Can heating and cooling really be flexible enough to have an impact on the energy infrastructure?

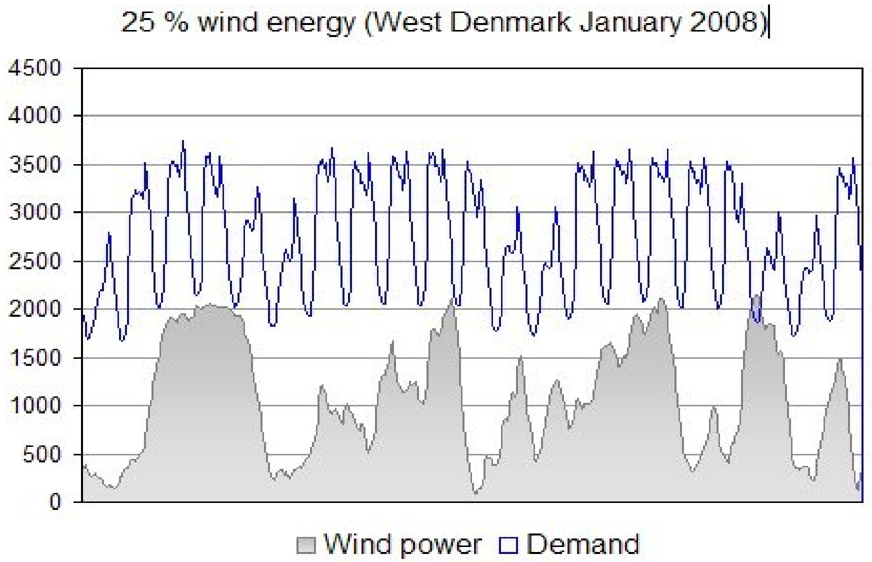
Henrik Madsen, DTU Compute

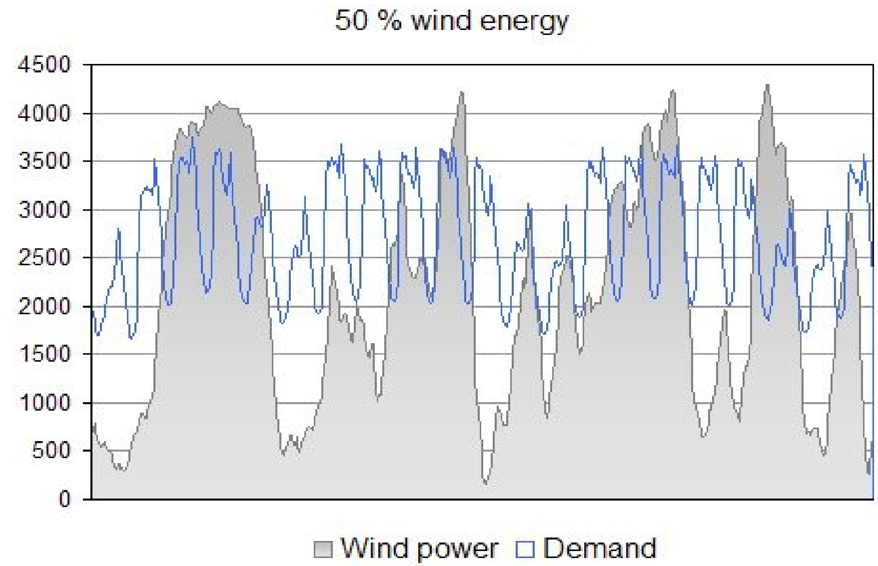
http://www.henrikmadsen.org

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

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.

Periods with more than 140 pct of the power load covered by wind power are seen

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Challenges

Conclusion: Almost no flexibility ?!

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.

iiESI International Institute for Energy Systems Integration

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

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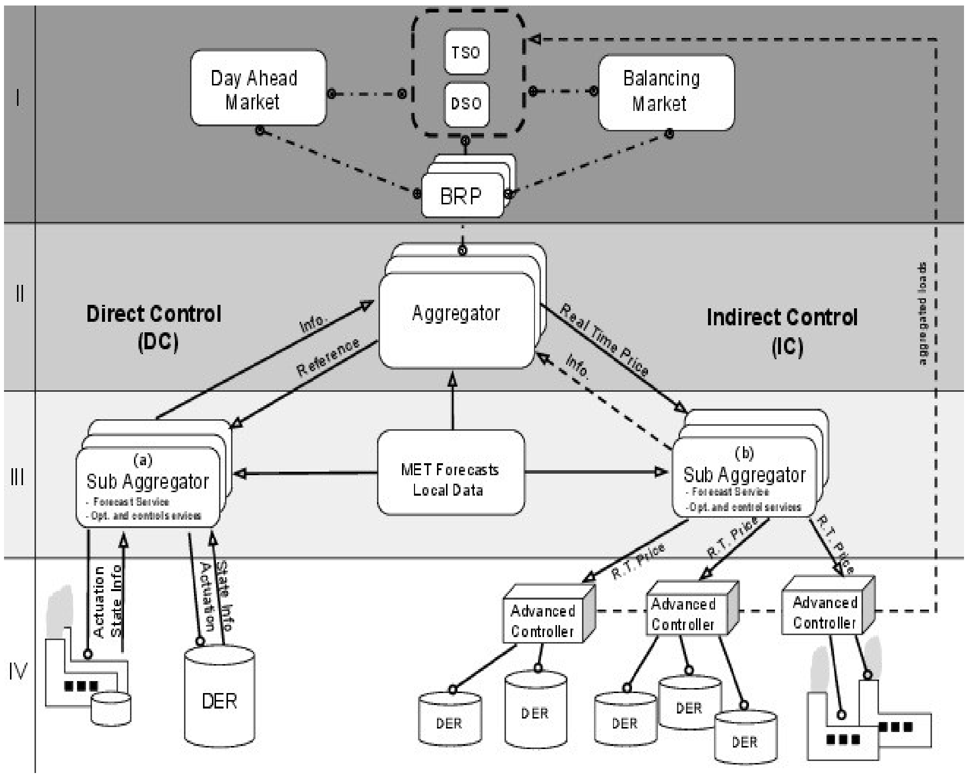
Smart-Energy OS



In New Wiley Book: Control of Electric Loads in Future Electric Energy Systems, 2015

Day Ahead:

Stoch. Programming based on eg. Scenarios

Cost: Related to the market (one or two levels)

Direct Control:

Actuator: **Power**

Two-way communication

Models for DERs are needed

Constraints for the DERs (calls for state est.)

Contracts are complicated

Indirect Control:

