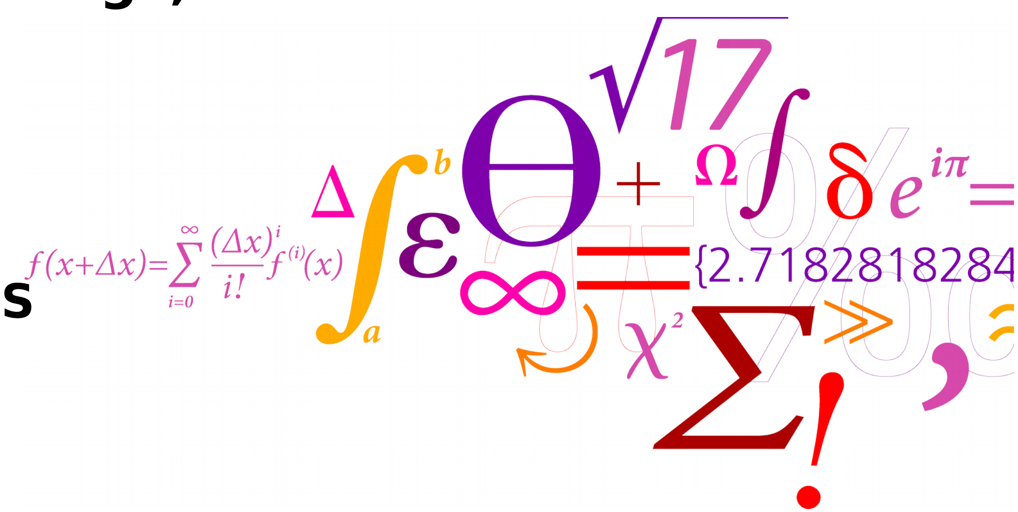
CITIES
Centre for IT Intelligent Energy Systems

Methods for using existing and new data

Results from CITIES, SCA and REBUS projects

IDA Energi: Cognitive Buildings, November 2017

Henrik Madsen,
Results from REBUS and CITIES
www.henrikmadsen.org



DTU Compute
Department of Applied Mathematics and Computer Science

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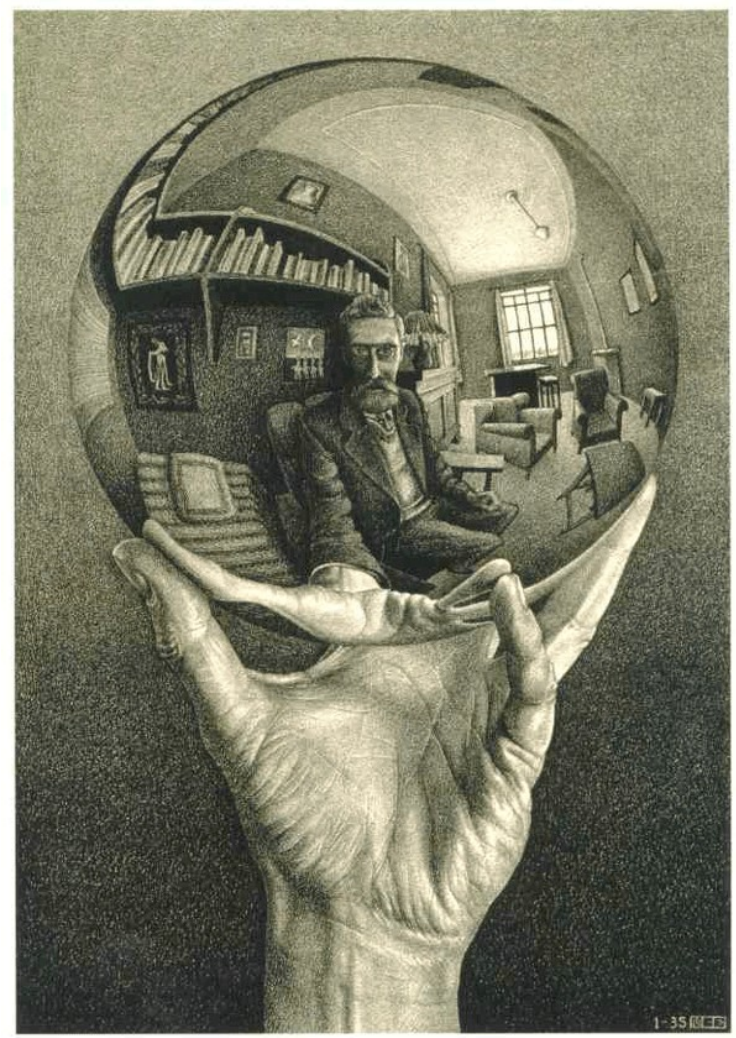

- Using meter data for characterizing the thermal performance of buildings
- Intelligent control of power load using data
- Smart-Energy OS
- Optimal control (Energy efficiency, Cost, Emission – or a combination)

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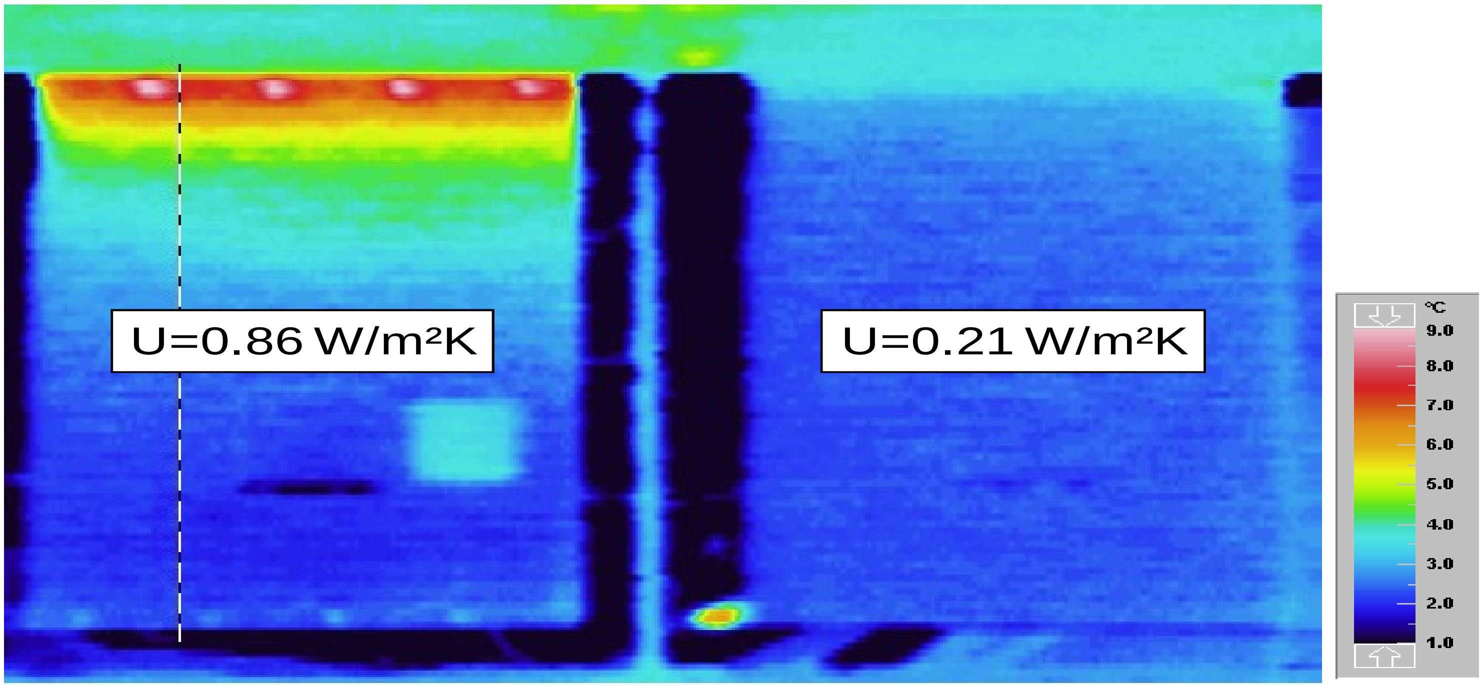
Case Study No. 1

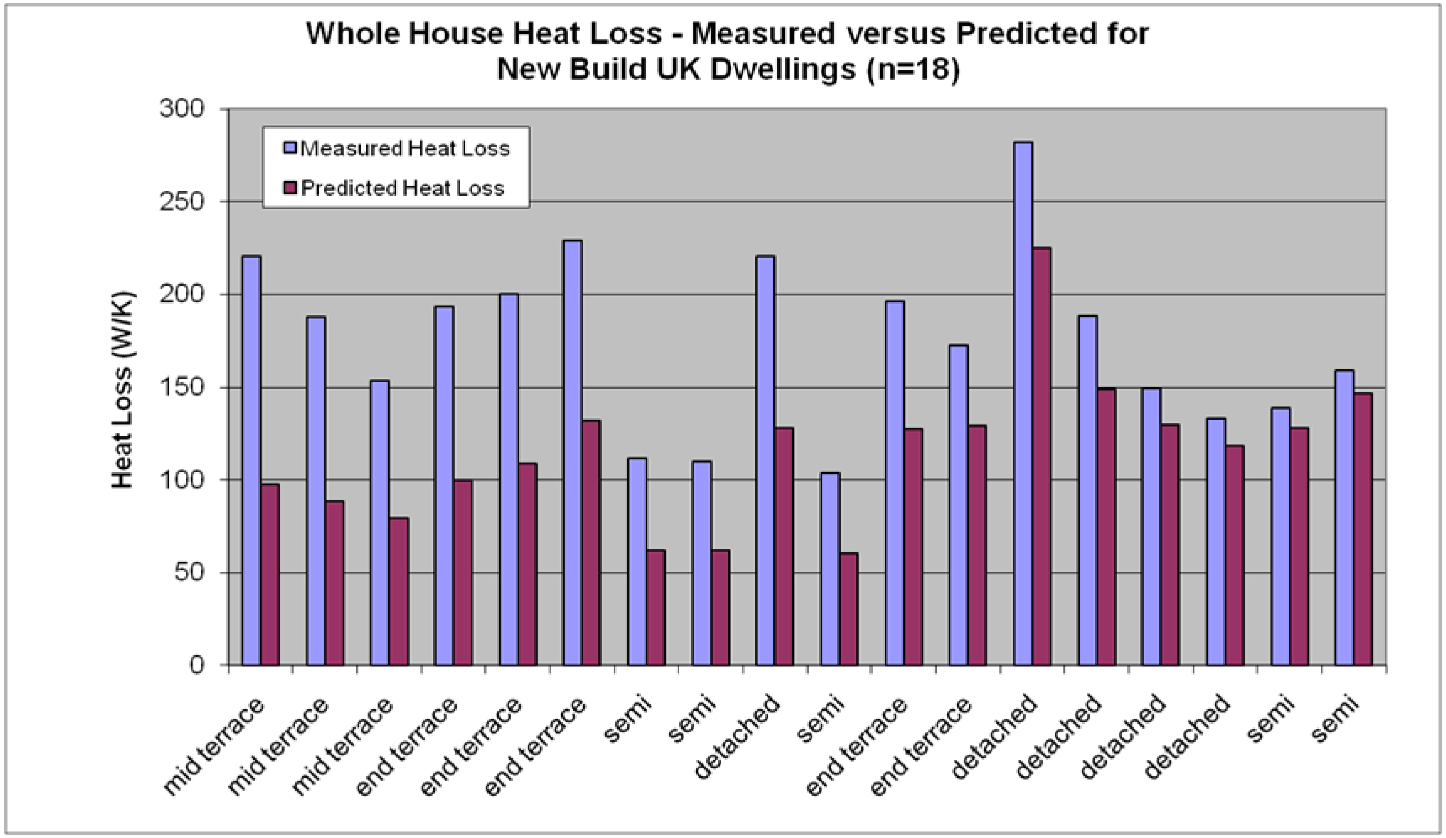
Modelling of Thermal Performance of Buildings using Smart Meter Data

Example



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

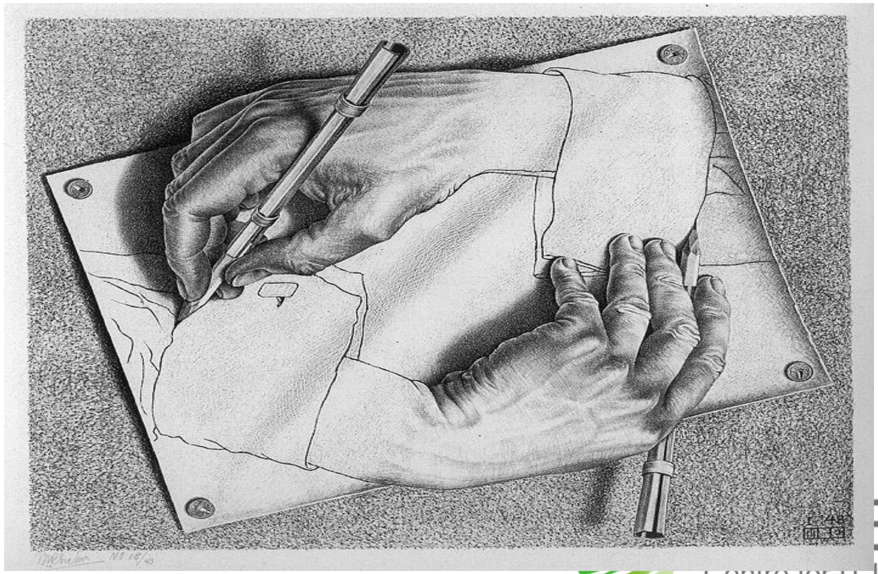
Examples (2)



