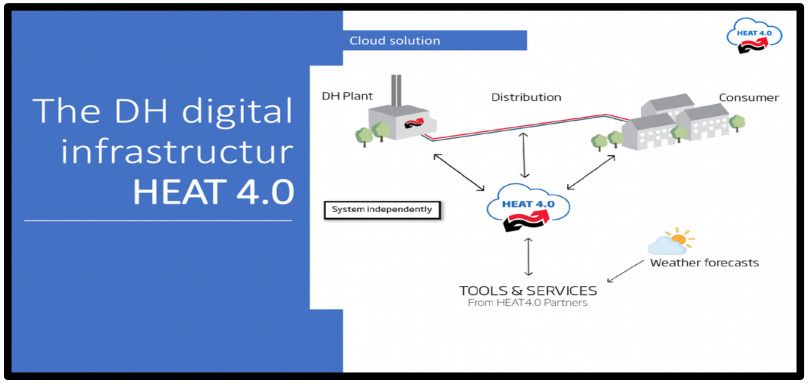
New Opportunities and

Smart Energy Systems Integration



Digital Operation of DH Systems - HEAT4.0 - Lessons Learned

Henrik Madsen, Hjorleifur Bergsteinsson, Daniela Guericke,

Amos Schledorn, Christian A. Thilker, Phillip B. Vetter, Jan K. Møller

Technical University of Denmark

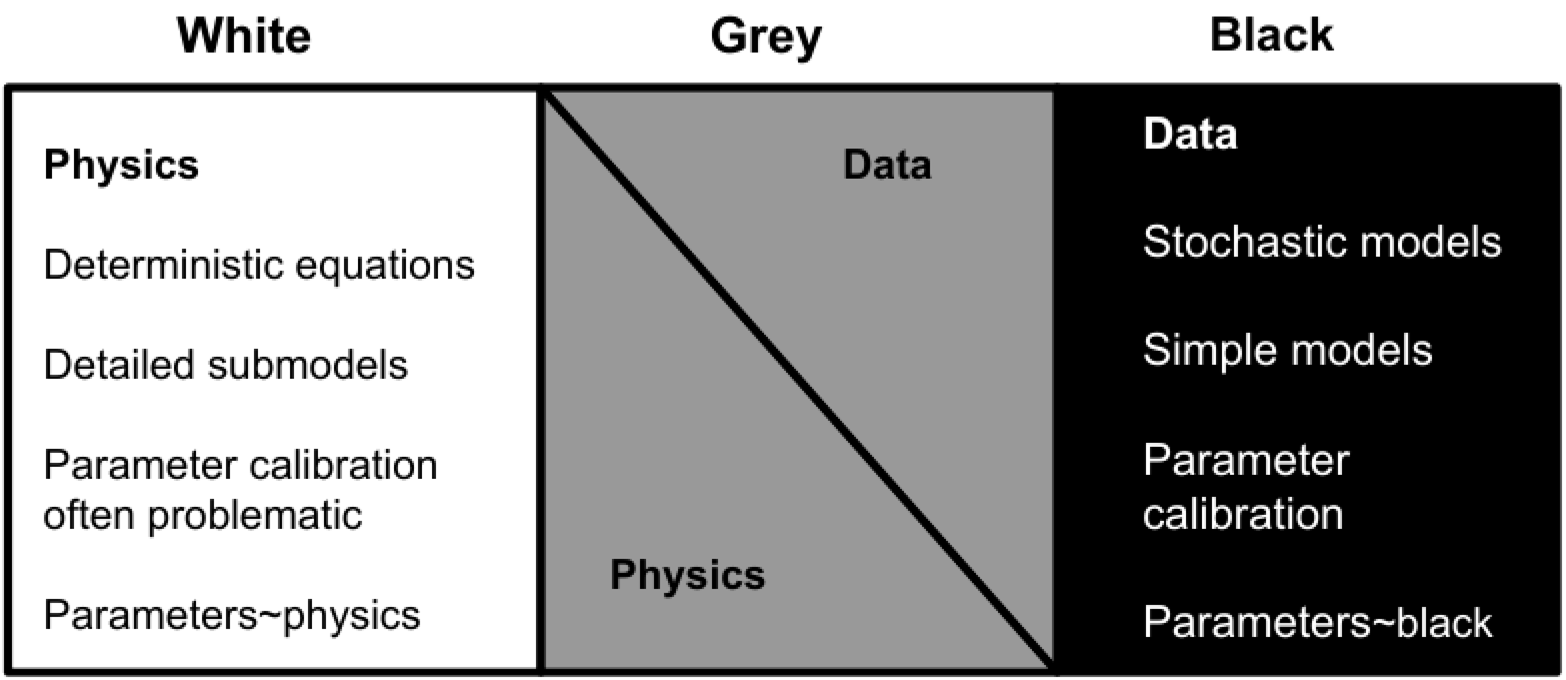
http://www.henrikmadsen.org

Outline

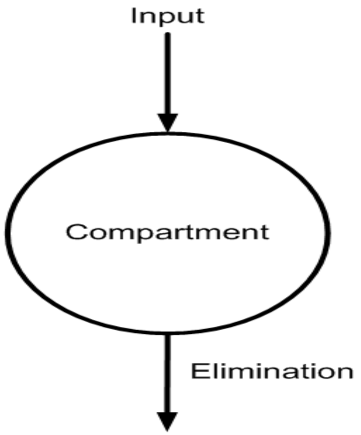
- **Bridging the gap between physical and statistical modelling (grey-box modelling)**
- **Combined and hierarchical forecasting**
- **Simulation** versus **data-driven/prediction-based** methods
- **Weather forecasting in cities**
- **Load forecasting**
- **Temperature Optimization**
- Use of **meter data**
- **Flexible load** in buildings and DH systems
- **Cloud Hub** at Center Denmark (HEAT4.0 cloud)
- **Optimal Bidding** for District Heating Providers

Grey-box Modelling

Grey-box Modelling

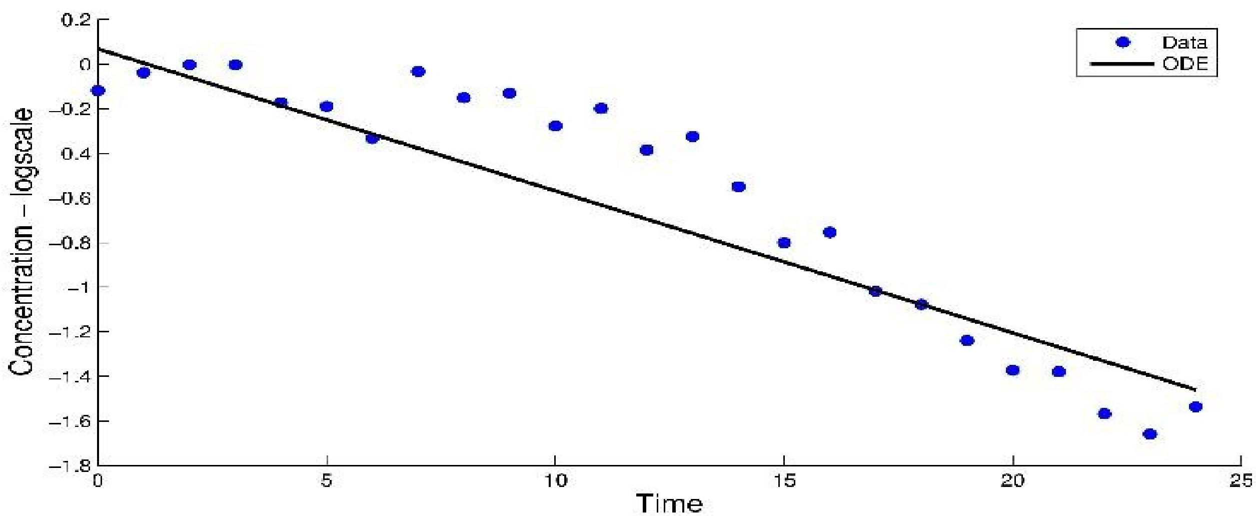


Traditional Dynamic Model

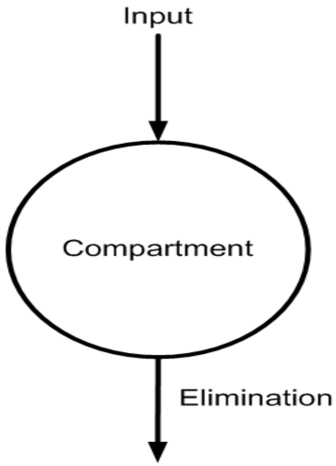


- Ordinary Differential Equation:

