Evidence-based Energy Performance and Flexibility

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Case Study No. 1

Thermal Performance Characterization of Buildings using (Smart) Meter Data

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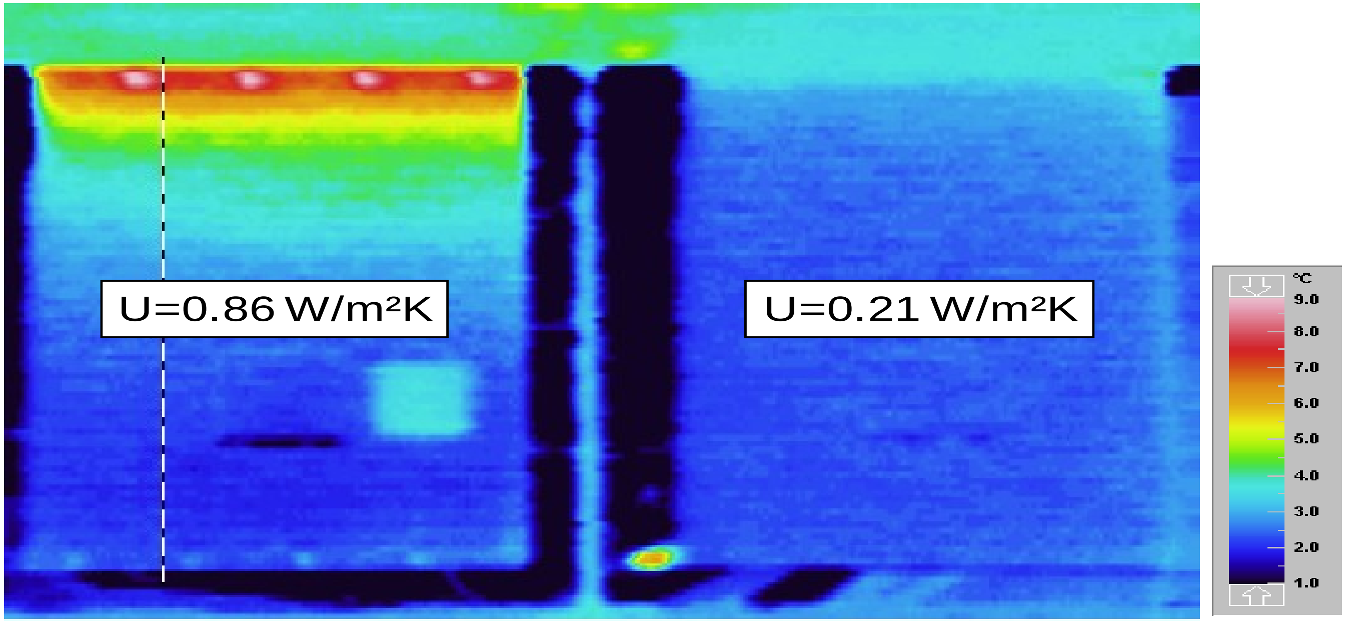
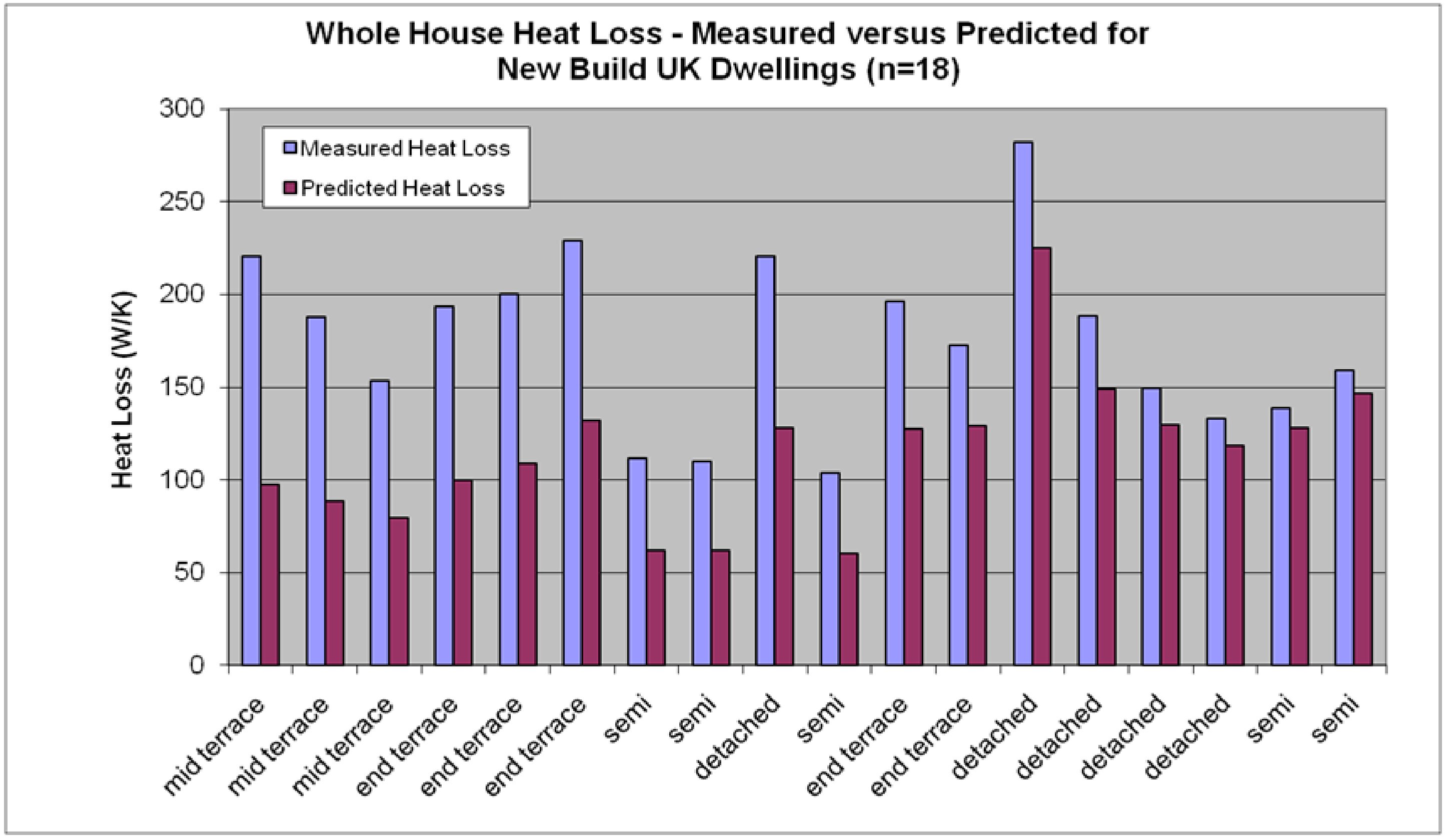
Example



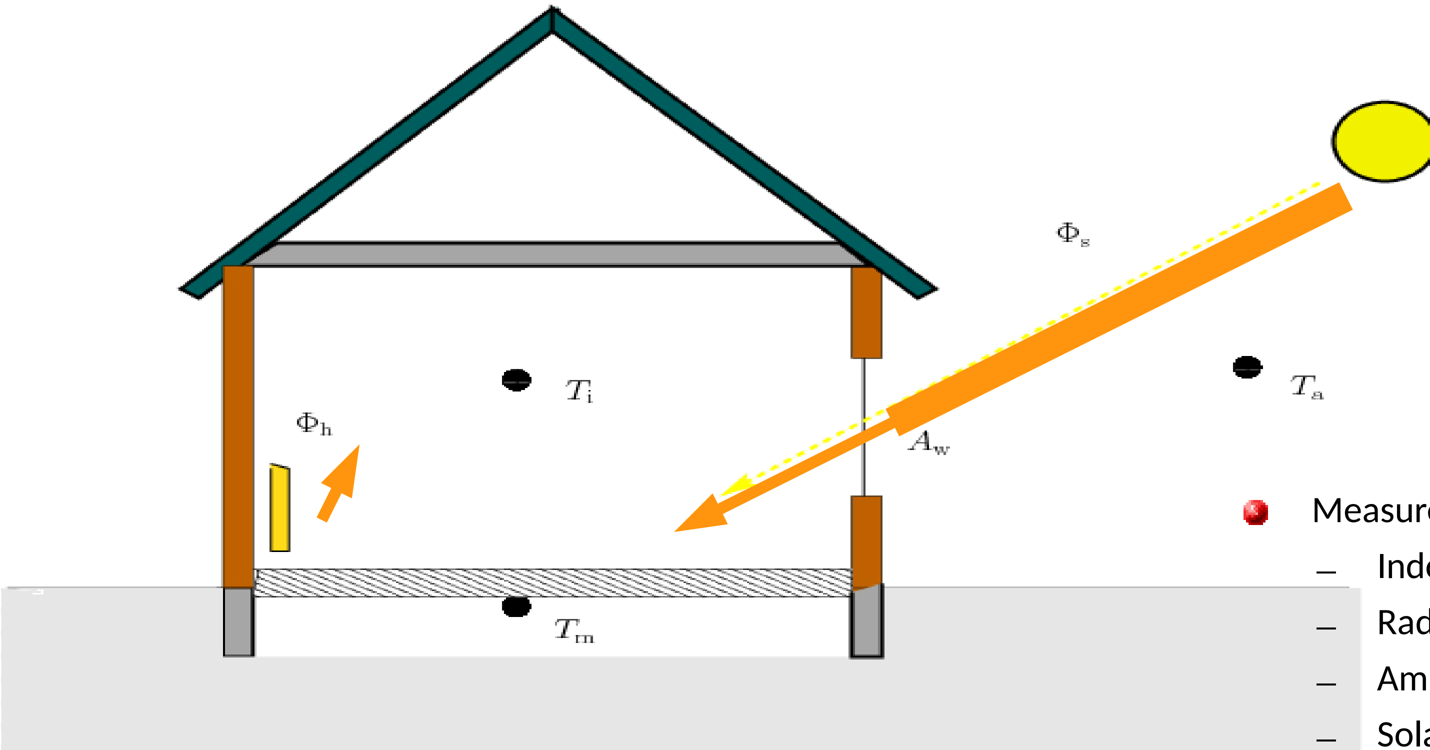
Consequence of good or bad workmanship (theoretical value is U=0.16W/m2K)

