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EFFICIENCY AND OPERATIONAL BEHAVIOUR OF SMALL-SCALE PELLET BOILERS INSTALLED IN RESIDENTIAL BUILDINGS

Elisa Carlon(a) (b) **, Markus Schwarz*(a)*, Laszlo Golicza*(a)*, Vijay Kumar Verma*(a)*, Alessandro Prada*(b)
Marco Baratieri(b)*, Walter Haslinger*(a) *and Christoph Schmidl*(a)

(a) Bioenergy 2020+, Gewerbepark Haag 3, 3250 Wieselburg Land, Austria
(b) Free University of Bozen-Bolzano, Universitätsplatz - piazza Università 5, 39100 Bozen - Bolzano, Italy
** Corresponding author*

Corresponding Author: Elisa Carlon
Address: Bioenergy 2020+, Gewerbepark Haag 3, 3250 Wieselburg Land, Austria
Email address: elisa.carlon@bioenergy2020.eu
Phone number: +43 7416 5223859 +43 6508101749

Abstract

Biomass-based heating and domestic hot water supply systems in residential buildings need optimised system design to maximise the boiler's efficiency. Although the efficiency of pellet boilers is certified through standard laboratory tests, there is only little information available in the literature about their performance in field conditions. The aims of this study were to compare the laboratory and field performance of small scale pellet boilers, and to characterise the boilers' operation in the field, finding the parameters having the strongest influence on the efficiency. This research consisted in the extensive monitoring of five pellet boilers installed in residential buildings in Austria, including new and recently refurbished houses, as well as pre-fabricated, high performance houses. Different system configurations without buffer storage tank were monitored for one year, to determine annual and monthly efficiencies. Moreover, operational parameters such as the number of completed ignitions, the hours of operation and the boiler load characterised the boilers' operational regimes in different seasons. Results showed that annual efficiencies ranged from 65 % to 85 %, thus evidencing a lower performance if compared to the 90-94 % efficiencies certified by standard laboratory tests. Efficiencies measured in field conditions were correlated to the boilers' load factors and to the number of ignitions, leading to the development of modified efficiency curves.

Highlights

- Extensive experimental monitoring on five boilers in field conditions.
- Case studies include passive and low energy houses, refurbishment, boiler exchange.
- Measured annual efficiencies in the range 65 % - 85 %
- Correct sizing and avoidance of operation during summer maximise annual efficiency
- Development of an efficiency curve based on number of ignitions and load factor

Keywords: Pellet boiler, long-term monitoring, annual efficiency, pellet consumption, load factor, ignitions

NOMENCLATURE

f_{el}	*Primary energy conversion factor for electricity [-]*
f_{pellet}	*Primary energy conversion factor for pellets [-]*
ig	*Number of ignitions [-]*
ig_{min}	*Minimum number of ignitions [-]*
K	*Parameter for the determination of the boiler's efficiency in field conditions [-]*
$LHV_{pellet,\ w.b.}$	*Lower heating value of pellets, wet based* [$kJkg^{-1}$]
R_{day}	*Number of rotations of the screw conveyor, during one day* [day^{-1}]
R_{year}	*Number of rotations of the screw conveyor, during one year* [$year^{-1}$]
m_{pellet}	*Pellet consumption of the boiler [kg]*
$m_{pellet,rot}$	*Pellet transferred to the boiler at every rotation of the screw conveyor [kg]*
$m_{pellet,day}$	*Pellet transferred to the boiler during one day* [$kgday^{-1}$]
$m_{pellet,year}$	*Pellet transferred to the boiler during one year* [$kgyear^{-1}$]
P_N	*Boiler's nominal capacity [kW]*
Q_{in}	*Energy input to the boiler [kJ]*
Q_{out}	*Energy output of the boiler [kJ]*
Q_{pellet}	*Energy input of the pellets [kJ]*
r	*Latent heat of vaporization of water* [$kJkg^{-1}$]
W_{el}	*Electricity required to operate the boiler [kJ]*
w	*Moisture content of pellets [%]*

Greek letters

β	*Load factor [%]*
β_{mod}	*Modified Load Factor [%]*
η_{direct}	*Efficiency according to EN 303-5, direct method [%]*
η_{fuel}	*Fuel conversion efficiency [%]*
$\eta_{overall}$	*Overall efficiency [%]*
τ	*Time interval for the efficiency calculation [s]*
$\tau_{avg,ig}$	*Average time of operation after one ignition [s]*
$\tau_{max,ig}$	*Maximum time of operation after one ignition [s]*
τ_{on}	*Total operation time of the boiler [s]*
τ_{sb}	*Total stand-by time of the boiler [s]*

Abbreviations

DHW	*Domestic Hot Water*
EPC	*Energy Performance Certificate*
HVAC	*Heating, Ventilation and Air Conditioning*
U_{value}	*Overall Heat Transfer Coefficient* [$Wm^{-2}K^{-1}$]

1. INTRODUCTION

The requirements of Energy Performance of Buildings Directive (EPBD) are forcing the Member States of the European Union to take actions in order to increase the energy performance of buildings [1]. Well-insulated building envelopes and high efficient energy systems contribute to reduce the consumption of primary energy. In the last years the EU residential building stock has been subjected to renovation, thus reducing its energy demand [2] [3]. As they are neutral concerning GHG emissions, HVAC systems based on renewable energy sources have excellent environmental performances [4]. In this regard, biomass is one of the most promising renewable sources. For instance, the new German energy policy highlights that biomass is expected to cover two thirds of Germany's renewable energy production by 2020 [5].

One of the challenges in the buildings′ sector is to optimize HVAC systems for recently renovated buildings and for new buildings. The components of heating and hot water supply systems shall be suitable for different types of installations, as for example the replacement of one or more components either in existing buildings, or in recently refurbished buildings and in new, high performing buildings. Among heating devices, pellet boilers are one of the renewable-based alternatives to gas and oil boilers. In Austria, where the population has high environmental awareness and biomass is a local resource, pellet boilers are particularly widespread [6] [7]. Pellet boilers can completely cover the heating and DHW demands or can be installed in combination with other technologies, such as solar collectors [8]. Thanks to their technological development during the last 20 years, pellet boilers ensure high efficiency, load modulation, and a high degree of automation [9]. Moreover, the environmental performance of boilers having low emissions is certified in the frame of several national and international labelling schemes [10]. Efficiency and emission factors of pellet boilers are determined by means of standard laboratory tests carried out in stationary conditions [11] [12] [13]. Several recent studies aimed at reproducing in the laboratory the real life operating conditions, by means of dynamic tests. Wim et al. [14] determined the gaseous and particulate emissions of pellet heating systems adopting a six day operation sequence. Haberl et al. [15] developed a concise cycle test to evaluate in a laboratory the performance of a combined systems. Carlon et al. [16] tested two pellet boilers by means of a 8-hour load cycle test. Tests results were then used to calibrate and validate a TRNSYS boiler model. While several studies focussed on laboratory tests, there is only little information available about the performance of pellet boilers in field conditions.

Chasapis et al. [17] monitored for six months a solar-biomass heating system installed in an office in Greece. Their results showed the importance of correctly sizing the pellet boiler and the hot water storage tank, and of correctly setting the system controls. Similar conclusions were drawn by Fiedler et al. [18], who monitored a water-jacketed pellet stove combined with solar collectors. Their findings evidenced how a buffer storage tank helps to reduce the ignitions. Zandeckis [19] et al. monitored a solar and pellet combisystem in an apartment building and improved the boiler's efficiency by adjusting its operational parameters based on the results of laboratory tests. Hartl et al. [20] monitored three hot water storage tanks, equipped with integrated pellet burners, installed in single family houses in Austria. Successively, a simulation study was performed to optimise the system's controls [21]. Verma et al. [22] measured emission factors and efficiencies of pellet boilers at the test stand and during short-term field measurements. They found lower efficiencies in real life conditions (2–5% less) than in standard laboratory conditions. Schraube et al. [23] monitored several pellet boilers installed in residential buildings in South-West Germany. The majority of the monitored boilers had efficiencies around 70 %, which were much lower than the values certified by standard type tests. Annual efficiencies in the range from 70 % to 81 % were measured by Kunde et al. [24], who monitored several central heating pellet boilers installed in Germany. Their results showed that appropriate sizing and system controls are essential to increase efficiency and reduce emissions. Both Schraube et al. [23] and Kunde at al. [24] suggest that, in field conditions, the non-stationary operation of the boilers and the frequent ignitions reduce their efficiency. However, efficiencies measured in these studies were not correlated to the boiler's operational parameters. Moreover, previous studies mainly consider systems equipped with a buffer storage, investigating its heat losses and improving its controls. No study was done yet with a specific focus on systems without buffer storages, which are recommended by several boiler manufacturers and heating installers in Austria.

