SOLAR & PELLET HEATING:
SPECIFICATIONS FOR HIGH EFFICIENCY SYSTEM DESIGN

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Abstract

Combined biomass and solar heating systems provide the opportunity for a heat supply of single family houses without the use of fossil energy. Pellet fired boilers play a predominant role within these systems because their standardised combustible allows for the fully automated operation. However, the combination of biomass boilers and solar collectors places special requirements in view of a good system solution. To analyse the proper combination of both technologies three separate projects were carried out at SPF. the main instrument thereby was the Concise Cycle Test method supplemented by preliminary tests of the boiler and subsequent simulations. It was shown that a modulating boiler operation is superior in terms of both, high energetic efficiency and low emissions compared to intermitting boiler operation. But this is only the case if the following requirements are met:

- Low excess-air factors for the complete modulation range,
- low envelope losses,
- a fast adaption of the output power,
- correct dimensioning of the boiler.

Beside the characteristics of the boiler the hydraulic connection and the control is important to reach a good system performance. Mostly for combined biomass and solar heating systems the best solution is a connection of the boiler to the thermal energy store instead of a direct connection to the heating circuit. The requirements that have to be fulfilled for the control of TES charging are:

- Temperature sensors within the store to control the boiler dependent to the demand for space heating or domestic hot water.
- In order to control the power modulation of the boiler, the best option is to reduce the volume flow rate of the boiler pump based on an algorithm that takes into account the temperature measured in the TES. Other options are to increase the return temperature of the boiler using a motorized mixing valve, or to reduce the set-temperature for the water leaving the boiler.

1. Motivation and objectives

Solar thermal systems can contribute substantially to the heat demand for space heating (SH) and domestic hot water (DHW) preparation in single family houses on a carbon-free and renewable basis. However, they typically do not cover 100 % of the load, so that an auxiliary heater is used in times when not enough heat is available only by using solar energy. With a growing environmental awareness and rising cost for fossil fuels biomass heating systems become more and more attractive. Thereby pellet fired boilers play a predominant role because their standardised combustible allows for a fully automated operation which is state of the art for heating with fossil fuels like oil or gas. However, for the use of solid fuels the control over the combustion rate is limited and usually higher time-constants exist for starting, stopping or changing the rate of combustion compared to liquid or gaseous-fired boilers. Thus the combination imposes special requirements in view of a good system solution which can be specified by:

- low losses of both, components and whole system
- high efficiency of the interacting components
- high solar fraction
- low total emissions

In order to provide practical advice how to realize good system solutions, measurements have been conducted to identify not only steady state operation of the heating system but also the dynamic operation under realistic conditions. Those measurements were complemented with simulations to study the effect of various changes in the system. For the simulations it is important to work with models that allow for a detailed replica of reality. This paper summarizes the essential requirements on components, system design and control based on a series of projects and measurements where whole system testing and evaluation has been applied.

2. Recapitulation of performed projects

To analyse the combination of pellet fired boilers with solar thermal collectors three separate projects were carried out at SPF. The main instrument thereby was the CCT (Concise Cycle Test) method, where the combisystem must be installed completely by an installer on a test rig for a dynamic, 12-day lasting test sequence (Vogelsanger, 2002). For this purpose, the test rig at the Institut für Solartechnik SPF, that had previously been used for testing solar thermal systems in combination with oil- and gas-fired auxiliary heaters, was extended to meet the special requirements of solid fuels (Konersmann et al., 2007). Subsequently, the following projects were carried out.

PelletSolar

The focus of the *PelletSolar* project was a very detailed analysis of one single solar and pellet heating system. Therefore the CCT method was combined with preliminary tests of the boiler and subsequent simulations. The test revealed that the modulation of the boiler was restricted to 70 % of the nominal power as a consequence of its hydraulic integration into the system although the boiler would allow for a constant fuel burning down to 30 % of its nominal power. A second test with an optimised hydraulic scheme showed a significant reduction of the boiler's start and stop cycles during the 12 day test period. The simulations showed that the solar and pellet combination of an 800 litre store and 15 m^2 of flat plate collectors used 27 % less wood pellets compared to an non-solar reference system using the same boiler. The fuel reduction is composed of the solar gain on the one hand and an improved boiler efficiency on the other hand. The latter is due to the fact that the boiler barely has to start for DHW preparation during summer and that the solar part covers part of the low heat demand for space heating in the transition periods in autumn and spring which would require a very inefficient operation of the boiler otherwise. With the help of the simulation model a great number of influencing variables was analysed. Thereby it was shown that it would be possible through improvements in insulation, control strategy and hydraulics to save up to 32 % of pellets and 17 % of electricity. In this improved system, the combustion starts of the pellet-burner were reduced by 50 % compared to the non-solar reference system (Konersmann et al., 2007).

