# Digitalisation for the Future
# Weather-driven Energy System


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**https://www.flexibleenergydenmark.dk/**

**https://www.smart-cities-centre.org**

**http://www.henrikmadsen.org**


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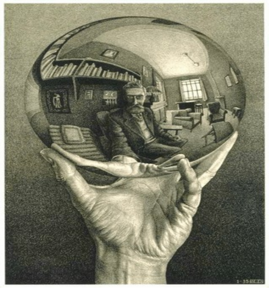
# Content

- Challenges
- Digitalisation in smart cities
- Flexibility and smart grids
- Energy, cost or emission efficiency?
- Peak shaving
- Energy storage in buildings
- Data-driven methods for district heating
- Data-driven methods for wastewater handling
- Data-driven characterization of the performance of buildings
- Indoor comfort and user-feedback



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Integrated energy systems powered by intelligent data

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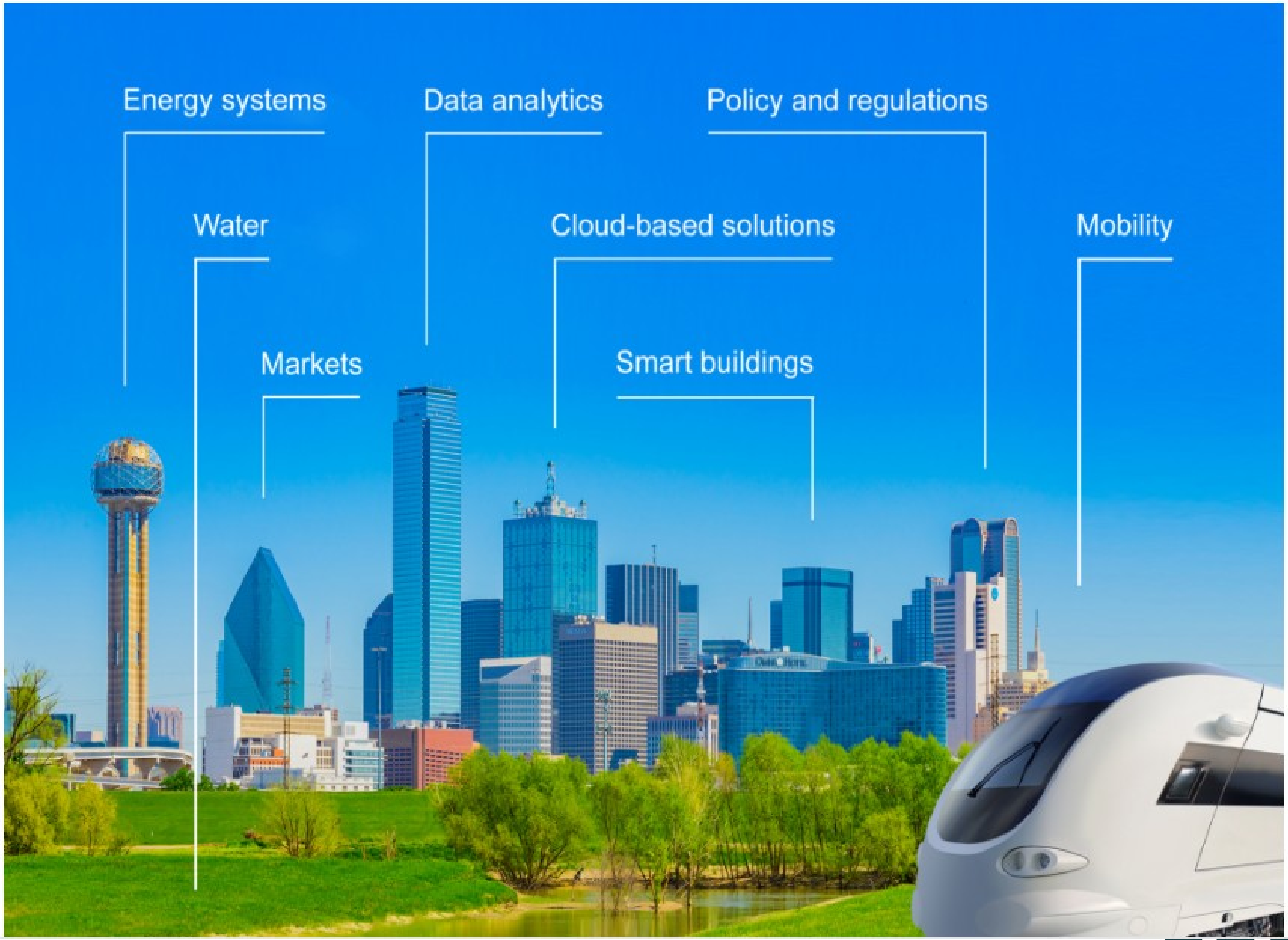
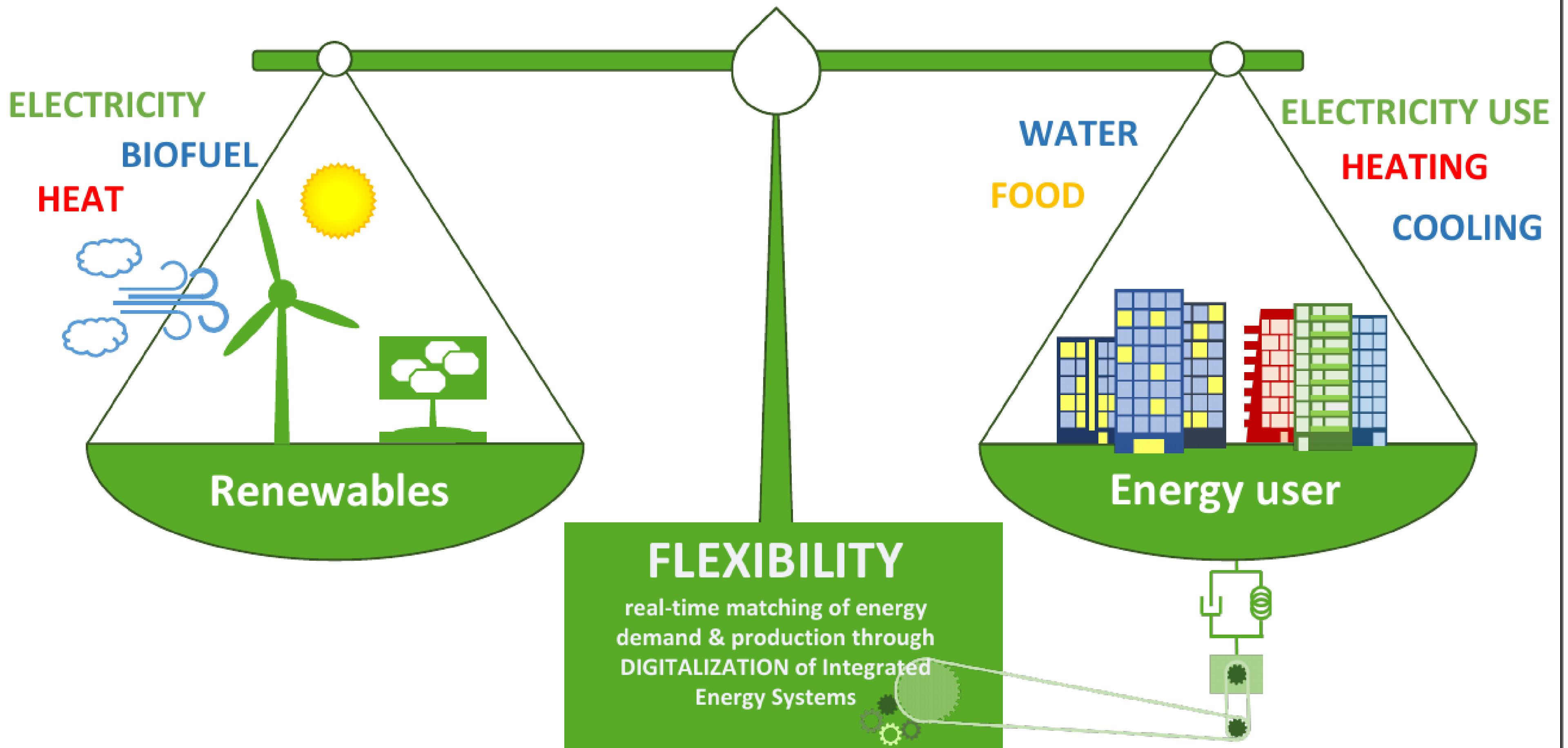
## Topics



# Challenges

# The Challenge: Denmark Fossil Free 2050



# Challenges

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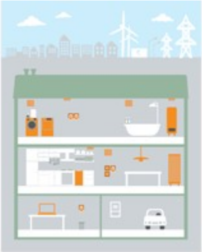

Preparatory study on Smart Appliances

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**

# 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**

# Data-Intelligent and Flexible Energy Systems

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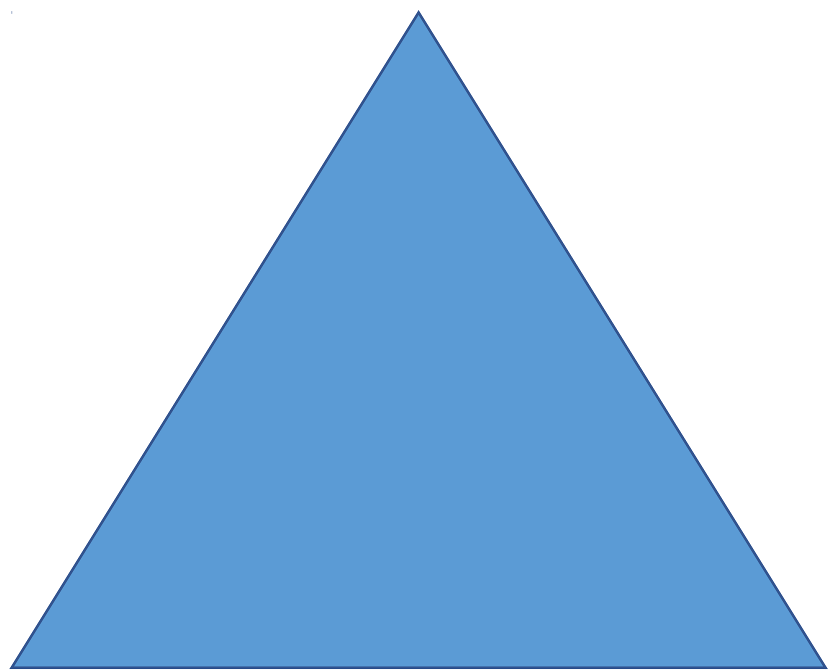
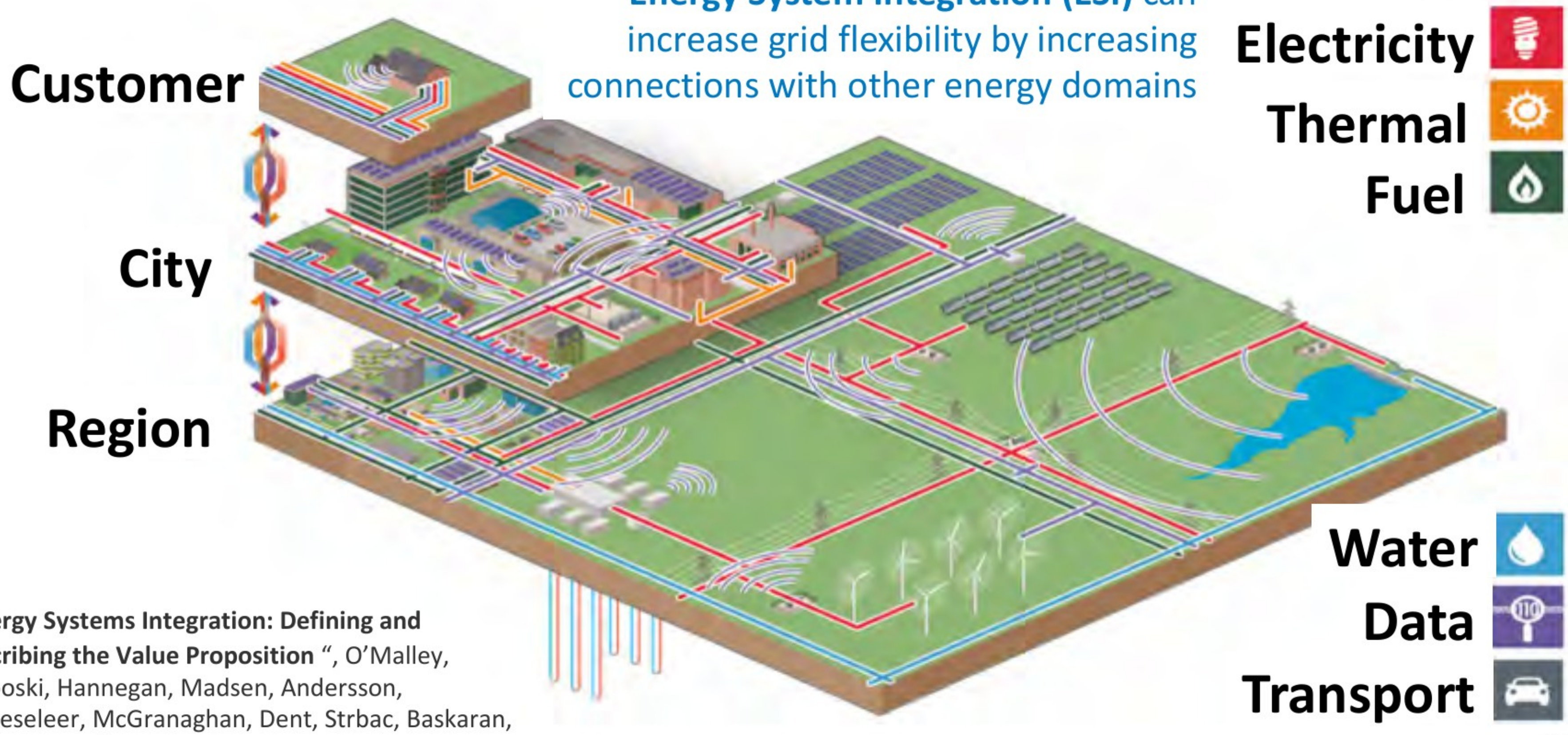
# Space of Solutions



# Energy Systems Integration

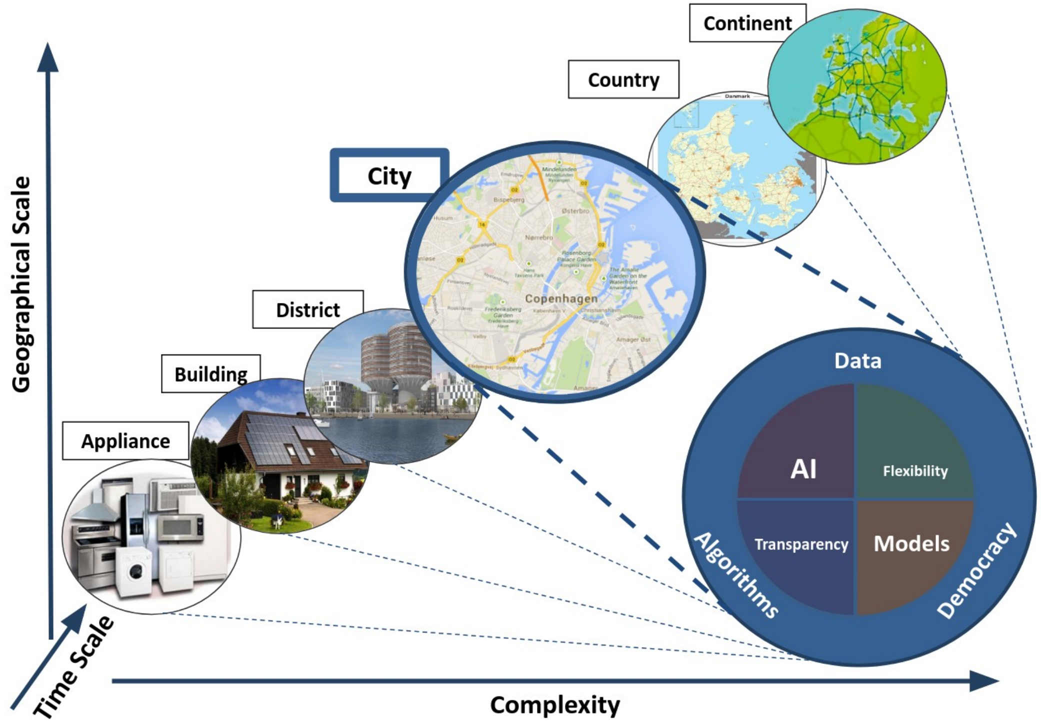
**Energy System Integration (ESI)** can increase grid flexibility by increasing connections with other energy domains



