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Energy efficiency monitoring – which sensors are really needed?

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Abstract

Plant balancing of waste-to-energy plants is a key issue in determining plant performance and operating efficiency. Traditionally, plant efficiency is determined only during the acceptance test by the means of an ex-post energy balance. For continuous operation, energy efficiency is estimated on a monthly or yearly basis using the waste throughput and average lower heating value. At Afval Energie Bedrijf in Amsterdam efficiency has to be reported on a monthly basis. Measured data from 83 positions is required to obtain the efficiency of the Hoog Rendement Central block with an ex-post energy balance on a continuous basis. This study investigated the importance of the different sensors. Efficiency calculations were performed after discarding the less important measuring positions. The measured data was replaced by the design value in the calculation. The total average margin of error per year for the efficiency value was found to be only 0.1% when the 23 most significant (instead of 83) measuring points were used, whereas individual values may differ by less than 0.5%. Operators of plants with fewer sensors can monitor their efficiency continuously if they know the most important positions.

Keywords

Waste-to-energy, waste incineration, energy efficiency, monitoring, sensors, Amsterdam

Introduction

Resource and energy efficiency are the keys for a sustainable society. This fact also applies to the waste-to-energy business. Energy efficiency has become a design criterion for new energy from waste plants. What is more, legal energy efficiency thresholds have been introduced in countries such as Austria, Switzerland and the Netherlands (Murer et al., 2009) as well as by the European Union in the form of the Waste framework directive (EU-Commission, 2008) (Table 1).

All above-mentioned laws require energy efficiency to be reported on a regular basis. This can be every month or every year. Energy efficiency is calculated from the exported electricity and heat as well as from the consumed energy in the form of waste and additional fuels. However, the energy content supplied by the waste fluctuates with its lower heating value. Therefore the typical way to determine the heat released during the combustion of waste is an ex-post energy balance. This energy balance determines the gross heat input from the waste (chemical energy in the waste) by balancing the useful heat produced in the form of steam, all the losses and all additional heat input. All energy streams entering and leaving the boiler needed for the calculation are indicated in Figure 1. Table 2 lists the abbreviations that are used in Figure 1 and specifies how the said energy streams are determined.

The exact method is described in the guideline for the acceptance test of waste-to-energy boilers (FDBR Arbeitskreis Abfallverbrennung, 2000) or in the VDI guideline 3460 (VDI, 2007). During the boiler acceptance test additional measuring equipment is installed so that all the data needed for the ex-post calculation can be measured. In normal operation, however, some of this data is not available and therefore the energy balance cannot be performed with the same data quality.

In the new Hoog Rendement Central (HRC) block at Afval Energie Bedrijf (AEB) Amsterdam, efficiency has to be monitored continuously for the monthly energy efficiency report (Minister van Economische Zaken, 2003). A detailed description of the plant, its features and design philosophies is freely available (Van Berlo and Wandschneider, 2006). At this plant most of the sensors needed for the ex-post calculation are operated permanently. These sensors are typical sensors used in the field of waste incineration with their respective measurement uncertainty and sensor drift. Therefore the sensors must be serviced and calibrated on a regular basis, increasing the plants operational cost. The objective of this investigation is to evaluate which are the

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Table 1. Comparisons of energy efficiency criteria in Europe.

Name	Valid in	Reference	Threshold	Relative weighting factor for heat compared to electricity
Ökostromgesetz Novelle	Austria	(Republik Österreich, 2006)	60%	0.67
R1	European Union	(EU-Commission, 2008)	0.65 (new plants)	0.42
Strom VV	Switzerland	(Bundesamt für Energie, 2008)	0.67 R1-equivalent (Murer et al., 2009)	0.39
SDE-Efficiency	The Netherlands	(Minister van Economische Zaken, 2003)	22%	0.67