PelletSolar-2

This project was started in order to validate the generality of the conclusions from *PelletSolar*. Within the project two solar & pellet heating systems were tested that use different hydraulic schemes to integrate the automatic fired pellet boiler into the system and different methods for fuel feed inside the combustion chamber. It was found that both systems operate the boiler in start-stop cycles, although both were equipped with the means for power modulation. Subsequent to the physical test sequence, the acquired data was used to generate measurement validated simulation models that were used to evaluate various system setups in light of annual performance. The simulations revealed analogous to *PelletSolar* a considerable potential for improvement in the overall energetic efficiency of the systems, in particular by enabling the power modulation of the boilers. In addition to the evaluation of the energetic efficiency, the emissions were also considered. This was achieved on the basis of emission-factors that were determined for transient operation at the Lucerne University of Applied Sciences (Good and Nussbaumer, 2009). The results show that as long as continuous part-load operation is achieved with low emission-factors, a modulating boiler operation reduces annual emissions significantly. Should the boiler show considerably higher emissions in part load compared to its operation at full load (in particular higher CO-emissions may be observed together with higher values of excess air), the annual emissions can be higher compared with a simple On/Off operation. (Haberl et al., 2010).

SimPel

The goal of the project *SimPel* was to develop a precise method to determine the energy utilisation ratio of a pellet fired boiler that is easy to apply. The energy utilisation ratio is the ratio of the energy delivered to the energy fed. This is in contrast to the efficiency of the boiler which is the ratio of output and input in a stationary operation condition. The efficiency is measured according to EN 303-5 test standard for accreditation of devices at nominal load and part load. The approach that is called SimPel is based on annual simulations with a simulation model. The parameters for the simulation model are obtained with the help of data of the test for accreditation of devices EN 303-5 plus additional measurements that show its transient behaviour. The additional measurements were in this case performed by a cooperation partner (Bioenergy2020+). The resulting energy utilisation ratio was compared to the result that the cooperation partner obtained with a different approach based on an 8 h lasting measurement with an dynamic load and in addition with the energy utilisation ratio that was determined in field tests. It was found that the results of both approaches showed a good match with the data of field tests. To illustrate the possibilities of the SimPel approach, annual simulations were performed in which the pellet boiler was embedded in different heating systems. The SimPel method allows thus to deduce recommendations for the optimised use of biomass boilers giving answers to questions like when the integration of a buffer storage into the pellet heating system is advisable or how the part-load capability affects the overall system efficiency (Konersmann et al., 2011).

3. Complexity of combined solar & pellet heating systems

Wood pellets are a combustible with a regular geometry and small size that can be fed to a boiler automatically. The characteristics of pellets, like energy content, geometry, moisture content and the maximum value of sulphur and chlorine are defined by standards, e.g. DIN 51731 or ÖNORM M 7135. The pellets are fed to the interim storage of the boiler by a screw or vacuum conveyer. Dependent on how the pellets are fed to the burner, different types of burners may be distinguished: top fed-, horizontally fed- or bottom fed burners. During the start-up phase the pellets are ignited in the burner automatically by a hot air blower or a hot surface igniter. The ignition may cause a high demand of electric energy, at least when the combustion chamber has cooled down since the last start (cold start). Besides the electric power consumption also the emissions during the start-up of the boiler are of particular interest.

The steady state operation is achieved with a stable combustion when carbon monoxide (CO) concentration, flue gas temperature and operating power have reached stationary values. As with any combustion of hydrocarbons the combination of oxygen (mostly from the combustion air) and hydrogen (mostly from the hydrocarbons of the fuel) forms steam from which latent heat could theoretically be recovered. At the time of writing this paper, most pellet boilers are not constructed for the utilisation of latent heat and in order to avoid corrosion or fouling of the heat exchanger surfaces it must be ensured that no condensation occurs. This is usually ensured by the installation of a thermostatic tree-way valve that guarantees a return temperature that is higher than the dew point temperature of the flue gas, or by pre-heating the return line of the boiler by exchanging heat with the bulk water volume before the water is released into the bulk water volume.

