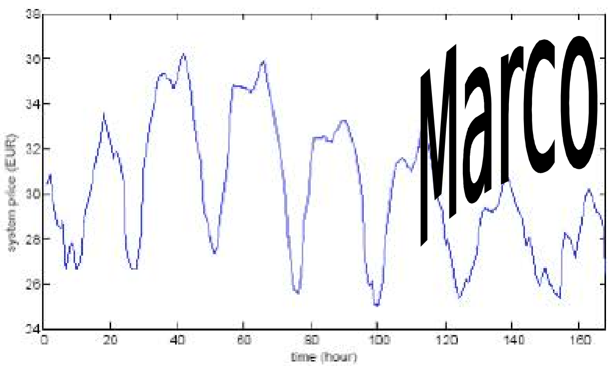
- Static -> **Dynamic**
- Deterministic -> **Stochastic**
- Linear -> **Nonlinear**
- Many power related services (voltage, frequency, balancing, spinning reserve, congestion, ...) -> **Coordination + Hierarchy**
- Speed / problem size -> **Decomposition + Control Based Solutions**
- Characterization of flexibility (bids) -> **Flexibility Functions**
- Requirements on user installations -> **One-way communication**

COMPETITIVE BIDDING AND STABILITY ANALYSIS IN ELECTRICITY MARKETS USING CONTROL THEORY

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

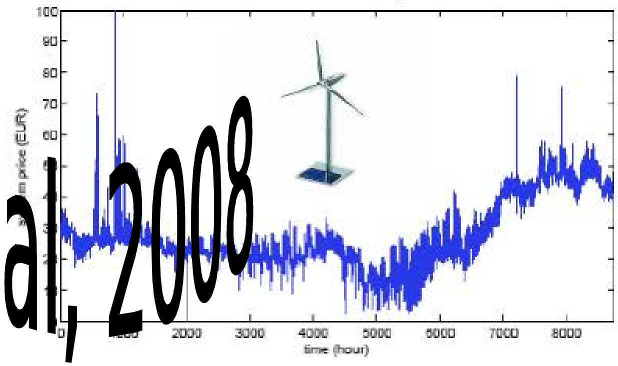
Advantages in handling effectively

Dynamics



Marco Zugno et.al, 2008

Uncertainty



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

↓

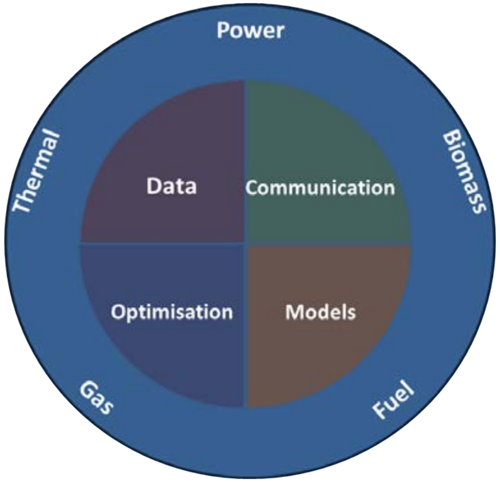
it is possible to develop advanced bidding strategies which exploit the inclusion of the dynamics in the model

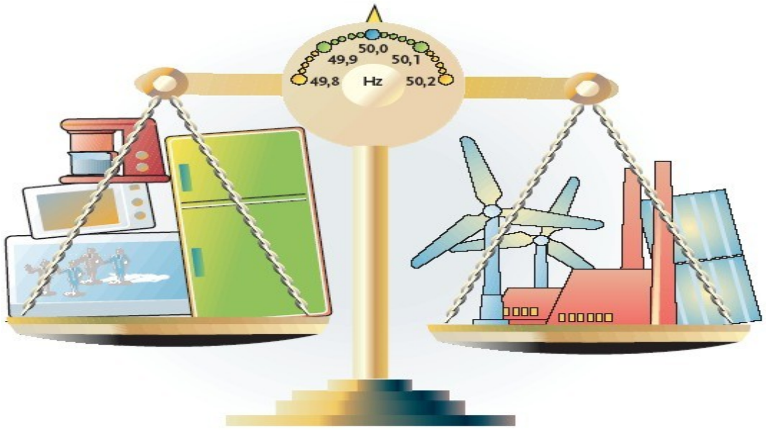
stochastic control theory allows for taking into account different sources of uncertainty (wind, ...)

↓

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

Use of AI and Energy Systems Integration

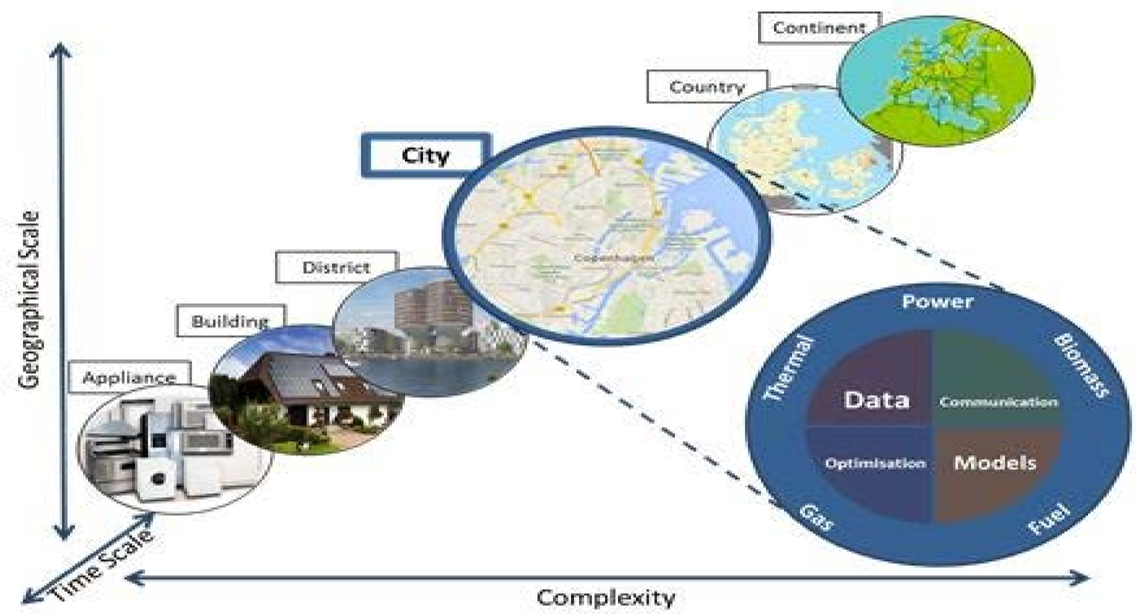




The **central hypothesis** is that by **intelligently integrating** currently distinct **energy** (heat, power, gas and biomass) and **water** components using **AI and ICT solutions** we can **balance** very large shares of renewables - and consequently obtain substantial reductions in CO2 emissions.

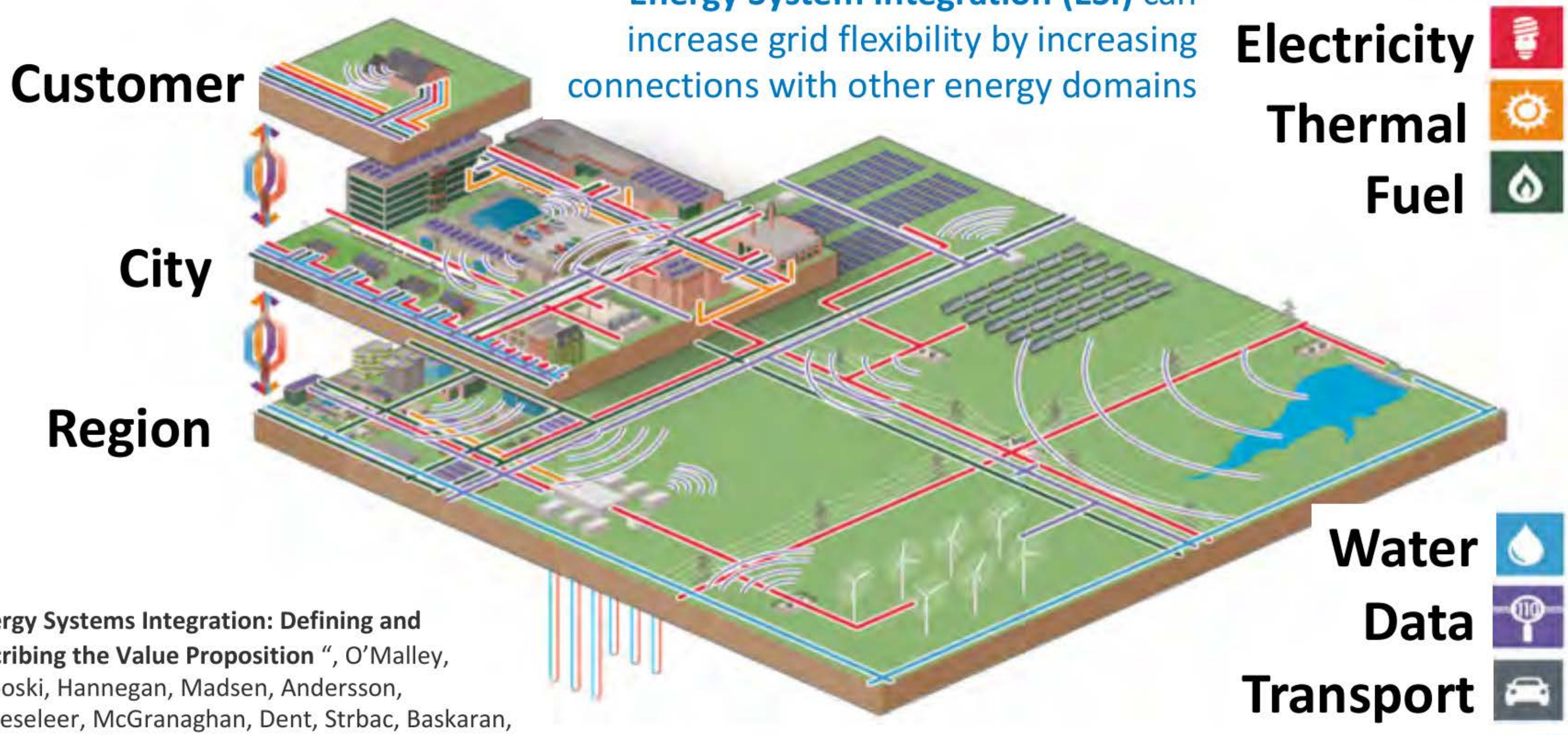
Temporal and Spatial Scales

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**.



Energy Systems Integration

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

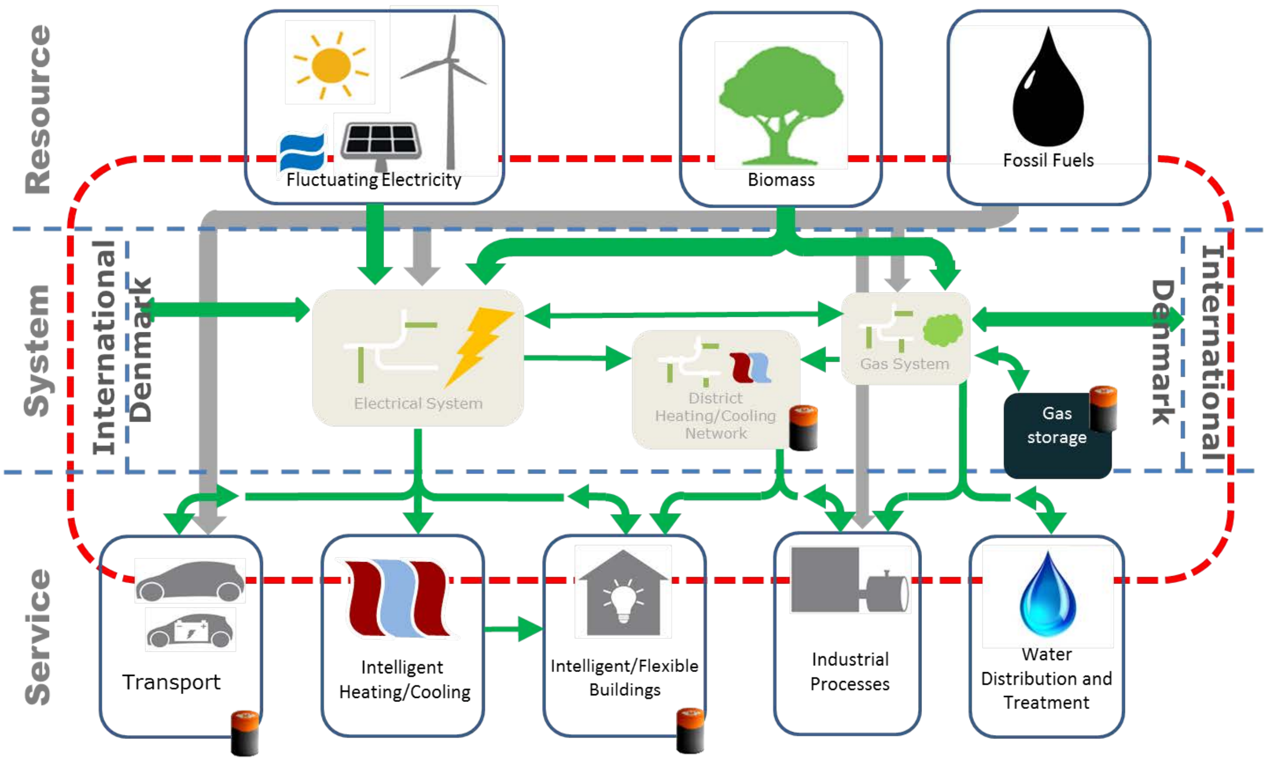


"Energy Systems Integration: Defining and Describing the Value Proposition ", O'Malley, Kroposki, Hannegan, Madsen, Andersson, D'haeseleer, McGranaghan, Dent, Strbac, Baskaran, Rinker., NREL/TP-5D00-66616. June 2016