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

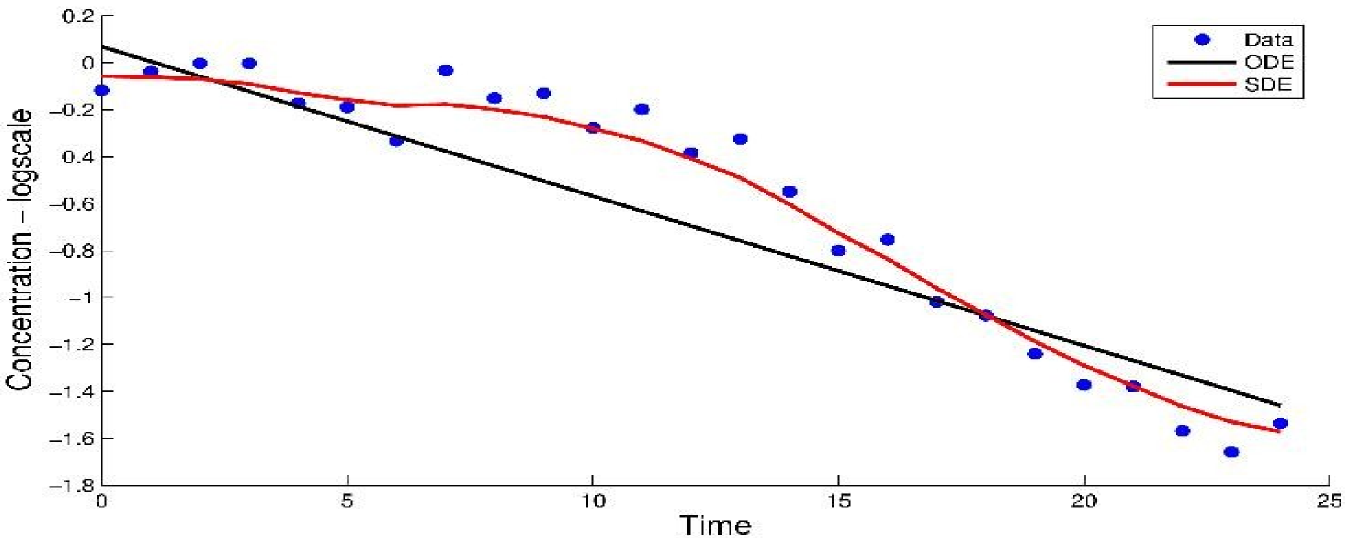


Stochastic Dynamic Model



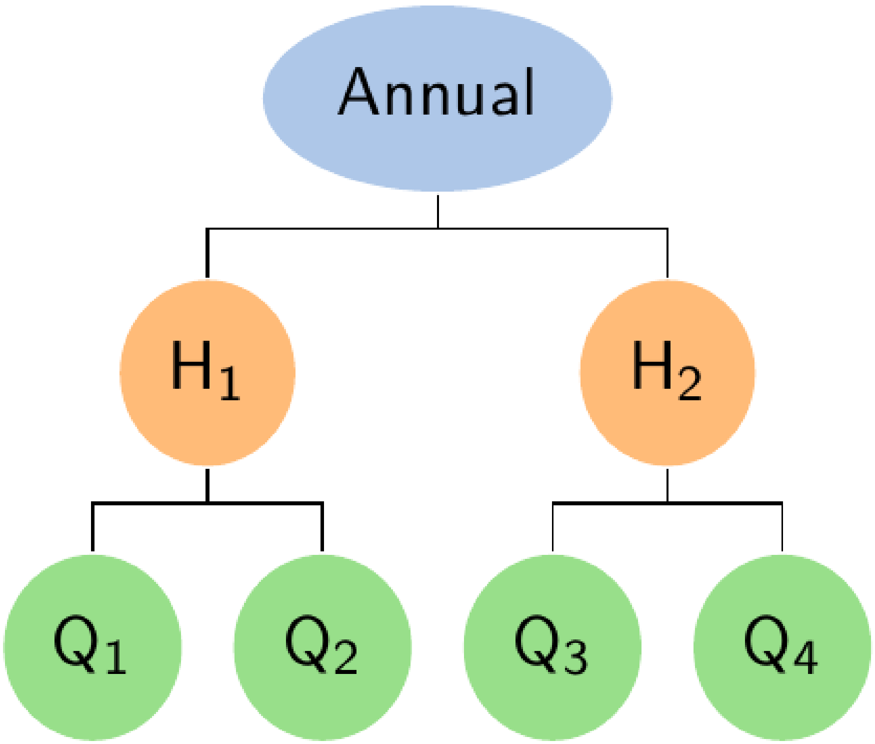
- Stochastic Differential Equation:

$$
\begin{aligned}
dA &= -KAdt + \sigma dw \\
Y &= A + e
\end{aligned}
$$



Forecasting using Temporal Hierarchies

Temporal hierarchy for quarterly series (Consistent forecasting across scales)



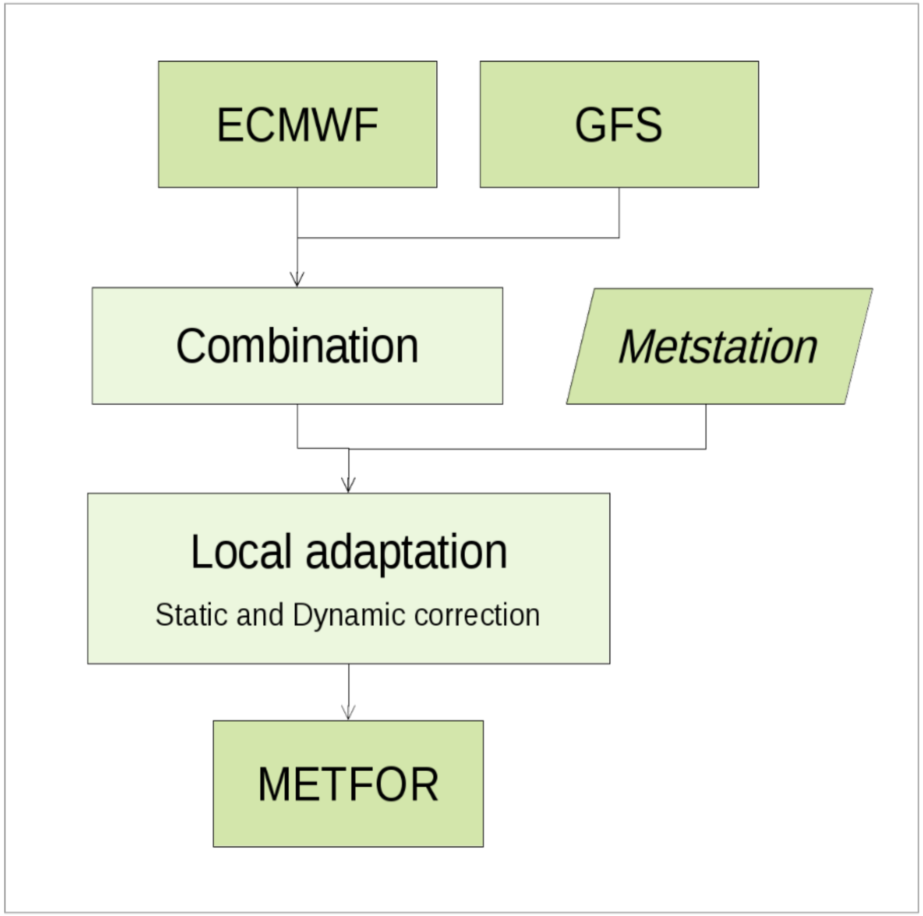
$$S = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Weather Forecasting

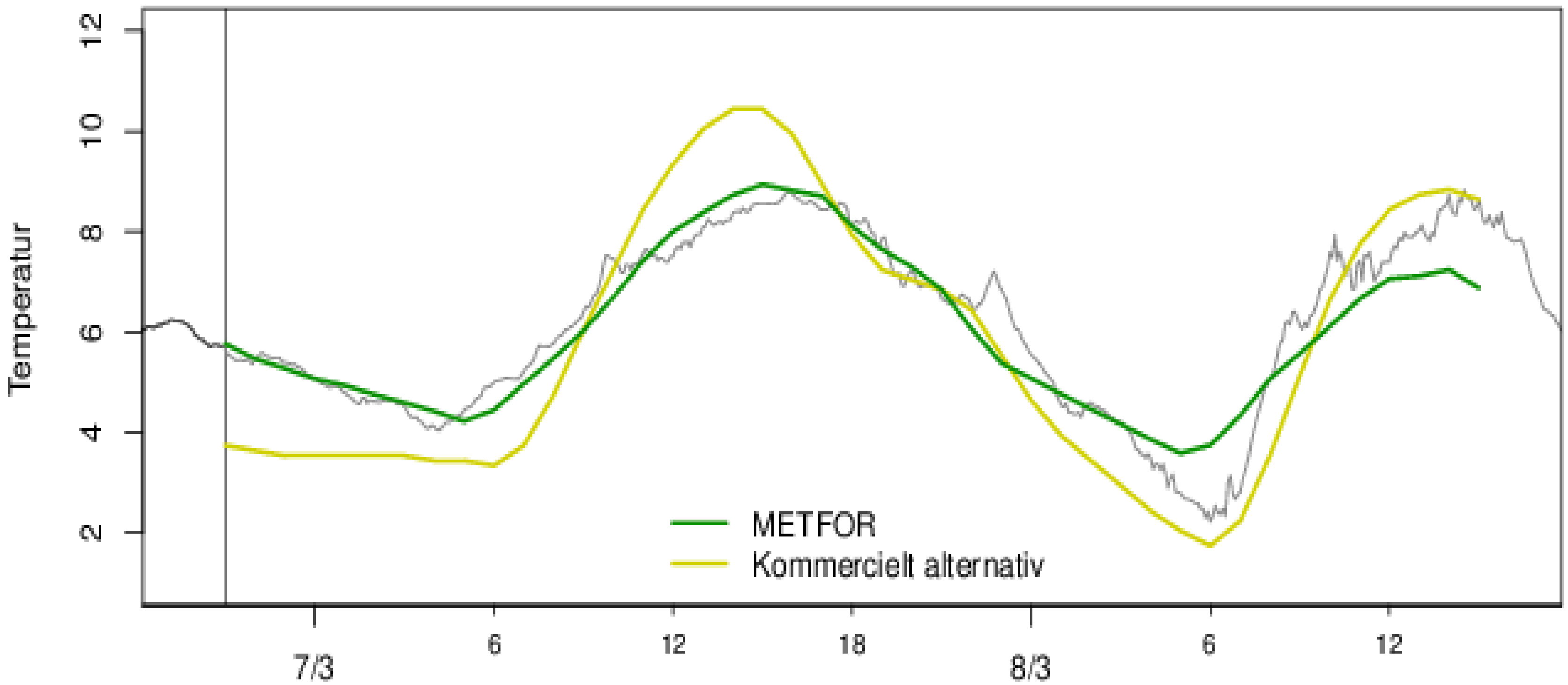
Weather data and forecasts
Combined forecasting

Optimize local weather forecast base on:

- Local climate data
- Several MET forecasts
- **Improvements in accuracy: 20 – 98 pct**