The efficiency of the energy conversion in steady state operation can be described with different methods. The combustion efficiency accounts only for the flue gas losses. It is equal to 100 % minus the percentage of heat losses through the flue gas (sensible and latent losses). It will not take into account whether the remaining energy is transferred as useful heat to the water flow through the boiler or lost by the envelope of the boiler to the ambient. The boiler efficiency is lower than the combustion efficiency mainly due to radiation and convection of heat from the boiler's envelope to the ambient. For determination of the boiler efficiency besides the measurement of fuel performance a heat quantity measurement in the water flow through the boiler is necessary. The boiler efficiency is calculated as the ratio of the enthalpy gain of the water flow and the fuel consumption of the boiler.

Pellet boilers for central heating do allow for modulation of the combustion power down to 30 – 50 % of its nominal combustion power. Because of the characteristics of the combustible the control of burner power can take place only slowly. In doing so beside the fuel feed also the supply of combustion air must be adjusted to regulate the excess air (λ-value). The power modulation is normally used to reach a required set temperature. When the set temperature is exceeded even with the lowest possible power the boiler stops feeding fuel. During the stop phase (analogous to the start phase) the emissions are usually increased.

Due to the possibility of power modulation it is possible to deliver the energy directly to the space heating circuit without a technical storage in between. However, since the heating power demanded by the space heating loop may still be lower than the lowest power that the boiler is able to provide with continuous fuel combustion, also a modulating pellet boiler is usually connected to a technical store which in turn feeds the heating circuit. That means that the boiler is decoupled from the load for space heating. The boiler is switched on when the temperature in the store is not high enough to provide the heat output for space heating. The usually implemented control of the pellet boiler is to keep a constant flow temperature in which case a reduction of combustion power follows is preceded by a rise of the return temperature. However, if the return temperature is kept constant by a thermostatic three-way valve, only an increase of the temperature returning from the storage to the valve above the set temperature of the valve (e.g. 45 °C) will lead to power modulation. Better options to enable power modulation are a reduction of the volume flow of the boiler pump, a reduction of the set-temperature of the pellet boiler, or an increase of the set temperature of the return valve. All of these measures must be controlled based on temperature measurements in the boiler-charged zone of the heat store.

By the integration of the boiler and the control results the operation mode during real operating conditions and therefore the efficiency during real operating conditions. For the overall efficiency (energy utilisation ratio) are all occurring operating modes inclusive the starts and stops as well as standby phases important.

Efficiency in steady state operation

The operation of the boiler at lower combustion power implicates also lower flue gas temperatures because the flue gas to water heat exchanger is operated at lower power. Therefore an increase of the combustion efficiency is expected with the reduction of the combustion power. However, Konersmann et al. (2007) demonstrated that the combustion efficiency of a pellet boiler that was measured at SPF was constant over the complete modulation range due to increased excess air at lower combustion power (and therefore increased heat losses through the flue gas) (see Figure 1). These two opposing effects (lower flue gas temperature and increased excess air) were also demonstrated in Haberl et al. (2010) based on measurements on two other pellet boiler models. The boiler efficiency is lower than the combustion efficiency because it additionally takes into account the losses from the boiler envelope to the ambient through radiation and convection . Since these losses are proportionately higher at lower combustion power the boiler efficiency decreases with decreasing effective thermal power output.