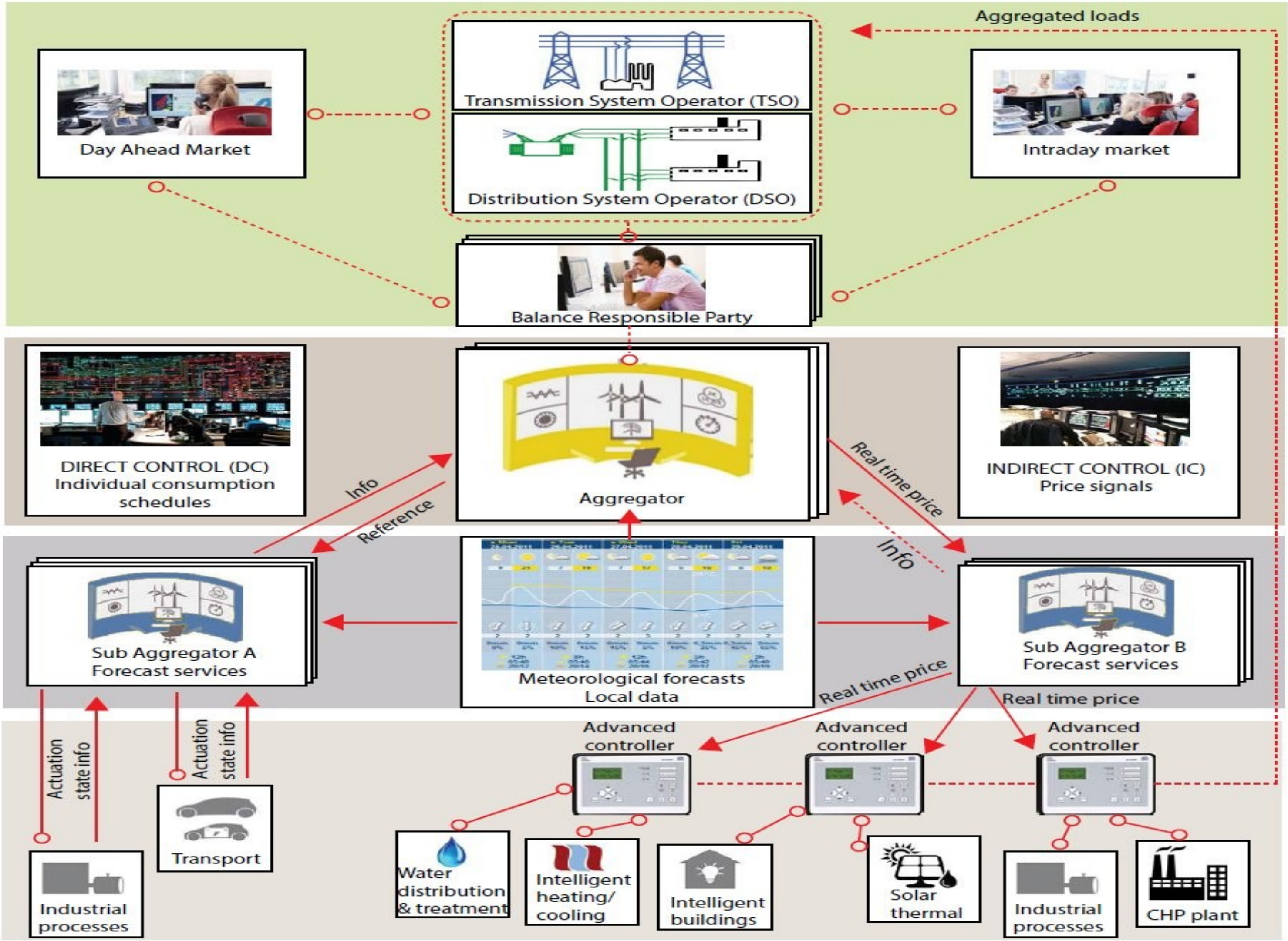

"**Energy Systems Integration: Defining and Describing the Value Proposition** ", O'Malley, Kroposki, Hannegan, Madsen, Andersson, D'haeseleer, McGranaghan, Dent, Strbac, Baskaran, Rinker., NREL/TP-5D00-66616. June 2016

# 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
## The Transformative Power of Digitalization

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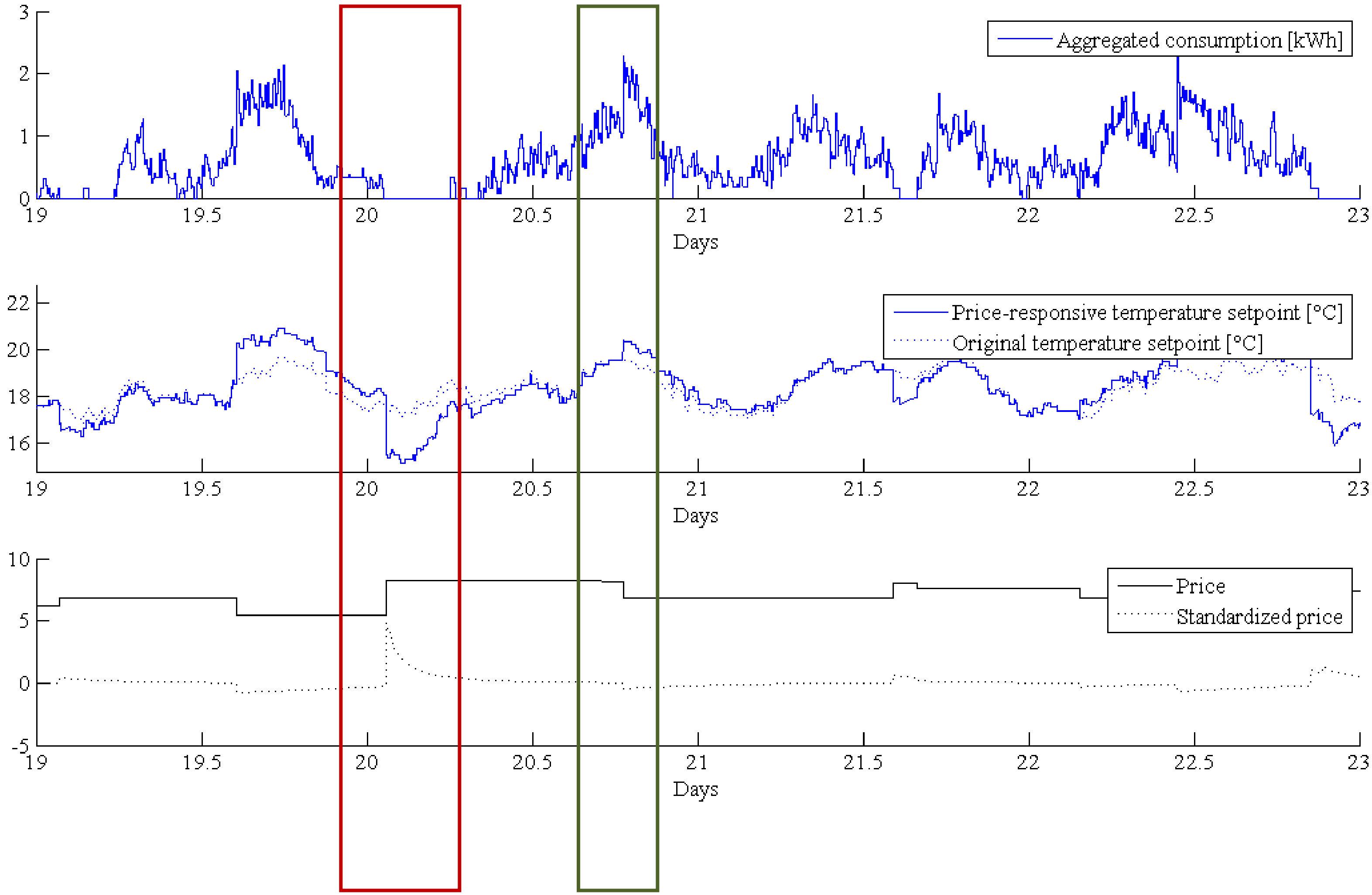
## Case study (Level III)

# Price-based Control of Power Consumption (Peak Shaving)

# **Aggregation** (over 20 houses)

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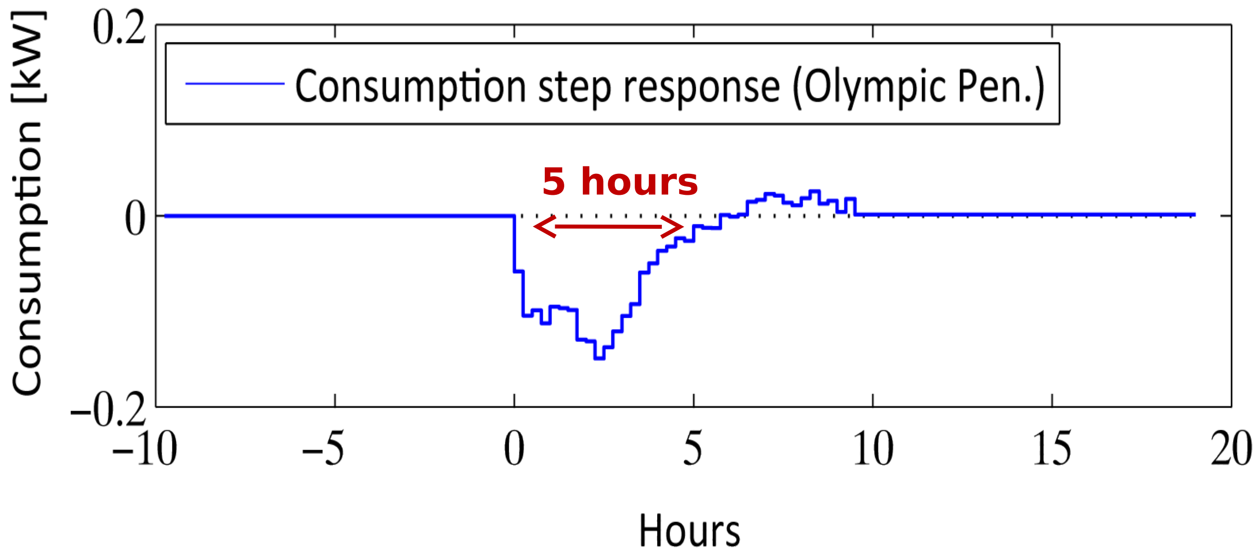
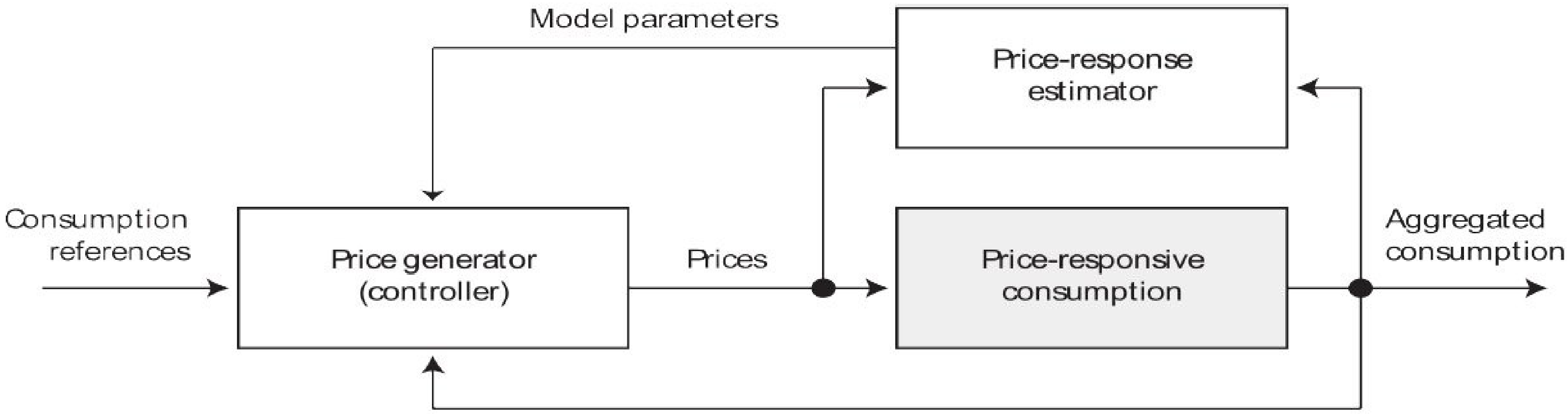
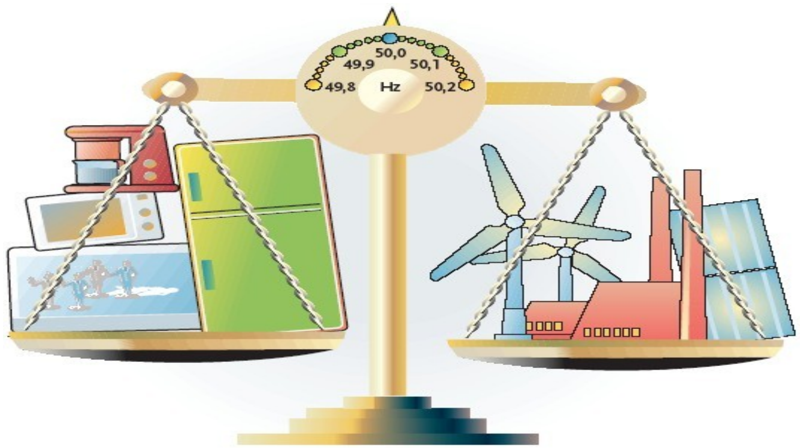
# Response on Price Step Change