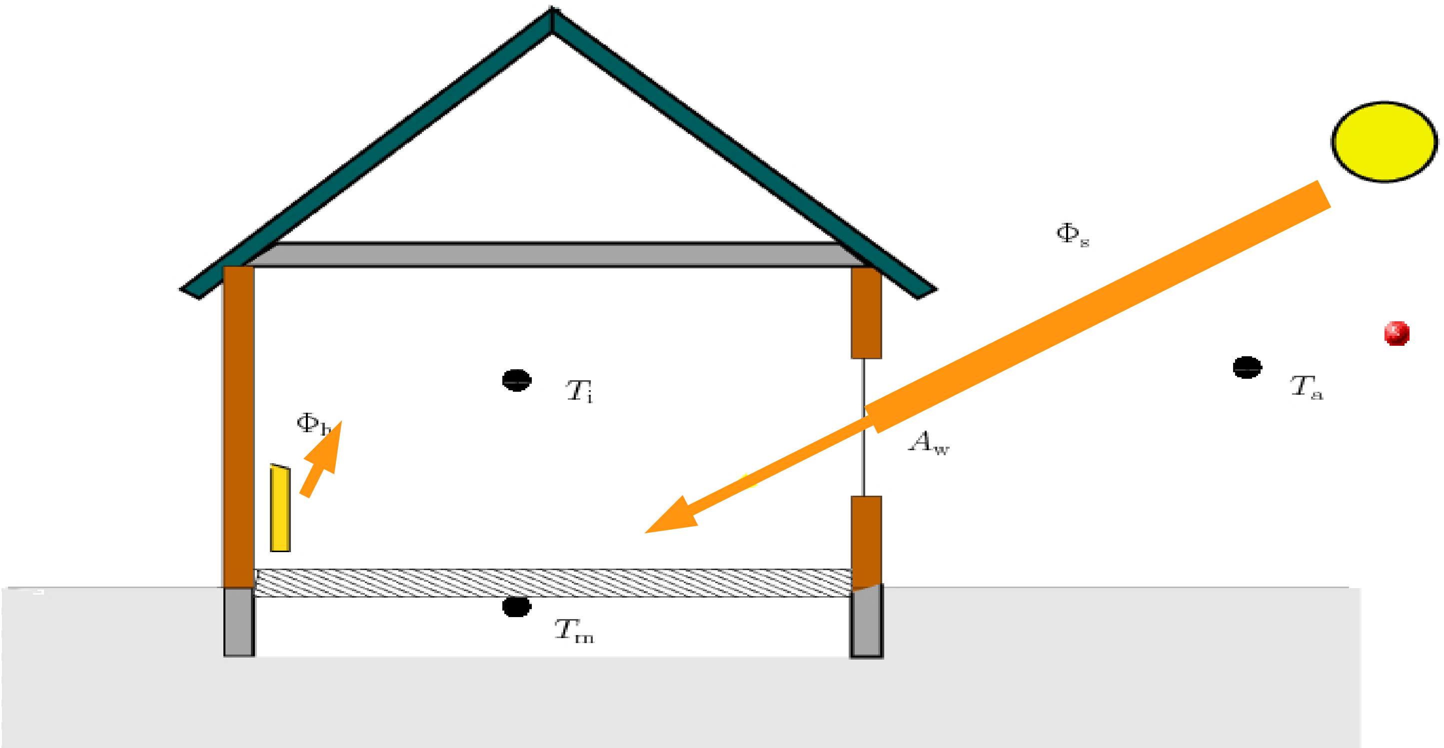
Measured versus predicted energy consumption for different dwellings

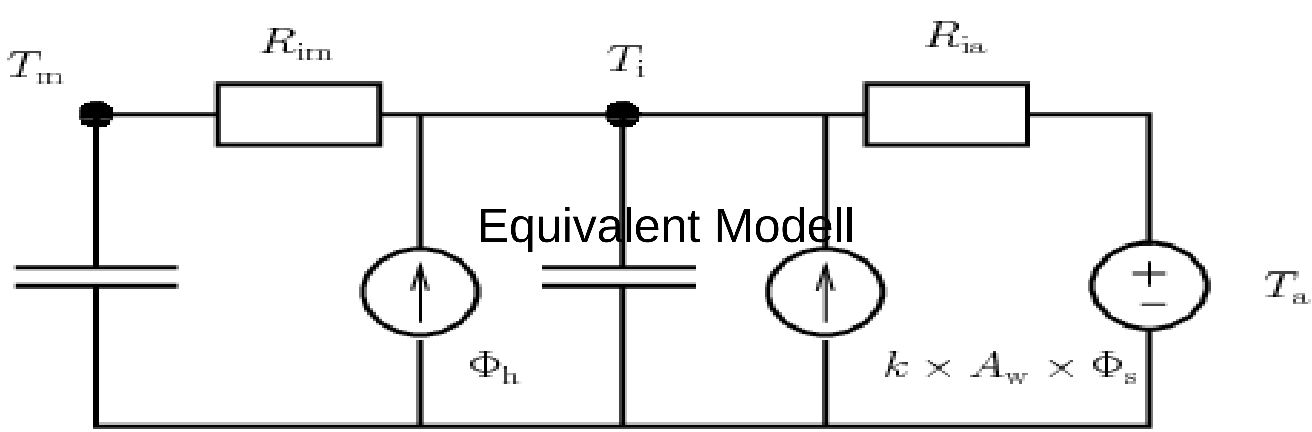
Energy Labelling of Buildings

- Today building experts make judgements of the energy performance of buildings based on drawings and prior knowledge.
- This leads to 'Energy labelling' of the building
- However, it is noticed that two independent experts can predict very different consumptions for the same house.



Model for the heat dynamics



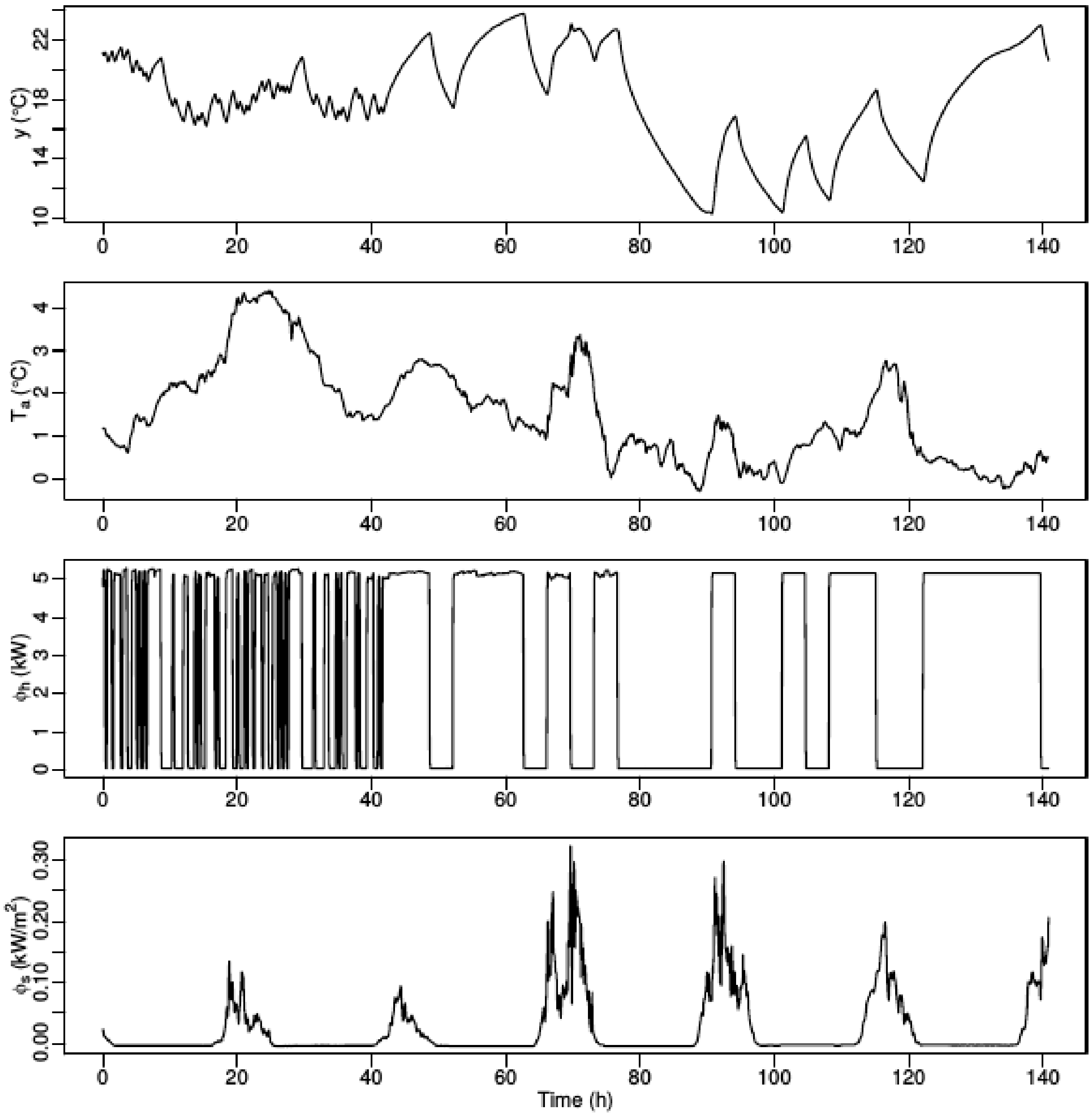


- Measurements:
  - Indoor air temp
  - Radiator heat sup.
  - Ambient air temp
  - Solar radiations
- Hidden states are:
  - Heat accumulated in the building
  - *k*: Fraction of solar radiation entering the interior

DATA

Measurements of:

- y_t Indoor air temperature
- T_a Ambient temperature
- Φ_h Heat input
- Φ_s Global irradiance



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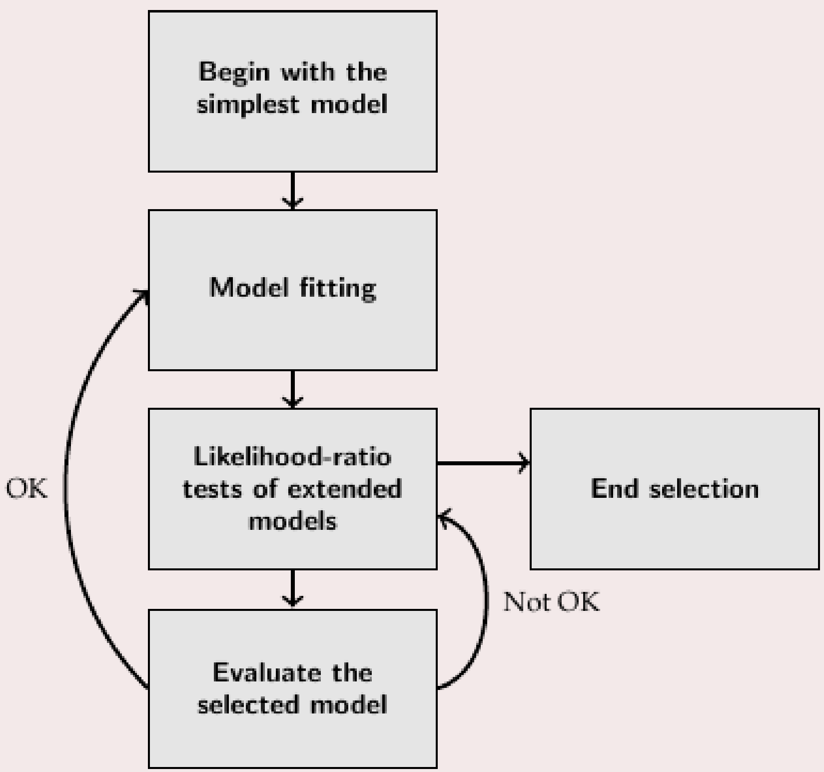
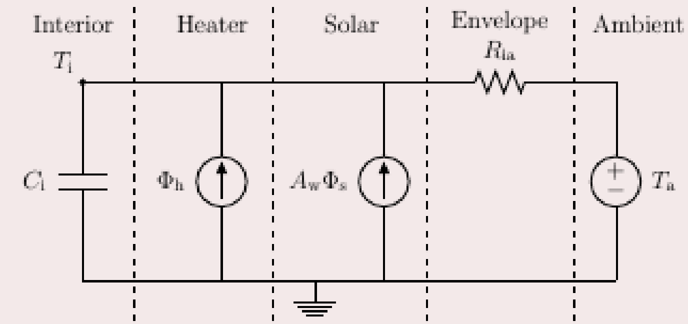
SELECTION PROCEDURE

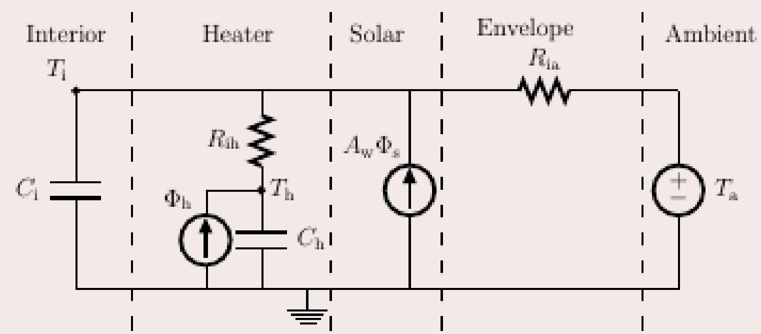
Iterative procedure using statistical tests



Simplest model



First extension: heater part



Start	$Model_{Ti}$			
$l(\theta;\mathcal{Y}_N)$	2482.6			
m	6			
1	$Model_{TiTe}$	$Model_{TiTm}$	$Model_{TiTs}$	$Model_{TiTh}$
$l(\theta;\mathcal{Y}_N)$	3628.0	3639.4	3884.4	3911.1
m	10	10	10	10
2	...			

Results

	UA W/°C	σ_{UA}	gA^{max} W	wA_E^{max} W/°C	wA_S^{max} W/°C	wA_W^{max} W/°C	T_i °C	σ_{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

Perspectives (2)

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

Control of Indoor Climate

Log ind

hmad

••••••••

Log ind

Login med dit brugernavn og adgangskode.