The aims of this study were to compare the laboratory and field performance of small scale pellet boilers (in particular with respect to the annual efficiency), and to characterise the boilers' operation in the field, finding the parameters having the strongest influence on the efficiency.

The research consisted in the extensive monitoring of five pellet boilers installed in residential buildings in Austria. Only heating systems without buffer storage tank were chosen, in order to determine the boiler's efficiency in this system configuration, which was not extensively investigated yet in the existing literature. The monitored houses were representative of different building categories: the boiler exchange in existing buildings and in recently refurbished buildings, as well as the installation of pellet boilers in new buildings, including pre-fabricated, high performing houses. The boilers were monitored for one year (long-term monitoring), to determine their annual and monthly efficiencies and to characterise their operational regimes in different seasons. Moreover, the operational parameters influencing the boiler's efficiency were identified and correlated to the efficiency, leading to the development of efficiency curves which characterize the boiler's performance in field conditions.

2. MATERIALS AND METHODS

2.1 Pellet boilers under investigation

All the pellet boilers monitored in this study were manufactured by the Austrian company Windhager Zentralheizung Technik GmbH [27] and were sold after 2010. During the monitoring period, all boilers were supplied with pellets from the same producer [28]. Pellets are stored in steel sheet silos and loaded via pneumatic conveyer tubes into the boiler's hopper, or they are bought in bags and loaded manually. A screw auger brings the pellets from the hopper into the top-fed burner pot, made of high-temperature-resistant stainless steel and equipped with automatic ignition and automatic ash removal. A speed controlled vacuum fan regulates the primary and secondary air supply. The control concept of the combustion process is based on the flue gas temperature, directly measured at the exit of the combustion chamber. This thermo-controlled concept, developed to increase the efficiency during operation at part load, is used to modulate the power output of the boilers between 30 % and 100 % of their nominal capacity.

Two models, i.e. VarioWIN and BioWIN pellet boilers were investigated.

VarioWIN boilers, available with nominal capacities of 6 and 12 kW, have low space requirements. Moreover, hydraulic elements such as circulation pump and mixing valves can be directly integrated into the boiler body. VarioWIN boilers can also be installed without a hopper. In this case, a direct dosing auger transfers the pellets from the pellet storage directly into the top-fed burner. A small water accumulation tank (45 litres) can be optionally added on the top of the boiler, to reduce the number of ignitions. Because of the low space requirements (a floor area of 0.45 m^2 and a height of 1.26 m), VarioWIN boilers do not need a separate room.

BioWIN boilers are available with nominal capacities of 9.9, 15, 21 and 26 kW. In comparison to VarioWIN boilers, they have larger bodies and larger ash boxes which requires a less frequent maintenance. BioWIN boilers are always installed with hoppers and no hydraulic elements are integrated into the boiler body, resulting in higher space requirements (0.95 m^2 floor area and 1.65 m height). Therefore, BioWIN boilers are usually placed in a separate rooms, with the water distribution system mounted on the walls. This study included also a BioWIN 2 boiler, the new version of the BioWIN boiler, designed to reduce its space requirements, weight and costs. The BioWIN 2 boiler is equipped with an innovative ignition element, a stainless steel burner with low-dust technology and a new automatic cleaning system.

In compliance with EN 303-5 [12] the boilers' efficiencies had been certified by means of standard laboratory tests, performed at nominal load and part load (30% of the nominal load). According to the "direct method" (Eq (1)), efficiencies were calculated as the ratio of the delivered useful heat output (Q_{out}) to the pellet's energy input (Q_{pellet}), within a tolerance threshold of ± 3 %.

$$\eta_{direct} = \frac{Q_{out}}{Q_{pellet}} \cdot 100 \tag{1}$$

As reported in Eq. (2), Q_{pellet} is defined as the product of the mass of pellet consumed during the tests and the pellet's lower heating value (wet based).

$$Q_{pellet} = m_{pellet} \cdot LHV_{pellet,w.b.} \tag{2}$$

Test results showed that at nominal load, efficiencies ranged from 90 % to 94 % while at part load, efficiencies ranged from 91 % to 93 % (with the exception of the 6 kW VarioWIN boiler, which had a lower performance at part load). The high efficiencies certified by standard type tests show that the boilers are optimised for stationary operation both at maximum and minimum load.

2.2 Monitoring sites

The five monitoring sites are located in the Austrian regions of Lower Austria and Salzburg (Figure 1), and are subject to a rather uniform climate, especially the heating degree days (referred to an indoor temperature of 20°C) range from 3500 to 3700 in all the locations [25]. Outdoor design temperatures, used to size the heating system according to EN 12831 [26], range from –13 °C to –16 °C.

None of the monitored heating systems has a buffer storage tank, therefore the pellet boilers are directly connected to the heat distribution systems (floor heating and radiators). The boilers fulfil completely the heat demand of the houses, whereas additional heating devices, if present, are only used to support DHW production. As an example, Figure 2 shows a scheme of the heating and DHW supply system of one monitoring site (Site 2).

A questionnaire answered by the house owners provided general information about the houses (heated volume, type of construction, recent renovations etc.) and Energy Performance Certificates (EPC) were provided when available. The characteristics of the monitoring sites are summarized in Table 1 and Table 2 and described in the next paragraphs.

Site 1: The pre-fabricated passive house at Site 1 was built in 2010. The external lightweight walls ensure a high thermal insulation (U_{value} 0.11 $Wm^{-2}K^{-1}$) and the triple-glazed windows have a U_{value} of 0.79 $Wm^{-2}K^{-1}$. The house is heated by a 12 kW pellet boiler The ventilation system, manufactured by the company Nilan A/S [29], is equipped with a an active heat recovery unit, where an air-source heat pump is used to pre-heat inlet airflow. Moreover, the heat pump is used for DHW production in combination with the pellet boiler.

Site 2: The house, built in 2012, is a pre-fabricated single family house. The external lightweight walls have a heat transfer coefficient of 0.14 $Wm^{-2}K^{-1}$ and all the windows are triple glazed (U_{value} 0.84 $Wm^{-2}K^{-1}$). The annual heat demand of the house (30 $kWhm^{-2}$) fulfils the Austrian standard requirements for Low Energy Houses [30]. A 6 kW pellet boiler supplies hot water to the floor heating system and to the DHW storage tank. Hot water production is also supported by solar collectors. The living room is heated by a briquette stove.

Site 3: The semi-detached house was built in 2004 and is currently inhabited by two people. The external walls are made of concrete (30 cm thickness) and are insulated by an insulation layer of expanded polystyrene (EPS), which reduces the U_{value} to 0.18 $Wm^{-2}K^{-1}$. All the windows are double glazed. The house, heated by a 9.9 kW pellet boiler, does not have additional heating devices, therefore the pellet boiler covers completely the heating and DHW demands.

Site 4: The two-family house was constructed in the 18th century and renovated three times (1950, 1985 and 2012). In 2012 the old boiler was changed with a new pellet boiler and part of the house was renovated by changing the windows and insulating the internal ceilings. The total heated surface is 305 m^2, of which 120 m^2 are refurbished. A 26 kW pellet boiler supplies hot water to the radiators, to the floor heating system and to the hot water storage tank. DHW production is also supported by solar collectors.

Site 5: The two-family house was built in 1963. Minor renovations were carried out in 1990 when windows were replaced and internal ceilings were insulated. In 2012, the old oil boiler was replaced with a 21 kW pellet boiler, which supplies hot water to the floor heating system and to the radiators. The boiler is also used for DHW production in combination with solar collectors.

