Assessing different control algorithms to minimize energy cost of electrically heated residential buildings while maintaining thermal comfort of occupants

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SAGA-project

Smart Control Architectures for Smart Grids

- Partners:
  - School of Science, Automation and System Technology (Prof. Kari Koskinen),
  - School of Engineering, Energy Technology (Prof. Kai Sirén)
  - School of Business, Economics (Prof. Matti Liski)
  - School of Electrical Engineering, Electrical Engineering (Prof. Matti Lehtonen)
- Duration: 1.9.2012 – 31.8.2016
- Funded by Aalto Energy Efficiency Research Programme (AEF)

The research aims of this study

1. To show how much indoor air temperature and operative temperature can be decreased without sacrificing thermal comfort in the different buildings.

2. To develop and compare real-time control and predictive control algorithms for space heating.

3. To show the effect of demand response actions on the heating energy consumption and energy costs of the buildings with different control algorithms.

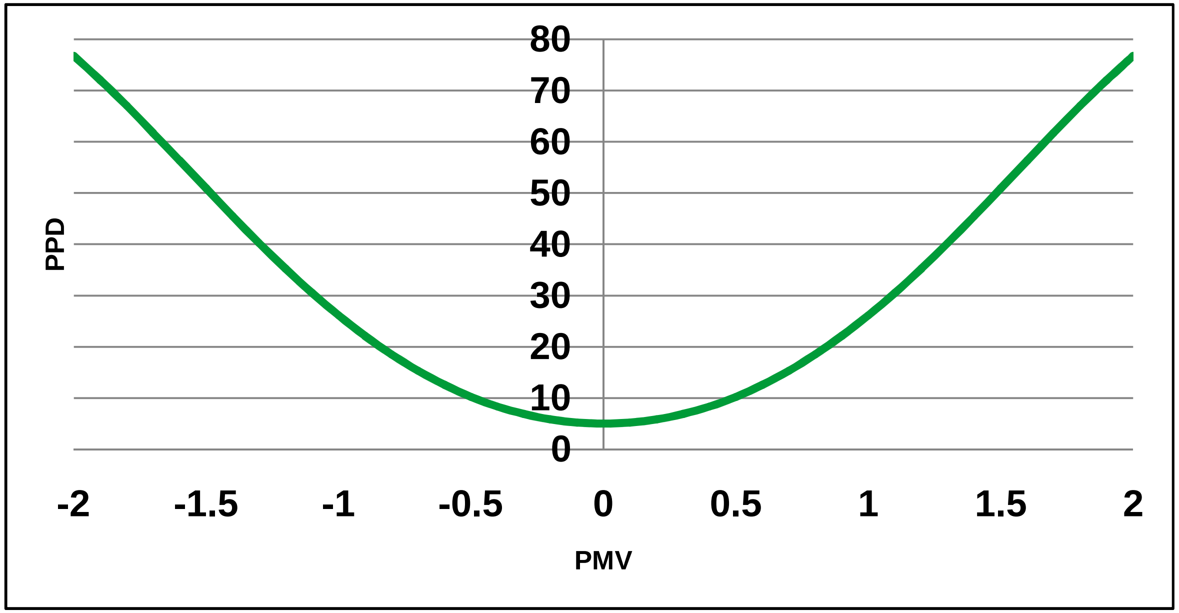
Fanger method

PMV=Predicted Mean Vote
PPD=Predicted Percentage of Dissatisfaction

$$PMV = f(T_{air}, T_{op}, RH, v_{air}, clo, met)$$

$$PPD = 100 - 95\, e^{-(0.03353PMV^4 + 0.2179PMV^2)}$$

PMV	Description
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
1	Slightly warm
2	Warm
3	Hot



