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Selecting boilers in an energy flexible heating systeme based on lowest running cost

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Abstract

This paper presents two different methods for calculating the final energy requirement from the heating system per time step – one with a predefined yearly mean efficiency and one with calculated efficiency for each time step. Further the paper presents a simple method for selecting the most cost efficient boiler, based on lowest running cost, and the possible consequences of selecting wrong boiler. A simulation example demonstrates the effect of selecting boilers based on yearly mean efficiencies rather than calculated mean efficiencies for the actual time step in question.

Keywords: Selecting boilers; Yearly mean efficiency; Actual efficiency; Control strategy; Lowest running cost

1. Introduction

Selecting the wrong boiler for heat production can result in unnecessary use of energy and may be expensive if the condition is allowed to continue. In many cases the operations manager do not know how to select the most cost efficient boiler for each time step based on varying outdoor temperature, load pattern and energy prices. Often used as criteria is the yearly mean boiler efficiency. These predefined efficiencies are often introduced to the operations manager by people how do not know the actual heat station in question and therefore can not know what exact efficiency to use. Very often operators are told to use 75% efficiency on oil fired boilers and 95% on electrical boilers. This paper presents two different methods for calculating the final energy requirement from the heating system per time step – one with a predefined yearly mean efficiency and one with calculated efficiency for each time step. Further the paper presents a simple method for selecting the most cost efficient boiler, based on lowest running cost, and the possible consequences of selecting wrong boiler. The process is divided into three steps. First the total energy requirement to the heating system is calculated (as described in section 2). Then the expected final energy requirement is calculated based on the two different methods of boiler efficiencies (as described in section 3), and finally the selection of the most cost efficient boiler based on lowest running cost (as described in section 4).

2. Total energy requirement to the heating system

First the total energy requirement by the building to the heating system must be calculated.

The total energy requirement to the heating system, Q_d, consists of energy requirement for space heating (including infiltration), mechanical ventilation and domestic hot water

$$Q_d = Q_h + Q_v + Q_w \text{ [kWh]} \qquad (2.1)$$

where

Q_h	energy requirement for space heating [kWh]
Q_v	energy requirement for ventilation [kWh]
Q_w	energy requirement for domestic hot water [kWh]

Heat demand for space heating, Q_h, without taking into account the system losses are calculated under standardised conditions, according to EN 832, EN ISO 13790 or similar. In this paper a simplified method for calculation of heat loss through the building envelope, Q_h, has been used

$$Q_h = H \cdot (\theta_{in} - \theta_e) \cdot t \text{ [kWh]} \qquad (2.2)$$

where

H	total heat loss coefficient of the building [W/K]
θ_{in}	indoor set-point temperature [^{o}C]
θ_e	average external temperature during the calculation period [^{o}C]
t	duration of the calculation period

Heat demand for ventilation, $Q_{v,}$ is calculated by

$$Q_v = c \cdot \rho \cdot V \cdot (1 - \eta_v) \cdot (\theta_{in} - \theta_e) \cdot t \text{ [kWh]} \qquad (2.3)$$

where

c	air specific heat capacity [kJ/kgK]
ρ	density or air [kg/m^3]
V	airflow rate [m^3/s]
η_v	heat recovery efficiency [ ]
θ_{in}	supply air set-point temperature [^{o}C]
θ_e	average external temperature during the calculation period [^{o}C]
t	duration of the calculation period

Heat demand for domestic hot water, Q_w, is given by

$$Q_w = \rho \cdot c \cdot V_w \cdot (\theta_w - \theta_o) \cdot t \text{ [kWh]} \qquad (2.4)$$

where

ρ	density of water [kg/m^3]
c	specific heat capacity of water [kJ/kgK]

V_w	volume of hot water required [m^3/s]
θ_w	temperature of the hot water [^{o}C]
θ_o	temperature of water entering the domestic hot water system [^{o}C]
t	duration of the calculation period

In this paper the heat demand for domestic water is set for an example building, see the simulation example in section 6.

3. Final energy requirement by the heating system

Next the final energy requirement by the heating system must be calculated.

The correct selection of boiler based on lowest running cost for one time step, for instance one hour, necessitates calculation of the required final energy (net energy) for that exact time step.