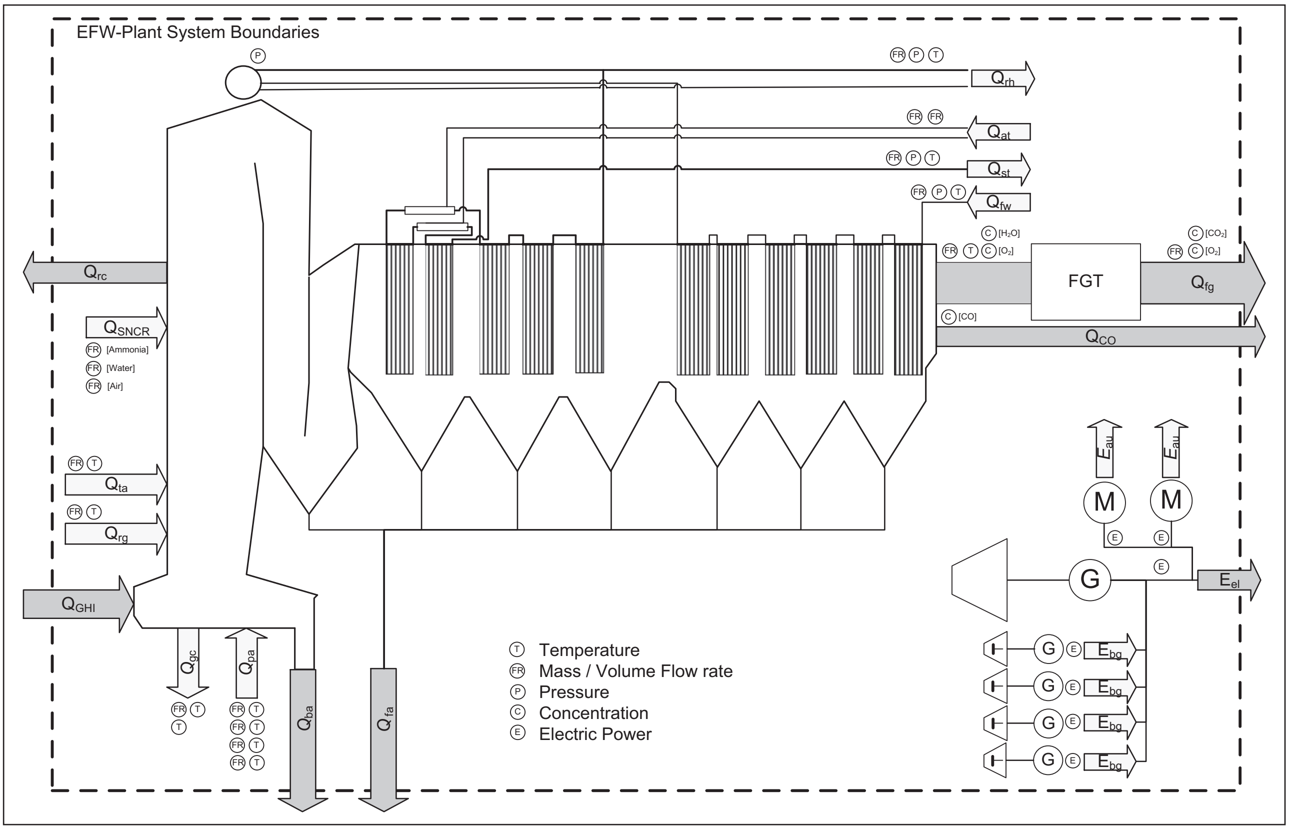

Figure 1. Energy flows in and out of the boiler considered in the ex-post energy balance. Energy streams leaving the system boundaries are highlighted in dark grey. 38 measuring points for one boiler and seven for the electrical systems of the block are used for calculating the energy flows.

most important sensors needed for the ex-post calculation. This investigation helps reducing costs of sensor maintenance at the Amsterdam plant, but allows also less well equipped plants to monitor their efficiency continuously. The results can be transferred to other plants since the used method is based on thermodynamics and mathematics and not on correlations and fitted parameters.