Examples (2)

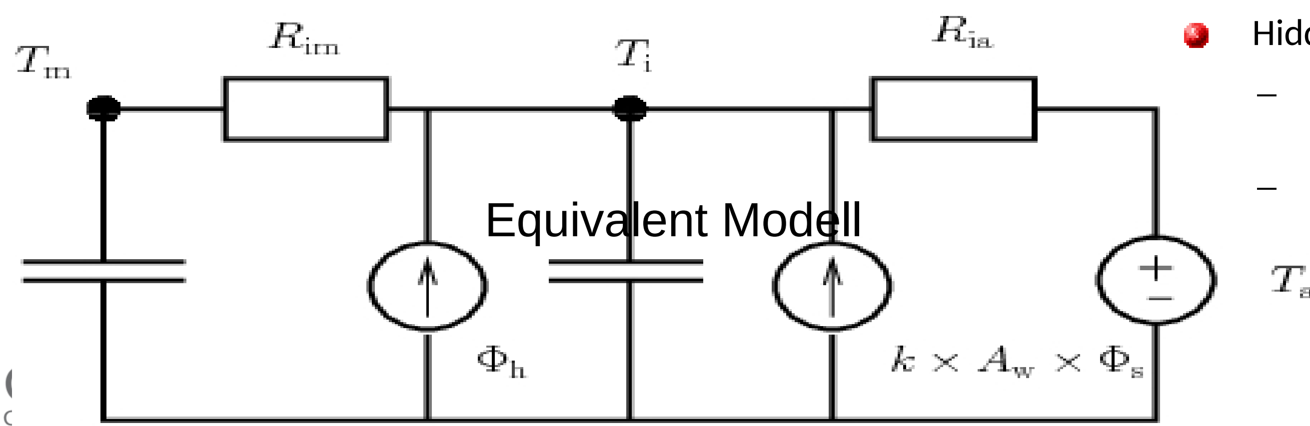


Measured versus predicted energy consumption for different dwellings

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



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 (.. see later on ..)

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Perspectives (2)

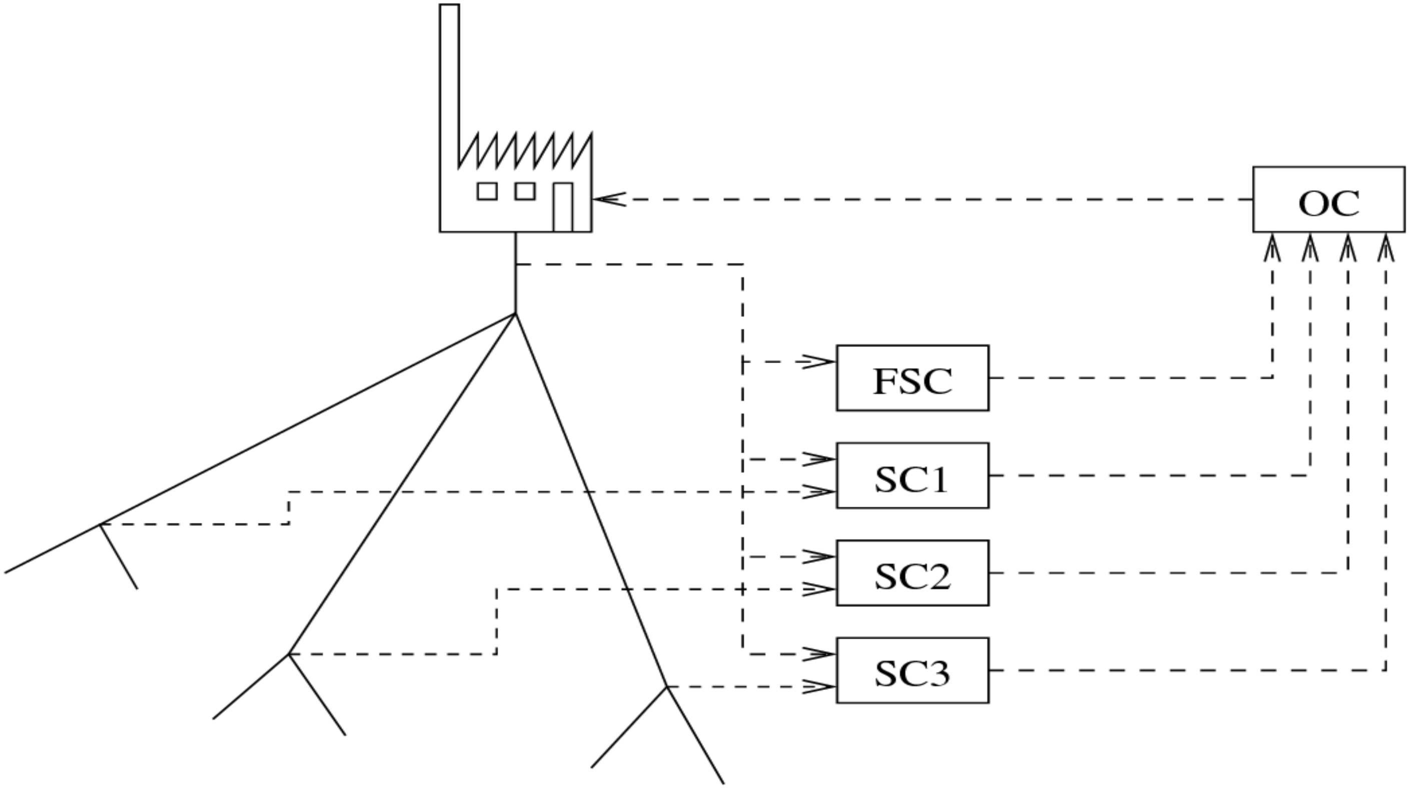
"Skat, jeg kan se på k-værdierne, at vinduerne skal pudses"

Case Study No. 2
Data Intelligent Temperature Optimization

Danish Energy Agency, February 2018

Models and Controllers

(Highly simplified!)



