# Biomass-Based Heating and Hot Water Supply Systems for Prefabricated, High Energy Performance Houses: a Comparison of System Configurations and Control Strategies

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**Abstract**

*Nowadays prefabricated houses are becoming increasingly popular, thanks to their low cost and high energy performance. Heating systems installed in these houses should be carefully designed and controlled, to ensure sufficient thermal comfort while maintaining low fuel consumptions. This study presents the simulation of different system configurations and control strategies for a pre-fabricated house, located in Lower Austria. The house is heated by a 6 kW pellet boiler directly connected to a floor heating system, in a configuration without buffer storage tank. Using the TRNSYS simulation suite, a coupled simulation of the house and its heating and hot water supply system was set up, calibrated and validated with reference to monitoring data. As monitoring data evidenced that the control strategy of the heating system is not ideal to maintain a comfortable indoor temperature during the whole day, two improved strategies were simulated over the heating season and evaluated in terms of thermal comfort, pellet consumption and boiler's efficiency. Moreover, to better understand the influence of the system configuration, simulations have been repeated considering another heat distribution system (radiators instead of floor heating). Results show that the radiators' network, if adequately controlled, reduces by 85% the total discomfort time. In addition, the pellet boiler mainly operates in load modulation regime, leading to lower pellet supply rates and therefore to lower pellet consumptions (18% less than floor heating). However, the lower operational loads and frequent ignitions result in a slightly lower efficiency of the pellet boiler (4% less than the configuration with floor heating.*

***Keywords: prefabricated house, system configuration, control strategy, pellet boiler***

## 1. Introduction

Nowadays prefabricated houses are becoming increasingly popular, thanks to their low cost and high energy performance. These houses are often equipped with heating and hot water supply systems based on renewable energy ([1], [2]). In particular, systems combining pellet boilers and solar collectors are widespread in Central Europe [3]. However, it has been observed that high performance houses which approach the zero energy target while maintaining economical convenience might be easily subject to problems of insufficient thermal comfort [4]. Because of the low thermal mass of the lightweight construction, fast temperature gradients may occur in the indoor environment and bring the indoor temperature out of the comfort range. Therefore, HVAC systems must be correctly sized and adequately controlled to meet the building's heat demand. Moreover, control strategies should account for the response time of the heat distribution system, especially in the case of floor heating systems, having a large thermal lag [5]. The installation of pellet boilers in pre-fabricated buildings is even more challenging, because the system design and controls should also account for the operating conditions of the pellet boiler, which should be suitable to reach maximum efficiencies and minimum emissions [6].

This study presents the simulation of different system configurations and control strategies for a pre-fabricated house, which was monitored within a European Project (BioMaxEff [7]), aiming at the demonstration of biomass boilers in real life conditions.

## 2. Materials and methods

### House under investigation and monitoring data

The house analyzed in this study is a pre-fabricated single family house situated in the municipality of Persenbeug-Gottsdorf (48°11' N, 15°06' E) in Lower Austria, 220 m above sea level. The house was built in 2012 and it is inhabited by two people. The heated volume (561 $m^3$) comprises the ground floor and the first floor, each one having a 90 $m^2$ floor area, whereas attic and basement are unheated. The heated volume is enclosed in a fully insulated envelope: external walls have an overall heat transfer coefficient of 0.14 W $m^{-2}$ $K^{-1}$ and all windows have triple-glazed panels ensuring U-values below 1 W $m^{-2}$ $K^{-1}$. The south-oriented façade has a glazed surface of 27 $m^2$, which maximizes solar radiation gains during winter.

The house is heated by a 6 kW pellet boiler and solar collectors installed on the roof are used to support the domestic hot water supply. As the boiler can modulate the heat output between 30% and 100% of the nominal capacity, the system is not equipped with a buffer storage tank. The boiler is directly connected to a floor heating system consisting of a network of plastic pipes embedded in 6 cm thick concrete layer. The heating system, installed in ground floor and in the first floor, is controlled by a thermostat located in the living room: the indoor temperature is currently set to 21 °C, with a night setback to 18 °C.