Methods

Figure 1 shows one of the boilers in the HRC block in Amsterdam. All energy streams crossing the boiler system boundary are marked in the representation. These energy streams have to be determined so that the ex-post boiler calculation can be performed. Most of the energy streams are calculated from measured temperatures, pressures and mass or volume flow rates. However, some of the energy streams can only be estimated. This applies to the heat released from the system with bottom and fly ash as well as to convective and radiation losses at the outside of the boiler. A suggested correlation for the convective and radiation losses is presented in the FDBR guideline (FDBR Arbeitskreis Abfallverbrennung, 2000). Additional losses for unburned in the ashes is assumed to be 3% as suggested by the reference document for best available techniques for waste incineration (EU-Commission, 2006). For the monthly efficiency report, the Amsterdam plant operators use a Microsoft Excel spreadsheet in

Table 2. List of considered heat flows in the ex-post calculation for determining the gross heat input of the HRC block at AEB Amsterdam.

	Description	Data acquisition
Q_{GHI}	Gross heat input with waste	Target value
Q_{gc}	Heat loss due to grate cooling	Calculated
Q_{pa}	Heat in primary air	Calculated
Q_{ba}	Bottom ash heat loss	Estimated
Q_{fa}	Fly ash heat loss	Estimated
Q_{CO}	Energy loss due to unburned matter in flue gas	Calculated
Q_{fg}	Flue gas energy loss	Calculated
Q_{fw}	Heat in feed water	Calculated
Q_{st}	Heat in live steam	Calculated
Q_{at}	Heat in attemperator water	Calculated
Q_{rh}	Heat to external reheater	Calculated
Q_{rc}	Radiation and convection losses	Estimated
Q_{SNCR}	Heat in SNCR injection	Calculated
Q_{ta}	Heat in tertiary air	Calculated
Q_{reci}	Heat in recirculated flue gas	Calculated
E_{el}	Electricity exported	Measured
E_{bg}	Electricity biogas engine	Measured
E_{au}	Electricity for auxiliary systems	Measured

which hourly average values from more than 100 sensors are entered. Fifty-eight sensors per boiler are used for the ex-post calculation. Information from additional sensors is needed to calculate net electrical efficiency and the thermal efficiency for the heat supply to the district heating network:

$$\eta_{net} = \frac{E_{el,net}}{Q_{waste} + Q_{fuels}} \tag{1}$$

Data from 123 measuring points is needed to determine the net electrical efficiency of the whole block. In 2010, an investigation was performed on the measurement uncertainty for the efficiency calculation. The focus of this investigation was to determine which sensor is primarily responsible for the uncertainty. The investigation showed that only a handful of sensors is responsible for more than 99% of the net electric efficiency uncertainty, i.e. the sensors for measuring the live steam mass flow, flue gas volume flow, electrical power, and live steam temperature (Murer et al., 2010). An important step in this investigation was the performance of a numerically sensitivity analysis of the boiler and plant efficiency regarding all data gathered by sensors:

$$\eta(\vec{x}) = f\left(x_1, x_2, \ldots x_i, \ldots x_n\right) \tag{2}$$

The efficiency η is a function of all measured data x_1 to x_n. The sensitivity corresponds to the derivative of efficiency:

$$s_i = \eta(\vec{x})' \tag{3}$$

It is determined numerically by calculating the central difference quotient (Schwetlick and Kretzschmar, 1991) for each sensor data at its design value:

$$s_i = \frac{f(x_i + \Delta x_i) - f(x_i - \Delta x_i)}{(x_i + \Delta x_i) - (x_i - \Delta x_i)} \tag{4}$$

with $\Delta x_i = 0.01 \cdot x_i$.

Data from 123 sensors are included in the calculation of net electric efficiency. However, some measuring points are represented several times due to safety issues, large cross-sections or control issues. For example, the drum pressure is controlled by three pressure sensors; six thermocouples are installed at the boiler outlet to measure the flue gas temperature and there are three flow meters to determine the air flow in each zone of the three grate runs. These multiple sensors are averaged or added up to obtain one single value, which is subsequently used to calculate efficiency. By reducing all multiple measurements of the block, the number of sensors (measuring points) investigated is reduced from 123 to 83 and (38 per boiler and seven for the block, see Figure 1).