NREL | 17

Energy System Models
for Real Time Applications and Data Assimilation

- **Grey-box models are simplified models for the individual components facilitating system integration and use of sensor data**



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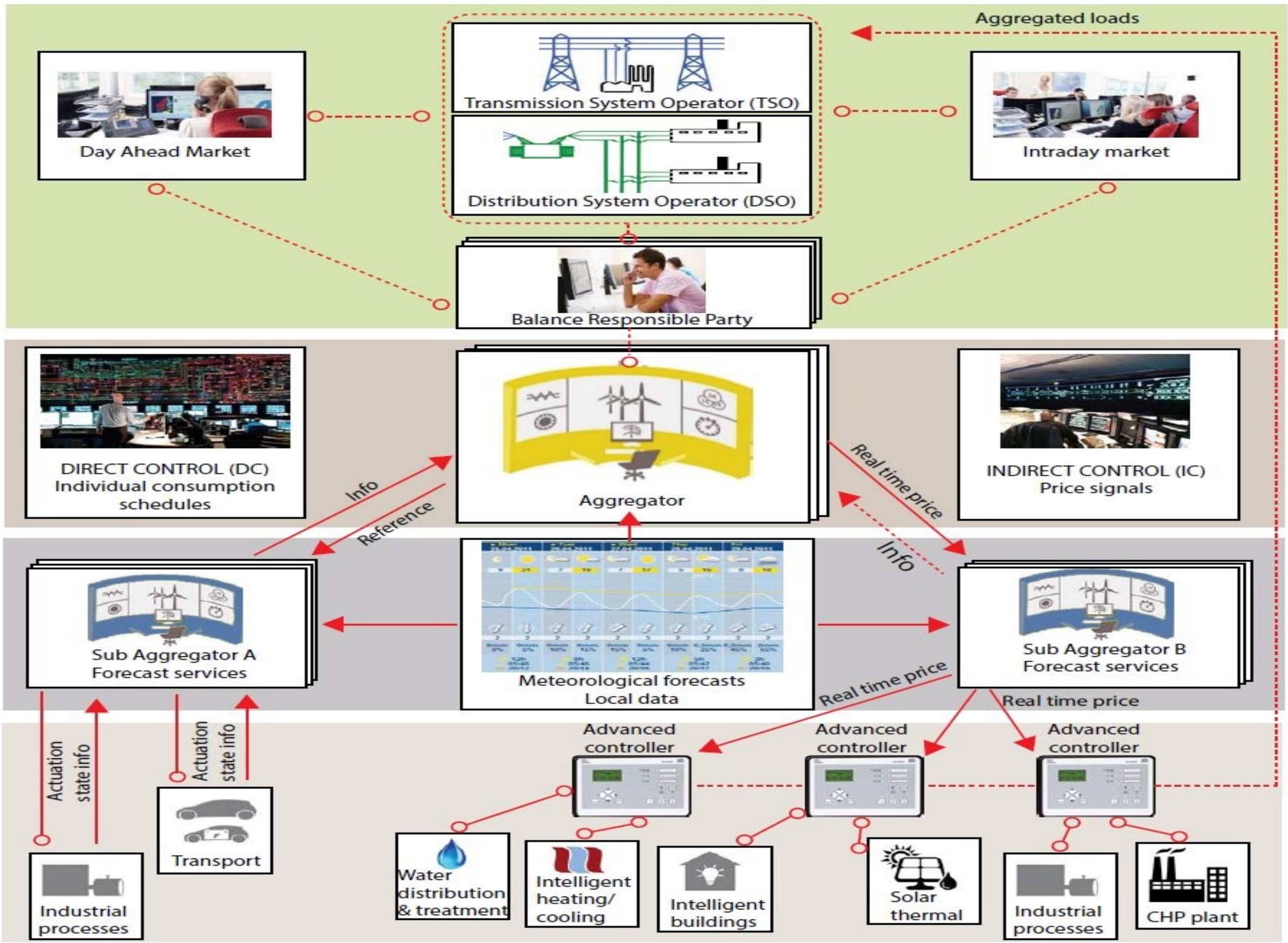
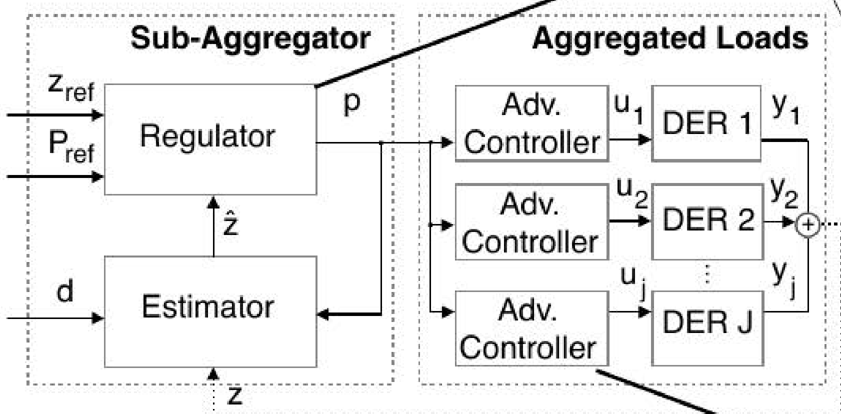
Smart-Energy OS



Proposed methodology
Control-based methodology

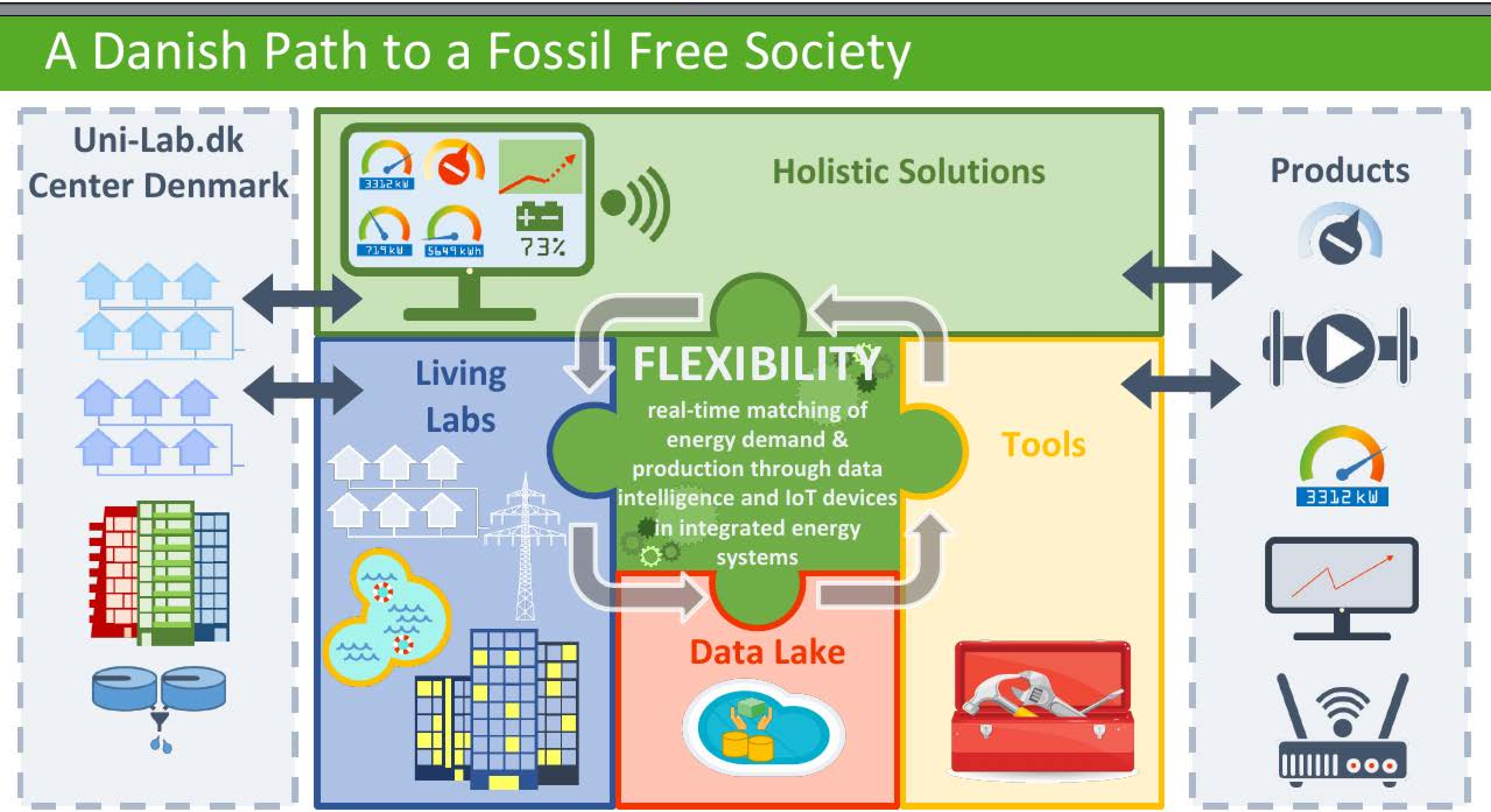
$$\min_{p} \quad \mathrm{E}\Big[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||\Big]$$
$$\text{s.t.} \quad \hat{z}_{k+1} = f(p_k)$$



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

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

Flexibility enabled using AI



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, Fog, Edge based (IoT, IoS) 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 problems
- Harvest flexibility at all levels -> max. Virtual storage

Innovation Fund Denmark

DTU

Case study (Level III)

Price-based Control of Power Consumption (Peak Shaving)