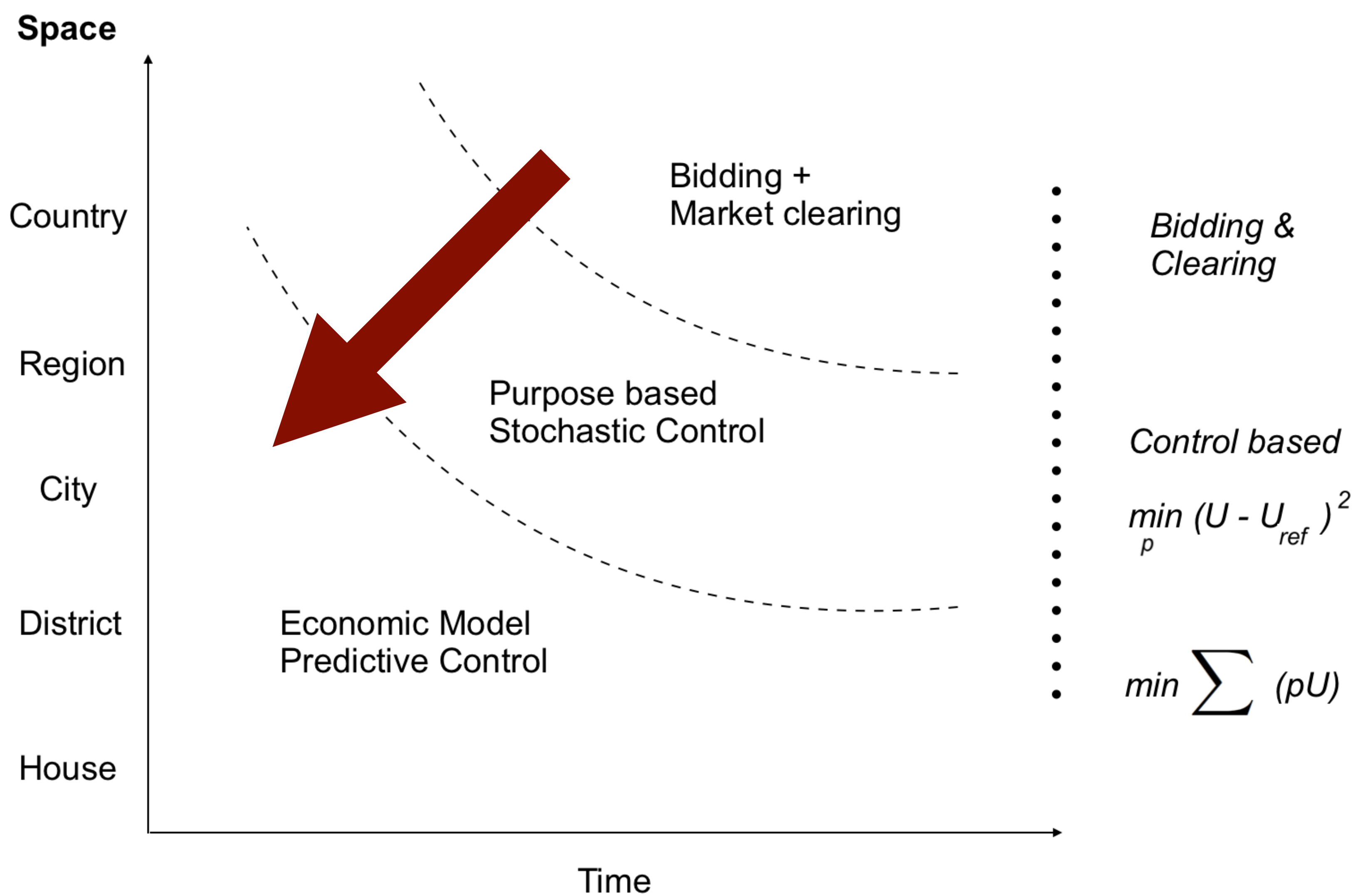
Actuator: **Price**

Cost: E-MPC at **low (DER) level**, One-way communication

Models for DERs are not needed

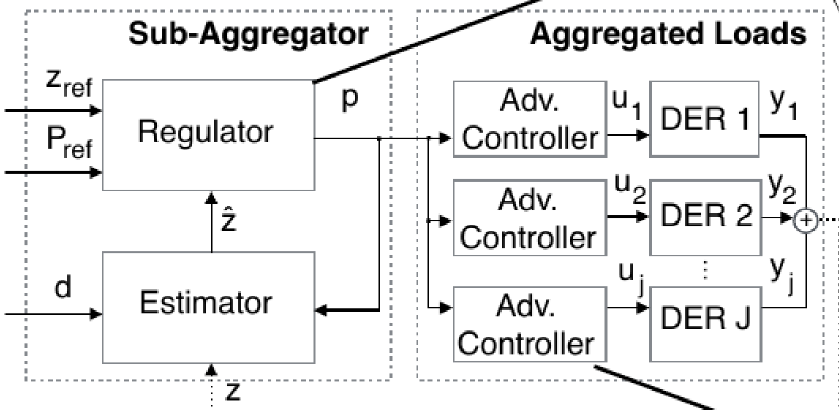
Simple 'contracts'

The ‘market’ for future Smart Grids



Proposed methodology
Control-based methodology

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



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

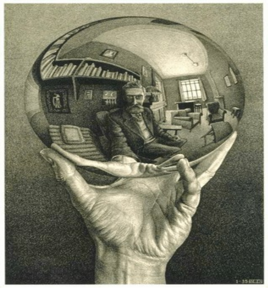
$$
\begin{aligned}
\min_{u} \quad & \mathrm{E}\Big[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)\Big] \\
\text{s.t.} \quad & x_{k+1} = Ax_k + Bu_k + Ed_k, \\
& y_k = Cx_k, \\
& y_k^{min} \le y_k \le y_k^{max}, \\
& u_k^{min} \le u_k \le u_k^{max}
\end{aligned}
$$