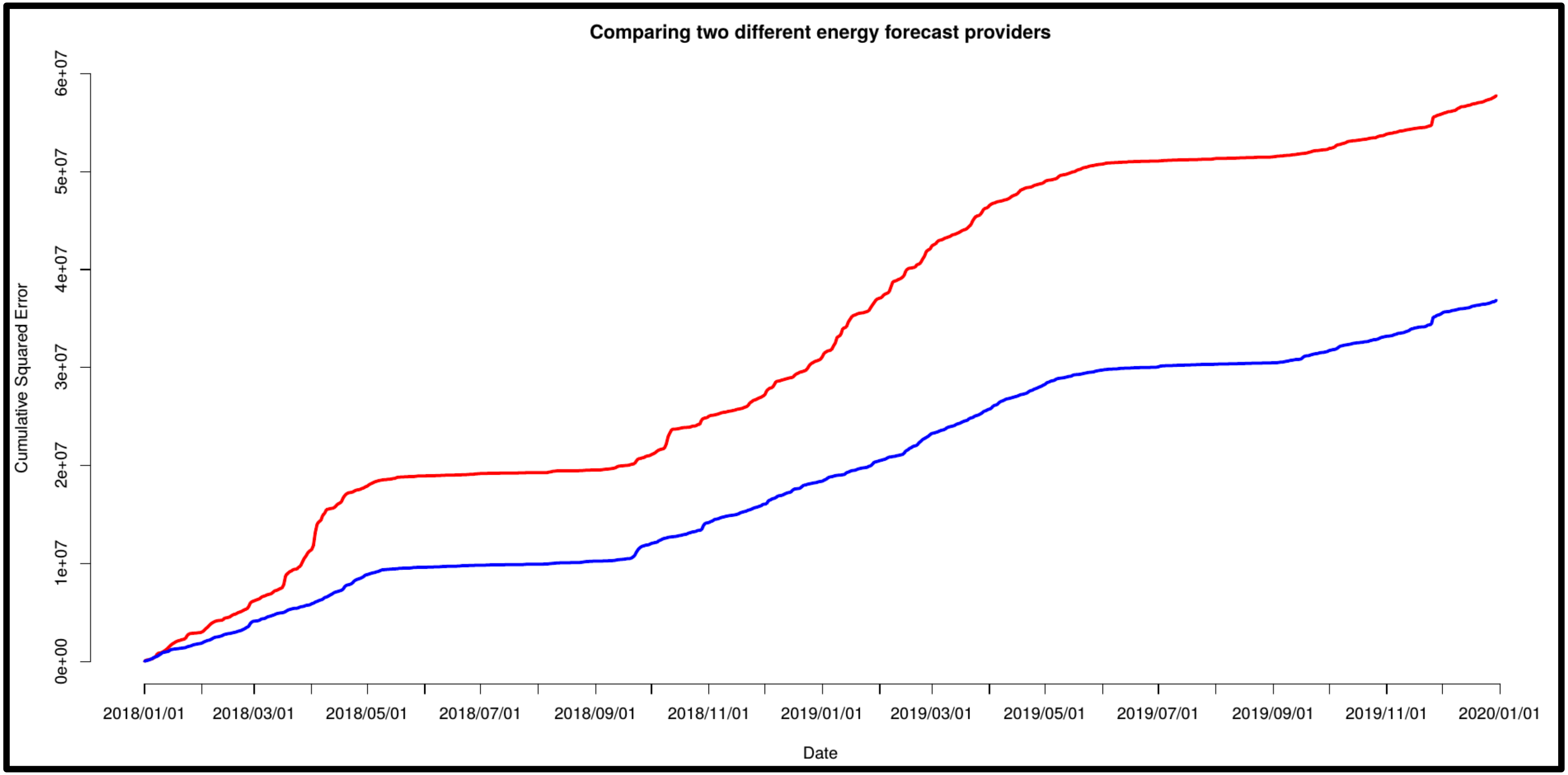


METFOR forecast example



Heat Load Forecasting

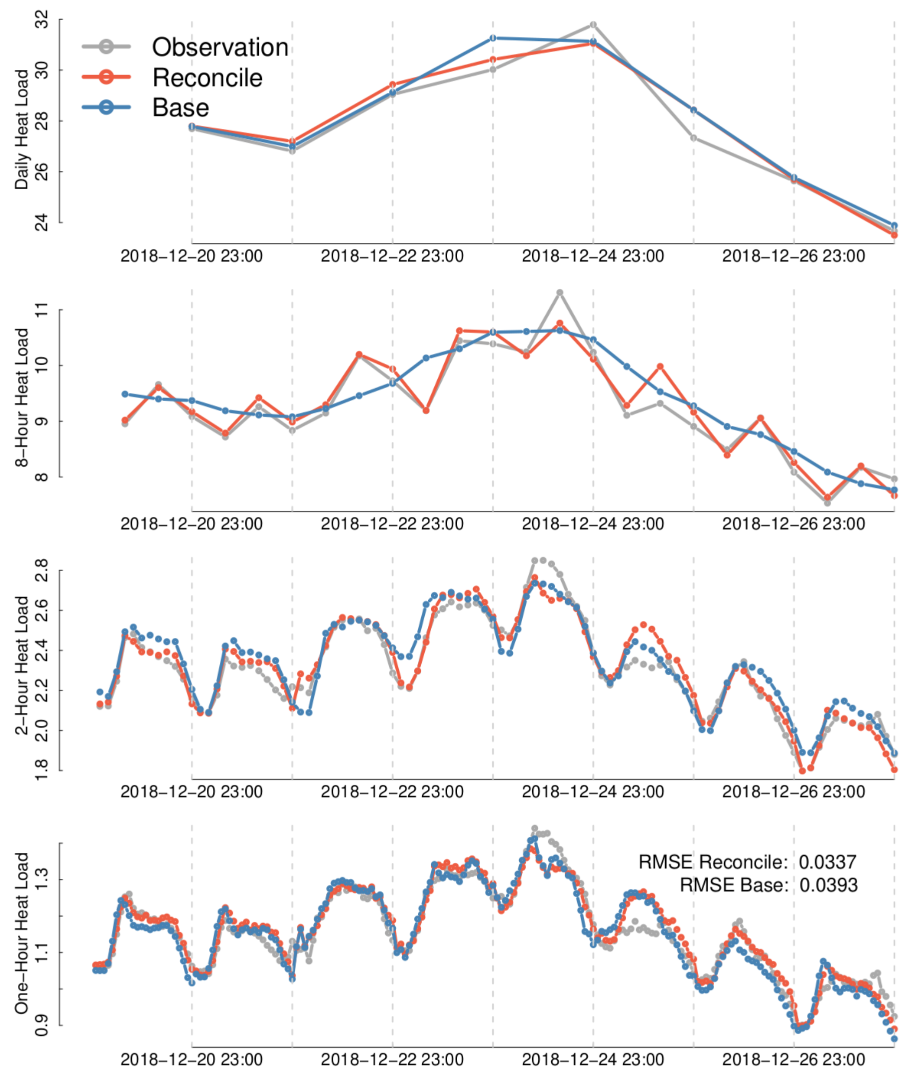
Heat Load Forecasts at Varmelast



36 pct improvements with forecasting tool from HEAT4.0

Improvements with Temporal Hierarchies

- Forecast for different aggregation levels
- Share information between levels
- Reconciled forecast is the process of optimally combining hierarchial forecast to yield coherent forecast
- The result are guaranteed to be at least as good as the base forecast



Heat Load Forecasting Improvements Using Temporal Hierarchies in HEAT4.0

	2017				2018			
	Base RMSE	Expanding Window	Rolling Window	Exp. Smoothing	Base RMSE	Expanding Window	Rolling Window	Exp. Smoothing
Daily	0.5585	-17.88	-17.7	**-18.1**	0.6218	**-23.02**	-19.56	-22.94
Twelve-hourly	0.3151	-17	-16.72	**-17.19**	0.3766	-25	-22.25	**-25.01**
Eight-hourly	0.3333	-39.78	-39.61	**-39.9**	0.3508	-40.24	-38.56	**-40.48**
Six-Hourly	0.2628	-41.07	-40.77	**-41.17**	0.2876	-42.16	-40.21	**-42.23**
Four-hourly	0.1715	-35.24	-34.86	**-35.34**	0.1725	-31.81	-30.16	**-32.32**
Three-hourly	0.1273	-31.98	-31.62	**-32.09**	0.1315	-30.34	-28.62	**-30.75**
Two-hourly	0.0846	-29.07	-28.64	**-29.16**	0.088	-27.99	-26.33	**-28.51**
Hour	0.0372	-14.83	-14.26	**-14.92**	0.0389	-14.77	-12.91	**-15.44**

	2019				2017:2019			
	Base RMSE	Expanding Window	Rolling Window	Exp. Smoothing	Base RMSE	Expanding Window	Rolling Window	Exp. Smoothing
Daily	0.6022	-30.4	**-31.03**	-30.94	0.5947	-23.86	-22.7	**-24.07**
Twelve-hourly	0.3579	-29.22	-29.07	**-29.46**	0.3508	-24.16	-22.97	**-24.29**
Eight-hourly	0.3735	-49.89	-49.58	**-50.13**	0.3529	-43.5	-42.75	**-43.7**
Six-Hourly	0.3095	-49.84	-49.63	**-50.06**	0.2872	-44.68	-43.83	**-44.81**
Four-hourly	0.1839	-40.73	-40.3	**-41.06**	0.1761	-36.03	-35.19	**-36.34**
Three-hourly	0.1401	-36.35	**-35.62**	-36.55	0.1331	-33.01	-32.05	**-33.25**
Two-hourly	0.092	-33.06	-32.21	**-33.27**	0.0883	-30.12	-29.12	**-30.4**
Hour	0.0387	-14.52	-13.22	**-14.7**	0.0383	-14.71	-13.44	**-15.02**

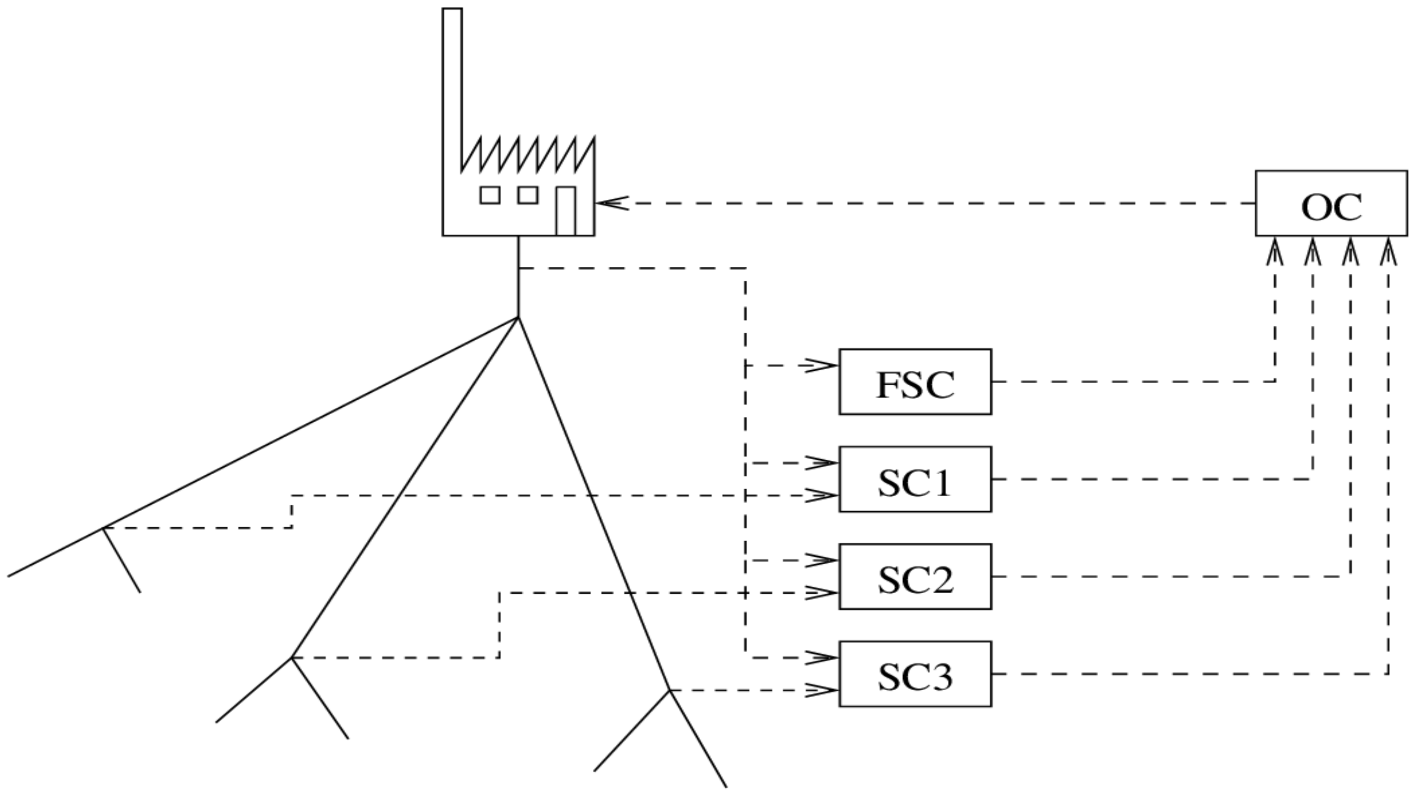
Table 2

Out-of-sample RMSE for the base forecasts and RRMSE for the reconciled forecasts for daily heat load consumption in the Greater Copenhagen area. It shows the results for three different years and the whole period from 2017 to 2019.