The sensitivity analysis of the plant's net electric efficiency clearly showed that some values have a greater effect not only on the uncertainty but also on the efficiency determination itself. The unit of sensitivity is percent efficiency per unit of measured data. For example, an increase in live steam temperature of 1 °C changes efficiency by -1.5×10^{-2}% and an increase in tertiary air flow of 1 Nm^3 h^{-1} changes the efficiency by 4.2×10^{-7}%. For these ex-post calculations, the effect on efficiency is reversed in comparison with efficiency optimization. This implies an increase in live steam temperature increases efficiency, whereas measuring a higher live steam temperature than the effective live steam temperature decreases the calculated plant efficiency. However, it has to be considered that the live steam temperature is controlled to stay at a constant temperature, whereas the tertiary air flow changes with combustion control and load. Therefore it is important to consider not only the value of the sensitivity analysis but also the yearly fluctuations. At the Amsterdam plant, the measured data of all 123 sensors has been available since start-up in 2007. For this investigation, however, only the data from 2011 is considered. Hourly average values are used for each sensor to perform this investigation. To estimate the influence of each individual measuring point on efficiency, a value called dependence d_i is calculated for each measuring point:

$$d_i = s_i \cdot \sigma\,(x_i) \tag{5}$$

Dependence equals sensitivity multiplied by the standard deviation of the data trend for 2011 of the respective measuring point. Dependence is thus the average net electric efficiency fluctuation caused by the measuring point. Sorting all 83 measuring points by the dependence gives a list ordered by the importance of the individual sensors. The fluctuations of the measured data are in the range typically known for waste incineration plants. This implies the ranking for the dependence can be transferred to other plants. Dependence ranges from 9.3% for the electric power output of the electric generator to 2.5E−5% for the mass flow rate of the pressurized air used for spraying the ammonia water

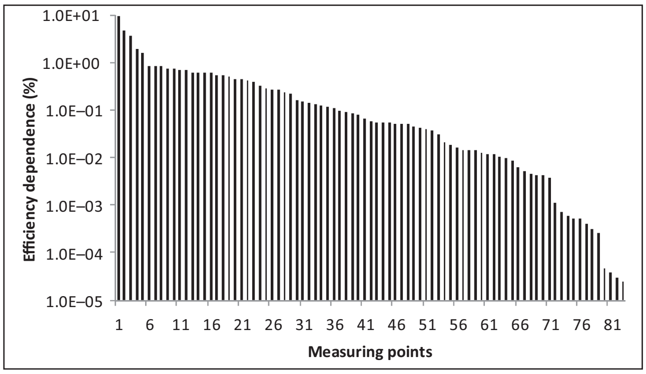

Figure 2. Dependence of the net electric efficiency for all 83 measuring points (in logarithmic scale). The figure shows clearly that net electric efficiency depends on a few sensors only.

mixture used in the selective non catalytic reduction (SNCR) system. The full spectrum of dependence is shown in Figure 2.

If the information provided by the dependence analysis is used, the data measured by the sensors with low dependence in the ex-post energy balance can be replaced with their design value. This occurs in steps by defining several thresholds for various dependence values. The ex-post energy balance and net electric efficiency calculation is subsequently evaluated with a mix of design values and measured data. The trend for efficiency is compared as well as the result of the average net electric efficiency weighted by exported electricity.

$$\overline{\eta} = \frac{\sum_0^{8760} \overline{P}_{\mathrm{el,net,t}} \cdot \eta_{\mathrm{t}}}{\sum_0^{8760} \overline{P}_{\mathrm{el,net,t}}} \tag{6}$$

Results and discussion

Trends for the net electric efficiencies are plotted using the method described previously. The graph, which uses all 83 sets of available data, represents efficiency as it is reported to the authorities. If the measured data with lowest efficiency dependence is gradually substituted by the design value this will lead to a deviation.

Figure 3 shows the resulting trends for using measured data from 83, 36, 23, 19 and only five measuring points. The calculated efficiencies are quite close to each other and fluctuate around 30%.