The floor heating system has a considerable thermal mass, which results in a high thermal inertia. After the boiler turns off in the evening, the concrete layer, in which the pipes are immersed, slowly releases the heat stored during the day and maintains a comfortable temperature during the night. However, when the set temperature changes instantaneously from 18 to 21 °C in the morning, the inertia of the floor heating system becomes a disadvantage, as the concrete layer needs some hours to heat up again. During this time, despite the boiler operates continuously at maximum load, the indoor temperature stays below the set value. For instance, Fig. 1 shows that on 27$^{th}$ January 2014, the boiler operated 10 hours at maximum load before the temperature reached again the set value. Similarly, all monitoring data collected during the winter months evidenced the need of better managing the high thermal inertia of the floor heating system, in order to avoid thermal discomfort [8].

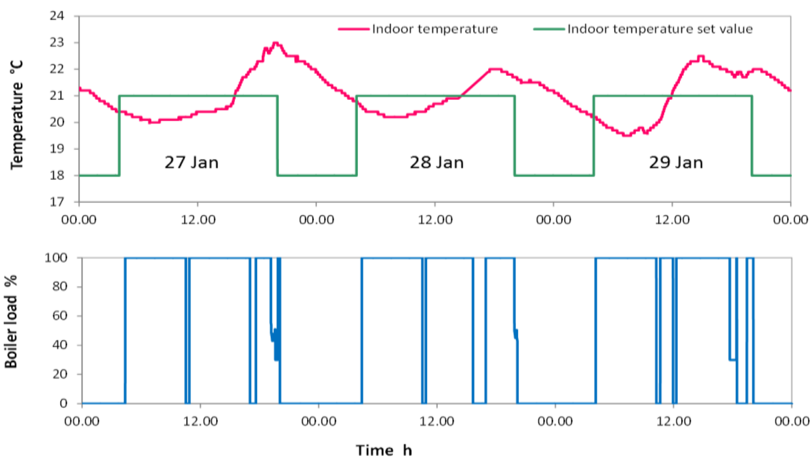


Fig. 1 Monitoring data of 26$^{th}$, 27$^{th}$ and 28$^{th}$ of January 2014

## Simulation setup, calibration and validation

Using the TRNSYS simulation suite, a coupled simulation of the house and its heating and hot water supply system was set up, calibrated and validated [8]. The heated volume was divided into two thermal zones, one for the ground floor and one for the first floor. The building envelope and the main system components were simulated using both standard and non-standard TRNSYS Types. Then, the simulation was calibrated and validated based on the indoor temperature profiles, measured in both floors. In addition, simulated pellet consumptions were validated according to the ASHRAE Guideline (2002) [9].

As monitoring data evidenced that the control strategy of the heating system is not ideal to maintain a comfortable indoor temperature during the whole day, two improved strategies were defined and compared to the strategy currently in use (Fig. 2). The strategy currently used to control the heating system has been named "**Strategy 0**". The first improved strategy (**Strategy 1**) shifts back of three hours the time interval of the night setback. With this adjustment, the boiler switches on at 01:00 A.M. and hot water starts to flow in the heating circuit, allowing to reach the comfort temperature earlier than with Strategy 0. The aim of Strategy 1 is to better manage the long response time of the floor heating system. The second improved strategy (**Strategy 2**) sets a constant temperature of 21.0 °C, thus eliminating the night setback. This solution aims at reducing the number of discomfort hours, even if this leads to a higher fuel consumption.

Moreover, to better understand the influence of the system configuration, all simulations have been repeated considering another heat distribution system (radiators instead of floor heating). For this purpose, the floor heating system was replaced by a radiator's network in the TRNSYS simulation.

Table 1 reports the test matrix adopted in this study: three control strategies have been combined with two system configurations, resulting in six test cases. Each simulation was carried out over the whole heating season (from January to May and from October to December 2014) and evaluated in terms of thermal comfort, pellet consumption and boiler's efficiency.

