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Impact of load variations on wood boiler efficiency and emissions:

in-situ monitoring of two boilers (2 MW and 0.65 MW) supplying a district heating system

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Abstract

This article relates the results of a research project aiming at characterising the impact of load variations on wood boiler efficiency and emissions. It is based on a case study consisting in a wood fired district heating system in Geneva canton (Switzerland). The heat is supplied by two wood boiler (2 MW and 0.65 MW). The boilers efficiency and emissions were measured on the entire load range. The results given by the traditional indirect method (based on Siegert formula) were corroborated by direct measurements of the efficiency. Surprisingly, the efficiency found not to be influenced by the load: a constant value was observed for both boilers over the entire load range, even during the stand-by periods (83% for the 2 MW boiler, 90% for the 0.65 MW boiler). On the other hand, CO emissions are strongly deteriorated at low load because of the necessary increase in the excess air. NOx emissions remained low over the entire load range. The operation of the overall district heating system was also analysed during all year 2011. High distribution losses (>20%) due to the low linear density of the district heating system (0.9 MWh/m/yr) and a high oversizing factor of the wood boiler (>1.5) were highlighted.

Keywords: *Wood boiler, load variations, efficiency, atmospheric emissions, in-situ monitoring, district heating*

Introduction

In Switzerland, energy from wood accounts for more than 20% of the total final energy from renewable sources and 4% of the total final energy consumption (Bundesamt für Energie 2013). The development potential of wood fired district heating systems is real, taking advantage of cost sharing together with high energy and environmental efficiency. The combustion of wood in large boilers is usually well controlled but its efficiency and emissions are not yet well characterised.

Several studies report efficiency values for existing wood boiler (Good et al. 2004, Lundgren et al. 2004b, Lundgren et al. 2004a, Sechaud Ingénierie 2004, Good et al. 2006, Beck et al. 2007, LECES et al. 2008, IRH Ingénieur Conseil 2009, Zhang et al. 2010), but not all have resulted in scientific publications. Some of them refer to instantaneous values (Sechaud Ingénierie 2004, Good et al. 2006, LECES et al. 2008, IRH Ingénieur Conseil 2009, Zhang et al. 2010) and others in annual values (Good et al. 2004, Sechaud Ingénierie 2004, Good et al. 2006, Beck et al. 2007). Instantaneous efficiency values are estimated using the indirect method (indirect calculation by quantification of the different heat losses). Fig. 1 gathers

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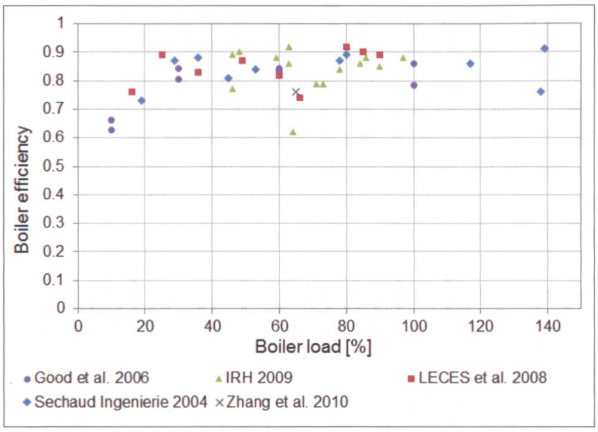

Fig. 1. Boiler efficiency versus boiler load, literature values.

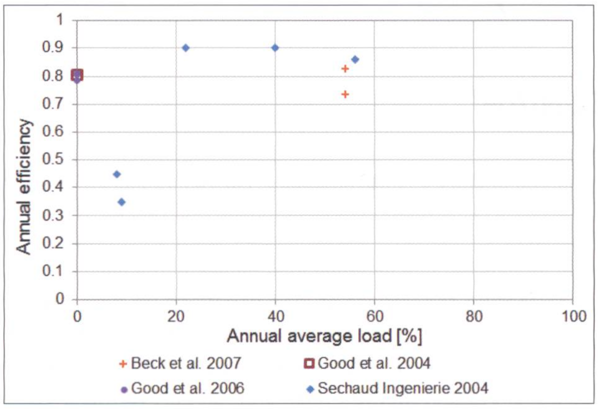

Fig. 2. Annual efficiency versus annual average load, literature values. Values at 0 indicate that the annual average load is not mentioned.

the values available in the preceding studies (from "spot" measurements). Most values are between 80 and 90%, with a downward trend at low load (<30%).

Fig.2 presents the values of annual efficiency available in literature versus the annual average load of the wood boiler. No clear trend can be identified, but the values essentially stand between 70 and 90%.

Concerning the atmospheric emissions of wood boiler, many values from spot measurements are available in literature (Lundgren et al. 2004b, Lundgren et al. 2004a, Sechaud Ingénierie 2004, Good et al. 2006, Beck et al. 2007, LECES et al. 2008, IRH Ingénieur Conseil 2009, Zhang et al. 2010). Figs. 3 and 4 present the CO and NOx emissions versus load. The Swiss legal limit for wood boiler (capacity between 1 and 10 MW) is also mentioned.

CO emissions are mainly below 1000 mg/Nm^3, although temporary peaks are noticed. No clear trend is observed but within a same study (i.e. with the same methodology), CO emissions generally increase when the boiler load decreases. The analysed boilers mostly show NOx emissions below the Swiss legal limit of 250 mg/Nm^3. The level of NOx emissions is not influenced by the boiler load.

The impact of load variations on efficiency and emissions of large wood boiler needs to be further studied. Both are generally known to be deteriorated when operating at low load but to what extent? Measured values for efficiency and emissions are available in literature at different loads but not their evolution versus load for the same boiler and during entire days of operation.

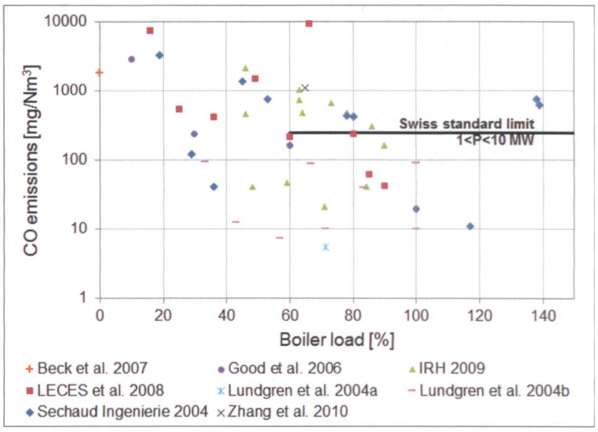

Fig. 3. CO emissions versus boiler load (log scale), literature values referring to 11% O_2 in the flue gas.