After the overhaul performed in summer 2011, the load of one boiler was increased to 110% (Murer et al., 2011). This also affects efficiency, as the efficiency graph shows after the gap at 4500 h. For reasons of clarity, an extract of about 9 days (210 h) is shown in detail in Figure 4. The difference between the full calculation and the reduced calculation is shown for the same period in Figure 5.

Down to 23 measuring points, the trends are close to the full set of sensors. With 23 sensors, the difference stays below a total of 0.2% during most of this period with only some peaks exceeding an absolute deviation of 0.5%. As expected, discarding data from some sensors does not lead to a deviation in one

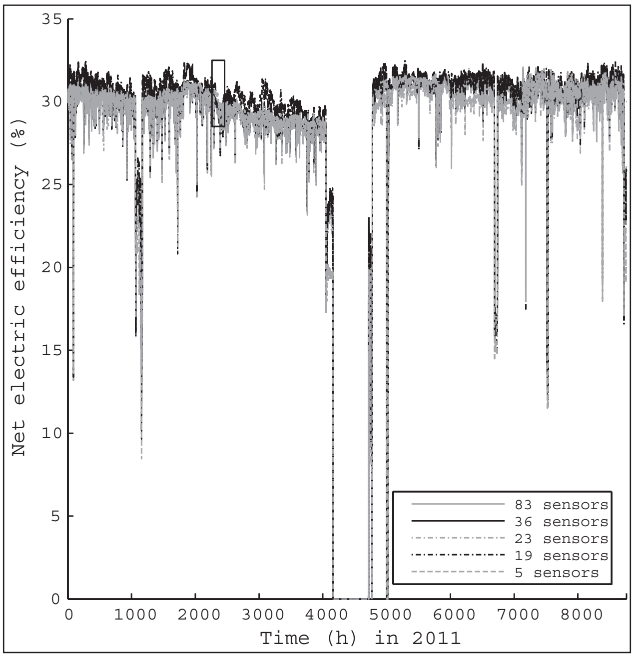

Figure 3. Graph of net electric efficiency determined with different number of sensors, no large difference was detected. The marked square at time 2250 to 2460 h is shown in detail in Figure 4. After the revision the load of one of the two boilers was raised to 110% of its design capacity; this effect can be seen by slightly increased efficiency

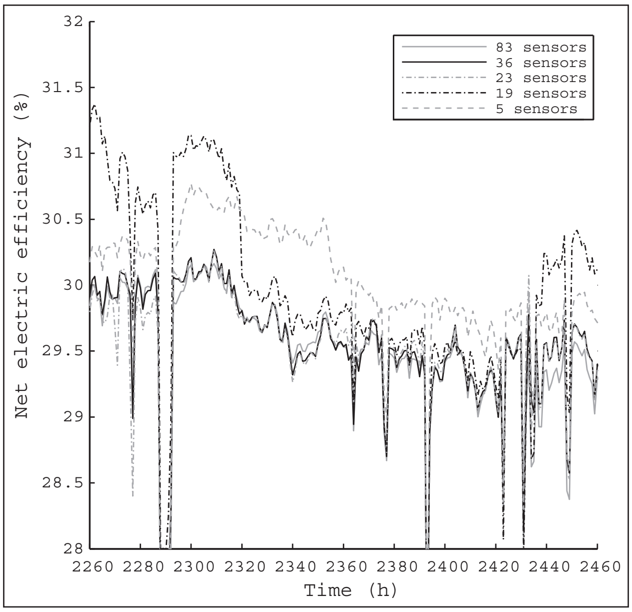

Figure 4. Detailed view of trends for net electric efficiency calculated using different numbers of sensors. All trends down to 23 sensors make a good prediction of efficiency possible.

direction. If data from some sensors is discarded, efficiency is increased, whereas others decrease it. The small deviations are caused by missing information of the less important discarded sensors. For 19 and five sensors much more data is neglected, which results in an interesting phenomenon. Although the trend with five sensors uses much less information to calculate