iiESI International Institute for Energy Systems Integration

DTU

SE-OS Characteristics

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

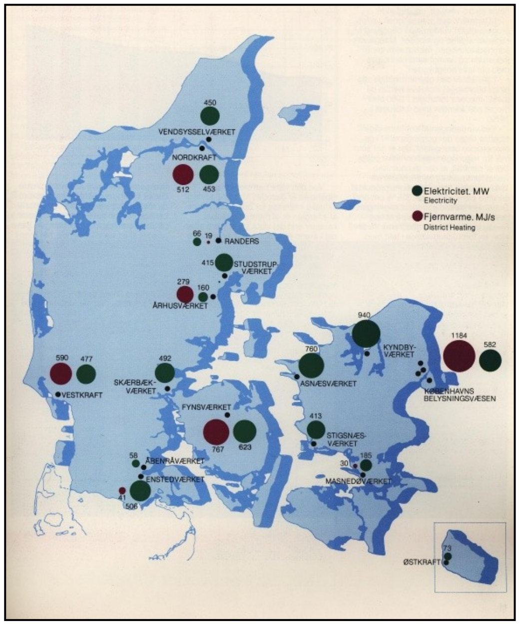


Case study No. 1

Flexibility in CHP Systems

From large central plants to Combined Heat and Power (CHP) production

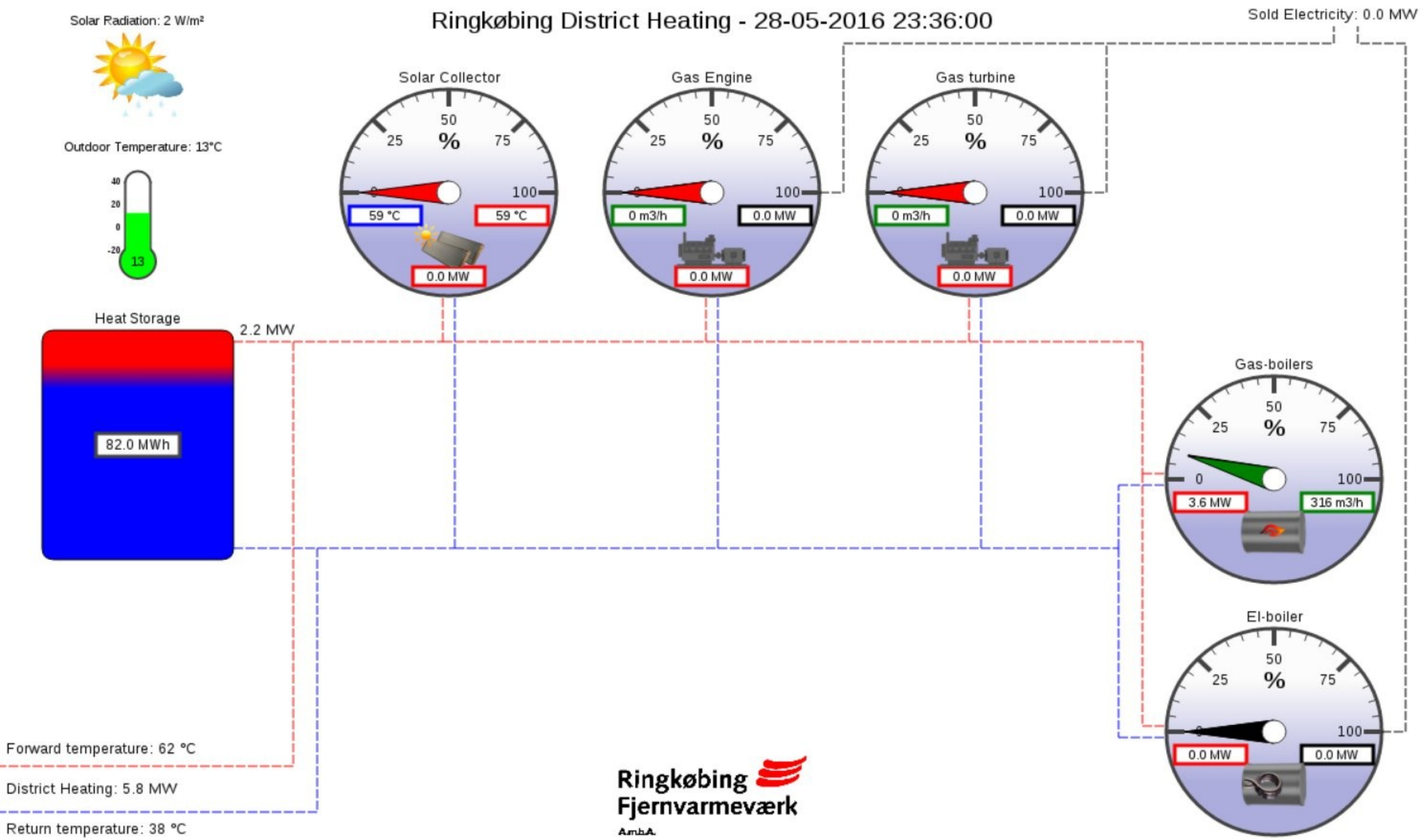
1980



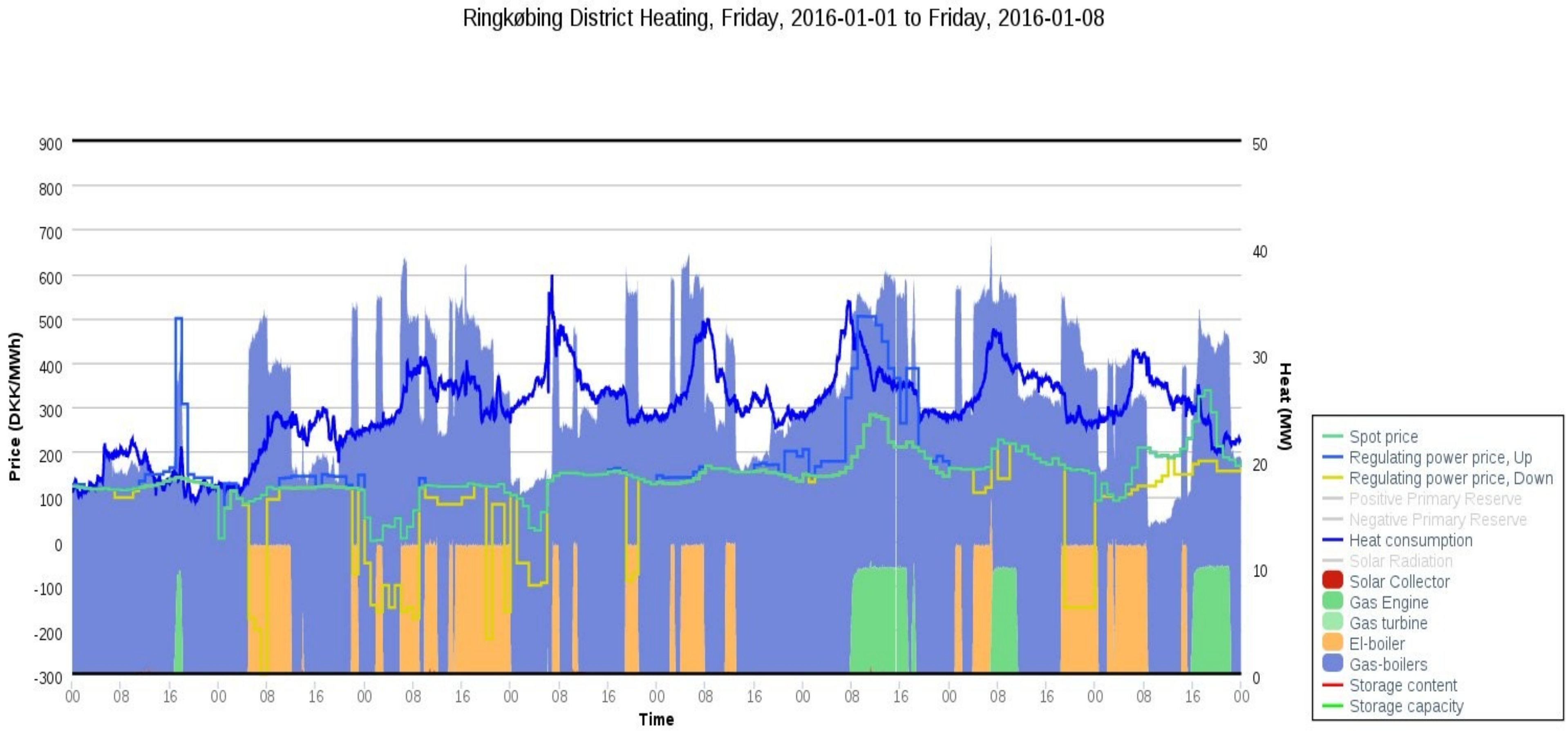
Today

*From a few big power plants to many small **combined heat and power** plants – however some still based fossil f.*

Flexibility – Ringkøbing CHP

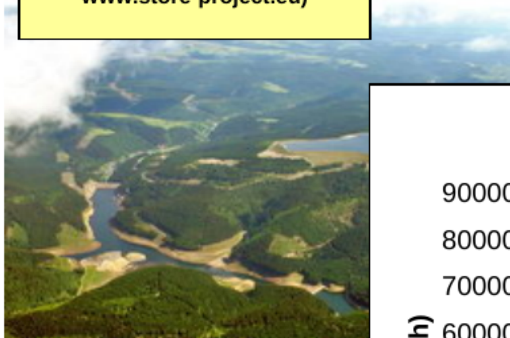


Flexibility – Ringkøbing CHP

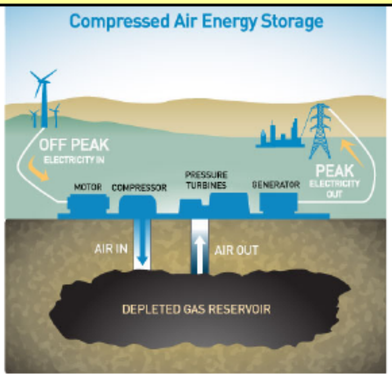


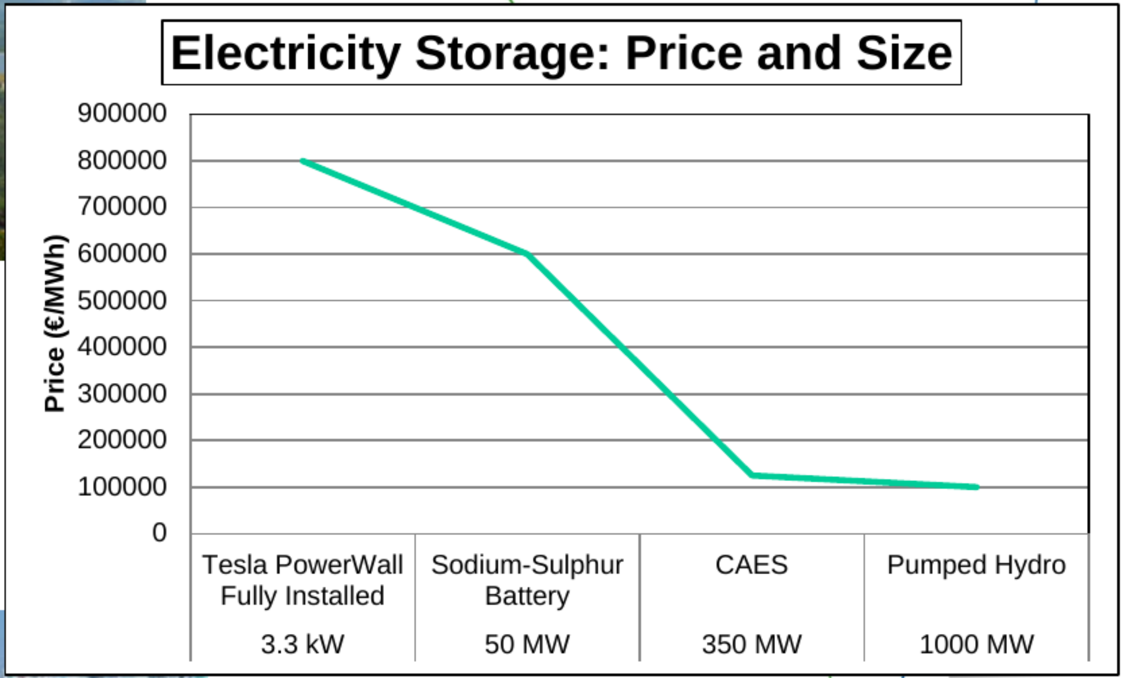
Electricity Storage

Pump Hydro Storage
100 €/kWh
(Source: Goldisthal Pumped Storage Station, Germany, www.store-project.eu)



Compressed Air Energy Storage
125 €/kWh
(Source: http://www.sciencedirect.com/science/article/pii/S0196890409000429)



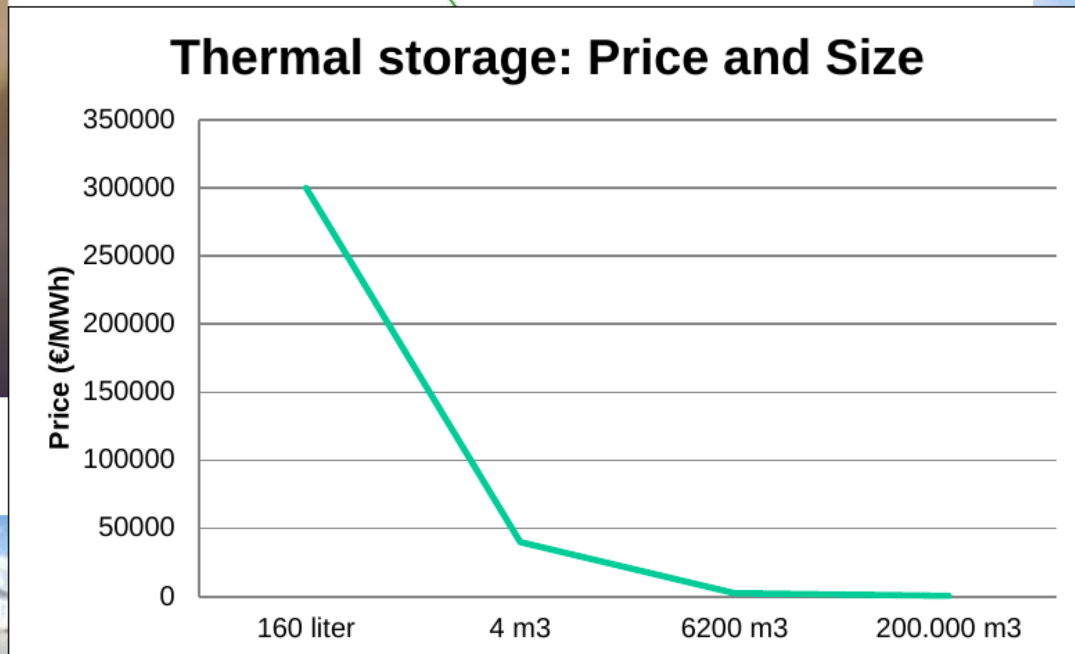


Sodium-Sulphur Battery
600 €/kWh
(Source: Table 4: http://large.stanford.edu/courses/2012/ph240/doshay1/docs/EPRI.pdf)

