IEA Bioenergy
Technology Collaboration Programme

Low emission operation of automatic wood boilers operated in cascades

IEA Bioenergy: Task 32

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Wood boiler cascade with four automatic wood boilers and heat storage tank. Photo: Heitzmann AG.

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Content

1 Introduction

Bioenergy is currently the main renewable energy worldwide contributing to about 10 % to the global primary energy supply, as shown in Figure 1 [1]. The IEA estimates the bioenergy supply of 51 EJ in 2010 to double to 102 EJ in 2050 as illustrated in Figure 2 (Pelkmans 2021, [2]). Other estimations vary from 10 % to more than 60 % of the world's energy supply (Duarah al. 2022, [3]) with projections from currently 56 EJ per year to 145 EJ by 2060 (Scarlat & Dallemand 2019, [4]).

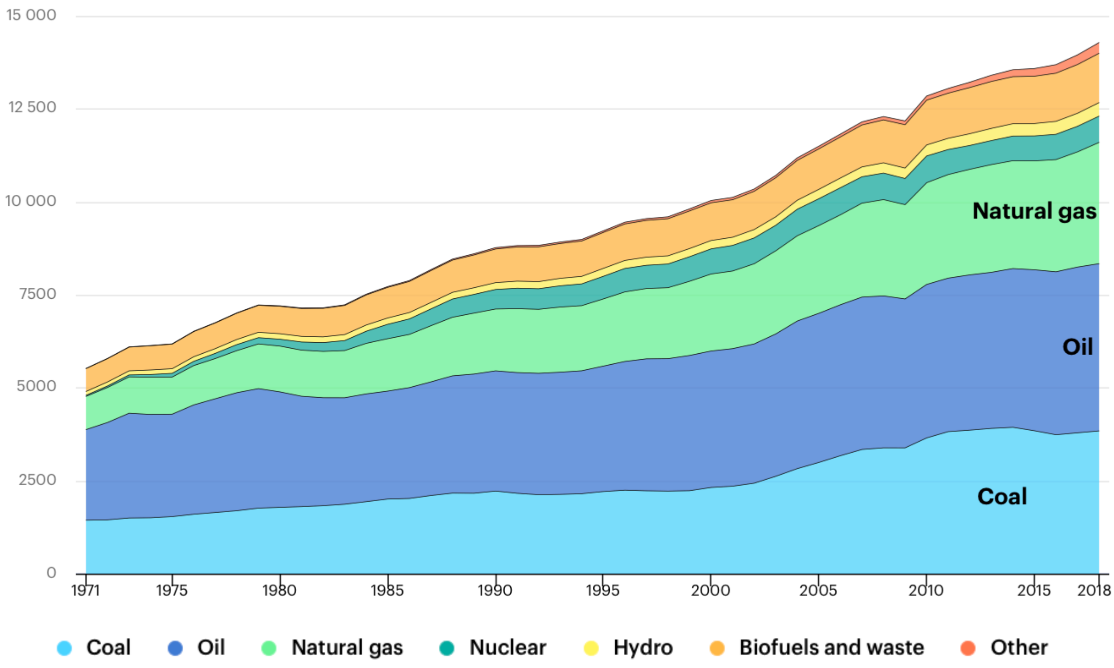


Figure 1 World total energy supply by source from 1971 to 2018 by IEA World Energy Outlook 2022 [1]. Notes: Peat and oil shale are aggregated with coal. Other includes geothermal, solar, wind, tide/wave/ocean, heat and other sources.

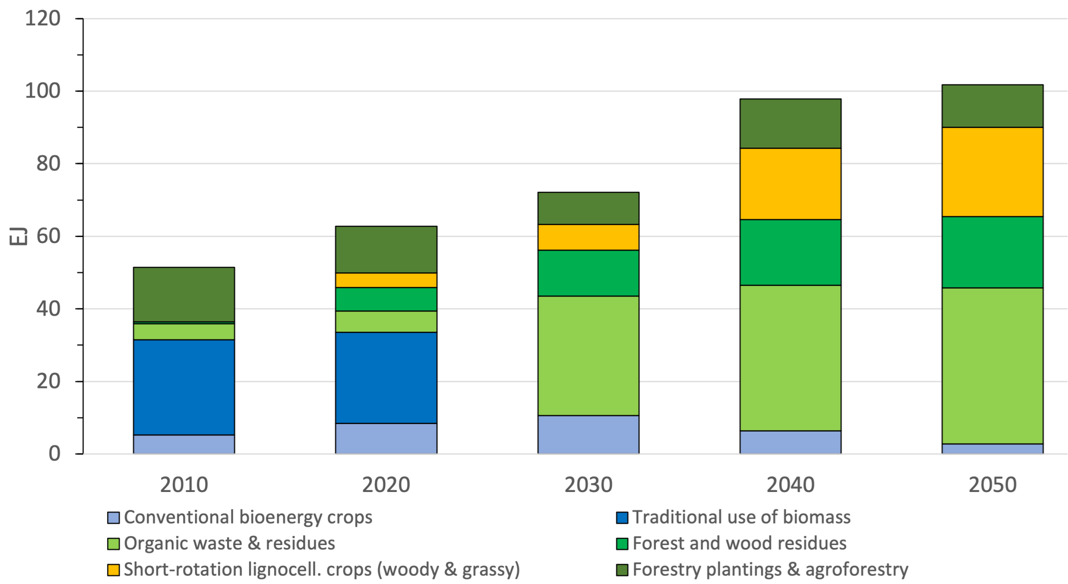


Figure 2 Global bioenergy supply from 2010 to 2050 in the IEA Net-Zero by 2050 scenario [2].