Savings
(Reduction of heat loss = 18.3 pct)

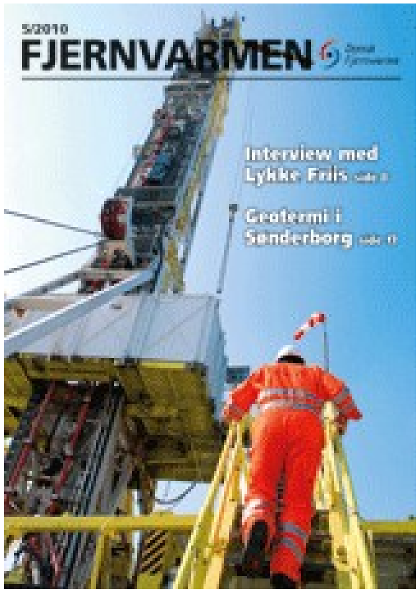
	Varmekøb		Elkøb	
	GJ	1000kr	kWh	1000kr
Før PRESS	653,000	30,750	499,000	648
Med PRESS	615,000	28,990	648,000	842
Forskel	37,400	1,760	-149,000	-194

Total besparelse (9 første måneder af normalår): **1,566,000kr**

Besparelse for et normalår:

- $12/9 \times$ 1,566,000kr $=$ **2.1 mill.**
- Imidlertid står jan.–sept. (75% af året) kun for ca. 65% af graddagen i er normalår.
- 1,566,000kr$/0.65 =$ **2.4 mill.**

Control of Temperatures in DH Systems



FJERNVARMEN | 5 2010

Styring af temperatur rummer kæmpe sparepotentiale

Lesson learned:

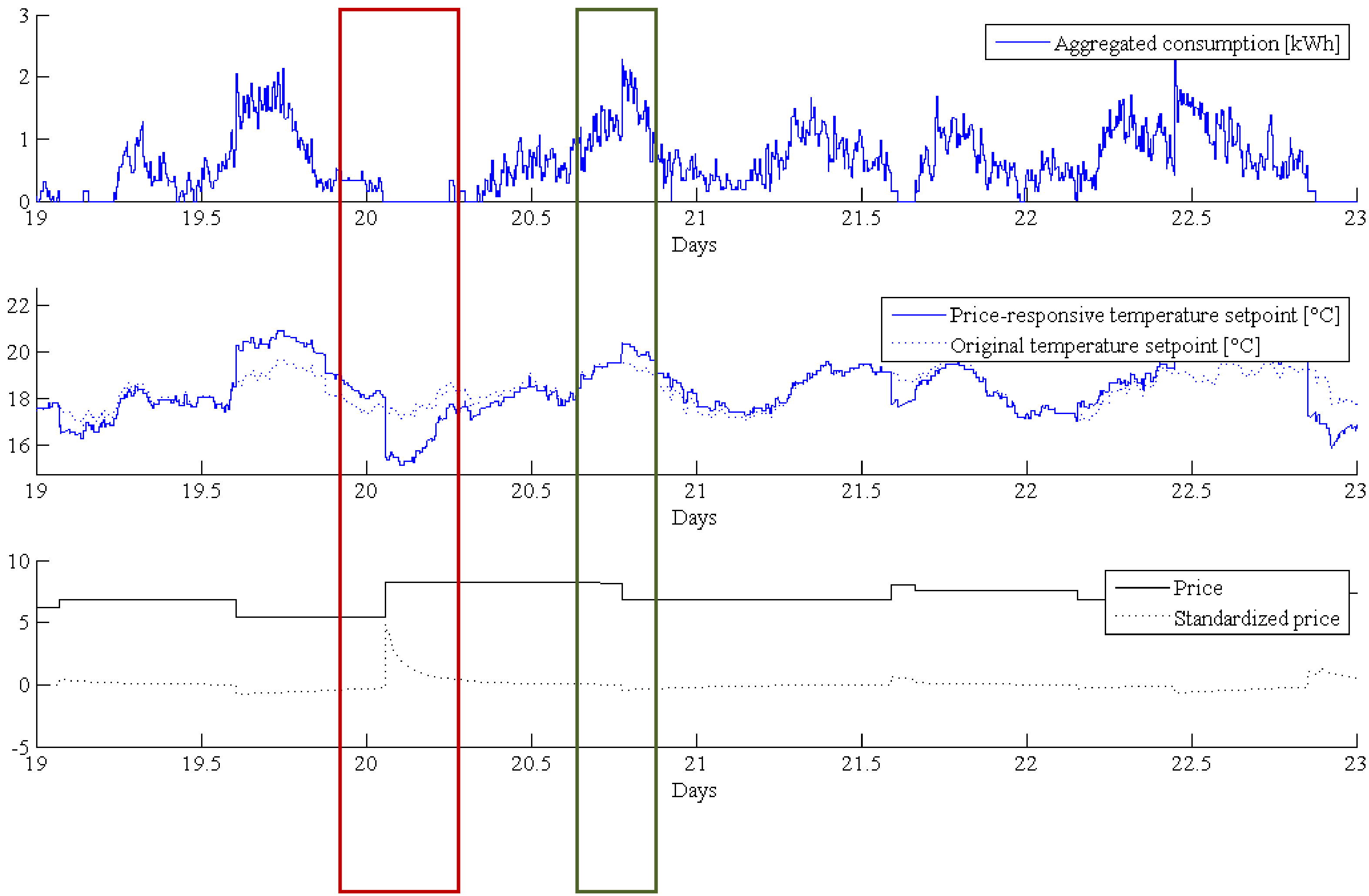
- Control using **simulation** of temperature gives **up to 10 pct reduction** of heat loss.
- Control using **data and predictions** gives **up to 20 pct. reduction** of heat loss.

Case study No. 3

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

Danish Energy Agency, February 2018

Aggregation (over 20 houses)



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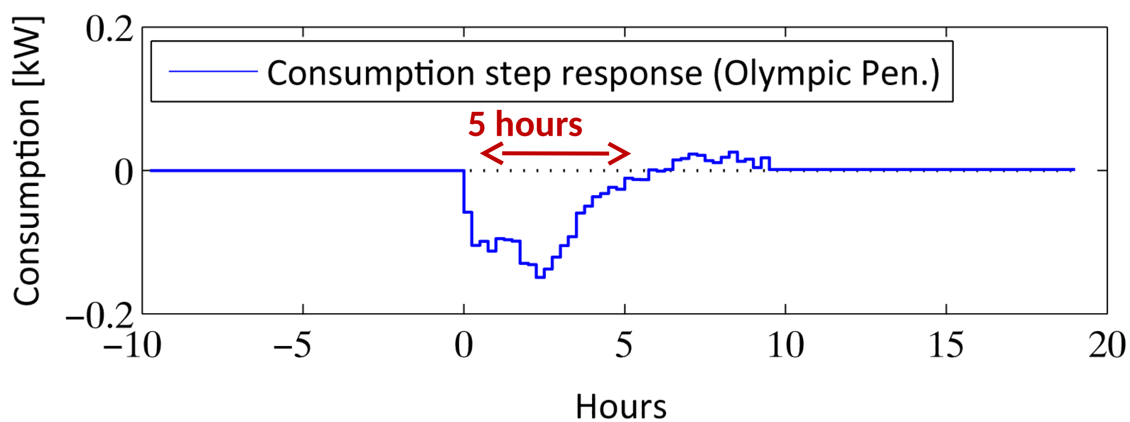
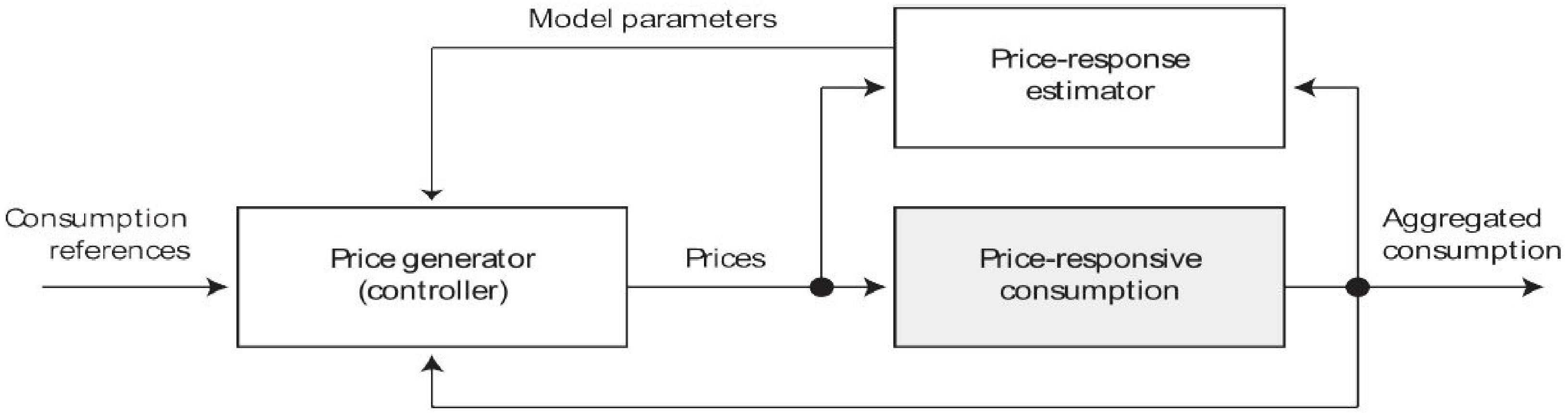
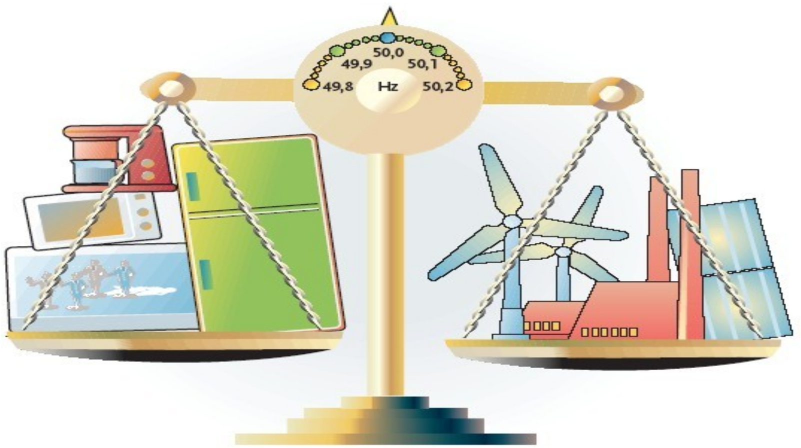
Response on
Price Step Change