Tesla PowerWall
800 €/kWh
(Source: Dahl KH, Oil tanking Copenhagen A/S, 2013: Oil Storage Tank. 2013)

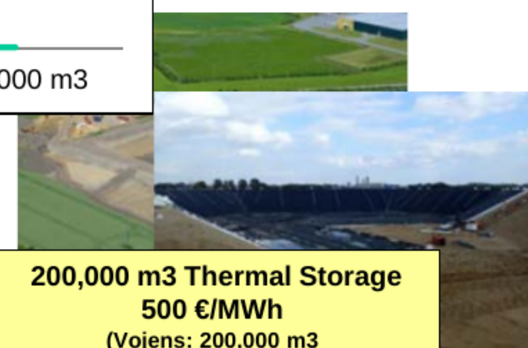
Thermal Storage

0.16 m3 Thermal Storage
300.000 €/MWh
(Private house: 160 liter for 15000 DKK)



6200 m3 Thermal Storage
2500 €/MWh
(Skagen: 6200 m3 for 5.4 mio. DKK)

4 m3 Thermal Storage
40,000 €/MWh
(Private outdoor: 4000 m3 for 50,000 DKK)



200,000 m3 Thermal Storage
500 €/MWh
(Vojens: 200,000 m3 for 30 mio. DKK)

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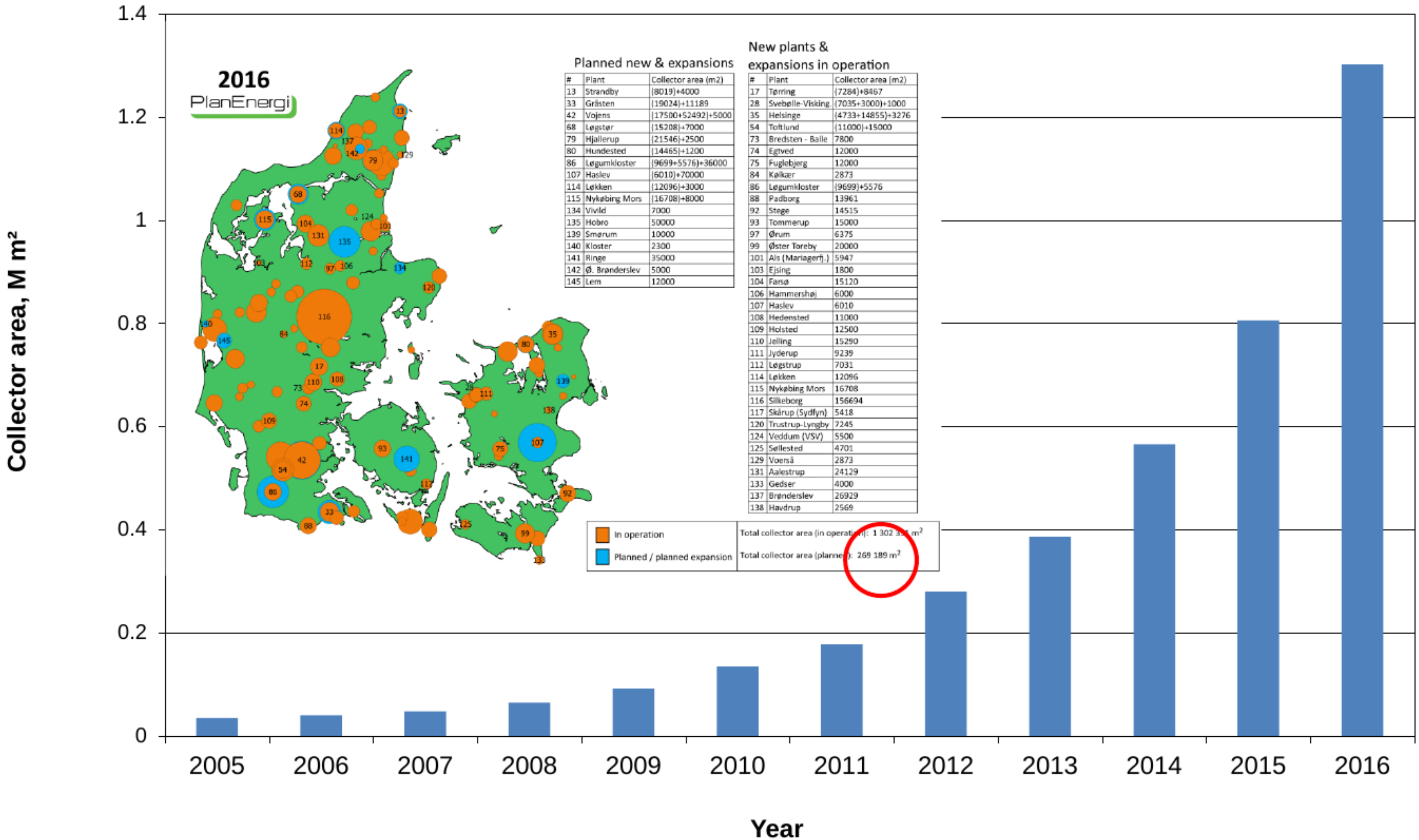
Solar heating plants in Denmark



Planned new & expansions

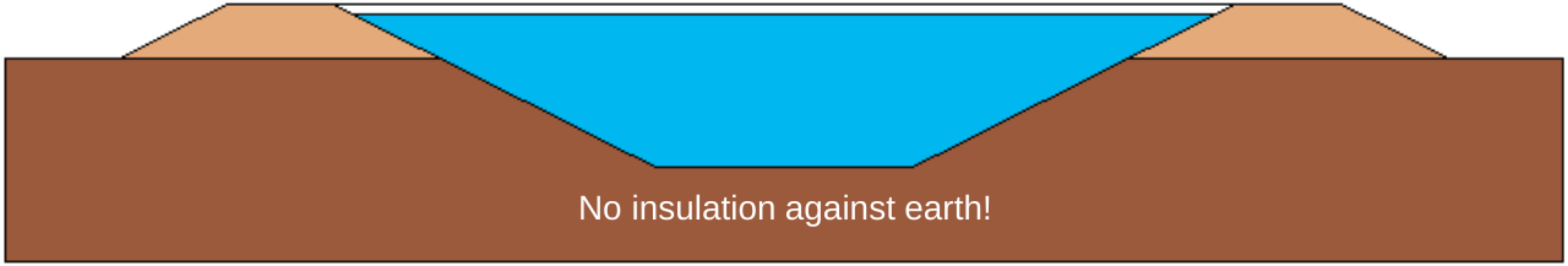
#	Plant	Collector area (m2)
13	Strandby	(8019)+4000
33	Gråsten	(19024)+11189
42	Vojens	(17500+52492)+5000
68	Løgstør	(15208)+7000
79	Hjallerup	(21546)+2500
80	Hundested	(14465)+1200
86	Løgumkloster	(9699+5576)+36000
107	Haslev	(6010)+70000
114	Løkken	(12096)+3000
115	Nykøbing Mors	(16708)+8000
134	Vivild	7000
135	Hobro	50000
139	Smørum	10000
140	Kloster	2300
141	Ringe	35000
142	Ø. Brønderslev	5000
145	Lem	12000