Ved log ind fejl skal du kontakte
kontakt@skoleklima.dk

Centre for IT Intelligent Energy Systems

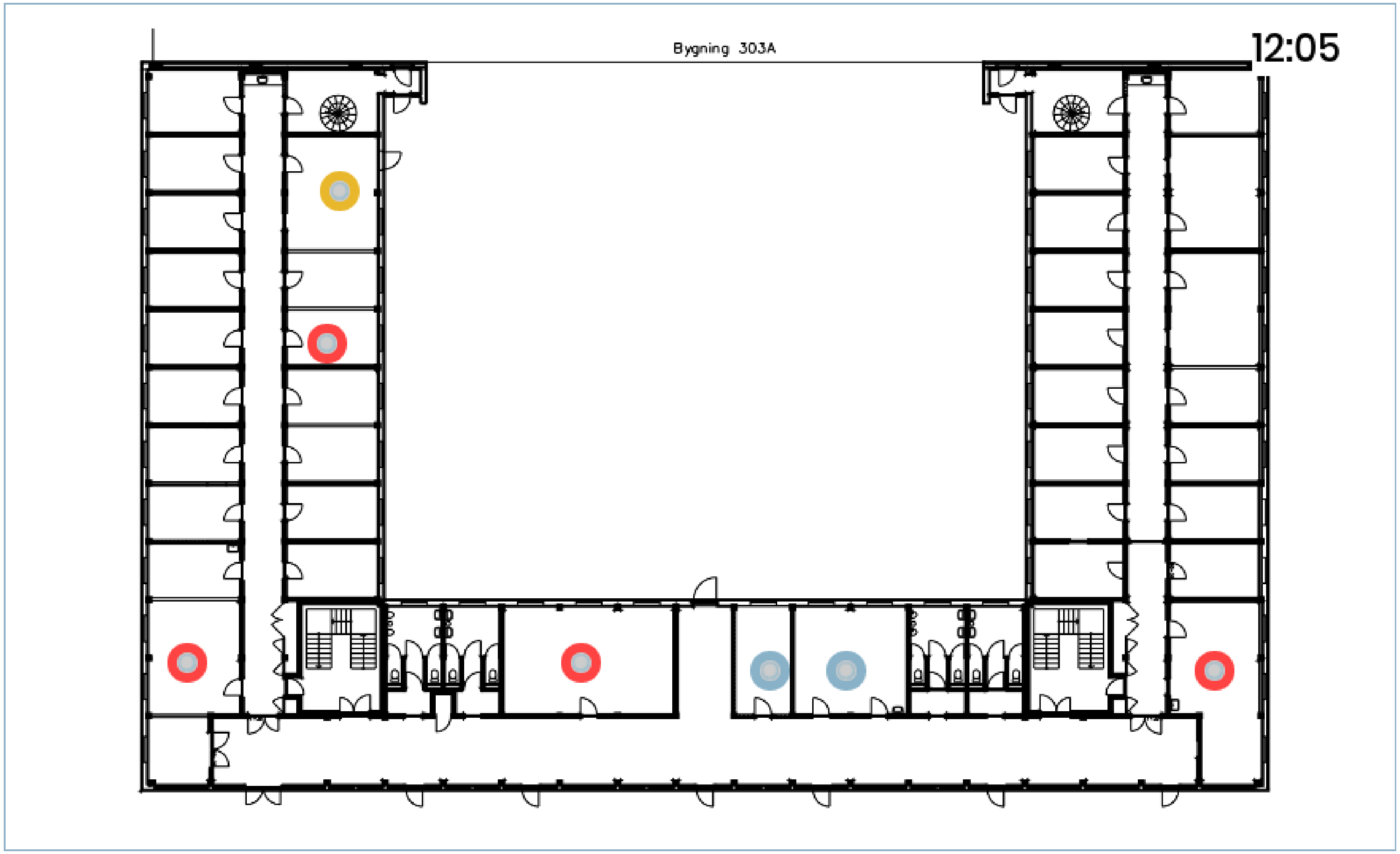
Klimaovervågning Log ud

Plantegning

Oversigt over opsatte målere

DTU303B | Vis info

B303B Ground floor



B303B Ground floor

Vælg visningsform

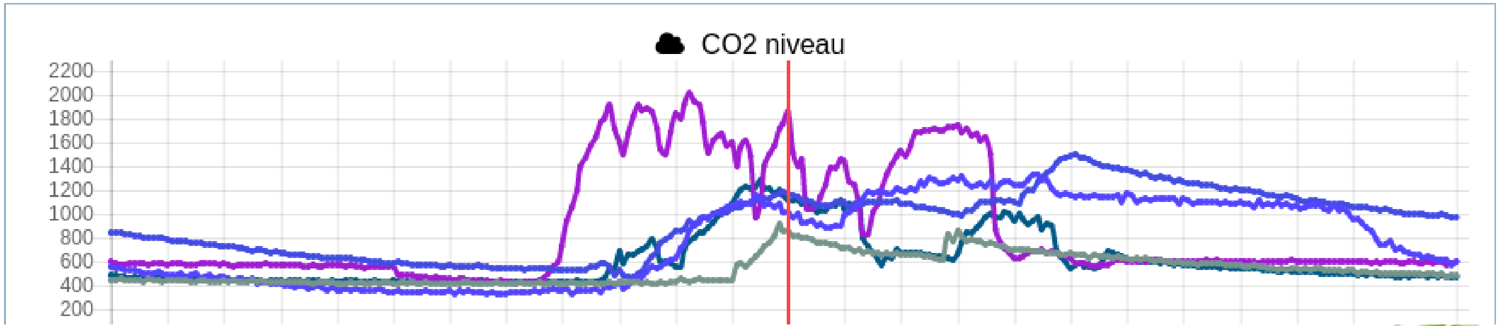
Vælg dato | Start livestream

08 November 2017 kl. 12:05

Sæt tidspunkt på dag

Overvåg følgende:

- [ ] Temperatur
- [ ] Luftfugtighed
- [x] CO2 niveau
- [ ] Støj



Graf indstillinger

Vælg størrelse

Lille

Valgt måler: Ingen måler valgt

Nulstil valgte | Opdater graf

Control of Power Consumption using the Thermal Mass of Buildings

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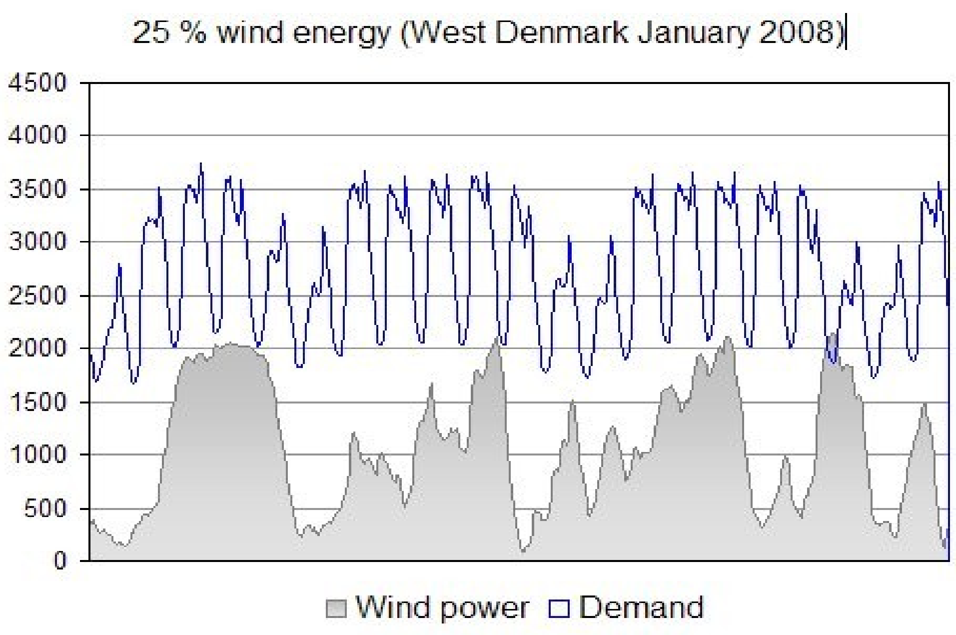
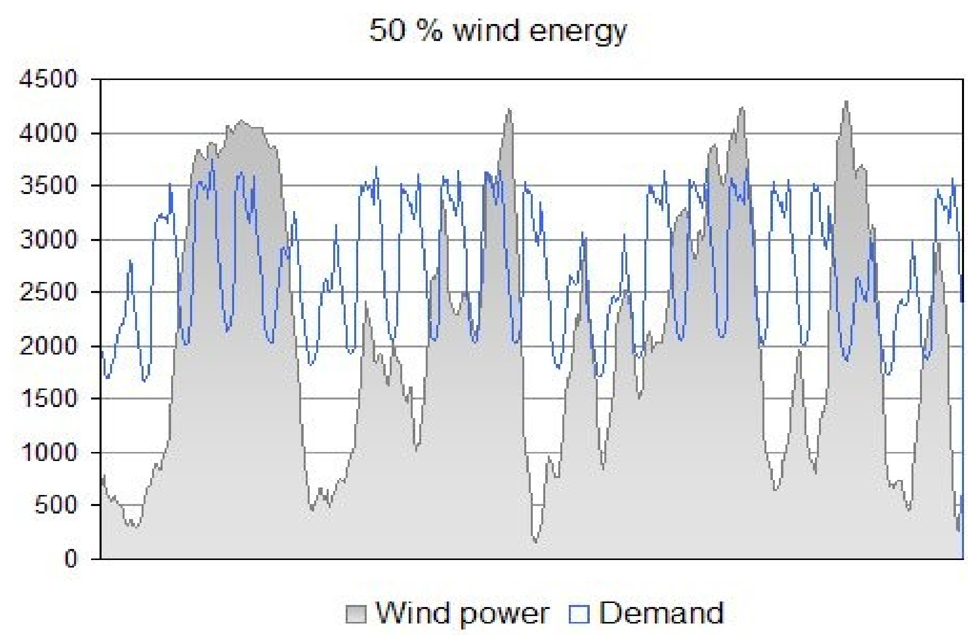
The Danish Wind Power Case

.... balancing of the power system





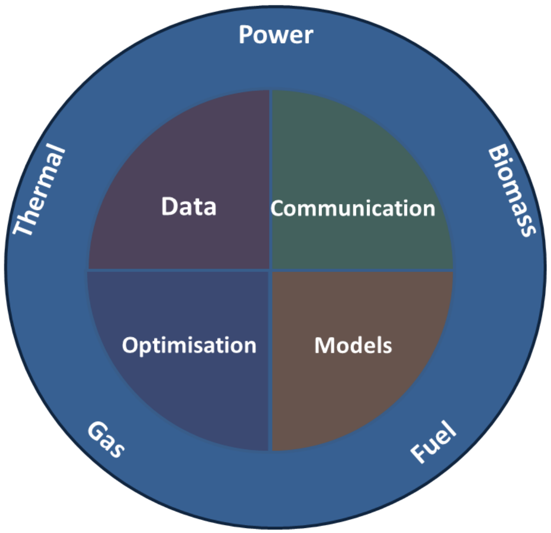
In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

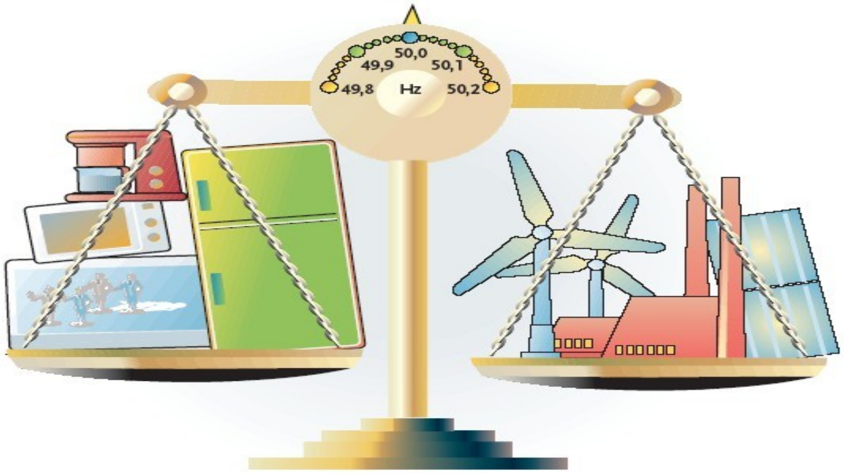
In the first half of 2017 more than 44 pct of electricity load was covered by wind power.

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

Energy Systems Integration



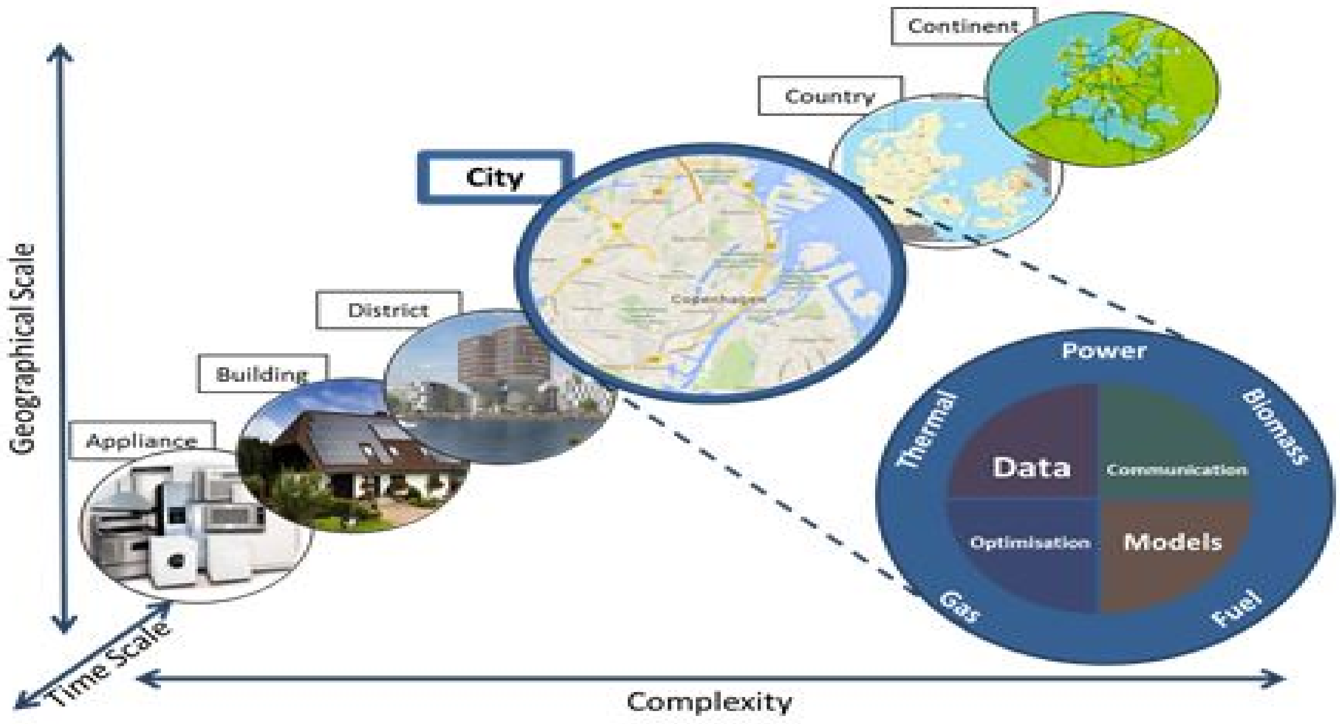


The **central hypothesis** is that by **intelligently integrating** currently distinct energy flows (heat, power, gas and biomass) using **data intelligence** we can balance very large shares of renewables, and consequently obtain substantial reductions in CO2 emissions.