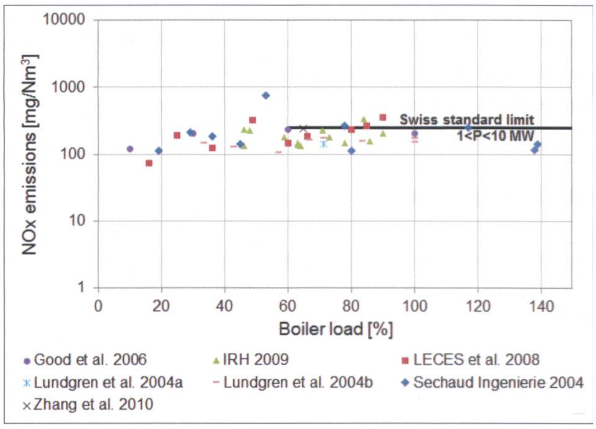

Fig. 4. NOx emissions versus boiler load (log scale), literature values referring to 11% O_2 in the flue gas. NOx expressed as NO_2 equivalent.

Case study

The research project is based on the one-year monitoring of an existing wood fired district heating system located in the village of Cartigny (900 inhabitants) in Geneva canton (Switzerland). The work focused on the analysis of the impact of varying the boiler load on efficiency and emissions in the flue gas, presently not well characterised. As it was not possible to measure the efficiency and emissions on the whole year, specific measurement campaigns (each of several days) were organised at different periods of the year. This differs from the results available in literature, which typically relate to spot measurements concerning short periods of time (typically less than 12 hours). The analysis also covered economic aspects, not addressed in this article. The reader can refer to the full report (Haroutunian et al. 2013) for further information.

The case study is a wood fired district heating system operating since 2008. The network is 5.8 km long and supplies approx. 120 consumers (mainly single-family houses) in heating and domestic hot water. Two wood boiler of 2 MW (Müller TM20, called "large boiler") and 0.65 MW (Müller TM15, called "small boiler") were installed to provide heat to the customers. The system operates all year: the large boiler is supposed to operate during winter (complemented by the small boiler during peak loads) and the small boiler during summer for domestic hot water production. The wood boiler cover the whole capacity of the district heating system. An oil boiler can be used in back-up case of failure.

Methodology

3.1. Instrumentation

The monitoring intended to measure the efficiency and emissions of the boilers but also to perform the analysis of the overall system on year 2011. Table 1 gathers the 24 measuring points in the system (temperature sensors, heat and electricity meters, wood mass flow meter, gas analysers), located in the system as presented in Fig. 5. Most of the measurements (17) were made during the entire monitoring period (all year 2011), but the sensors required for efficiency and emissions measurements could not be left permanently on site without human intervention. Thus measurement campaigns were organised in order to cover the entire load range of operation of the two boilers (see Table 2). Unless something else is specified, the sensors were scanned every ten seconds and the average/total values recorded every 5 minutes by the datalogger (Campbell Scientific CR3000).

As a complement, the Net Calorific Value NCV_{dw} of 5 samples (previously dried in oven) of the wood used on the plant was measured using a Parr oxygen bomb calorimeter (model 1341) according to the standard protocol. An average value of 18.2 MJ/kg ±3% was

Table 1: Instrumentation.

		Description	Periodicity	Unit	Sensor name
Permanent instrumentation	Large boiler	Output temperature	5 min	°C	T_{11}
		Input temperature	5 min	°C	T_{12}
		Output energy	5 min	kWh	E_1
		Load setpoint	5 min	%	L_1
		Residual oxygen in flue gas	5 min	vol%	O_{21}
		Electricity consumption	5 min	kW	El_1
	Small boiler	Output temperature	5 min	°C	T_{21}
		Input temperature	5 min	°C	T_{22}
		Output energy	5 min	kWh	E_2
		Load setpoint	5 min	%	L_2
		Residual oxygen in flue gas	5 min	vol%	O_{22}
		Electricity consumption	5 min	kW	El_2
	Network	Supply temperature	5 min	°C	T_{31}
		Return temperature	5 min	°C	T_{32}
		Σ Users heat consumption	1 hour	kWh	E_3
	Other	Oil boiler output energy	5 min	kWh	E_4
		Outdoor temperature	5 min	°C	T_4
Campaigns	Flue gas	Flue gas temperature	5 min	°C	T_5
		Residual oxygen (dry basis)	1 min	vol%	O_2
		CO_2 (dry basis)	1 min	vol%	CO_2
		CO (dry basis)	1 min	vol%	CO
		NOx (dry basis, equiv. NO_2)	1 min	vol%	NOx
	Wood	Mass flow	5 min	kg	M_{wood}
		Humidity	30 min	wt%	H

Table 2: Measurement campaigns.

Camp. nb.	Day	Hours	Duration	Load range
Large boiler			**120 hours**	**15-100 %**
1	29.11.2010	6 a.m. – 10 p.m.	16 hours	55-80 %
	1-2.12.2010	6 a.m. – 6 a.m.	24 hours	55-90 %
	3-4.12.2010	6 a.m. – 6 a.m.	24 hours	35-100 %
	5.12.2010	6 a.m. – 10 p.m.	16 hours	65-100 %
2	27.01.2011	6 a.m. – 6 p.m.	12 hours	60-80 %
3	29.03.2011	6 a.m. – 8 p.m.	14 hours	15-50 %
	31.03.2011	6 a.m. – 8 p.m.	14 hours	20-35 %
Small boiler			**72 hours**	**10-100 %**
4	16.08.2011	6 a.m. – 6 p.m.	12 hours	10-30 %
	18.08.2011	6 a.m. – 6 p.m.	12 hours	10-20 %
5	11.10.2011	6 a.m. – 6 p.m.	12 hours	25-60 %
	12.10.2011	6 a.m. – 6 p.m.	12 hours	30-70 %
6	15.11.2011	6 a.m. – 6 p.m.	12 hours	85-100 %
	16.11.2011	6 a.m. – 6 p.m.	12 hours	50-100 %

obtained, which is very close to the usual value of 18.0 MJ/kg. Since the Net Calorific Value measurements were only performed on "spot" samples during the first measurement campaign and thus not representative of the wood quality during the whole period of measurements, the usual value of 18 MJ/kg was used in the calculations (the difference between the measured and usual values is lower than the measurement error).