New plants & expansions in operation

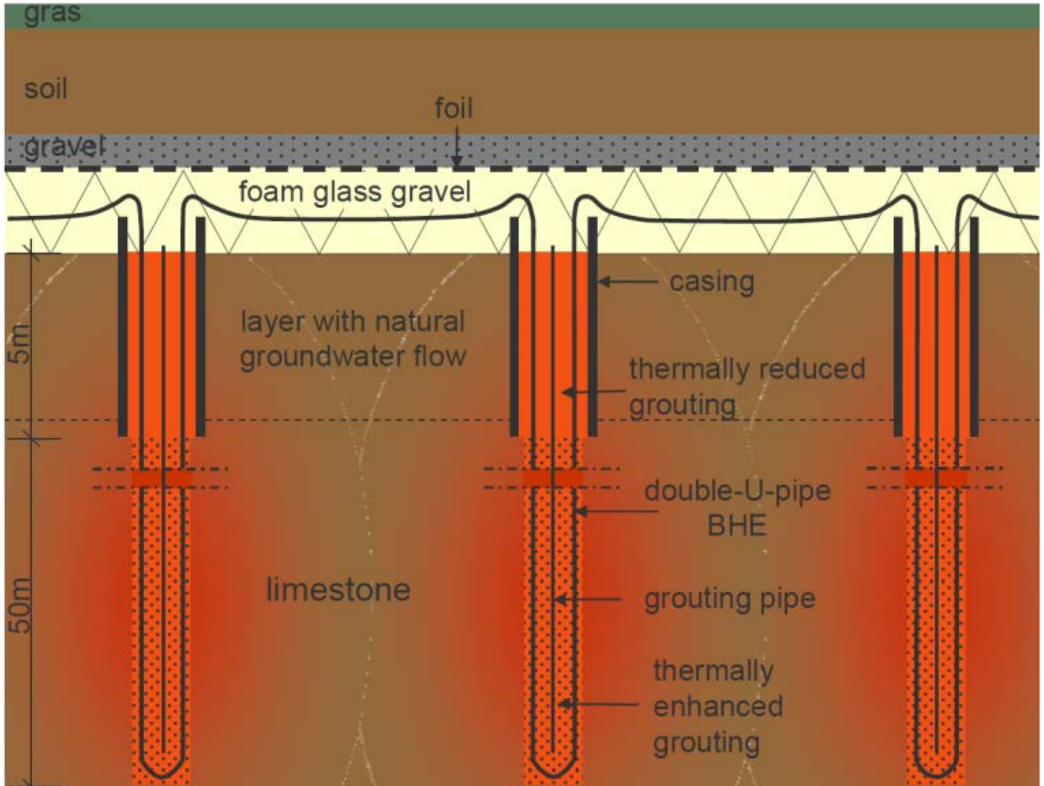
#	Plant	Collector area (m2)
17	Tørring	(7284)+8467
28	Svebølle-Visking.	(7035+3000)+1000
35	Helsinge	(4733+14855)+3276
54	Toftlund	(11000)+15000
73	Bredsten - Balle	7800
74	Egtved	12000
75	Fuglebjerg	12000
84	Kølkær	2873
86	Løgumkloster	(9699)+5576
88	Padborg	13961
92	Stege	14515
93	Tommerup	15000
97	Ørum	6375
99	Øster Toreby	20000
101	Als (Mariagerfj.)	5947
103	Ejsing	1800
104	Farsø	15120
106	Hammershøj	6000
107	Haslev	6010
108	Hedensted	11000
109	Holsted	12500
110	Jelling	15290
111	Jyderup	9239
112	Løgstrup	7031
114	Løkken	12096
115	Nykøbing Mors	16708
116	Silkeborg	156694
117	Skårup (Sydfyn)	5418
120	Trustrup-Lyngby	7245
124	Veddum (VSV)	5500
125	Søllested	4701
129	Voerså	2873
131	Aalestrup	24129
133	Gedser	4000
137	Brønderslev	26929
138	Havdrup	2569

Seasonal heat storage types

Water pit

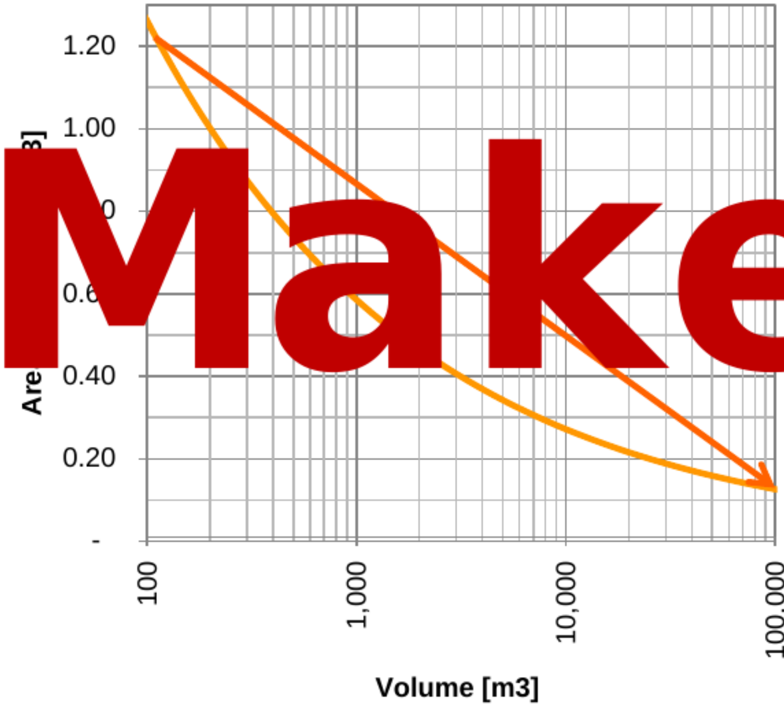


Borehole storage

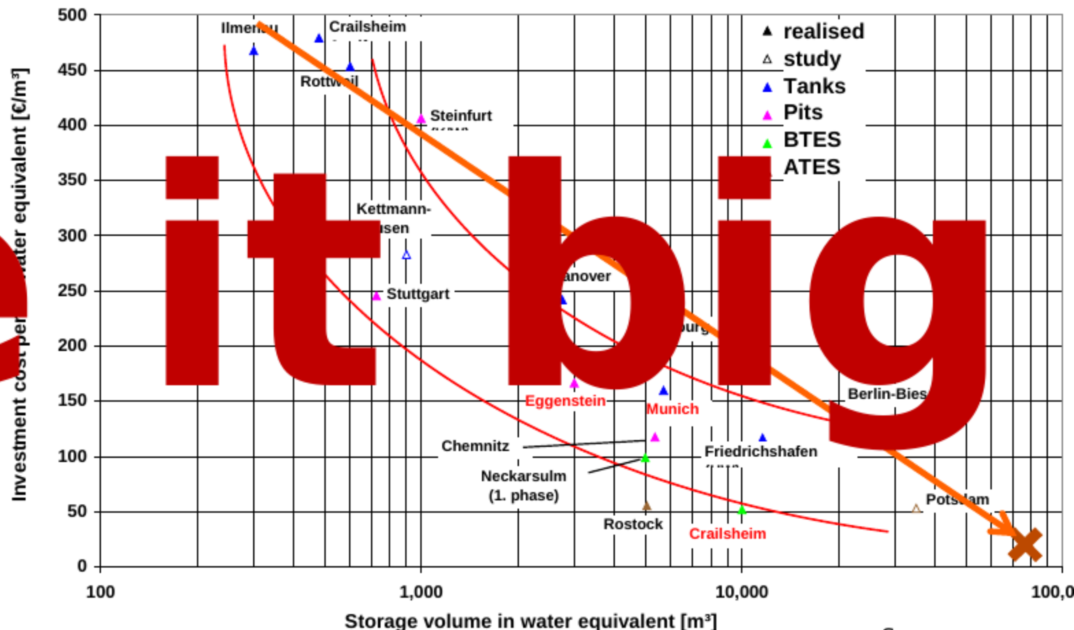


LARGE SYSTEMS → small storage losses & lower specific costs

Surface area per volume (Cylinder, Radius = Height)



Cost per equivalent m³



Source: SOLITES

Make it big

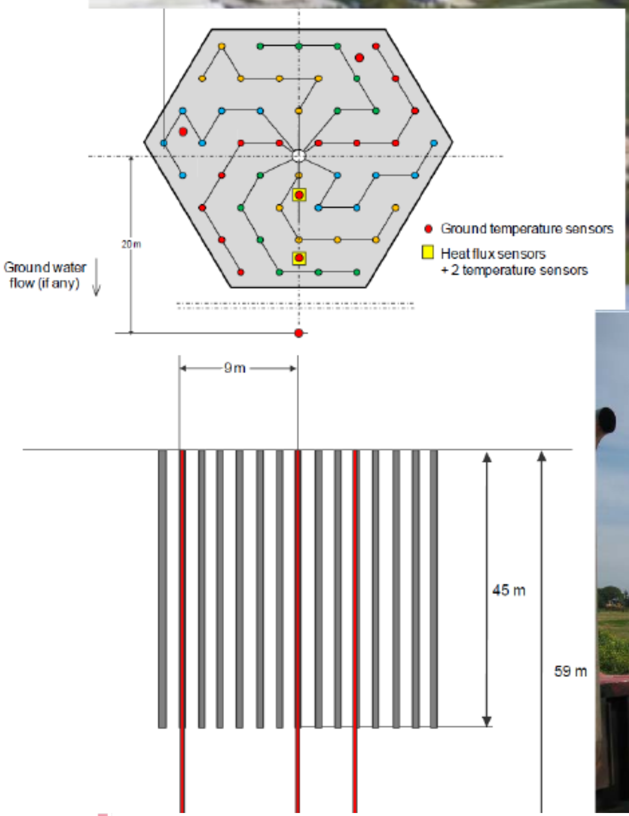
1.2 → 0.1 ➔ Factor 12!

500 → 20 ➔ Factor 25!