Recommended categories of thermal comfort by EN15251

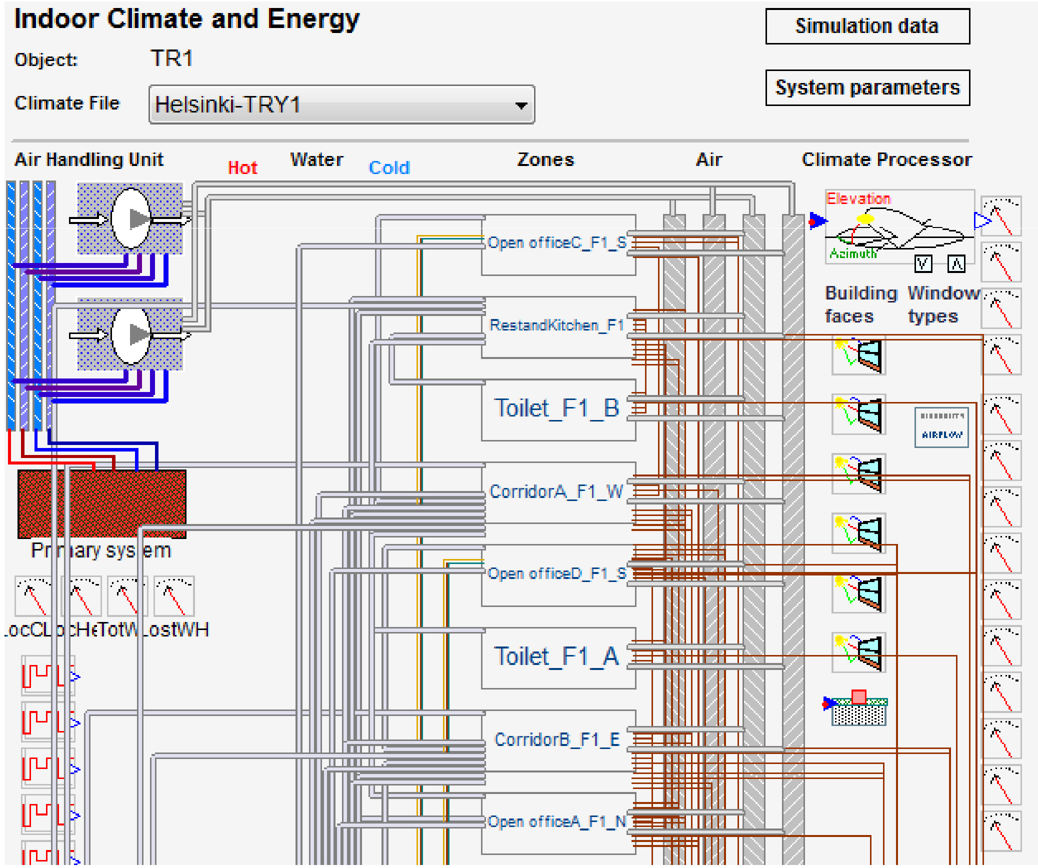
Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

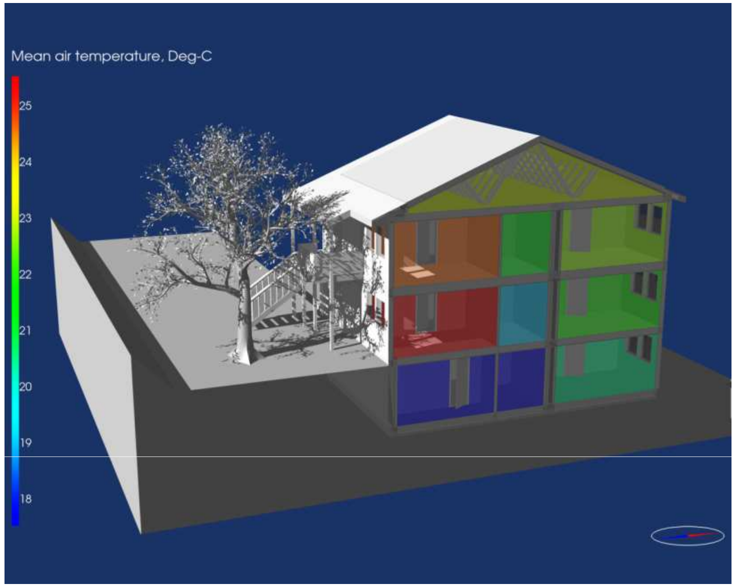
Category	Thermal state of the body as a whole	
	PPD %	PMV
I	<6	-0.2 < PMV <+0.2
II	<10	-0.5 < PMV < +0.5
III	<15	-0.7 < PMV < +0.7
IV	>15	PMV < - 0.7 or +0.7 < PMV

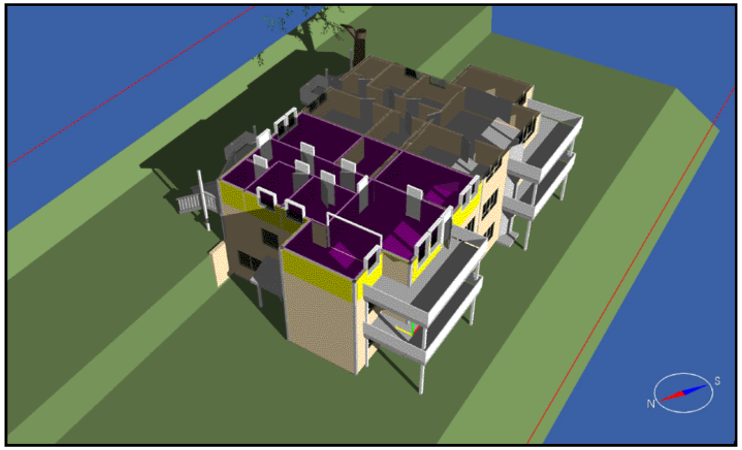
IDA-ICE 4.5 building simulation tool

(IDA – Indoor Climate and Energy)

-The first release in 1998
- Originally developed at the KTH and the Swedish Institute of Applied Mathematics