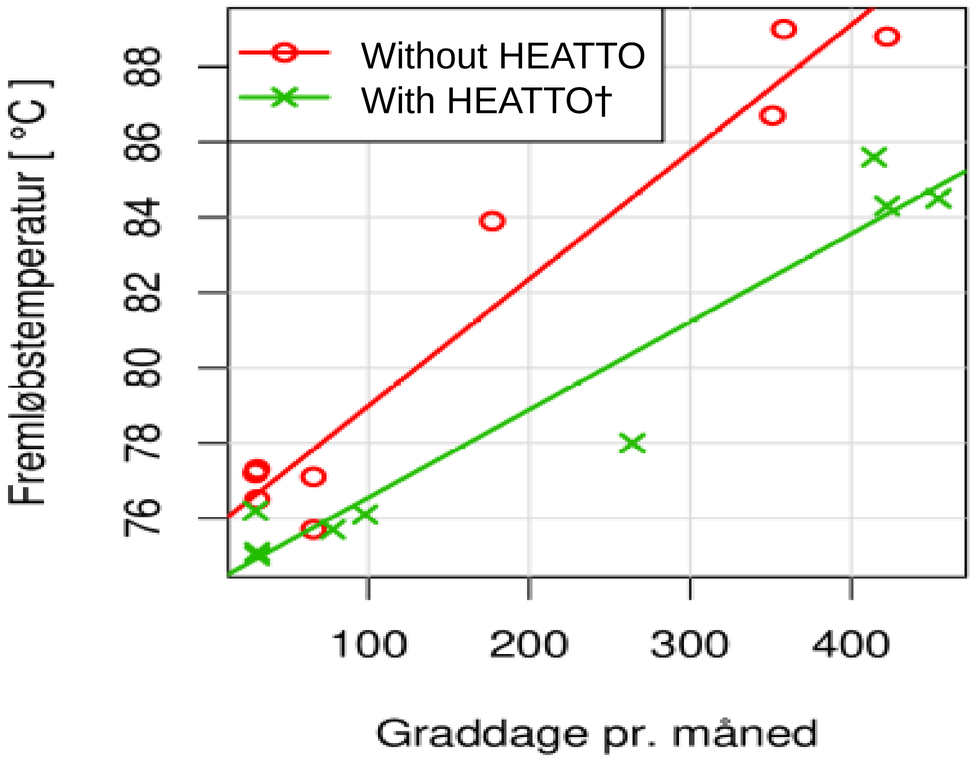
- **Further improvements: 15+ pct**

Data-driven
Temperature Optimization

Models and Controllers
(Highly simplified!)



Supply temperature with/without data-driven temperature opt.



Savings:
Reduction in heat loss
18.4 pct
Annual cost saving
2.4 mill dkr

DIGITALISERING I FJERNVARMEN BIDRAGER TIL 2030-MÅL

Det sparer penge og CO_2, når fjernvarmesektoren styrer temperaturen med data og lokale vejrudsigter i stedet for tegninger af ledningsnettet og mavefornemmelsen.

Hanne Kokkegård
Sven Müller, DTU, Dansk Fjernvarme/Nils Rosenvold

1,7 mio. husstande i Danmark (ca. 64 pct.) bliver opvarmet med fjernvarme, der løber gennem 60.000 kilometer fjernvarmenet. Rejsen fra fjernvarmeværket til radiatorerne tager typisk flere timer, og derfor skal varmebehovet kunne forudsiges.

Man skal ikke skrue mere op for varmeproduktionen end nødvendigt, for det koster penge og er energispild, ligesom temperaturtabet i rørene er større ved højere temperaturer. Samtidig skal vandet være tilstrækkelig varmt på de såkaldt kritiske punkter i udkanten af ledningsnettet. Så det er en videnskab at styre fjernvarmeproduktionen optimalt.

På DTU Compute arbejder professor Henrik Madsen og hans kolleger med datadrevet energi- og temperaturoptimering. Flere forskningsprojekter viser, at digitalisering forbedrer prognosen for varmebehovet og tilmed letter vejen til Danmarks 2030-klimamål.

En undersøgelse, som Damvad Analytics har lavet sammen med Danmarks største smart city-projekt, CITIES, ledet af netop Henrik Madsen, samt tænketanken Grøn Energi under Dansk Fjernvarme, viser, at fjernvarmesektoren kan spare mellem 240 og 790 mio. kr. ved at indføre datadrevet temperaturregulering af fremløbstemperaturen, fordi temperaturen kan sænkes tre til ti grader. Lavere temperatur sparer også CO_2, ligesom varmetabet i nettet mindskes.

"Der er store potentialer ved at gå fra erfaring og simulationsbaseret styring ud fra tegninger af ledningsnettet til datadynamisk optimering af fjernvarmen. Vores projekter viser, at når fremløbstemperaturen er baseret på flere her og nu-datakilder, herunder vejrdata fra lokale målestationer, optimerer vi produktionen og accelererer den grønne omstilling," siger Henrik Madsen.

Lavere varmepriser

Svebølle Viskinge Fjernvarmeselskab med 535 husstande er ét af de forsyningsselskaber, der har øget digitaliseringen. Siden oktober 2019 har fjernvarmeselskabet i Nordvestsjælland benyttet bearbejdede data fra DTU-spinout-firmaet ENFOR til optimal styring af fremløbstemperaturen.

På få måneder har man kunnet sænke fremløbstemperaturen med over 20 grader. Hvor temperaturen før lå på 80,9 grader, blev den først sænket til 68,1 grader, hvorefter den kunne sænkes yderligere til 60 grader.

Billedet viser udstyret til temperaturmåling i ventilbrøndene: en PT100-temperaturføler og en radiosender samt et motorcykelbatteri, der holder i seks år og forsyner udstyret med strøm, så det kan sende data videre.

"Dengang kørte vi lidt med bind for øjnene, fordi vi ikke vidste, hvordan det reelt stod til med temperaturen i fjernvarmenettet. Vi havde slet ikke forestillet os, at digitalisering kunne blive så stor en gevinst."

SVEND MÜLLER, BESTYRELSESFORMAND FOR SVEBØLLE VISKINGE FJERNVARMESELSKAB

Dynamisk datadrevet fjernvarmedrift

- Teknologien anvender AI til at bearbejde data til at forudsige varmebehov, pumpebehov og temperatur på 'kritiske' steder i fjernvarmenettet, hvor temperaturen er lavest.
- Ud fra vejrudsigter og lokale målestationer foreslår systemet en starttemperatur. Systemet sender realtidsdata for temperaturen i nettet, kritiske steder, varmeforbruget hos slutbrugeren og vejr tilbage. Temperaturen og trykket reguleres i rørene. Systemet agerer efter de lokale forhold og lærer nettet at kende på en til tre måneder.
- Data kan identificere potentielle fejl og brud.
- Forskerne i CITIES og andre DTU-ledede projekter arbejder også med styring af varmepumper efter CO_2-baserede elpriser, så produktionen øges, når strømmen er grøn.

KILDE: RAPPORTEN 'POTENTIALET VED DYNAMISK DATADREVET TEMPERATURREGULERING I FJERNVARMESEKTOREN', FRA DAMVAD ANALYTICS, GRØN ENERGI OG CITIES.

Transformationen

Figuren skitserer, hvordan den digitale transformation i fjernvarmen kommer til at foregå med data fra fjernaflæste målere (smartmeters).

KILDE: INTEGRERING AF LAVTEMPERATURFJERNVARME TIL EKSISTERENDE BYOMRÅDER, JANUAR 2020, DTU M.FL.

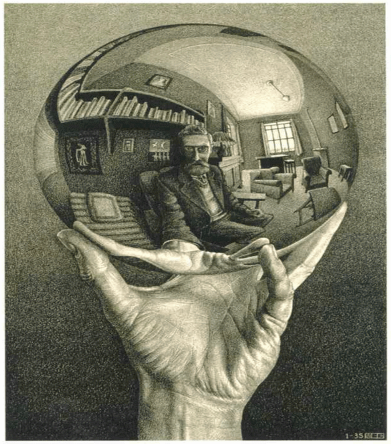
Det giver en anslået besparelse på mindst 550 MWh og en reduktion på 110.000 kr. i årlige produktionsomkostninger. Man regner med på sigt at sænke varmetabet i nettet til under 30 pct., og at varmeprisen falder med 47 pct. i perioden 2015-2025.

Inden Svebølle Viskinge Fjernvarmeselskab gik over til datadrevet drift, benyttede man såkaldt simulationsbaseret drift baseret på viden om fjernvarmenettet, erfaring og kun lidt forecast.