Water pits for seasonal heat storage with water volumes > 60,000 m³: Yearly heat loss < 10%

Marstal
Seasonal heat storage - 75000 m^3 water pit

19000 m^3 borehole storage in Brædstrup



Measurements

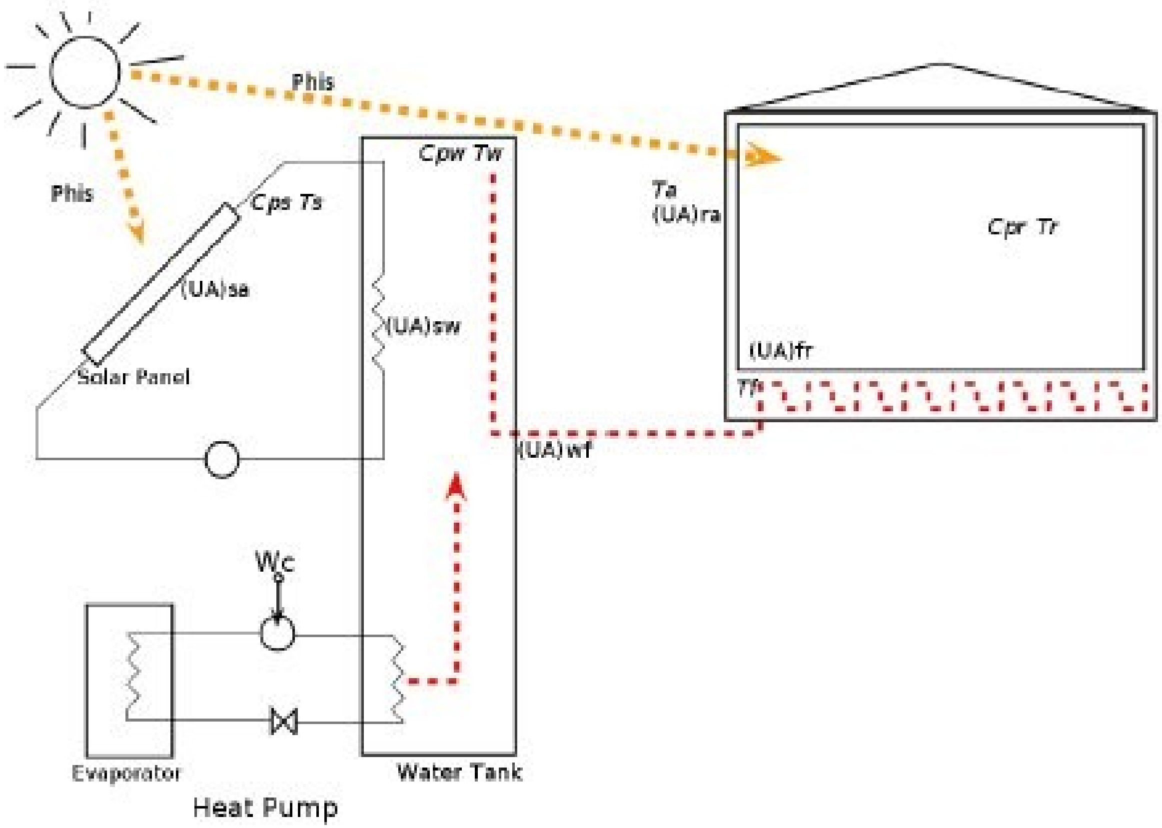
	Borehole storage, Brædstrup	Water pit storage, Marstal	Water pit storage,Dronninglund	Water pit storage, Gram
Size	19000 m^3 soil, corresponding to about 12000 m^3 water	75000 m^3 water	62000 m^3 water	110000 m^3 water
Maximum storage temperature	50°C	90°C	90°C	90°C
Heat recovered from heat storage during 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%	

Case study No. 2

Heat Pumps and Local Storage (thermal mass and water tank)