Olympic Peninsula



Control of Energy Consumption

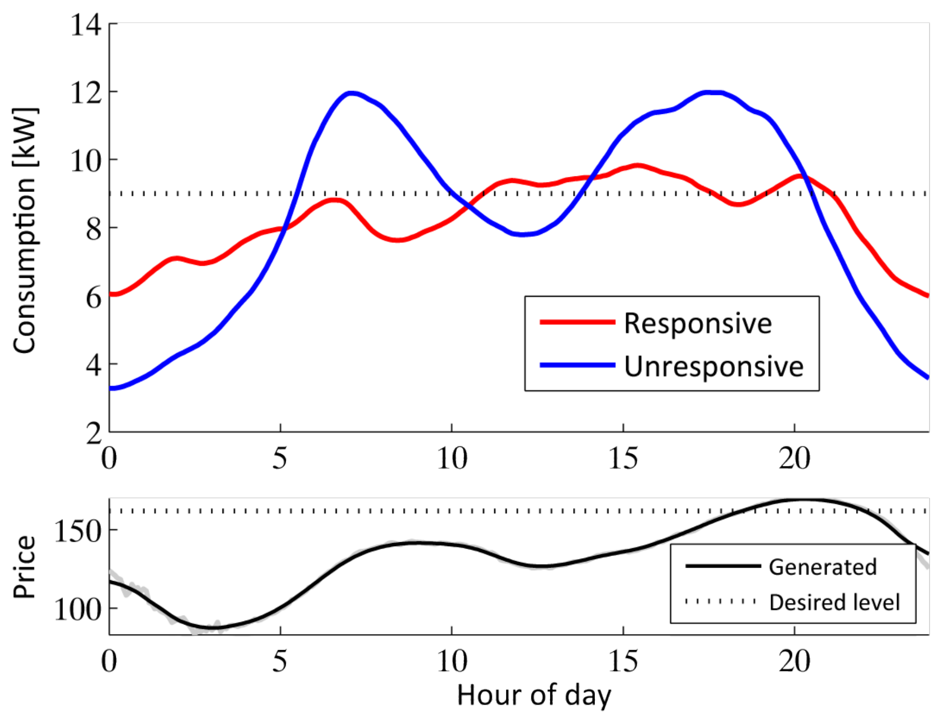




Control performance

Considerable **reduction in peak consumption**

Mean daily consumption shift

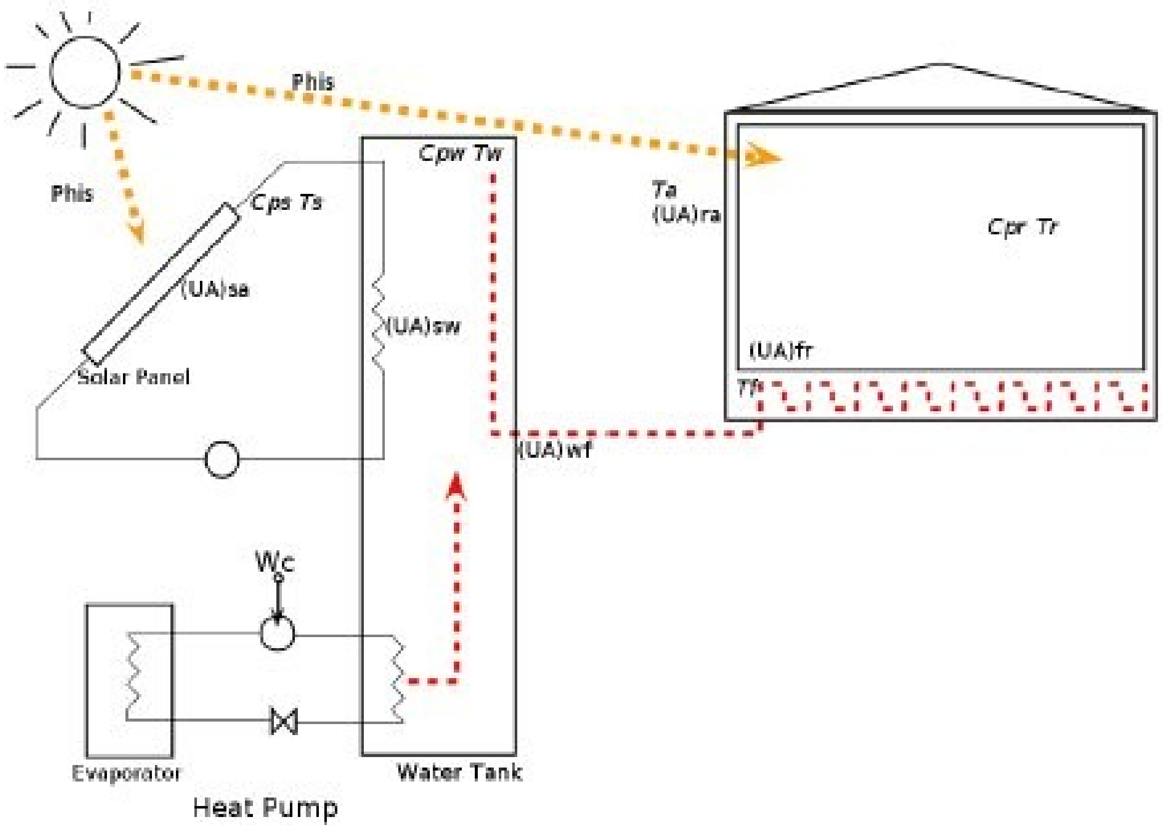


Case study No. 4

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

Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

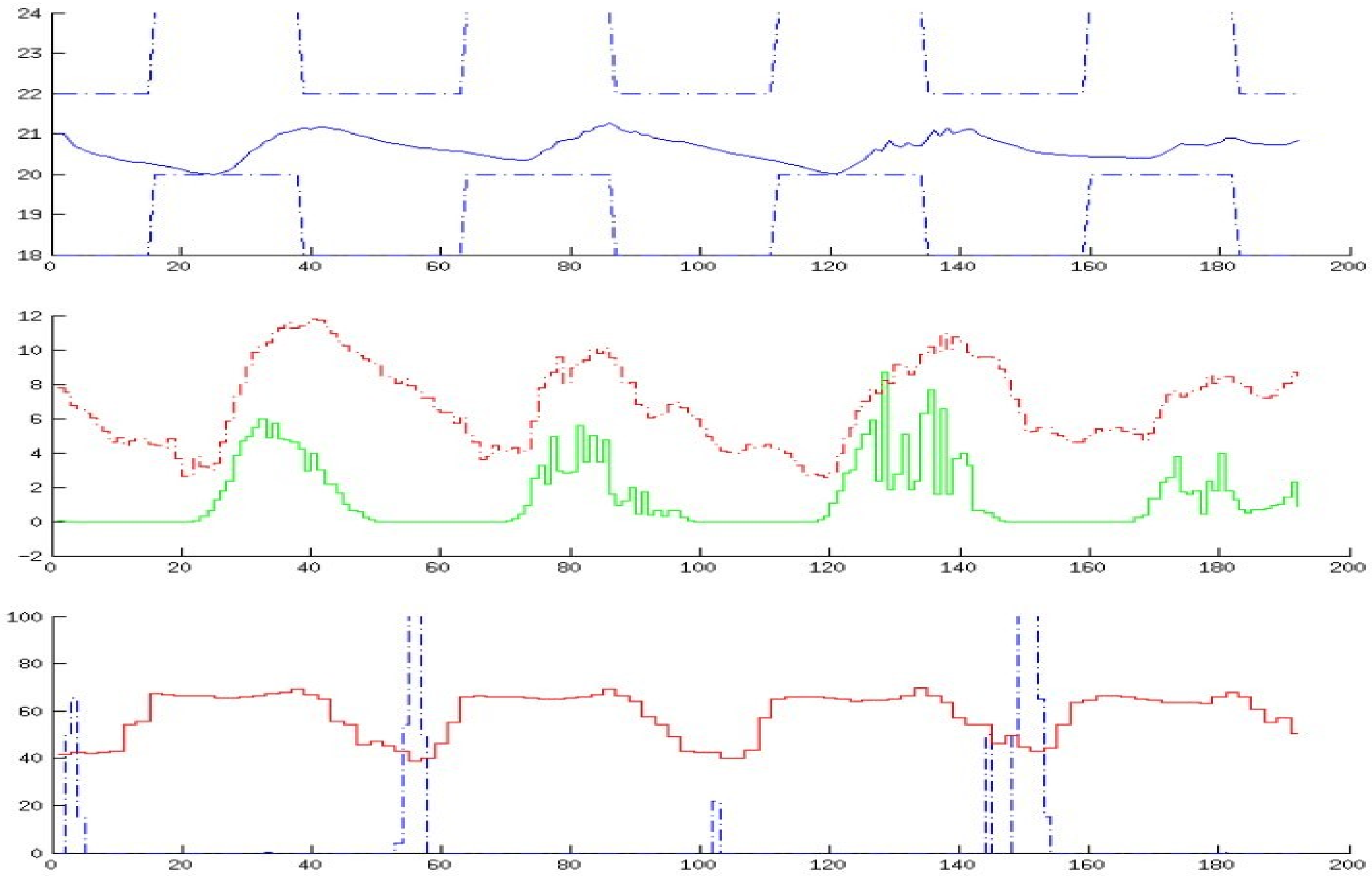
Formulation

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

$$\min_{\{u_k\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c' u_k \tag{4a}$$

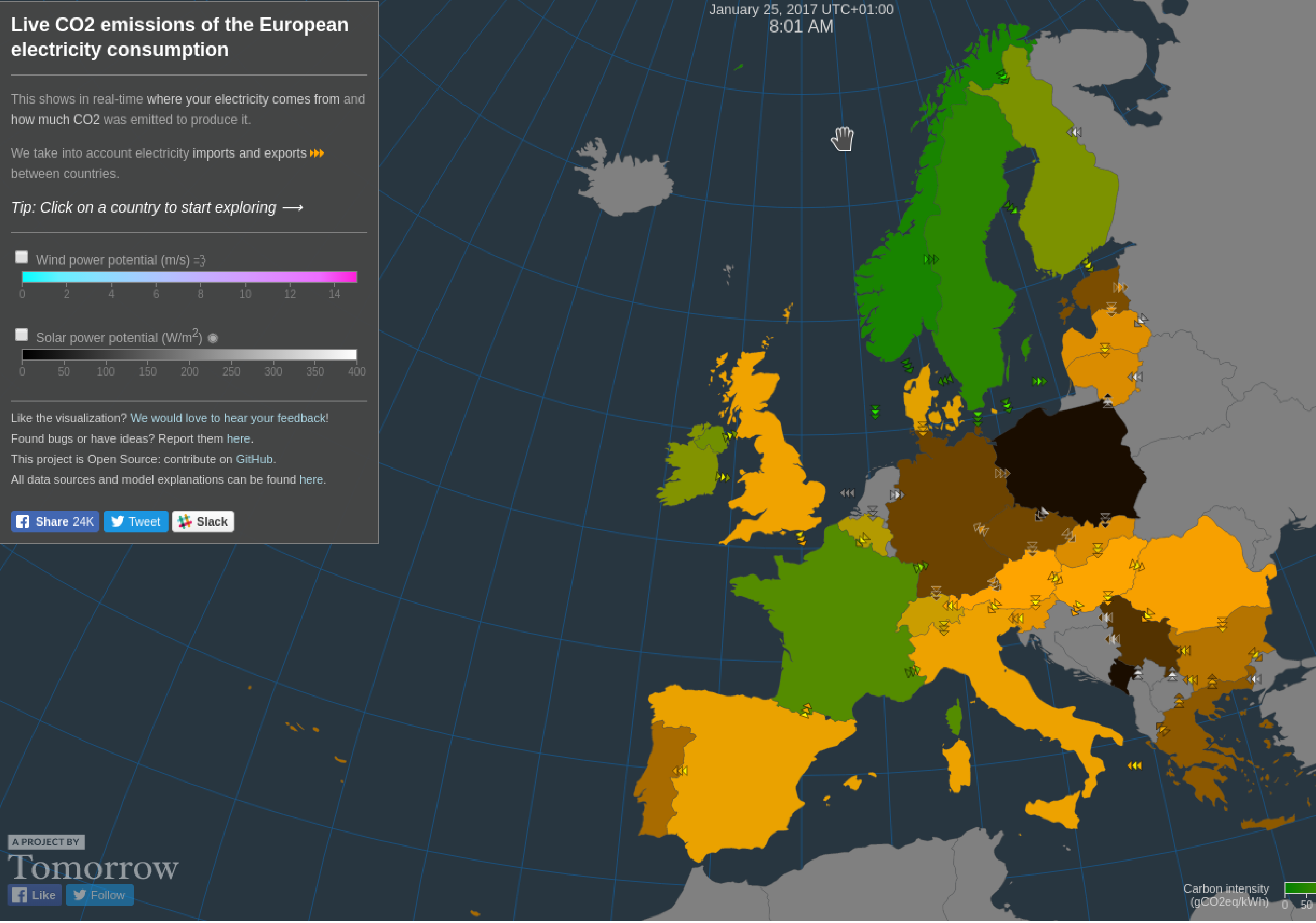