In Switzerland, energy wood contributes with 16 TWh/a (0.06 EJ/a) to around 6 % of the energy consumption of 206 TWh/a (0.74 EJ/a). The sustainably and economically available potential allows an increase of approximately 50 % [5], [6]. In the frame of the Energy Strategy 2050, the use of this potential is aimed at with a focus on applications with high valorisation such as process heat, combined heat and power (CHP) and covering peak demand for buildings in winter to supplement the reduced production of solar and hydro power in winter.

Energy wood including forestry wood residues, wood residues from industry and urban waste wood is mainly used for heat and partly for combined heat and power [7]. Today, mainly combustion systems are applied to provide heat for buildings and district heating with automated wood boilers, often in the size range from 100 kW up to more than 10 MW. In case of CHP, combustion plants are used to drive steam turbines or to heat thermal oil to supply an Organic Rankine Cycle. In addition, a limited number of fixed bed gasifiers are in operation to drive internal combustion engines for electricity production in small-scale applications which are coupled to local heat consumers.

The focus of the present investigation covers the range of 200 kW to 2 MW, where as an alternative to industrial boilers, cascades of three or more usually identical serial devices of smaller wood boilers can be installed. Potential advantages are lower investment cost, the lower height for applications with limited room height, e.g., in residential buildings, the periodic shutdown of boilers for step-by-step service and maintenance, and the possibility to vary the total heat production in a wide load range, e.g., by operation of one single boiler during the summer period. Serial devices in the investigated size range, however, require higher quality fuel compared to industrial boilers, in particular limited water, ash and fines content, and are therefore often operated with wood pellets. In addition, they are commonly equipped with a periodic cleaning and ash removal from the grate, which cause shutdowns and re-starts of the boiler.

While the use of energy wood is often funded due to its advantage with respect to CO_2, biomass combustion contributes to air pollution, mainly to organic pollutants and to Particulate Matter (PM_{10} and $PM_{2.5}$) in the ambient air. As shown in Figure 3, wood combustion contributes to approximately one third of the $PM_{2.5}$ emissions in Switzerland [8].

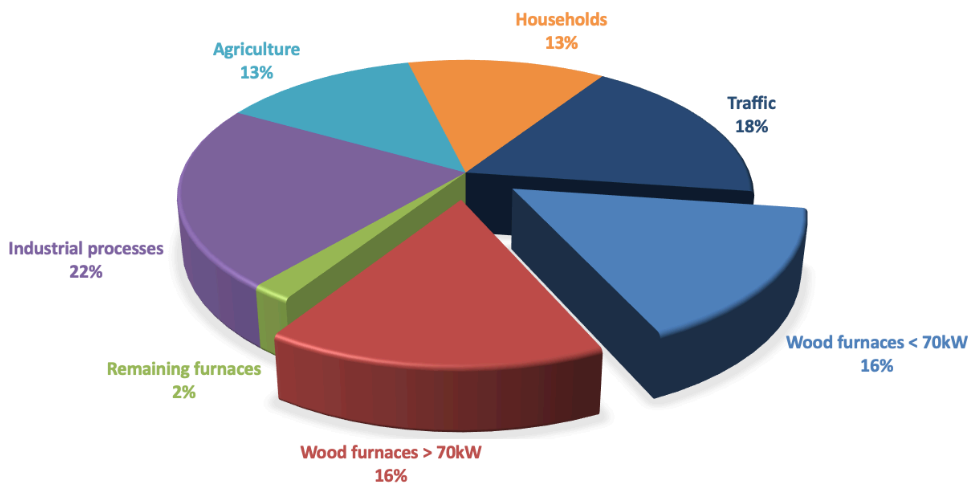


Figure 3 Contribution of different sources to $PM_{2.5}$ in the ambient air in Switzerland [8].

Since the limit values on PM in ambient air are regularly exceeded in residential areas, PM emissions from biomass combustion need to be reduced. One important measure is that wood stoves and log wood boilers need to be properly operated, since inappropriate fuel or operation can cause high emissions. Compared to this, automated boilers are beneficial since the continuous operation enables improved combustion conditions and an operation with controlled air and fuel input. However, in most applications for heat supply, the heat demand is varying which may lead to an unsteady boiler operation with frequent starts and stops or boiler operation at very low load. Such conditions can lead to increased emissions due to non-ideal combustion or due to non-ideal operation of the flue gas cleaning systems such as electrostatic precipitators (ESP).

In Switzerland, Germany, Austria and Italy the quality management system "QM Holzheizwerke®" (QM) has been implemented since 1998 to assist the plant planning and operation of wood heating plants. Since QM aims to reduce non-ideal operation conditions such as start-up of the boilers and low-load operation, it recommends the implementation of a thermal energy storage in the system with a capacity for one hour of the nominal output for one boiler or of two-thirds of the total output in case of two-boiler systems [9]. However, due to economic reasons, such heat plants have often been designed as bivalent systems and equipped with a fossil fuelled boiler for peak-load and for low-load. This results in a fossil share of 10 % to 15 % of the annual heat production at optimum operation as shown in Figure 4, while at non-ideal operation, the fossil share can exceed 20 % [10]. As an alternative, cascade systems with three and more wood boilers are available, which cover a large output range and are economical thanks to series devices with 70 kW to 500 kW output. Since there is little experience with the dimensioning and operation of cascade systems and QM does not yet offer any design guidelines, this topic was investigated in a research project in Switzerland. The work was supported by the Swiss Federal Office of Energy and carried out in cooperation between the university and industry. It includes practical measurements and an accompanying process modelling to investigate how the operation of such systems can be influenced by design and control and how low-emission operation can be achieved [11]. The focus of the investigation is on cascades with three and more boilers with identical output, while for configurations with two boilers, the output is often divided into one third and two thirds of the total output.