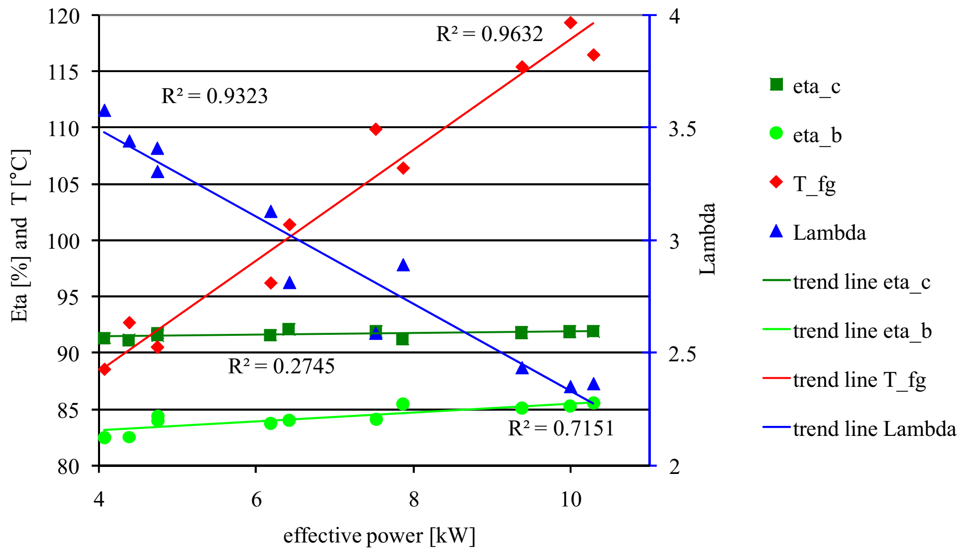

Figure 1: Measurement results of an pellet boiler in steady state operation in different modulation stages, based on the net heating value. Combustion efficiency (eta_c), boiler efficiency (eta_b), flue gas tempetrature (T_fg) and excess air (Lambda). Source: Konersmann et al. 2007.

Transient operation

Within the projects *PelletSolar* and *PelletSolar-2* three pellet boilers were measured. In each case, the stationary boiler operation at lower power was compared to intermitting On/Off boiler operation with the same average power. Konersmann et al. (2007) showed that the boiler energy utilisation ratio of steady state operation and intermitting boiler operation is approximately the same, when only the fuel consumption is taken into account. However, because of electric energy input during the ignition phase, the consideration of the electric energy input (weighted with the primary energy factor $F_{el} = 3$) revealed that the efficiency of the steady state operation with a heat load of 3 kW is by 3.6 % higher compared to the intermitting operation with the same average heat load.

Haberl et al. (2010) showed that the steady state operation of two pellet boilers is superior to the On/Off operation even without taking the electrical power consumption into account. In consideration of the electrical power consumption are differences of the boilers apparent though the electrical power consumption is dependent to the model. One of the devices tested required hardly any electric energy for a warm start while the electric energy consumption of the other device used the same amount of electric energy for warm start as for cold start.

Konersmann et al. (2011) examined the effect of power modulation on the efficiency of the pellet boiler with a simulation study. Therefore a pellet boiler was implemented in different heating systems. In each case an annual simulation with and without power modulation was performed. The results showed that the proportional flue gas losses were scarcely affected by the modulation capability of the boiler. However, the proportional heat losses to the ambient were increased for those simulations that had no modulation capability (see Figure 2). That means that the annual efficiency of a pellet boiler may be decreased when power modulation is not possible.

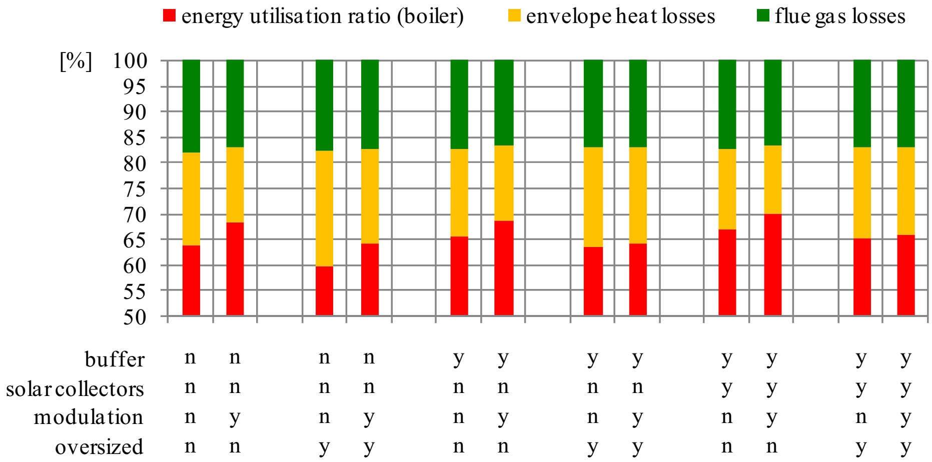

Figure 2: Results of system simulations with a pellet boiler that was implemented in different heating systems. Results based on the gross heating value. The results are arranged in pairs that differ in the modulation capability. Source: Konersmann et al. 2011

Emissions

As part of the project *PelletSolar-2* emission measurements on the two pellet boilers that were examined during the project were conducted at the Lucerne University of Applied Sciences (HSLU). Emission factors for each operating condition, including transient operating conditions were determined with details regarding the duration and the measured energy turnover of each phase. The emission measurements that were conducted provide important insights into the emission characteristics of pellet boilers in dynamic operation. By comparing the two boilers, the difference in emission behaviour of the two devices was remarkable:

Boiler #1 showed a clear increase of specific emissions (CO, in combination with high excess air) at part load, while emissions in the start and stop phase increase only little. Under these conditions the part-load operation of the boiler has a negative effect on the emissions. However, if a lower excess air factor and lower CO-emissions could be ensured in part load operation, the modulating operation could also reduce the annual emission load and thus reduce the environmental impact. Moreover, this would also have an energetically positive impact. Figure 3 shows the emissions of solid particles and CO during the measured operating conditions. The corresponding information about duration and the applied energy has been published in Good and Nussbaumer (2009). Boiler # 2, however, shows very low emission values in the entire modulation range, but relatively high emissions in the start phase and the stop phase.

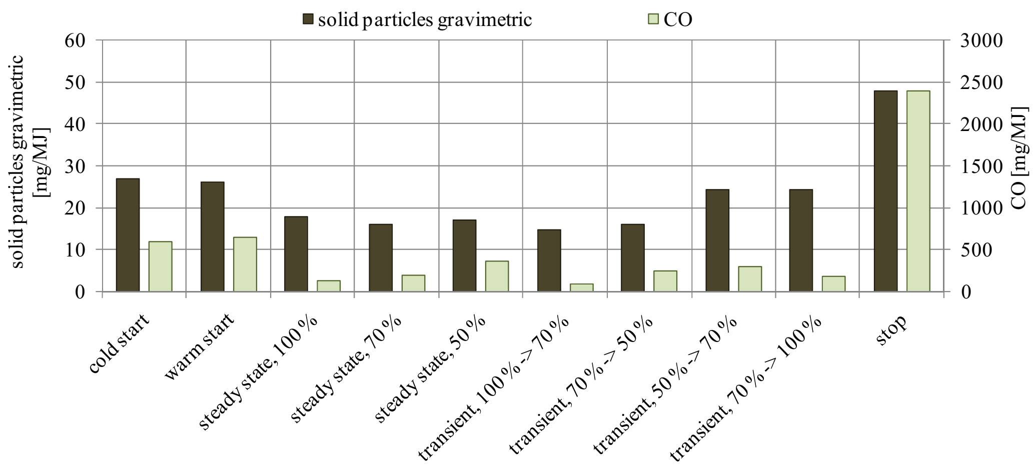

Figure 3: Emission factors of a pellet boiler subject to the operating condition. The energy (MJ) refers to the gross heating value of the fuel. Source: Good and Nussbaumer 2009.

Integration of the boiler

The integration of a buffer storage into the pellet heating system vs. a direct connection to the heating circuit was examined by Konersmann et al. (2011). It is shown that the integration of the pellet boiler to a buffer store leads to an improvement of the overall system in various cases. Especially if the pellet boiler did not modulate its power the annual efficiency of the boiler improved, since the buffer store helps to minimise the boiler starts and therefore also the boiler losses (see Figure 4). In contrast, the boiler energy utilisation ratio of modulating boilers remains nearly unaffected by the use of a buffer store . A properly sized boiler is able to utilise its modulation capability in both cases. When looking at the system level an improvement can be observed for modulating boilers connected to a buffer store especially if the boiler is oversized. In this case the cumulated heat losses of piping and TES are lower for a pellet boiler that charges a buffer store than for a boiler connected directly to the space heating circuit due to the fact that for the directly connected boiler the boiler circuit pump had to run during the complete heating season. Thus the boiler line losses and the boiler heat losses are increased and surpass the additional TES losses when the boiler charges the buffer store. Thus it can be summarised that mainly for suboptimal pellet boilers (poor modulation capability, high heat losses to the ambient, high λ-values especially in part load operation) as well as for over-sized devices, the connection of the boiler to the buffer store contributes to an enhancement of both annual boiler and annual system efficiency. With a good and properly sized pellet boiler however, it may be better to provide the energy for space heating directly to the space heating circuit. This is also in agreement with results from an experimental investigation by Haller and Konersmann (2008).