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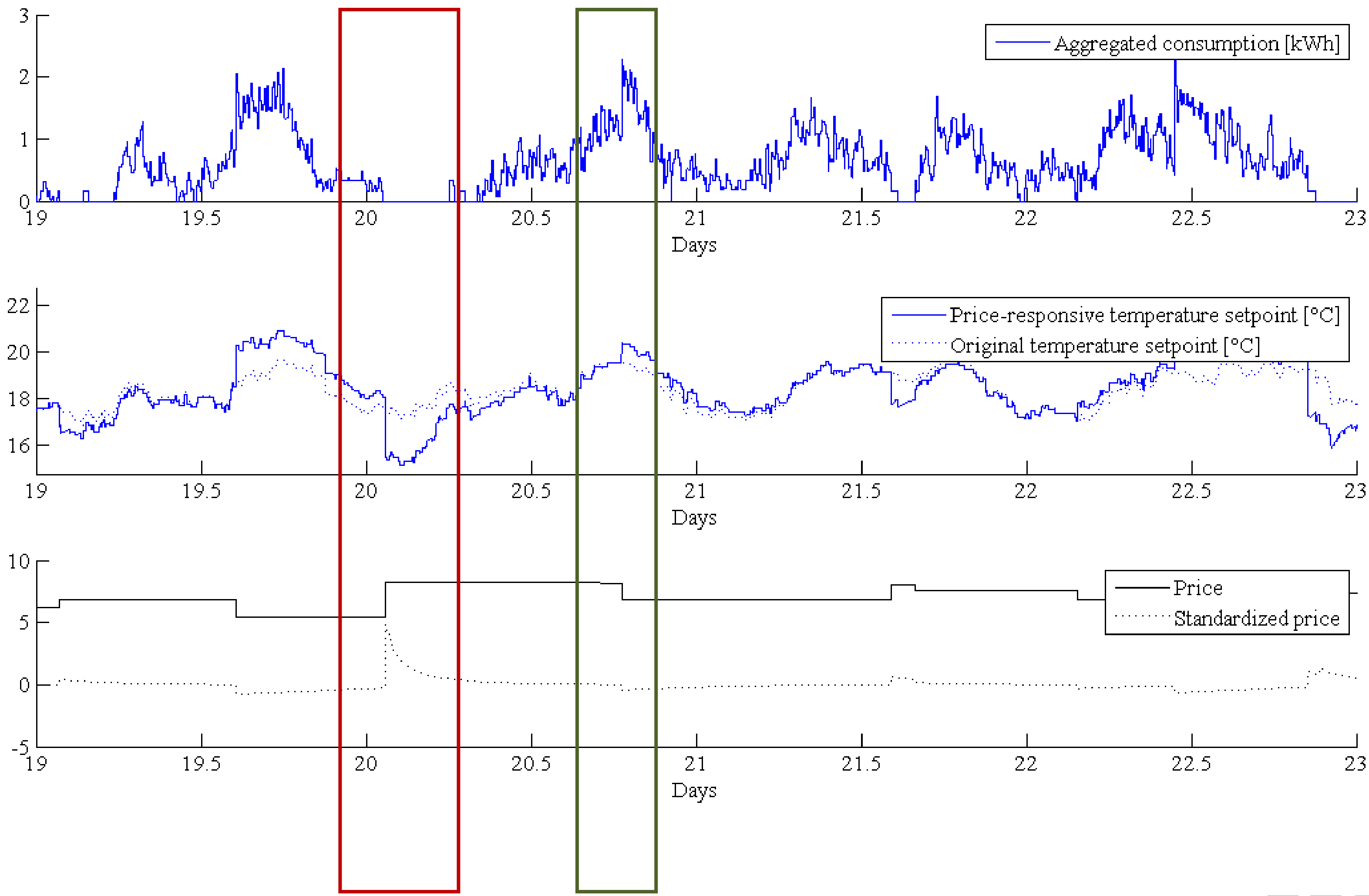
Aggregation (over 20 houses)



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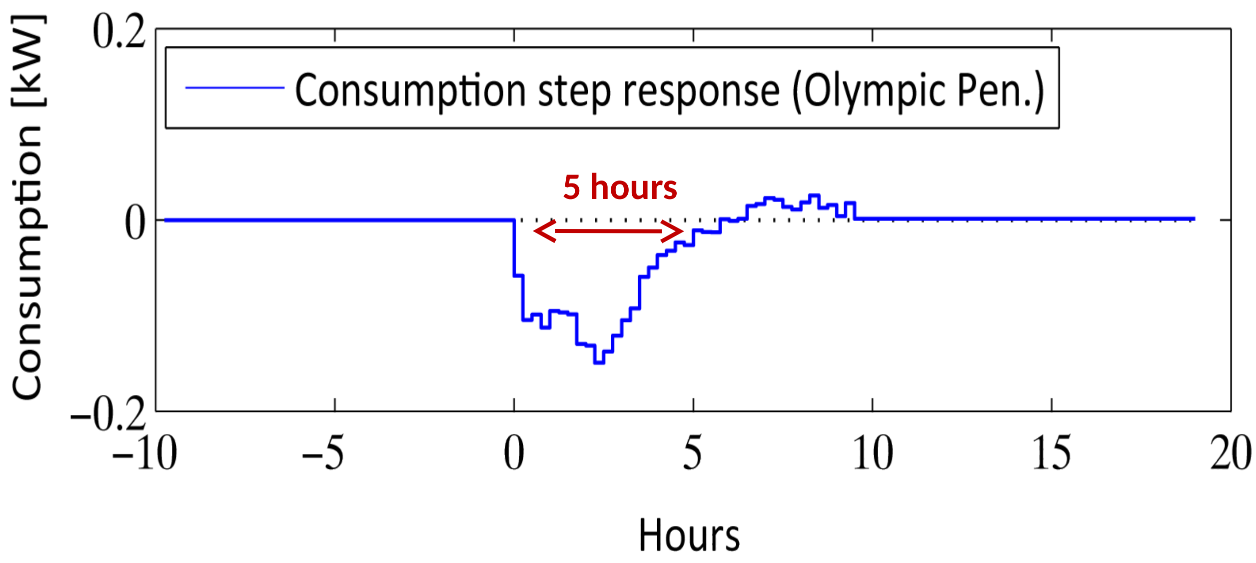
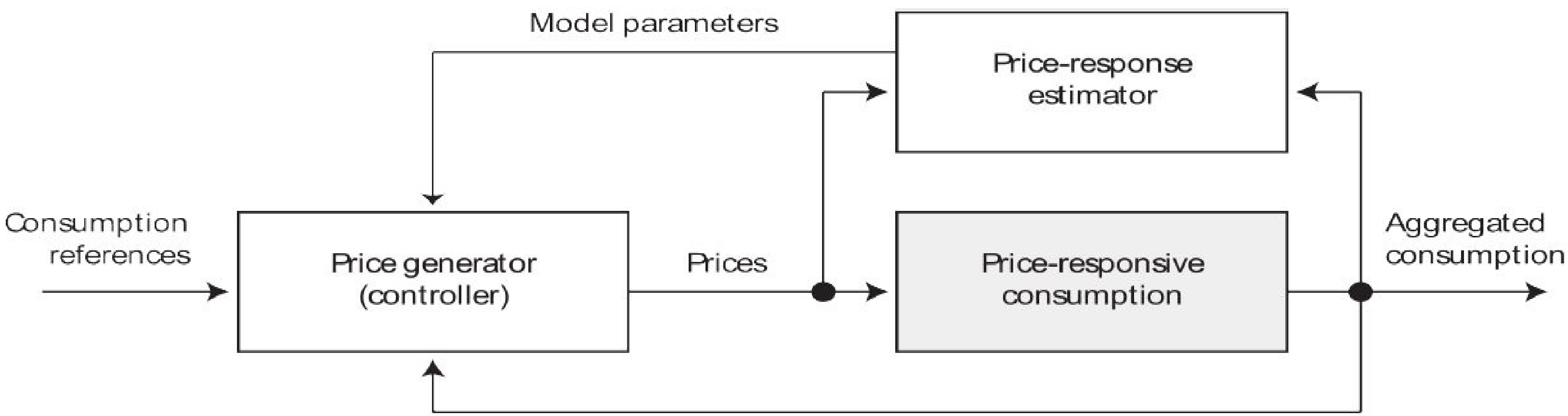
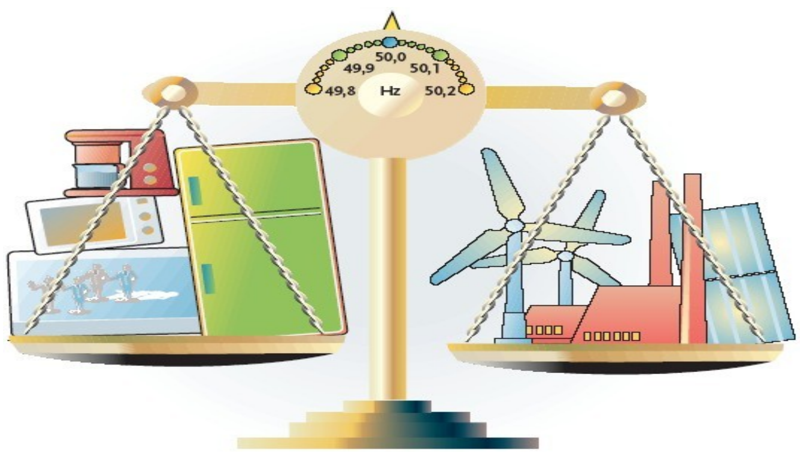
Response on
Price Step Change



Control of Power Consumption





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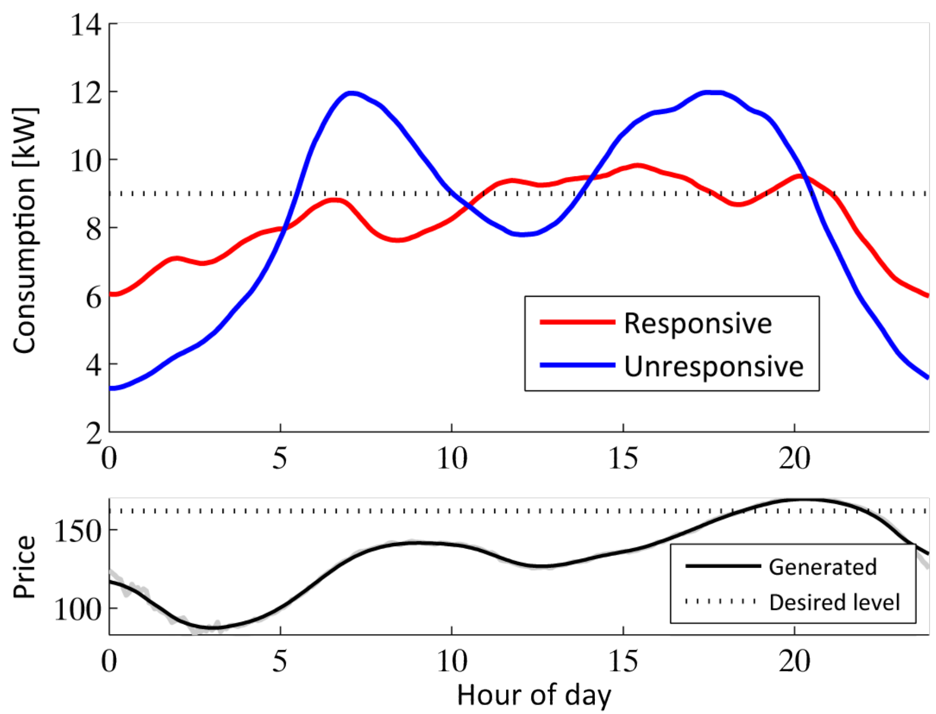
Control performance