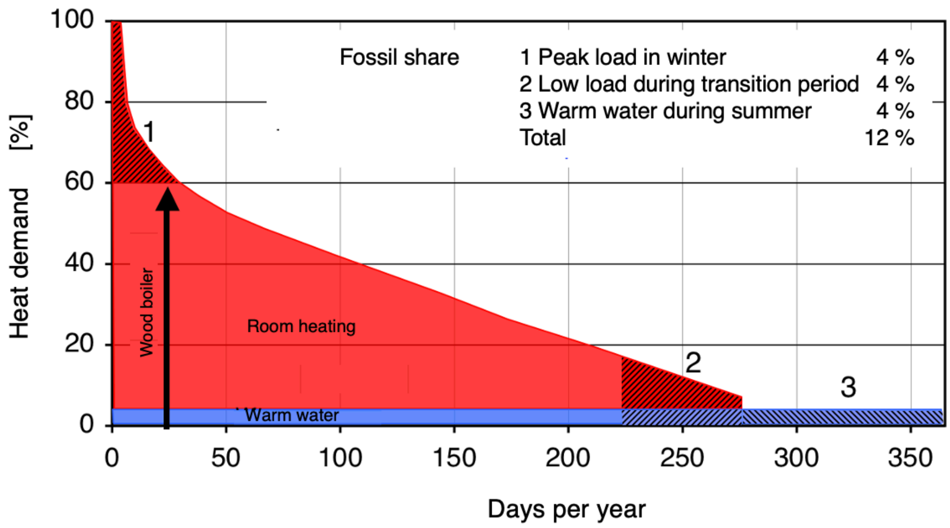


Figure 4 Annual load duration curve of the heat demand for residential heat and share of fossil heat production for a bivalent heating system with one wood boiler dimensioned for 60 % of the maximum daily heat demand [10].

2 Concepts and fundamentals of heating plant design

2.1 Thermal energy storage and heat storage charging status

In a heat accumulator according to Figure 5, stratification is the aim, with the temperature at the top being adapted to the boiler flow and at the bottom to the consumer return. The control system ensures that the heat demand is permanently covered by having the wood boilers follow the average heat demand and the storage tank compensate for fluctuations. The heat storage charging status (short: storage charging status or charging status) (S) serves as the controlled variable. It is calculated as a function of five or more temperatures that are measured in the storage tank by use of one of the following definitions:

In variant 1 according to QM [12], each sensor is defined as 'cold' or 'hot', so that five sensors each contribute 0 % or 20 %. S can take a discrete value of 0 %, 20 %, 40 %, 60 %, 80 % or 100 % and is a measure of the heat available at usable temperature. As Figure 6 shows, the signal is stepped, which is sufficient for controlling one boiler, but not for several boilers. Variant 2 therefore uses a delay, which, however, is not considered here. In variant 3, the sensor below the lowest hot zone is called the 'active sensor' and is given a floating value between 0 % and 20 %, as described in Figure 7. The signal is thus higher resolved and damped and allows more switch-on and switch-off points for multi-boiler systems. It is, however, unfavourable in situations with poor stratification in the storage tank.

In variant 4 according to QM, the medium heat storage temperature T_S is determined from all temperatures and from this a storage charging state between a cold temperature T_c and a warm T_w is determined (Figure 8 and Figure 9). The setpoint for T_s must be selected as a function of the feed temperature and the return temperatures and the signal is influenced by changes in the return temperature. In addition, it is stepped with ideal stratification and is not a measure for the usable heat in case of unstratified (i.e., mixed) heat storage tank. Therefore, variant 5 according to Figure 10 is proposed here, which is introduced in [11] and in which each sensor assumes a sliding value between 0 % and 20 %. The storage charging status determined in this way is identical to an average temperature determined from each temperature which previously to averaging is limited between cold and warm. It is therefore referred to as "limited storage tank temperature" and is advantageous according to experience described in [11].

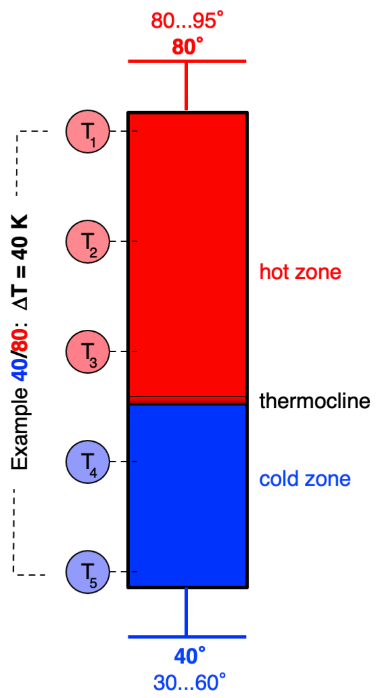


Figure 5 Heat accumulator with stratification and five evenly distributed temperature sensors. The hot zone is often between 80 °C and 95 °C, the cold zone between 30 °C and 60 °C. In the example, 80°/40° with 40 K temperature difference applies.