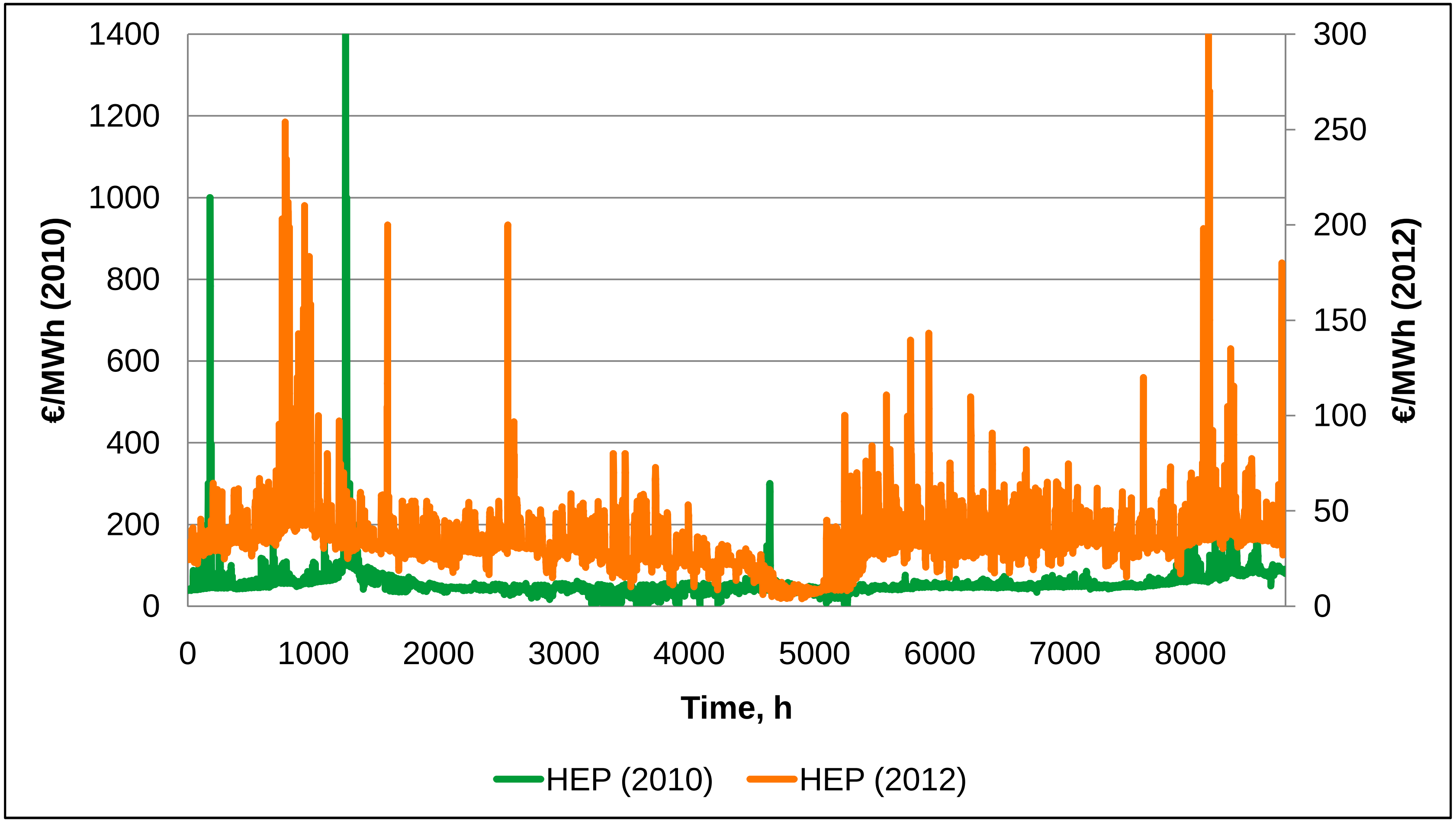






Source: http://www.equa.se/

Hourly electricity price (HEP)



Simulated control algorithm A

This is the simplest algorithm which controls indoor temperature set point (T_{set}) according to HEP.

$$If\ HEP < LP\ then\ T_{set} = T_{set,normal}$$

$$else\ T_{set} = T_{set,min}$$

$$End$$

$$HEP = Hourly\ electricity\ price$$

$$LP = Limiting\ price$$

$$T_{set,\ normal} = The\ normal\ set\ point\ temperature\ used\ for\ detached\ houses$$

$$T_{set,\ min} = The\ minimum\ indoor\ temperature\ set\ point\ defined\ in\ this\ study$$

Simulated control algorithm B

The main idea of this new control algorithm is to manage the indoor temperature set point according to previous HEPs.