Final energy requirement, Q_f, can easily be calculated when the heat demand needed to be delivered from the heating system and the efficiencies of each boiler is known

$$Q_f = \frac{Q_d}{\eta_l} \text{ [kWh]} \qquad (3.1)$$

where:

Q_d	total energy requirement to the heating system [kWh]
η_l	efficiency of boiler *l* [ ]

The next two subsections present two different methods for calculation of final energy requirement based on two different approaches of defining the boiler efficiencies.

3.1 Final energy requirement with predefined fixed yearly mean efficiency

The first method for calculating final energy requirement is based on yearly mean boiler efficiencies.

A predefined fixed yearly mean efficiency for each boiler is used to calculate the expected final energy, Q_{ef}, based on the total energy requirement.

$$Q_{ef} = \frac{Q_d}{\eta_{l,m}} \text{ [kWh]} \qquad (3.2)$$

where:

Q_d	total energy requirement to the heating system [kWh]
$\eta_{l,m}$	assumed yearly mean efficiency for boiler *l* [ ]

This approach is widely used where real efficiencies are not known. Often an efficiency of 75% is used on oil fired boilers and 95% for electric boilers. In some cases operators even use the boiler efficiency with flue gas loss as the only heat loss from the oil fired boiler which is given as the boilers efficiency by service personnel.

When using this method it is most likely that the calculated expected final energy requirement for each time step will differ compared with actual energy consumption, and hence there is a possibility that the most expensive boiler alternative will be chosen.

3.2 Final energy requirement with mean power efficiency for each time step

The second method for calculating final energy requirement is based on mean boiler efficiencies for each time step calculated as a function of the heat demand from the building for the same time step.

Nielsen /1/ presents a set of equations to find the efficiency as a function of the heat demand from the heat system for an intermittently controlled boiler. These equations have been modified to take into account relative distribution heat loss, L_d. Loss in the distribution system will influence on the intermittency of the boilers and hence the efficiency.

$$\eta_l = \frac{Q_{out}}{Q_{inst}} \cdot \left(I_l + 1\right) \tag{3.3}$$

The intermittence rate can be obtained by using equation (3.4)-(3.7) as follows:

$$I_l = \frac{N_l - 1}{\dfrac{N_l}{I_{l,\max}} + 1} \tag{3.4}$$

$$N_l = \frac{Q_{inst} \cdot \eta_{l,\max}}{Q_{out}} = \frac{Q_{\max}}{Q_{out}} \tag{3.5}$$

$$\begin{aligned} I_{o,\max} &= \frac{1 - L_{eg} - L_r - L_d}{L_r + L_g + L_d} \\ I_{e,\max} &= \frac{1 - L_r - L_d}{L_r - L_d} \end{aligned} \tag{3.6}$$

$$\begin{aligned} \eta_{o,\max} &= 1 - L_{eg} - L_r - L_d \\ \eta_{e,\max} &= 1 - L_r - L_d \end{aligned} \tag{3.7}$$

where

η_l	mean efficiency for the boiler in question [ ]
Q_{out}	heat output from heat system [kWh/h]
Q_{inst}	gross installed boiler capacity [kWh/h]
Q_{max}	maximum heat output from heat system
I	intermittence rate [ ]
N	help variable
I_{max}	maximum intermittence rate, when $\eta=0$ [ ]
η_{max}	maximum operating efficiency ($I=0$) [ ]

L_{eg} relative exhaust gas loss [ ]
L_r relative radiation and convection heat loss for boiler surface [ ]
L_d relative distribution heat loss [ ]
L_g relative heat loss caused by air draught at boiler off time [ ]

Losses from each boiler must be obtained from calculations, measurements or from the boiler manufacturer.

When the efficiency for each boiler for the time step in question have been calculated it is a simple matter to determine the final energy requirement, Q_f, by combining equation (3.1) and (3.3) for that time step:

$$Q_f = \frac{Q_d}{\eta_l} = \frac{Q_d}{\frac{Q_{out}}{Q_{inst}}\left(I_l + 1\right)} \text{ [kWh]} \qquad (3.8)$$

This approach is not widely used in cases where the selection of boilers is done manually, but it have become more and more common in automated heat stations where a control unit selects the optimal boiler based on lowest running cost.

4. Selecting boiler based on lowest running cost

Finally selection of the most cost efficient boilers can be addressed.

When the final energy requirement for the time step is calculated the selection of boilers can be done based on lowest running cost. For this, the energy purchase price per kWh must be known.