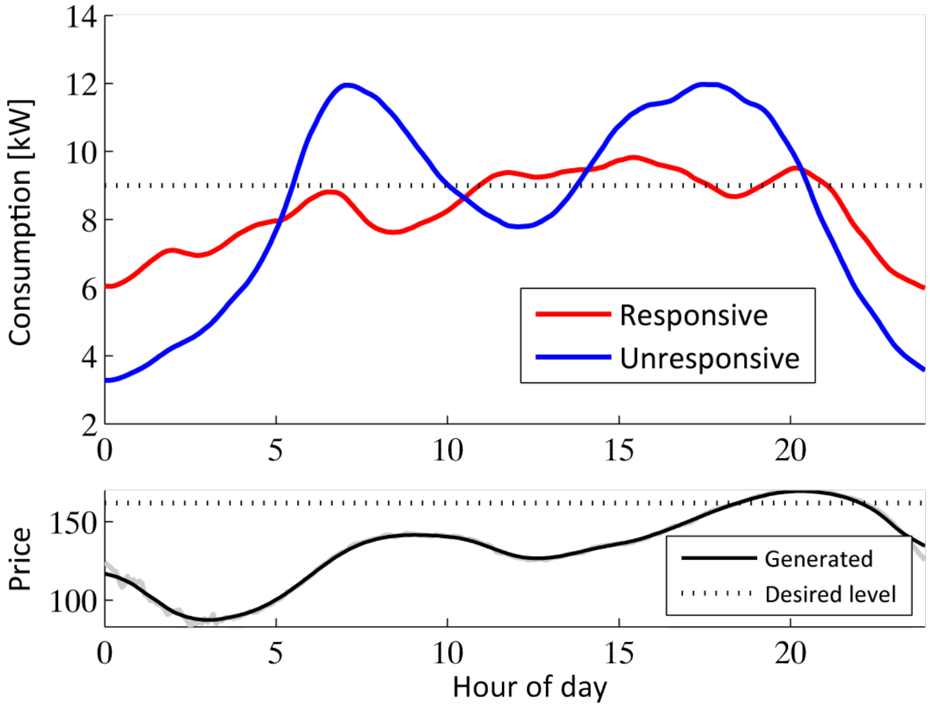
# Control of Power Consumption



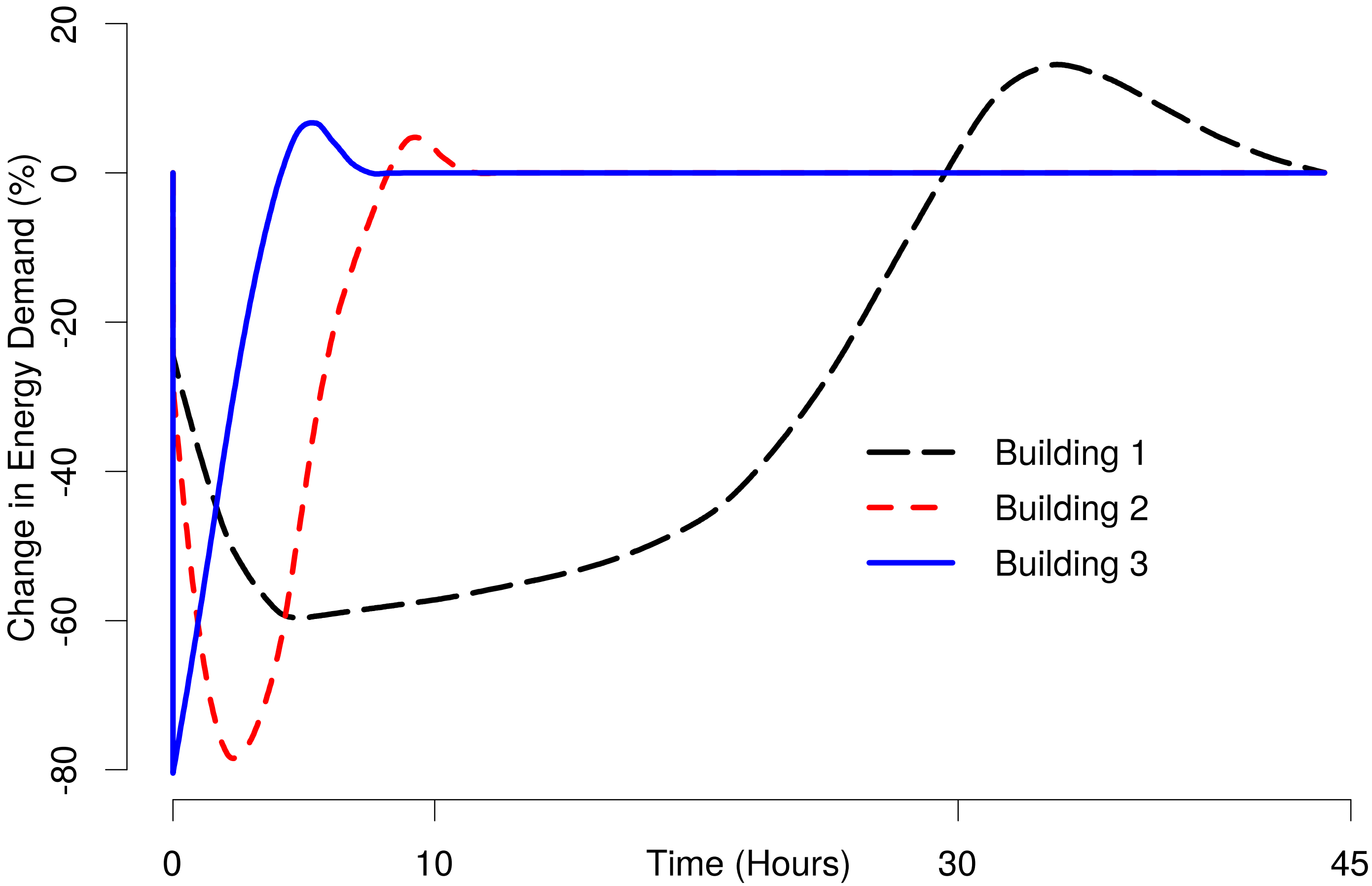



# Control performance

Considerable **reduction in peak consumption**



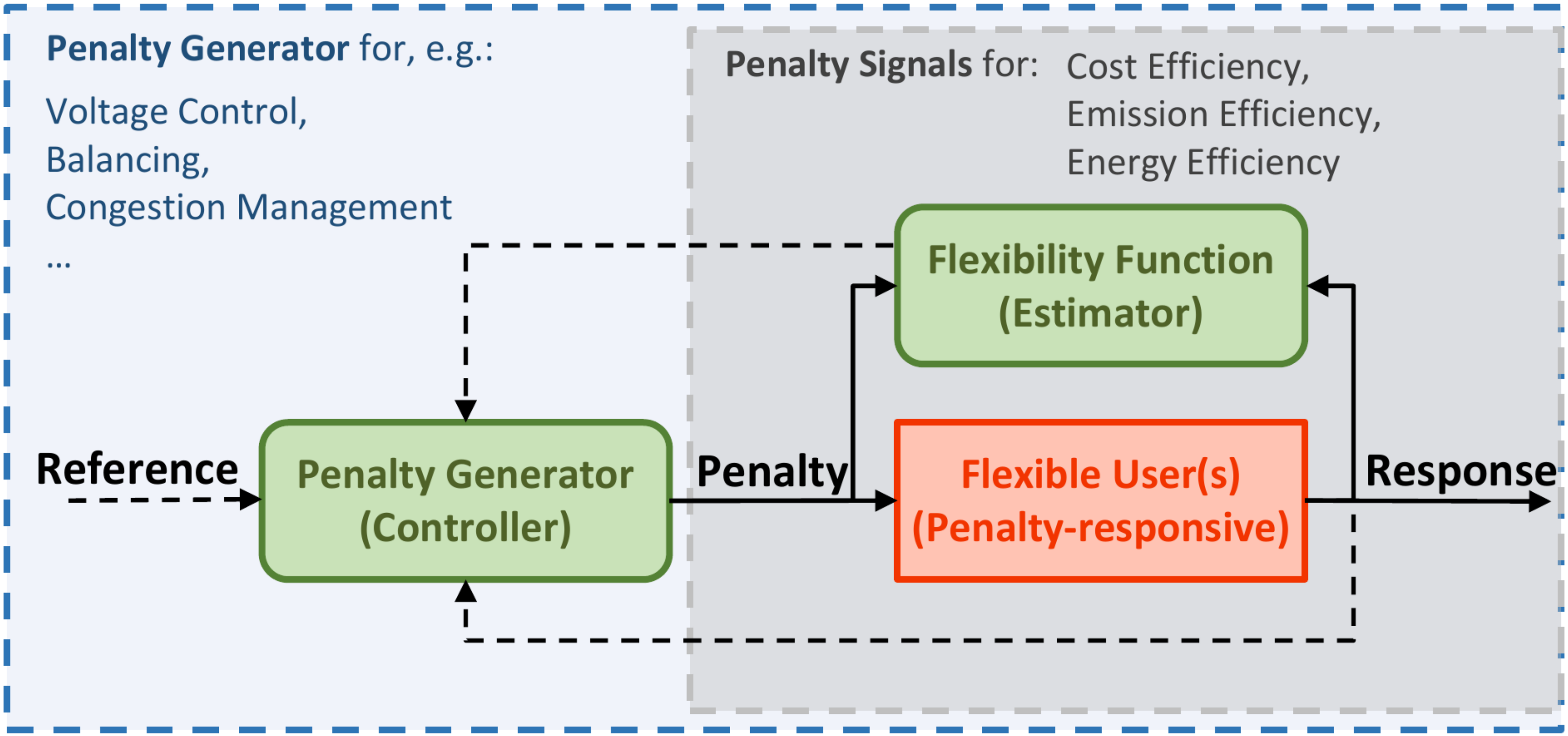
# Examples: Flexibility Function



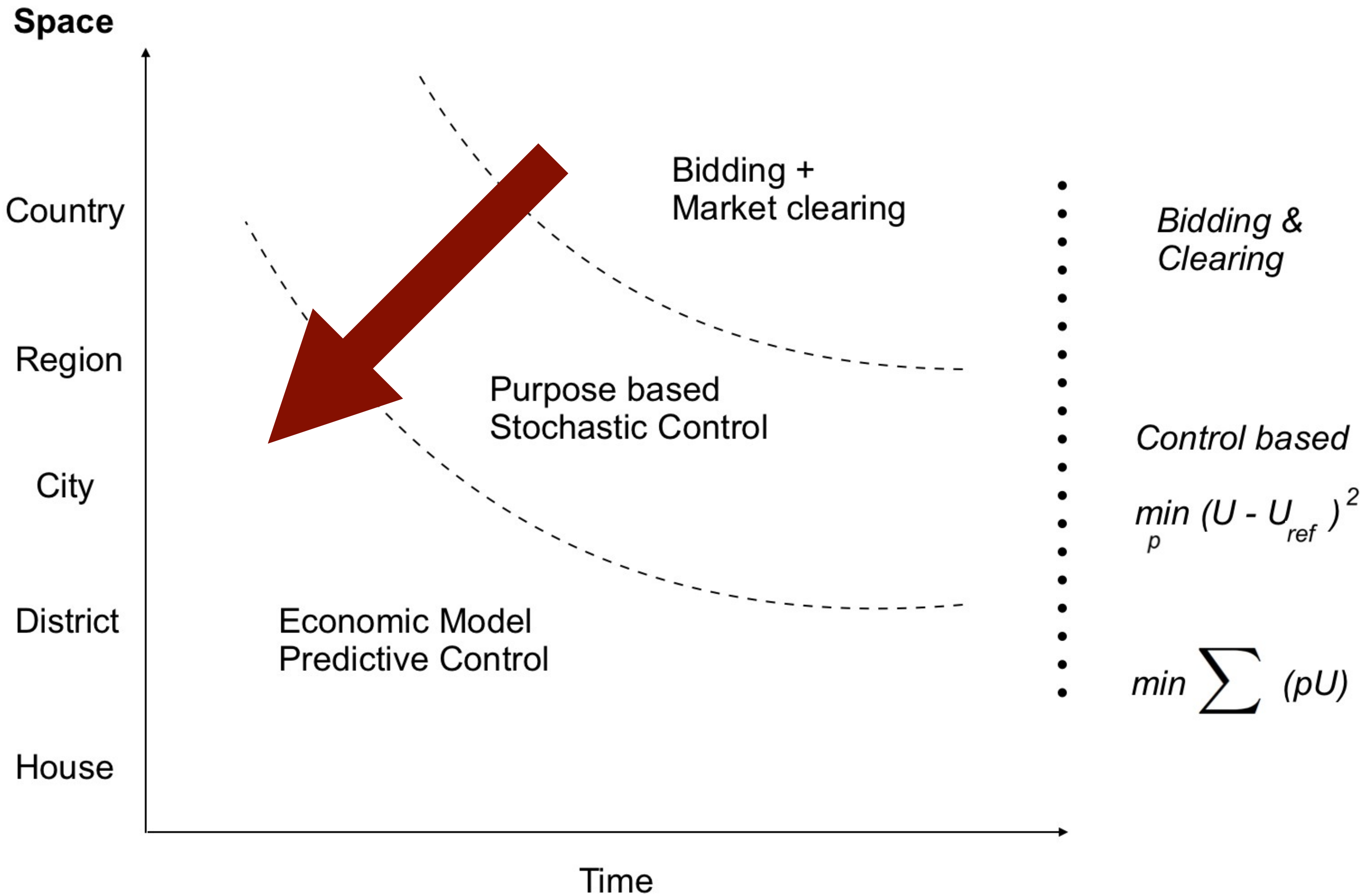
# Penalty (examples)

- **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*.