Considerable **reduction in peak consumption**



Flexibility Function

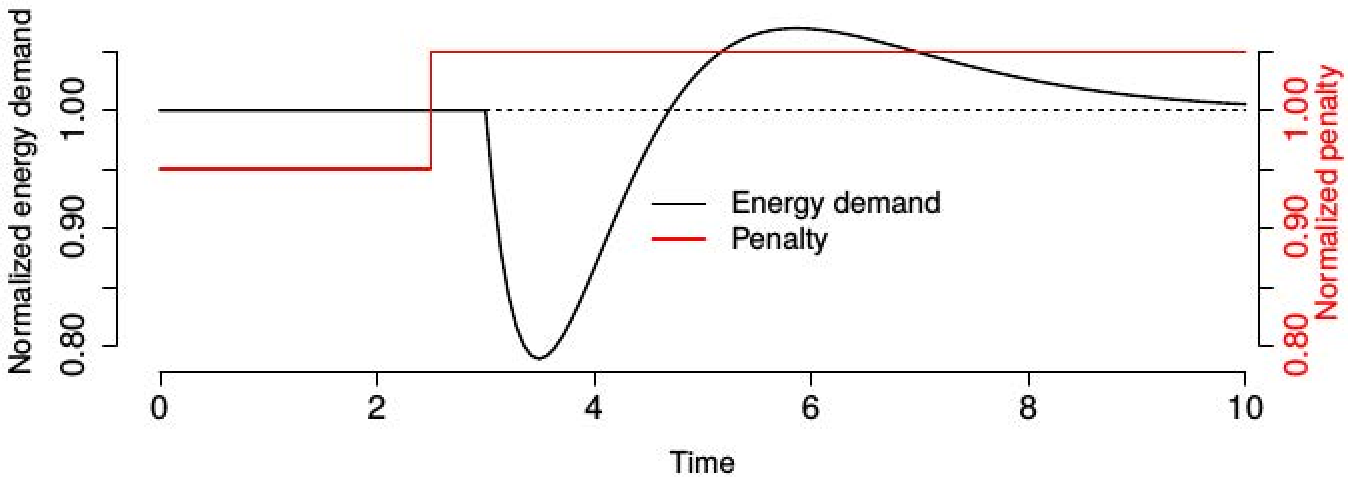
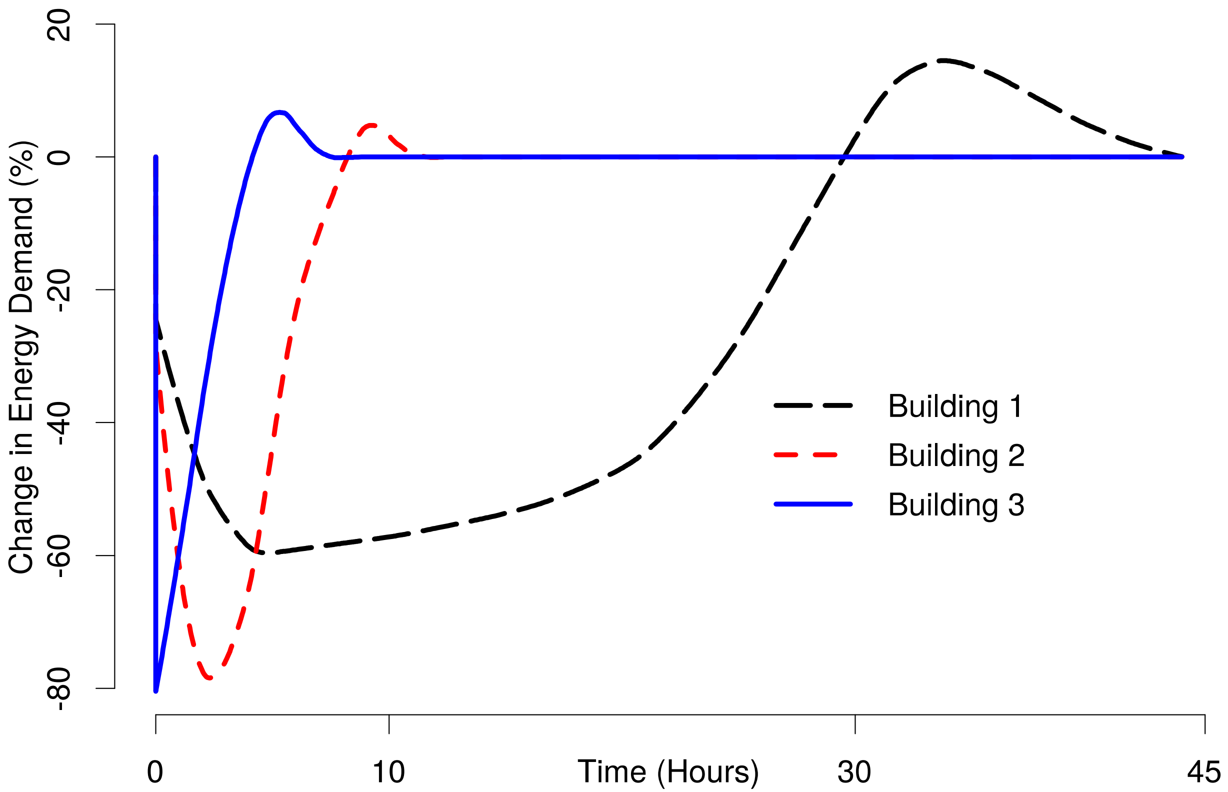
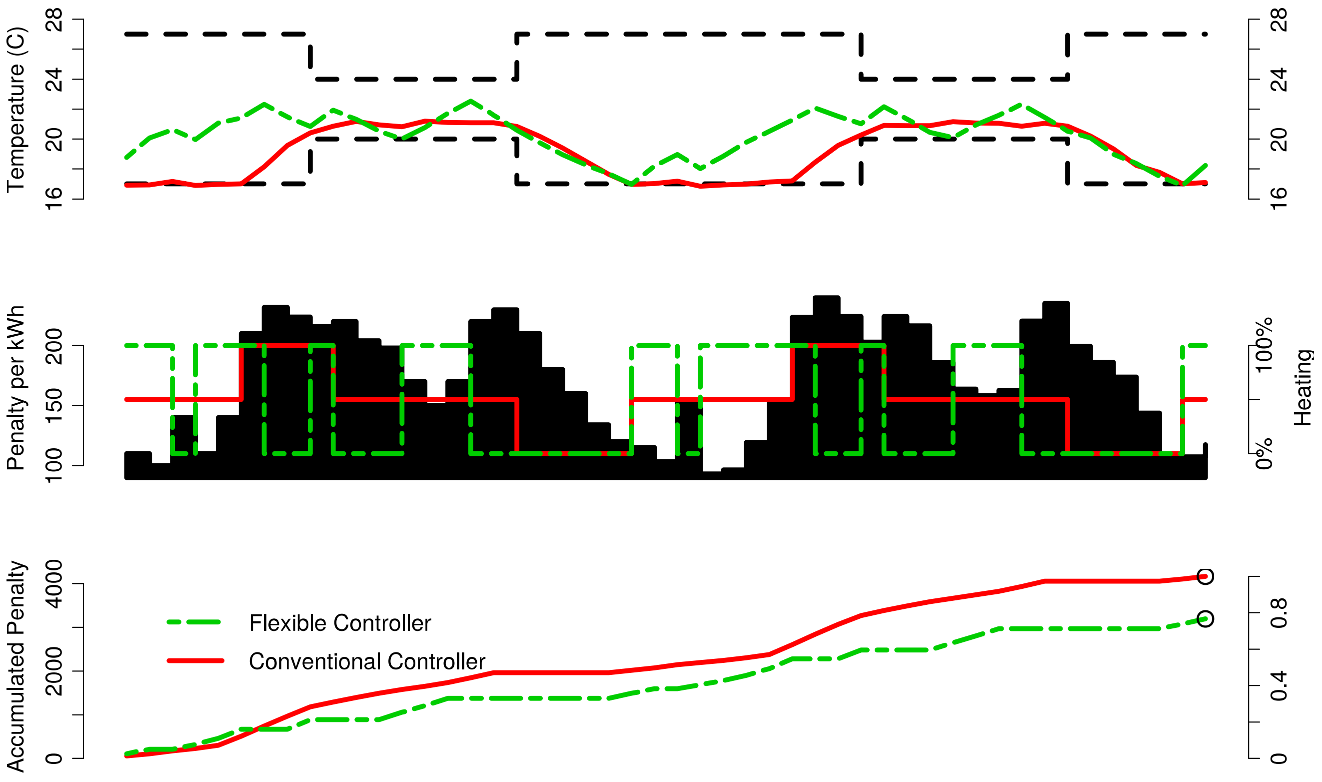


Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

Examples of Flexibility Functions



Penalty based setup



Penalty Function (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*.

Smart Grid Applications

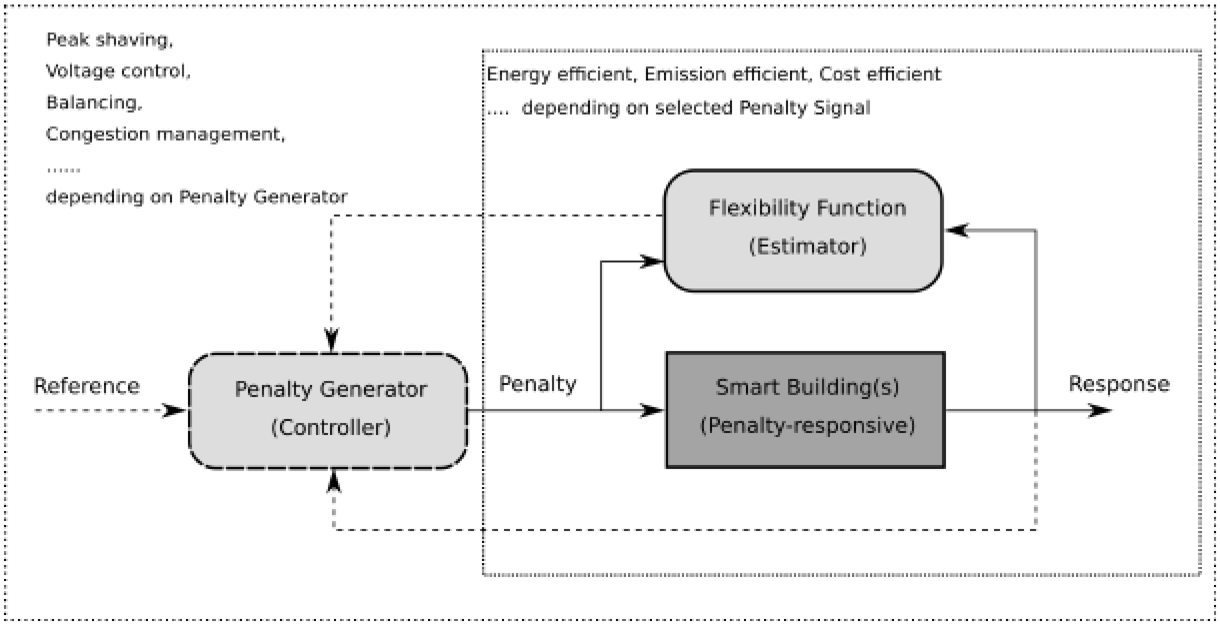
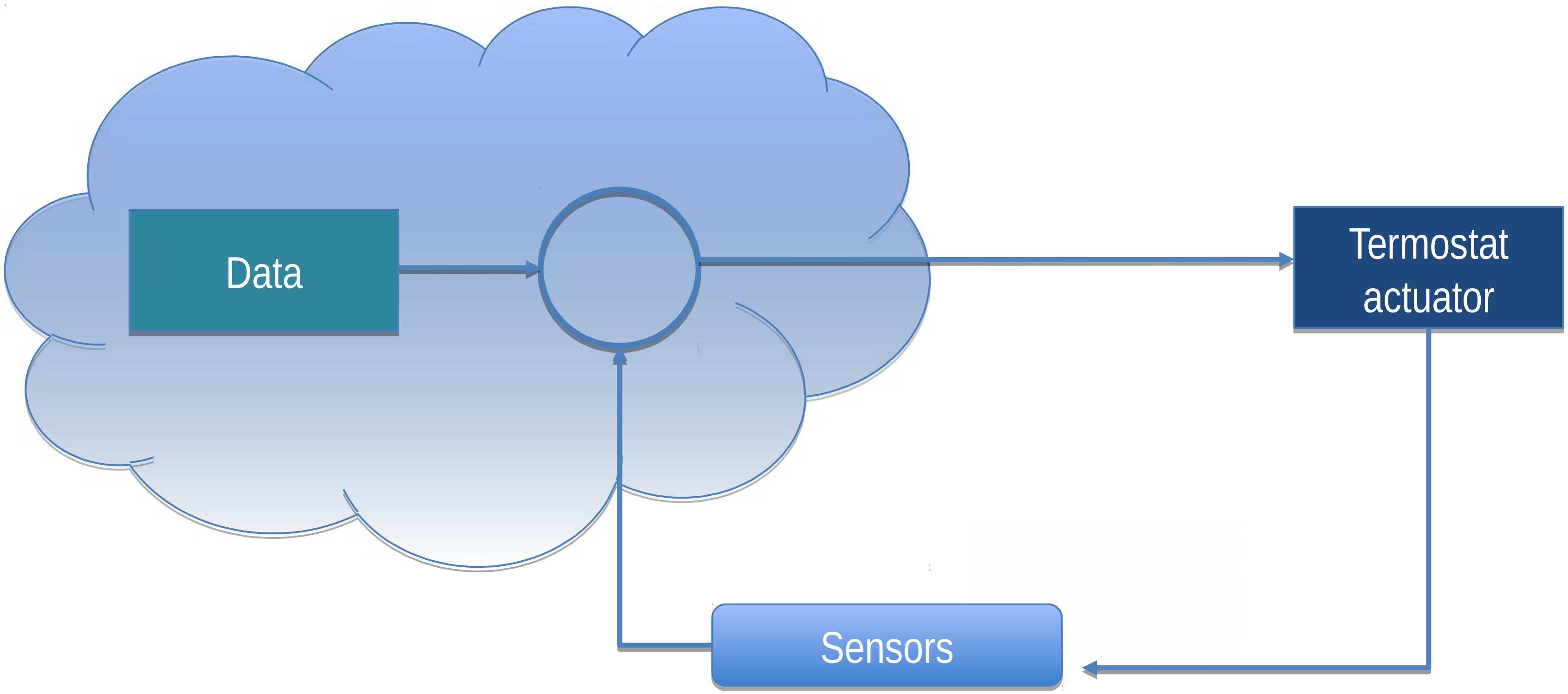


Figure 8: Smart buildings and penalty signals.