3.2. Boiler efficiency determination

The instantaneous efficiency of a wood boiler is usually estimated using an indirect method based on Siegert formula for the calculation of the flue gas losses. This method provides only dimensionless values for the losses, but has the advantage of not requiring the measurement of the flue gas flow (which is difficult to perform in situ). However it cannot apply during

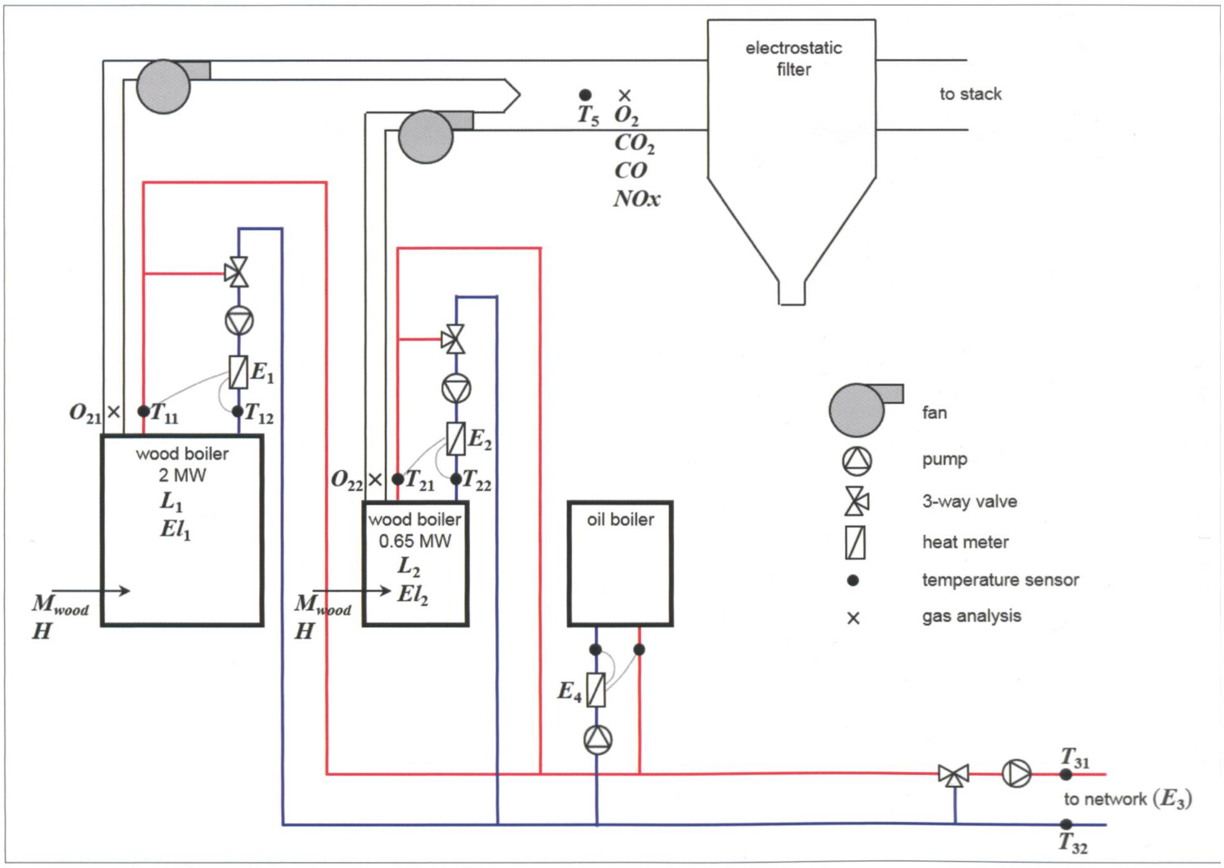

Fig. 5. System diagram.

stand-by periods since the calculation is based on the instantaneous composition of the flue gas. Thus some authors such as Good et al. (Good et al. 2006) consider an empirical value for heat losses during stand-by periods – 5 % of the full load – for the determination of the annual efficiency.
This study aims at validating the usual indirect method by confronting the results obtained with "direct" measurements of the efficiency. This has not been done before dealing with wood boiler although this indirect method is widely used. Thereby in this study two separate methods were used to quantify the instantaneous efficiency over the entire load range of the boilers:

- the "indirect" method, which quantifies the different heat losses sources (flue gas, walls, unburnt products)
- the "direct" method, based on direct measurements of the produced heat and of the supplied energy in wood

3.2.1. Indirect method

The efficiency η is calculated following Eq. 1:

$$\eta_{indirect} = 1 - Q_{flue\,gas} - Q_{walls} - Q_{unburnt}\ [-] \qquad \text{Eq. 1}$$

where:

$Q_{flue\,gas}$ is the thermal loss by sensible heat in the flue gas, calculated following Eq. 2 proposed by Good et al. (Good et al. 2006), adapted from Siegert formula:

$$Q_{flue\,gas} = \frac{(T_{flue\,gas} - T_{outdoor})\cdot(1.39 + \frac{122}{CO + CO_2} + 0.02\cdot H_{db})}{\frac{NCV_{dw}}{100} - 0.2442\cdot H_{db}}\ [-] \qquad \text{Eq. 2}$$

in which $T_{flue\,gas}$ is the flue gas temperature (T_5) [°C], $T_{outdoor}$ the outdoor temperature (T_4) [°C], CO and CO_2 the carbon monoxide and carbon dioxide concentration in the flue gas [vol %], NCV_{dv} the Net Calorific Value of the dry wood (18 000 kJ/kg),

$$H_{db} = \frac{m_{H_2 0}}{m_{dry\,wood}}\cdot 100$$

the wood moisture content in dry basis [wt %].