For an electric fired boiler the total running cost, C_e, for each time step is:

$$C_e = Q_f \cdot c_e \text{ [money/h]} \qquad (4.1)$$

where

Q_f final energy requirement by the heating system [kWh/h]
c_e purchase price for electricity [money/kWh]

For an oil fired boiler the total running cost, C_o, is:

$$C_o = Q_f \cdot c_o \text{ [money/h]} \qquad (4.2)$$

$$c_o = \frac{k_o}{h_n} \text{ [money/kWh]} \qquad (4.3)$$

where

Q_f final energy requirement by the heating system [kWh/h]
c_o purchase price for oil [money/kWh]
k_o purchase prise for oil [money/litre]

h_n lower calorific value per litre oil [kWh/litre]

It is now a simple matter to calculate which boiler to choose:

$$F = \frac{C_o}{C_e} \tag{4.4}$$

F the rate between the efficiencies [ ]

If

F > 1 choose electric boiler
F < 1 choose oil fired boiler
F = 1 choose from preferred criteria other than running cost, e.g. environmental impact.

5. Consequences from selecting wrong boilers

When determining final energy requirement by using yearly mean efficiency it is most likely that calculated expected final energy requirement will differ from the real energy consumption since the real efficiency for the time step in question most likely will differ from the assumed yearly mean efficiency. Calculation using the mean boiler efficiencies for each time step will be more accurate since these efficiencies are calculated as a function of the heat output from the boiler at the same time step.

When determining final energy requirement per time step based on yearly mean efficiencies only the expected running cost is calculated, not the real running cost. The real running cost can only be calculated with use of the exact efficiencies per time step. In this paper the time step is set to one hour since external temperature and electricity purchase costs are given on an hourly basis.

To be able to demonstrate the effect of selecting the wrong boiler both methods presented in the paper must be used to calculate running cost per time step.

When selecting boilers based on lowest running cost from calculations with yearly mean efficiencies and the actual energy price the wrong boiler can be chosen. Table 1 shows a simple example of a typical situation.

Table 1 Example of calculations

Calculation method	$Q_{d,i}$ [kWh/h]	η		$Q_{f,i}$ [kWh/h]		Energy price Time step *i* [NOK/kWh]		Total energy cost time step *i* [NOK]	
		Oil	El	Oil	El	$c_{o,i}$	$c_{e,i}$	$C_{o,i}$	$C_{e,i}$
Yearly mean efficiency η_m	100	0.70	0.90	142	111	0.625	0.75	88.75	83.25
Hourly mean efficiency η_i	100	0.83	0.92	120	108	0.625	0.75	77.00	81.00

The rate between the yearly mean efficiencies is:

$$F = \frac{C_{o,i}}{C_{e,i}} = \frac{88.75}{83.25} = 1.07$$

Since F > 1 the electric boiler is chosen according to the definition in section 4.

The rate between hourly calculated mean efficiencies is:

$$F = \frac{C_{o,i}}{C_{e,i}} = \frac{77.00}{81.00} = 0.95$$

Since F < 1 the oil fired boiler is chosen according to the definition in section 4.

In this example, when the choice of boiler was based on yearly mean efficiencies, the electric boiler would have been operated for time step *i*. Calculations with hourly mean efficiencies show that the correct choice would have been the oil fired boiler. By running the electric boiler the total running cost would have been 81.00 NOK, but the total cost could have been only 77.00 NOK if the oil boiler chosen.

The calculated expected running cost of 88.75 NOK and 83.25 NOK are only expected cost calculated with an assumed efficiency. The real running cost are 77.00 NOK for the oil fired boiler and 81.00 NOK for the electric boiler.

6. Simulation example

Based on previous sections a simulation example that demonstrates the effect of running a heat station for a year based on inaccurate boiler efficiencies is given.

6.1 Building description

Total energy requirement to the heating system have been calculated according to section 1 with the building data shown in table 2.

The temperature distribution for each 24-hour period are estimated based on formula given by Programbyggerne /3/

$$T_e(t) = \overline{T_e} + \hat{T}_e \cdot \cos\left(\pi \frac{t - t_{\max}}{12}\right) \; [^{o}\mathrm{C}] \qquad (6.1)$$

where

$T_e(t)$ external temperature at time t [^{o}C]

$\overline{T_e}$ mean external temperature during 24-hour period [^{o}C]

$\hat{T}_e$ temperature amplitude during period [^{o}C]

t hour of day [ ]

t_{max} hour of day when maximum temperature occurs (here $t_{max}=13$) [ ]

Average external temperatures are shown in figure 6.1.