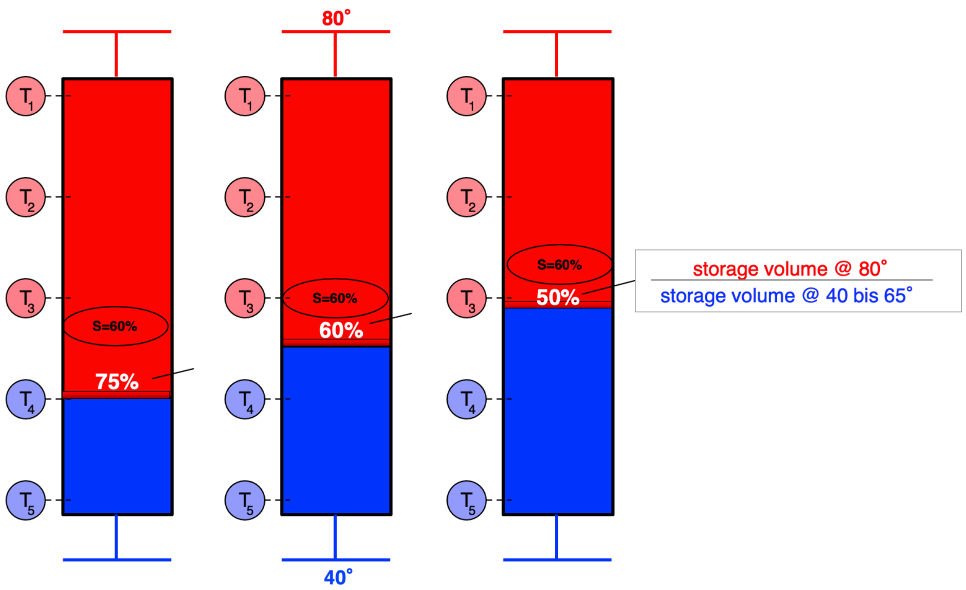


Figure 6 Example for the heat storage charging status according to variant 1. In all three cases, S = 60 % (three warm sensors = 3 x 20 %). This value covers a range of 50 % to 75 % warm storage tank volume.

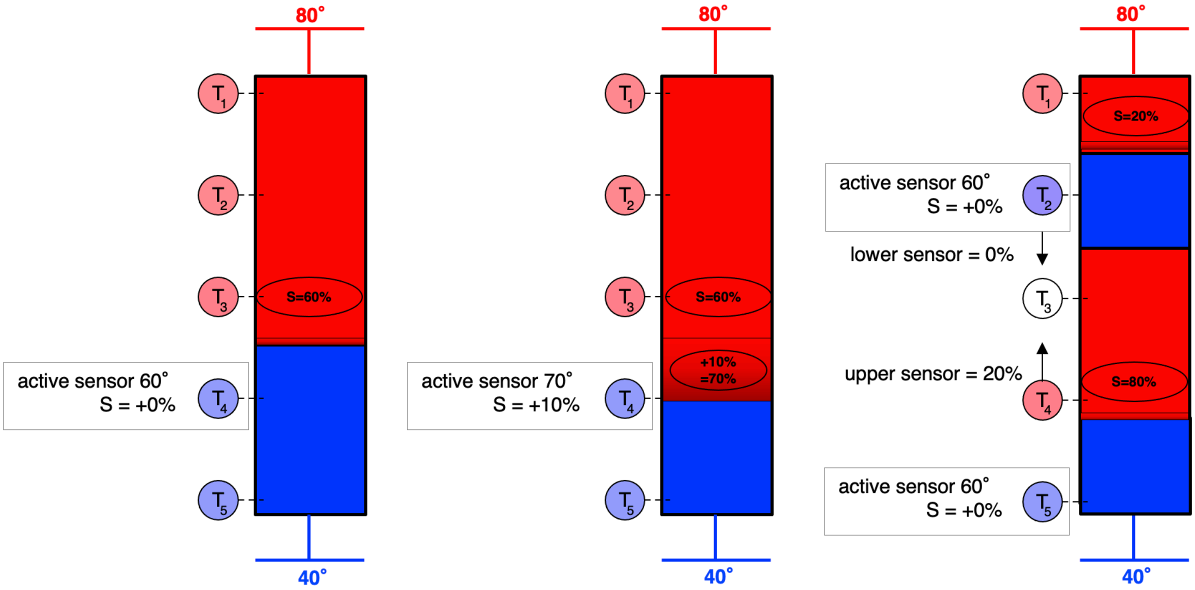


Figure 7 Example of heat storage tank charging status according to variant 3 with active sensor.

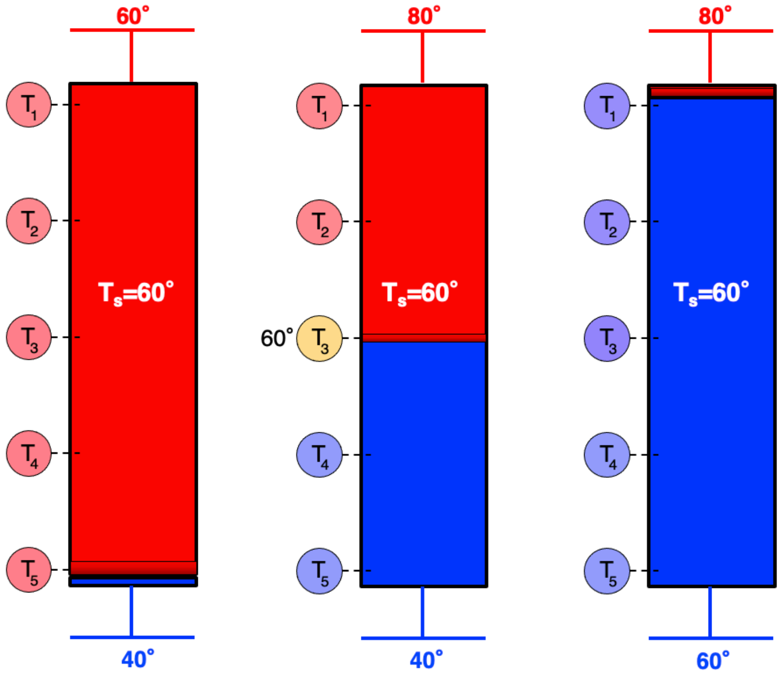


Figure 8 Meaning of a storage medium temperature T_s of 60 °C (variant 4) for three different levels of flow and return temperature.