Site number	Location coordinates	Elevation [m ASL]	Construction Type	Building type	Heated volume [m^3]	Annual heat demand according to EPC [kWhm^{-2}year^{-1}]	Number of inhabitants	Heat distribution system
Site 1	48°11′ N 16°05′ E	315	Lightweight (pre-fabricated)	New building (Passive house)	627	14	4 (2 adults, 2 children)	Floor heating
Site 2	48°11′ N 15°05′ E	230	Lightweight (pre-fabricated)	New building (Low Energy House)	450	30	2 (adults)	Floor heating
Site 3	47°57′ N 13°12′ E	561	Heavyweight	New building	410	67	2 (adults)	Floor heating and radiators
Site 4	48°00′ N 15°10′ E	339	Heavyweight	Renovated house	825	170	6 (4 adults, 2 children)	Floor heating and radiators
Site 5	47°5′ N 13°04′ E	548	Heavyweight	House built in 1963	500	Not available	Not available	Floor heating and radiators

Table 1: Key information on the monitored houses

Site number	Additional devices for DHW production	Additional devices for space heating	Boiler's nominal capacity [kW]	Boiler	Pellet feeding system	Volume of DHW storage tank [m^3]
Site 1	Heat Pump	Heat Pump	12.0	VarioWIN	Manual feeding	0.16
Site 2	Solar collectors	Briquette stove	6.0	VarioWIN	Pneumatic	0.50
Site 3	Not present	Not present	9.9	BioWIN	Pneumatic	0.30
Site 4	Solar collectors	Not present	26.0	BioWIN	Pneumatic	0.50
Site 5	Solar collectors	Not present	21.0	BioWIN 2	Pneumatic	0.80

Table 2: Key information on the heating and DHW supply systems

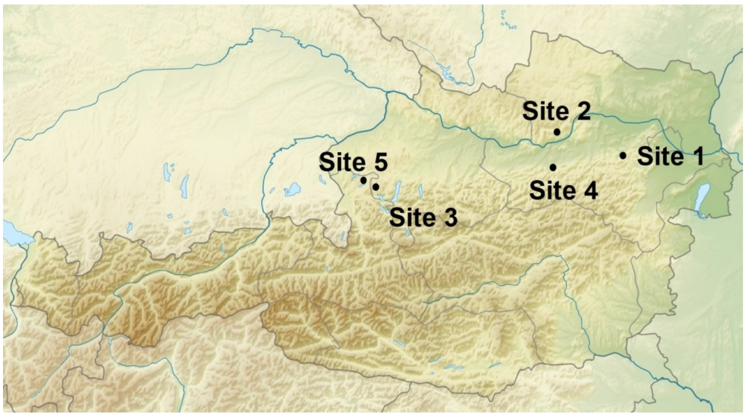

Figure 1: Location of the monitored houses

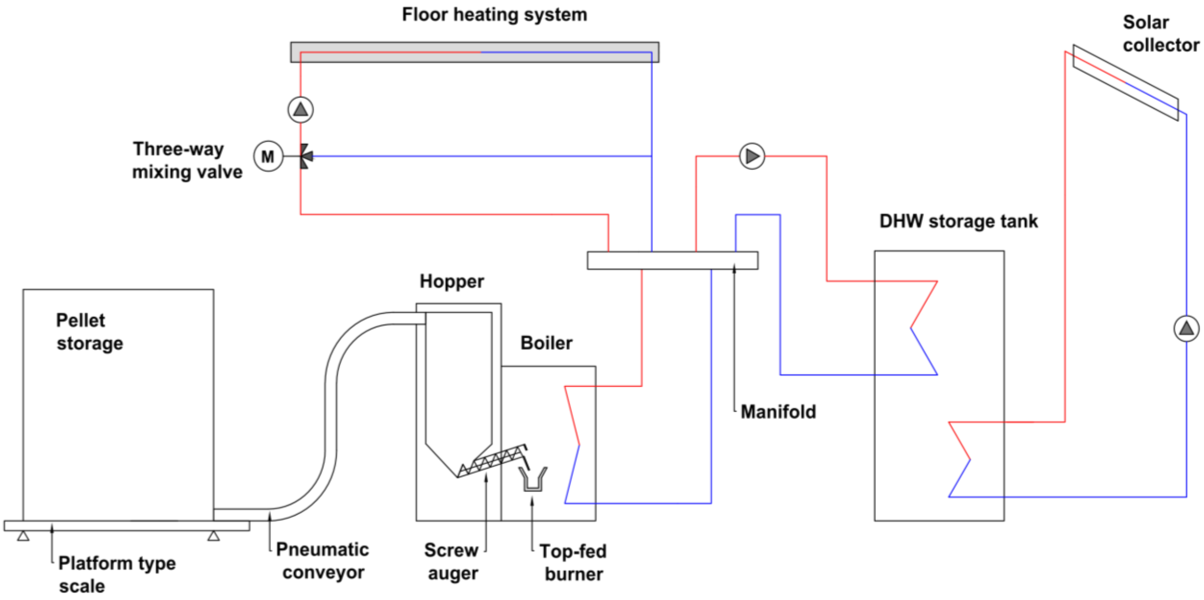

Figure 2: Scheme of the heating and DHW supply system at Site 2

2.3 Efficiency in field conditions

The pellet boilers were monitored for one year, starting in June 2013 and ending in May 2014. The monitoring period of one year was chosen to determine both the annual and monthly boiler efficiencies, and to characterise the boiler operation in different seasons. The efficiency was calculated according to the European Standard EN 15316-Part 1 [31], which defines the efficiency of a heat generation system ($\eta_{overall}$) as the ratio between its energy output (Q_{out}) and its energy input (Q_{in}). The energy inputs of a pellet boiler are represented by the pellets (Q_{pellet}) and by the electric energy (W_{el}) required to operate the boiler (for fuel supply, pellet ignition, forced draught fan, cleaning installations). Both the terms Q_{pellet} and W_{el} are multiplied by their primary energy conversion factors (f_{pellet} and f_{el}, as shown in Eq (3)), determined nationally by every Member State. For Austria, values of f_{pellet} and f_{el}, equal to 1.08 and 1.89 respectively, were proposed by the Austrian Energy Agency [32]. The conversion factor of pellets includes the energy required for the pelletisation process and for the transport.

$$\eta_{overall} = \frac{Q_{out}}{Q_{in}} \cdot 100 = \frac{Q_{out}}{f_{pellet} \cdot Q_{pellet} + f_{el} \cdot W_{el}} \cdot 100 \tag{3}$$

The European Standard EN 15316-Part 1 [31] defines also a second indicator of the boiler's performance, which is the fuel conversion efficiency (η_{fuel}). For pellet boilers, η_{fuel} is defined as the ratio between Q_{out} and Q_{pellet} (Eq (4)).

$$\eta_{fuel} = \frac{Q_{out}}{Q_{pellet}} \cdot 100 \tag{4}$$

As it does not account for the electricity consumption and for the primary energy conversion factors, the fuel conversion efficiency is comparable to the efficiency measured in standard type tests according to the direct method (η_{direct}, Eq (1)).

In this study both the overall efficiency ($\eta_{overall}$) and the fuel conversion efficiency (η_{fuel}) of the monitored boilers were calculated from the monitoring data.

2.4 Measurements and data acquisition

2.4.1 Parameters for the determination of the efficiency

To calculate the efficiency, the heat output of the monitored boilers (Q_{out}) and their electricity consumption (W_{el}) were measured using heat and electricity meters. The heat meters were Diehl "Sharky 775 compact" ultrasonic heat meters having a class 2 accuracy according to EN 1434 [34]. The electricity consumption was measured using Janitza "UMG 604" power analysers, having a class 0.5 accuracy according to IEC 62053-11 [35]. The pellet consumption (m_{pellet}) was determined with different methods, depending on the feeding system:

- At **Site 1** pellets were bought in plastic bags (each one containing 15 kg of pellets) and manually refilled into the boiler's hopper. The house owners recorded the date of every refill and the number of bags filled.
- At **Site 2** and **Site 5** a Bosche load cell, having a C3 Class accuracy according to OIML 60 [36], was installed under the pellet silo. The weight loss of the silo, recorded every 10 seconds, determined the pellet consumption.
- At **Sites 3** and **Site 4** the house owners organised pellet transports to refill the pellet silos when needed. The pellet producer documented all the delivery dates and the delivered pellet quantities.