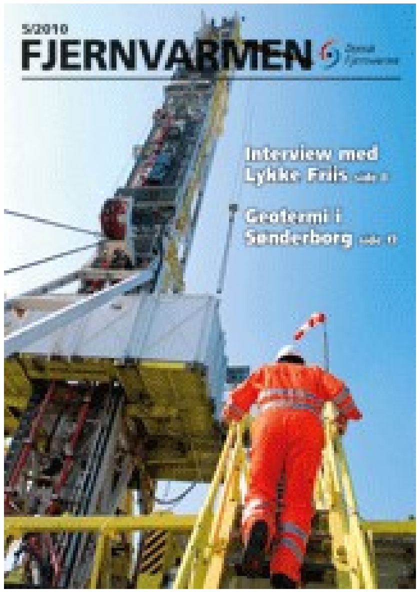
Svebølle-Viskinge DH: Lowered the temperature with 15 – 20 degrees
Brønderslev DH: Approx. 3 degrees

Data-driven Temperature Optimization

- Able to take advantage of **information in data**
- **Self-calibrating** models for the DH network
- Easy to maintain
- Shows where to **upgrade** the DH network
- **Fast** (real time) calculations
- Use DH net for **peak shaving** and **storage**
- Able to use **online MET forecasts** etc.
- **Savings up to 800 mill DKK annually** by using data-driving temperature opt. (Damvad report 2019)



Control of Supply Temperatures



FJERNVARMEN | 5 2010

Styring af temperatur rummer kæmpe sparepotentiale

Lessons learned:

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

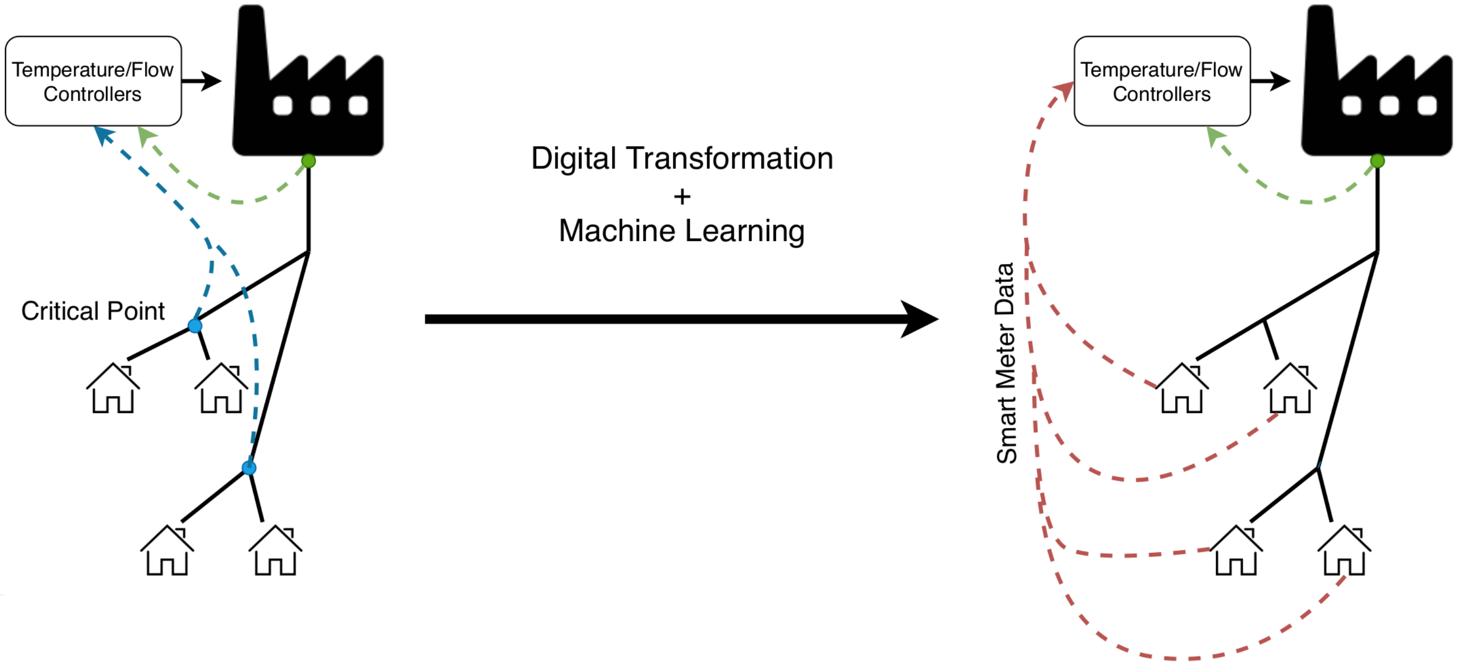
Which approach to use?

- Use **simulation based** control if:
  - No access to data from the DH network
  - Want an evaluation of new operational scenarios
- Use **prediction based** control if:
  - Access to network data online
  - Want to used meteorological forecasts online
  - Want to combine MET forecasts with local climate data
  - Want automated update of models

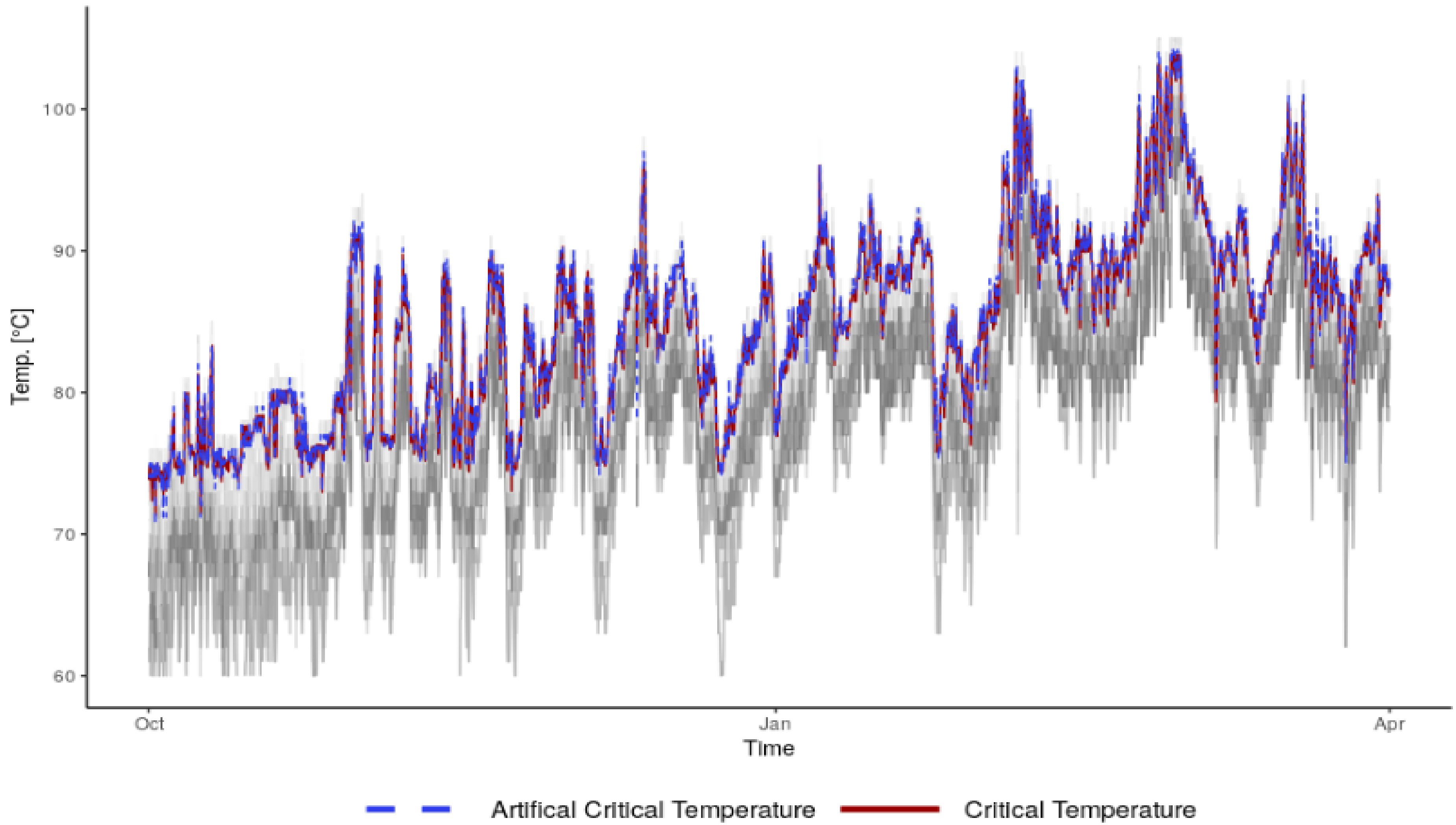
Data-driven Temperature Optimization v.4.0 (Incl. use of meter data)

Replacing the netpoint sensors at the critical point using meter data

- Use readings from end-user to create a **artificial critical temperature** for a distribution of houses in the network
- **Replacement** of critical netpoint sensors
- **Dynamic location** of netpoints

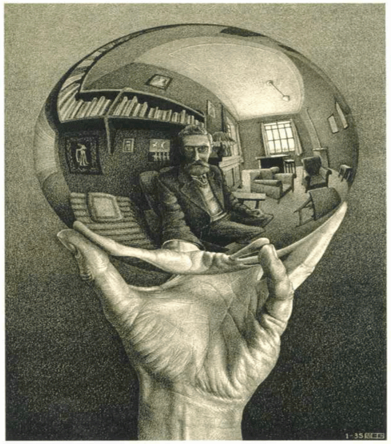


Critical Temperature estimated from Smart-Meter Data (Brønderslev DH)



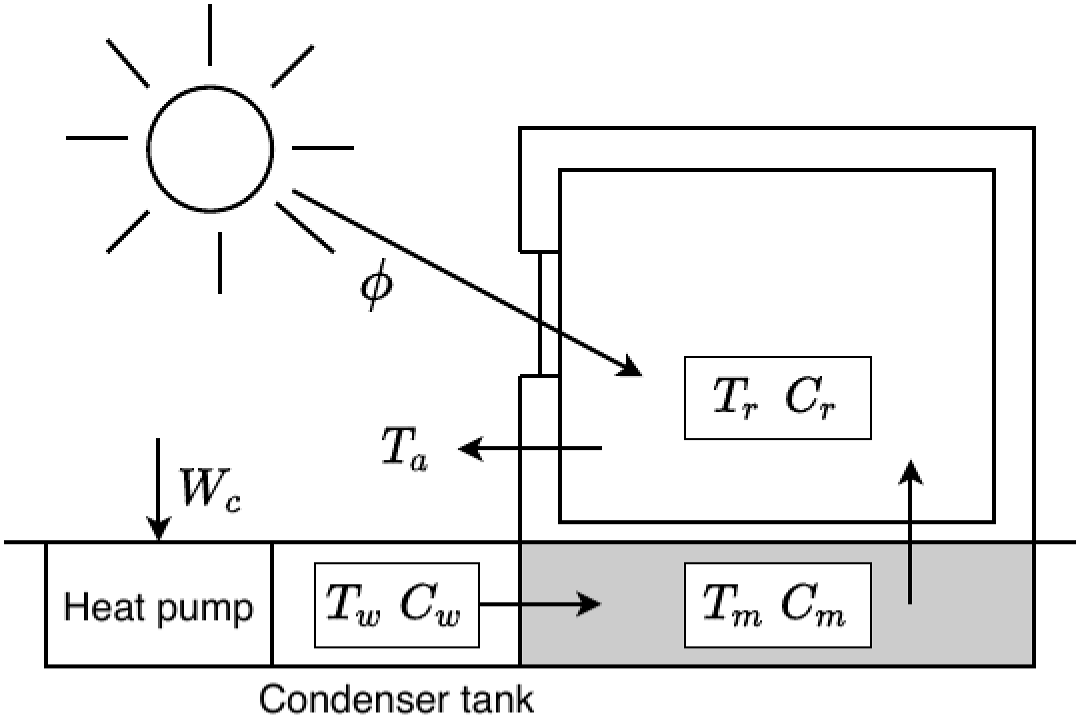
Data Intelligent Temperature Optimization Using Smart Meter Data