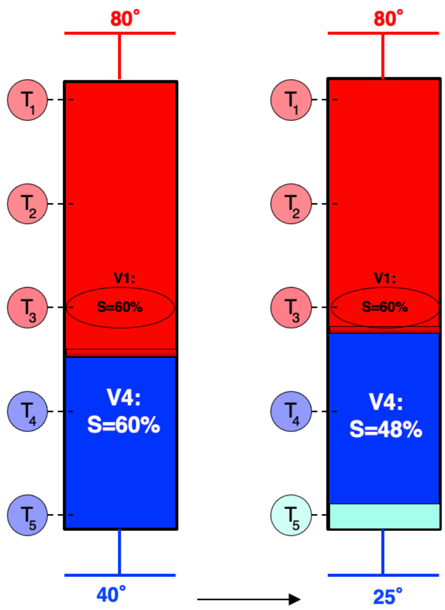


Figure 9 Example of the heat storage charging status according to variant 4 with S calculated from the mean storage tank temperature. In the initial state on the left, S = 60 % according to variant 4 and variant 1. When the return temperature is reduced on the right, S drops to 48 % according to variant 4, while S = 60 % is shown unchanged according to variant 1.

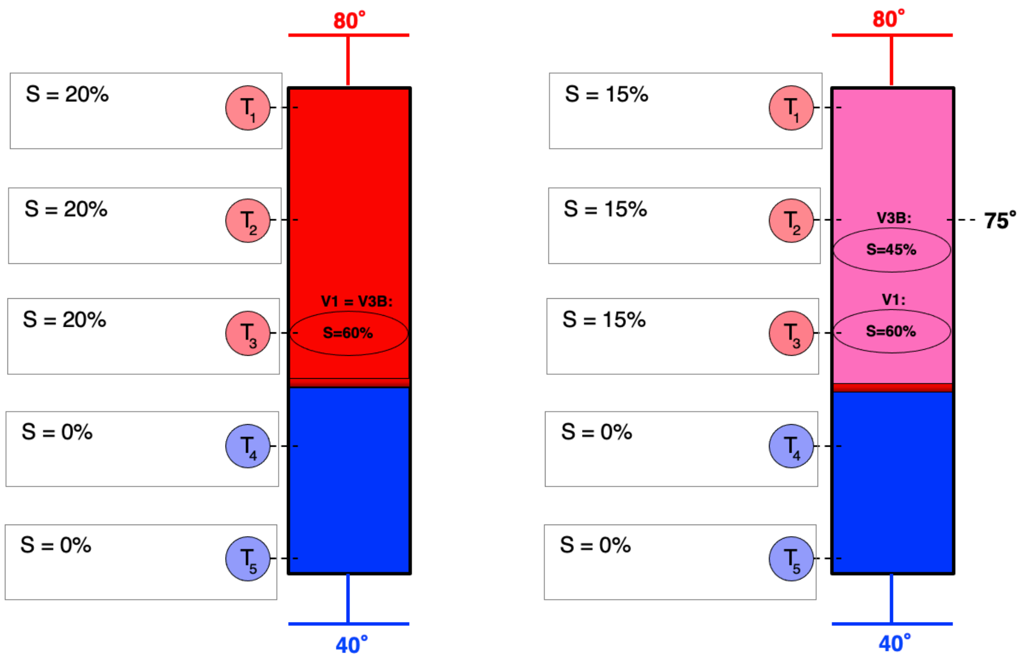


Figure 10 Heat storage tank charging status after variant 5. On the left, variants 1 and 5 provide the value S = 60 %. After the storage tank has cooled down (right), variant 1 still shows 60 %, while variant 5 shows a value that has dropped to 45 %.

2.2 Control concepts for multi-boiler systems

QM describes control concepts for heating systems with two wood boilers that assume seasonal changeovers. For more than two boilers, the control is extended and uses additional information such as the rate of change of S (dS/dt), the duration of operating phases and delay elements. Two concepts are distinguished for switching on and off of the boilers:

Concept A: Individual conditions for *each* boiler to switch-on and switch-off this boiler.

Concept B: General conditions to switch-on and switch-off the *next* boiler in a series of boilers.

Table 1 describes the effect of the control concepts as well as typical switching points. If the storage charging status increases and decreases alternately, a switching point can be passed through repeatedly. With general switch-on and switch-off conditions, more boilers can be started than necessary, which can be avoided with individual conditions, as shown in the example in Figure 11 [13].

Table 1 Typical conditions to switch-on and switch-off boilers for a cascade with four wood boilers.

Operation with storage charging status S	Control concept A	± Boiler 1	± Boiler 2	± Boiler 3	± Boiler 4
	Control concept B	± one Boiler	± one Boiler	± one Boiler	± one Boiler
S decreasing	Switch-on at S =	80 %	60 %	40 %	20 %
S increasing	Switch-off at S =	100 %	90 %	80 %	70 %