At **Sites 1, 2** and **5** daily pellet consumptions could be exactly calculated, while at **Sites 3** and **4** the documentation about the pellet deliveries was only sufficient to determine the overall annual consumption. To calculate pellet consumptions with a higher time resolution, the rotations of the screw auger which brings pellets to the burner were recorded every 10 seconds. Successively, the average mass of pellet transported at every rotation of the screw conveyor ($m_{pellet,rot}$), was calculated as the ratio between the annual pellet consumptions ($m_{pellet,year}$) and the total number of rotations during the whole year (R_{year}, Eq (5)).

$$m_{pellet,rot} = \frac{m_{pellet,year}}{R_{year}} \tag{5}$$

Daily pellet consumptions were obtained by multiplying the values of $m_{pellet,rot}$ and the number of rotations per day (R_{day}, Eq. (6)) Although the mass of pellets transported at every rotation of the auger can vary, in particular depending on the pellet size, the use of an average value of $m_{pellet,rot,}$ allowed to maintain a reliable reference to the overall annual consumption.

$$m_{pellet,day} = m_{pellet,rot} \cdot R_{day} \tag{6}$$

At the beginning of the monitoring period, a set of pellet samples was provided by the same pellet producer who also supplied all the monitored houses. The chemical composition and heating value of the pellet samples were determined according to the testing standards reported in Table 3. Considering that all the houses are supplied with EN*plus* [37] certified pellets coming from the same production site [28], where only locally available wood is used, the dry based lower heating value resulting from the laboratory analysis (18.85 MJ/kg) was assumed as common reference value for all the monitoring sites.

During the monitoring period, three additional pellet samples were taken at every house and their moisture content was determined according to EN 14774-1 [38]. The wet based lower heating values were then calculated based on the moisture content of pellet samples taken from each house (Table 4).

Parameter	**Unit**	**Value**	**Testing standard**
C	% wt $_{(d.\ b.)}$	50.01	EN 15104 [40]
H	% wt $_{(d.\ b.)}$	6.18	EN 15104 [40]
O	% wt $_{(d.\ b.)}$	43.37	by difference
N	% wt $_{(d.\ b.)}$	0.06	EN 15104 [40]
S	% wt $_{(d.\ b.)}$	< 0.01	EN 15289 [41]
Cl	% wt $_{(d.\ b.)}$	< 0.01	EN 15289 [41]
Ash content	% wt $_{(d.\ b.)}$	0.38	EN 14775 [42]
HHV	MJkg^{-1} $_{(d.\ b.)}$	20.20	EN 14918 [39]
LHV	MJkg^{-1} $_{(d.\ b.)}$	18.85	EN 14918 [39]

Table 3: Dry based pellet composition and heating value resulting from the laboratory analysis (wt= weight , d.b.=dry based)

Site number	**Average moisture content of pellet samples** w-% $_{(w.\ b.)}$	**Pellet LHV** MJkg^{-1} $_{(w.\ b.)}$
Site 1	7.96	17.16
Site 2	5.76	17.63
Site 3	6.20	17.53
Site 4	6.71	17.42

Site 5	6.63	17.44

Table 4: Average water contents and lower heating values of the pellets at each site

2.4.2 Parameters characterising the boiler's operation

In addition to the data necessary to calculate efficiency, the parameters characterising the boiler's operation were continuously monitored during the whole year.

The hours of operation and the number of completed ignitions were both logged as cumulative values in the boiler's control unit. Additional data available from the boiler's control unit were the current boiler load and power output, as well as the boiler state (ignition phase, flame stabilisation, load modulation, burnout, or stand-by). All measurement data were recorded every 10 seconds by means of a PC-based data acquisition system connected to the boiler's-internal data transmission system.

3. RESULTS AND DISCUSSION

3.1. Annual and monthly efficiencies

3.1.1 Annual efficiencies

For all monitoring sites, monthly and annual efficiencies were calculated based on the measured heat productions, electricity consumptions and pellet consumptions (Table 6). Overall annual efficiencies ($\eta_{overall}$) ranged from a minimum of 54.8 % to a maximum of 77.4 %, while fuel conversion efficiencies (η_{fuel}) were comprised between 66.8 % and 85.5 %. (Table 5). Overall efficiencies describe the boiler's performance in relation to primary energy use, while fuel conversion efficiency characterises the boiler technology.

The maximum efficiencies were found at **Site 4** (renovated house) and the minimum efficiencies at **Site 1** (passive house). The two VarioWIN boilers, installed in pre-fabricated houses, have annual conversion efficiencies of 66.8 % and 74.3 %. The three BioWIN boilers, installed in heavyweight buildings, had annual conversion efficiency, in the range 83 - 85 %, significantly higher than those found in previous studies of Kunde et al. [24] and Schraube et al. [23]. The majority of their monitored installations in Germany showed annual conversion efficiencies in the range 70 - 75 %. The better performance of the BioWIN boilers was achieved thanks to their capability to quickly adapt to transient operation regimes at different loads, together with a correct boiler sizing and good system design, suited to the heat demand of the houses.

As already mentioned in Section 2.3, the definition of the boiler's efficiency according to the direct method (Eq. (1)) is equivalent to the fuel conversion effieciency (Eq. (4)). Therefore the comparison of standard type tests results and annual fuel conversion efficiencies measured at the monitoring sites quantifies the difference between the boiler's performance in the laboratory and in the field. While standard type tests are performed in stationary conditions, the field operation is characterised by time-variable loads and by frequent starts and stop sequences. For the boilers monitored in this study, the deviation between the laboratory and field performance ranged from 7 to 25 percentage points (Figure 4: Annual pellet consumptions per heated volume
).

The boiler showing the major difference between overall efficiency and fuel conversion efficiency is the one at **Site 1** (Table 5). As shown by Eq. (3) and Eq. (4), a higher electricity consumption results in a higher difference between η_{fuel} and $\eta_{overall}$. At Site 1, the measurement of the electricity meter included not only the electricity consumed by the boiler itself but also the consumption of other devices that are part of the distribution system, such as the circulation pump. Consequently, the annual electricity consumption was 6.8 % of the total energy consumption, whereas for the other Sites it was always below 4 %.

Site number	Boiler	Boiler's nominal capacity [kW]	Overall annual efficiency [%]	Fuel conversion efficiency [%]	Annual pellet consumption [kg]	Annual hours of operation [h]
Site 1	VarioWIN	12.0	54.8	66.8	1095	1024
Site 2	VarioWIN	6.0	66.6	74.3	2277	2244
Site 3	BioWIN	9.9	71.7	83.3	3141	2309
Site 4	BioWIN	26.0	77.4	85.5	9300	3730
Site 5	BioWIN 2	21.0	76.6	85.1	3567	1976

Table 5: Boilers'annual efficiencies, pellet consumption and hours of operation

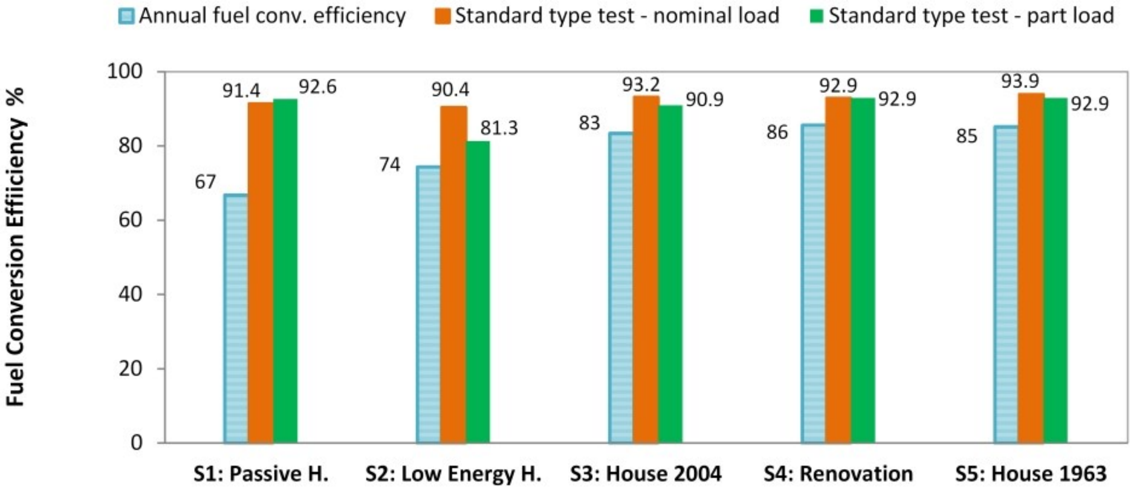

Figure 3: Comparison of the boilers' performances at the test stand and in field conditions