Modeling Heat Pump and Solar Collector

Simplified System



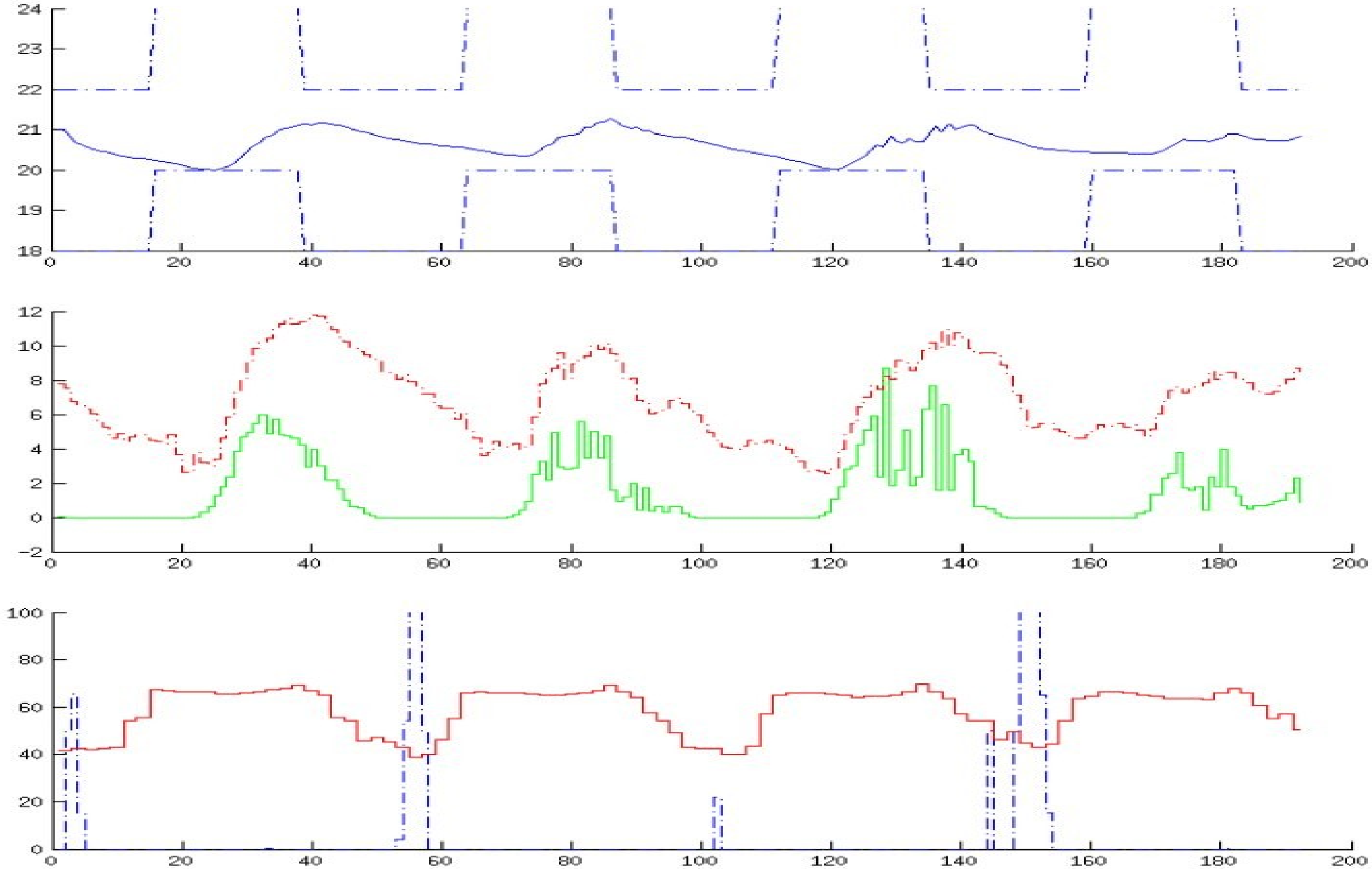
Formulation

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

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

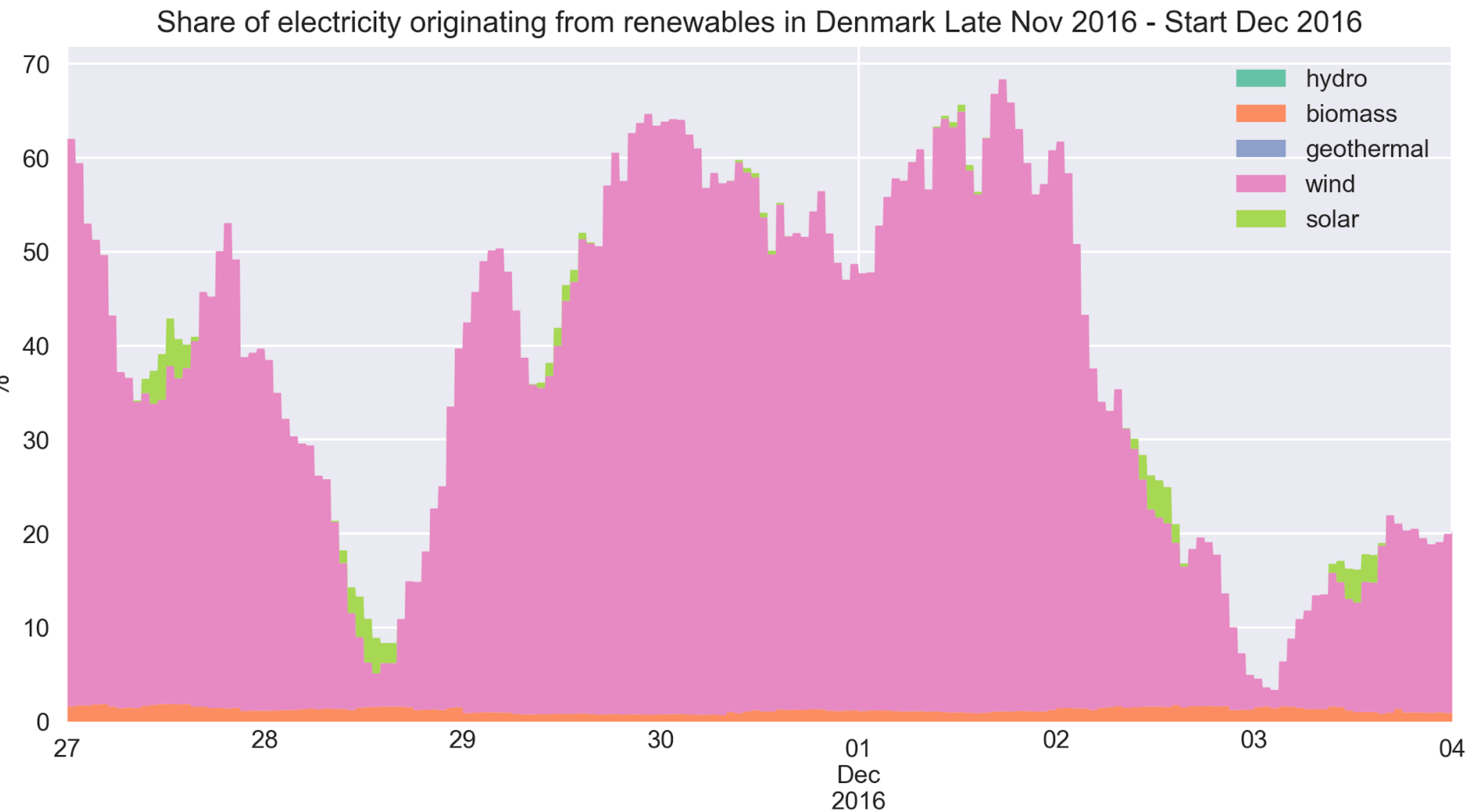
$$\begin{aligned}
\text{Subject to} \quad & x_{k+1} = Ax_k + Bu_k + Ed_k & k = 0, 1, \dots, N-1 \quad & (4b)\\
& y_k = Cx_k & k = 1, 2, \dots, N \quad & (4c)\\
& u_{min} \leq u_k \leq u_{max} & k = 0, 1, \dots, N-1 \quad & (4d)\\
& \Delta u_{min} \leq \Delta u_k \leq \Delta u_{max} & k = 0, 1, \dots,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

Heat pump with thermal solar collector and storage
(cost savings up to 25 pct – increased energy consumption 8 pct)

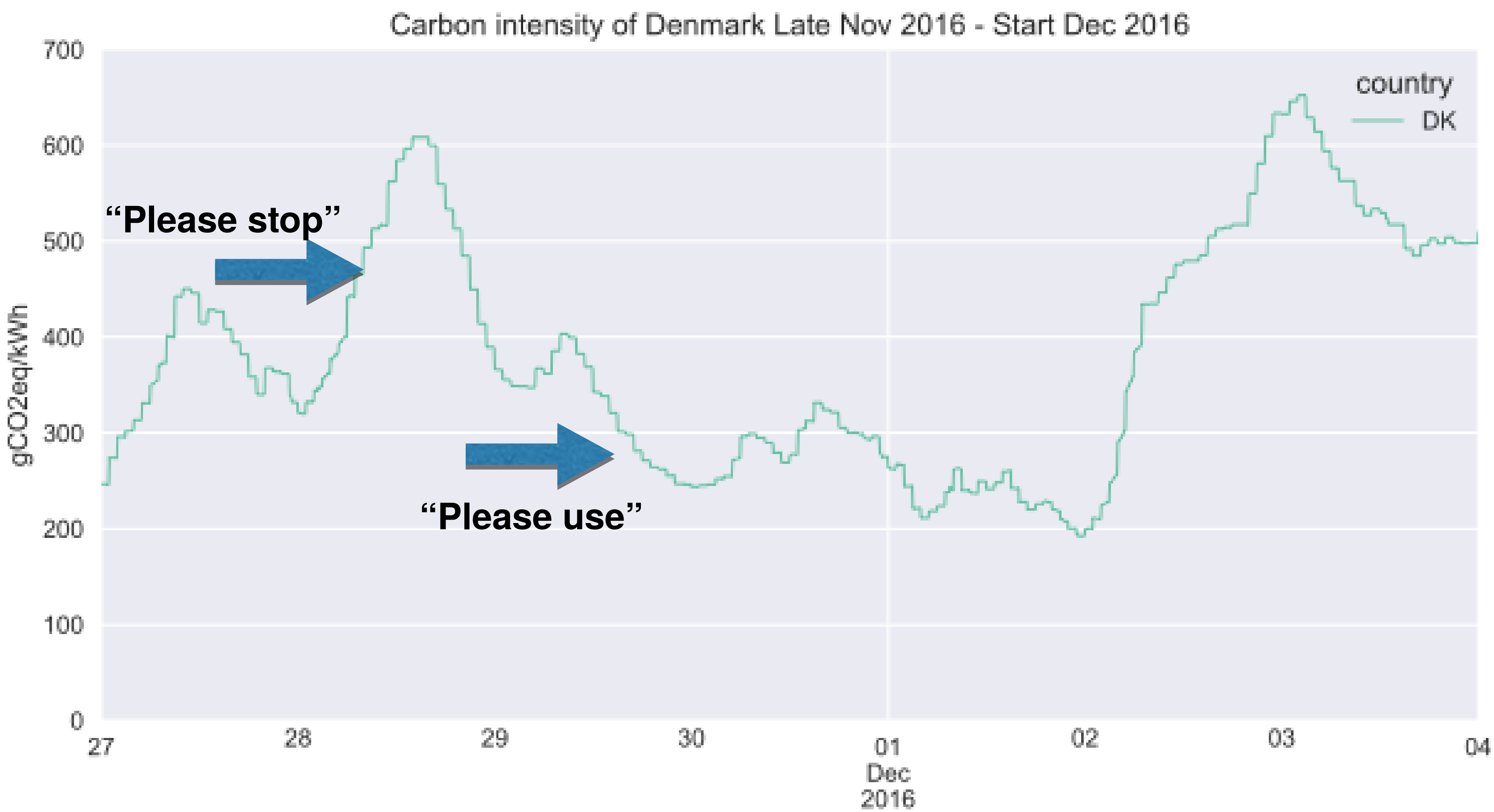


Case study No. 3

Control of heat pumps; houses with a swimming pool (CO2 minimization)



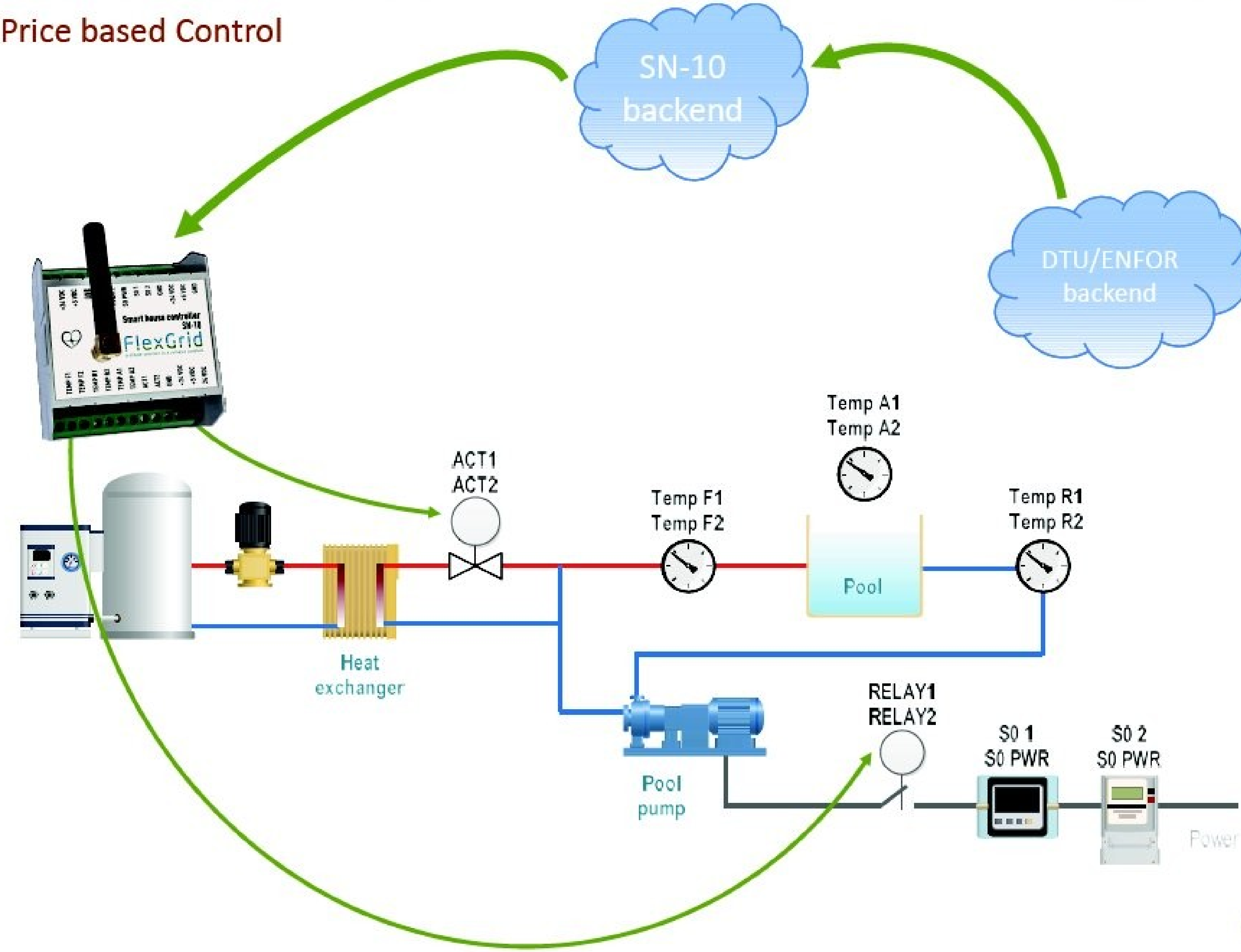
Source: pro.electicitymap.