# A FED example: Flexible Users and Penalty Signals



# The 'market' of tomorrow

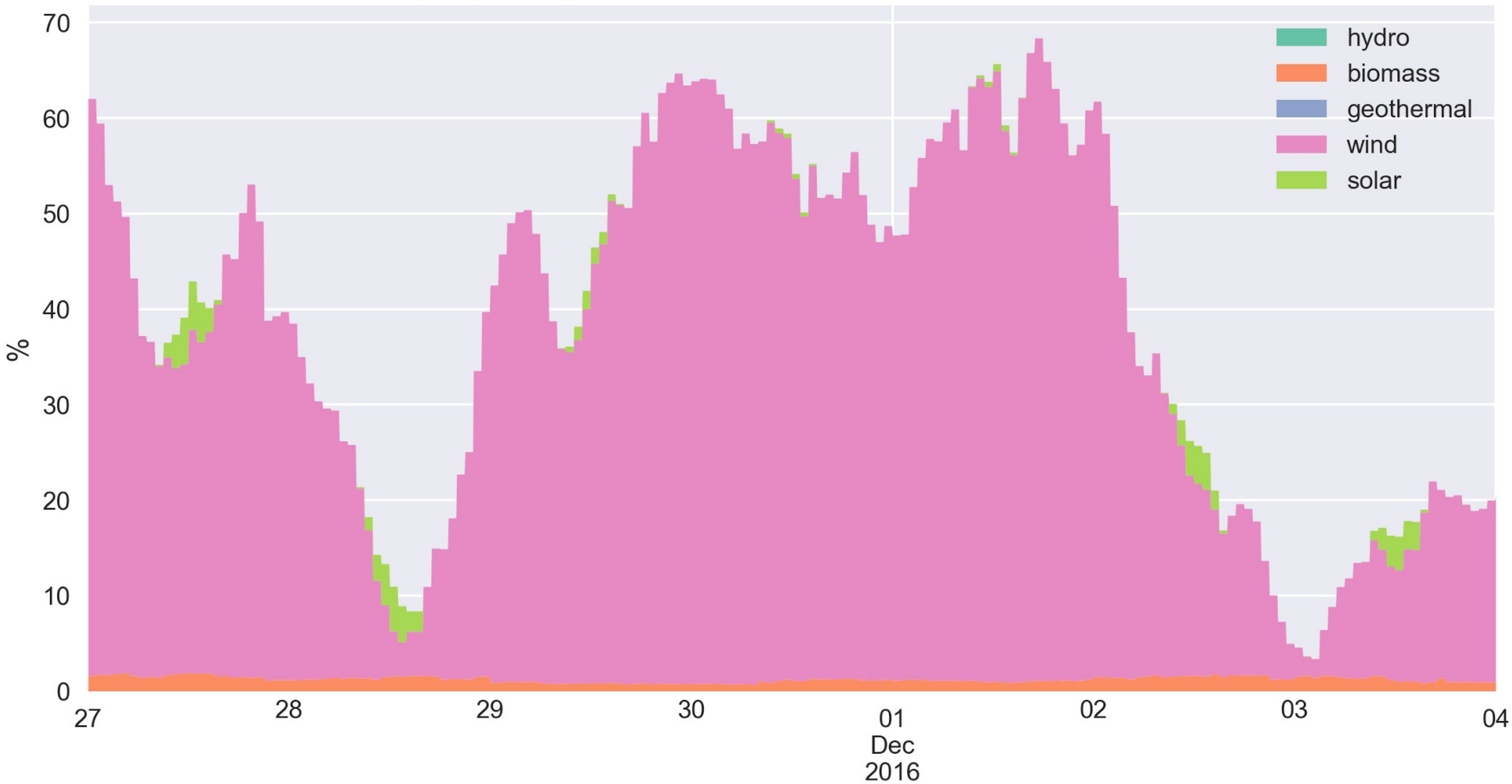


# Case study (level IV)

# Control of Heat Pumps

## (Price/CO2-based control)

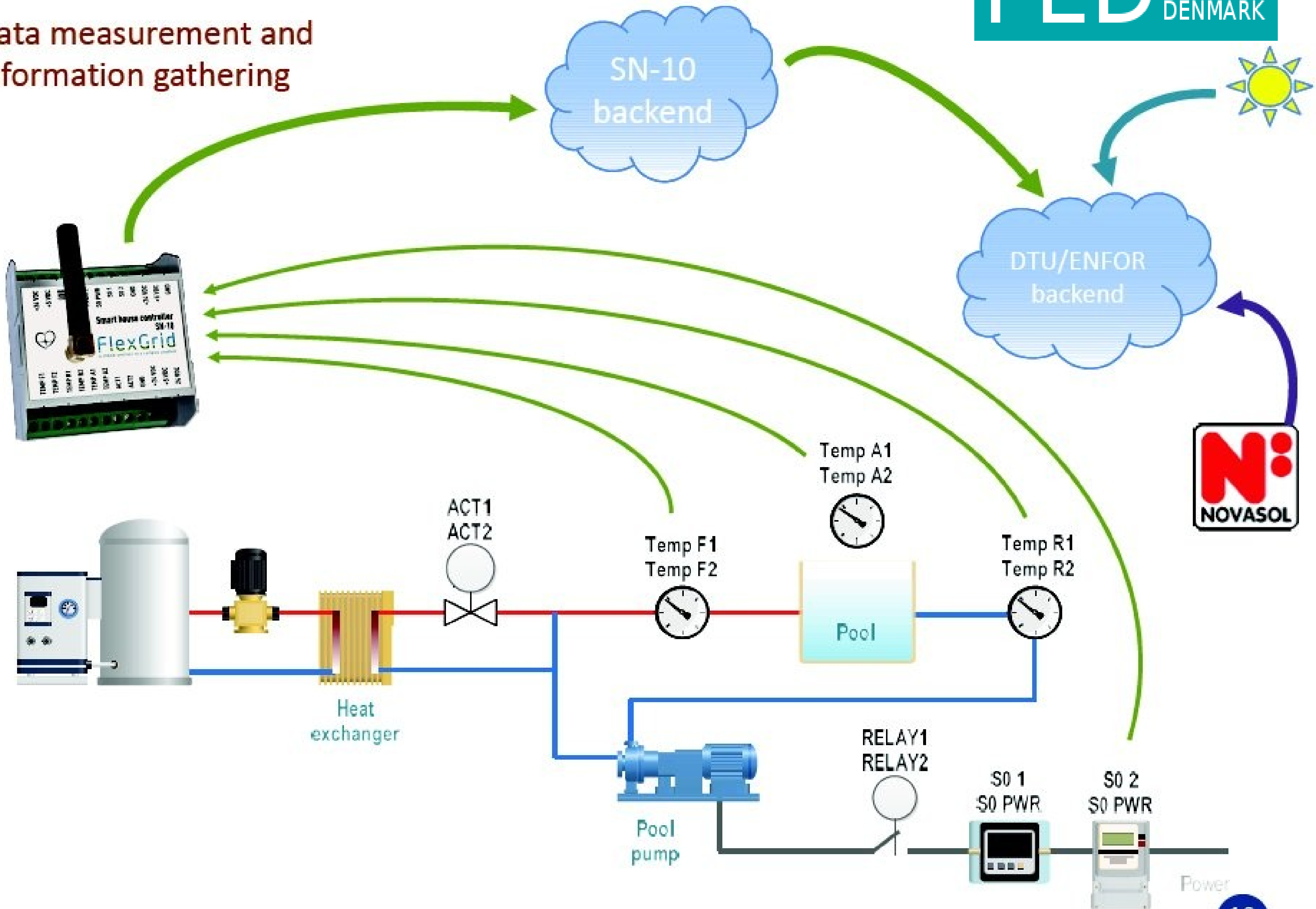
Share of electricity originating from renewables in Denmark Late Nov 2016 - Start Dec 2016




Source: pro.electicitymap.org

# How does it work?

## Data measurement and information gathering



# Example: Price-based control

# Example: $CO_2$-based control (savings 10-30 pct)

# Case study

# Data-driven methods for district heating systems

## (with CPH Solution Lab and HOFOR)

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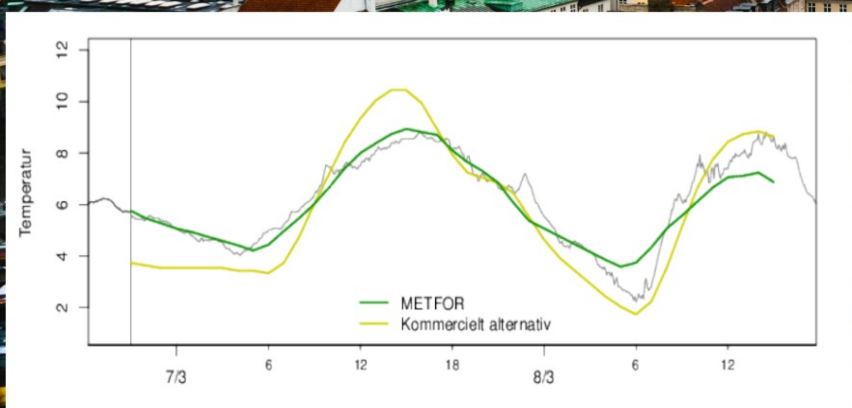
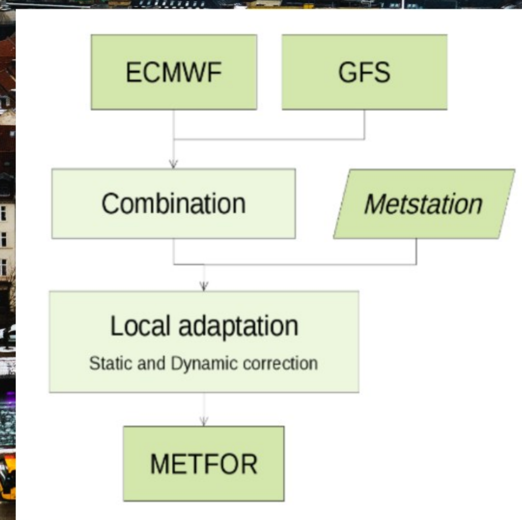
# Data på lokale vejrforhold + flere MET prognoser

**Forbedring i nøjagtighed:**
**20 – 90 pct**

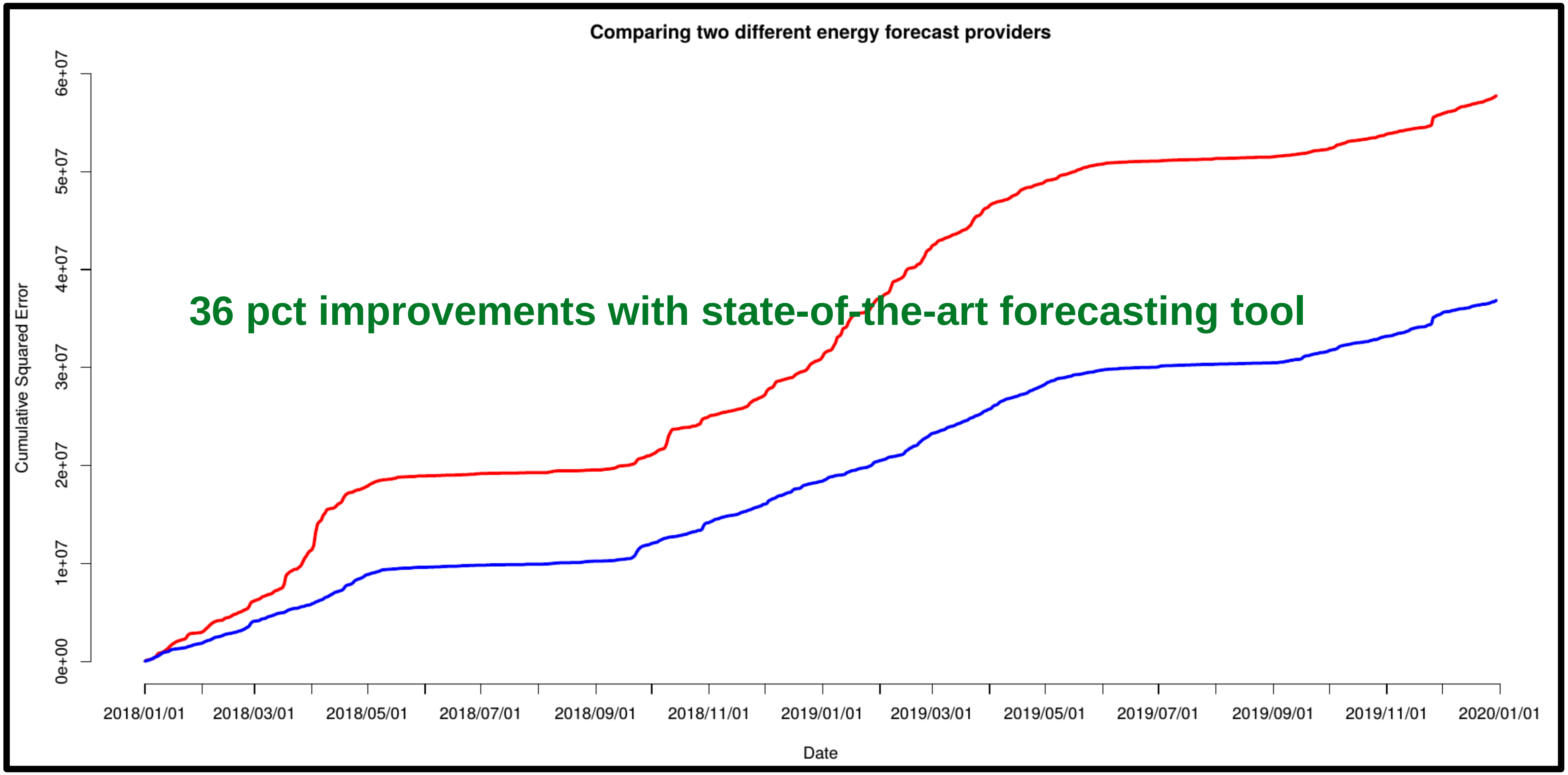
**Gothersgade**
Temperatur +1
Luftfugtighed 87%
Vind 3 m/s