Q_{walls} [–] is the thermal loss by radiation, convection and conduction and depends on the temperature of the boiler walls. Generally a fixed value is assumed since the walls temperature – and thus the heat losses – are almost the same over the entire load range of the boilers. As an example, Good et al. (Good et al. 2006) consider walls losses as 2 % of the full load.

$Q_{unburnt}$ [–] is the chemical loss due to incomplete combustion of the wood, including solid and gaseous unburnt products; in the following, the loss due to solid unburnt products is neglected (<0.1 % according to spot ash analyses); the loss due to gaseous unburnt products is estimated following Eq. 3 proposed by Good et al. (Good et al. 2006):

$$Q_{unburnt} = \frac{CO}{CO + CO_2}\cdot\frac{11'800}{\frac{NCV_{dw}}{100} - 0.2442\cdot H_{db}}\ [-] \qquad \text{Eq. 3}$$

3.2.2. Direct method

The efficiency η is calculated following Eq. 4:

$$\eta_{direct} = \frac{E_{output\_\Delta t}}{E_{input\_\Delta t}} = \frac{E_1\ or\ E_2}{M_{wood}\cdot NCV}\ [-] \qquad \text{Eq. 4}$$

where:
$E_{output\_\Delta t}$ is the heat supplied by the boiler within the considered time step, measured by the heat meter E_1 (large boiler) or E_2 (small boiler) [kJ].

M_{wood} [kg] is the mass of wood supplied to the boiler within the considered time step, measured by the Rembe C-lever 50 (see below).

NCV is the Net Calorific Value of the wood, calculated following Eq. 5:

$$NCV = (1 - \frac{H}{100})\cdot NCV_{db} - L_v\cdot\frac{H}{100}\ [kJ/kg] \qquad \text{Eq. 5}$$

in which $H = \frac{m_{H_2 0}}{m_{wood}}\cdot 100 = \frac{H_{db}}{1 + H_{db}}\cdot 100$

is the wood moisture content [wt %], NCV_{db} the Net Calorific Value of the dry wood (18 000 kJ/kg) and L_v the latent heat of vaporisation of water (2260 kJ/kg).

The direct method is hardly used for wood boiler because the instantaneous measurement of the wood flow and moisture content is difficult to perform. In this work, an apparatus designed for the mass flow measurement of cereals by centrifugal force in food industry (Rembe C-lever 50, see Fig. 6) was tested with the woodchips used in the district heating system. The equipment was first calibrated in real conditions by comparing the value given by the flowmeter and the mass of wood really supplied. For this purpose, a scale was placed under the flowmeter and the boiler supply was forced. The calibration gave a good correlation with a deviation <3 %. Concerning the wood moisture content measurement, different sensors such as radiofrequency or infrared technologies were tested but resulted in poor correlations (deviation >20 %), as already observed by Jensen et al. in a previous study (Jensen et al. 2006); since the wood moisture content is not supposed to vary rapidly, we decided to proceed to periodic sampling (every 30 min) analysed in laboratory later on (weighing before and after complete drying in oven).

Fig. 6. Wood chips flowmeter Rembe C-lever 50 (source: Rembe GmbH).

3.3. Atmospheric emissions measurements

CO and NOx emissions were measured on both boilers over the entire load range, and the results were compared to the Swiss emission standards. The composition of the dried flue gas (CO, O_2, NO, NO_2, CO_2) was analysed using a portable analyser Testo 350XL with a sampling period of 1 min. As a calibration in real conditions, our values were compared to those obtained by the Service of Air Protection in Geneva, present on the site during our first measurement campaign: as the authority in charge of controlling emissions, their equipment is officially calibrated. The comparisons showed that: (i) O_2 concentration in the flue gas is well correlated (ii) our analyser slightly overestimates the CO concentration (+30 mg/Nm^3, <10% of the measured value) (iii) our analyser underestimates the NOx concentration (-50 mg/Nm^3, ~25% of the measured value).

3.4 Excess air determination

The excess air λ is the ratio between the quantity of air really supplied and the quantity of air necessary for a stoichiometric combustion (Eq. 6):

$$\lambda = \frac{O_{2\,measured}}{O_{2\,stoichio}} = 1 + \frac{O_2}{20.96 - O_2} \; [-] \qquad \text{Eq. 6}$$

where O_2 is the residual oxygen fraction in the dried flue gas [vol%], measured with the Testo analyser during the measurement campaigns.

Results

4.1. Impact of load on boilers operation

4.1.1. Excess air vs. load

The residual oxygen fraction in the flue gas is controlled by a setpoint value depending on the load. It is continuously measured by the lambda sensor of the boilers (O_{21} and O_{22}) and the flow delivered by the fan is adjusted to meet this setpoint. In order to ensure complete combustion, the residual oxygen fraction – and therefore the excess air – is usually set to increase when load decreases. Fig. 7 shows the excess air versus boiler load during the measurement campaigns.

For the large boiler, the excess air decreases when the load increases. For the small boiler, the variation of excess air with load is not obvious. Above 50% load, the excess air is similar for both boilers (between 1.5 and 2), which is in the range of usual recommended values (Nussbaumer 2007) but higher than the manufacturer recommendations (1.5). The values even exceed 2.5 at low load for the large boiler. This is not a single case: Good et al. (Good et al.

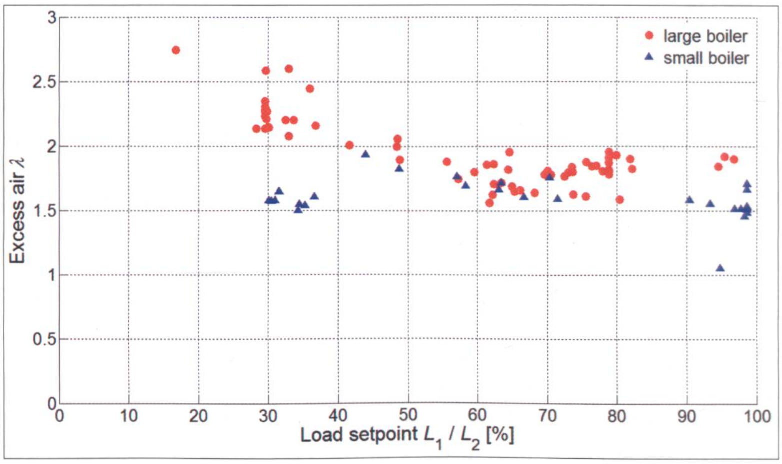

Fig. 7. Excess air versus boiler load during the measurement campaigns (hourly values).