$$\begin{aligned}
\text{Subject to} \quad & x_{k+1} = Ax_k + Bu_k + Ed_k && k = 0, 1, \dots, N-1 && \text{(4b)}\\
& y_k = Cx_k && k = 1, 2, \dots, N && \text{(4c)}\\
& u_{min} \leq u_k \leq u_{max} && k = 0, 1, \dots, N-1 && \text{(4d)}\\
& \Delta u_{min} \leq \Delta u_k \leq \Delta u_{max} && k = 0,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

EMPC for heat pump with solar collector (savings 25 pct; + 8 pct)



Case study No. 5

Control of heat pumps for swimming pools (CO2 minimization)



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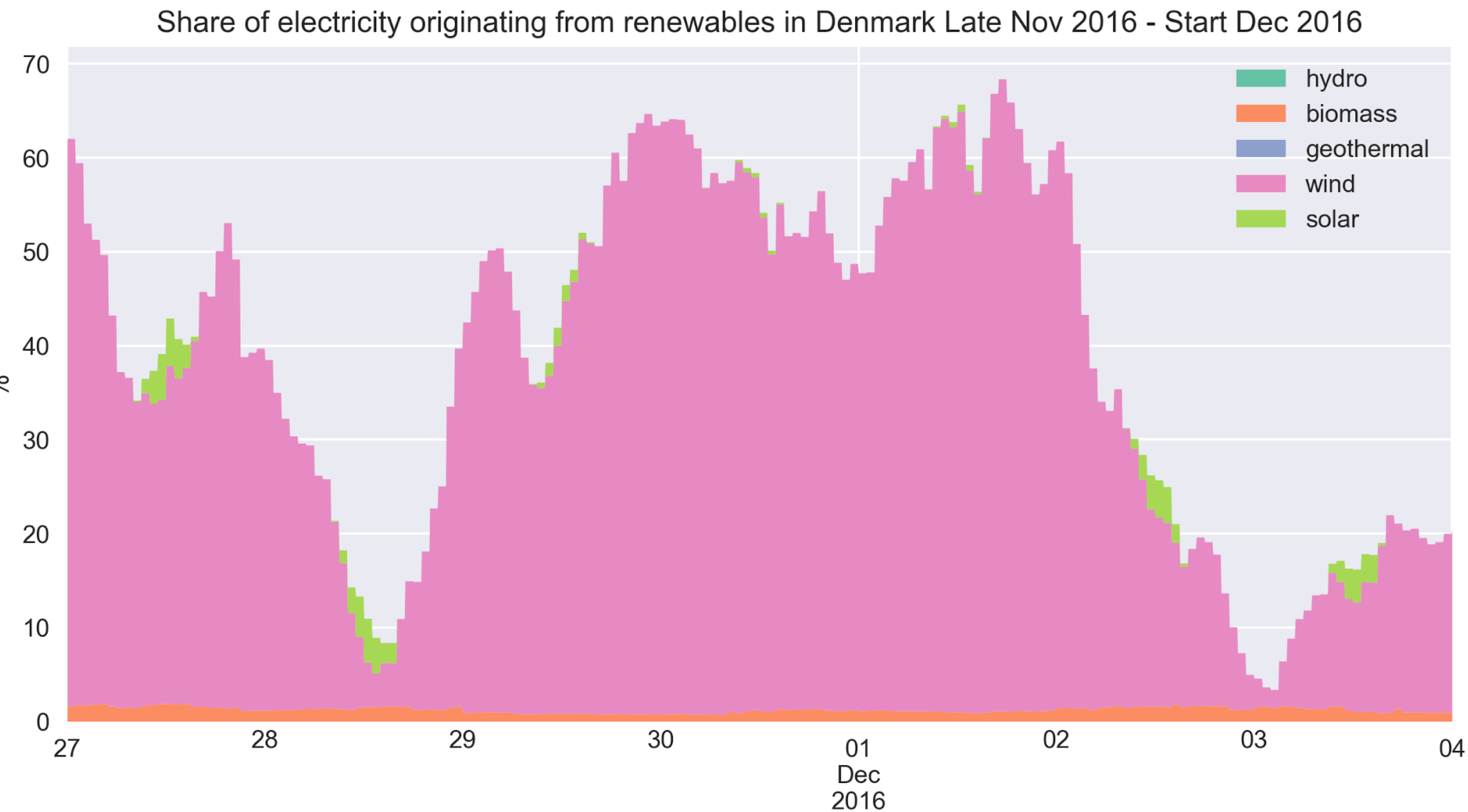