**Holmens kanal**
Temperatur -1
Luftfugtighed 84%
Vind 7 m/s



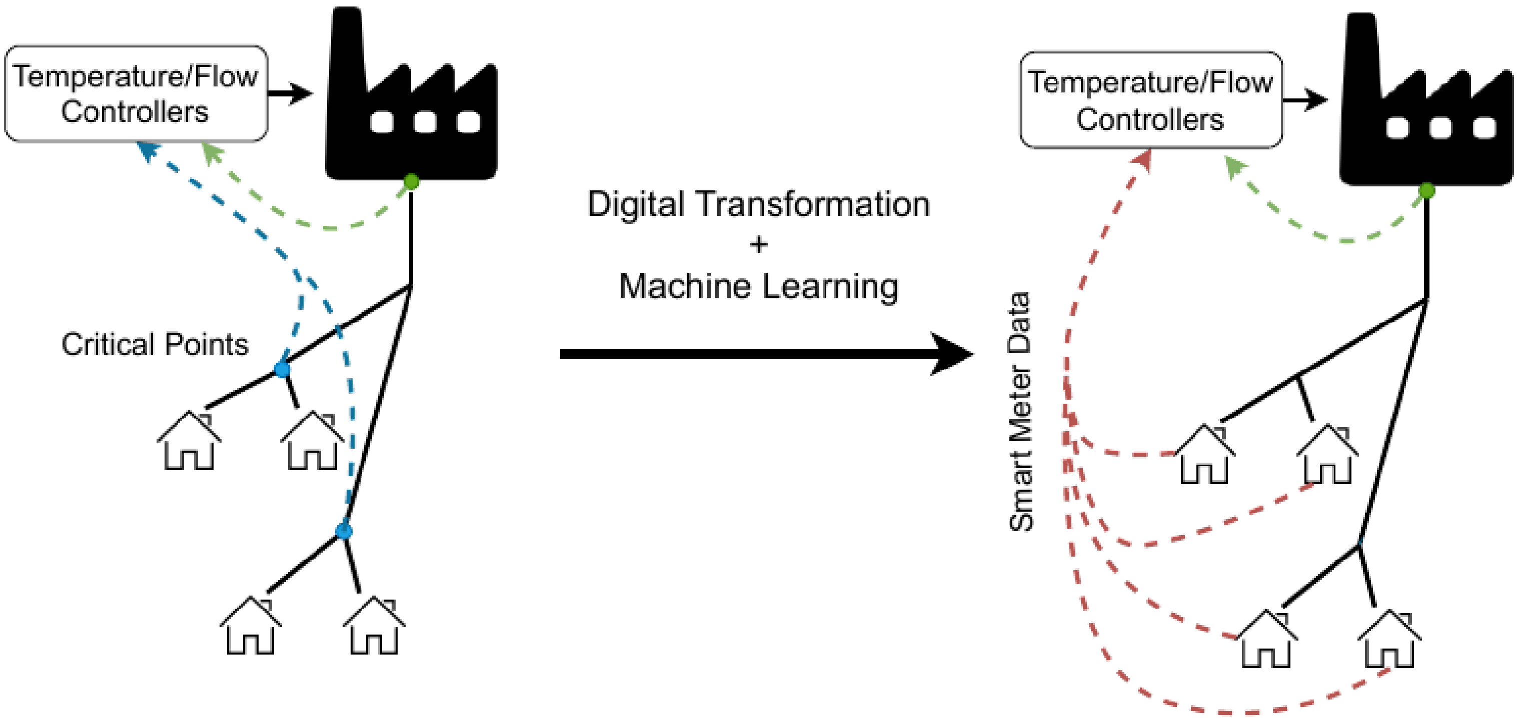



# Heat Load Forecasts at Varmelast

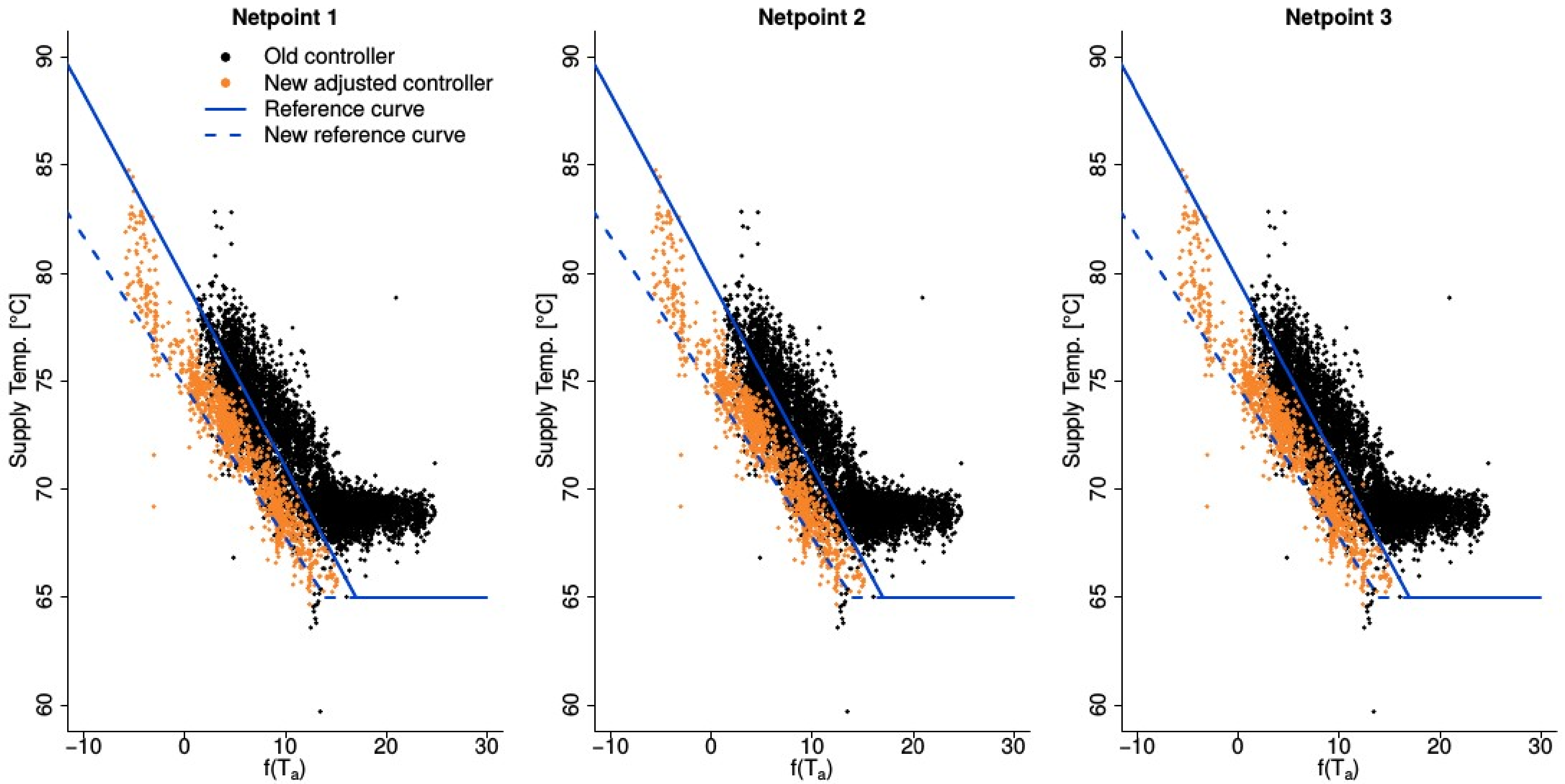


# Controllers for supply temperature

## Frequent meter data gives new possibilities



# Temperature at end-users (Tingbjerg)

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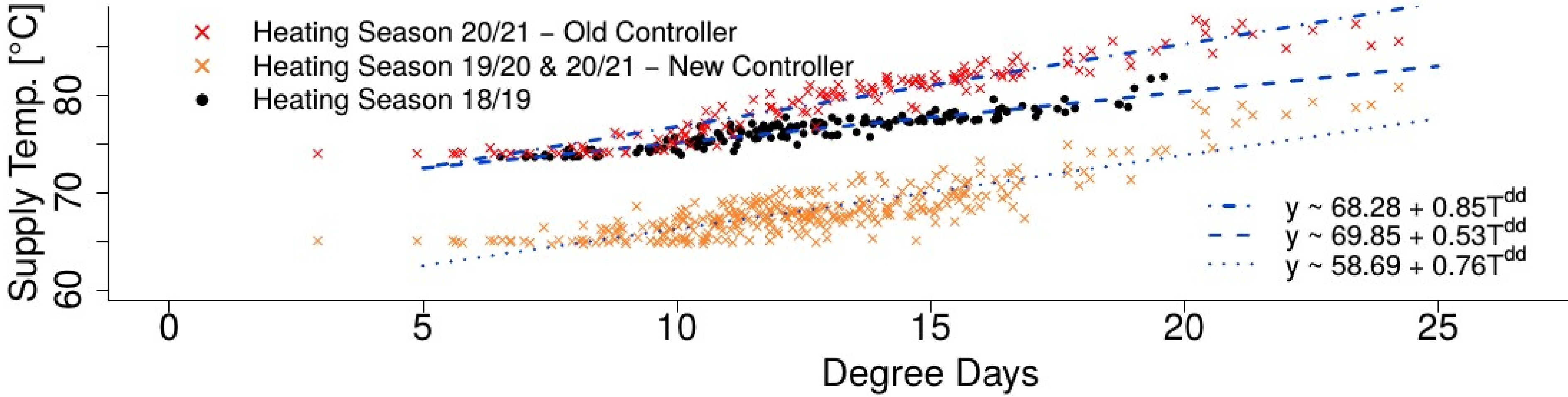
# Supply temperature (Svebølle-Viskinge)
# Old and new controllers

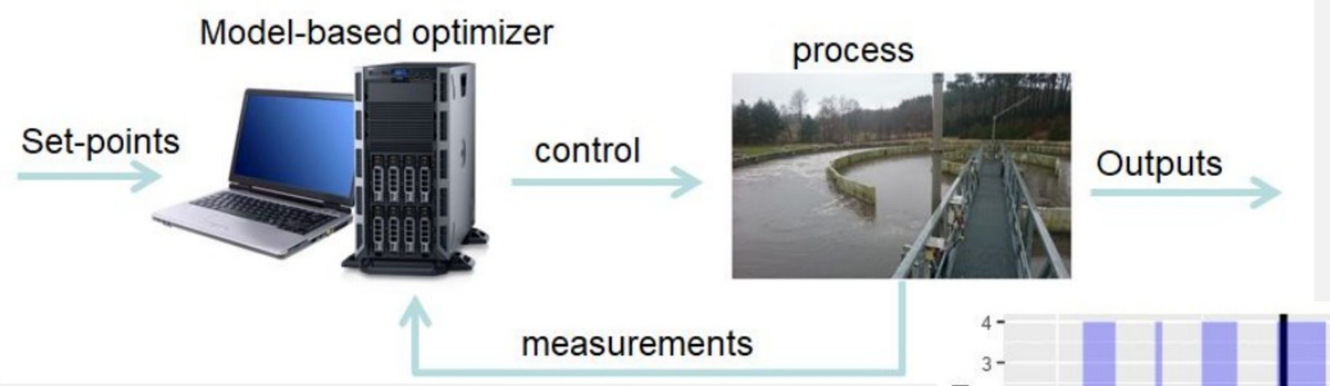


# Case study

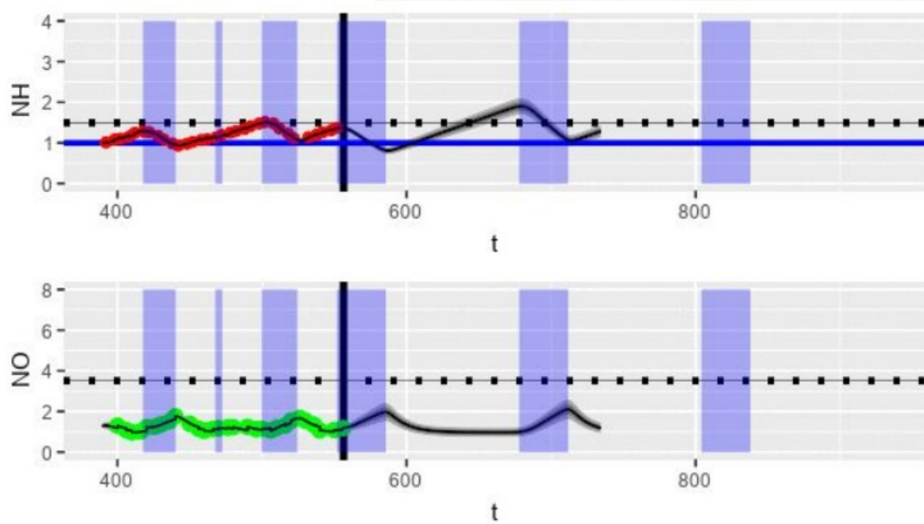
# Wastewater Treatment

# Wastewater Treatment Plants

## Predictive control of Water Resource Recovery Facilities




- Controls aeration by using a predictive model to optimize future control
- Manages requirements in the optimization
- Can use different inputs such as electricity prices and greenhouse gas emissions



# Example: Control of Wastewater Treatment Plant (Nørre Snede)

| Objective (minimize) | Cost [DKK/day] | GHG emissisions [kg-CO2-eq/day] |
|---|---|---|
| Effluent concentrations | 409.6 | 269.9 |
| Electricity consumption | 298.3 | 406.5 |
| Operational costs | 288.5 | 395.7 |
| GHG emissions | 352.5 | 232.3 |
| Current control | 317.5 | 358.4 |

- Optimizing operational costs – 9.2 pct savings compared to currently implemented control
- Optimizing (minimizing) GHG emissions – 40.9 pct lower emission compared to optimizing for costs

# Case study
# (using existing markets)

# Water Distribution Network
## (joint work with Grundfos)

# Auto-commissioning and MPC for water distribution networks

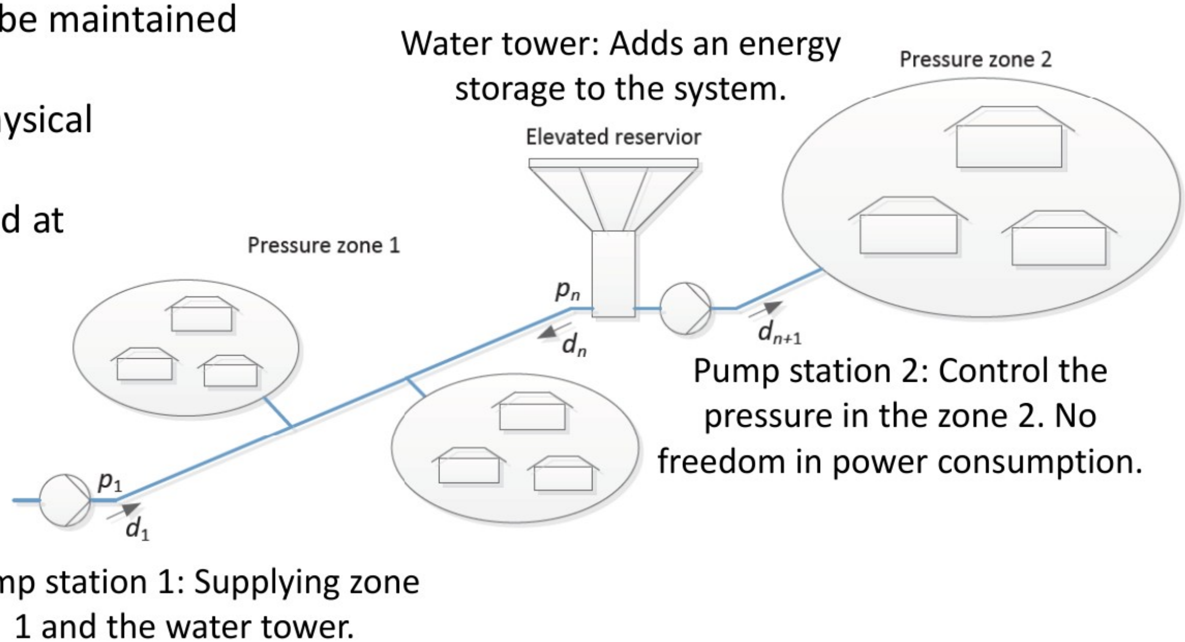
## Application setup

- or CO2 level.

- Control objective: Control the pump station 1 to minimize the energy cost.

- Constraints:
  - The level in the water tower must be maintained within certain limits.
  - The pump flow is limited by the physical constraints of the pumps.
  - Water quality should be maintained at all times (water age).

- Disturbances:
  - Water consumption in zone 1 and zone 2.

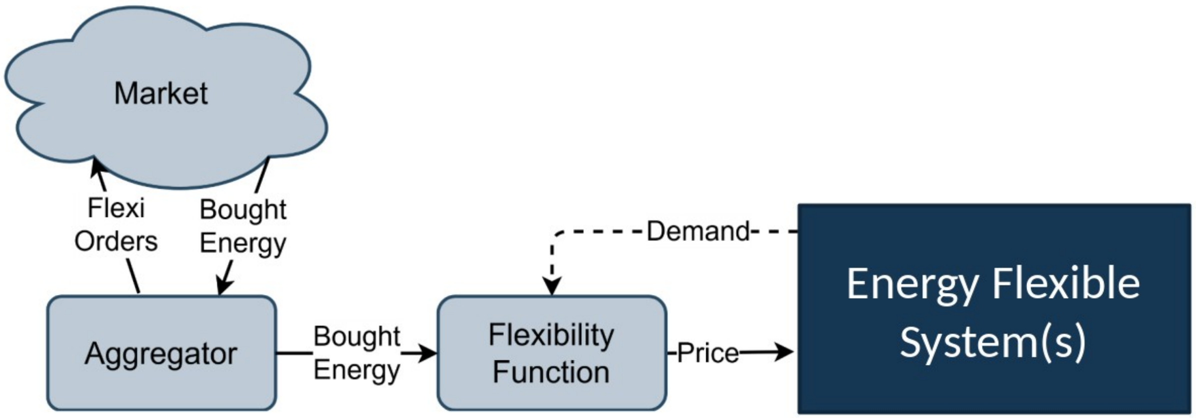


# Flexibility Function (key concept)

- Input: Price
- Output: Demand

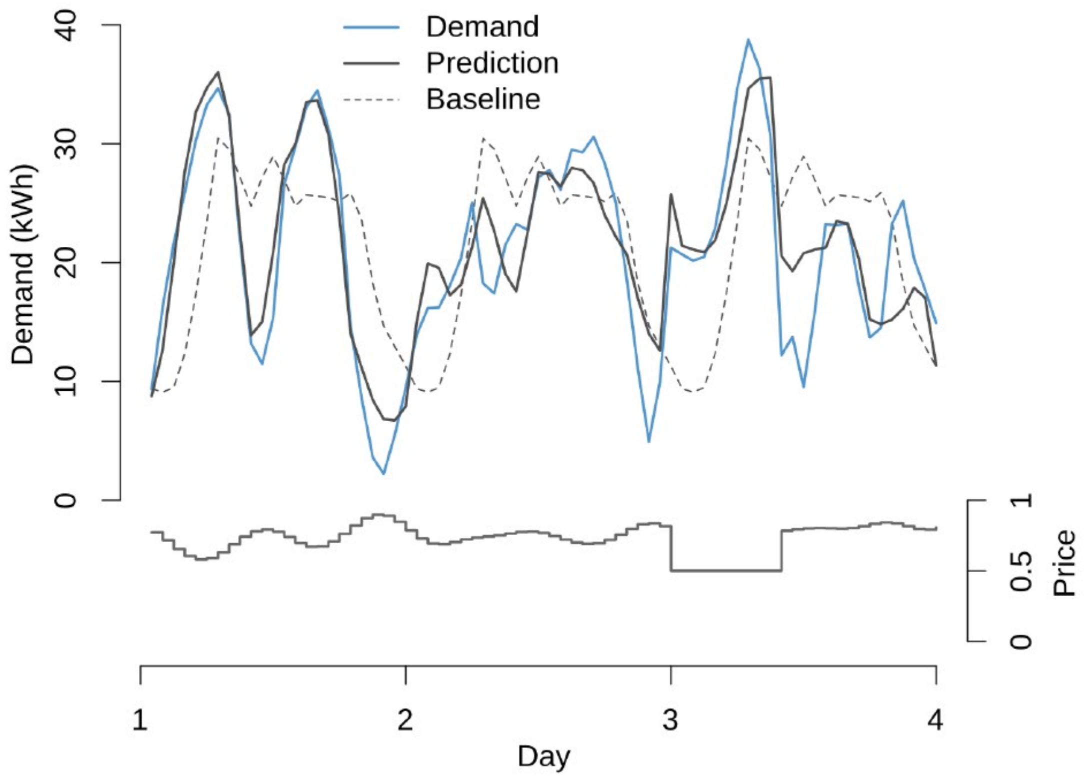
- Estimate relation: Flexibility Function!

- Use Flexibility Function to design price signals.



# Flexibility Function: Accuracy

- Accurate several days ahead.
- We need only 24 hour predictions.