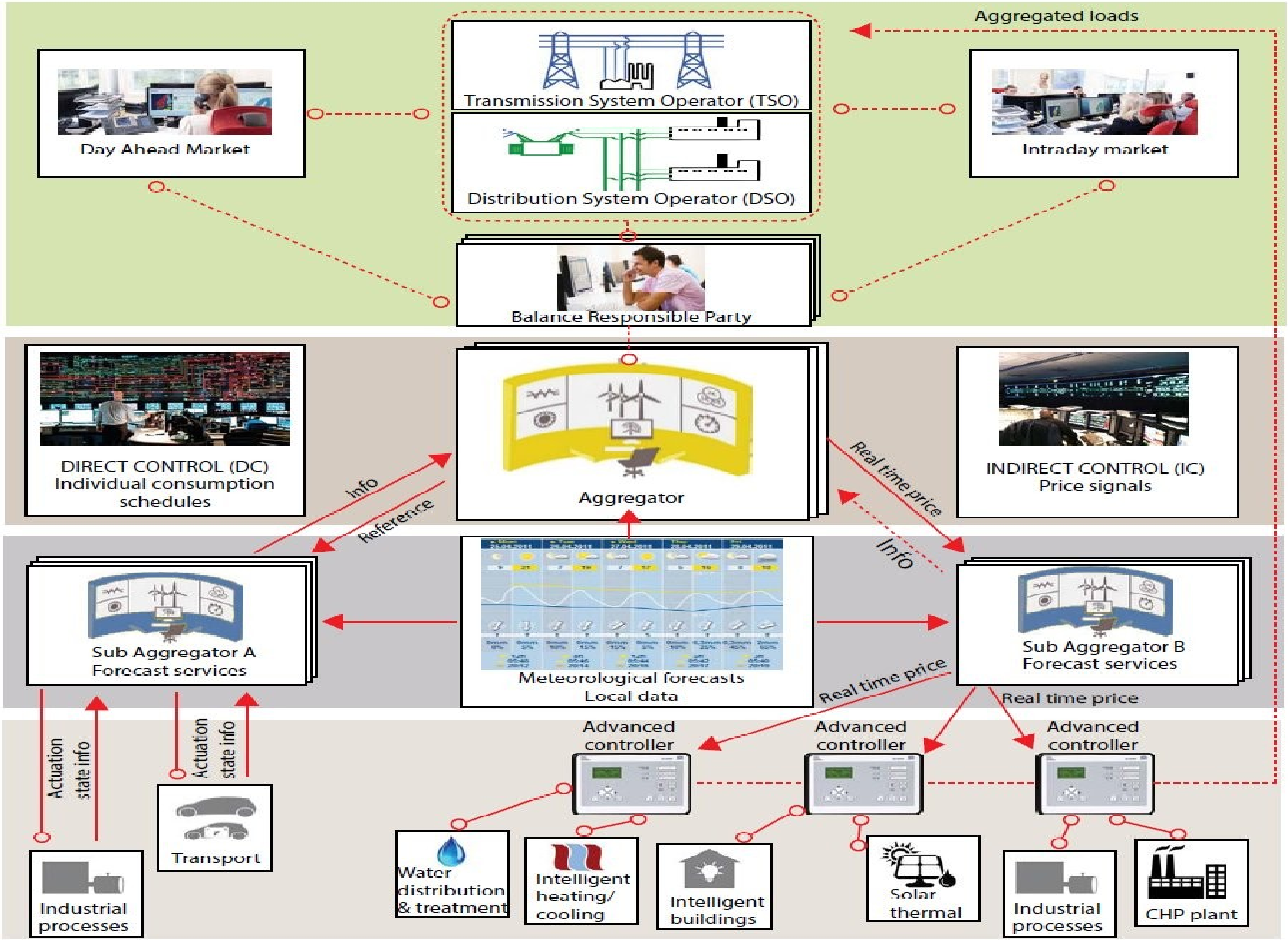
Intelligent integration will (for instance) enable lossless 'virtual' storage on a number of different time scales.

CITIES – Research Challenges

To establish methodologies and solutions for design and operation of integrated electrical, thermal, fuel pathways at all scales

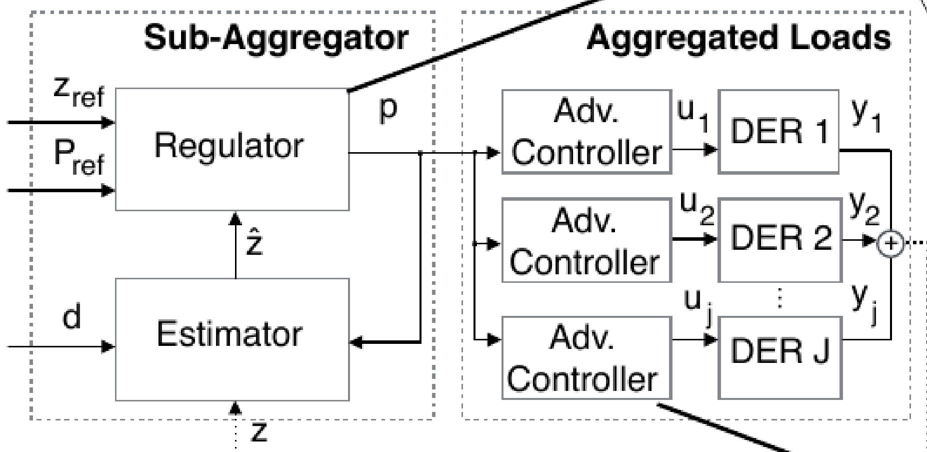


Smart-Energy OS



Proposed methodology
Control-based methodology

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

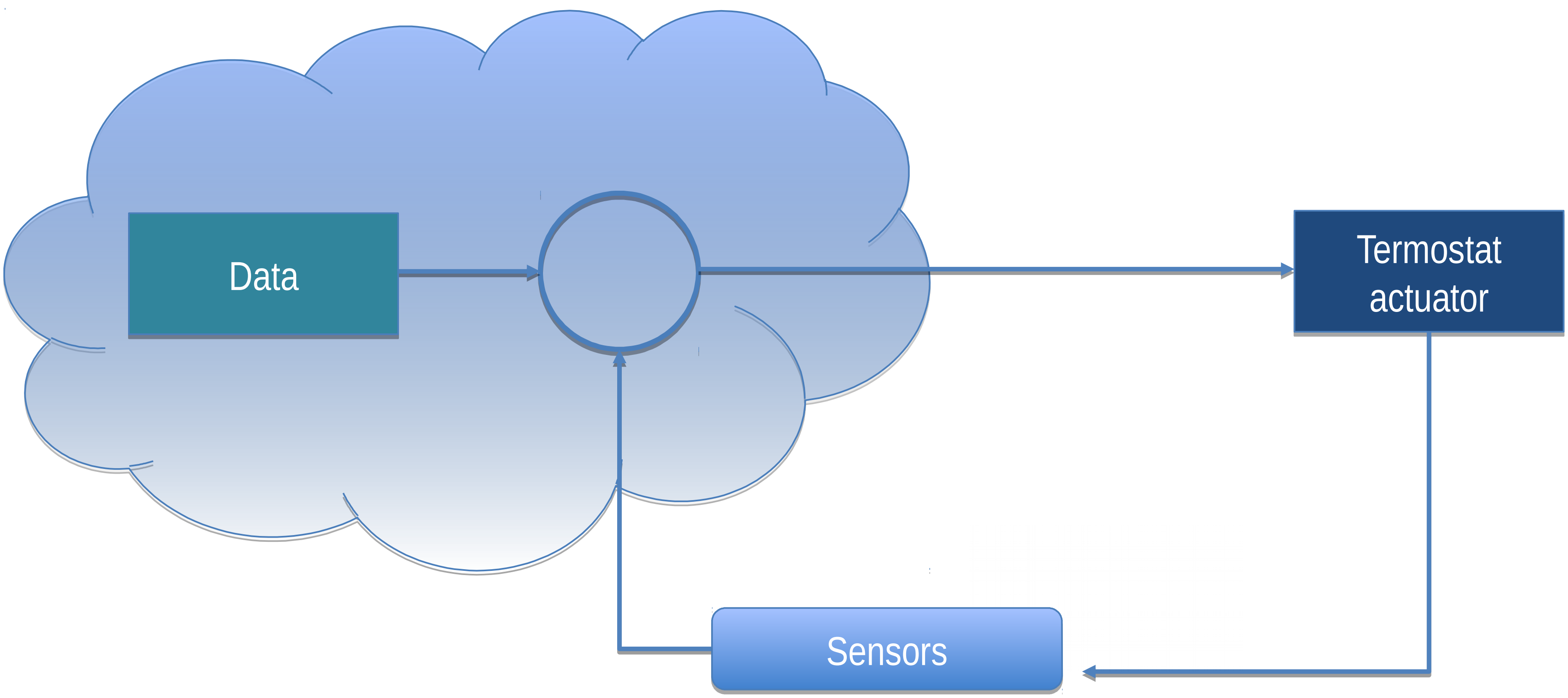


$$\min_{u} \quad \mathrm{E}[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)]$$
$$\begin{aligned} \text{s.t.} \quad x_{k+1} &= Ax_k + Bu_k + Ed_k, \\ y_k &= Cx_k, \\ y_k^{min} \le y_k &\le y_k^{max}, \\ u_k^{min} \le u_k &\le u_k^{max} \end{aligned}$$

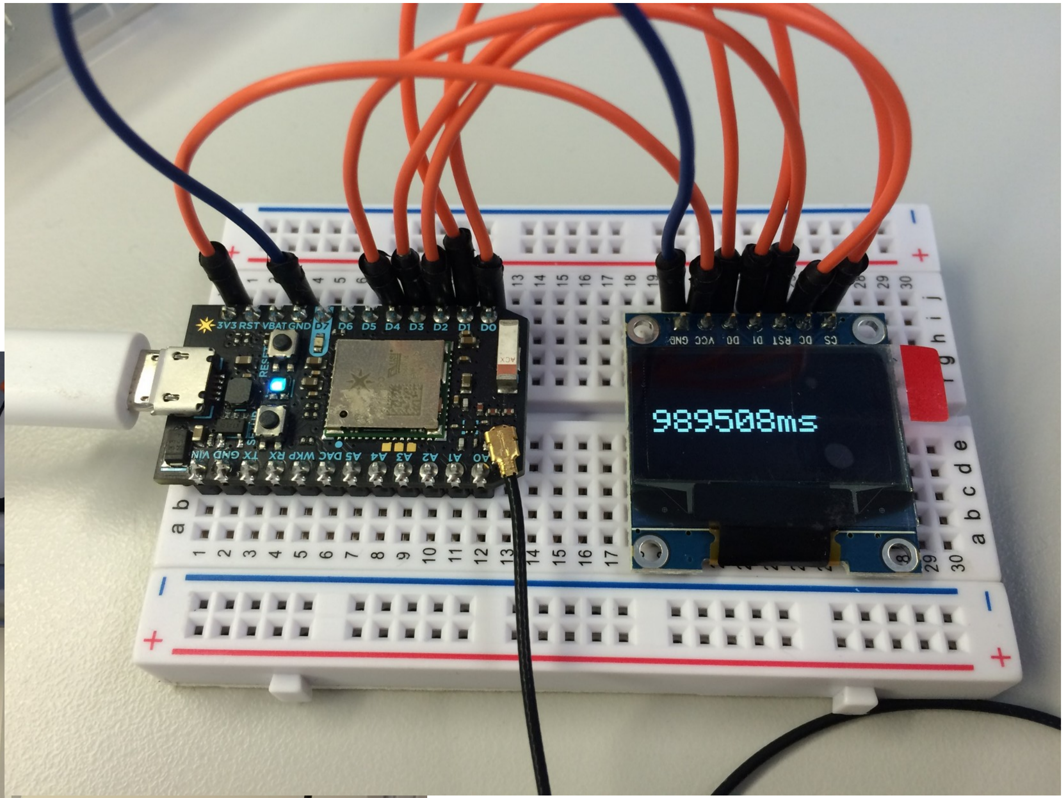
We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

```r
# slow approach, but we are sure things get do
# Try to parallelize anyway
require(multicore)
numcores<-multicore:::detectCores()
mclapply(
  1:N, 
  function(i,data) {
    print(paste(i, "/", N))

    # Find the indices of rows corresponding to
    j <- which(data$dt_agg %in% aggdata$dt[i])

    # Filter out those who are NA
    j <- j[!is.na(data$last_one_min_power[j])]

    # Count number of readings
    aggdata$num_readings[i] <- length(j)
```