Source: pro.electicitymap.

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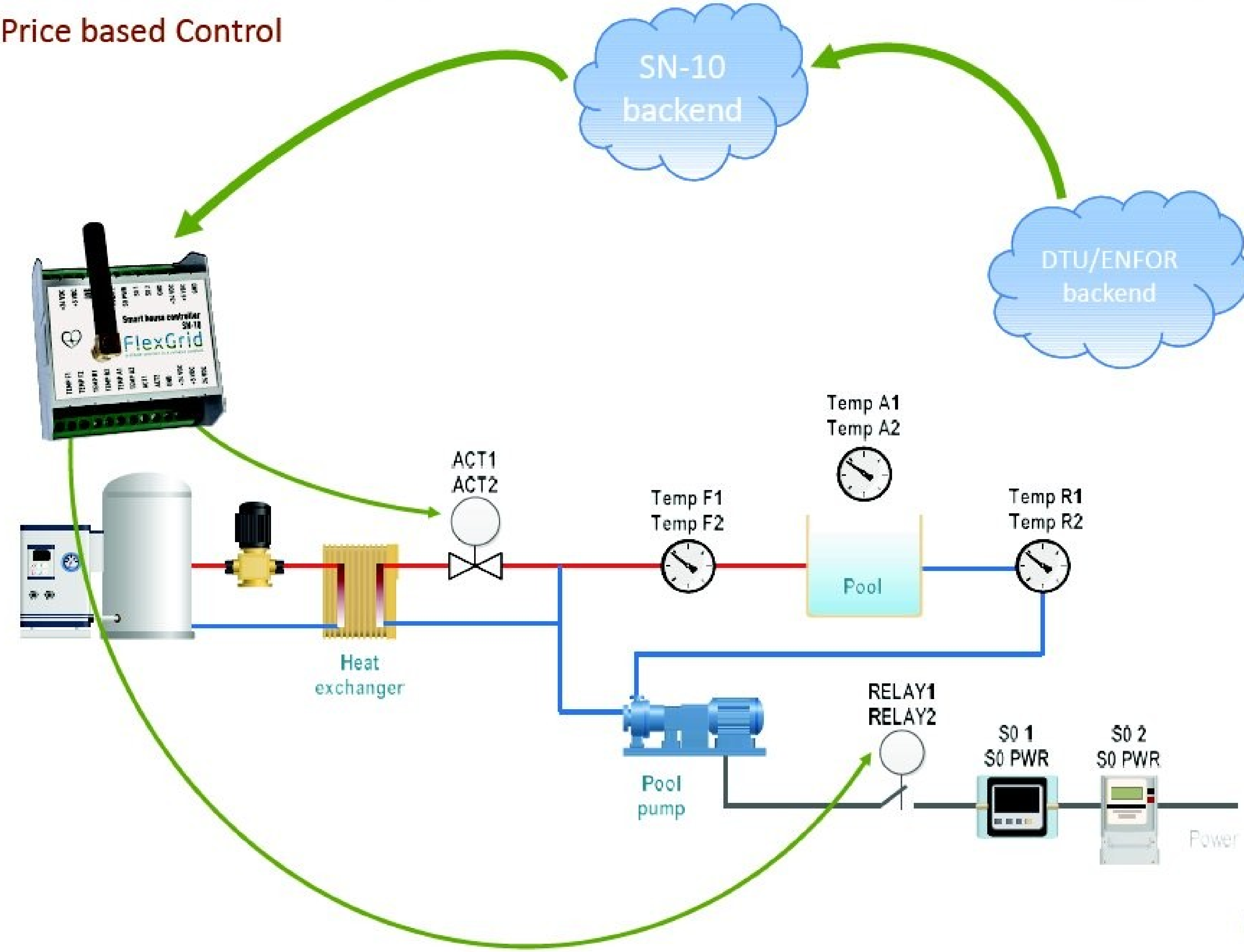
How does it work?

Price based Control



Example: CO2-based control

Flexibility Setup and Control

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Characteristics

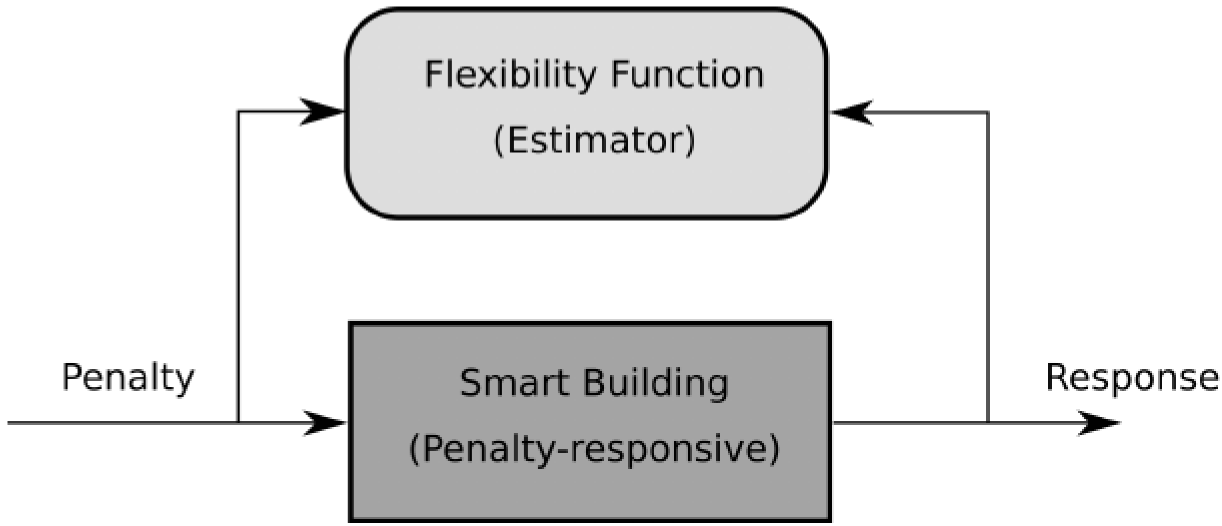

Figure 1: A smart building is able to respond to a penalty or external control signal.