Only one boiler is allowed to run at each time step, and both boilers net capacity are larger than the heat demand under design climate conditions.

Table 2 Data for the simulation example

Type of building	Office building
Year of construction	1954
Indoor set-point temp	17^{o}C
Area	3100 m^{2}
Volume	9900 m^{3}
Infiltration rate	0.3 h^{-1}
Total heat transfer incl. infiltration	3258 W/K
Heat demand domestic hot water	5 W/m^{2}
Air specific heat capacity	0.35 Wh/(m^{3}K)
Airflow rate	20.000 m^{3}/h
Heat recovery efficiency	0.75
Operating time ventilation	0600-1600 (Monday-Sunday)
Oil boiler gross installed capacity	400 kW
Electric boiler gross installed capacity	350 kW
External temperature	Daily maximum and minimum temperature given by Norwegian Meteorological Institute. Location Narvik. Year 2005
Electricity prices	Hourly electricity prices given by Nord Pool ASA. Figure 6.2 shows average daily prices for 2005 including transmission charges, NOK/kWh, from local power grid owner, Narvik Energi AS
Oil prices	Approximately marked price for fuel oil for 2005. For simulation purposes it is assumed different prices for each month of the year. Figure 6.3 shows prices for each month used in the simulation example.
Lower calorific value	10 kWh/litre
Specific oil boiler losses	L_{eg} 8.5% L_r 3.5% L_g 2.0% L_d 0.6%
Specific electric boiler losses	L_r 2.5% L_d 0.6 %

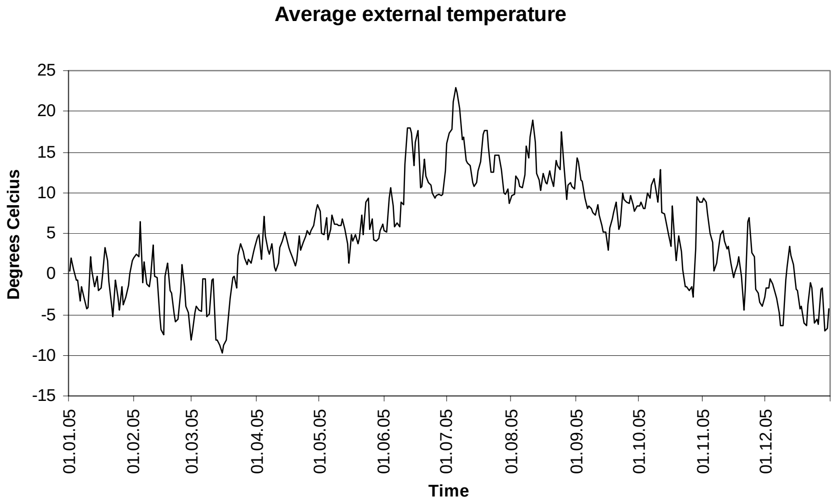


Figure 6.1 Average external temperature Narvik 2005.

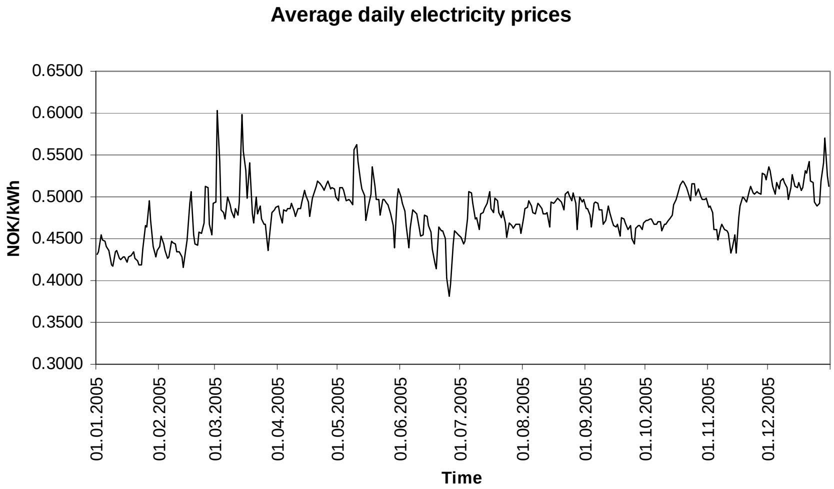


Figure 6.2 Average daily electricity prices including transmission cost.