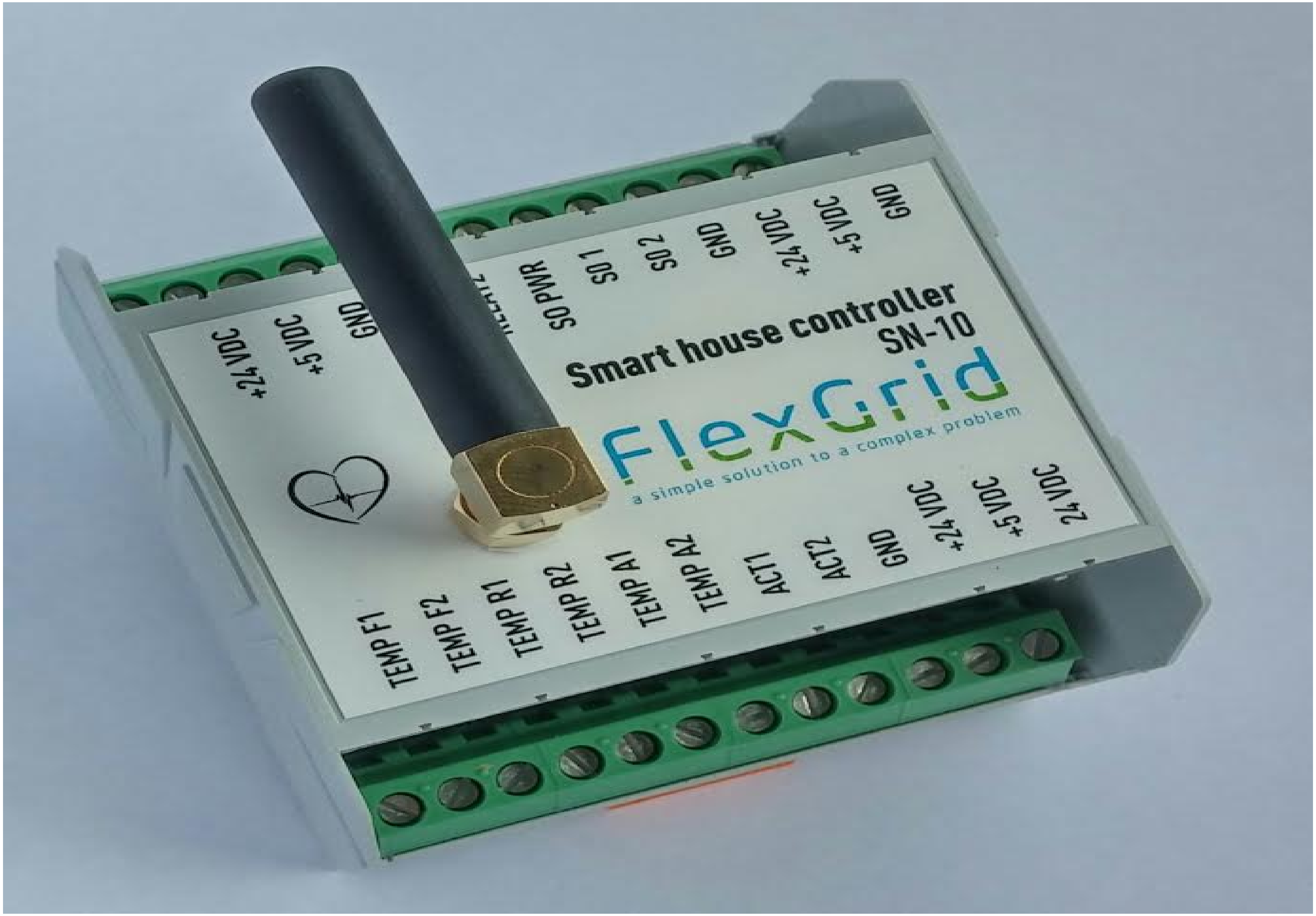
SE-OS
Control loop design – **logical drawing**



Lab testing ....



SN-10 Smart House Prototype



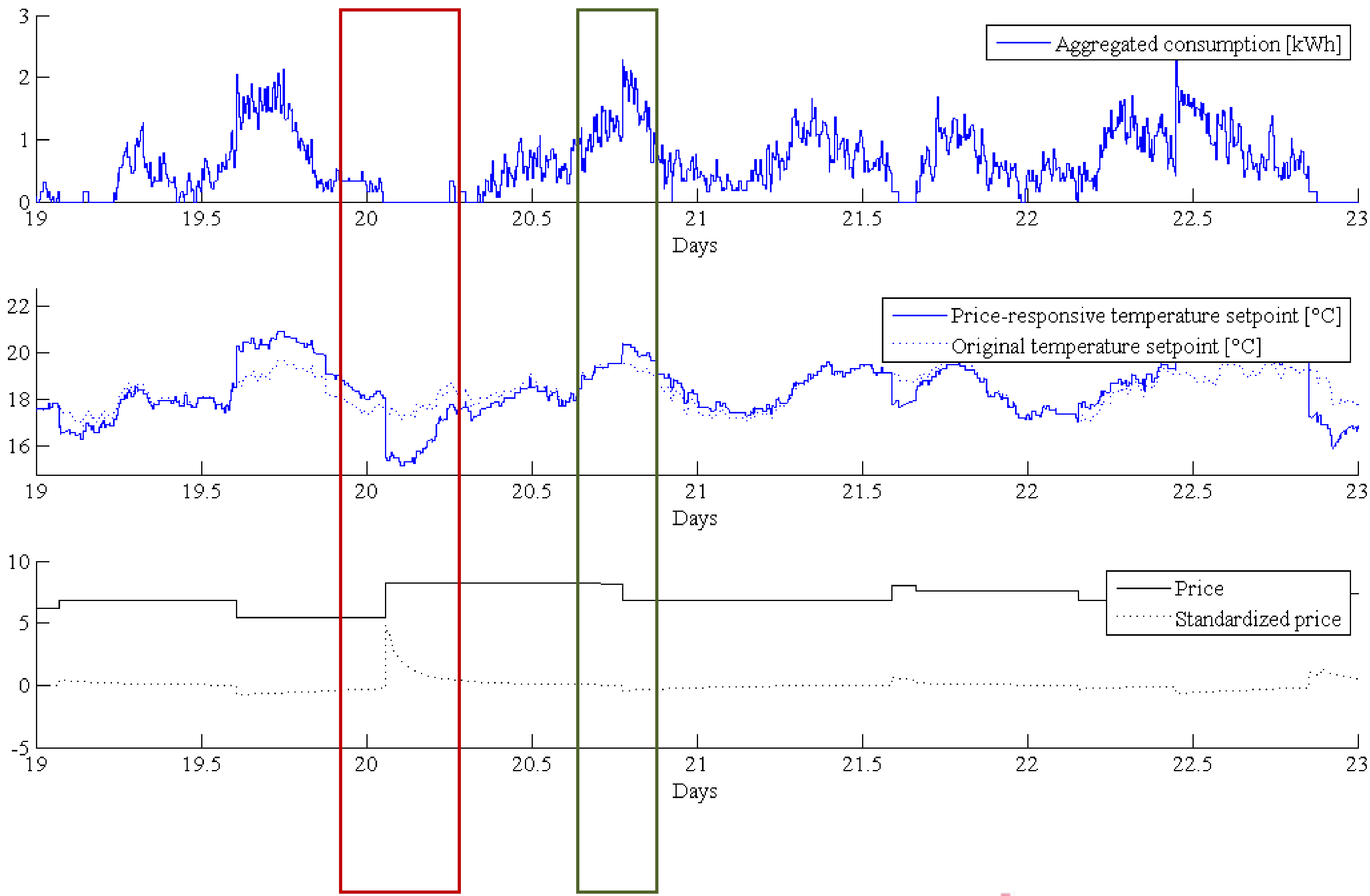
SE-OS Characteristics

- '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

Case study No. 2

Control of Power Consumption using the Thermal Mass of Buildings (Peak shaving)

Aggregation (over 20 houses)



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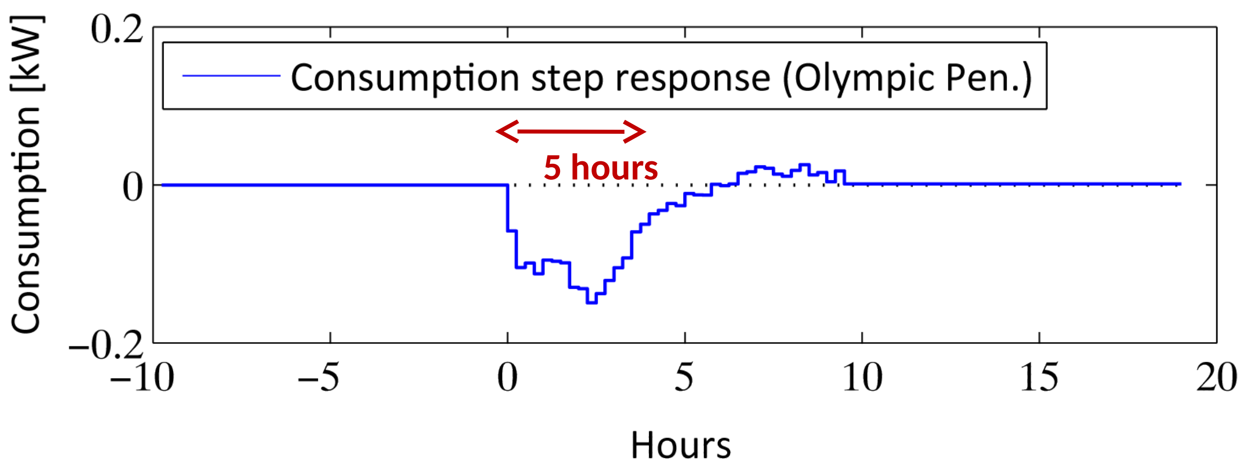
Non-parametric Response on Price Step Change

Model inputs: price, minute of day, outside temperature/dewpoint, sun irrandiance

Olympic Peninsula



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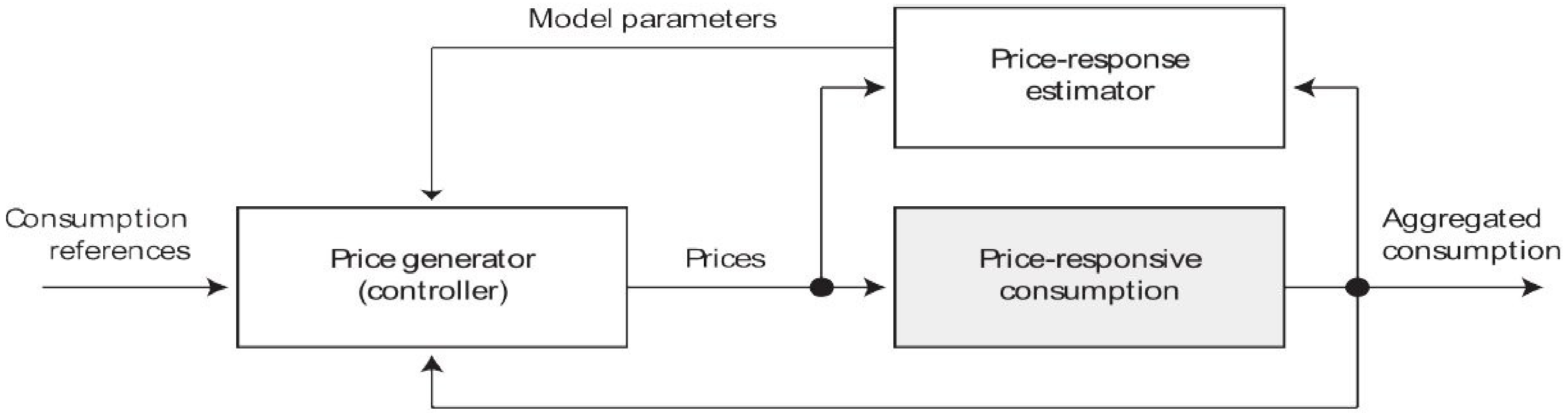
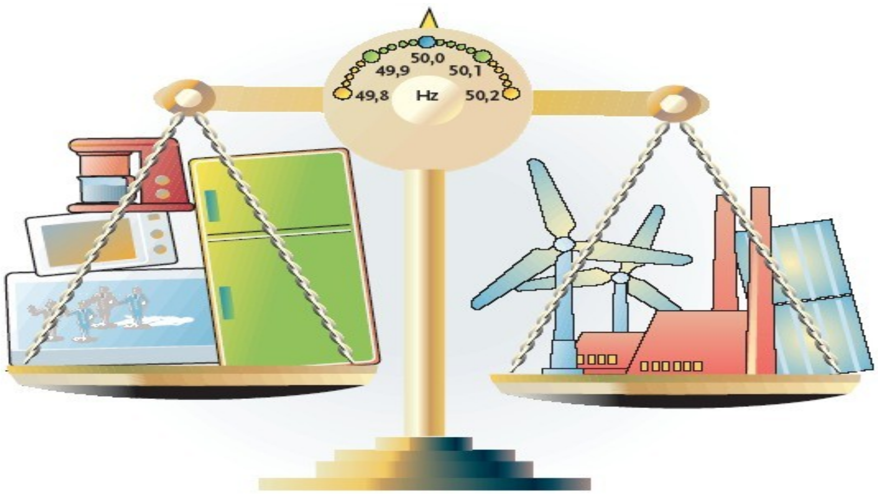
Control of Energy Consumption

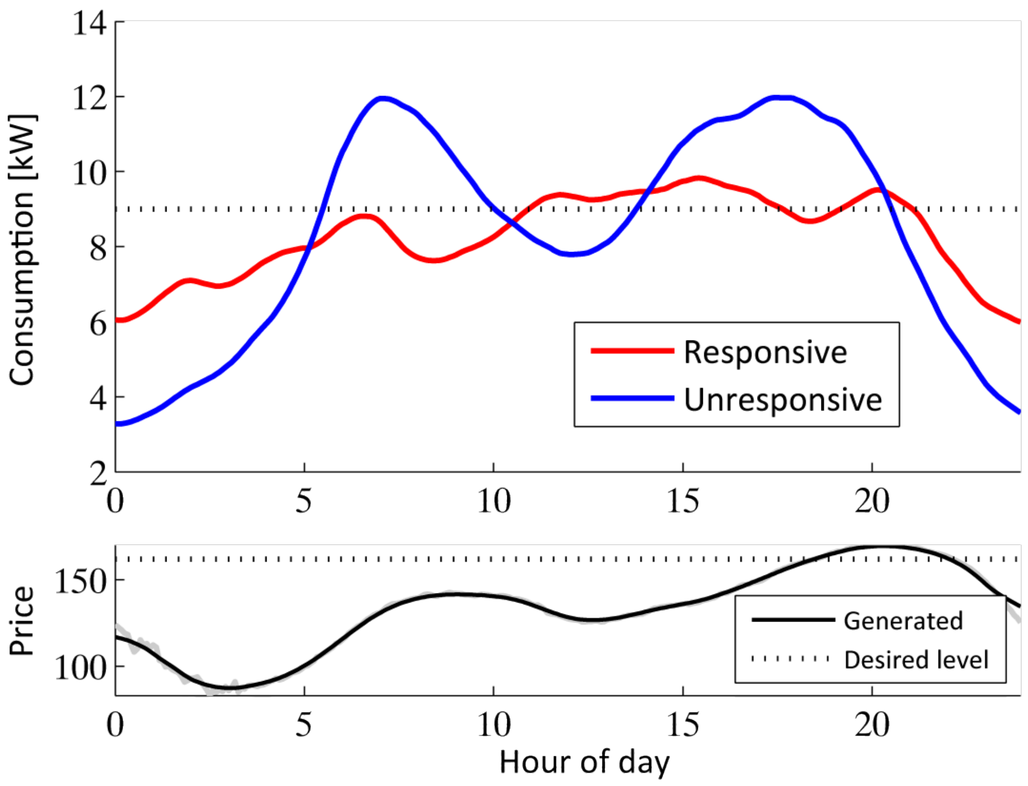




Control performance

With a price penality avoiding its divergence

- Considerable **reduction in peak consumption**
- Mean daily consumption shift



Case study No. 3

Control of Heat Pumps for buildings with a thermal solar collector (minimizing cost)