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Flexibility Function

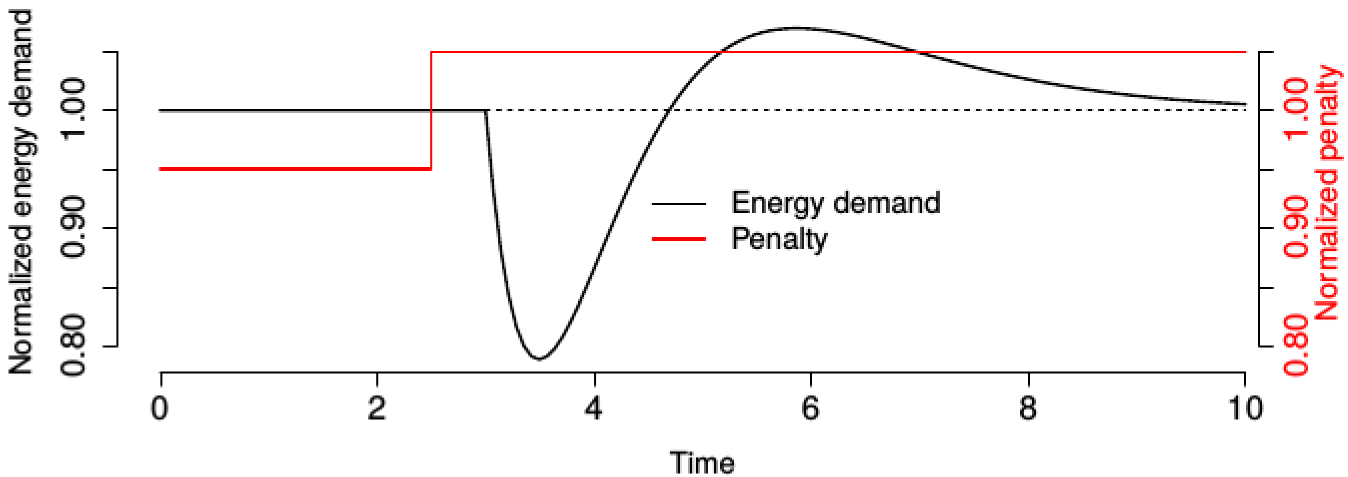


Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

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 Application

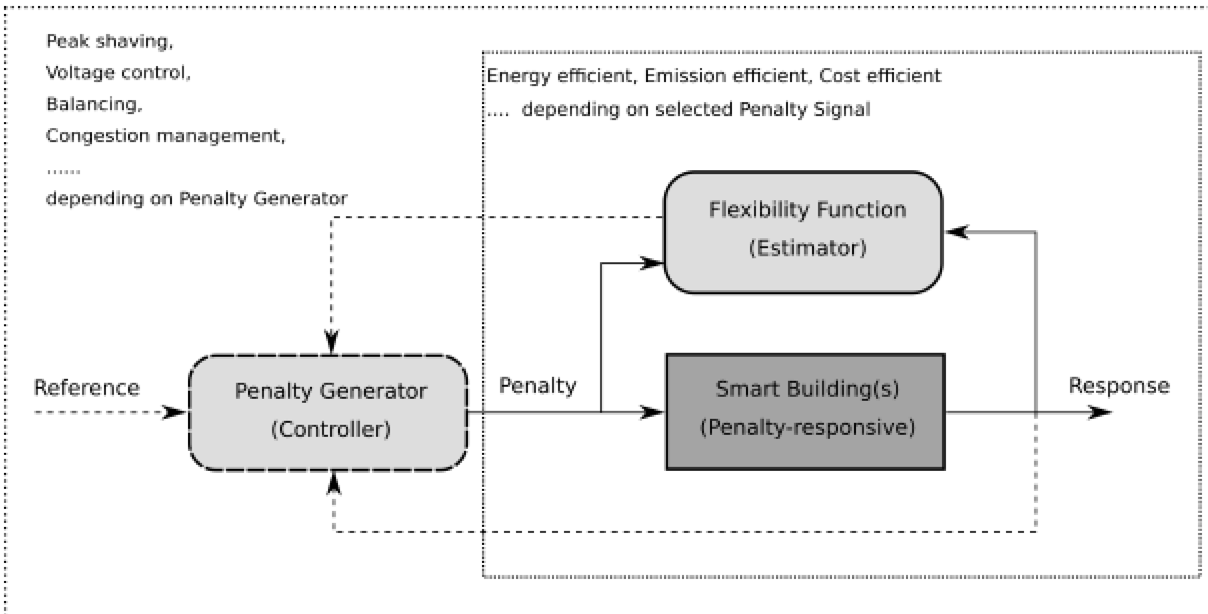


Figure 8: Smart buildings and penalty signals.

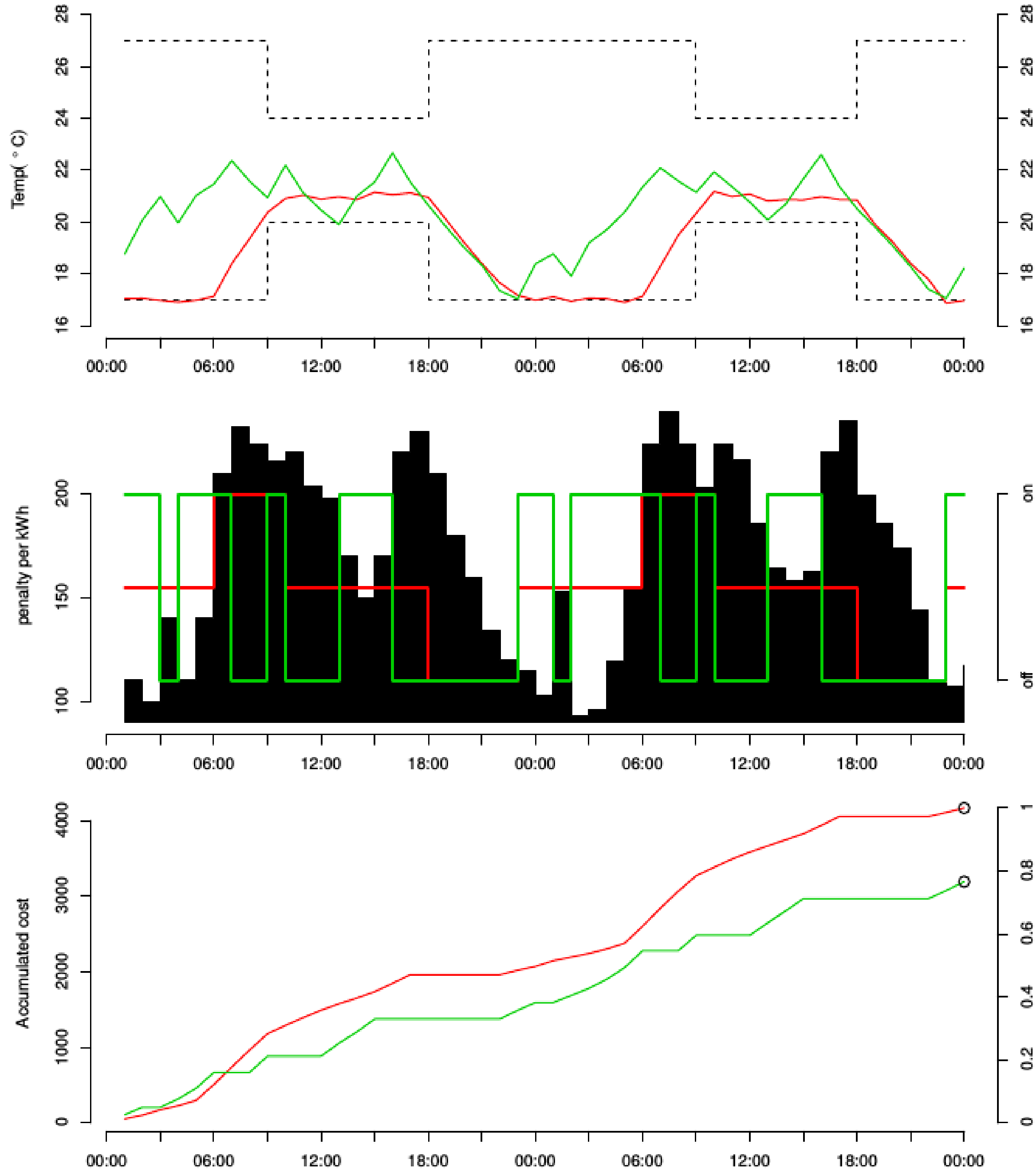
Procedure for calc. Flex. Index

for energy, price and emission based flexibility char.

The test consists of the following steps:

1. Let λ_t be the price of electricity at time t.
2. Simulate the control of the building *without considering* the price, and let u_t^0 be the electricity consumption at time t.
3. Simulate the control of the building *considering* the price, and let u_t^1 be the electricity consumption at time t.
4. The total operation cost of the price-ignorant control is given by $C^0 = \sum_{t=0}^{N} \lambda_t u_t^0$.
5. Similarly the operation cost of the price-aware control is given by $C^1 = \sum_{t=0}^{N} \lambda_t u_t^1$.
6. $1 - \frac{C^1}{C^0}$ is the result of the test, giving us the fractional amount of saved money.

This test is inspired by minimizing total costs for varying electricity prices, but in general λ_t could just represent ones desire to reduce electricity demand at time t.