2006) report an annual average excess air of 2.34 for a 0.35 MW wood boiler in operation in Switzerland. According to Nussbaumer et al. (IEA Bioenergy Task 32 2008), the optimal excess air value to minimise CO emissions is around 1.5, and higher values can significantly deteriorate the emissions.

4.1.2. Efficiency vs. load

The efficiency was measured over the entire load range of both boilers, with two different methods described in Section 3.2., namely indirect and direct.

The technical minimal load of the boilers is 30%, and below this value, the boilers start to oscillate between operation at 30% load and stand-by. These periods are named "ML-SB" (as mixed operation between Minimum Load and Stand-By) in the following. The monitoring showed that the boilers operate for entire days in ML-SB mode (see Section 4.2.1.).

The indirect method cannot apply in ML-SB mode (see Section 3.2.), therefore the calculation of the efficiency was only performed using the direct method during these periods. The hourly characterisation of the ML-SB mode was impossible due to the capacitive effects inside the boiler, thus daily energy values were considered for the efficiency calculation. Fig. 8 presents the evolution of efficiency versus load for both boilers. The efficiency is nearly constant over the entire load range for each boiler with both methods, whereas two phenomena were expected: (i) Deterioration of the efficiency when the load decreases due to the walls loss. The walls loss is assumed to be constant regardless the load because the walls temperature does not vary much. Considering the fixed value of 2% of the full load suggested by Good et al. (Good et al. 2006), the walls loss would raise to 4% at 50% load and 7% at 30% load. However the walls of our boilers are almost at ambient temperature thanks to their excellent insulation, thus the walls loss is negligible and does not impact the boiler efficiency (ii) Deterioration of the efficiency during ML-SB periods was also expected as observed in literature (see values below 30% load in Fig. 1), since no heat is supplied while walls and flue gas losses still exist. In our case, as stated before the walls loss is negligible, and the flue gas loss during stand-by periods is limited by switching off the air fan.

The average efficiency was calculated at 82.6% with the direct method and 84.2% with the indirect method for the large boiler, respectively 89.9% and 88.5% for the small boiler. The results obtained with both methods differ by 1.5%, but less dispersion is observed with the indirect method. For the direct method, the measurement error is 5-6% for the large boiler and 6-7% for the small boiler, while it is <1% for both boilers with the indirect method (NB: if neglecting walls and stand-by losses). Despite this high measurement error, the direct method is the only point of comparison and also the only way to characterise the ML-SB periods. Since the indirect method cannot be applied during stand-by periods, the previous studies only considered a fixed and empirical value for the calculation of the heat losses during stand-by periods.

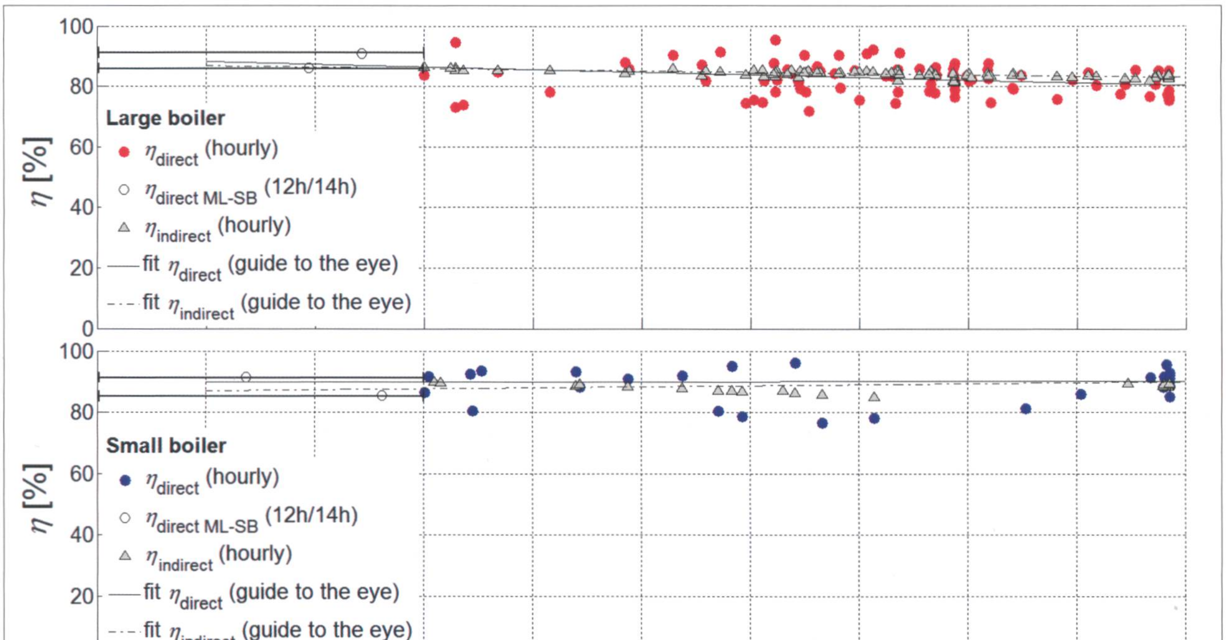

Fig. 8. Evolution of the efficiency versus boiler load, obtained during the measurement campaigns with direct and indirect methods (hourly values). Top: large boiler, bottom: small boiler.