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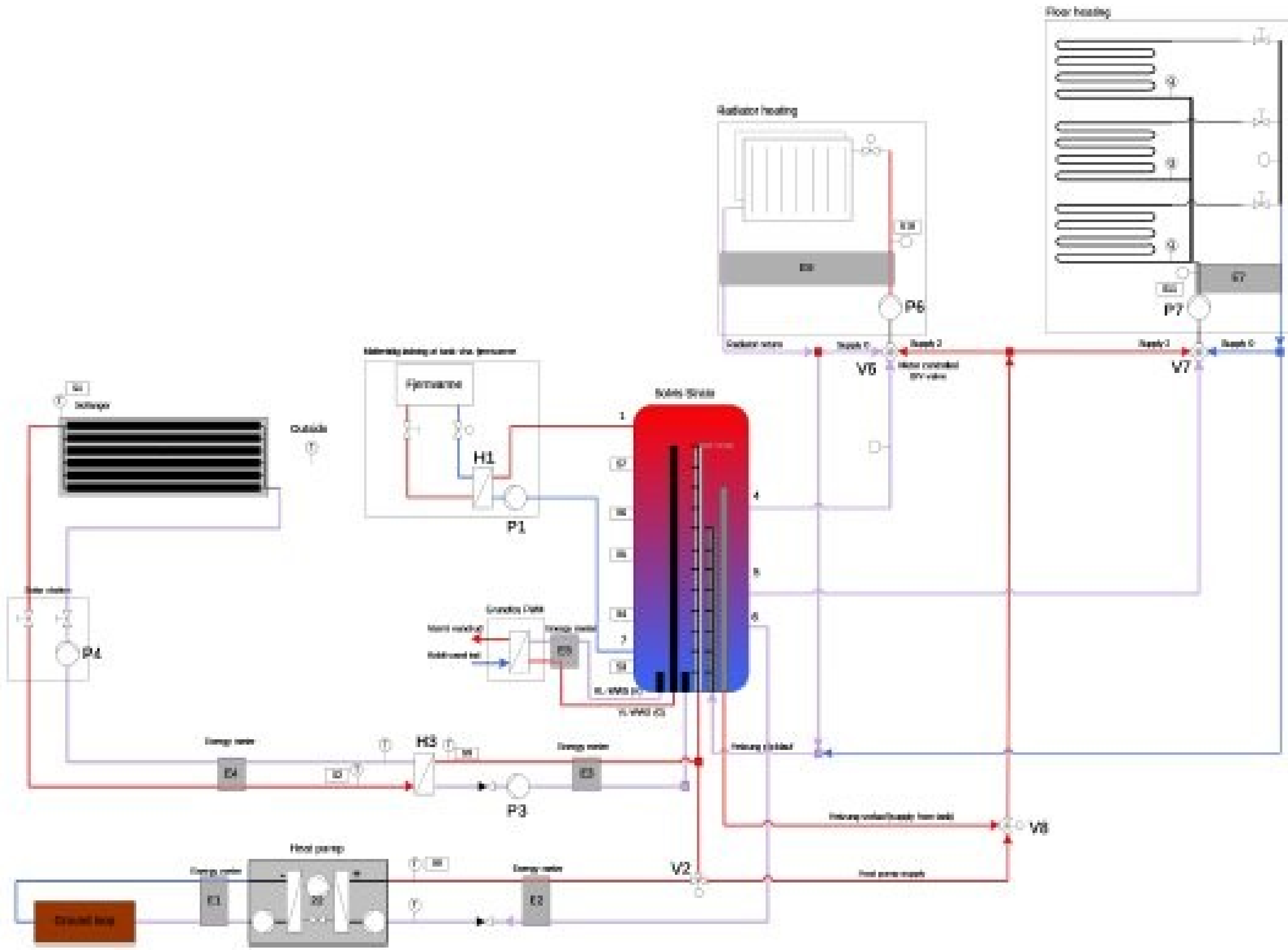
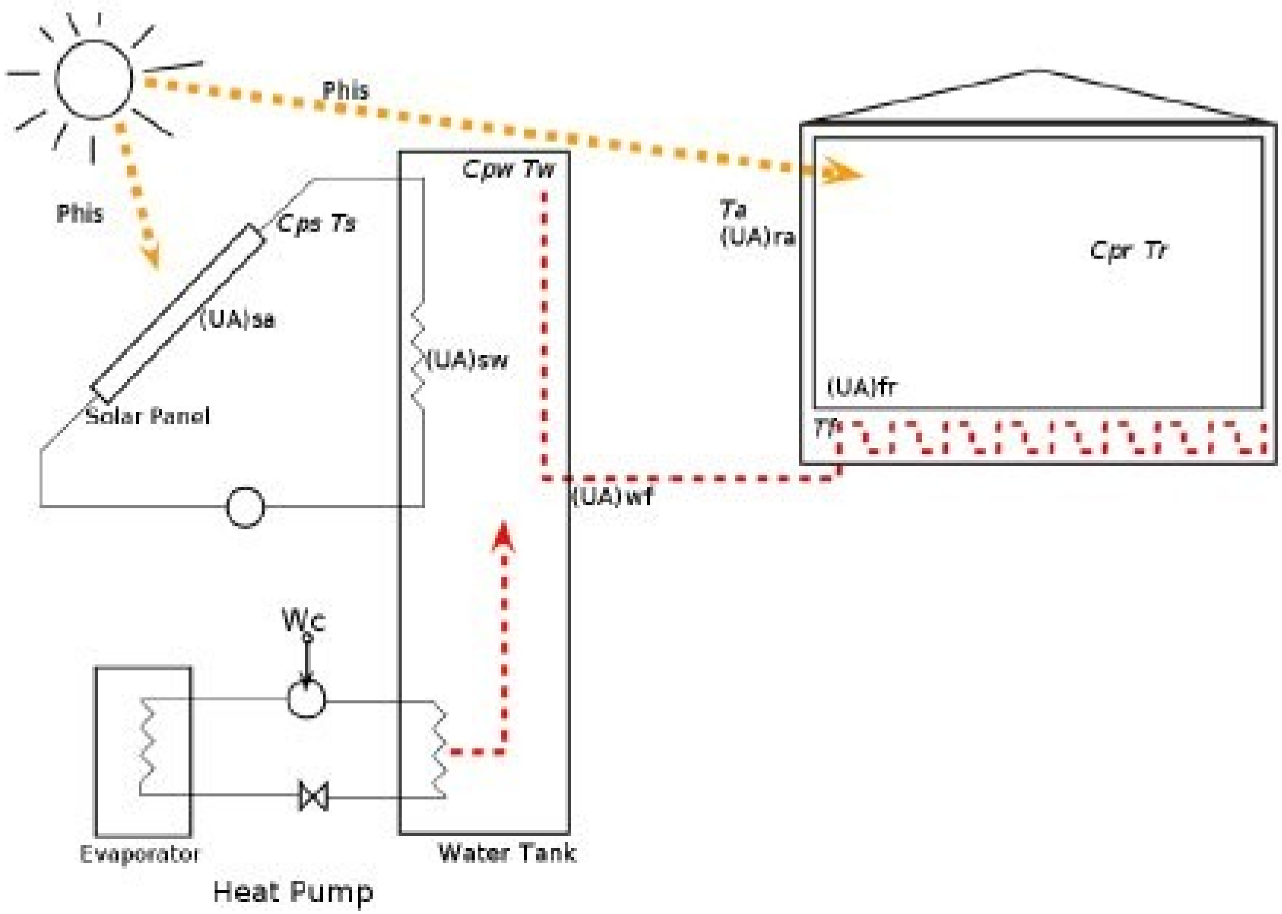
Grundfos Case Study

Schematic of the heating system



Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

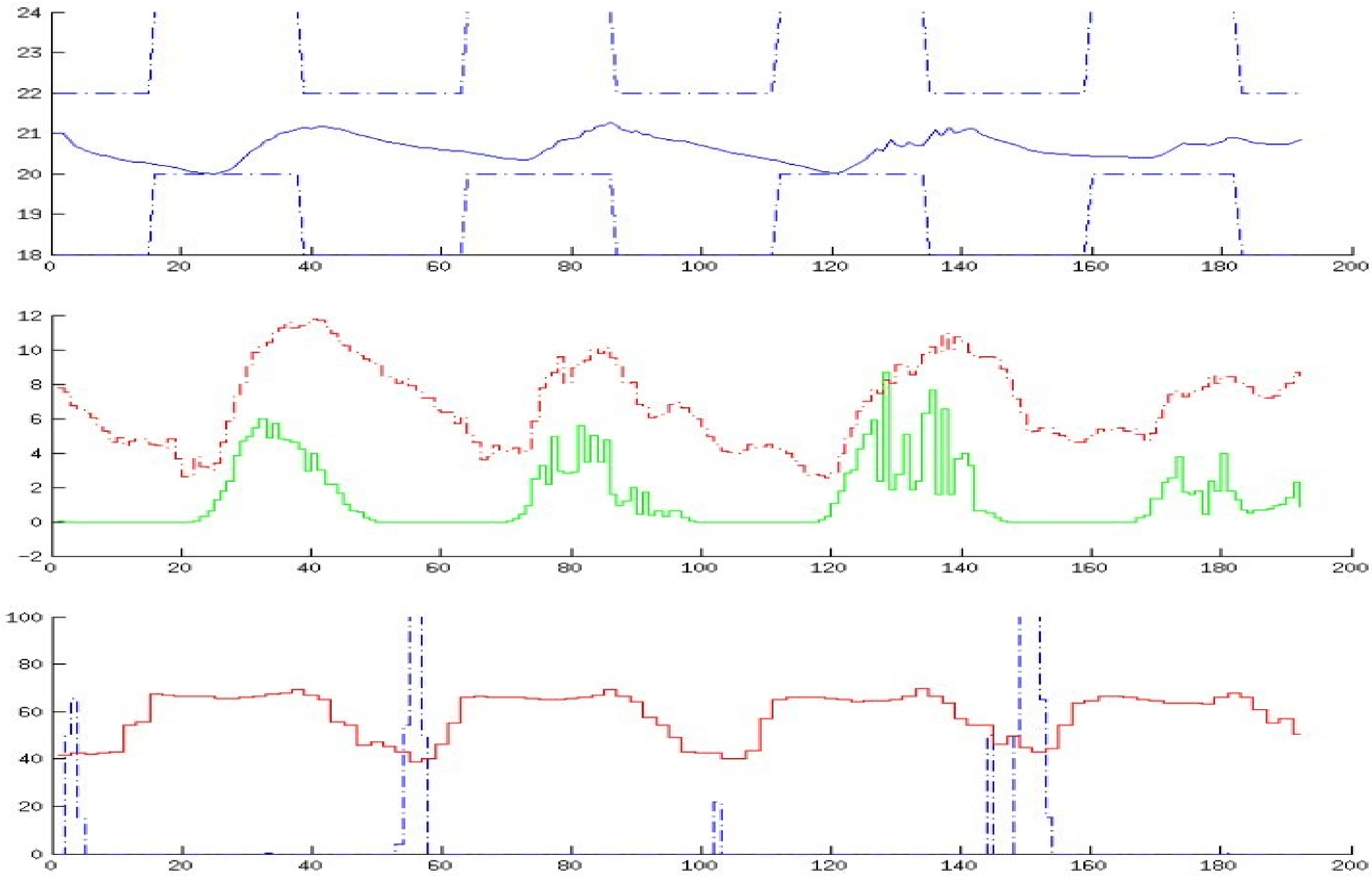
Economic Model Predictive Control

Formulation

The Economic MPC problem, with the constraints and the model, can be summarized into the following formal formulation:

$$
\begin{aligned}
&\min_{\{u_k\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c' u_k && && \text{(4a)}\\
&\text{Subject to} \quad x_{k+1} = Ax_k + Bu_k + Ed_k && k = 0, 1, \dots, N-1 && \text{(4b)}\\
&y_k = Cx_k && k = 1, 2, \dots, N && \text{(4c)}\\
&u_{min} \le u_k \le u_{max} && k = 0, 1, \dots, N-1 && \text{(4d)}\\
&\Delta u_{min} \le \Delta u_k \le \Delta u_{max} && k = 0, 1, \dots, N-1 && \text{(4e)}\\
&y_{min} \le y_k \le y_{max} && k = 0, 1, \dots, N && \text{(4f)}
\end{aligned}
$$

EMPC for heat pump with solar collector (savings 35 pct)