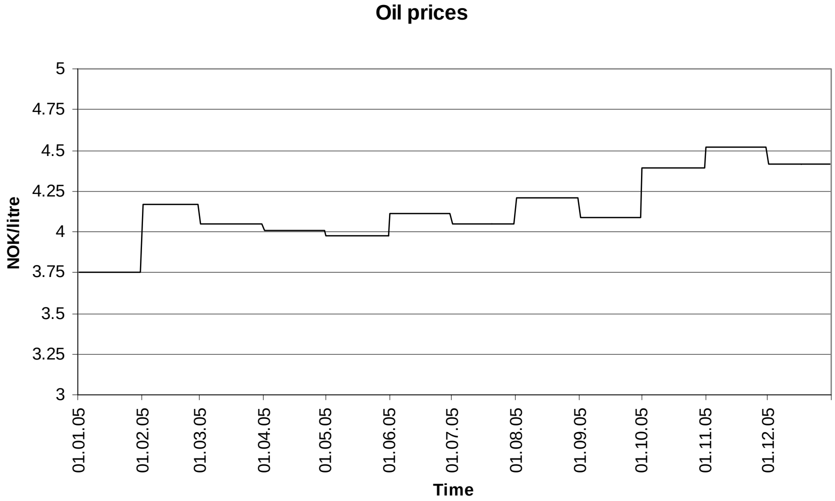


Figure 6.3 Average monthly oil prices.

6.2 Results of simulation

Final energy requirement

With yearly mean efficiency	834.712 kWh
With hourly calculated mean efficiency	824.045 kWh

Total running cost

With yearly mean efficiency	374.553 NOK
With hourly calculated mean efficiency	371.267 NOK

Number of hours running the most expensive boiler 1.682

By controlling the boilers based on yearly mean efficiencies and actual energy prices, the most cost expensive boiler was operated 1.682 hours resulting in an unnecessary energy consumption of 10.667 kWh at a cost of 3.286 NOK.

Figure 6.4 displays the various efficiencies determined in the simulation and the predefined yearly mean efficiencies for both boilers.

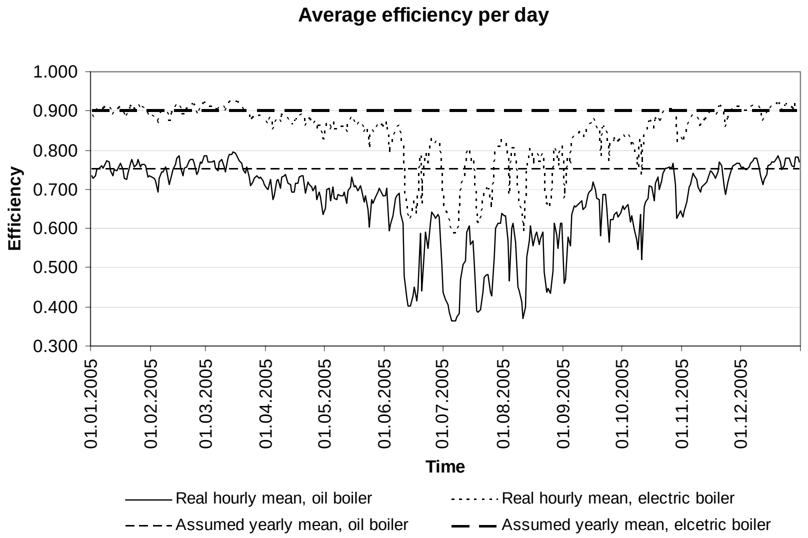


Figure 6.4 Average boiler efficiency per day.

Figure 6.5 shows the average running cost per day for both control strategies.