$$If\ HEP \geq MHEP, \qquad then \quad T_{set} = T_{set,min}$$

$$elseif \begin{Bmatrix} HEP < MHEP \\ and \\ T_{max} < T_{set,max} \\ and \\ T_{out}^{ave,24} < T_{out}^{lim} \end{Bmatrix} \qquad then \quad T_{set} = T_{set,max}$$

$$else\ T_{set} = T_{set,normal}$$

$End.$

$MHEP = Median\ hourly\ electricity\ price$

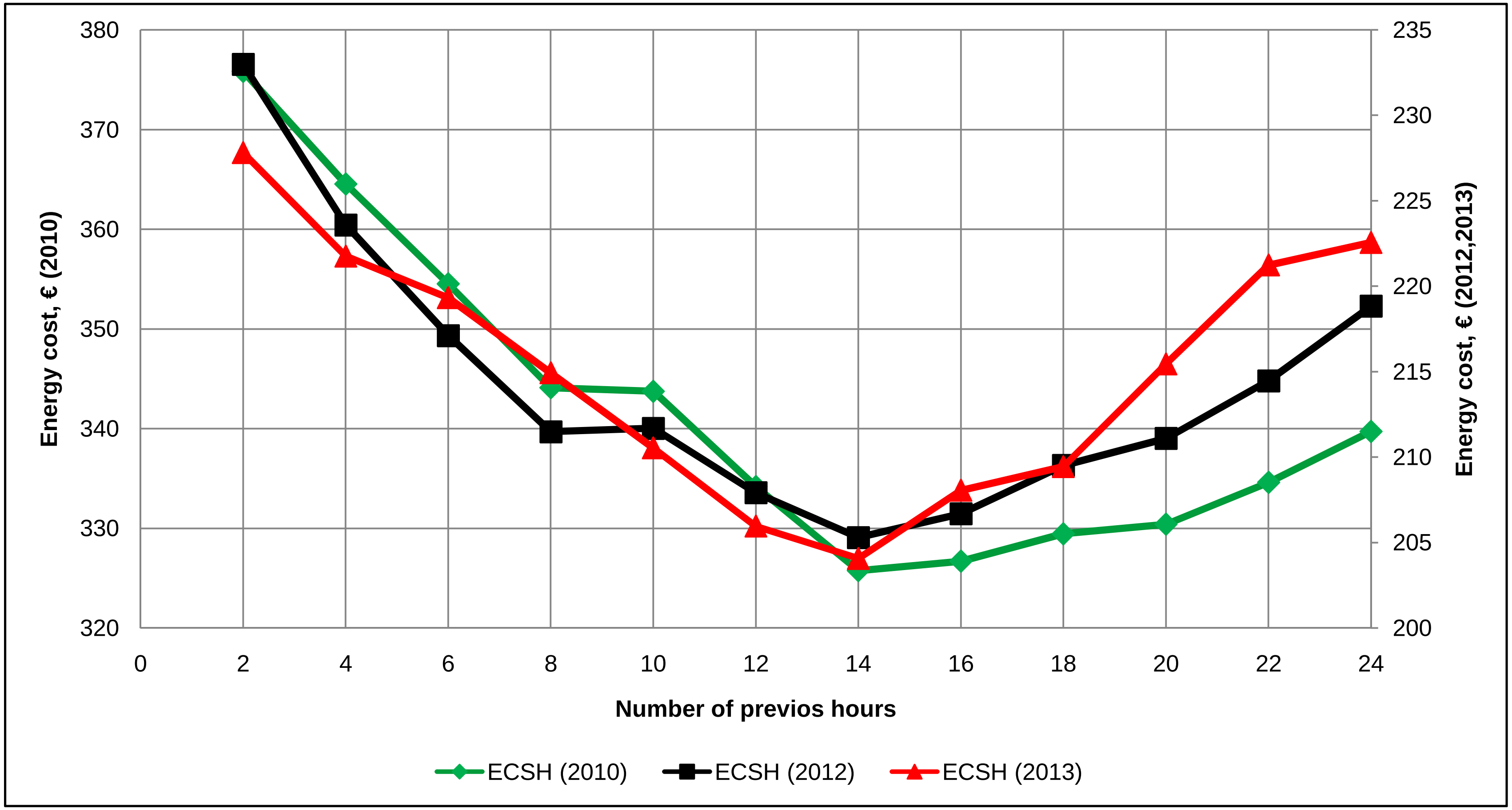
$T_{max} = The\ maximum\ hourly\ indoor\ temperature\ of\ the\ house$