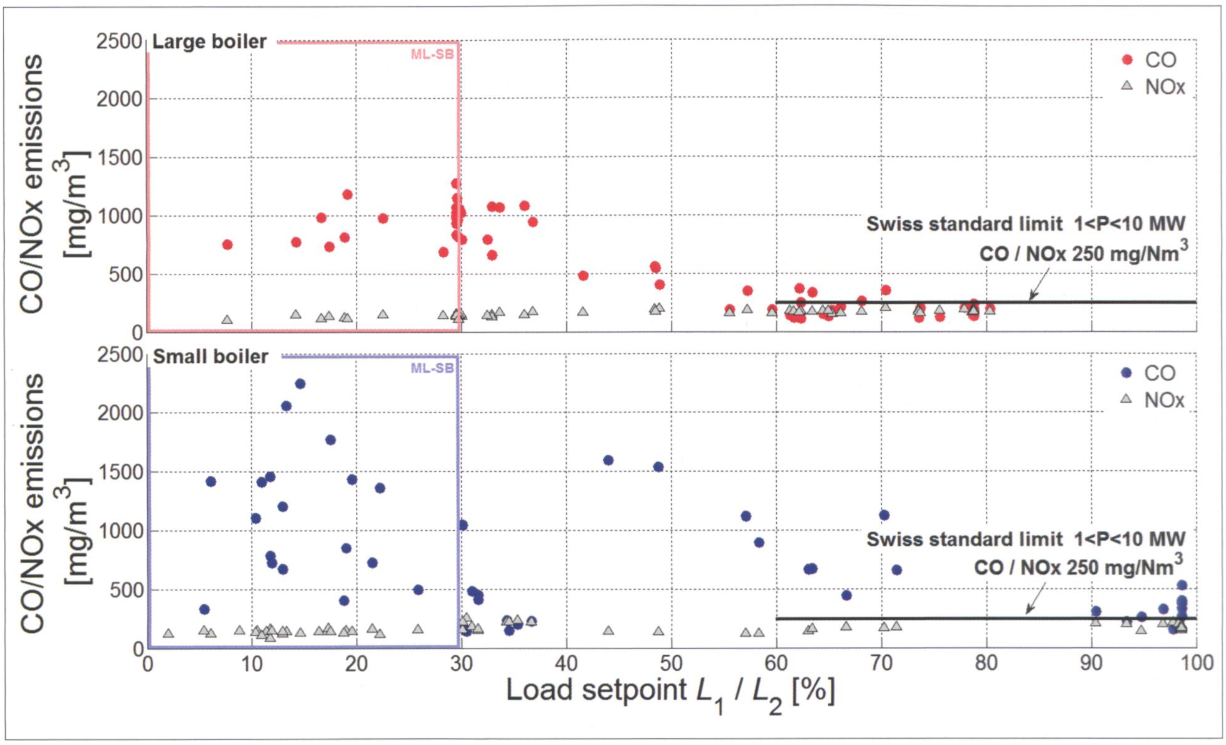

Fig. 9. Evolution of CO and NOx emissions versus boiler load, observed during the measurement campaigns and referring to 11% O_2 in the flue gas (hourly values). NOx expressed as NO_2 equivalent. Top: large boiler, bottom: small boiler.

The measured efficiencies are good and in the range of those generally announced by manufacturers for full-load operation (80-85%). It is higher for the small boiler than for the large one; according to the manufacturer, this can be due to the fact that the small boiler is standard and totally automatic while the large one is "custom-made". As indicated by the indirect method results, the sensible heat in the flue gas accounts for the majority of the losses (chemical losses due to incomplete combustion are below 0.5%).
NB: The wood moisture content is also known to influence the boiler efficiency, since more water has to be evaporated before wood combustion. However on the studied plant the wood moisture content does not vary much: it is approx. 30% (±2-3%) in summer, and mainly between 30 and 35% in winter.

4.1.3. Emissions vs. load

Fig. 9 shows the evolution of CO and NOx emissions versus load measured on both boilers. For both boilers NOx emissions do not vary with load, as observed in literature (see Fig. 4). However CO emissions strongly increase when load decreases. This result is consistent with literature (see Fig. 3) and is due to the combustion process, optimal at full capacity but deteriorated at low load. Especially the operation at low load requires an increase of the excess air to allow complete combustion, which leads to an increase of CO emissions (see Fig. 10).

NB: on Fig. 9 one can note load values below the minimal technical load of 30%. They do not refer to operation below the minimal load but concern ML-SB periods for which hourly average load value are used. During these specific periods, CO emissions are very high (especially for the small boiler), because the boilers turn on and off frequently and the combustion is incomplete when the boiler restarts. This also implies temperature fluctuations into the furnace, causing early deterioration of the boiler.

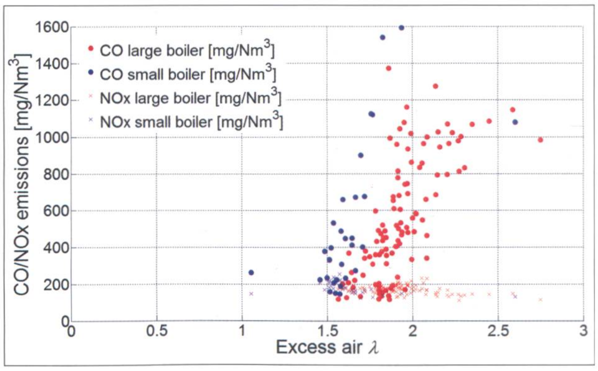

Fig. 10. CO and NOx emissions versus excess air observed during the measurement campaigns and referring to 11% O_2 in the flue gas (hourly values). NOx expressed as NO_2 equivalent.

Table 3: Energy flows measured in the system in 2011 and for a standard year.

GWh	Primary energy	Supplied heat	Users consumption
2011	6.2	5.3	4
winter	5.25	4.45	3.55
summer	0.95	0.85	0.45
Standard year	7.4	6.3	5

Regarding the regulations, NOx emissions comply with the legal limit at any time for both boilers. CO emissions are close or below the legal limit for the large boiler, but mainly above the legal limit for the small boiler (NB: this has now been corrected). It has to be noticed that in this capacity range, the Swiss standard (OPair 1985) stipulates a limit of 250 mg/Nm^3 for both CO and NOx emissions at 11% O_2 in the flue gas, which applies only above 60% load. It is assumed that boilers hardly operate below 60% load but it is not always the case, e.g. on the studied plant the boilers operate in ML-SB mode during entire days. The importance of properly size a wood boiler has to be emphasized since both emissions and boiler durability are strongly affected by operating at low load.