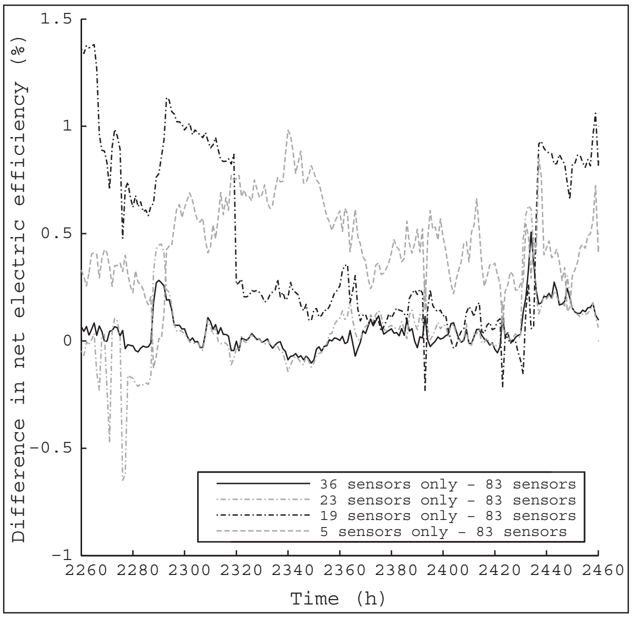

Figure 5. Detailed view of graphs concerning difference in net electric efficiency calculated using different numbers of sensors. It is noticeable that sometimes the graph calculated on the basis of only five sets of data shows better results than the one with 19.

efficiency, it is, for some periods, more representative than the trend with 19 sensors. This effect is caused by discarding some specific sensors, whereas for some points two data sets have proportional values, such as feed water mass flow and live steam mass flow. With only five sensors, only the live steam is accounted for in the efficiency calculation. If the load deviates, the live steam changes, whereas the value used for the feed water mass flow rate stays the same. The same effect also applies to the air temperature, air volume flow and flue gas volume flow. Using the design value for the air temperature and changing the air volume flow and air temperature due to changing waste properties, affect the heat added by the combustion air. These changes are not accounted for when using the design value for these measuring positions.

The annual net electric efficiency calculated by all 83 sensors is 30.05% for 2011. In that year, the HRC block exported a total of 447.7 GWh of electricity and 42.9 GWh of heat to the district heating system since it combines heat and power generation. At two pressure levels steam can be extracted from the turbine to be condensed in a heat exchanger. A power loss coefficient for the delivered heat of 0.27 was determined at full heat extraction potential (Murer, 2008). For part load heat, a lower power loss coefficient of 0.2 is assumed, since steam is extracted only from the low pressure extraction point. This implies that without heat supply the amount of exported electricity could be increased by 7.7 GWh, raising the annual electricity average to 30.57%. This high value confirms the energy efficiency and high availability envisaged by the plant designers (van Berlo and Wandschneider, 2006).

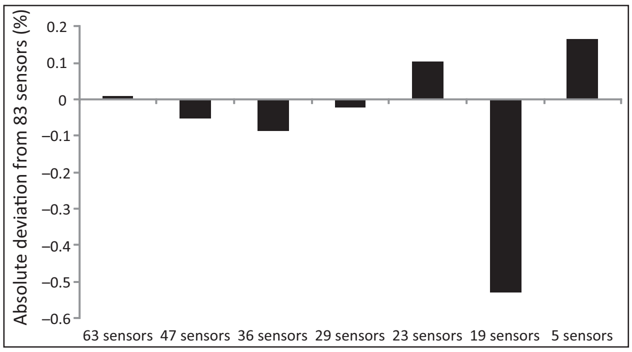

Figure 6. Absolute deviation of annual average net electric efficiency weighted by exported electricity.