$T_{set,max} = The\ maximum\ acceptable\ indoor\ temperature$

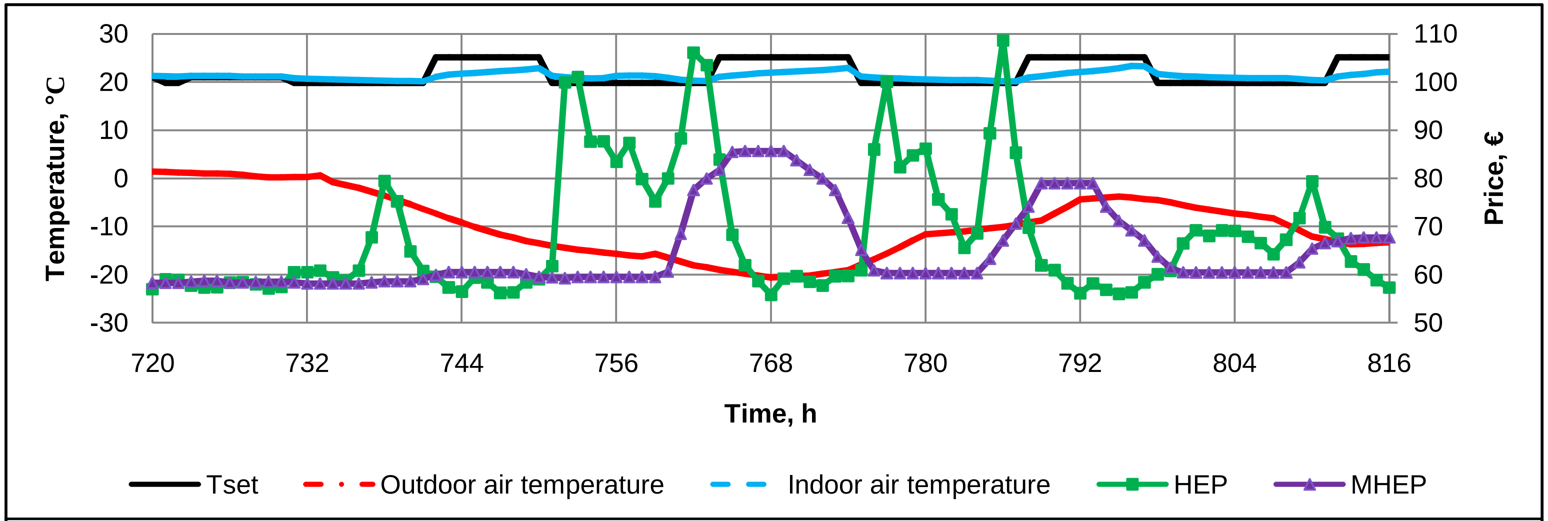
$\mathrm{T}_{\mathrm{out}}^{\mathrm{ave,24}} = The\ average\ outdoor\ temperature\ of\ previous\ 24\ hours$

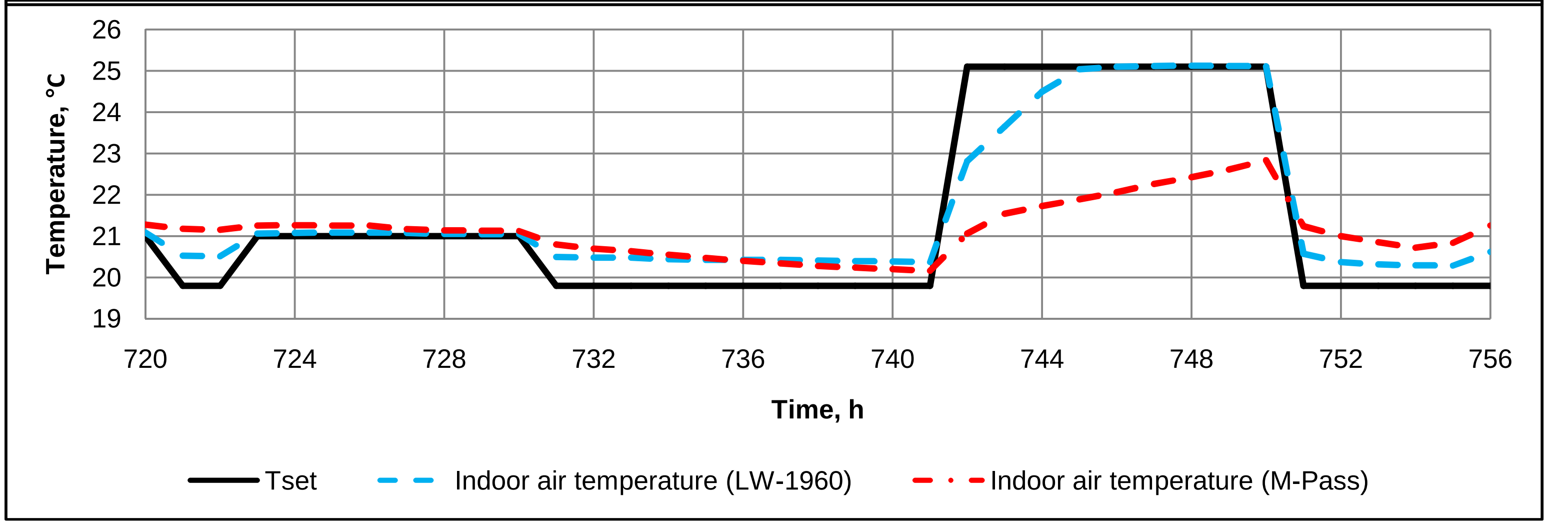
$\mathrm{T}_{\mathrm{out}}^{\mathrm{lim}} = The\ limiting\ outdoor\ temperature$

The optimum number of previous hours



Operation's results of control algorithm B :