Fig. 10 clearly shows that CO emissions increase with the excess air for both boilers. There is an optimal excess air value to minimise CO emissions: below this value, CO emissions increase because of substoichiometric conditions and above it, reduced residence times due to high flue gas flows do not allow complete combustion. According to Nussbaumer et al. (IEA Bioenergy Task 32 2008), this optimal excess air value is around 1.5. NB: the effect of substoichiometric combustion at lower excess air values cannot be observed on Fig. 10 since the boilers never operate below 1.5.

On the contrary, NOx emissions are not affected by the excess air, whereas the latter influences the temperature into the furnace. NOx emissions are supposed to increase with the temperature into the furnace, except if it is too low to allow the thermal formation of NOx with N_2 and O_2 from the supplied air. In this case, NOx are mostly formed with the nitrogen naturally present from the wood (typically 1 wt%).

To our regret, we were not able to measure the dust emissions by ourselves since a special equipment is necessary. However, we can mention that legal emission controls were carried out on the large boiler in January 2012. During the tests, very low dust emission (<10 mg/Nm^3) were observed thanks to the electrostatic filter; CO and NOx emissions were approx. 80 and 180 mg/Nm^3 respectively; in conclusion, the large boiler fulfils the Swiss requirements in terms of atmospheric emissions.

4.2. Overall system operation

In addition to studying the impact of varying load on boiler efficiency and emissions, a comprehensive analysis of the overall system was performed.

4.2.1. Energy flows and load curves (2011)

Annual energy flows in the system are presented in Table 3. In 2011 the total heat consumption was 4 GWh and the total primary energy consumption was 6.2 GWh (5.8 of wood and 0.4 of oil). But it has to be noticed that winter 2011 was exceptionally warm, and thus 2011 is not representative of the heat demand: it is rather 5 GWh during a standard year. The boilers annual efficiency is 85%, which is a good value considering wood boiler (see Fig. 2). The overall efficiency is 68% (for a standard year). This low value can be attributed to high distribution losses (>20% of the supplied heat), due to the low linear heat density of the district heating system (0.9 MWh/m/yr). This value is much lower than the Swiss average of 4.1 MWh/m/yr (Euroheat & Power 2011), but the corresponding distribution losses are comparable to those mentioned by Good et al. (Good et al. 2005) for such linear heat densities. In summer, the distribution losses represent almost half of the supplied heat because the heat demand is very low (limited to domestic hot water production). In order to limit the distribution losses and the networks costs, the best practises (e.g. "Quality Management" label[1] in Switzerland) recommend a minimal value of 1.3 to 1.5 MWh/m/yr. Fig. 11 presents the load curves in the studied system for 2011: users consumption load, network load (supplied heat), large and small wood boiler load, oil boiler load.

The network load shows that the maximal load was around 1.6 MW in 2011, which is lower than the large boiler capacity alone. The heat capacity of the plant (2.65 MW for the wood boiler) is oversized by a factor >1.5. Fig. 11 also allows identifying the base load for domestic hot water production which is around 0.2 MW. This value is only one third of the small boiler capacity although it is especially dedicated to summer operation. The oversizing of the wood boiler results in important stand-by periods. The monitoring showed that in 2011, the large and small boilers ran in ML-SB mode (see definition in Section 4.1.2.) respectively 17% and 72% of their operating time. This is prejudicial for emissions (see Section 4.1.3.) and durability, especially for the small boiler.

This could have been avoided by mixing wood and conventional energy sources: traditionally, the wood boiler capacity is set at 50-60% of the maximum heat load of the district heating system and complemented

[1] http://www.qmbois.ch

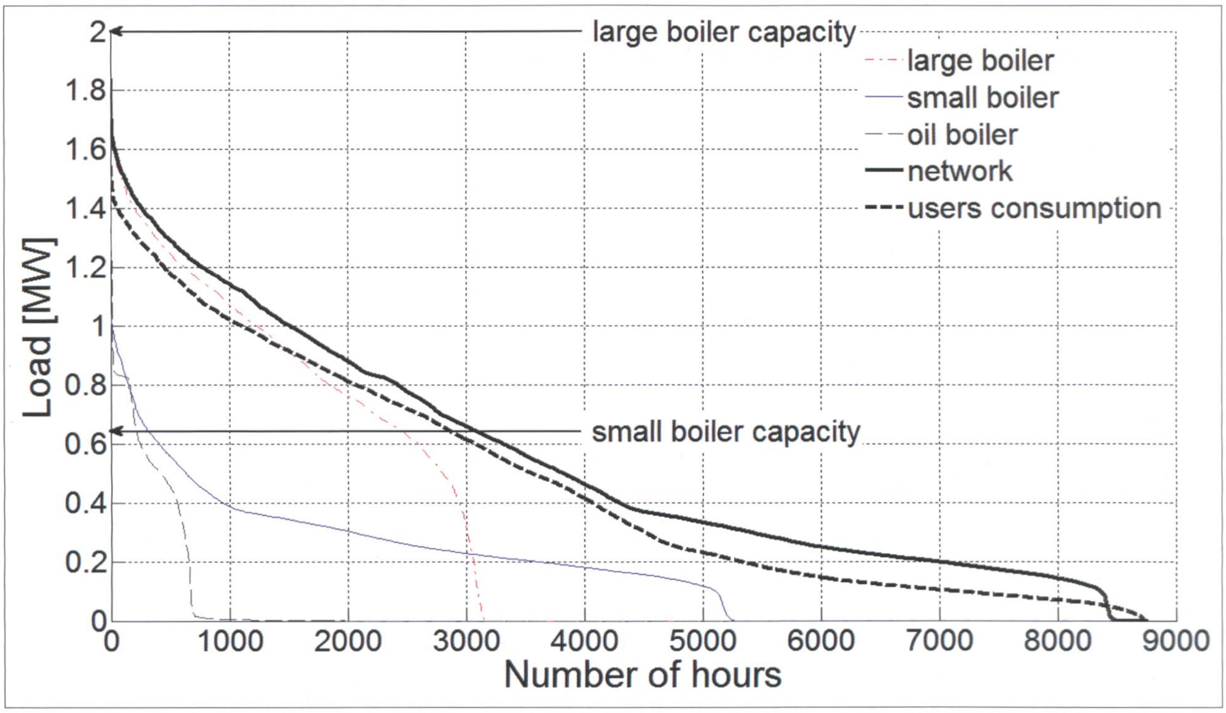

Fig. 11. Monitored load curves (hourly values for 2011): users load, network load (supplied heat), large and small wood boiler load, oil boiler load.

by a gas or oil boiler in back-up, which is approx. 10 times cheaper than a wood boiler for the same capacity. Such a sizing maximises the operation of the wood boiler at high loads, preserving its environmental performance and durability; the annual wood fraction is still >80% and the possible oversizing is covered by the conventional boiler and not by the wood boiler.