Source: pro.electicitymap.

How does it work?

Price based Control



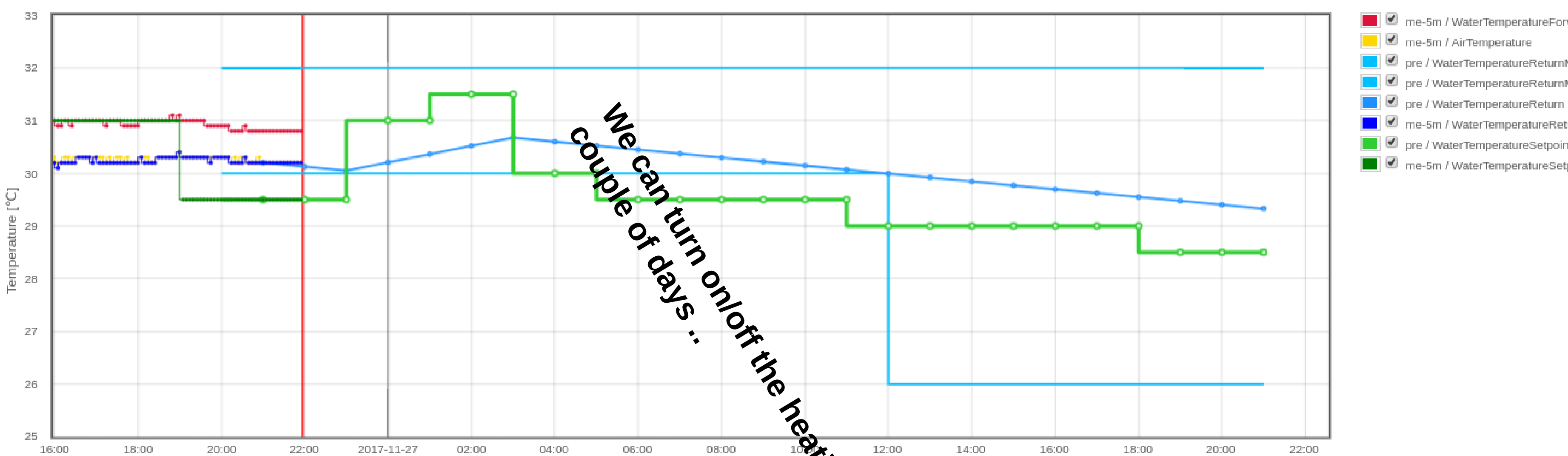
ENFOR SmartNet

SmartNet > D7811

Measurements | Weather forecast | Booking plan | Controller | Temperature limits

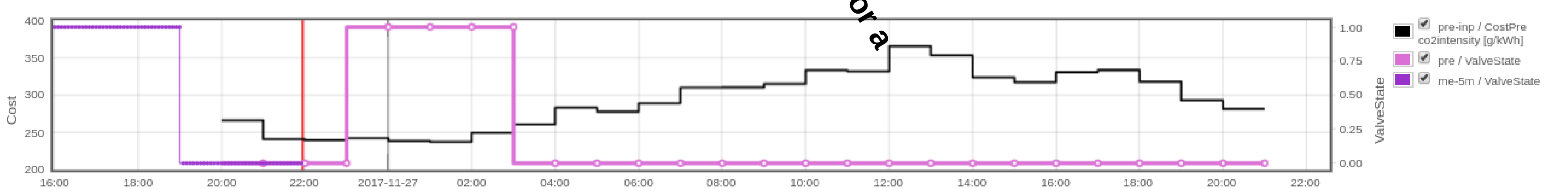
D7811 Controller

Cost: co2intensity [g/kWh]



We can turn on/off the heating for a couple of days ..

Download



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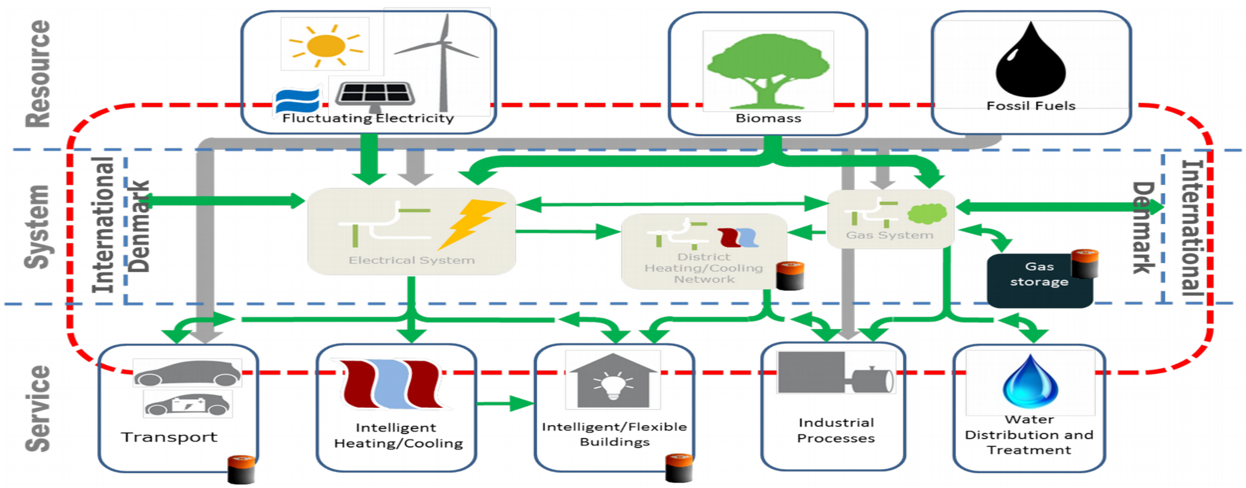
Online mode <<<< <<< << < Now > >> >>> >>>> 2017-11-26 21:58:10 CET Go User: SmartNet

Thermal Flexibility Characteristics



- **Flexibility (or virtual storage) characteristics:**
  - Supermarket refrigeration can provide storage 0.5-2 hours ahead
  - Buildings thermal capacity can provide storage up to, say, 5-10 hours ahead
  - Buildings with local water storage can provide storage up to, say, 2-16 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

Conclusion

- YES! I don’t think we need all these super grids (like the Viking Link)
- Intelligent Energy Systems Integration with thermal systems can provide flexibility and long term storage solutions
- District heating (or cooling) systems can provide flexibility on the essential time scales
- Gas systems can provide seasonal virtual storage solutions
- Seasonal thermal storage in DH systems (summer to winter)
- <u>Scale matters!</u> (Sub-optimal to consider household level systems)
- We see a large potential in Demand Response and Flexibility. Automatic solutions, price based control, and end-user focus are important
- Markets, taxes and pricing principles need to be reconsidered. We see an advantage of having a physical link to the mechanism (eg. nodal pricing, capacity markets)

Thanks .....

Slides on thermal seasonal storage: Thanks to Simon Furbo, DTU

Slides about costs for storages: Thanks to Henrik Lund, AAU

For more information see for instance

www.smart-cities-centre.org

...or contact

– Henrik Madsen (DTU Compute)

hmad@dtu.dk

Acknowledgement - DSF 1305-00027B

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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 on GitHub.

MPCR is a toolbox for building Model Predictive Controllers written in R, the free statistical software. It contains several examples for different MPC problems and interfaces to opensource solvers in R . The software is available on GitHub.

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