A comparison of the differently calculated average efficiencies for the whole year shows that all values are close. The average deviation for the whole year is represented in Figure 6. For 23 (instead of 83) sensors the annual average efficiency deviates by about 0.1%. For 19 and five sensors, the difference is −0.5 and +0.16%, respectively. The decrease from 19 to five sensors is again attributed to the effect described above. The measurement uncertainty determined for the efficiency of the HRC block is 1% (Murer et al., 2010). This implies the error of the reduced efficiency calculation over one year is smaller than the measurement uncertainty for all 83 measuring points. As mentioned above, the measurement uncertainty is due to a few sensors. These are mainly the same sensors with the highest dependence. Therefore the uncertainty of the reduced efficiency model is within the same range. Another 0.5% of uncertainty should be added to the uncertainty of the plants net electric efficiency as safety margin to account for uncertainty in the reduced model. This value is taken from the absolute deviation with 19 sensors presented in Figure 6.

By using the data for the ex-post calculation, it is also possible to monitor the R1 efficiency of the plant continuously within a small margin of error.

The overall objective of this investigation was to determine which of the measuring points is really needed for the ex-post energy balance. The sensors are presented in Table 3.

The most important value for determining efficiency is the generated power, followed by the live steam mass flow rate and temperature. The feed water mass flow rate and temperature are next on the list. However, their dependence is already half of the live steam's dependence. The grate cooling temperature is also of importance, since it determines the amount of heat extracted with the grate cooling water. The sensors for the flue gas volume flow and temperature are also among the most important sensors. This is in accordance with the formula suggested by Reimann and Hämmerli (1995) to determine the lower heating value. The formula uses enthalpy changes in the water depending on feed water and live steam parameters and the flue gas temperature at the boiler outlet (Reimann and Hämmerli, 1995). However the influence of grate cooling is not considered.

Table 3. Dependency ranking of the first 37 measuring positions. The rest of the 83 measuring positions have a dependency lower than 0.1%. The sensitivity on the electric efficiency is also presented. The four biogas engines are on the same electric grid inside the system boundaries and have to be balanced too.