Table 4 presents the operation hours and supplied heat for the two wood boiler and the oil boiler in 2011. The large and small boilers operated respectively 3150 and 5300 h, or 1400 and 2400 equivalent full-load hours. Together they produced 93% of the supplied heat with 2000 equivalent full-load hours. For a standard year, 2400 equivalent full-load hours would be reached (but it is still low since a value of 3000 hours is considered as a minimal value for a proper sizing). The oil boiler operated almost 1000 hours in 2011 to compensate the wood boiler unavailability, producing 7% of the supplied heat. NB: in 2011, many failures occurred on the wood boiler due to necessary start-up adjustments, but did not repeat the years after.

Table 4: Operation hours of the three boilers in 2011.

	Large boiler	Small boiler	Oil boiler
Operating hours	3150 h	5300 h	800 h
Equivalent full-load hours	1400 h	2400 h	
Supplied energy	**59 %**	**34 %**	**7 %**

4.2.2. Temperature levels

Table 5 presents the average temperature levels observed on the boilers and the network for 2011 (annual and seasonal, see their location in the system in Fig. 5). The boilers output temperature is a setpoint fixed by the operator depending on the outdoor temperature and the boiler load is adjusted to meet this setpoint value. The operating temperatures are similar for both boilers, but with a supply/return temperature difference 4K higher for the large boiler. The network supply temperature is constant (~80°C all year) even in summer, when the heat demand is limited to domestic hot water. During this period, the return temperature is only 10K lower than the supply temperature, and the latter could be reduced to 70°C to limit the distribution losses in summer (almost half of the supplied heat, see Section 4.2.1.). Following our recommendation, this modification was implemented in summer 2012.

The flue gas temperature increases with the boiler load because the exchanger efficiency decreases when the flow increases. It linearly rises from 150°C at 30% load to 250°C at 80% load for the small boiler and from 170°C at 30% load to 270°C at 80% load for the large boiler. These are rather high values thus the thermal loss by sensible heat in the flue gas is important (>95% of the boilers heat losses). An economiser could have limited these flue gas losses.

Table 5: Seasonal and annual average temperatures in the system (2011).

	Annual average	Winter average (Oct.-Apr.)	Summer average (May-Sept.)
Large boiler			
Output T_{11}		84°C	
Input T_{12}		71°C	
ΔT		13K	
Small boiler			
Output T_{21}			82°C
Input T_{22}			73°C
ΔT			9K
Network			
Supply T_{31}	78°C	77°C	79°C
Return T_{32}	67°C	61°C	69°C
ΔT	11K	16K	10K

The efficiency was assessed using two separate methods (indirect and direct) which led to similar results (±1.5%). Although it is widely used, the validity of the indirect method for wood boiler had never been demonstrated before. A specific method consisting in "direct" efficiency measurements was developed in this work and corroborated the indirect method results. The latter was found to be more accurate than the direct method, however the direct method enabled to characterise the stand-by periods (which is not the case of the indirect method).

4.2.3. Electricity consumption

A wood boiler includes an important number of electrical devices for wood conveying, boiler air supply, ash extraction and dust removal. The electricity consumption of these auxiliary equipments (excluding network pumps) was measured for both boilers. For the large boiler, it linearly increases from 0.008 kWh_e/supplied kWh_{th} at 20% load to 0.013 kWh_e/supplied kWh_{th} at 80% load. For the small boiler, the electricity consumption is constant over the entire load range (0.008 kWh_e/supplied kWh_{th}).

Very little information is available in literature concerning the electricity consumption of wood boiler auxiliary equipments. The values reported in (Perdurance 2010) concern the whole plant (including network pumps), and stand between 0.02 and 0.04 kWh_e/supplied kWh_{th}. In our case, the annual average value is slightly higher at 0.046 kWh_e/supplied kWh_{th} (according to the electricity bills of the plant); this might be explained by the low linear heat density, which requires a lot of electricity for pumping in the network. According to (Perdurance 2010), the electricity for pumping in wood fired district heating systems typically accounts for 40% of the total electricity consumption. Since the linear heat density is low in our case, the share of electricity consumed by the network pumps is rather 80%.

Conclusions

The impact of varying load on efficiency and emissions of two existing wood boiler (2 MW and 0.65 MW) was characterised. The boilers efficiency was measured over significant periods of time and covering the entire load range. Contrary to what was expected, it is not depending on the boiler load (however this result cannot be generalised to all wood boiler). The values are good (83% for the large boiler and 90% for the small boiler), in accordance with those announced by the manufacturer.

The atmospheric emissions (CO and NOx) were measured over the entire load range of both boilers. NOx emissions are independent of the boiler load. On the contrary, as expected CO emissions strongly increase (by a factor 5) at low load hence the importance of maximising the operation at high load by properly sizing the wood boiler.

The monitoring of the overall district heating system showed distribution losses >20% of the supplied heat due to a network linear heat density <0.9 MWh/m/yr, whereas a minimum value of 1.3 to 1.5 is generally recommended for economic and energy reasons. The monitoring also showed that the wood boiler are oversized by a factor >1.5. As a result the small boiler, dedicated to the domestic hot water needs in summer, runs ¾ of its operating time in a mode oscillating between stand-by and 30% load, affecting CO emissions and boiler durability. To prevent from low load operation and high investment costs, the best practices suggest to limit the wood boiler capacity to 50-60% of the maximal heat load; a complementary conventional boiler (gas or oil) covers the peak demand, supplying less than 20% of the annual heat demand in energy.

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