- Eliminates or reduces the need for critical points in the DH net
- Identify needs for upgrade of the local net
- Find users with a high flow and other issues
- Next generation of temperature zones
- Use user installations to store energy locally
- Time-varying prices – active use of end-users
- Establish a possibility for effect limitations
  (should be reflected in the contract)



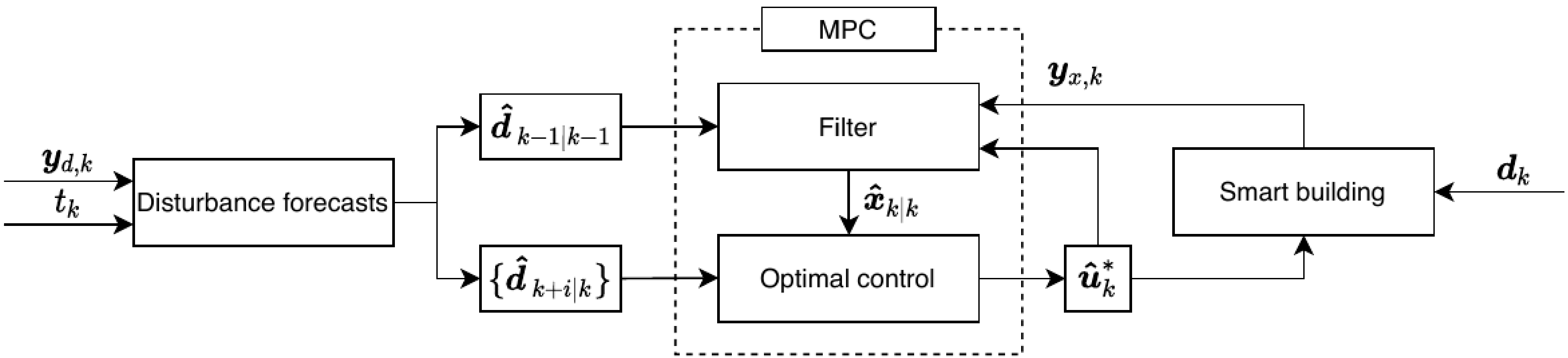
Integrated Forecasting and Control for Buildings

Grey-box Model for a Smart Building



Integrated Forecasting and Control

The MPC framework for smart house control and how distrubance forecasts are incorporated



$$\begin{aligned} \mathrm{d}\boldsymbol{x}(t) &= f_s(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t))\mathrm{d}t \\ &\quad + g_s(\boldsymbol{x}(t), \boldsymbol{u}(t), \boldsymbol{d}(t))\mathrm{d}\boldsymbol{\omega}_s(t) \,, \end{aligned} \tag{1a}$$

$$\mathrm{d}\boldsymbol{d}(t) = f_d(\boldsymbol{d}(t))\mathrm{d}t + g_d(\boldsymbol{d}(t))\mathrm{d}\boldsymbol{\omega}_d(t) \,, \tag{1b}$$

$$\boldsymbol{y}_s(t_k) = h_s(\boldsymbol{x}(t_k)) + \boldsymbol{v}_{s,k} \,, \tag{1c}$$

$$\boldsymbol{y}_d(t_k) = h_d(\boldsymbol{d}(t_k)) + \boldsymbol{v}_{d,k} \,, \tag{1d}$$

The school used for smart district heating control

- Borgerskolen in Høje Taastrup

Figure 1: The building in question

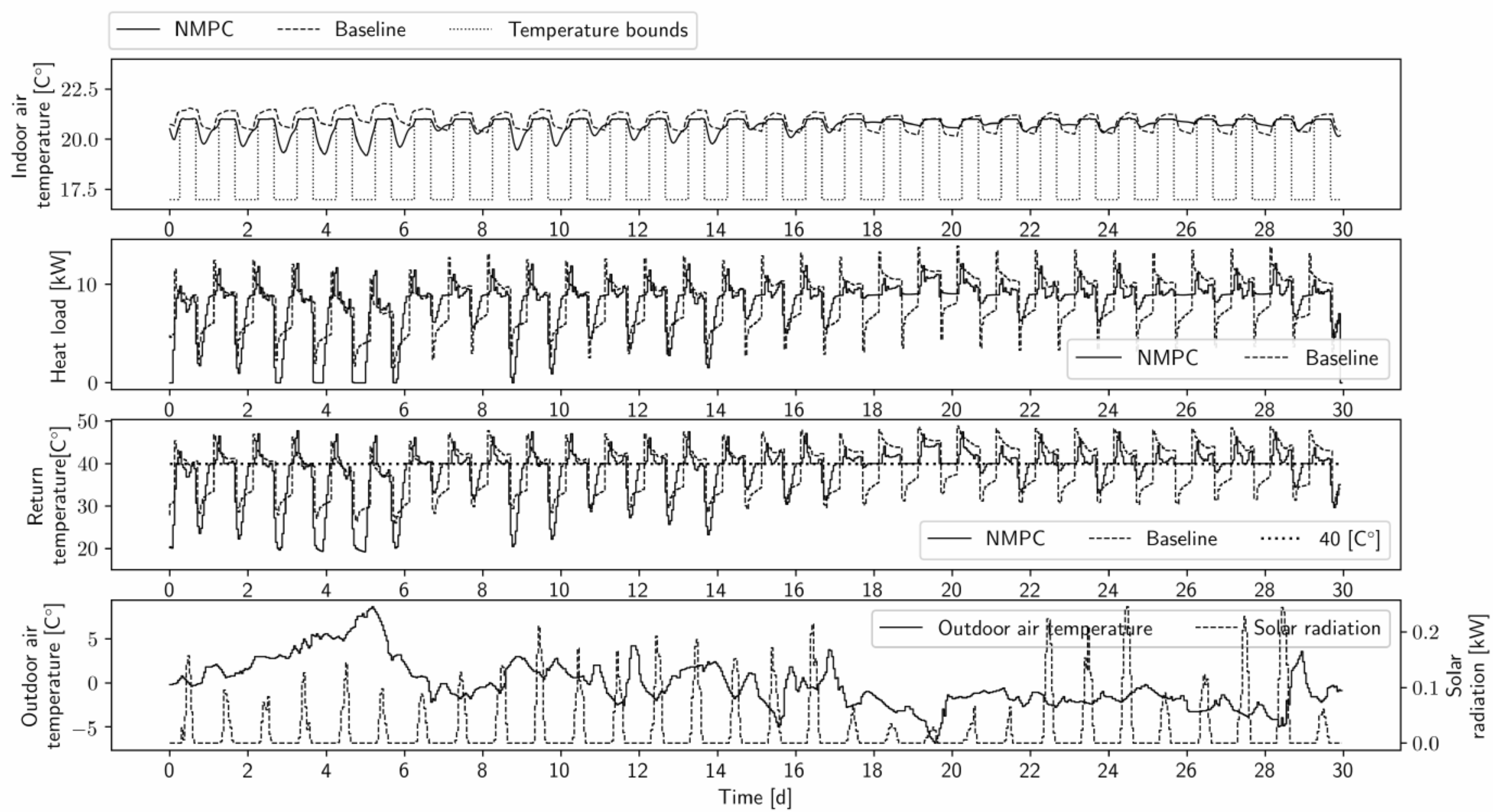
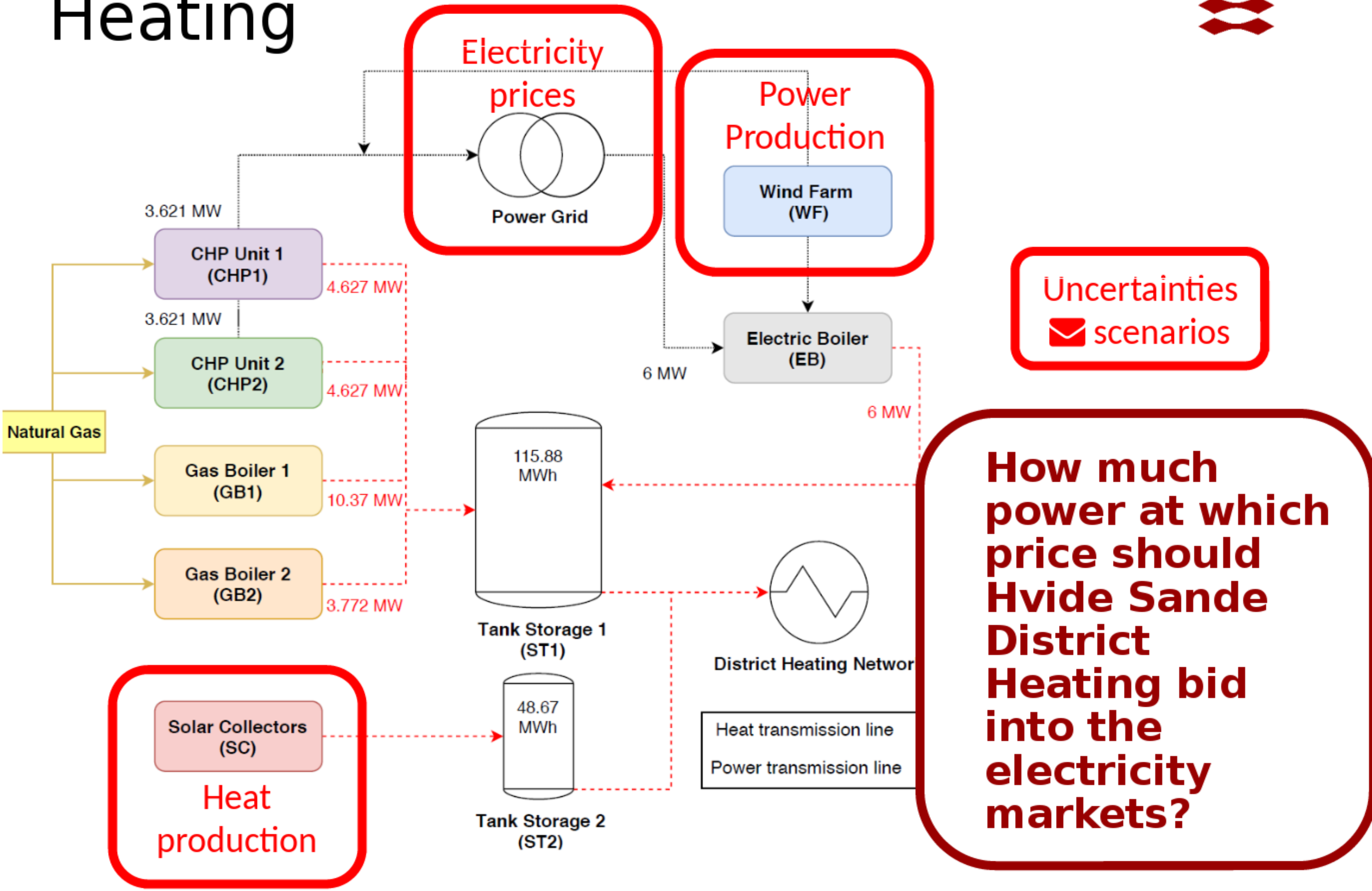


Figure 4: A simulation study that compares a current standard set-point control in today's buildings (Baseline) and the NMPC presented in this paper. The heat costs are constant at 0.1 EUR/kWh plus a penalty of 2% for each °C the return temperature is above 40 °C. Results suggest an economic reduction by around 10%.