Simulated control algorithm C

The principle of this new predictive control algorithm is to control the indoor temperature set point by adjusting it in accordance with future hourly prices.

$$If\ CS = -1 \qquad then \quad T_{set} = T_{set,min}$$

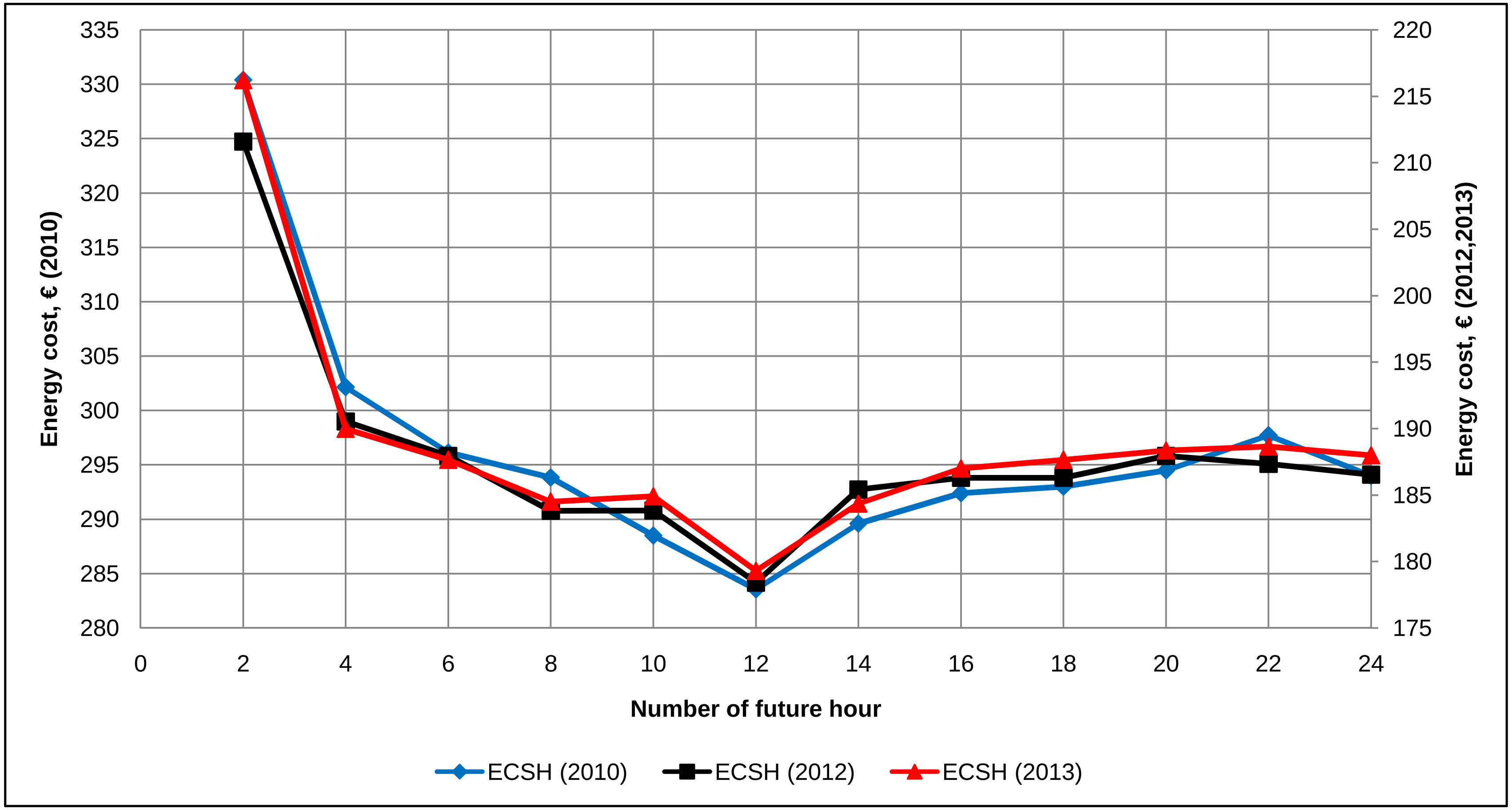
$$elseif \quad \left\{ \begin{matrix} CS = +1 \\ and \\ T_{max} < T_{set,max} \\ and \\ T_{out}^{ave,24h} < T_{out}^{lim} \end{matrix} \right\} \qquad then \quad T_{set} = T_{set,max}$$