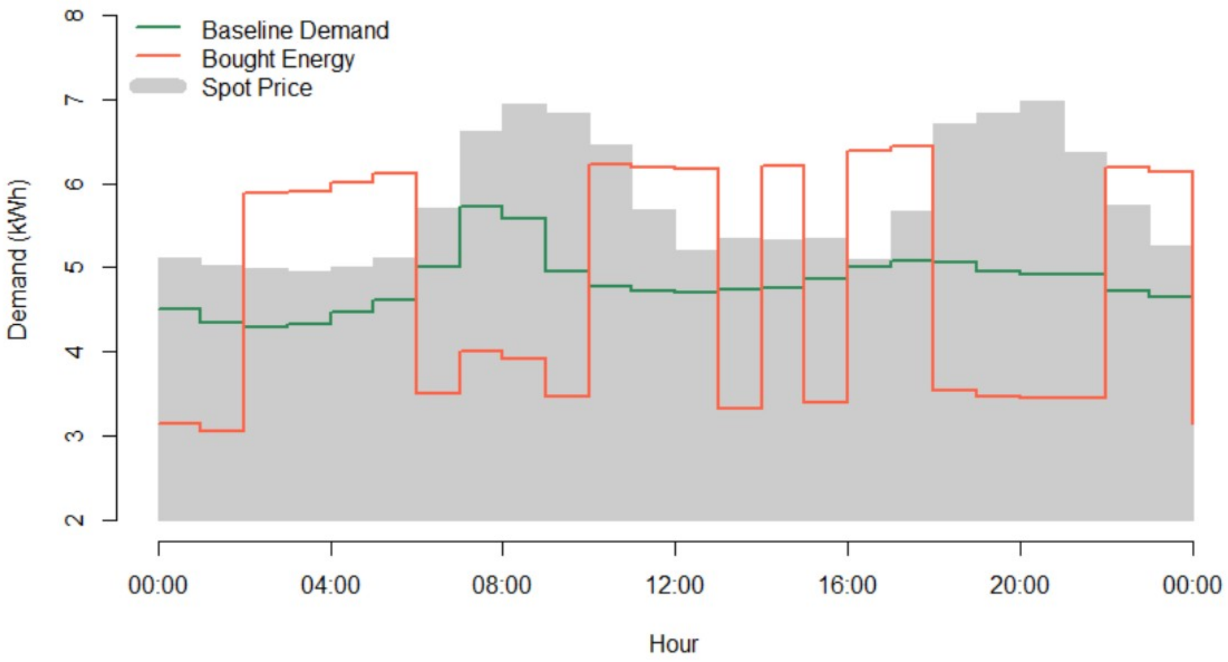


# Bidding Flexibility into Markets

- Flexi orders consists of an **interval**, an amount of **energy**, and a **duration**.
- For example, **interval**: 08:00 – 12:00, **energy**: 1 MWh, **duration**: 2 hours.
- Result: 1 MWh bought in the 2 cheapest hours between 08:00 and 12:00.
- Can be combined with regular spot market bids to obtain part flexibility

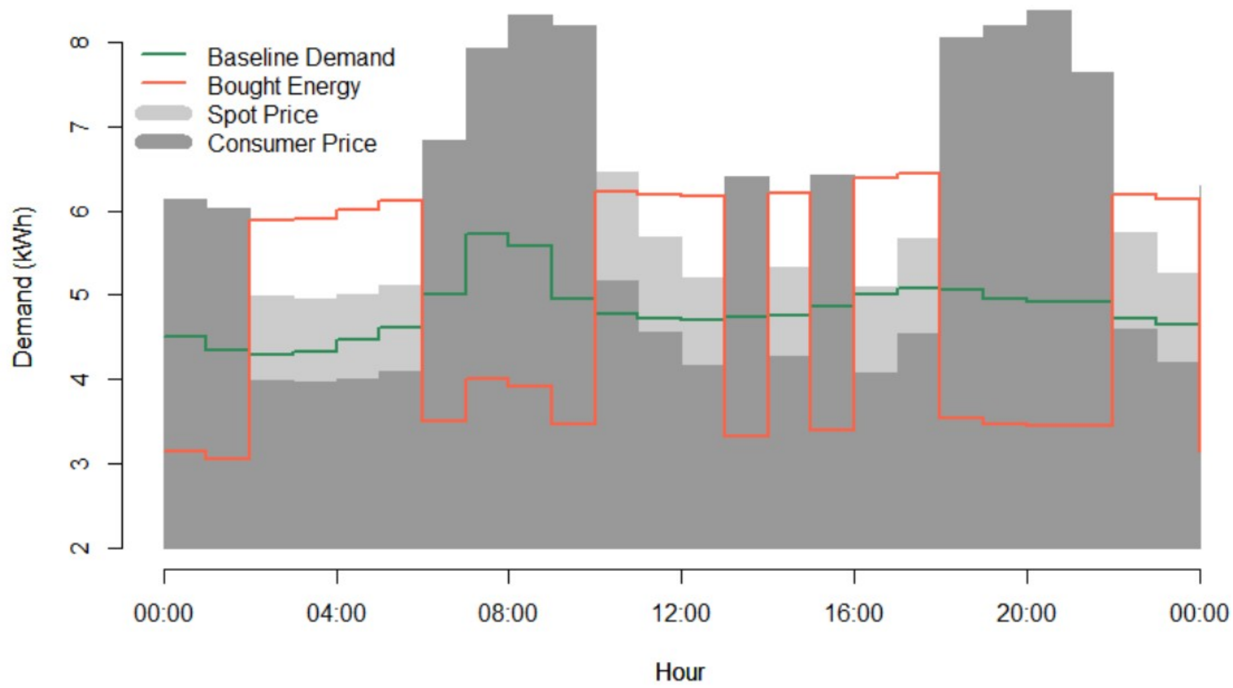
# Bidding Flexibility into Markets

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



# Bidding Flexibility into Markets

Solve FF(Price)=Bought Energy:



# Results

- For one year of current market conditions 4.1% of the costs can be saved.
- With perfect foresight of spot prices and demand 5.4% could be saved – often assumed by other researchers.

| Strategy | Costs $\left(\frac{\text{EUR}}{\text{year}}\right)$ | Price $\left(\frac{\text{EUR}}{\text{MWh}}\right)$ | Energy $\left(\frac{\text{MWh}}{\text{year}}\right)$ |
|---|---|---|---|
| Baseline | 44457 | 65.2 | 682 |
| Flexible | 42627 (-4.1%) | 62.0 (-4.8%) | 687 (+0.75 %) |
| Potential | 42070 (-5.4%) | 61.6 (-5.4%) | 683 (+0.05%) |

**Larger savings with optimized market conditions – i.e. the Smart-Energy OS**

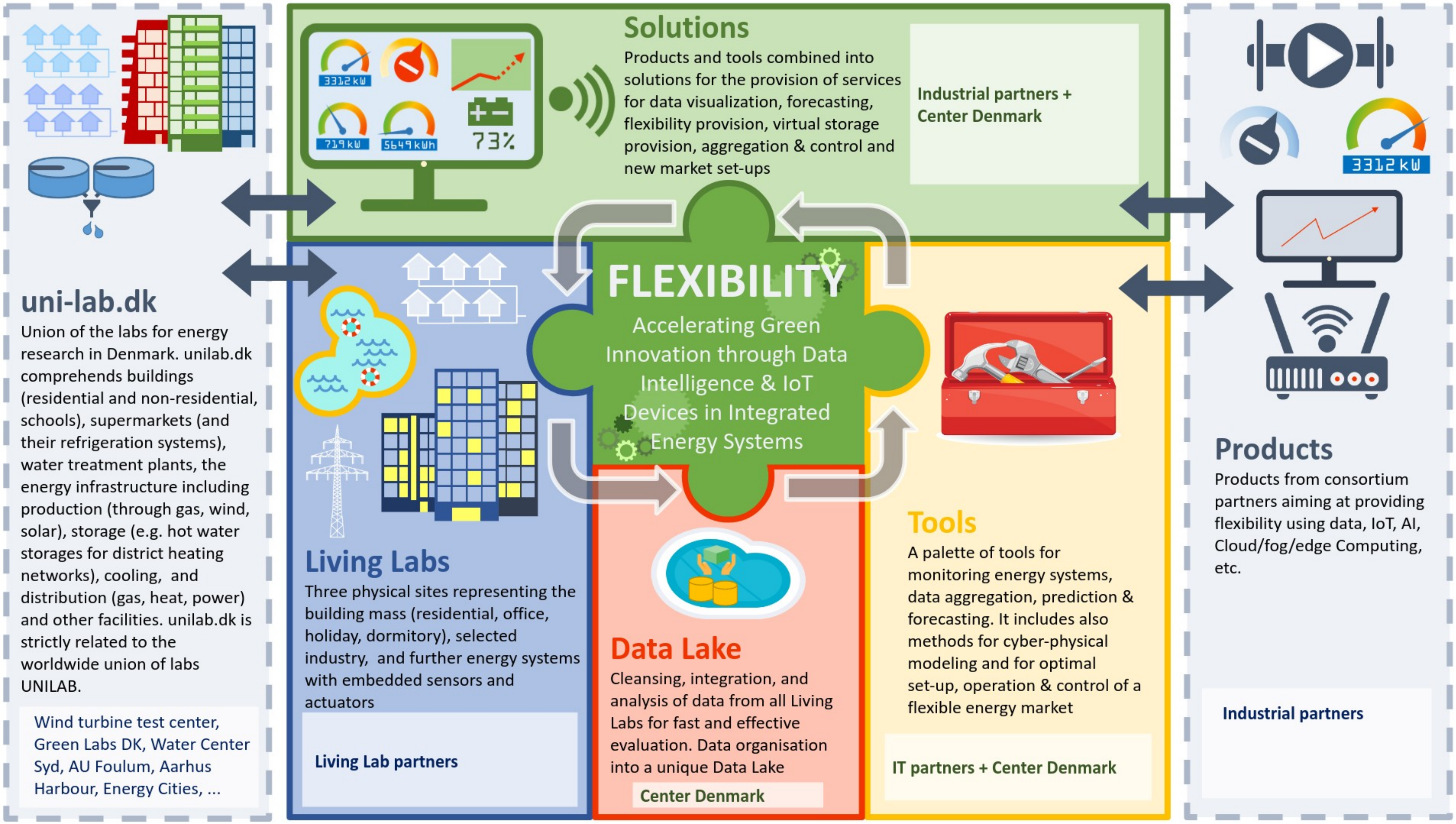
For more information:

Junker, R. G., Kallesøe, C. S., Real, J. P., Howard, B., Lopes, R. A., & Madsen, H. (2020). Stochastic nonlinear modelling and application of price-based energy flexibility. Applied Energy, 275(1), 115096. https://doi.org/10.1016/j.apenergy.2020.115096

# Center Denmark

# Digitalization Hub for Accelerating the Green Transition

# Business Ecosystem



# Trusted Data Sharing Platform

Data Exchange Facilities Market provide neutral (infrastructure and rules) mechanisms in the background for controlled, trusted and secure data transactions.

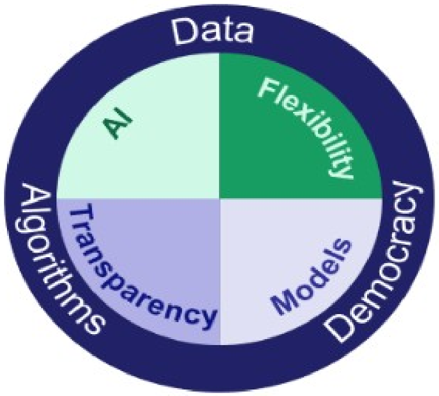
Participants accepting the market rules benefit from the exchange mechanisms and shape together an open market for data.

This is how we work together

# Center Denmark – Control Room
# Spatio-Temporal Thinking

# Summary

- The future weather-driven energy system calls for digitalization of the energy systems in Smart Cities.
- We need **a deep digitalisation** (AI, IoT, Cloud/Fog/Edge Computing, etc.)
- We need **transparent**, **safe** and **democratic** solutions
- We need **data hubs** for energy related streaming data (like **Center Denmark**)
- We need a **Business Ecosystem** with **Living Labs**
- We are looking forward to EU's upcoming 'Digitalisation of Energy Action Plan'



# Data-driven Characterization of the Thermal Performance of Buildings

## (Digital X-ray)

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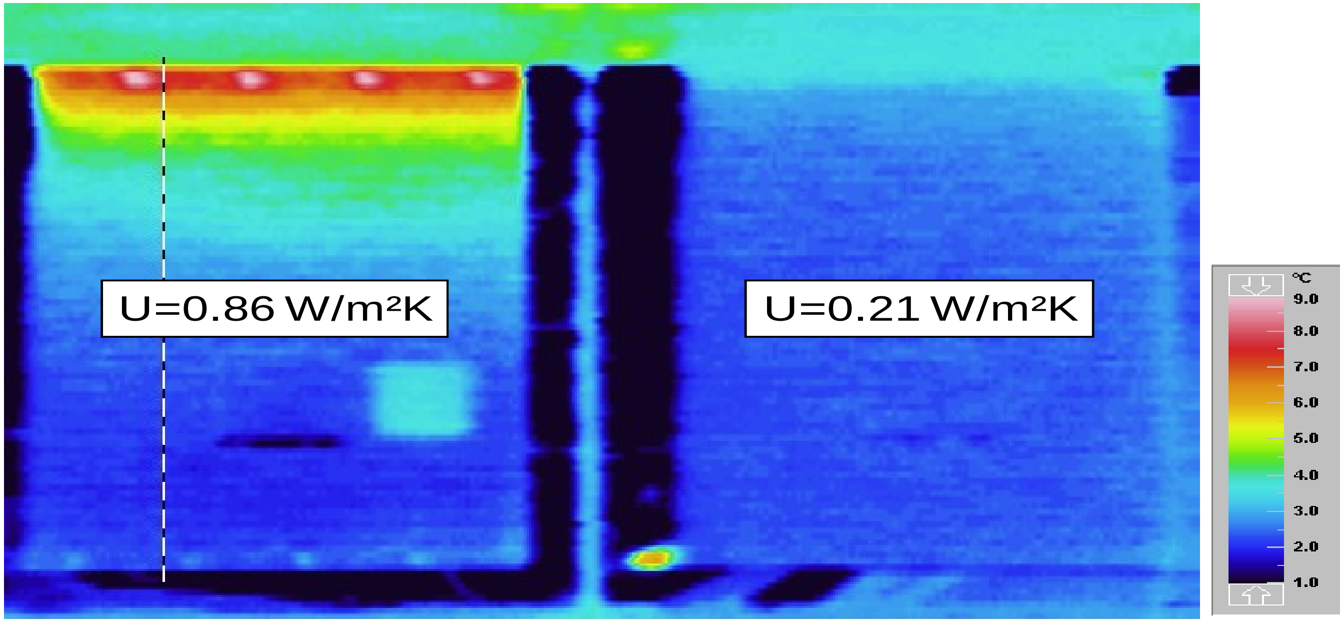
# Example




Consequence of good or bad workmanship (theoretical value is U=0.16W/m2K)

# Results

| | UA W/°C | $\sigma_{UA}$ | $gA^{max}$ W | $wA_E^{max}$ W/°C | $wA_S^{max}$ W/°C | $wA_W^{max}$ W/°C | $T_i$ °C | $\sigma_{T_i}$ |
|---|---|---|---|---|---|---|---|---|
| 4218598 | 211.8 | 10.4 | 597.0 | 11.0 | 3.3 | 8.9 | 23.6 | 1.1 |
| 4381449 | 228.2 | 12.6 | 1012.3 | 29.8 | 42.8 | 39.7 | 19.4 | 1.0 |
| 4711160 | 155.4 | 6.3 | 518.8 | 14.5 | 4.4 | 9.1 | 22.5 | 0.9 |
| 4836681 | 155.3 | 8.1 | 591.0 | 39.5 | 28.0 | 21.4 | 23.5 | 1.1 |
| 4836722 | 236.0 | 17.7 | 1578.3 | 4.3 | 3.3 | 18.9 | 23.5 | 1.6 |
| 4986050 | 159.6 | 10.7 | 715.7 | 10.2 | 7.5 | 7.2 | 20.8 | 1.4 |
| 5069878 | 144.8 | 10.4 | 87.6 | 3.7 | 1.6 | 17.3 | 21.8 | 1.5 |
| 5069913 | 207.8 | 9.0 | 962.5 | 3.7 | 8.6 | 10.6 | 22.6 | 0.9 |
| 5107720 | 189.4 | 15.4 | 657.7 | 41.4 | 29.4 | 16.5 | 21.0 | 1.6 |
| . | . | . | . | . | . | . | . | . |