Table 1. Test matrix for the simulation

| | | System configuration | |
|---|---|---|---|
| | | Floor Heating | Radiators |
| Control strategy | 0 | FLH ST0 | RAD ST0 |
| | 1 | FLH ST1 | RAD ST1 |
| | 2 | FLH ST2 | RAD ST2 |

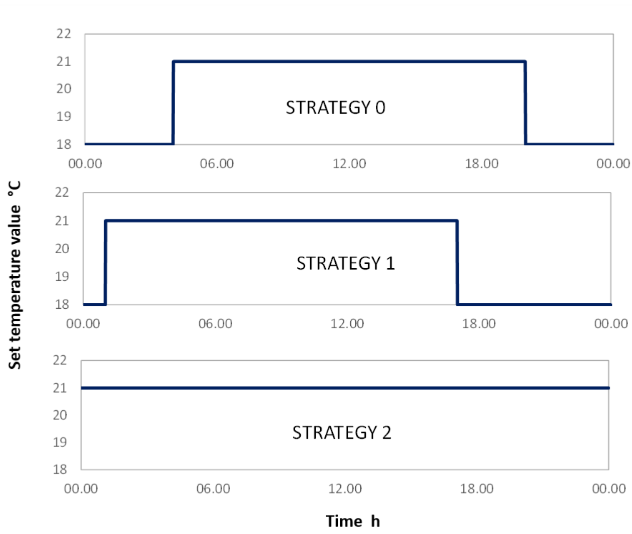


Fig. 2 Control strategies analysed in this study

## 3. Results and discussion

### System dynamics over two consecutive days

A first comparison between the two system configurations under analysis is reported in Fig. 3 and Fig. 4. The plots show the simulation results obtained during two consecutive winter days, if heating system is controlled using Strategy 0. (Indoor temperature profiles and energy balances of the distribution system are calculated in the thermal zone representing the ground floor).

Both system start operation at time t = 4h, when the set temperature is changed from 18 °C to 21 °C. At this point the room temperature is approximately 19.5 °C in both simulations and the boiler is operated at full load in order to heat the rooms and reach the set temperature value. In the following hours, the heat delivered by the circulating water is partly transferred to the room and partly stored within the distribution system (the concrete layer in case of the floor heating system and the radiators' bodies in case of the radiator network). Because of the lower thermal mass, radiators heat quickly and reach stable operating conditions at time = 6h, when the whole heat input to the radiators is transferred to the room and no heat is stored in the radiators' bodies. In contrast to that, the floor heating system is characterized by a much slower response: the heat storage within the floor's concrete mass continues until time = 12 h. At this time the heating system is switched off, and for the following two hours the heat output of the boiler is used to heat domestic hot water (DHW) tank. (In the system under study, DHW production has priority on space heating, therefore when the boiler heats the hot water tank, the heating system is switched off). After the DHW tank is recharged, the boiler continues operation to heat the house, until the room temperature is 2 K above the set value. In the configuration with radiators, a room temperature of 23 K is reached at time = 16 h, and the heating system is switched off. As the heat stored within the radiators is quickly released towards the room, temperature of the radiators' bodies approaches the room air temperature. On the other hand, the floor heating system remains switched on until time = 20 h, when the set temperature value is lowered from 21 °C to 18 °C. Afterwards, the room temperature (approximately 21.5 °C) is 3.5 K higher than the setpoint, therefore the heating system is switched off. The heat accumulated within the floor is then slowly released during the night, with an average heat transfer rate of 1 kW.