3.1.2 Annual pellet consumption

The pellet consumption of the monitored boilers comprises the pellet consumed to heat the houses and the pellet consumed for DHW production. The heat demand, representing the most important share during the winter season, depends on the heated volume, on the aspect ratio, on the insulation level, and on the control strategy of the heating system. The DHW demand mainly depends on the number of inhabitants and maintains a constant profile (usually represented by daily or weekly schedules) throughout the whole year [43].

As reported in Table 5, the lowest annual pellet consumption was found at **Site 1**, where the passive house has a very low heat demand. Moreover a heat pump is used for DHW production and to pre-heat the inlet air flow of the ventilation system. This system configuration additionally reduces the demand which has to be covered by the boiler, leading to the lowest pellet consumption per heated volume of all the monitored sites (1.75 kgm^{-3}, Figure 4) and to minimum annual operating hours (1024, Table 5).

The highest pellet consumption (approximately 9 tons) was measured at **Site 4** (renovated house). Here the low insulation level of the building envelope is combined with a 850 m^3 heated volume (two-family house), resulting in a pellet consumtion per heated volume of 11.3 kgm^{-3}. Moreover, the boiler was controlled based on the outdoor temperature: during winter, when the outdoor temperature decreased, the boiler tended to operate continuously, resulting in the highest number of operating hours of all sites (3730).

The pellet consumptions per heated voluem of the remaining sites (Sites 2, 3 and 5) were all comprised between 5 and 8 kgm^{-3}.. In particular, **Site 3** represents a unique case study: this house has a low heat demand thanks to its relatilvely small heated volume (410 m^3) and its good insulation level. However, because the pellet boiler is the only heating device in the system, it has a high pellet demand for DHW production. For instance, in the time period between 15th June 2014 and 15th September 2014, the boiler operated exclusively to heat the DHW storage tank, with a total pellet consumption of 215 kg. In the same time period, the maximum pellet consumption found in the other monitored systems, having a second heating device supporting DHW production, was 18 kg (one twelfth of the consumption at Site 3).

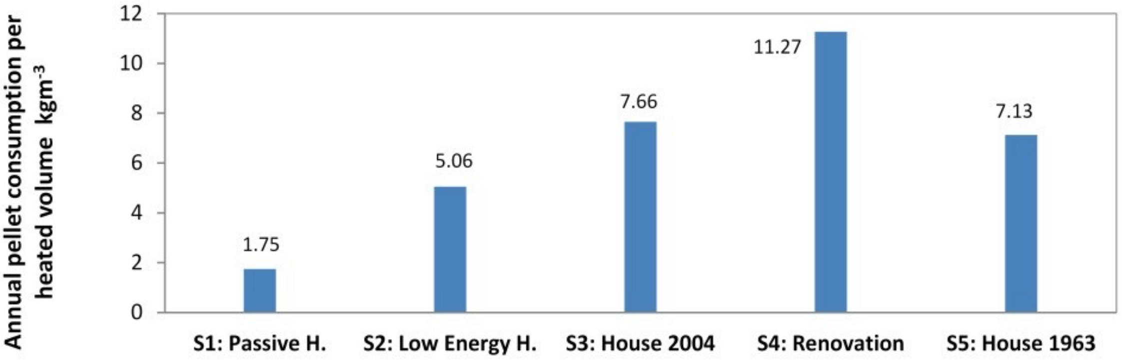

Figure 4: Annual pellet consumptions per heated volume

3.1.3 Monthly efficiencies

Monthly efficiencies, reported in Figure 5, characterise the boilers' performance in different seasons. The maximum fuel conversion efficiency was 92 %, and was measured at **Site 4** (renovated house), in January 2014. In this month the efficiency in field conditions almost reached the value certified during standard type tests. The lowest monthly efficiencies were found at **Site 1** (passive house), where the boiler operated for the lowest number of hours. For instance, in December 2013, the boiler at Site 1 operated for an average time of 6 hours/day, while operation time of the boiler at **Site 4** was three times higher (18 hours/day on average).

At all monitoring sites, the highest monthly efficiencies were found during the winter season. In particular, from September 2013 to April 2014, all the BioWIN boilers, monitored at Sites 3, 4 and 5 had fuel conversion efficiencies above 80 %. During winter the boilers had the longest operation times and highest pellet consumption, therefore the winter months represent the most important contribution in the calculation of the annual efficiency; as reported in Table 6, the pellet consumption from November 2013 to March 2014 was in the range 75 % - 85 % of the annual pellet consumption for all the monitoring sites.

During summer, the only boiler operating for a significant number of hours was the one installed at **Site 3**, where the boiler is the only heating device in the house. As during summer the house was not heated, the boiler was used only to heat the DHW storage tank. This operational regime was characterised by short-time ignitions especially in July and August, when the boiler ignited once per day and successively operated for 1-2 hours. Monthly efficiencies measured during summer were below 70 % (Figure 5) and were much lower that the efficiencies in the winter months.

Concerning **Site 2** (low energy house), during summer the house owners set the control unit of the boiler to "summer mode". With this option, the boiler is used to heat the DHW storage tank if the heat produced by the solar collectors is not sufficient to maintain the water temperature in the tank above the set value. Measurements show that, during July and August, the boiler ignited only 4 times and operated for 7 hours in total, with a pellet consumption of 34 kg (Table 6). This intermittent operation resulted in a low fuel conversion efficiency of 31 % in July and 43 % in August. However, the contribution of these months to the overall annual efficiency is almost negligible: the total pellet consumption of July and August was only 0.32 % of the annual pellet consumption and the heat production was 0.15% of the annual heat production. Consequently, the low efficiencies in the summer months did not affect significantly the overall annual conversion efficiency (74.3 %). At **Sites 4** and **5**, the house owners manually turned the boilers to stand-by mode in July (and in August at Site 5). The DHW storage tanks were heated only by the solar collectors, and no efficiency was defined for the pellet boilers. Also at **Site 1**, the boiler remained in stand-by mode during July and August, when DHW was entirely supplied by the heat pump.

Altogether, monitoring results show that the summer months are characterised by short-time operation cycles and have a negative influence on the annual efficiency, especially for systems in which the boiler is the only heating device, used for both heating and DHW production. In this perspective, the integration of a second heat generation system in the system, such as solar collectors or heat pumps, is advantageous, because it reduces the boiler’s operation time during summer, thus increasing the overall annual efficiency.