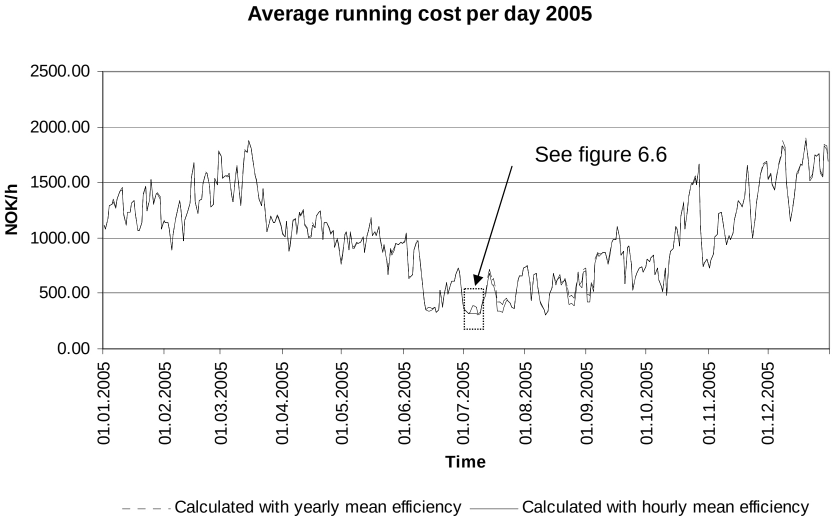
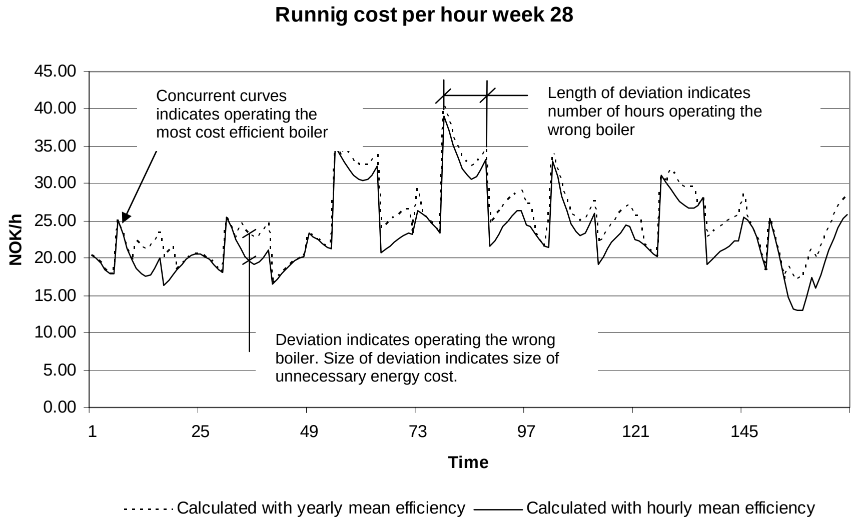


Figure 6.5 Average running cost per day.

A closer inspection of the curves of figure 6.5 is shown in figures 6.6 and 6.7.



Concurrent curves indicates operating the most cost efficient boiler

Length of deviation indicates number of hours operating the wrong boiler

Deviation indicates operating the wrong boiler. Size of deviation indicates size of unnecessary energy cost.

Figure 6.6 Running cost per hour for week 28.

Figure 6.6 shows where the deviation in the control strategy with yearly mean efficiencies compared with hourly mean efficiencies occurs. Where there cost curves are concurrent the most cost effective boiler was operated even though the decision basis was wrong. Where the curves deviate the wrong boiler was operated.

Figure 6.6 only shows the cost deviation in the two control strategies. Figure 6.7 shows which boiler who was operated at each time step in week 28.

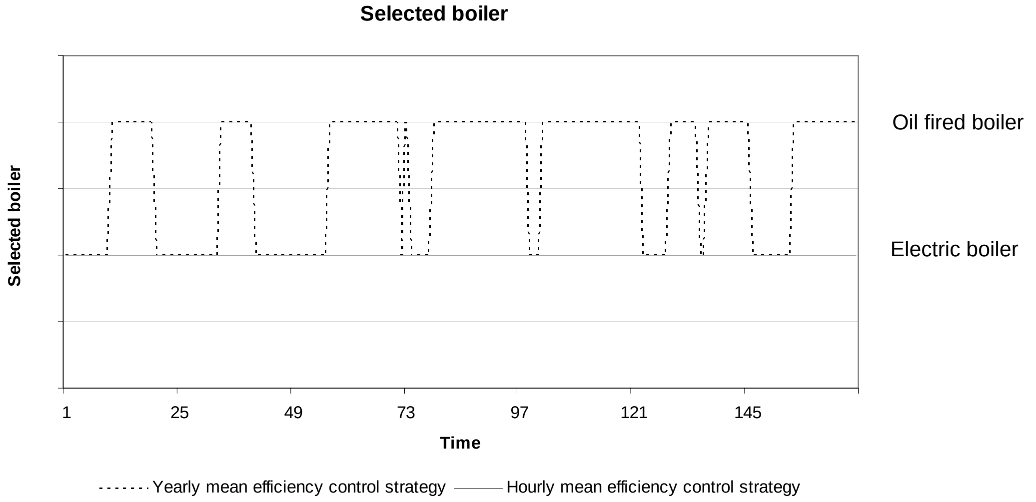


Figure 6.7 Selected boilers during week 28.