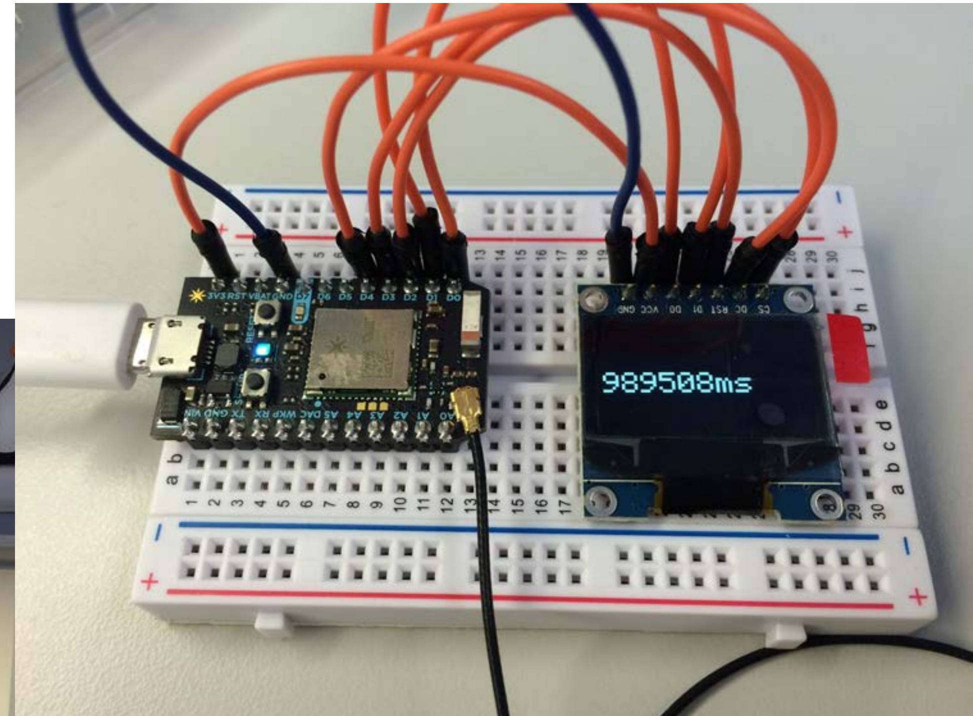
Case study
(Level IV – Indirect Control)

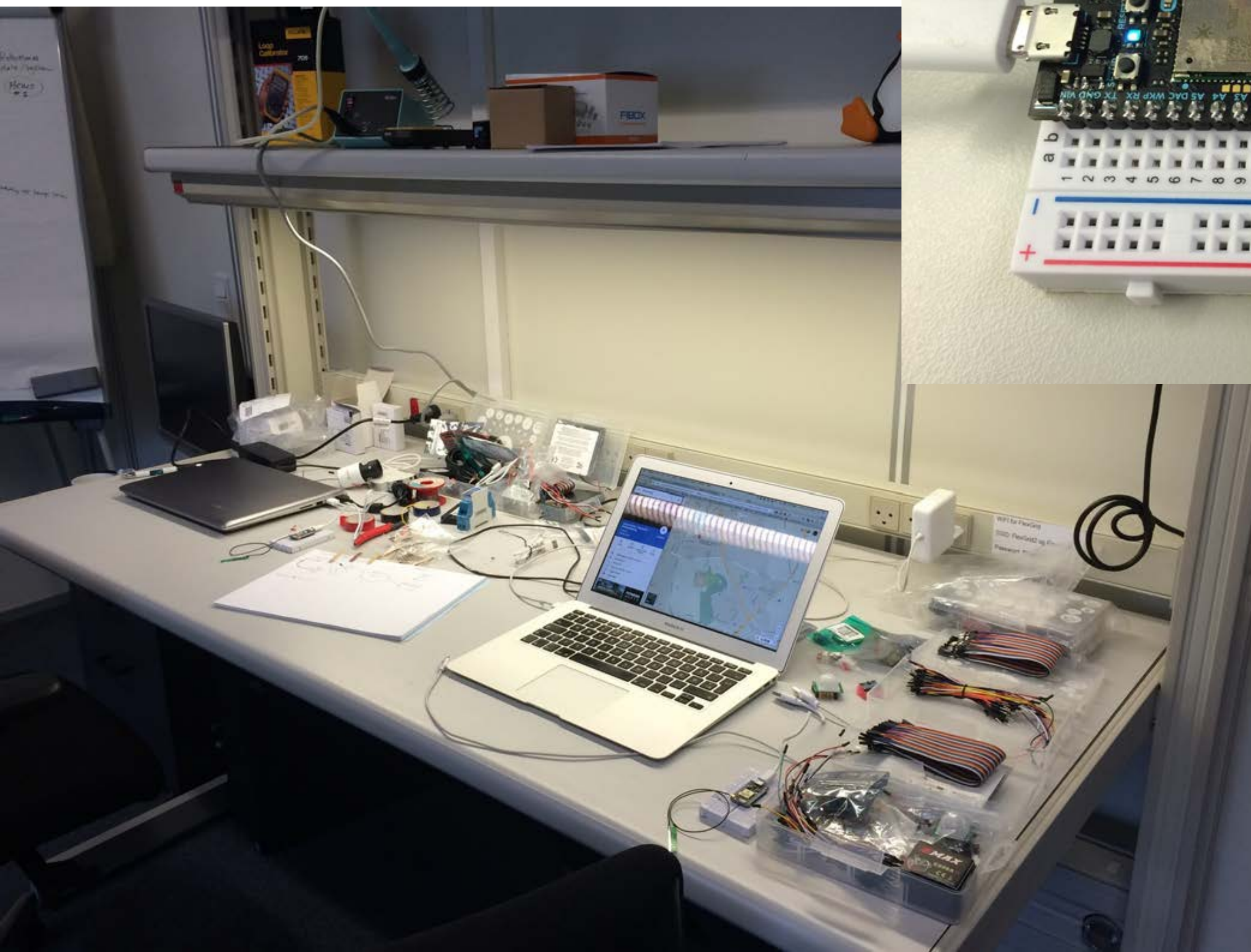
Control of HVAC Systems
(based on varying prices from Level III)

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

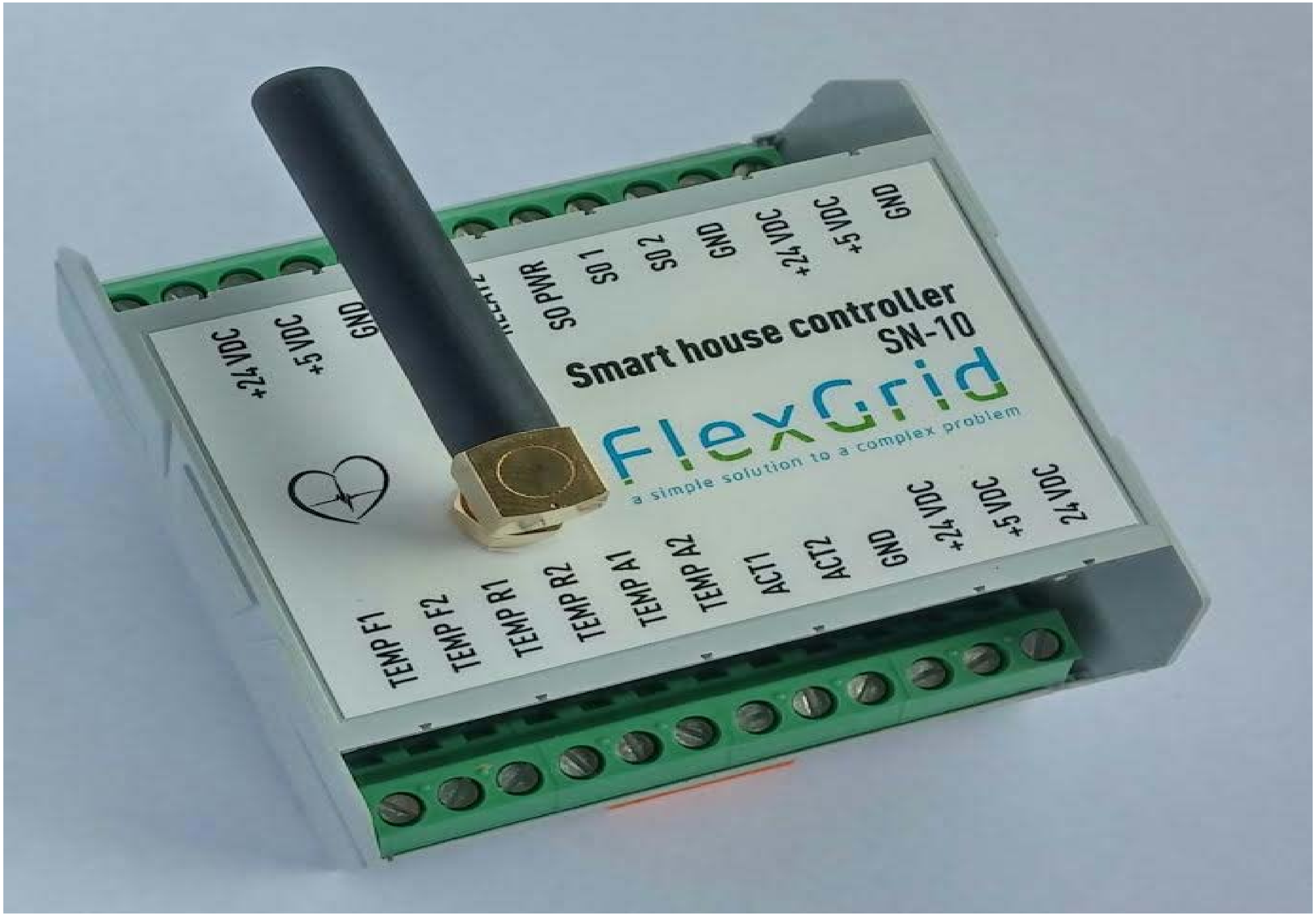


Lab testing ….





SN-10 Smart House Prototype



Case study

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

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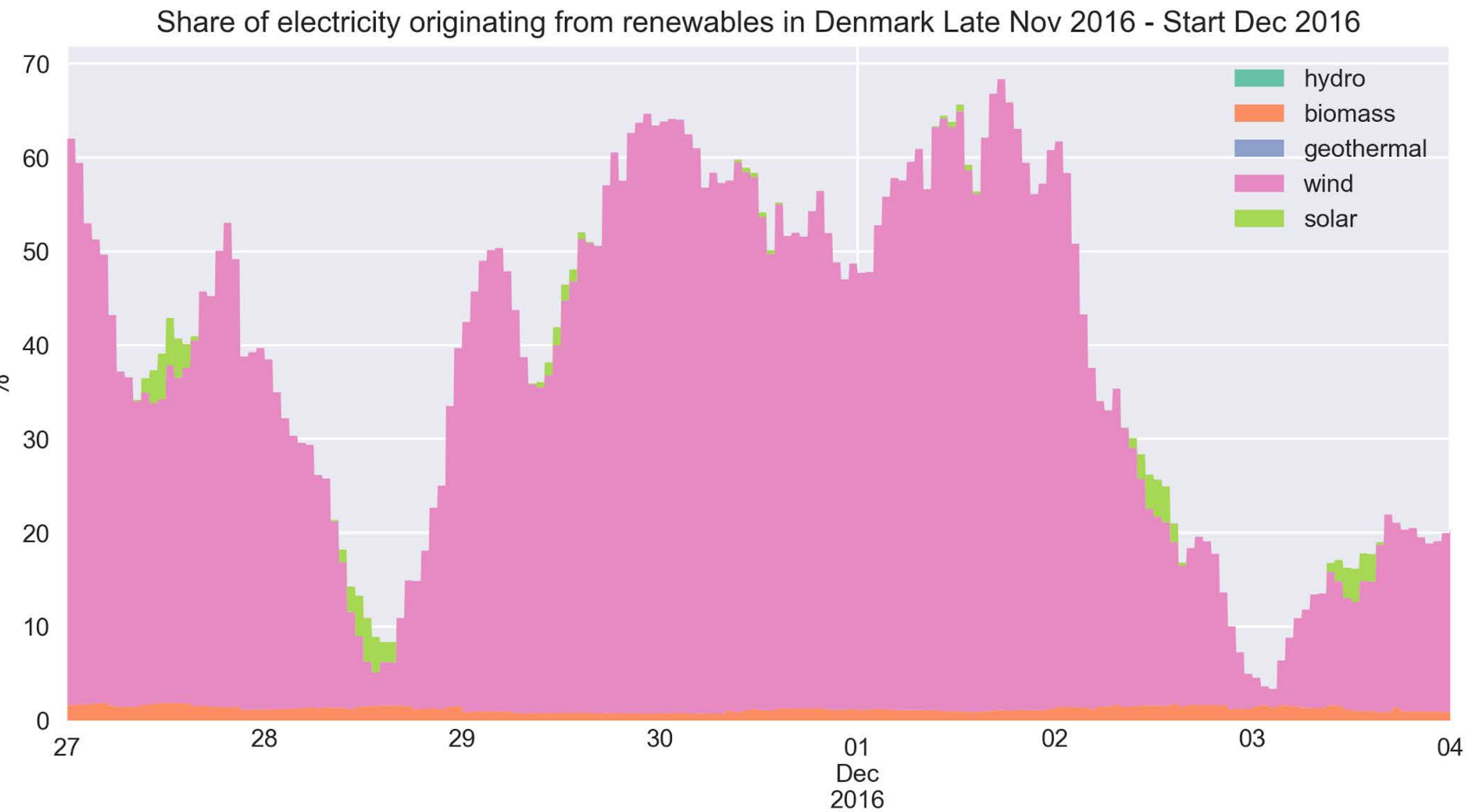

Source: pro.electicitymap.