$$else \qquad CS = 0, \qquad then \quad T_{set} = T_{set,normal}$$

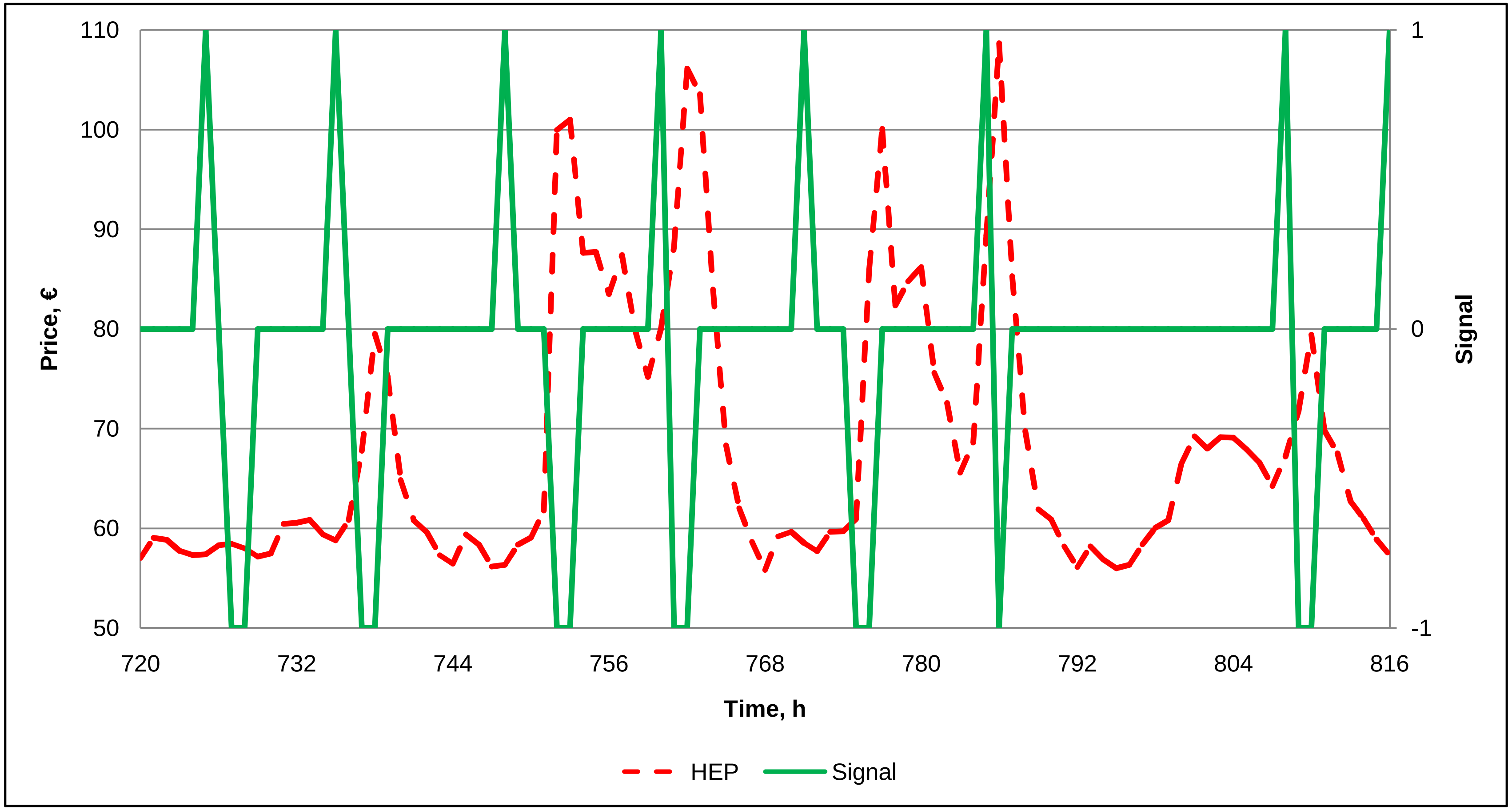
$$End.$$

$$CS = Control\ signal$$

The optimum number of future hours



Operation's results of control algorithm C :



Studied factors

- Case study (LW-1960)