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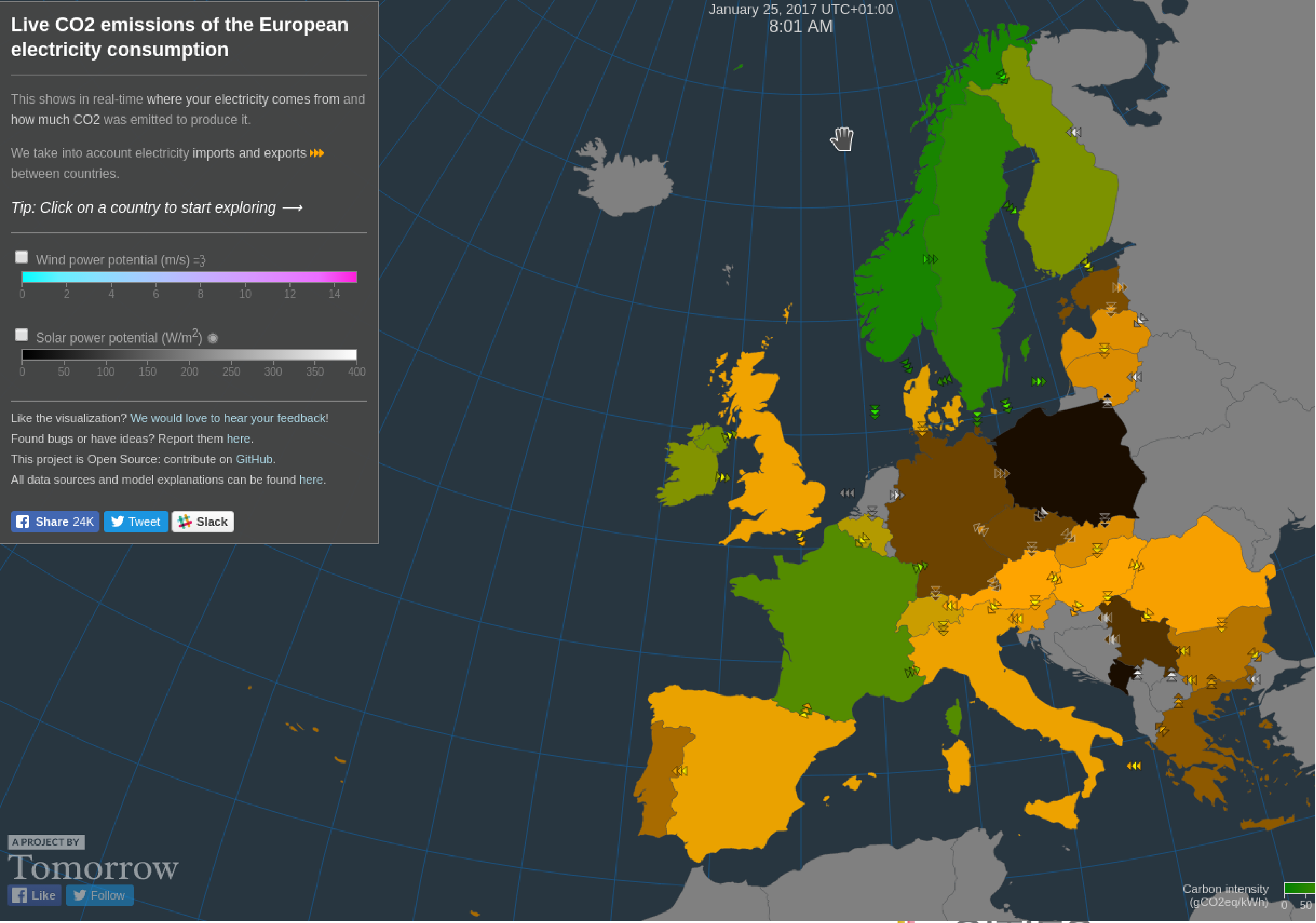
Case study No. 4

Control of heat pumps for swimming pools (CO2 minimization)



IDA Energi – Cognitive Buildings

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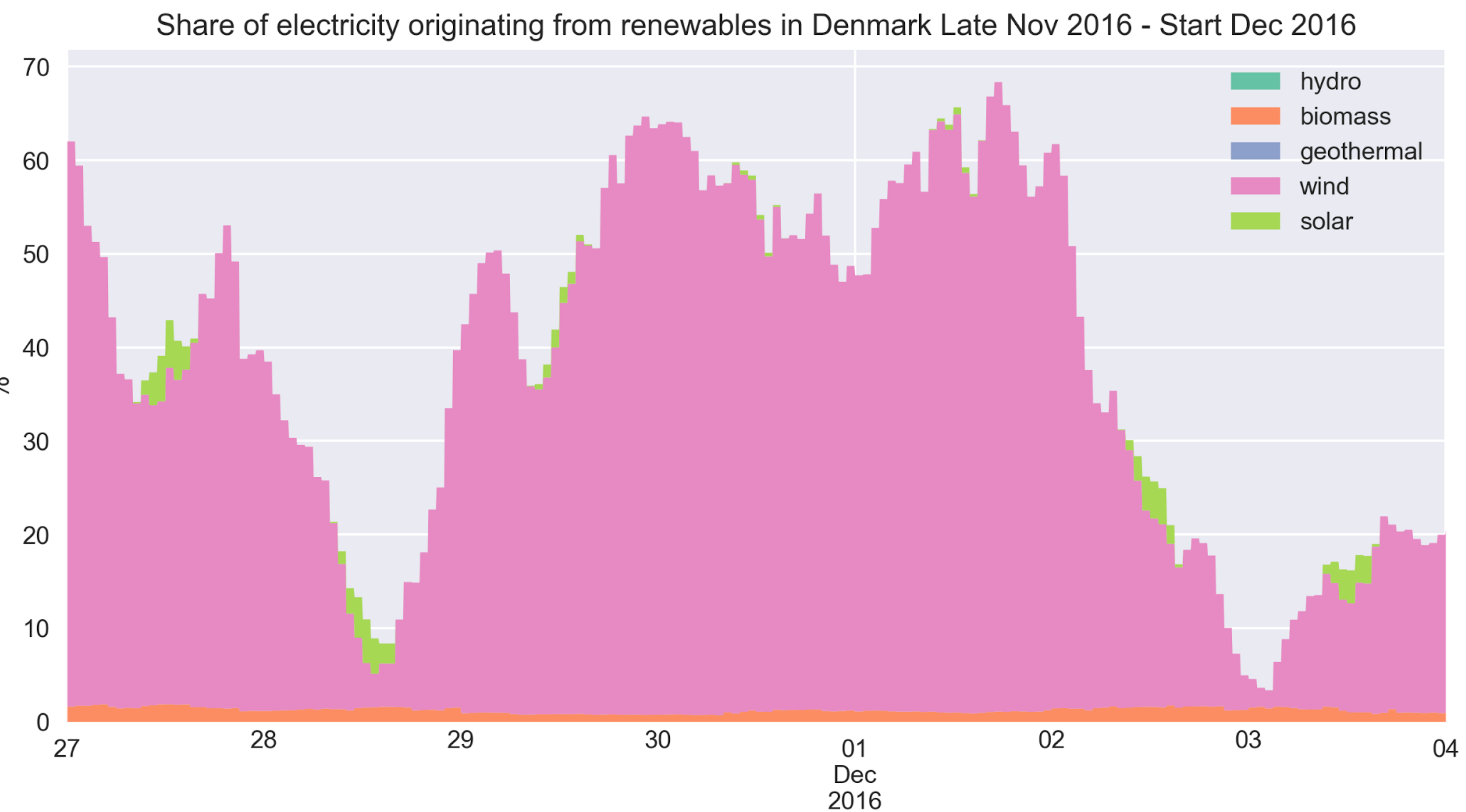
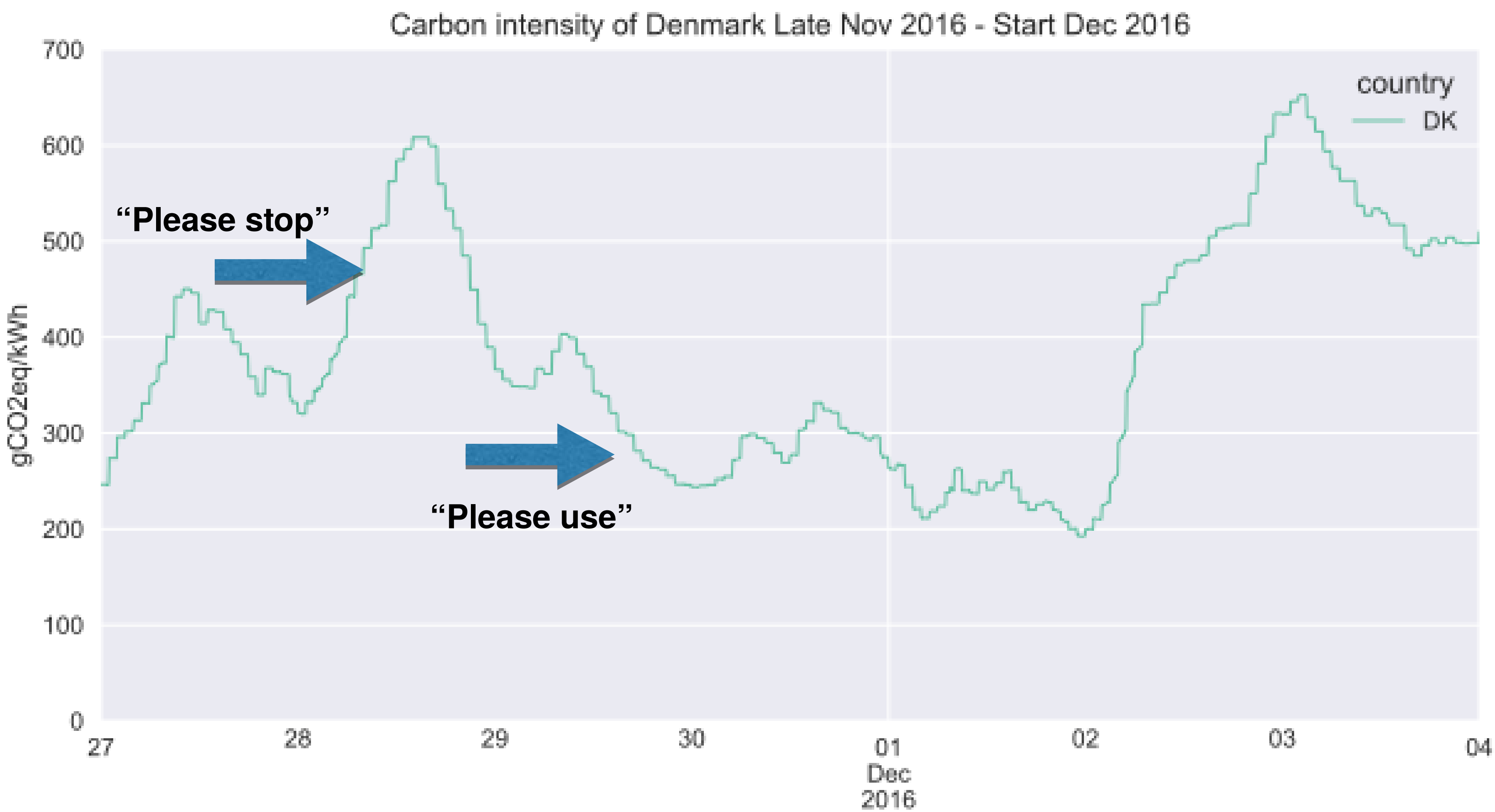