Live CO2 emissions of the European electricity consumption

This shows in real-time where your electricity comes from and how much CO2 was emitted to produce it.

We take into account electricity imports and exports between countries.

Tip: Click on a country to start exploring ⟶

Wind power potential (m/s)

0 2 4 6 8 10 12 14

Solar power potential (W/m²)

0 50 100 150 200 250 300 350 400

Like the visualization? We would love to hear your feedback!
Found bugs or have ideas? Report them here.
This project is Open Source: contribute on GitHub.
All data sources and model explanations can be found here.

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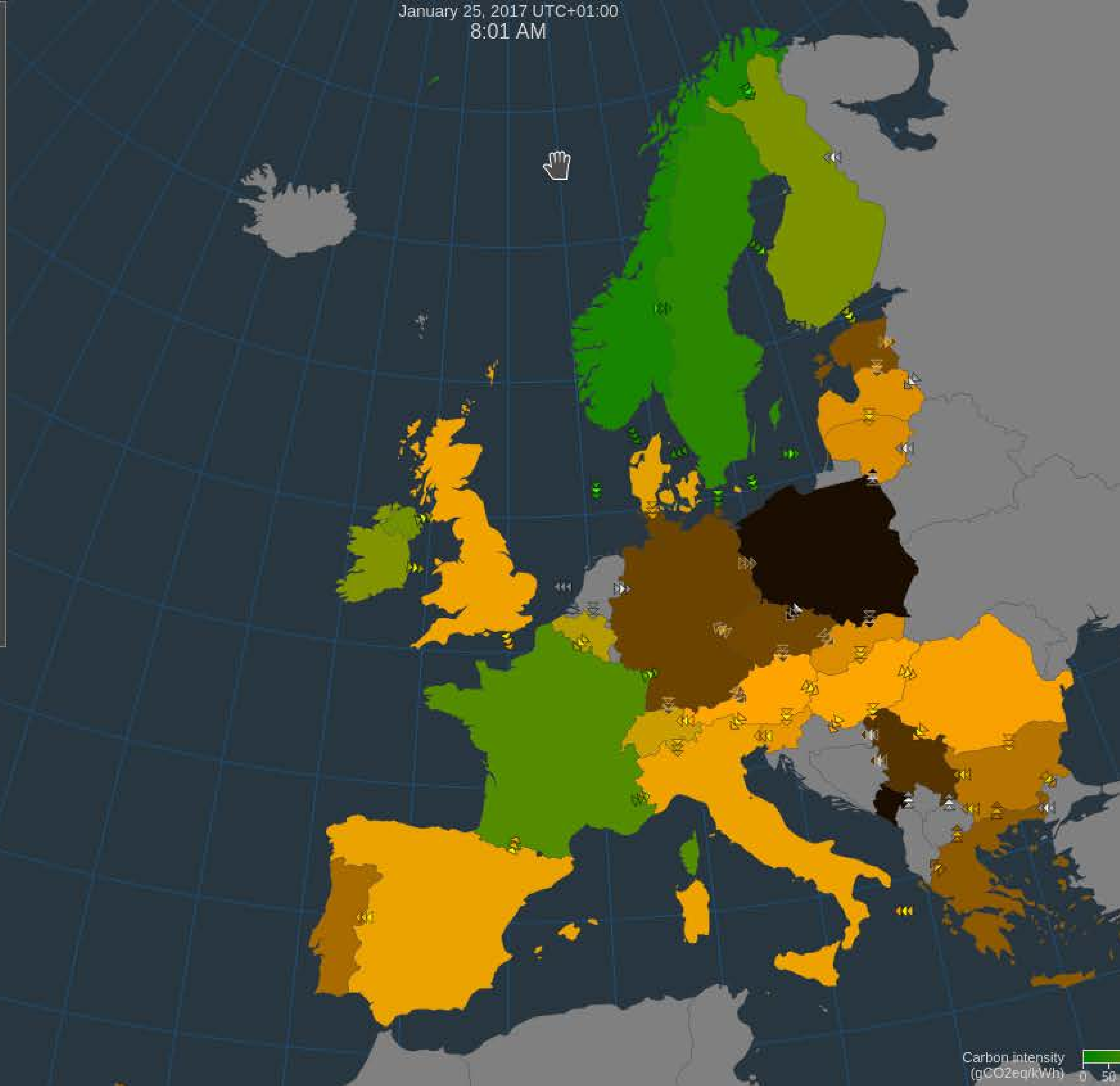
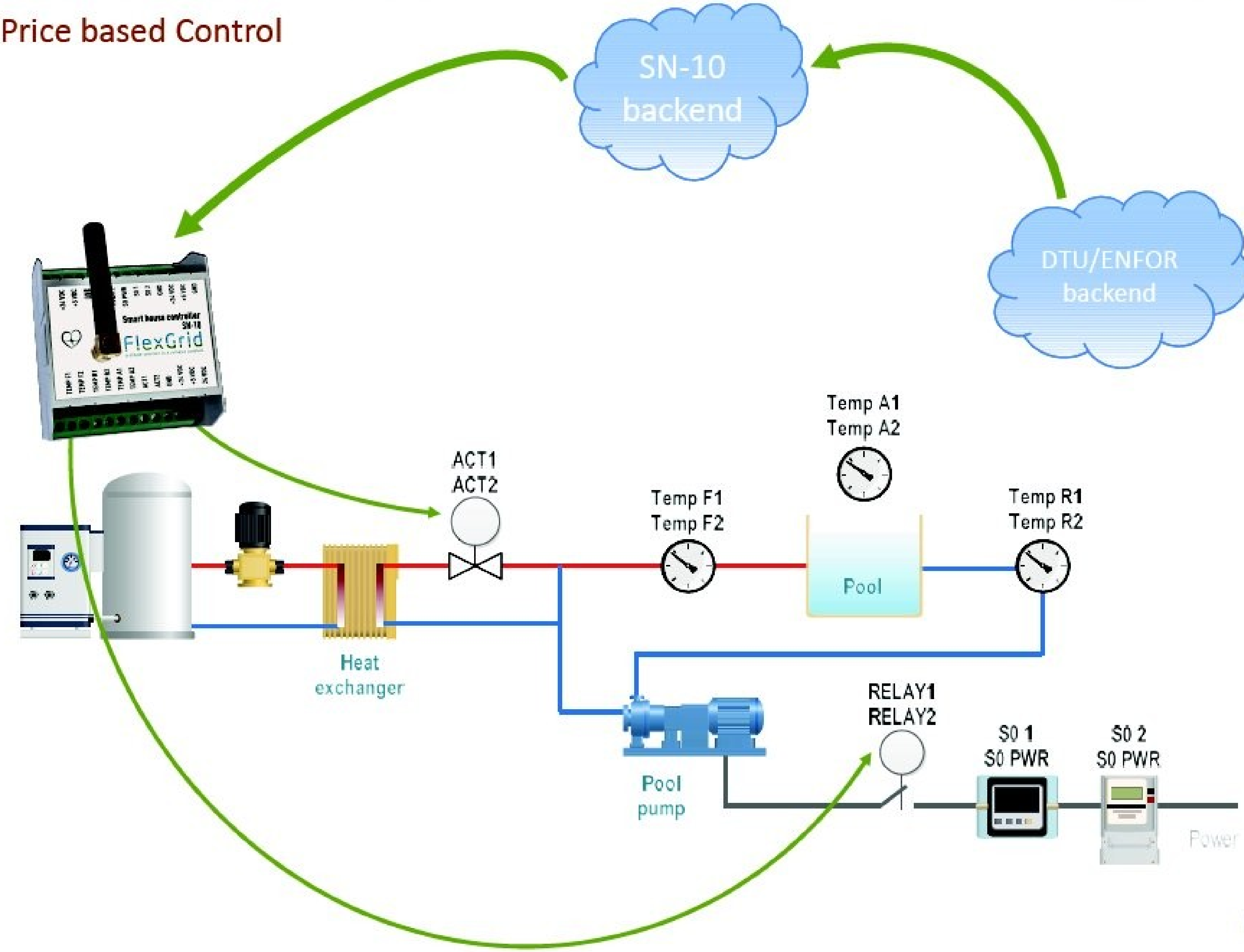


How does it work?

Price based Control

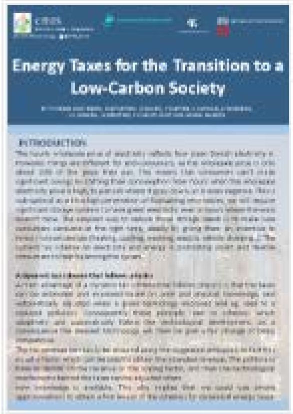


Example: Price-based control

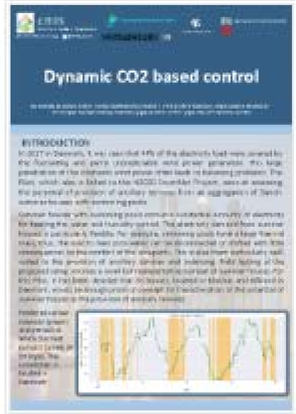
Example: CO2-based control (10-15 pct savings in CO2 e.)