Rank	Name	Unit	Location	Dependence		Sensitivity	Unit
1	Generator Active Power	MW	Block	9.34E+00	%	5.41E−01	% (MW)$^{-1}$
2	Live steam mass flow rate	t h^{-1}	Boiler 2	4.61E+00	%	1.46E−01	% (t h^{-1})$^{-1}$
3	Live steam mass flow rate	t h^{-1}	Boiler 1	3.65E+00	%	1.46E−01	% (t h^{-1})$^{-1}$
4	Live steam temperature	°C	Boiler 2	1.89E+00	%	1.50E−02	% (°C)$^{-1}$
5	Live steam temperature	°C	Boiler 1	1.58E+00	%	1.50E−02	% (°C)$^{-1}$
6	Feed water mass flow rate	t h^{-1}	Boiler 2	8.56E−01	%	2.79E−02	% (t h^{-1})$^{-1}$
7	Feed water temperature	°C	Boiler 2	8.55E−01	%	2.12E−02	% (°C)$^{-1}$
8	Grate cooling water cold temperature	°C	Boiler 2	8.19E−01	%	3.48E−02	% (°C)$^{-1}$
9	Feed water temperature	°C	Boiler 1	7.25E−01	%	2.12E−02	% (°C)$^{-1}$
10	Grate cooling water warm temperature	°C	Boiler 2	7.17E−01	%	3.50E−02	% (°C)$^{-1}$
11	Feed water mass flow rate	t h^{-1}	Boiler 1	6.88E−01	%	2.79E−02	% (t h^{-1})$^{-1}$
12	Grate cooling water cold temperature	°C	Boiler 1	6.86E−01	%	3.48E−02	% (°C)$^{-1}$
13	Flue gas volume flow rate	1000 Nm^3 h^{-1}	Boiler 2	6.20E−01	%	9.55E−03	% (1000 Nm^3 h^{-1}) $^{-1}$
14	Flue gas temperature boiler outlet	°C	Boiler 2	6.05E−01	%	1.16E−02	% (°C)$^{-1}$
15	Reheater condensate return temperature	°C	Boiler 2	6.04E−01	%	6.87E−03	% (°C)$^{-1}$
16	Grate cooling water warm temperature	°C	Boiler 1	6.02E−01	%	3.50E−02	% (°C)$^{-1}$
17	Auxiliary Power 1	MW	Block	5.53E−01	%	5.41E−01	% (MW)$^{-1}$
18	Reheater condensate return temperature	°C	Boiler 1	5.31E−01	%	6.87E−03	% (°C)$^{-1}$
19	Flue gas temperature boiler outlet	°C	Boiler 1	5.06E−01	%	1.16E−02	% (°C)$^{-1}$
20	Flue gas volume flow rate	1000 Nm^3 h^{-1}	Boiler 1	4.47E−01	%	9.55E−03	% (1000 Nm^3 h^{-1})$^{-1}$
21	Reheater condensate mass flow rate	kg s^{-1}	Boiler 2	4.45E−01	%	2.08E−01	% (kg s^{-1})$^{-1}$
22	Auxiliary Power 2	MW	Block	4.10E−01	%	5.41E−01	% (MW)$^{-1}$
23	Reheater condensate mass flow rate	kg s^{-1}	Boiler 1	4.02E−01	%	2.09E−01	% (kg s^{-1})$^{-1}$
24	Live steam pressure	bar (g)	Boiler 2	3.22E−01	%	8.82E−03	% (bar (g))$^{-1}$
25	Biogas engine 4 power	kW	Block	2.88E−01	%	5.41E−04	% (kW)$^{-1}$
26	Live steam pressure	bar (g)	Boiler 1	2.68E−01	%	8.82E−03	% (bar (g))$^{-1}$
27	Biogas engine 2 power	kW	Block	2.62E−01	%	5.41E−04	% (kW)$^{-1}$
28	Biogas engine 1 power	kW	Block	2.37E−01	%	5.41E−04	% (kW)$^{-1}$
29	Biogas engine 3 power	kW	Block	2.24E−01	%	5.41E−04	% (kW)$^{-1}$
30	Primary air zone 2 temperature	°C	Boiler 2	1.58E−01	%	4.89E−03	% (°C)$^{-1}$
31	Primary air zone 2 volume flow rate	Nm^3 h^{-1}	Boiler 2	1.49E−01	%	5.69E−06	% (Nm^3 h^{-1}) $^{-1}$
32	Grate cooling water mass flow rate	m^3 h^{-1}	Boiler 2	1.39E−01	%	3.19E−03	% (m^3 h^{-1})$^{-1}$
33	Primary air temperature zone 2	°C	Boiler 1	1.35E−01	%	4.89E−03	% (°C)$^{-1}$
34	Drum pressure	bar (g)	Boiler 2	1.23E−01	%	3.15E−03	% (bar (g))$^{-1}$
35	Grate cooling water mass flow rate	m^3 h^{-1}	Boiler 1	1.15E−01	%	3.19E−03	% (m^3 h^{-1})$^{-1}$
36	Primary air zone 2 volume flow rate	Nm^3 h^{-1}	Boiler 1	1.07E−01	%	5.69E−06	% (Nm^3 h^{-1})$^{-1}$
37	Drum pressure	bar (g)	Boiler 1	9.83E−02	%	3.03E−03	% (bar (g))$^{-1}$

Conclusions

The investigation presented herein shows that not all sensors have the same importance for an ex-post efficiency calculation. Some sensors which measure the electricity, live steam and feed water parameters as well as the grate cooling system influence the efficiency figure more than others. The sensors found are not only important for calculating net electric efficiency but also for calculating boiler efficiency, gross heat input and thermal efficiency. An ex-post calculation with small errors can be performed if the data of the important sensors are used together with the design values for the rest of the needed data. Only about 20 sensors are needed for a block with two boiler lines to determine efficiency with a deviation of about 0.5%. This value is still lower than the combined measurement uncertainty for the efficiency of typically 1%. Most of these sensors, such as those for the live steam temperature and mass flow, are already installed for normal plant operation. As a result, efficiency can be monitored continuously during operation without installing many additional sensors. What is more, plant operators can detect inefficient operational settings at an early stage and hence improve plant performance on a continuous basis.

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