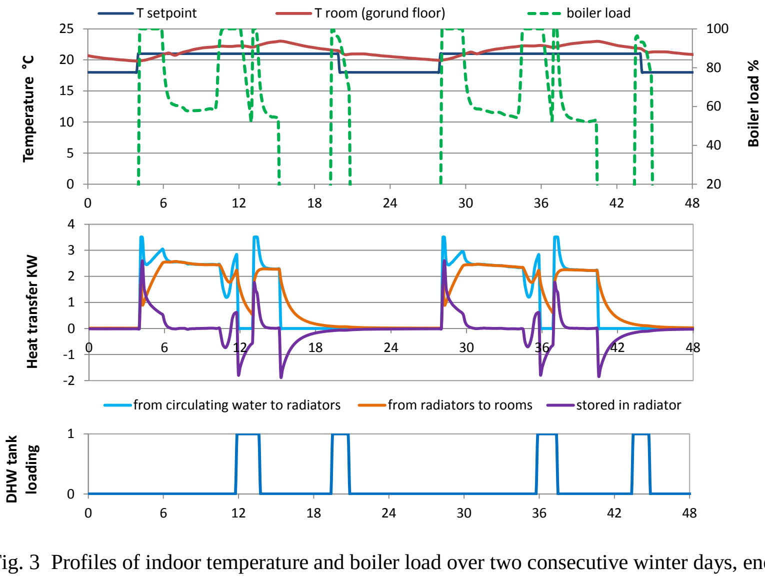


Fig. 3 Profiles of indoor temperature and boiler load over two consecutive winter days, energy balance of the radiator network in the ground floor and operating times for DHW production

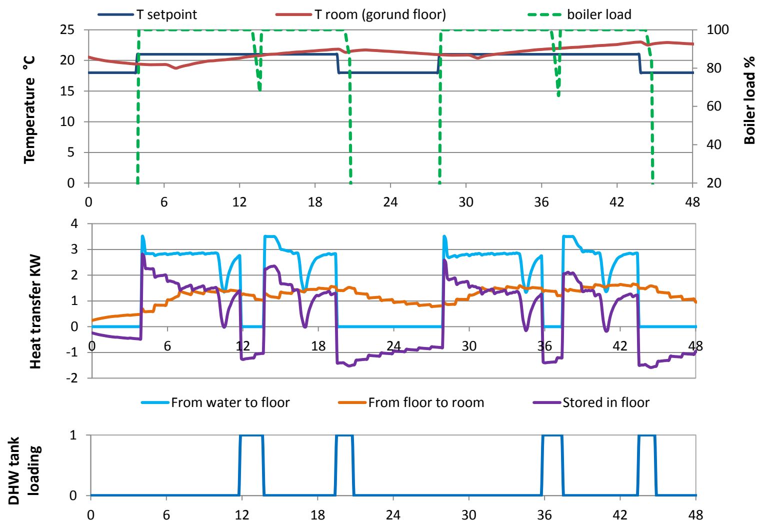


Fig. 4  Profiles of indoor temperature and boiler load over two consecutive winter days, energy balance of the floor heating system in the ground floor and operating times for DHW production

In the configuration with radiators, the indoor temperature profile in the ground floor is always close to the set value. The set temperature profile is not met only for one hour in the morning (from 4.00 A.M. to approximately 5.00 A.M.), otherwise the room temperature is in comfortable range, slightly above the set value. On the contrary, the room temperature profile obtained with the floor heating system is below the set temperature for long time intervals. Moreover, from t = 44 h to t = 48 h, the 23 °C temperature is 6 K above the set value. In this case, the heat released by the floor heating system is overheating the indoor environment.

If connected to the floor heating system, the pellet boiler operates all the time at full load, because of the high heat demand: a high heat transfer rate necessary in order to increase the temperature of the 6 cm concrete layer within the floor. In the configuration with radiators, the boiler operates at full load as long as the radiators' bodies are heated up and the room temperature reaches the set value. Afterwards, the boiler switches to load modulation mode, which allows to continuously adapt the heat output to the demand of the heating system.

## System performace over the whole heating season

A summary of the simulation results, obtained over the whole heating season, is provided in Fig. 5, which compares discomfort time, seasonal pellet consumptions and parameters characterizing the boiler operation.

Concerning the configuration with floor heating system, Strategy 1 can be highlighted as an improvement in comparison to the actual control strategy, as it increases the thermal comfort without significantly changing the pellet consumption and the boiler's efficiency. Strategy 2 provides an even higher thermal comfort together with a small (0.45%) increase of the boiler's efficiency, but it also increases the pellet consumption of 2.5% in comparison to Strategy 0.