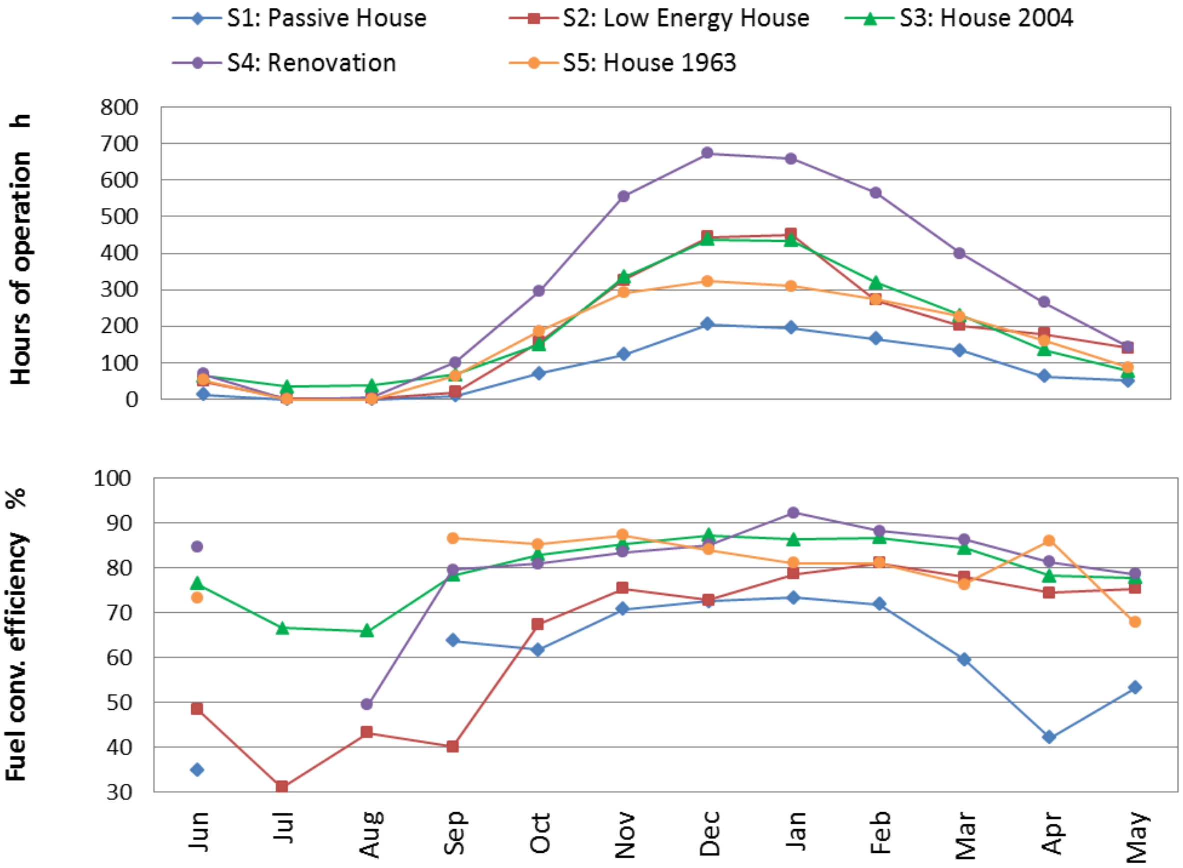

Figure 5: Monthly efficiencies and hours of operation

		June	July	August	September	October	November	December	January	February	March	April	May	***Annual Total***
Site 1	Fuel consumption [kg]	14	0	0	10	78	118	229	211	189	135	64	47	***1095***
	Electr. consumption [MJ]	60	53	53	60	93	140	203	197	175	158	97	82	***1371***
	Heat production [MJ]	86	0	0	104	828	1429	2851	2650	2326	1382	464	428	***12550***
	Hours of operation [h]	12	0	0	*9*	*71*	*122*	*205*	*195*	*165*	*133*	*63*	*50*	***1025***
	Number of ignitions [-]	9	0	0	7	38	37	97	104	92	74	41	28	***527***
Site 2	Fuel consumption [kg]	76	3	4	25	167	350	470	430	265	206	147	135	***2277***
	Electr. consumption [MJ]	34	19	19	26	57	90	103	107	96	77	61	60	***751***
	Heat production [MJ]	648	18	29	176	1987	4651	6026	5951	3784	2822	1922	1778	***29794***
	Hours of operation [h]	50	3	3	19	157	326	445	450	271	203	179	140	***2244***
	Number of ignitions [-]	18	2	2	15	46	67	80	82	62	42	37	36	***489***
Site 3	Fuel consumption [kg]	118	71	70	121	242	421	494	489	396	312	253	152	***3141***
	Electr. consumption [MJ]	125	78	98	147	200	261	293	289	257	259	195	157	***2358***
	Heat production [MJ]	1580	832	803	1667	3521	6300	7560	7398	6016	4619	3470	2077	***45842***
	Hours of operation [h]	73	41	43	77	165	323	405	403	299	238	150	92	***2309***
	Number of ignitions [-]	55	34	32	55	114	162	180	173	153	141	103	72	***1274***
Site 4	Fuel consumption [kg]	163	0	10	277	784	1283	1662	1571	1300	1089	736	425	***9300***
	Electr. consumption [MJ]	63	16	20	100	239	223	329	253	225	269	217	135	***2091***
	Heat production [MJ]	2408	0	86	3845	11052	18648	24660	25243	19987	16373	10426	5782	***138510***
	Hours of operation [h]	69	0	4	100	296	555	674	658	566	400	265	144	***3730***
	Number of ignitions [-]	56	0	4	87	233	148	171	154	142	248	205	118	***1566***
Site 5	Fuel consumption [kg]	79	0	0	98	262	480	622	724	583	448	230	35	***3567***
	Electr. consumption [MJ]	43	14	14	45	97	125	142	132	112	119	109	68	***1019***
	Heat production [MJ]	1030	0	0	1508	3910	7499	9223	10343	8323	5944	3316	1739	***52834***
	Hours of operation [h]	53	0	0	65	187	292	323	310	272	228	161	87	***1976***
	Number of ignitions [-]	41	0	0	41	113	142	143	115	100	119	n. a.	n. a.	***814***

Table 6: Monthly and annual values of pellet and electricity consumption, heat production, hours of operation and number of ignitions. At Site 5, the number of ignitions is not available in the last 2 months due to an interruption of the data logging (n.a. = not available).

3.2 Dynamic operation of the boilers

3.2.1 Time distribution of the boiler load

To characterise the boilers' dynamic behaviour, the boiler load values were continuously recorded, thus showing when the boilers operated at full or partial load, and when they were turned off. The range of load modulation (between 30 % and 100 % of nominal load) was divided into three classes, representing the boiler's operation at part load, at full load and in load modulation regime. Each monitored value, representing a time interval of 10 seconds, was assigned to the corresponding class, to obtain a time distribution as shown in Figure 6. The load percentages between 30 % and 35 % were assigned to the class "Part load", the percentages between 95 % and 100 % were considered as "Full load" operation, and the remaining values (between 35 % and 95 %) represent the "Load modulation" regime.

Results show that the 12 kW boiler at **Site 1** worked mainly with short-time cycles at part load, meaning that the heat demand was often below the lowest limit of the load modulation interval. This load profile suggested that the boiler, having a nominal capacity of 12 kW was oversized in comparison to the heat demand of the passive house. The oversizing was confirmed by the standard EN 12831 [26], according to which the maximum heat demand of the house (peak load) was 3 kW, four times lower then the nominal capacity of the boiler. At Site 1, the part load operation with frequent ignitions was characterised by low annual and monthly efficiencies, as reported in Figure 3 and Figure 5.

The 6 kW boiler at **Site 2** worked mostly at full load, due to the high thermal inertia of the floor heating system, embedded in a concrete layer. Monitoring data showed that, whenever the heating system started, 4-5 hours of operation at full load were necessary to heat-up the concrete layer and increase the room temperature above the set value, as also reported in a previous work [44].

At **Site 3** (house built in 2004), half of the boiler's operation time was spent at full load. In particular, during summer the boiler was used to heat the hot water storage tank, with one ignition per day, followed by a short-time cycle of 1-2 hours at full load. During winter, when the heat demand of the house became more important, the boiler operation was equally distributed between the three load classes, as the boiler continuously adapted its heat output to the time-variable heat demand of the house. A frequent load modulation regime characterises also the BioWIN and BioWIN2 boilers installed at **Sites 4** and **5.** These boilers had a very similar distribution among the three classes, with approximately 10 % of the operaton time at full load, 60 % in load modulation, and 30 % at part load. Both boilers were manually switched off for the same time period during summer. Moreover, the two BioWIN boilers heat multi-family houses whose variable heat demand during winter covers the whole range of load modulation. At Sites 4 and 5, the frequent operation in load modulation regime indicate the correct sizing of the boiler in comparison to the heat demand of the houses. Because the BioWIN boilers are optimised for the full power range, a high efficiency can be achieved both at full load and during load modulation, leading to annual efficiencies above 85 % (Figure 3).