The curve indicating the control strategy using hourly mean efficiency shows that the correct choice was the electric boiler for the whole period, but the yearly mean efficiency control strategy selected the more expensive oil fired boiler for 102 hours for week 28.

7. Other influences on boiler selection

It is difficult to be specific about possible cost savings by always selecting the boiler with lowest running cost for each time step. There are many different factors that can affect the final result.

In this paper start-up and shutdown costs for each boiler are not taken into account, only running cost. Start-up and shutdown costs will occur every time a boiler is started or shut down due to preheating and cooling of the boiler. Nilsen /3/ states that smaller boilers may have negligible shutdown costs but the start-up cost should be considered. Energy consumed during start-up period depends on the length of the period without production due to cooling of the unit. In addition to varying energy costs there will also be fixed costs such as labour hours and extra costs due to wear associated with start-up and shutdown of boilers. Figure 7.1 shows an example of how start-up costs vary as a function of time without production.

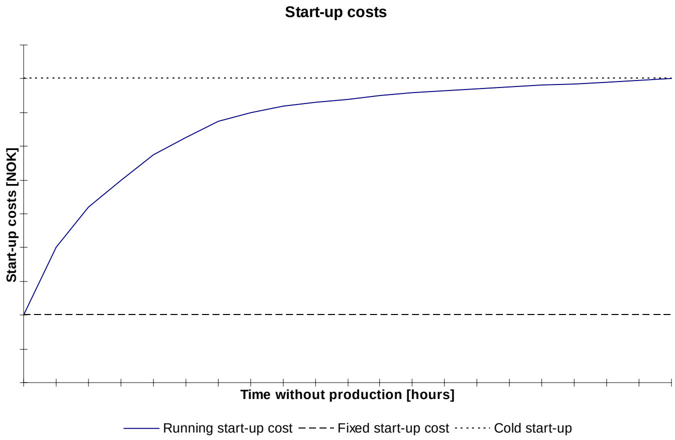


Figure 7.1 Example of varying start-up costs

In the simulation in section 6 the total number of start and stops are 455 for calculation with predefined yearly mean efficiency and 460 for calculation with hourly mean efficiency. The major problem determining the start-up cost is that it is difficult to predict for how long the selected boiler will be operated until it stops again. This makes it difficult to distribute the start-up cost for each time step. When start and stop costs are introduced in a model this cost must be taken into account on top of calculated running cost when choosing which boiler to use. Introduction of start- and shutdown cost for each boiler may result in fewer switches between boilers if the margins in running cost are small.

In addition to the purchase cost for electricity, money/kWh, often consumers have to pay a transmission charge for power, money/kW, based on the size of maximum used power tap during the year. These charges can be significant. The problem with adding these transmission charges is that we can not state until the last hour of the year how large this cost will be. In some cases a maximum power restriction can be set to the heat station to limit the transmission charge per kW.

More accurate climate model including a more accurate temperature prediction wind and solar radiation will improve the accuracy of the calculated heat demand and hence improving the accuracy of the final heat demand from the heating system. This will give a more accurate result.

8. Other possible selection parameters

In some cases building owners may have other parameters than lowest cost for optimizing the heat production. Such criteria may by:

- lowest possible energy consumption

- lowest possible emission of air pollution
- highest possible use of renewable energy.

For most cases lowest possible running cost will be the optimization criteria of choice, but for some buildings other parameters, such as mentioned above, may be decisive based on governmental or private policies. In such cases the selection models must be adjusted to each individual selection criteria before choosing which boiler to use.

9. Conclusion

This paper has presented two different methods for calculating final energy requirement from the heating system per time step - one with a predefined yearly mean efficiency and one with calculated efficiency for each time step. Further the paper presented a simple method for selecting the most cost efficient boiler, based on lowest operating cost, and the possible consequences of selecting wrong boiler.

A simulation example revealed that it is important to use actual efficiencies, rather than predefined yearly mean efficiencies, for each boiler when calculating the running cost based on actual heat demand and actual energy prices. Selecting the wrong boiler can be expensive.

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