Results show that Strategy 0, currently used to control the floor heating system installed in the house, leads to the highest discomfort time. The same strategy, if applied to a system with radiators, ensures the maximum thermal comfort. Therefore, the fast response of the radiators' network allows to achieve a better matching between heat demand and system response.

The operation regime of the pellet boiler is characterized by different indicators. Fig. 5 reports the total hours of operation, number of ignitions and load factor over the heating season. According to EN 15316-4 [11], the load factor (β) was calculated as the ratio of the boiler's overall heat output ($Q_{out}$) and the heat output available if the boiler always operates at nominal load ($P_N \cdot \tau_{ON}$, Equation (1))

$$\beta = Q_{out}/(P_N \cdot \tau_{ON}) \quad (1)$$

Fig. 5 shows that, in the configuration with radiators, the pellet boiler operates for a longer time, but with much lower operational loads, as evidenced by the lower load factor. Despite the higher operation time, the frequent load modulation regime results in lower pellet supply rates and therefore in a lower seasonal pellet consumptions (18% less than the configuration with floor heating).

However, as reported in recent publications [7, 10], low operational loads and increased number of ignitions have a negative influence on the boiler's efficiency. In this case, the configuration with radiators shows lower load factors and more frequent ignitions, which lead to a seasonal efficiency in the range 75-76 % for all control strategies. In the configuration with floor heating, the pellet boiler operates in optimal conditions: long operation cycles at full load lead to high load factors and reduced number of ignitions, which results in a higher seasonal efficiency (in the range 78-79 % for all control strategies).

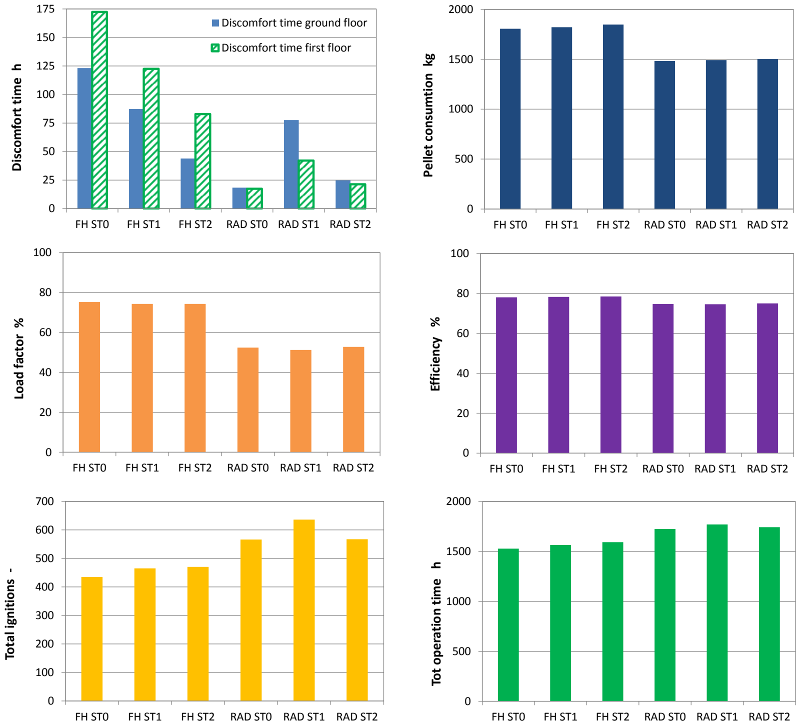


Fig. 5 Total discomfort times (in both floors of the house), seasonal pellet consumptions and paramters characterizing the boiler operation

## 4. Conclusions

This study demonstrates an application of dynamic building simulation to test different control strategies and system configurations. It was concluded that, for pre-fabricated houses, heat distribution systems having a fast time response ensure higher thermal comfort and lower fuel consumptions, but the frequent part load operation and higher number of ignitions lead to a slight reduction of the pellet boiler's efficiency (3-4 %)

It was also evidenced that heating systems must be carefully controlled in order to avoid thermal discomfort during winter by using enhanced control systems. In particular, if a night setback temperature is adopted, then the setback time interval should be chosen depending on the response time of the heat distribution system.

## Acknowledgment

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