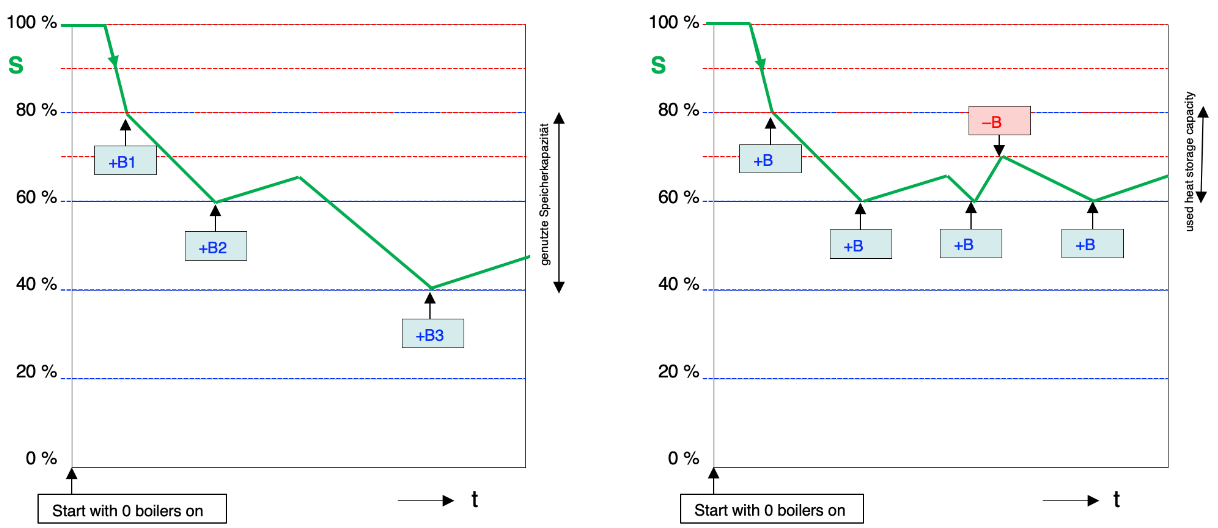


Figure 11 Influence of the control concept on the storage charging status S in an example with increasing heat demand, whereby the storage tank is 100 % charged at the start and no boiler is in operation [13]. Left: control concept A with individual switch-on and switch-off conditions, right control concept B with general switch-on and switch-off thresholds. Example for standard switch-on conditions and without power modulation and without time delays for switch-ons and switch-offs.
+B1, +B2 etc.: Switch-on of boiler 1 or boiler 2, etc.
+B, -B: Switch-on or switch-off of any boiler [13].

3 Real-life investigation

3.1 Investigated heating plants

Three heating plants were investigated in the project, which are described in Table 2 and have boilers with power modulation and automatic ash removal.

Table 2 Investigated heating plants.
*for two boilers, control concepts A and B become identical.
**the other boilers are operated at constant output.

	Plant 1	Plant 2	Plant 3
Fuel	Wood chips	Wood pellets	Wood pellets
Number of wood boilers	4	3	2
Boiler output	4 x 330 kW	100 kW + 2 x 80 kW	2 x 85 kW
Heat storage capacity for 2/3 of total installed capacity at ∆T 40 K	69 min	110 min	102 min
Control concept	Switch-on: Phase 1: concept B Phase 2: concept A	concept A	Switch-on: concept A*
Storage charging status S Reference temperatures	Variant 5 20 °C – 80 °C	Variant 4 30 °C – 80 °C	Variant 4 40 °C – 80 °C
Power control and Modulation range	all boilers 50 % – 100 %	one boiler** 40 % – 100 %	all boilers 35 % – 100 %
De-ashing interval of the grate	12 h	8 h	7 h

3.2 Results

Since start-up can lead to increased emissions, the number of starts is evaluated as a criterion according to the association of Swiss authorities and universities in the field of air pollution control (Cercl'Air). According to a recommendation of Cercl'Air, the number of starts is limited to a maximum of five starts per heating day and 500 starts per year for heating systems from 100 kW and up, while for systems up to 100 kW, a maximum of 1000 starts is accepted [14].

In the present report, all ignition cycles are counted as a start, regardless of the boiler temperature, and thus the start-up after ash removal is also counted as start. Further, the number of starts per year for multi-boiler systems refers to the sum of the starts of all boilers. If the quality of the boiler starts is independent of the output and the load is to be evaluated, the number of starts per boiler is relevant [11].

Table 3 shows that the investigated plants initially had 611 to 1030 starts per year and boiler and 1835 to 2469 starts per year and plant. In plant 1, the control concept was changed to individual start-up conditions after phase 1 and 136 days were recorded. Extrapolated, this results in a reduction in the number of starts by 44 % to 344 starts per boiler and year.

Figure 12 shows the number of daily boiler-starts in system 1 as a function of the total running time of all boilers, which is roughly proportional to the daily heat demand. For the plant with four boilers, the maximum boiler running time is 96 hours per day, which is why the x-axis is limited to this value. The red line shows the starts necessary for ash removal cycles. The upper graph describes the starts with general switch-on and switch-off conditions with about twice as many starts as necessary for ash removal. By switching to individual conditions in the lower graph, the number of starts is significantly reduced, namely by 44 % as an annual value according to Table 3. The evaluation also shows that the number of starts is only slightly greater than necessary for ash removal.

Table 3 Number of annual boiler-starts.
Phase 1: original control concept. Phase 2: modified control concept. *Extrapolation.

	Number of boilers	**Phase and control concept**	**Annual starts of the heating plant**	**Annual starts per boiler**
Plant 1	4	Phase 1 concept B	2469	617
		Phase 2 concept A	1377*	344*
Plant 2	3	–	1835	611
Plant 3	2	–	2060	1030