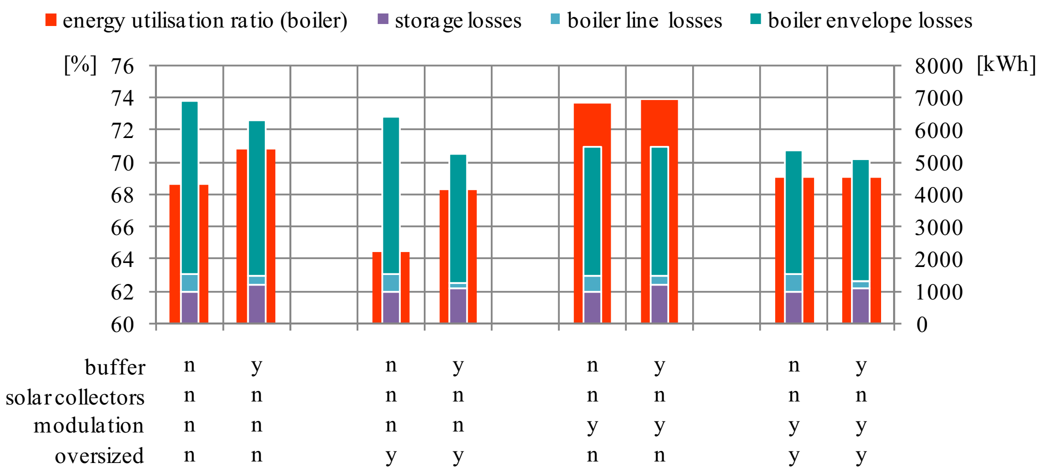

Figure 4: Influence of the integration of the pellet boiler on the degree of utilization of the boiler and the heat losses through pipes, TES and boiler. The results of annual simulations are presented by pairs that differ in the integration of the pellet boiler to the buffer store or via a low loss header directly to the space heating circuit. Source: Konersmann et al. 2011.

Control

Konersmann et al. (2007) have shown that the number of boiler starts of the system examined in *PelletSolar* was reduced remarkably by the implementation of a variable flow pump that was controlled according to the building load in order to be able to use the full range of boiler modulation. Since the building load is usually unknown, Haller (2010) achieved the same effect in simulation studies where one or more temperature measurements in the storage were used to control the volume flow rate of the boiler loop pump. In this study, the best results were achieved by using a measurement of the average temperature within the zone of the storage that was charged by the pellet boiler.

Haberl et al. (2009) tested two solar & pellet heating systems with the CCT Method and found that both pellet boilers did not use their ability of power modulation. In one system the cause was found to be an inappropriate control of the boiler. Within system simulations the control was modified to enable power modulation. A distinction was drawn between charging the DHW zone and the SH zone of the TES where both the flow rate and the boiler set-temperature for SH was lowered. The variation in the control strategy led to a reduction of the burner starts by 60 %.

4. Requirements for solar & pellet heating systems

The results presented above showed that a modulating boiler operation is superior in terms of both high energetic efficiency and low emissions compared to intermitting boiler operation. But this is only the case if the boiler operation during the complete modulation range, especially in part-load operation, is achieved with low emission and low excess-air factors.

- The excess air of the combustion is of particular interest as low CO-emissions have only been observed with **low excess air values**. Furthermore low excess air is also important to achieve a high energetic efficiency since it reduces flue gas losses.
- Another requirement for a high efficiency of pellet boilers are **low envelope losses**, which is achieved with good insulation. This is important especially during part-load operation because the losses through radiation and convection are proportionally higher in part-load operation.
- For a fast adaption of the output power in order to meet changes in the required load a **small thermal mass and thus a small bulk water volume** is advantageous.
- Attention has to be paid to a **correct dimensioning** of the boiler. Over sizing would lead to frequent on/off cycling of the burner and lower system performance, including also higher electricity consumption.

Beside the characteristics of the boiler the hydraulic connection and the control is important to reach a good system performance. A distinction can be made between a direct connection of the boiler to the heating circuit and a connection to the buffer store. Despite the good results that were shown with a direct connection of a good and properly sized pellet boiler to the heating circuit, in the majority of the cases a **connection to the TES** is the better solution. The requirements that have to be fulfilled for the control of TES charging are:

- At least one temperature sensor within the store to control the power modulation of the boiler. If the TES is a solar combistore, two temperature sensors have to be used in order to detect demand of both, the space heating zone and the domestic hot water zone of the TES. For well stratifying TES, the best control is achieved if the temperature sensors detect an average temperature of the charged zone rather than the temperature at a specific height of the TES.
- In order to control the power modulation of the boiler, the best option is to reduce the volume flow rate of the boiler pump based on an algorithm that takes into account the temperature measured in the TES. Other options are to increase the return temperature of the boiler using a motorized mixing valve, or to reduce the set-temperature for the water leaving the boiler.

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