CITIES Solutions

CITIES Solutions Brochures

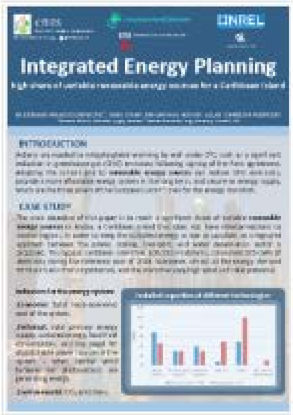


Energy taxes for the transition to a low-carbon society



Dynamic CO2 based control

Stability of electricity smart meter clusters

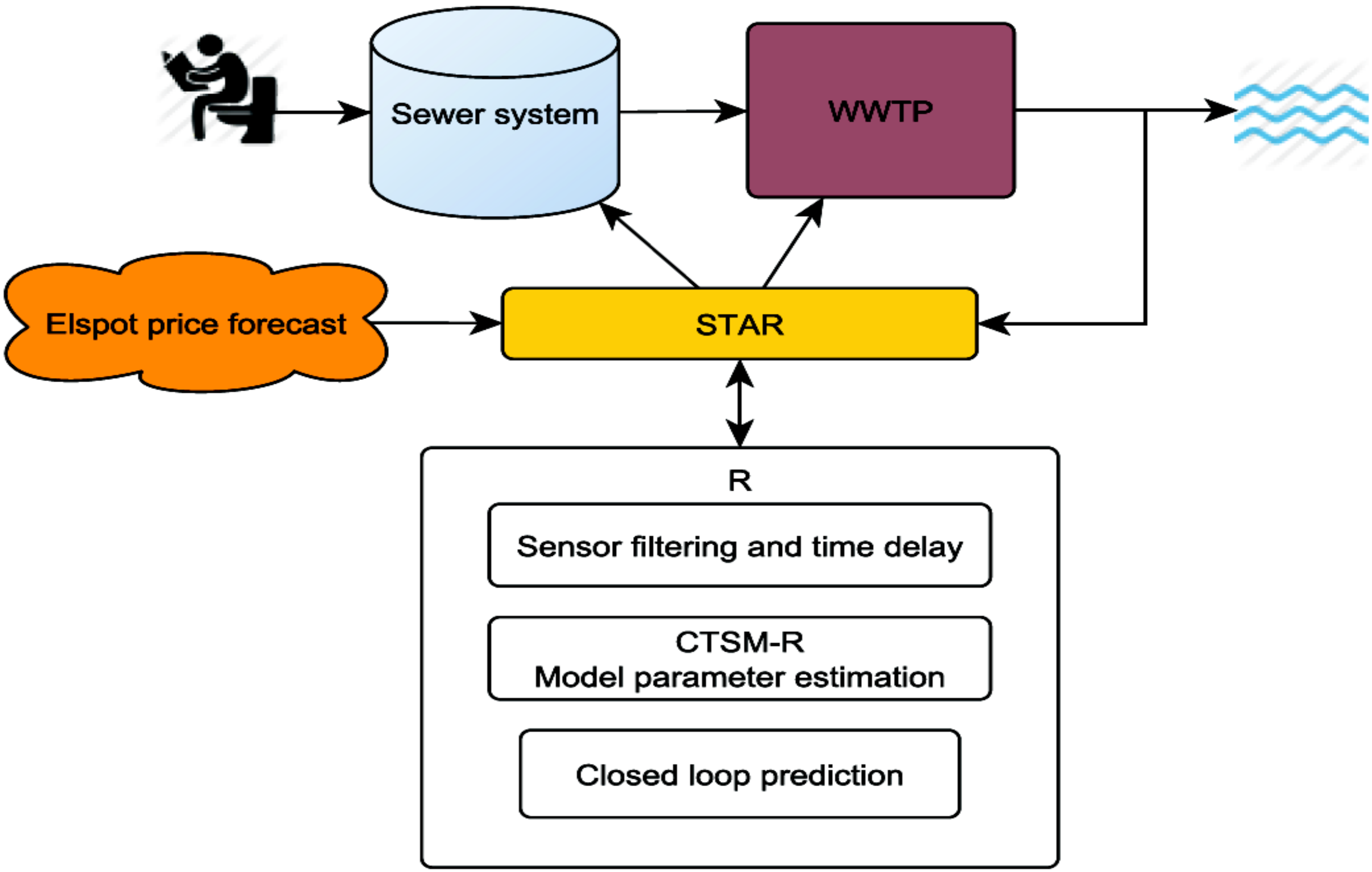


Integrated energy planning for a carribean island

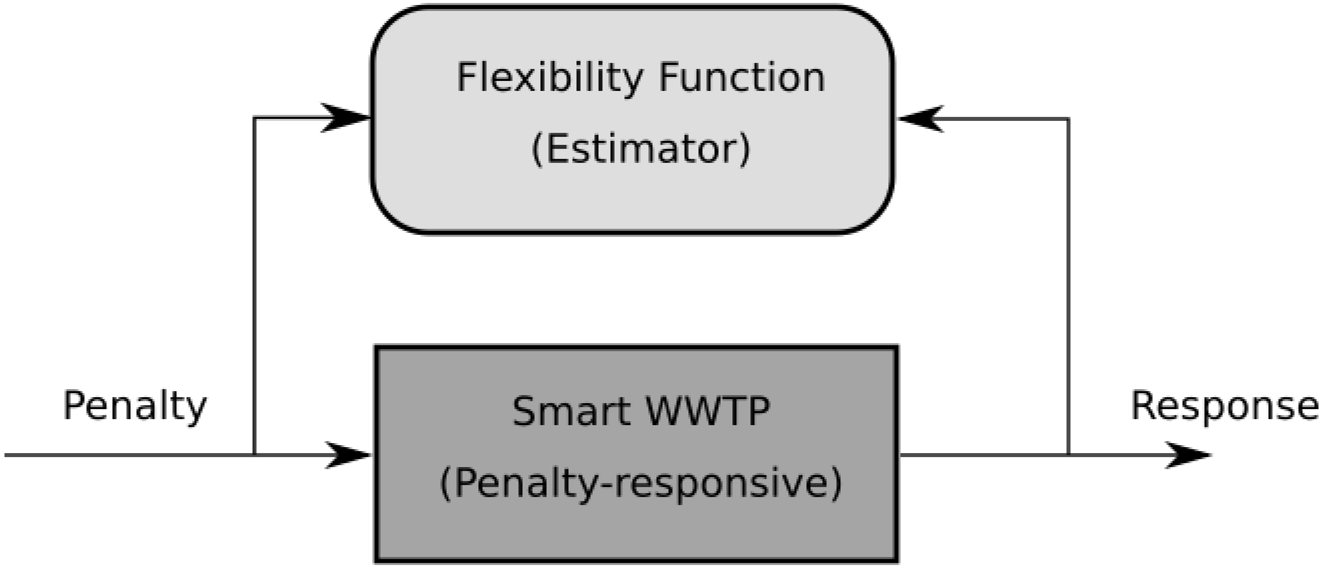
Potential of district cooling

Clustering based analysis of residential district heating data

Energy Flexibility in Wastewater Treatment



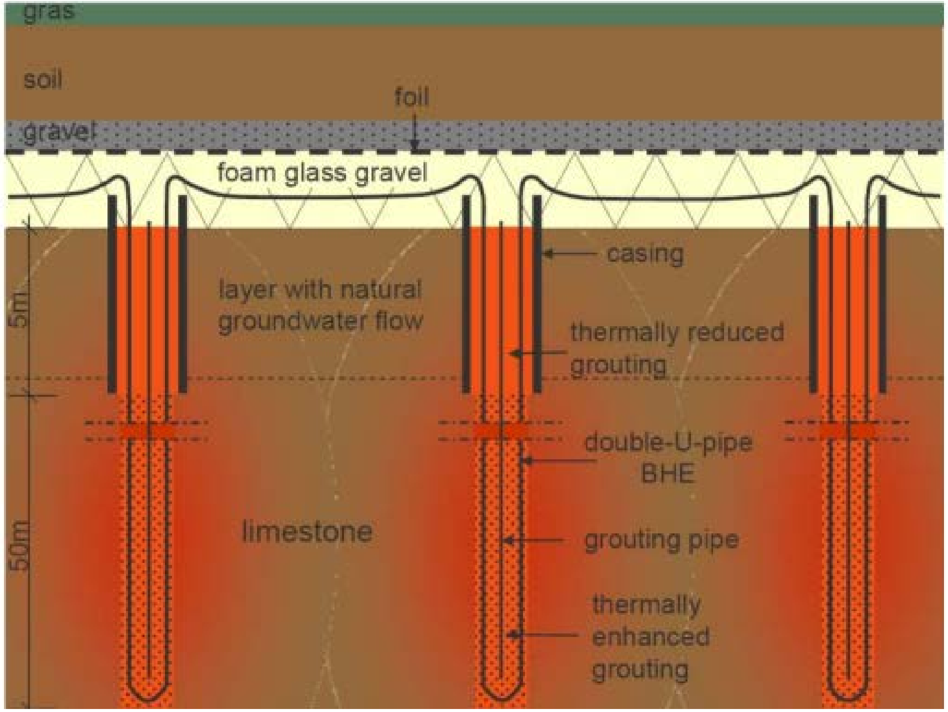
Flexibility Function



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

Water pit

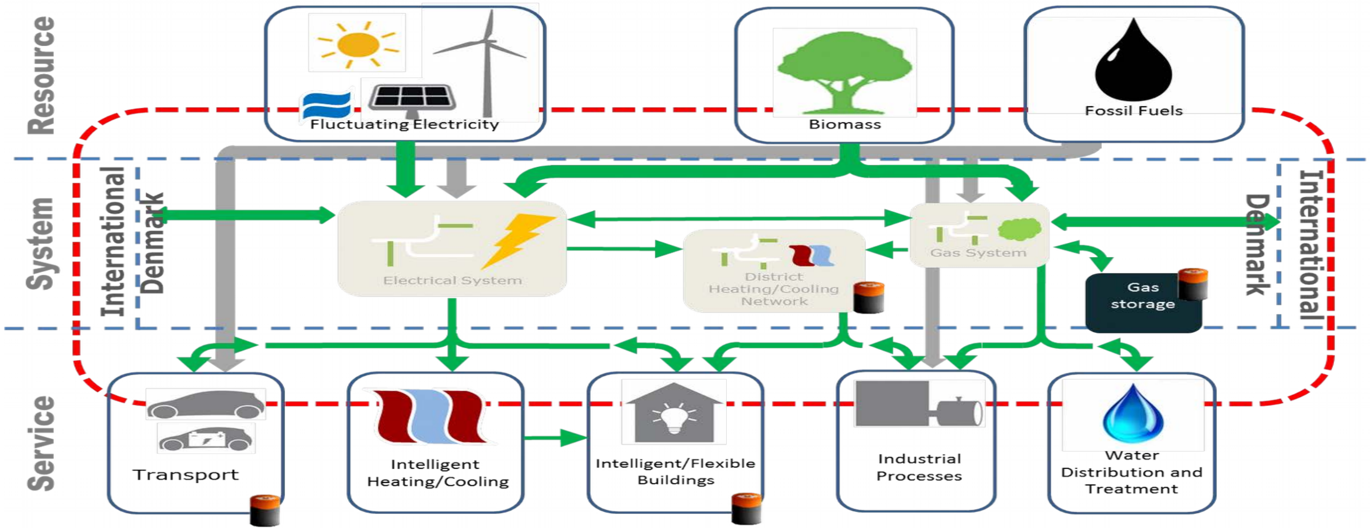
Borehole storage



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		

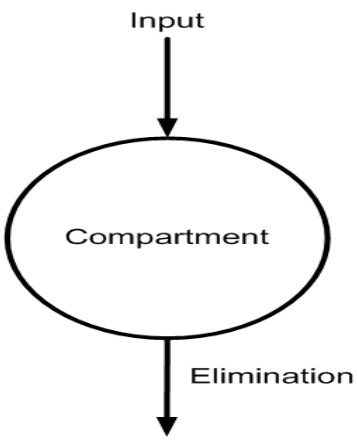
(Virtual) Storage Solutions



- **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

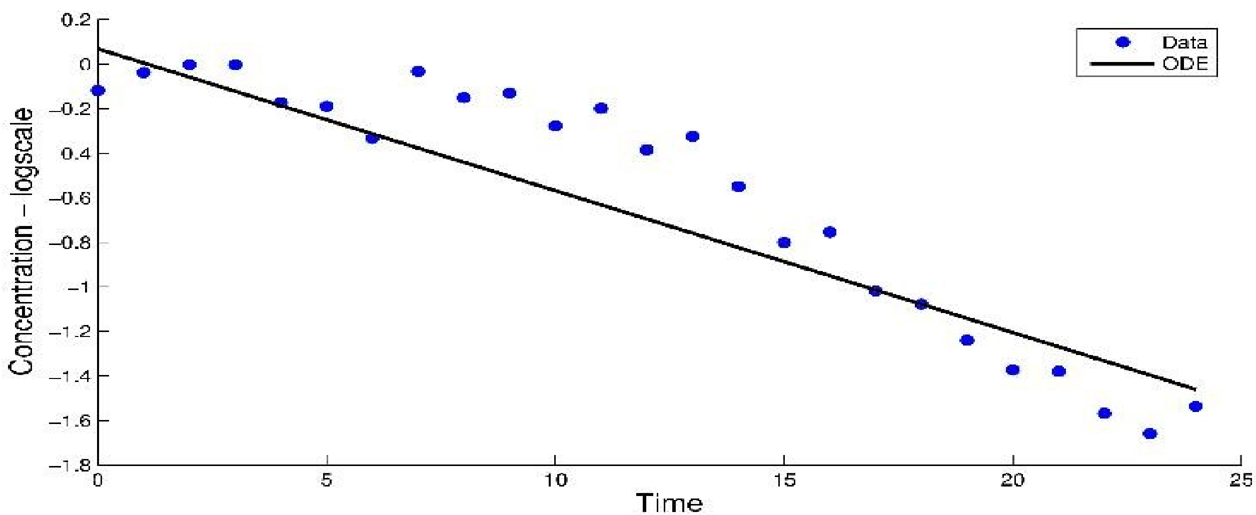
Grey-box Modeling

Traditional Dynamical Model

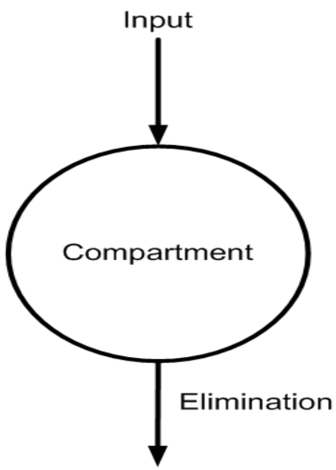


- Ordinary Differential Equation:

$$
\begin{aligned}
dA &= -KAdt \\
Y &= A + \epsilon
\end{aligned}
$$

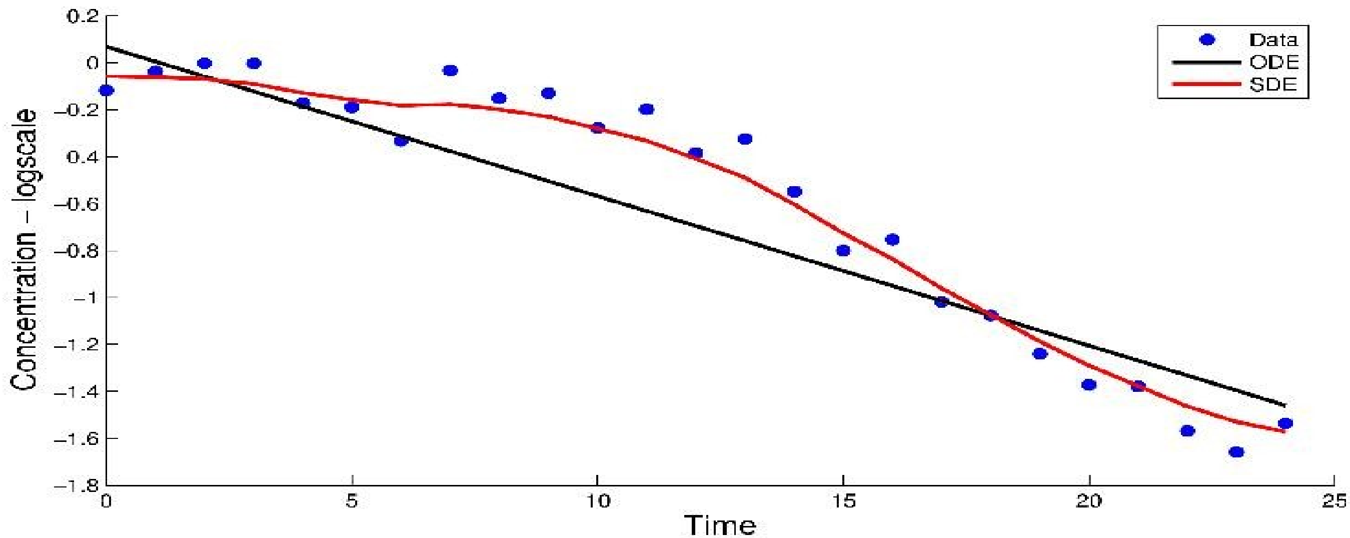


Stochastic Dynamical Model



- Stochastic Differential Equation:

$$dA = -KAdt + \sigma dw$$
$$Y = A + e$$



The Grey-Box model

Drift term

Diffusion term

$$dX_t = f(X_t, u_t, t, \theta)dt + \sigma(X_t, u_t, t, \theta)d\omega_t$$

System equation

$$Y_k = h(X_k, u_k, t_k, \theta) + e_k,$$

Observation equation

Observation noise

Notation:

X_t: State variables

u_t: Input variables

θ: Parameters

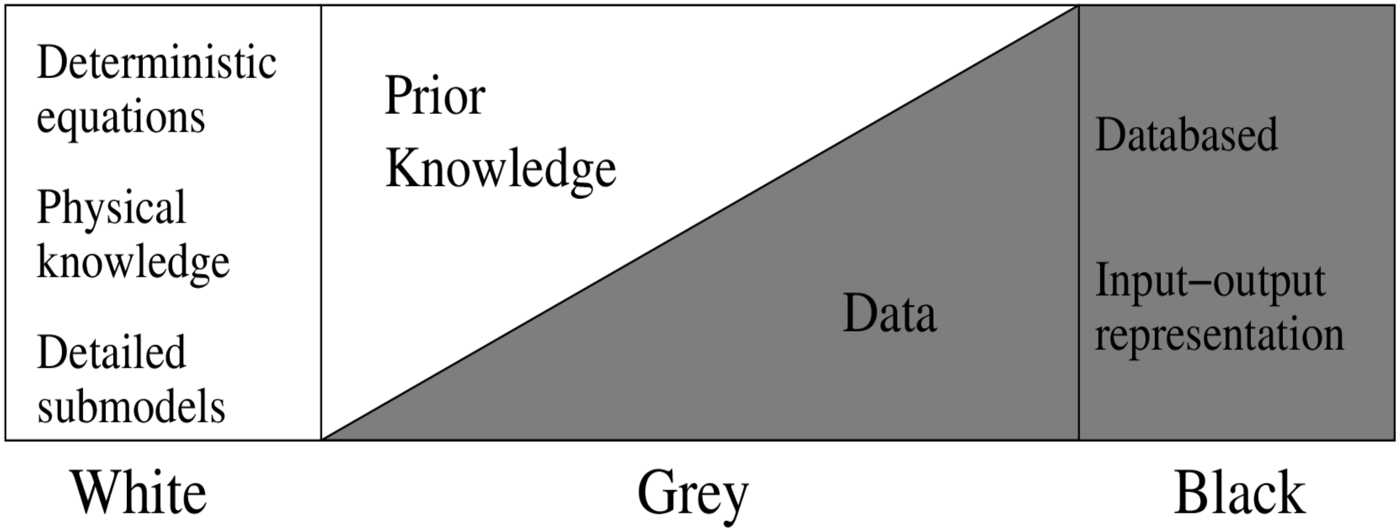
Y_k: Output variables

t: Time

ω_t: Standard Wiener process

e_k: White noise process with $N(0, S)$

Grey-Box modeling concept



- **Combines prior physical knowledge with information in data**
- **Equations and parameters are physically interpretable**

Grey-Box models are well suited for:

- One-step forecasts
- K-step forecasts
- Simulations
- Control
- … of both *observed* and *hidden* states.

- Provides a **framework for pinpointing model deficiencies –** like:
  - Time-tracking of unexplained variations in e.g. parameters
  - Missing (differential) equations
  - Missing functional relations
  - Lack of proper description of the uncertainty

Innovation Fund Denmark

DTU

Grey-Box Modeling

- **Bridges the gap between physical and statistical modeling**
- Provides methods for **model identification**
- Provides methods for **model validation**
- Provides methods for **pinpointing model deficiencies**
- Enables methods for a reliable description of the uncertainties, which implies that the same model can be used for k-step forecasting, simulation and control

Center Denmark

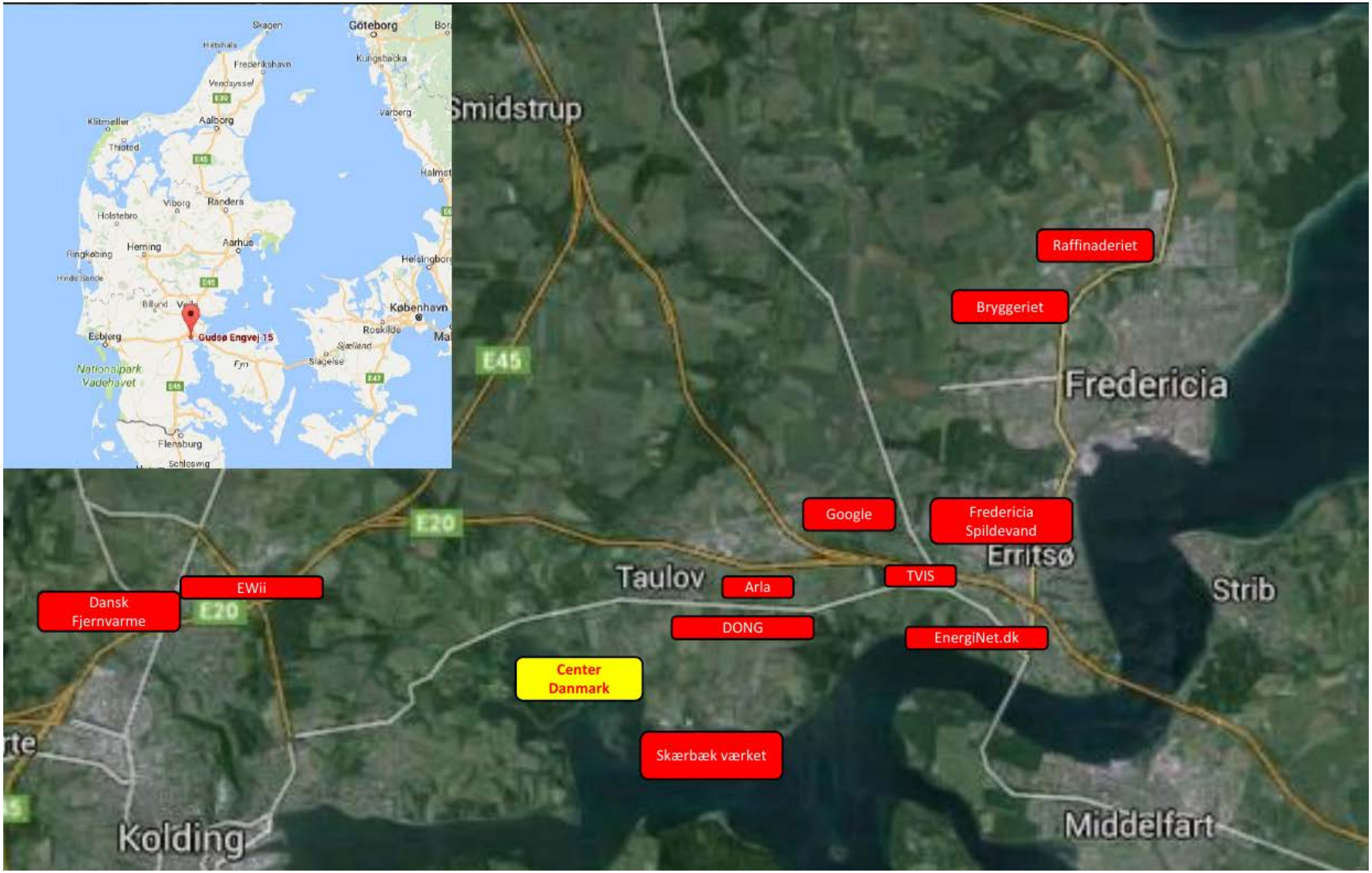
Green transition paved by green innovation


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.

Digitalization Hub - Center Denmark

- A digitalization hub for data intelligent operation of integrated energy systems (electricity, thermal, gas, water)
- A national hub for unlocking the flexibility potential for large scale integration of fluctuating renewable energy
- Tests on framework conditions have to be representative – and scaling is important
- The new national smart energy hub is Center Denmark (10.000 m2 facilities for Research, Education, Development and Testing - plus Dissemination)
- The Societal objective is to establish a realistic and concrete pathway to a fossil-free society
- The Scientific objective is to establish methodologies and solutions for the future intelligent and integrated energy system using digitalization and a smart energy hub
- The Commercial perspective is to being able to idenfy and test solutions which can form the background for commercial success stories. We believe that this setup has the unique characteristics for being the ultimate smart energy hub for test and demonstration of future smart energy solutions

Center Danmark
Test Center for Intelligent and Integrated Energy Systems



Centre for IT Intelligent Energy Systems

FLEXIBLE ENERGY DENMARK

Summary

- We have demonstrated a large potential in unlocking the flexibility / activating Demand Response. Automatic solutions are important
- We need new digitalized markets (based on AI and control)
- The Smart-Energy OS Controllers can focus eg. 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 related systems (water and food primarily). Main purpose is 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 evindence based measure of the smartness of a building, wastewater treatment plant, ... or even a (smart) city
- Energy communities and eg. district heating are important in order to establish the best solutions for the society
- We can design a building or DHC system such that it's optimal for a given climatic zone (using the Flexibility Index)

For more information ...

See for instance

www.smart-cities-centre.org

...or contact

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