# Perspectives

- Identification of most problematic buildings
- Automatic energy labelling
- Recommendations:
  - Should they replace the windows?
  - Or put more insulation on the roof?
  - Or tigthen the building?
  - Should the wall against north be further insulated?
  - ......
- Better control of the heat supply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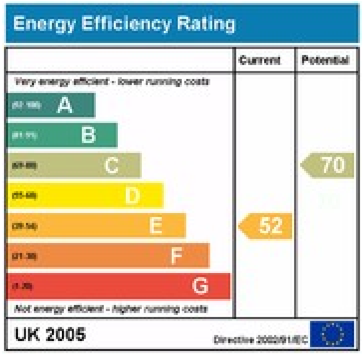
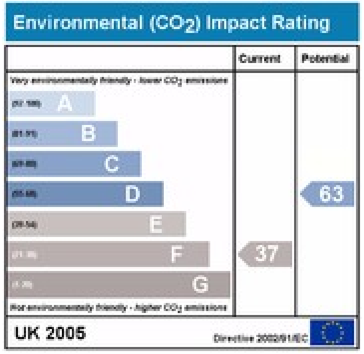
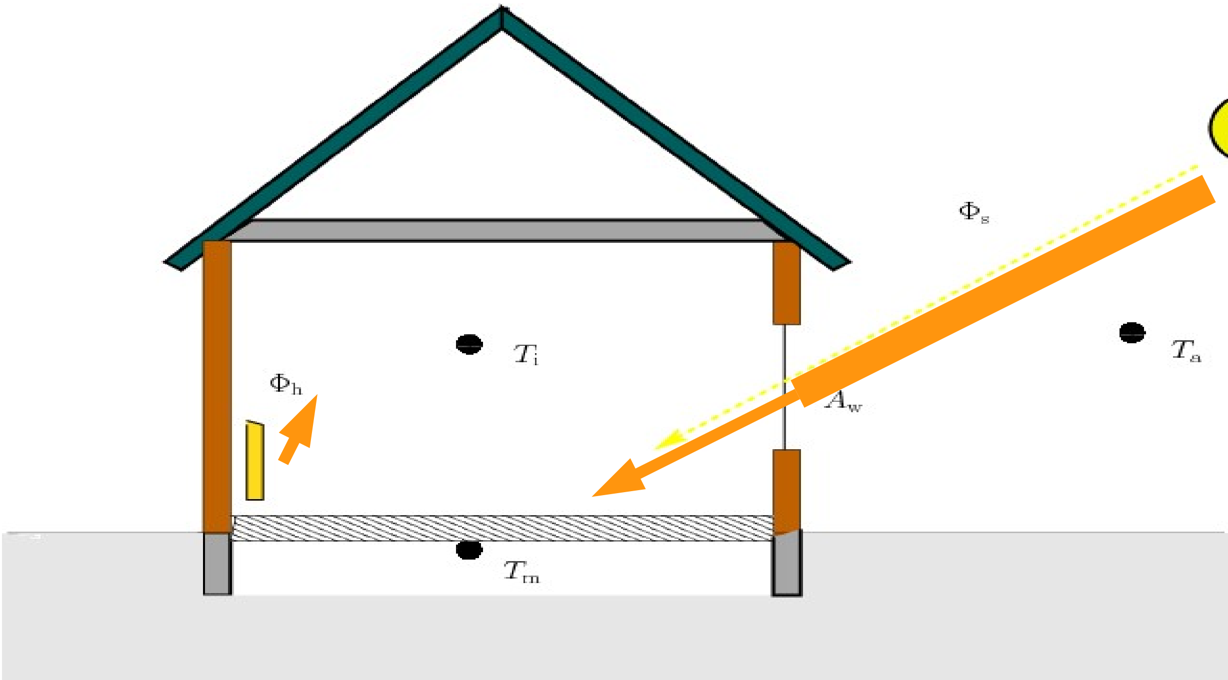
# Data-driven Energy Performance of Buildings

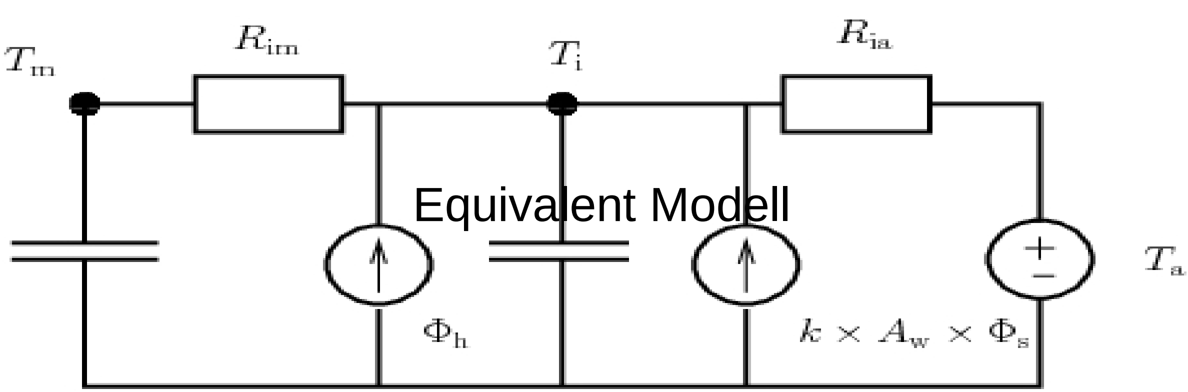
- Data-driven methods supporting the Renovation Wave Strategy
- Data-driven methods for identifying the efficiency of buildings
- Energy performance mapping of buildings
- Digital Energy Performance Certificates (EPC)
- Energy Flexibility Rating (Digital SRI)



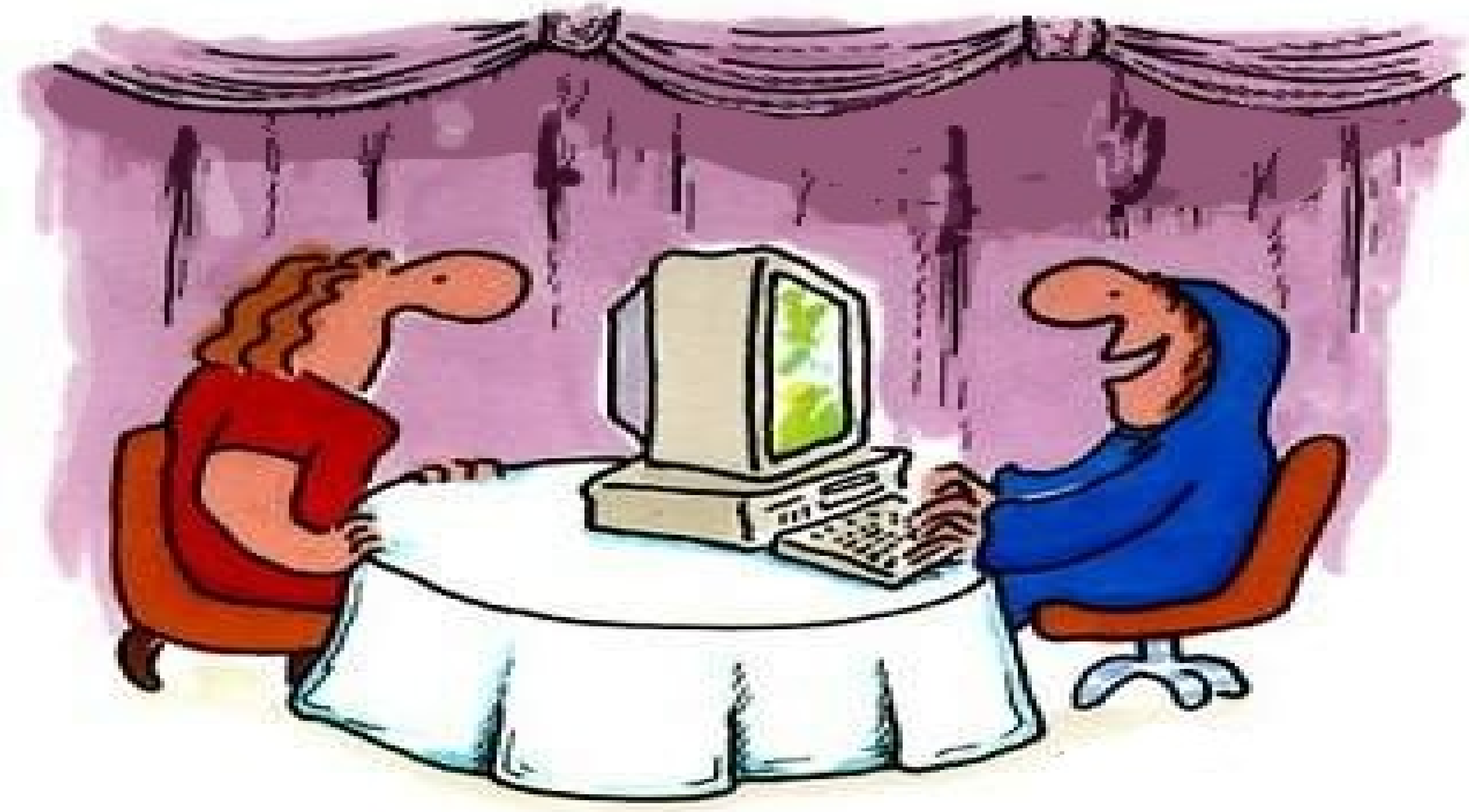

# Model for the heat dynamics




- Measurements:
  - Indoor air temp
  - Radiator heat sup.
  - Ambient air temp
  - Solar radiations
- Hidden states are:
  - Heat accumulated in the building
  - *k*: Fraction of solar radiation entering the interior

# Perspectives ...



"Skat, jeg kan se på k-værdierne, at vinduerne skal pudses"

# Data-driven Energy Performance Mapping of Buildings


Location…
Alingsås
Kungälv
Partille
Lerum
Majorna
Goteborg
Borås
Jönköping
Kungsbacka
Hjørring
Frederikshavn
Värnamo
Varberg
Kattegat
Falkenberg
Växjö
Halmstad
Kalmar
Skive
Randers
Viborg
Holstebro
Ängelholm
Silkeborg
Hässleholm
Karlshamn
Karlskrona
Herning
Helsingør
Helsingborg
Kristianstad
Hillerød
Horsens
Hørsholm
Lillerød
Eslöv
Charlottenlund
Holbæk
Ballerup
Vejle
Kalundborg
Lund
Roskilde
Fredericia
Ishøj
Copenhagen
Greve
Esbjerg
Kolding
Ringsted
Køge
Ystad
Slagelse
Trelleborg
Nyborg
Korsør
Haderslev
Næstved
Svendborg
Aabenraa
Sønderborg
Nykøbing Falster
Flensburg
Ustka
Slupsk
Schleswig
Husum
Eckernförde
Mecklenburger
Bucht
Stralsund
Rendsburg
Preetz
Ribnitz-Damgarten
Heide
Eutin
Kołobrzeg


Sønderborg, Denmark
Poor
Good
Insulation Level


Sønderborg, Denmark
Slotsgade 35
6400 Sønderborg
Year of construction
1947
Gross area
84 m²

DTU

## Bygningsoverblik

Nøgleparametre der har indflydelse på det samlede varmeforbrug grupperet efter bygningsegenskaber, vejrforhold og beboeradfærd.

*Klik* for at sortere en bestemt kolonne. *Shift + klik* for at sortere flere kolonner samtidig.
Over- og undervarmeforbrug relateret til beboeradfærden er baseret på indetemperaturen, det interne varmetilskud og ventilationsmængden specificeret i venstre kollonne. Positive værdier indikere at det faktiske varmeforbrug overskrider det beregnede varmeforbrug givet de estimerede bygningsfysiske og adfærdsrelateret forhold specificeret i venstre kolonne.

**Indetemperatur (°C)**
10 — 20 — 30

**Intern varmelast (W/m²)**
0 — 5 — 10

**Ventilation (l/s pr. m²)**
0 — 0.3 — 1

**Visning**

☐ Vis absolute værdier

Update

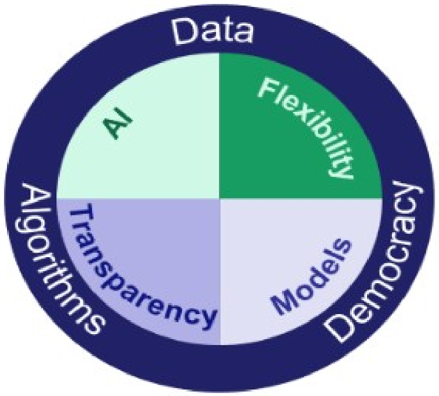
| | | | VARMEBUDGET | | | | | BEBOERADFÆRD |
|---|---|---|---|---|---|---|---|---|
| ADRESSE | OPFØRSELSÅR | BOLIGAREAL | ISO. | INF. | I/O | SOL. | FJV. | OVER-/UNDERFORBRUG |
| F...vej 10 | 1969 | 163 m² | 87% | 8% | 5% | 12% | 88% | 19% |
| L. S...vej 2 | 1963 | 140 | 90 | 9 | 2 | 16 | 84 | 30% |
| H. I...vej 5 | 1966 | 111 | 81 | 15 | 4 | 10 | 90 | 35% |
| A...vej 39 | 1965 | 160 | 74 | 16 | 10 | 15 | 85 | 4% |
| P. G...vej 5 | 1965 | 173 | | | | | | |
| G. A...vej 29 | 1965 | 123 | 80 | 13 | 7 | 17 | 83 | 24% |
| M...gade 23 | 1953 | 127 | | | | 17 | 83 | |
| G...vej 3 | 1967 | 137 | 84 | 9 | 7 | 9 | 91 | 7% |

**VARMEBUDGET**

Fordeling af varmetab og varmetilskud.

# Summary

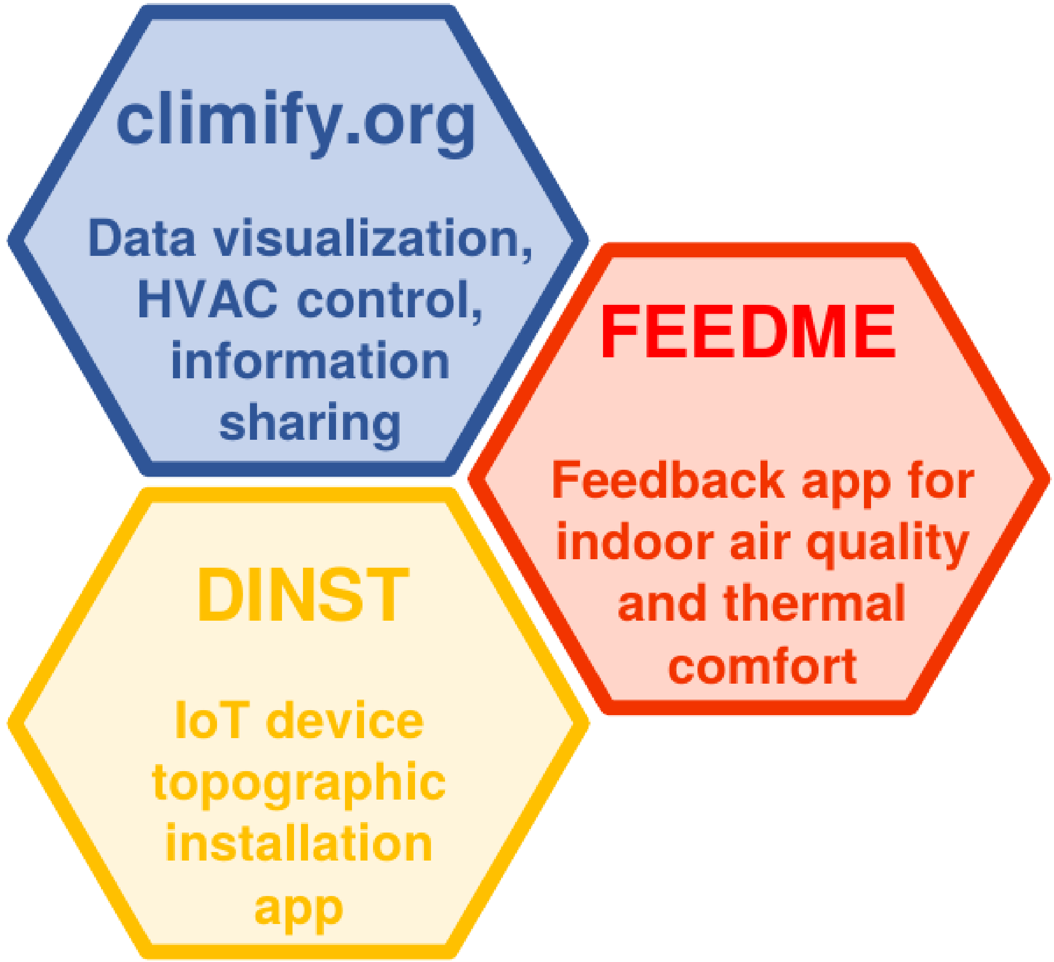
- The future weather-driven energy system calls for digitalization of the energy systems in Smart Cities.
- We need **a deep digitalisation** (AI, IoT, Cloud/Fog/Edge Computing, etc.)
- We need **transparent**, **safe** and **democratic** solutions
- We need **data hubs** for energy related streaming data (like **Center Denmark**)
- We need a **Business Ecosystem** with **Living Labs**
- We are looking forward to EU's upcoming 'Digitalisation of Energy Action Plan'