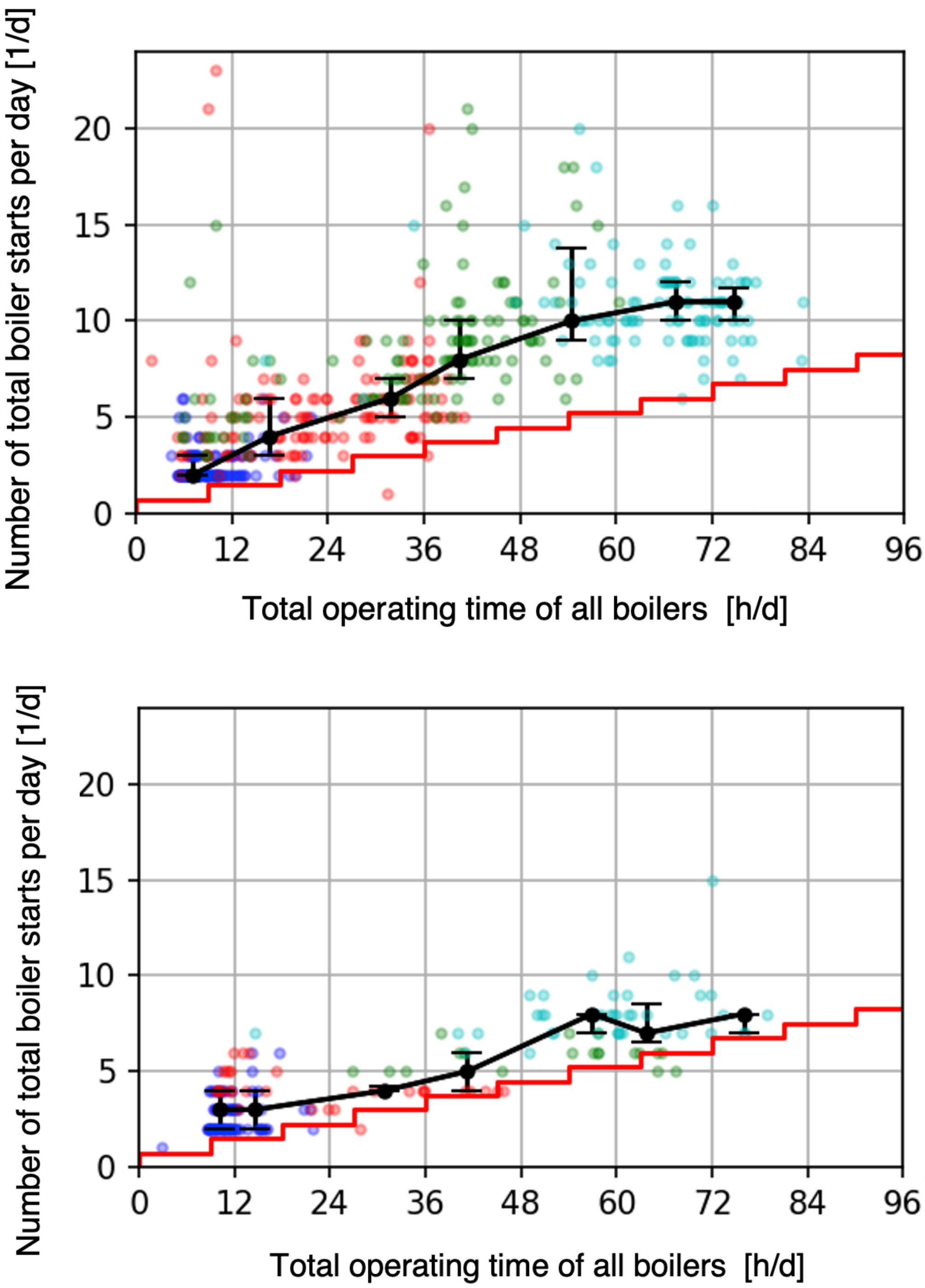


Figure 12 Number of daily boiler starts as a function of the summed operating hours of four wood boilers [11]. Above: Operation with general switch-on and switch-off conditions (original control concept). Below with individual switch-on and switch-off conditions (modified control concept). Maximum number of boilers in operation: blue = 1, red = 2, green = 3, turquoise = 4. Black: median and quartiles. Red line: Starts due to ash removals.

The evaluations show the following further results described in [11]:

- Starts of more than one boiler followed by shutdowns after a short running time caused by a simultaneous heating of all hot water tanks of the heat consumers.
- Short-term switching-on and switching-off of boilers, which can be avoided by a suitable control signal as according to variant 5, sufficient differences between the switching points as well as reference temperatures that are adapted to the boiler flow or mains return temperature according to QM.
- To avoid short run times, the power modulation should be triggered quickly after a boiler start when the storage charging status increases and applied to all boilers.
- An unsuitable linking of switch-on and switch-off conditions can lead to oscillation due to unnecessary boiler switching and can be avoided by evaluation of suitable settings.
- Preset time windows for ash removal can lead to unnecessary starts.

4 Process modelling

4.1 Model description

The model describes the thermodynamic and control behaviour of a wood-fired heating plant with an arbitrary number of boilers and a heat storage tank according to Figure 13 to cover a dynamic heat demand. It includes the heat generation with any number of wood boilers, a stratified heat storage tank and a controller for which different concepts for the control of the plant can be simulated. For a given configuration, this simulates the temporal behaviour for different control concepts. The model is based on the energy balance via the heat storage tank. When a correspondingly high storage charging status is reached, the boilers are switched off. If the storage tank is completely discharged and the current heat output demand exceeds the boiler output, the requirements are not met, and the configuration is not taken into account.