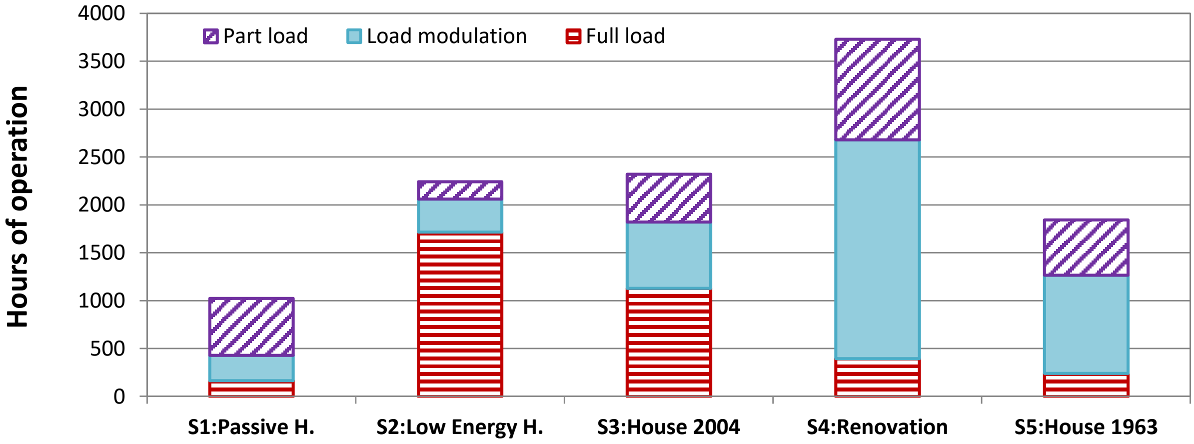

Figure 6: Time distribution of boiler loads in the monitored sites

3.2.2 Efficiency as function of operational load and number of ignitions

The monthly conversion efficiencies of the boilers at **Site 1** and **2** cover the whole range from 30 % to 80 %, making the two boilers suitable to investigate the dependency of the efficiency on different operational parameters. As already mentioned in previous studies [16] [23] [45] [46], the efficiency field conditions is lower than the efficiency measured in laboratory conditions due to:

- ***Non-stationary operation regime***. During load transitions, the boiler adapts the fuel and air supply, thus changing continuously its control settings and operation parameters. Moreover different loads correspond to different efficiencies, and often boilers are not optimized for the full power range.
- ***Energy losses due to intermittent operation (on-off cycles)***. When the boiler starts operation after it was turned off for some time, the boiler body is still cold and therefore, during the start-up sequence a major fraction of the heat released by the pellet combustion is stored in the boiler's body instead of being transferred to the circulating water. After the boiler stops, the forced air circulation induced by the fan favors the combustion of the pellet residues in the burner and removes flue gases from the boiler, but it also increases the energy losses to the chimney. In addition, the heat stored in the boiler body is lost to the surrounding environment, unless the water circulation is continued for some time.

These considerations suggest that, for a given time interval, the operational load and the number of ignitions could be the key-parameters in order to characterize the boiler's efficiency.

Boiler manufacturers usually correlate the efficiency and the load factor, with empirical functions obtained by combining the results of laboratory tests performed at different loads [47] [48]. A similar approach can also be applied for the the field conditions, by plotting the measured efficiencies as a function of the load factors [49]. For heating systems equipped with small-scale pellet boilers, the definition of the load factor is given by the European Standard EN 15316-4-1 [50] according to Eq (7):

$$\beta = \frac{Q_{out}}{P_N \cdot \tau_{on}} \cdot 100 \qquad (0 < \beta < 100) \tag{7}$$

Where Q_{out} is the boiler's thermal output and P_N its nominal capacity. The time period (τ) chosen for the analysis comprises both the total boiler's operation time (τ_{on}) and the time spent in stand-by mode (τ_{sb}, (Eq (8)). The product of P_N and τ_{on} is the energy generated by the boiler in case of a continuous operation at nominal load.

$$\tau = \tau_{on} + \tau_{sb} \tag{8}$$

According to the monitoring data, monthly efficiencies provided only a limited data set (12 values for the 6 kW boiler and 10 values for the 12 kW boiler respectively, as shown in Figure 5 and Table 6). To increase the number of available data, the analysis has been carried out on a 15 days period basis (i.e., period τ). The efficiencies of the two VarioWIN boilers were plotted as a function of the load factors, as shown in Figure 7, where each data point represents a 15-days period.

Comparing the pellet boiler to a dynamic system characterised by a first-order response [51], the efficiency can be written as a function of the load factor according to the following differential equation (Eq. (9)):

$$\frac{d\eta}{d\beta} = \frac{1}{K} \cdot \left(\eta_{lab,100\%} - \eta \right) \tag{9}$$

In which $\eta_{lab,100\%}$ is the efficiency measured during standard laboratory test at nominal load and K is a coefficient charactersing the inertia of the system.

In this analysis, the first-order response describes the performance of the boiler at different load factors. In order to have a "perfect" performance, the boiler shoud be forced to achieve the maximum efficiency ($\eta_{lab,100\%}$) in every operating condition, which means for the whole range of load factors. Therefore the maximum efficiency could be reached as soon as the load factor increases from the zero value to a first, infinitively small load factor $d\beta$. In case of a first-order response, the boiler does not achieve immediately the maximum efficiency, but it reacts with a certain inertia, quantified by the coefficient K: with increasing K, the boiler's reponse is closer to the ideal performance.

The integration of Eq. (9) leads to Eq. (10). The boundary condition for the integration is that a load factor equal to zero (no heat output from the boiler), results in a zero efficiency, as expressed in Eq. (11):

$$\eta = \eta_{lab,100\%} \cdot \left(1 - e^{-K \cdot \beta}\right) \tag{10}$$

$$\eta\big|_{\beta=0} = 0 \tag{11}$$

Eq. (10) represents an efficieny curve which estimates the actual boiler boilers' efficiency in field conditions as a function of the load factor. The first point of the curve ($\beta=0$) represents the case in which the heat generated by the pellet combustion is not extracted from the boiler ($Q_{out}=0$). In practice, this situation may occur during the stop-sequences, when there may be combustion of biomass residues in the burner without water circulation. With increasing load factors, the curve rises exponentially and approaches an asymptotic value ($\eta_{lab,100\%}$), representing the maximum efficiency achievable by the boiler. $\eta_{lab,100\%}$ was assumed equal to the efficiency measured in standard laboratory tests at nominal load: because such tests are performed in stationary operation and under controlled conditions, the resulting efficiency is always higher than the efficiency in the field. The coefficient K determines the increase of the curve towards the asymptote: a high K results in a fast rise of the curve and indicates a good optimization of the boiler technology, as high efficiencies can be reached also at low load factors.