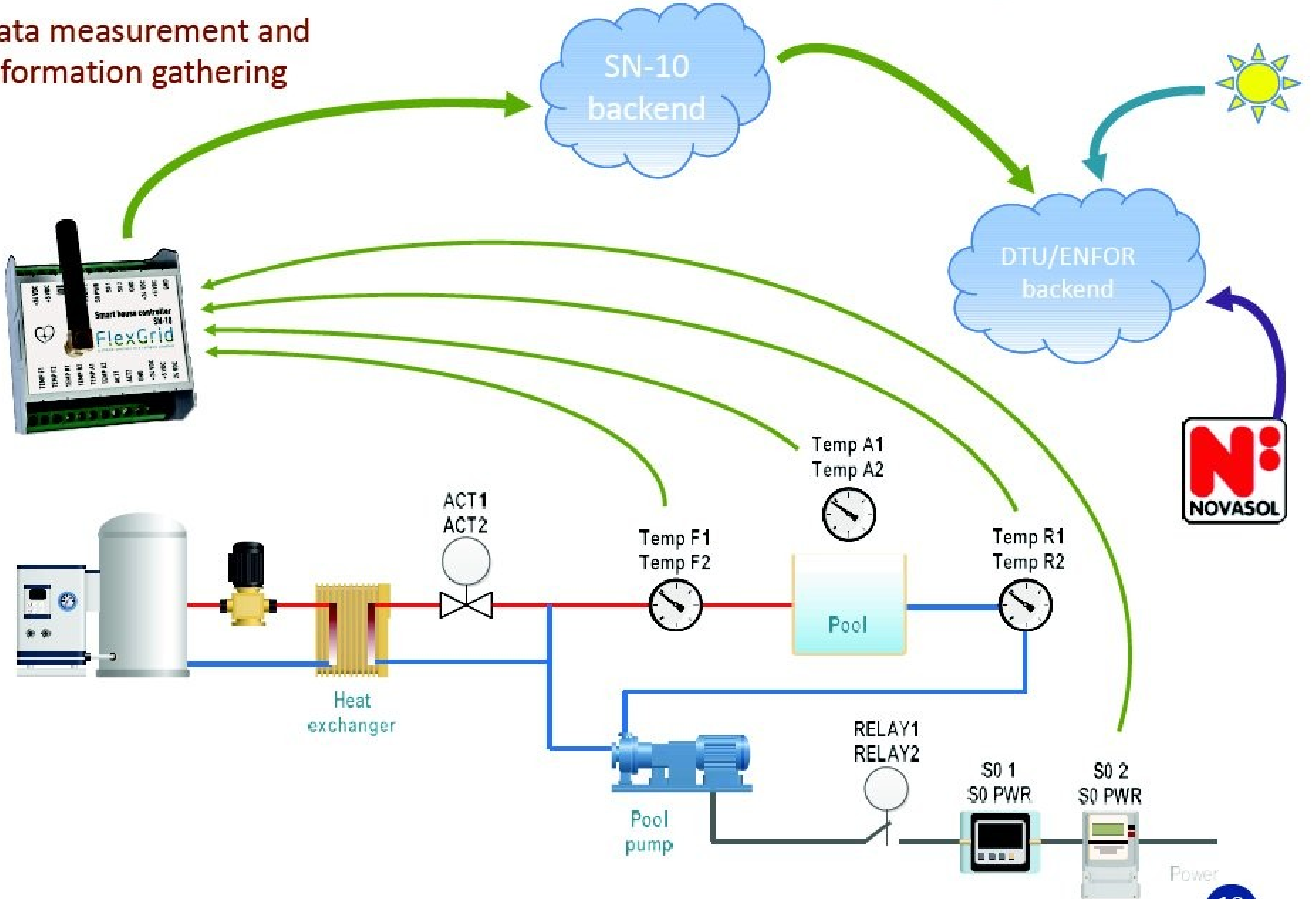
Source: pro.electicitymap.org



Source: pro.electicitymap.org

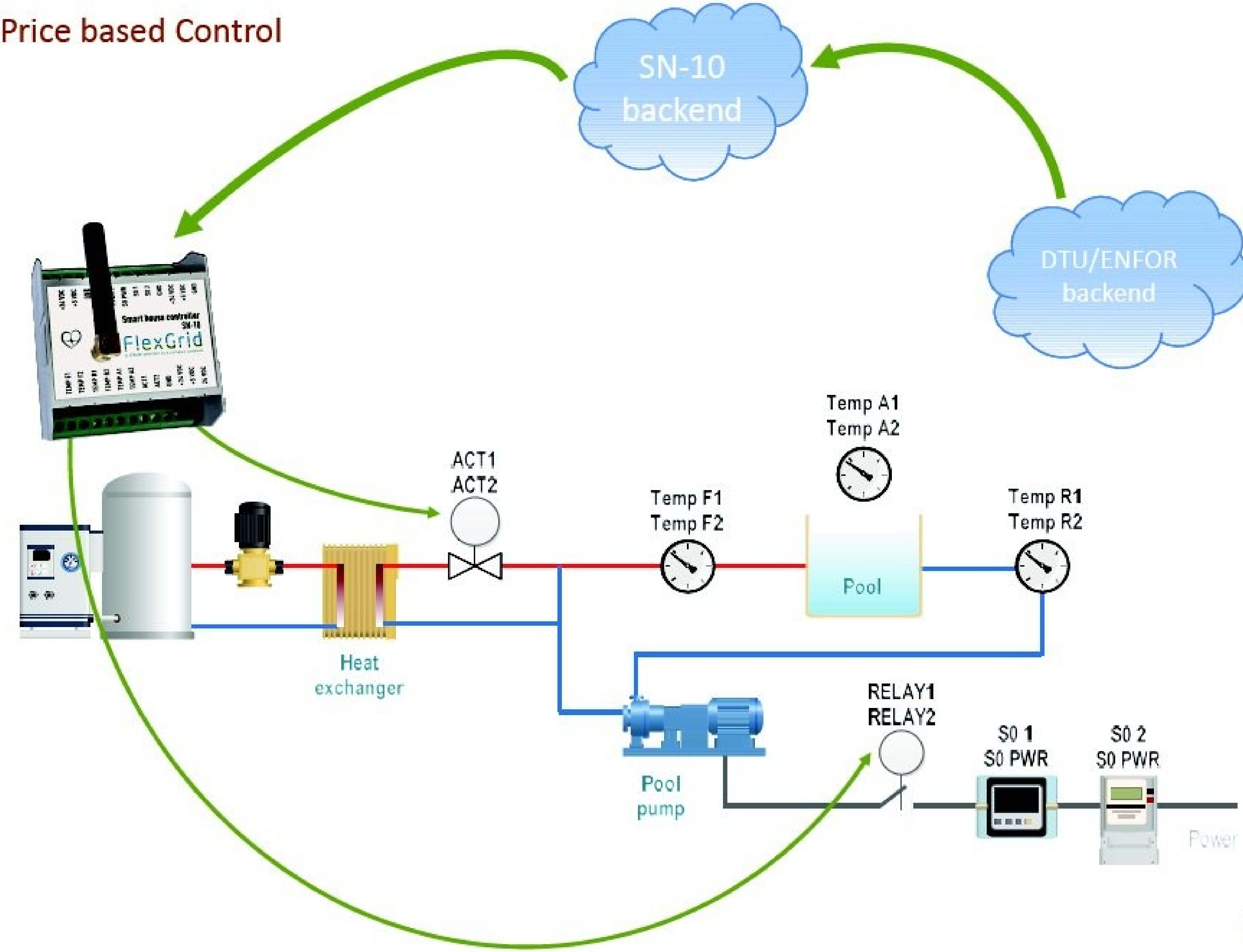
How does it work?

Data measurement and information gathering

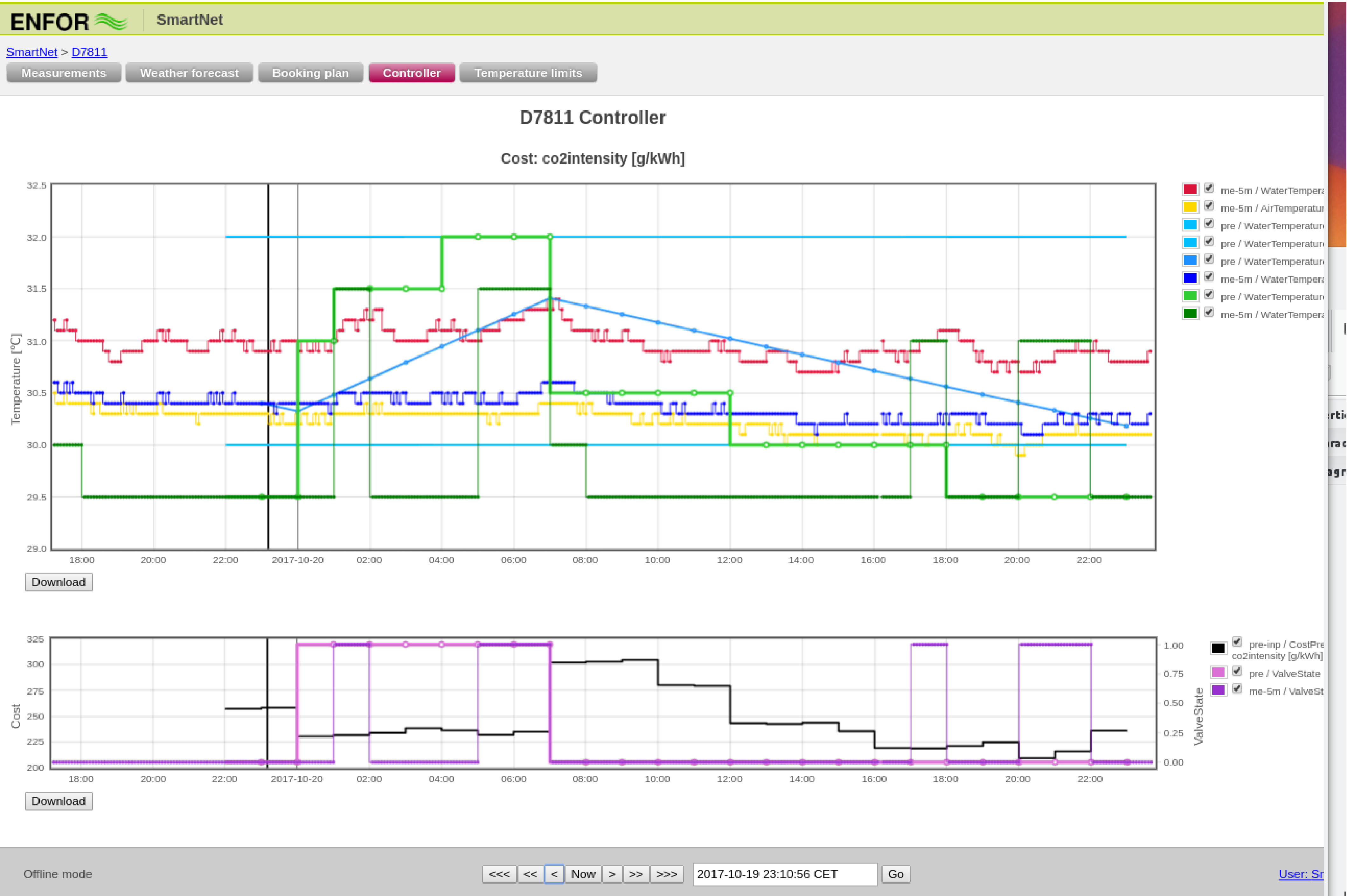


How does it work?

Price based Control



Example: CO2-based control



Ingeniøren

TEKNOLOGI • NATURVIDENSKAB • SAMFUND

18. AUGUST 2017

MARKANTE FAGFOLK TIL POLITIKERNE:

Her er vejen til smarte energiafgifter

Prisen på energi skal afspejle, hvilken forurening den medfører. Det er nødvendigt for at fremme den grønne omstilling, mener en gruppe fagfolk bag nyt udspil.

ENERGIPOLITIK

Af Sanne Wittrup sw@ing.dk

Følg fysikken. Det er hovedprincippet i et forslag til en ny model for energiafgifter fra en perlerække af store danske virksomheder, forskningsinstitutioner og forsyningsvirksomheder.

Gruppen foreslår, at de enkelte brændsler skal pålægges en 'forureningsafgift', der afspejler, hvad det koster at neutralisere forureningen fra brændslet. Hvad enten det så er CO_2, partikler eller svovl. Afgiften skal lægges på energien, når den går ind i værket, bilen eller fyret.

Samtidig skal også selve værket, bilen eller vindmøllen pålægges en afgift, der afspejler anlæggets miljøeffekt fra fremstilling til og med nedtagning i et livscyklusperspektiv – og hvad det koster at neutralisere denne effekt.

Ideen er så, at stærkt varierende forbrugerpriser på energi skal opmuntre forbrugerne til at flytte deres energiforbrug.

Med forslaget blander fagfolk med indsigt i dynamikken i energisektoren sig nu i debatten om, hvordan fremtidens energiafgifter skal indrettes. En debat, som Skatteministeriet tog hul på her i sommer med et såkaldt 'fagligt oplæg' til en ny afgiftsmodel.

Gruppen mener, at en ny afgiftsmodel er helt nødvendig for at få fremmet et meget mere fleksibelt energiforbrug, som ifølge dem er nøglen til en effektiv grøn omstilling, og som vil kunne åbne for at realisere masser af innovative, danske styringsmodeller og systemløsninger på energiområdet.

Professor Henrik Madsen fra Institut for Matematik og Computer Science på DTU, der taler på vegne af gruppen, synes nemlig ikke, at Skatteministeriet har gjort sit arbejde færdigt, blandt andet fordi anbefalingerne ikke tager tilstrækkelig højde for dynamikken i energisystemet.

»Den rigtige omkalfatring af energiafgifter og -tilskud vil kunne bringe Danmark helt i front med fleksible løsninger og forretningsmodeller. Vi oplever, at både firmaer og private investorer står i kø for at komme i gang med at udvikle og demonstrere kommercielle løsninger, der kan udnytte strømmen, når den er grøn og billig ,« forklarer Henrik Madsen og understreger, at virksomhederne gør det, fordi de er overbeviste om, at de kan tjene store penge på at kunne udvikle og demonstrere løsninger i Danmark og senere tilbyde dem til andre lande.

Gruppen er dannet af deltagere i et stort forskningsprojekt ved navn 'Cities', hvor man har udviklet styringer og systemløsninger til forskellige elementer i fremtidens intelligente og integrerede energisystem.

Disse demonstrationsprojekter har vist, at der rent teknisk findes mange muligheder for at integrere store mængder vind- og solenergi, hvis man på en intelligent måde kan udnytte den dynamik og fleksibilitet, der er i et energisystem, hvor produktion og forbrug af el, varme, vand, affald og transport er tænkt sammen.

Danfoss er en af virksomhederne bag den nye model. Leder af Danfoss' eksterne aktiviteter Torben Funder-Kristensen peger på, at Danmark har en unik mulighed for at udvikle disse nye løsninger, fordi vi har teknologien, knowhow og en moderne og samarbejdsvillig forsyningssektor:

»Men vi har kun et vindue på fem til ti år, før andre lande kommer ind og tager over, så det haster med at få omlagt energiafgifterne, der reelt dræber mange demonstrationsprojekter. Vi kan ikke vente!« siger han.

Professor i ressourceøkonomi på KU Peder Andersen – som sidder i referencegruppen for Skatteministeriets afgiftsrapport – finder, at gruppens afgiftsforslag ser interessant ud, men at det samtidig er lidt svært at gennemskue, om de økonomiske incitamenter rammer rigtigt:

»Når man primært lægger afgift på input af brændslet, risikerer man, at der ikke er incitamenter for virksomhederne til at undgå forurening, f.eks. ved at rense effektivt eller bruge ren teknologi. Det går imod korrekt økonomisk tænkning,« siger han.

Samtidig påpeger han, at den foreslåede afgift på selve produktionsanlæggene kan blive en meget tung ordning at administrere.

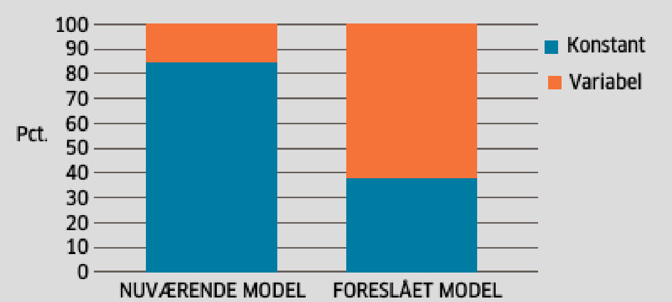
»Det vigtige er jo, at der gives klare økonomiske incitamenter til, at både økonomien og miljøet tilgodeses,« siger han.

Det nye forslag er baseret på møder og diskussioner med markante personer fra Danfoss, Grundfos, Kamstrup, Dansk Fjernvarme, Eniig, AffaldVarme Aarhus, Teknologisk Institut, DTU, KU, ProjectZero og Aarhus Kommune.

I den kommende tid vil gruppen gå videre med sit forslag til de relevante ministerier og har allerede en aftale i Energi-, Forsynings- og Klimaministeriet. ■

ELPRISEN SKAL VÆRE DYNAMISK

I dagens elpris er afgifter og tariffer faste, og kun selve elmarkedsprisen varierer. I den nye afgiftsmodel vil størstedelen af prisen kunne variere, da afgifterne skal variere på de brændselstyper, der kan levere strømmen.



Kilde: Henrik Madsen, DTU Grafik: LGJ

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Software solutions

Software for combined physical and statistical modelling

Continuous Time Stochastic Modelling (CTSM) is a software package for modelling and simulation of combined physical and statistical models. You find a technical description and the software at CTSM.info.

Software for Model Predictive Control

HPMPC is a toolbox for High-Performance implementation of solvers for Model Predictive Control (MPC). It contains routines for fast solution of MPC and MHE (Moving Horizon Estimation) problems on embedded hardware. The software is available at GitHub.

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CITIES Korean International Workshop – KIER, Daejeon, Korea, October 22nd 2015

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Summary

- Data can be used for reliable performance characterization of buildings (energy labelling, etc.)
- A procedure for data intelligent control of power load in buildings, using the Smart-Energy OS (SE-OS) setup, is suggested.
- The SE-OS controllers can focus on
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency
- We see a large potential in Demand Response. Automatic solutions, and end-user focus are important
- We see large problems with the tax and tariff structures in many countries (eg. Denmark).
- Markets and pricing principles need to be reconsidered; we see an advantage of having a physical link to the mechanism (eg. nodal pricing, capacity markets)

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For more information ...

- See for instance

  www.henrikmadsen.org

  www.smart-cities-centre.org

  www.citiesinnovation.org

- ...or contact
  - Henrik Madsen (DTU Compute)

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- Acknowledgement: CITIES, SCA and REBUS projects