## Case study

# Service-based Control of Indoor Comfort

# climify.org: the platform



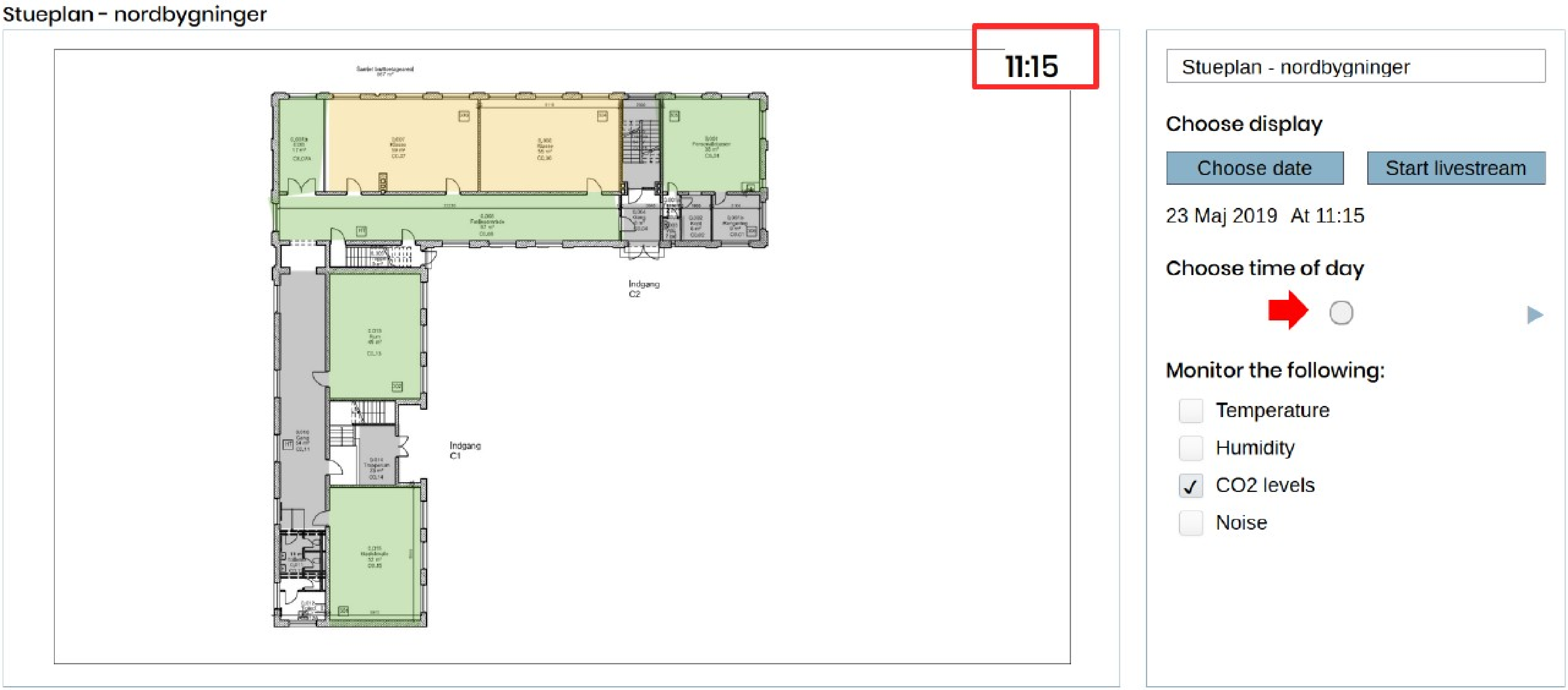

CITIES
Centre for IT Intelligent Energy Systems



FED FLEXIBLE ENERGY DENMARK

# CLIMIFY DINST: The Vendor-Neutral Device Installation App (indoor location using google map API services)

# https://climify.org



# The next level of HVAC Control: FeedMe, the Feedback App (BLE Beacons)


Easy

Taylored made indoor climate

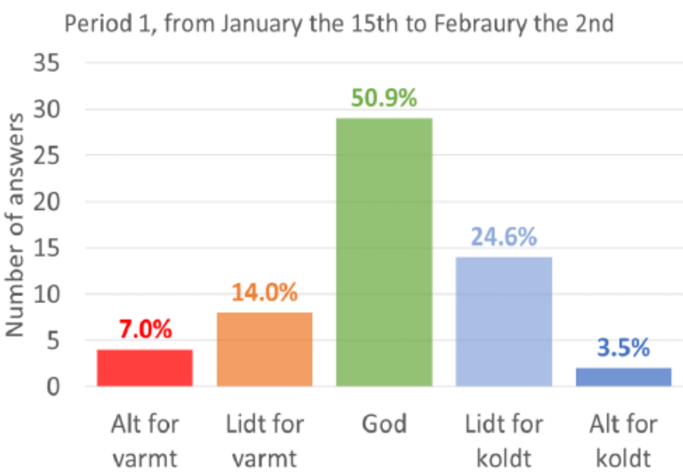
Democratic: Mediate needs

Predictive

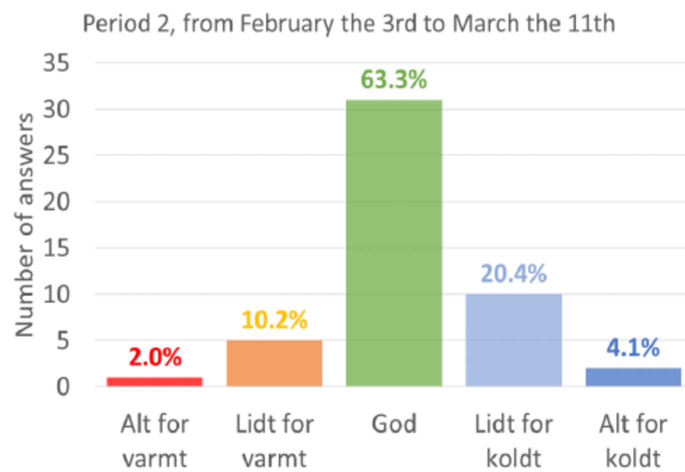
# The next level of HVAC Control: FeedMe, the Feedback App (BLE Beacons)

DTU

Standard settings (22° C)




FEEDME Perception-based controll



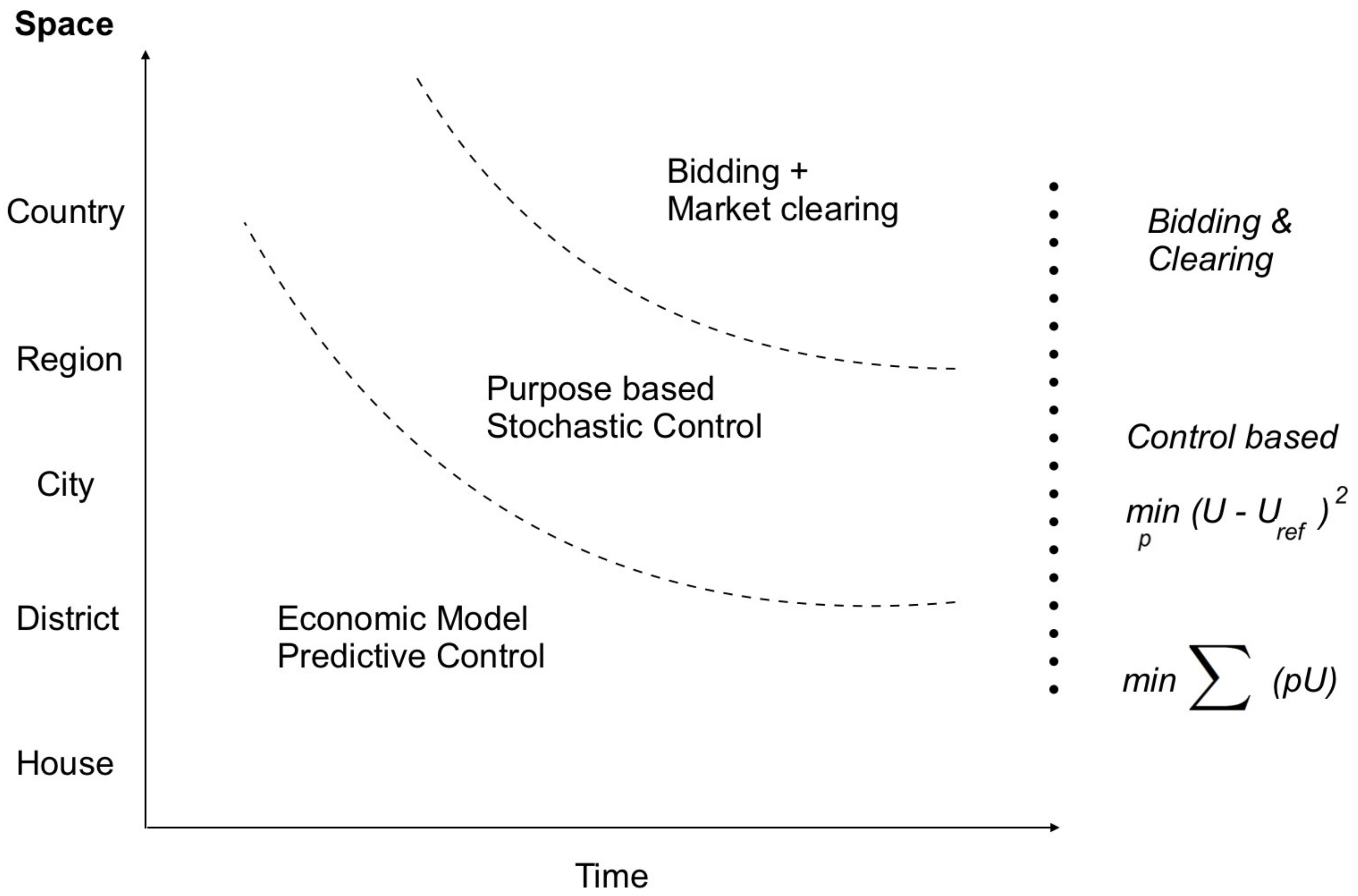

Easy

Taylored made indoor climate

Democratic: Mediate needs

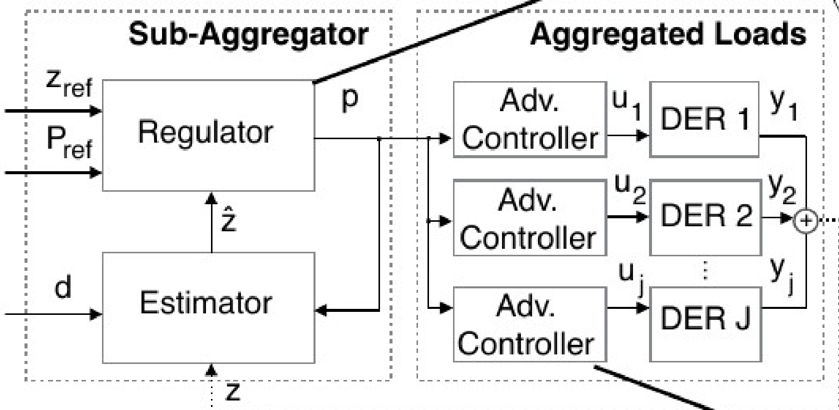
Predictive

# AS4.0 + SE-OS: Hierarchy of Optimatization and Control Problems



# Proposed methodology
# Control-based methodology

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

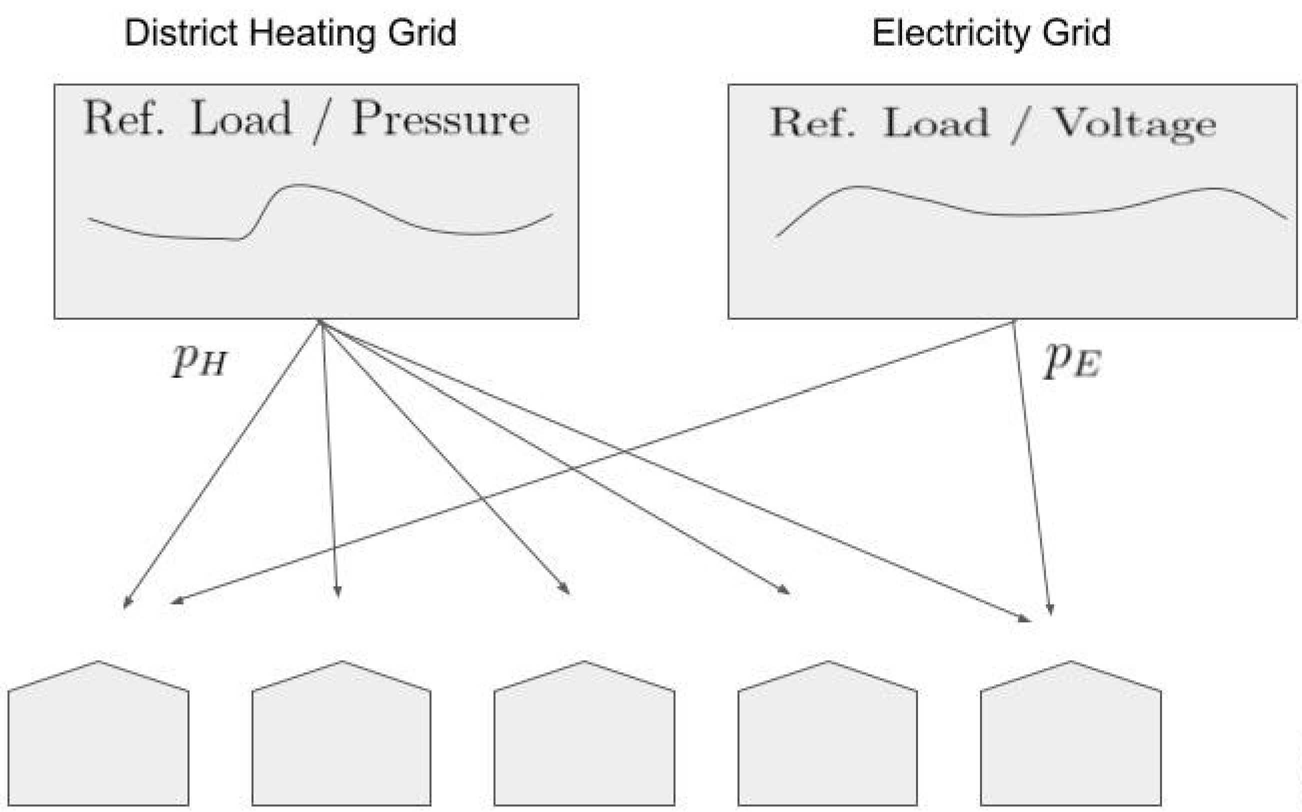



$$\min_{u} \quad \mathrm{E}\Big[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)\Big]$$
$$\begin{aligned} \text{s.t.} \quad x_{k+1} &= Ax_k + Bu_k + Ed_k, \\ y_k &= Cx_k, \\ y_k^{min} \le y_k &\le y_k^{max}, \\ u_k^{min} \le u_k &\le u_k^{max} \end{aligned}$$

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

# Sector coupling

**Smart-Energy OS for multi-supply systems (here DH and Electricity)**




$$\arg\min_{p} (L(p) - ref_{load})^2$$

$$\arg\min_{U_H, U_E} \sum_{k=1}^{N} (p_H U_H + p_E U_E)$$

s.t.

$$Temp(U_H, U_E) \in \text{Comfort}$$