Adopting Eq. (10) to describe the response of the 6 kW and 12 kW VarioWIN boilers, the values of the K coefficients were found by means of a non-linear regression through the monitoring data, as shown in Figure 7. The coefficients of determination (R^2), equal to 0.72 for the 12 kW boiler and to 0.78 fot the 6 kW boiler, show that the efficiency is correlated to the load factor. However, Eq. (10) cannot be used to calculate the efficiency with a good accuracy (e.g., above 90 %), thus suggesting that the boiler performance is also influenced by other variables. In particular, as mentioned above, the number of ignitions should be taken into account, together with the load factor. To include the number of ignitions, the definition of the load factor (β) was adjusted, leading to a "modified load factor" (β_{mod}). At first, the minimum number of ignitions (ig_{min}) for a boiler operating continuously for the time τ_{on} was defined according to Eq. (12):

$$ig_{\min} = \frac{\tau_{on}}{\tau_{\max,ig}} \tag{12}$$

In which $\tau_{max,ig}$ is the maximum operation time after one ignition, equal to 6 hours for both VarioWIN boilers [52]. Indicating with *ig* the actual number of ignitions monitored during a certain interval τ, the average duration of one operation cycle ($\tau_{avg,ig}$) can be calculated as in Eq. (13):

$$\tau_{avg,ig} = \frac{\tau_{on}}{ig} = \frac{ig_{\min}}{ig}\tau_{\max,ig} \qquad \left(0 < \frac{ig_{\min}}{ig} < 1\right) \tag{13}$$

If the ratio ig_{min}/ig is close to 1, the boiler operates with long cycles, close to the maximum duration $\tau_{avg,ig}$, whereas a value close to 0 indicates short cycles and frequent ignitions. Using the ratio ig_{min}/ig as a coefficient to adjust the load factor (β), a "modified load factor" (β_{mod}), was defined as the product of two non-dimensional parameters accounting both for the operational load and for the number of ignitions (Eq (14)):

$$\beta_{\text{mod}} = \beta \cdot \frac{ig_{\min}}{ig} = \frac{Q_{out}}{P_N \cdot \tau_{\max,ig} \cdot ig} \qquad (0 < \beta_{mod} < 100) \tag{14}$$

The modified load factor is the ratio of the average heat ouput per ignition (Q_{out}/ig) and the heat output $P_N \cdot \tau_{max,ig}$, achieved if the boiler operates continuously at nominal load for the maximum operation time after one ignition. The modified load factor (β_{mod}) was inserted in Eq (10) to replace the load factor (β), and a second non-linear regression through the data was performed, as shown in Table 7 and Figure 8.

The high coefficients of determination reported in Figure 8 show that, for the two VarioWIN boilers, Eq (16) can be used to calculate the efficiency in field conditions with an accuracy above 90 %. The use of the modified load factor (β_{mod}) highlights the influence of the short-time ignitions on the boiler performance: with longer operation cycles, resulting in a lower number of ignitions (ig), the efficiency increases exponentially. The exponential increase is achieved also if high heat outputs (Q_{out}) are produced after each ignition, showing that a stationary operation at nominal load is the optimal working condition for the VarioWIN boilers.

The K coefficients characterise the increase of the curve towards the asymptote $\eta_{lab,100\%}$ The 12 kW boiler had the higher K coefficient and the faster increase, indicating better performance over the whole range of load factors. For instance, monitoring data reported in Figure 8 indicate that, for $\beta_{mod} = 10$ %, the 12 kW boiler had an efficiency of 70 % whereas the efficiency of the 6 kW boiler was only 40 %.

Although it is characterized by the best performance, the 12 kW boiler is oversized in comparison to the heat demand of the passive house and therefore it operates at part load and with frequent ignitions, resulting in low values of $\beta_{mod.}$ With β_{mod} ranging between 0 and 15 % the efficiencies ranged between 35 % and 75 % resulting in an annual fuel conversion efficiency of 66.8 % as mentioned in Section 3.1.1. On the contrary, the 6 kW boiler operated with long cycles at nominal load, therefore most of its monitoring data show modified load factors β_{mod} in the range 40-60 % and efficiencies between 70 % and 85 %, leading to the annual conversion efficiency of 74.3 %.

		6 kW boiler	12 kW boiler
	$\eta_{lab,100\%}$ [%]	90.2	92.3
First regression (φ_{mod}) $\eta = \eta_{lab,100\%} \cdot \left(1 - e^{-K \cdot \beta}\right)$	*K* [-]	0.026	0.044
	R^2 [-]	0.78	0.72
Second regression (φ_{mod}) $\eta = \eta_{lab,100\%} \cdot \left(1 - e^{-K \cdot \beta_{\mathrm{mod}}}\right)$	*K* [-]	0.053	0.140
	R^2 [-]	0.90	0.96

Table 7: Parameters for the determination of the efficiency as a function of the load factor

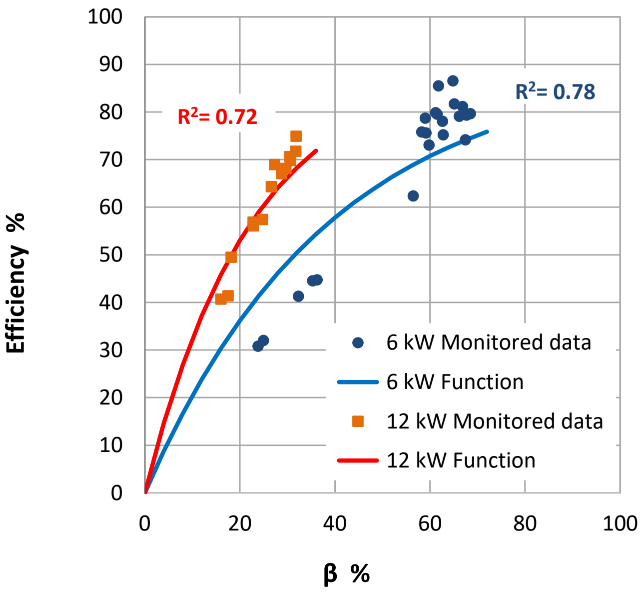

Figure 7: Fuel conversion efficiency as a function of the load factor

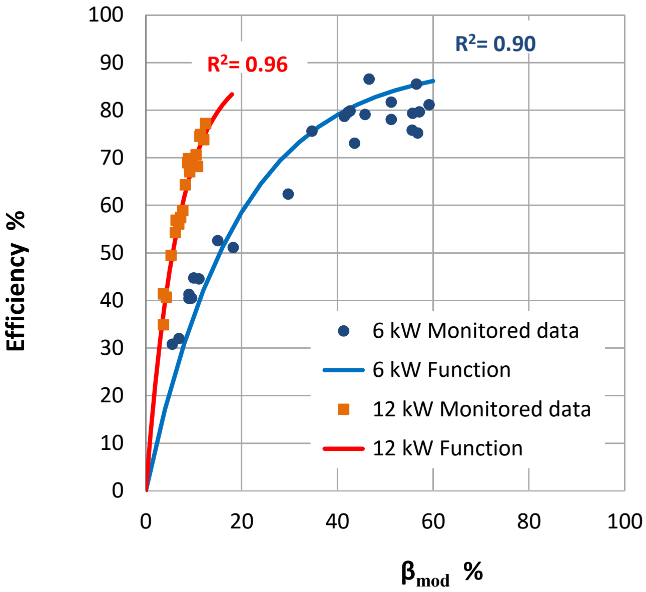

Figure 8: Fuel conversion efficiency as a function of the modified load factor

4 CONCLUSIONS

This study focussed on the continuous monitoring of pellet boilers installed in residential buildings in Austria. Five houses, representing different building types and having different energy standards were monitored for one year. The following conclusion are drawn:

1. In field conditions, annual efficiencies up to 85 % and monthly efficiencies up to 91 % can be reached with a good system design. A pellet boiler having a good capability to modulate its power output and quickly adapt to transient operating conditions is essential to achieve high efficiencies.
2. Differences between the efficiency certified by standard types test and the measured efficiency at the monitoring sites ranged from 7% to 25%. The high efficiencies certified by standard laboratory tests show that pellet boilers are already optimized for stationary operation, while the improvement potential remains for transient operating conditions.
3. The enhanced energy performance of a house has a positive impact on the heat demand, but it does not affect the boiler efficiency. In particular, wrong sizing can lead to a poorly efficient operation, as observed in the passive house monitored in this study, where the oversized boiler had an annual fuel conversion efficiency of 67 %. Hence, low heat demands stress the importance correctly integrating the boiler and the heat distribution system into the building envelope.
4. During summer, the boiler typically operates with frequent ignitions and short operation cycles, leading to lower efficiencies. Minimum monthly efficiencies of 30 % (fuel based) were found in this study. The integration of additional heat sources, such as solar collectors or heat pumps, reduces the boiler's operation time during summer, resulting in higher annual efficiencies and reduced pellet consumption.
5. A new performance curve, based on a modified load factor, has been proposed to estimate the boilers' efficiency in field conditions. The curve evidences how high operational loads and reduced number of ignitions are optimal operating conditions. For two pellet boilers, the curve paramters were estimated by means of a non-linear regression through the monitoring data with coefficients of determination (R^2) above 0.9.

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