Temp(°C)
16 18 20 22 24 26 28
00:00 06:00 12:00 18:00 00:00 06:00 12:00 18:00 00:00
penalty per kWh
100 150 200
on
off
Accumulated cost
0 1000 2000 3000 4000
0 0.2 0.4 0.6 0.8 1

FF for three buildings

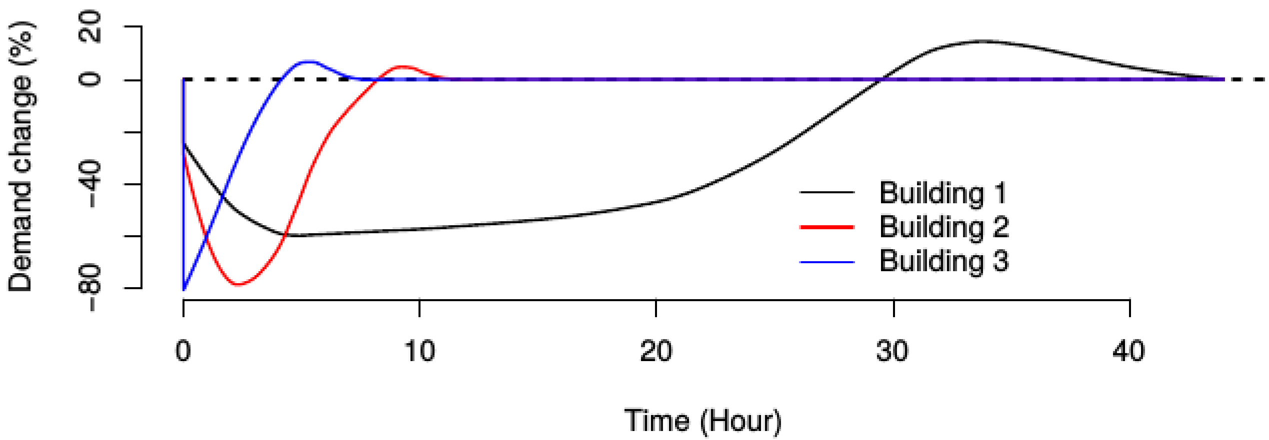


Figure 5: The Flexibility Function for three different buildings.

Realistic Penalties for DK

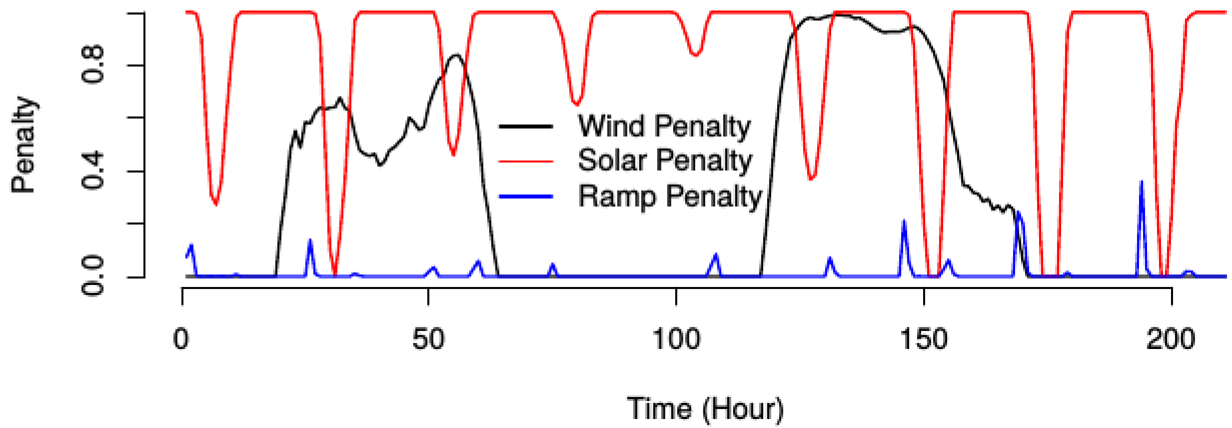


Figure 6: Penalty signals based on wind and solar power production in Denmark during some days in 2017.

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Expected Flexibility Savings Index

Table 1: Expected Flexibility Savings Index (EFSI) for each of the buildings based on wind, solar and ramp penalty signals.

	Wind (%)	Solar (%)	Ramp (%)
Building 1	11.8	3.6	1.0
Building 2	4.4	14.5	5.0
Building 3	6.0	10.0	18.4

Reference Penalties

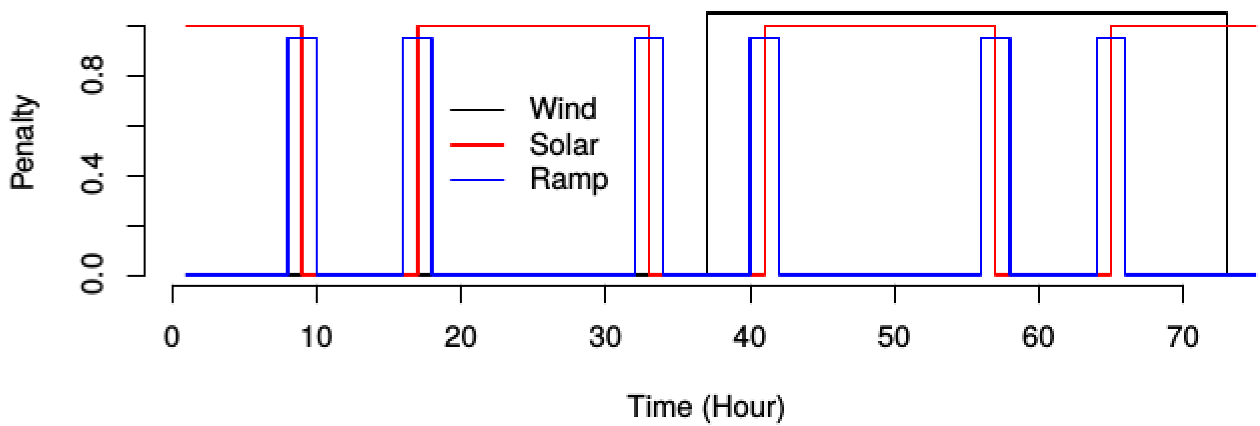


Figure 7: Reference scenarios of penalty signals related to ramping or peak issues as well as the integration of wind and solar power.

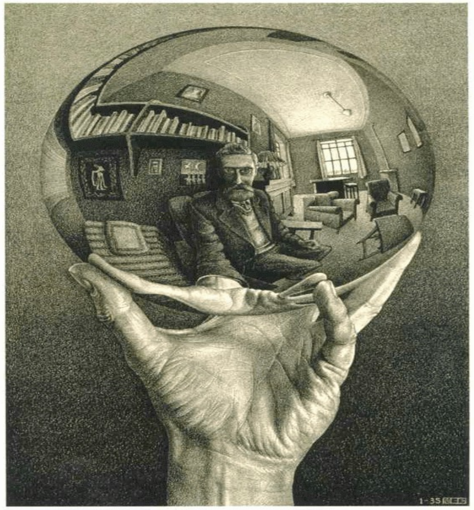
Flexibility Index

Table 2: Flexibility Index for each of the buildings based reference penalty signals representing wind, solar and ramp problems.

	Wind (%)	Solar (%)	Ramp (%)
Building 1	36.9	10.9	5.2
Building 2	7.2	24.0	11.1
Building 3	17.9	35.6	67.5

Understanding Power/Energy Flexibility
Some Demo Projects in CITIES:

- Control of WWTP (ED, Kruger, ..)
- Heat pumps (Grundfos, ENFOR, ..)
- Supermarket cooling (Danfoss, TI, ..)
- Summerhouses (DC, ENDK, Nyfors, ..)
- Green Houses (NeoGrid, ENFOR, ...)
- CHP (Dong Energy, EnergiFyn, ...)
- Industrial production
- EV (Eurisco, Enfor, ...)
- ....



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Summary

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- Methods for evidence based energy performance characterization is outlined for buildings and district heating (huge savings potentials)
- Automated methods for evidence-based energy labelling
- Automated methods for evidence-based flexibility labelling
- Flexibility Index for buildings (peak, solar, wind, ...)
- Automated methods for providing hints on how to improve the energy performance of buildings (and DH systems ...)
- Potentials for new evidence-based methodologies for energy savings support schemes

Summary

- A procedure for data intelligent control of power load, using the Smart-Energy OS setup, is suggested.
- The controllers can provide
  - Energy Efficiency
  - Cost Minimization
  - Emission Efficiency
  - Peak Shaving
  - Smart Grid demand (like ancillary services needs, ...)
- We have demonstrated 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.

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For more information ...

See for instance

www.smart-cities-centre.org

...or contact

- Henrik Madsen (DTU Compute)
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