Savings documented in HEAT 4.0: 8 – 10 pct

Optimal Operation and Bidding

Test case – Hvide Sande District Heating



How much power at which price should Hvide Sande District Heating bid into the electricity markets?

Results - Bids

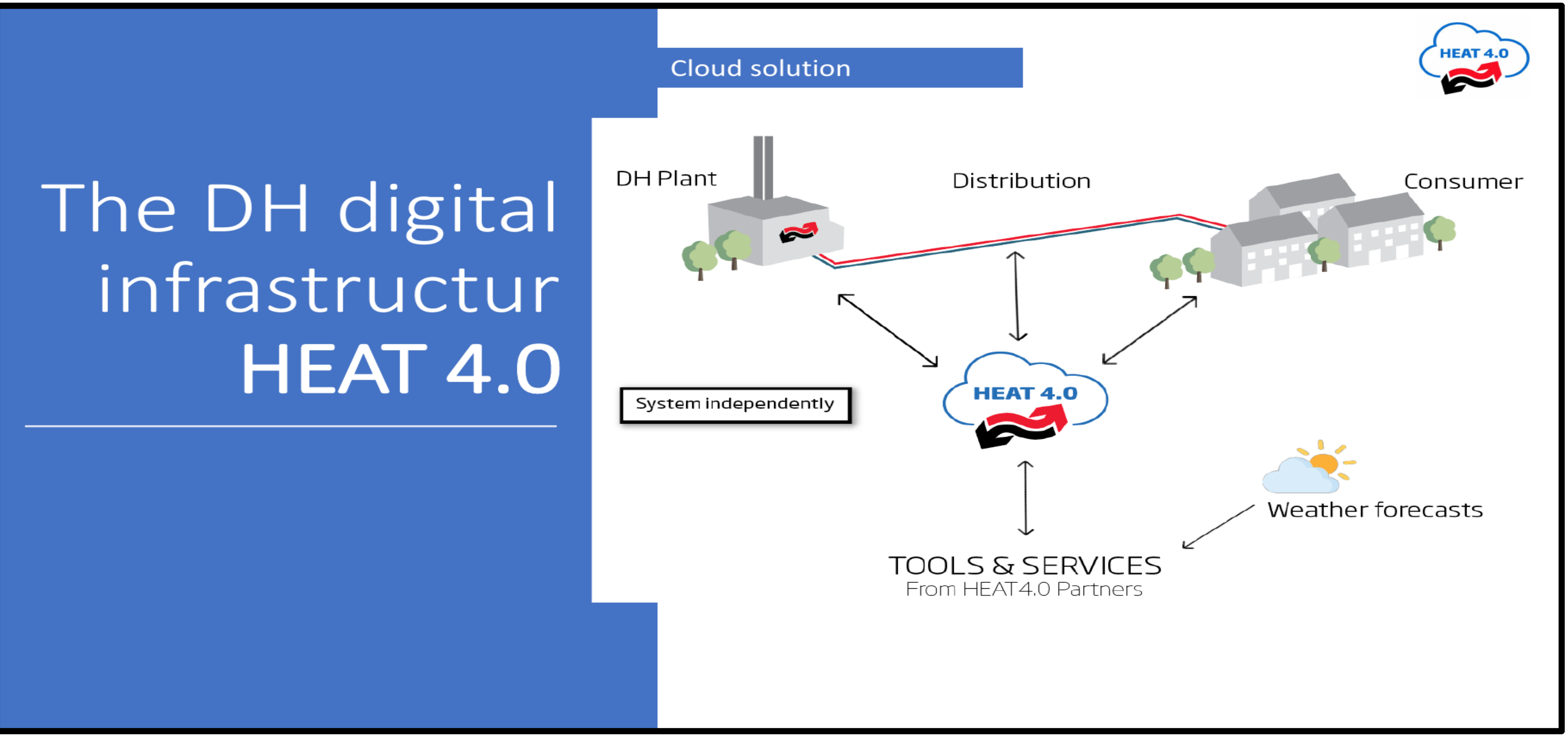
Percentage of hours with bids and won bids in one month averaged over several samples

Method	Receding Horizon	CHP 1		CHP 2	
		Bids	Won	Bids	Won
HURB Worst	1	**98.91**	**41.95**	98.70	41.91
HURB Avg.	-	**99.79**	**42.19**	99.75	42.15
HURB Best	10	**99.89**	**42.28**	99.87	42.26
Conejo et al.	10	44.92	39.34	44.92	39.31
Rodriguez & Anders	5	82.52	35.85	82.40	35.82
Schulz et al.	12	45.02	18.54	45.01	18.53
Dimoulkas & Amelin	12	75.55	26.56	75.55	26.55
Ravn et al.	5	44.84	32.58	44.83	32.57

We can take advantage of the portfolio of heat production units and base the bidding amounts and prices on the heat production.

HEAT4.0 savings approx. 5 pct

Summary – HEAT 4.0 savings



Savings by digital operation of DH Systems (CO2 + Costs)

- Many digital solutions for DH systems have already been established in HEAT4.0 (... and more will come)
- 10 – 40 pct improvements of heat load forecasts
- 800 mill dkr annually in Denmark by data-driven temperature optimization = (tons of CO2 savings)
- (TO v. 4.0 – use of meter data): Maybe 200 mill dkr extra (we don't know yet)
- 10 – 30 pct savings by predictive control of heat pumps
- 5 – 20 pct savings by integrating forecasts in smart house controllers
- Up to 10 pct savings by optimal operations of CHP and DH plants

Thanks for your attention ...

Center Denmark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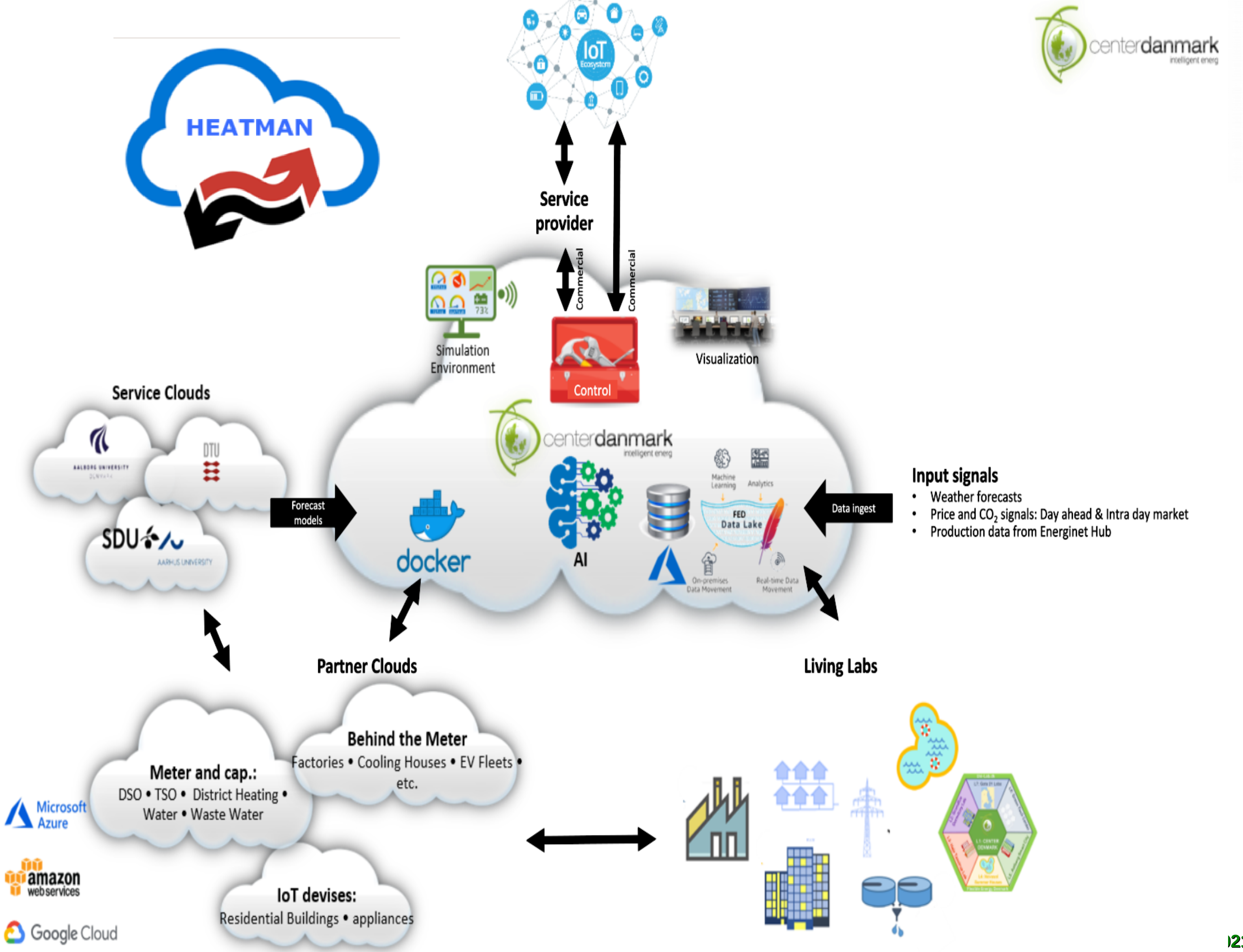
DENMARK
Connect networks and data
for a green world
Danmarks
nationale Center
Fremme den grønne omstilling.
Samle og bygge bro, mellem
forskning, teknologi, natur og formidling,
på tværs af interesseorganisationer,
virksomheder, skoler og
universiteter.