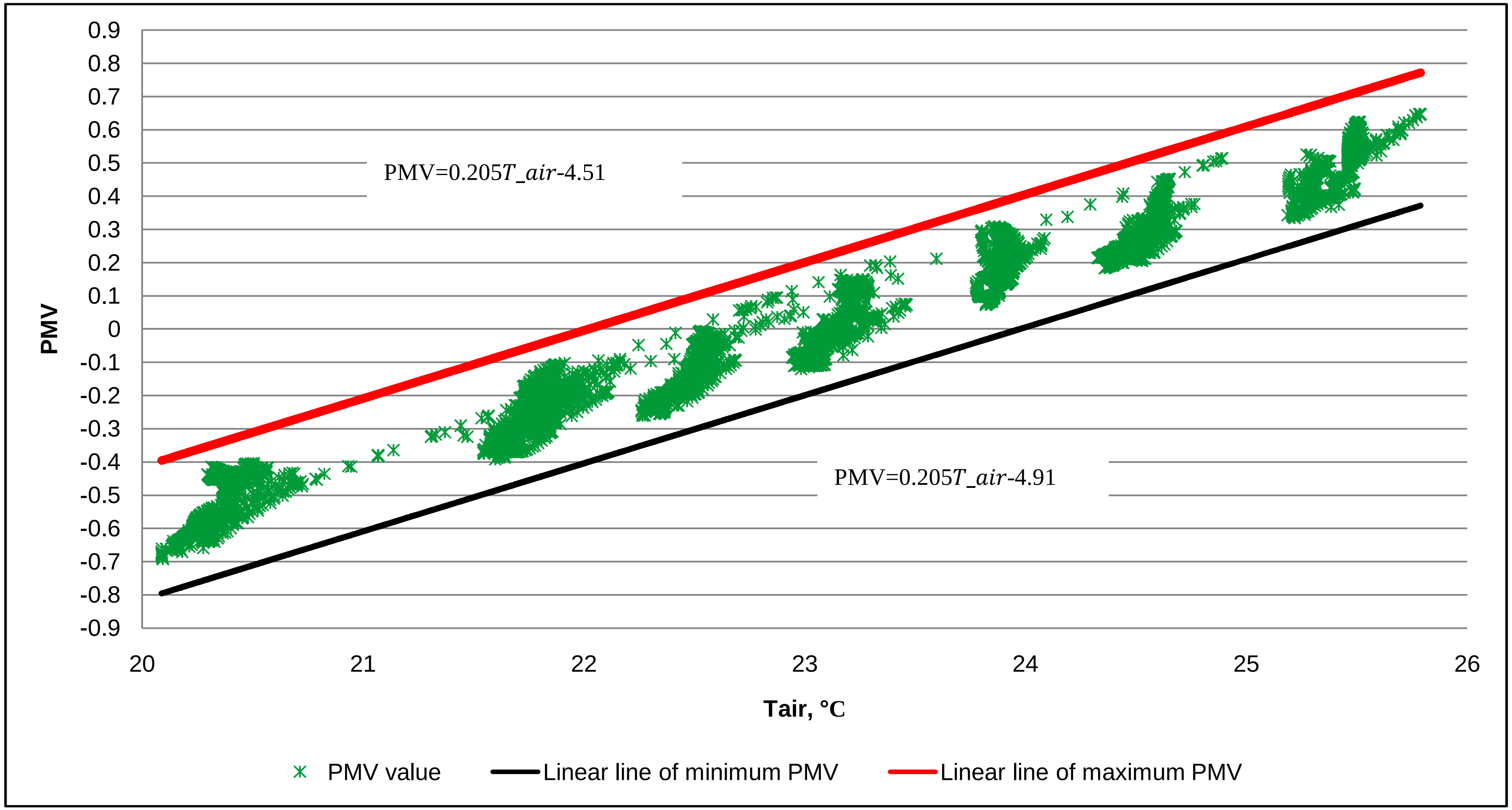
Cases	Thermal insulation	U-values (W/m²K)					Window properties		Air tightness
		Ext wall	Roof	Base floor	Doors	Windows	g[1]	ST[2]	q_{50} (m³/h.m²)
Lightweight									
LW-1960	Typical 1960	0.81	0.47	0.35	2.2	2.8	0.78	0.74	7.3

[1] Total solar heat transmittance (g)
[2] Direct solar transmittance (ST)

- Three different control algorithms
- Different controllers (P and on-off controllers)
- Activity level (1, 1.2) met
- Clothing level (0.96, 1.14) clo
- Air velocity inside the building (0.1, 0.2 m/sec)
- Heat distribution systems (electric radiator and floor heating systems)

Acceptable indoor air temperature

The correlation between PVM values and indoor air temperatures



Acceptable indoor air temperature in heating season

Category	LW-1960	
	Min-Max of Tair (℃)	Min-Max of Top (℃)
ERHS , On-off control		
I	22.4-22.5	22.6-22.7
II	21.0-22.9	21.2-24.0
III	20.0-24.0	20.2-24.4
ERHS , P-control		
I	22.8-22.9	22.3-22.8
II	21.4-24.3	20.8-24.3
III	20.4-25.3	19.8-25.3
EFHS , On-off control		
I	22.5-22.6	22.7-22.8
II	21.0-23.0	21.3-23.5
III	20.0-24.1	20.3-24.4
EFHS , P-control		
I	21.8-22.2	22.1-22.4
II	20.4-23.6	20.7-23.7
III	19.4-24.6	19.7-24.7

Results of control algorithms

- The lowest acceptable indoor air temperature set point is 19.4°C
- The highest acceptable indoor air temperature set point is 25.3°C

Control algorithm	Maximum total delivered energy saving (%)	Maximum total energy cost saving (%)
A	1	2.8
B	3.9	8.4
C	1.7	3.4

Compared with the reference case ($T_{set} = 21°C$)

Conclusion

- The energy cost of electrically heated detached houses was minimized by means of three different demand response control algorithms, without sacrificing the occupants' thermal comfort.
- Because of the higher potential of the thermal comfort category III to achieve lower energy cost, it was selected for this examination.
- The total delivered energy and cost can be reduced lower than minimum indoor temperature set point results.
- Compared with the reference case, the maximum energy and cost saved by the use of control algorithms are 3.9% and 8.4%, respectively.

Thanks for your attention