Center Denmark – Control Room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Simulation Environment
Control
Visualization
centerdanmark intelligent energ
Service Clouds
AALBORG UNIVERSITY
DTU
SDU
AARHUS UNIVERSITY
Forecast models
docker
AI
Machine Learning
Analytics
FED Data Lake
On-premises Data Movement
Real-time Data Movement
Data ingest
Input signals
• Weather forecasts
• Price and CO_2 signals: Day ahead & Intra day market
• Production data from Energinet Hub
Partner Clouds
Living Labs
Behind the Meter
Factories • Cooling Houses • EV Fleets • etc.
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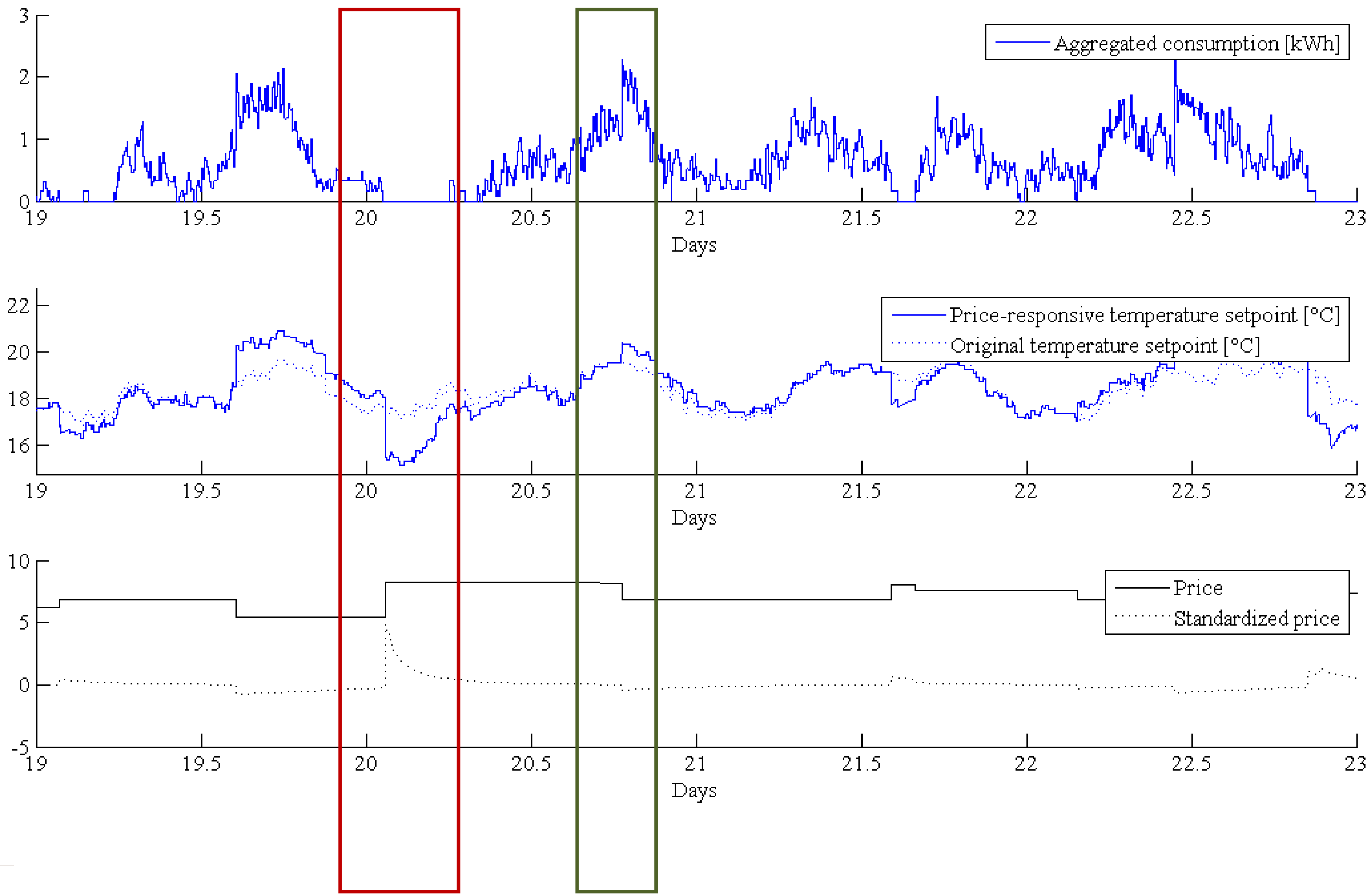
Purpose based controllers for DH systems

- **Peak shaving (morning peaks can be expensive)**
- Capacity constraints
- Optimal control of temperature versus flow
- CO2 optimal control of heat pumps in DH systems
- Flow controllers – also for individual customers
- Minimize return temperature
- Use DH system for heat storage
- Use of excess heat from industry, supermarkets, etc
- Heat pumps (eg. dual HP with local seasonal storage)
- Optimal operation of Power2X facilities

Price-based Control of Heat Consumption (Peak Shaving)

Aggregation (over 20 houses)



Flexibility Function

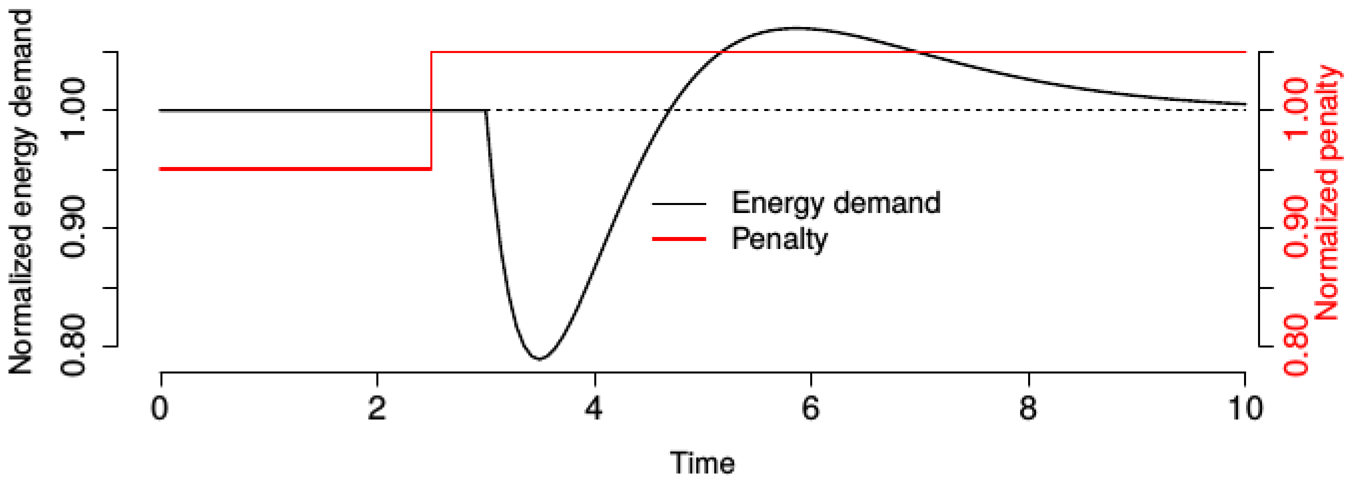
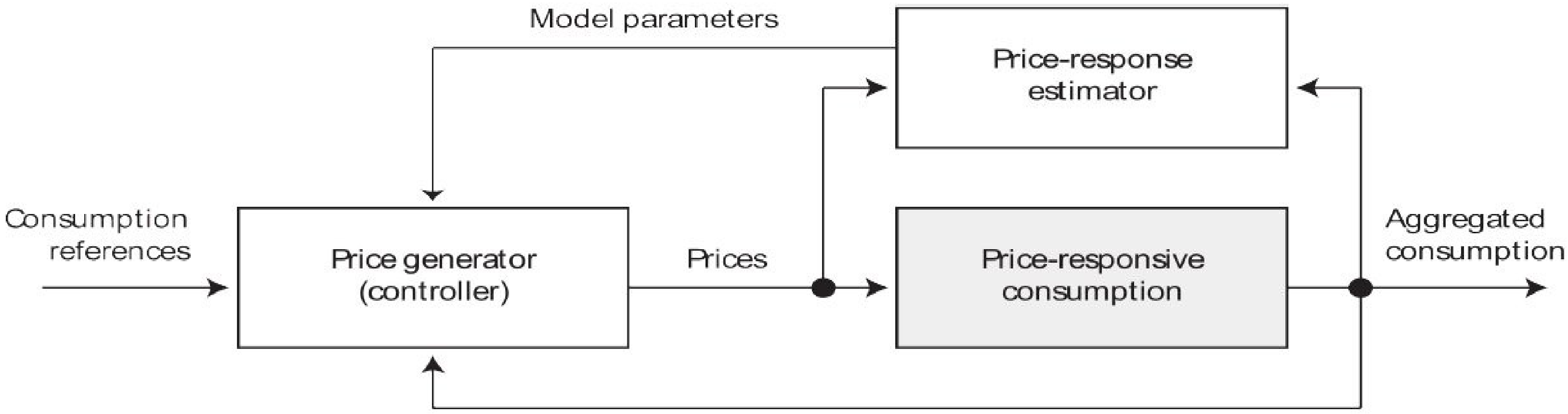
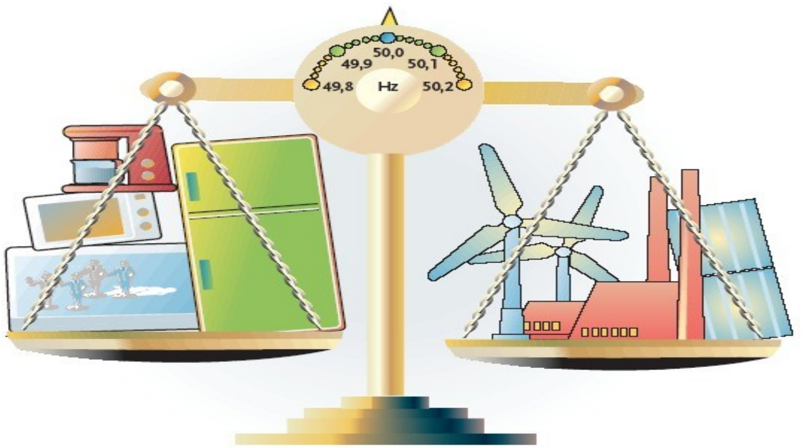


Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

Control of Heat Consumption





Control performance

Considerable **reduction in peak consumption**