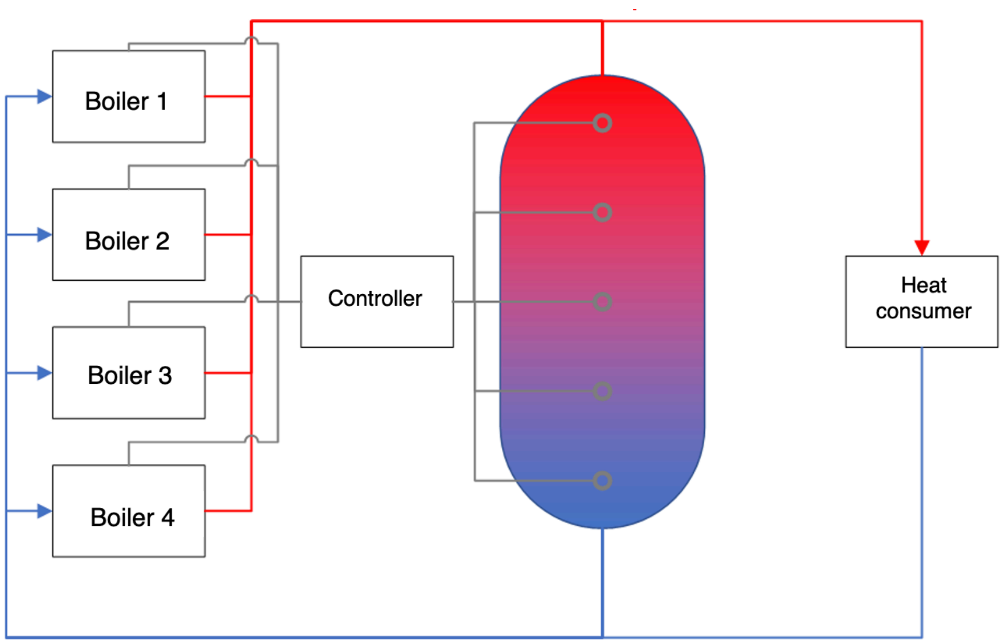


Figure 13 Flow diagram of the model approach. Blue lines: Return lines with low temperature. Red lines: Flow lines with high temperature. Grey lines: Signals from the temperature measurement in the heat storage tank and control signals from the controller to the boilers.

The model is based on the energy balance via the heat storage tank. The stored heat Q_S is used to compensate for differences between the instantaneous output of the boilers$\dot{Q}_K$ and the heat output demand $\dot{Q}_{BN}$

$$\frac{\partial Q_S}{\partial t} = \dot{Q}_K - \dot{Q}_{BN}$$

The boiler output corresponds to the sum of all boiler outputs:

$$\dot{Q}_K = \sum_{i=1}^{n_K} \dot{Q}_{K,i}$$

The heat in the storage tank is limited by the storage capacity $Q_{S,nenn}$:

$$0 \leq Q_S \leq Q_{S,nenn}$$

The storage capacity is specified using a time constant τ_S, which describes the ratio of the storage capacity to the sum of the installed boiler outputs $\dot{Q}_{K,nenn,i}$.

$$Q_{S,nenn} = \tau_S \cdot \sum_{i=1}^{n_K} \dot{Q}_{K,nenn,i}$$

When the upper limit is reached (storage tank full), the boilers must be switched off. When the lower limit is reached (storage tank empty), the storage tank can no longer provide any heat output. If the heat output demand is higher than the boiler output when the storage tank is empty, a heat deficit arises that should be covered as quickly as possible. In the model, the heat deficit is taken into account by differentiating between the heat output demand of the consumers $\dot{Q}_{BN}$ and the heat output demand of the network

$$\dot{Q}_{BN} = \dot{Q}_{BN} + \dot{Q}_K - \frac{\partial Q_S}{\partial t} - \dot{Q}_B$$

The control system comprises an outer loop of the cascade control for switching the boilers on and off according to variant 5. The output control of the boilers serves as an inner control loop and is based on a PI controller. The inertia of the boilers is taken into account on the basis of a measurement of the step response by a start-up time of 30 minutes, which corresponds to the situation determined in a plant according to Figure 14 with about 15 minutes delay plus 15 minutes ignition and power ramp-up. This is used to model systems with one to four wood boilers with variation of storage capacity, modulation range and heat demand peaks.

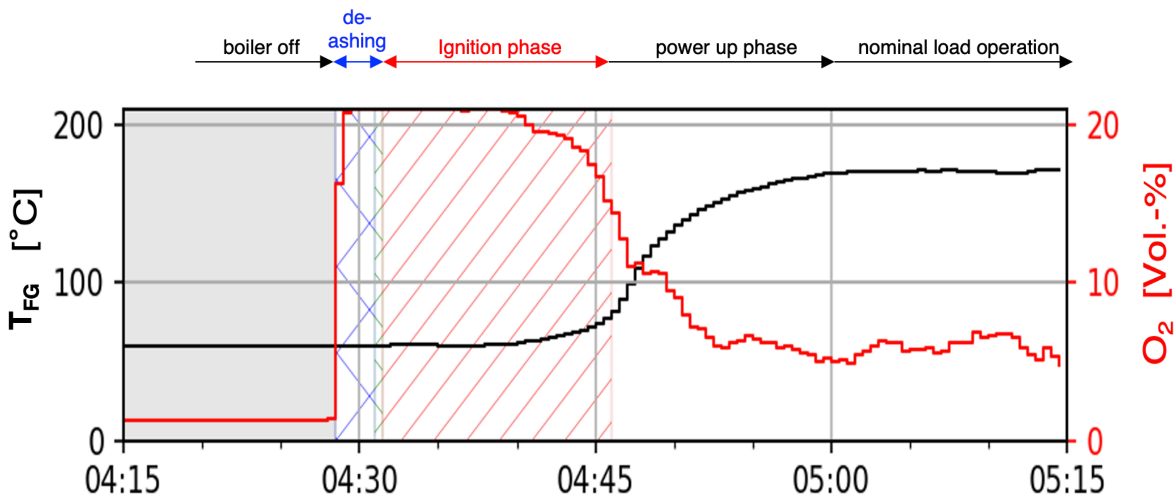


Figure 14 Flue gas temperature and oxygen concentration in the flue gas as function of time during a start-up of the boiler [11].

The load profile of the investigated plant 1 serves as the basis for the heat demand in the model. This system is used to supply a district heating network, which has two distinct load peaks for hot water in the daily cycle as shown in Figure 15. Individual daily profiles are used for modelling, from which a daily demand profile is derived using meteorological data. For the simulation, operation over a year is calculated in time steps of one minute.

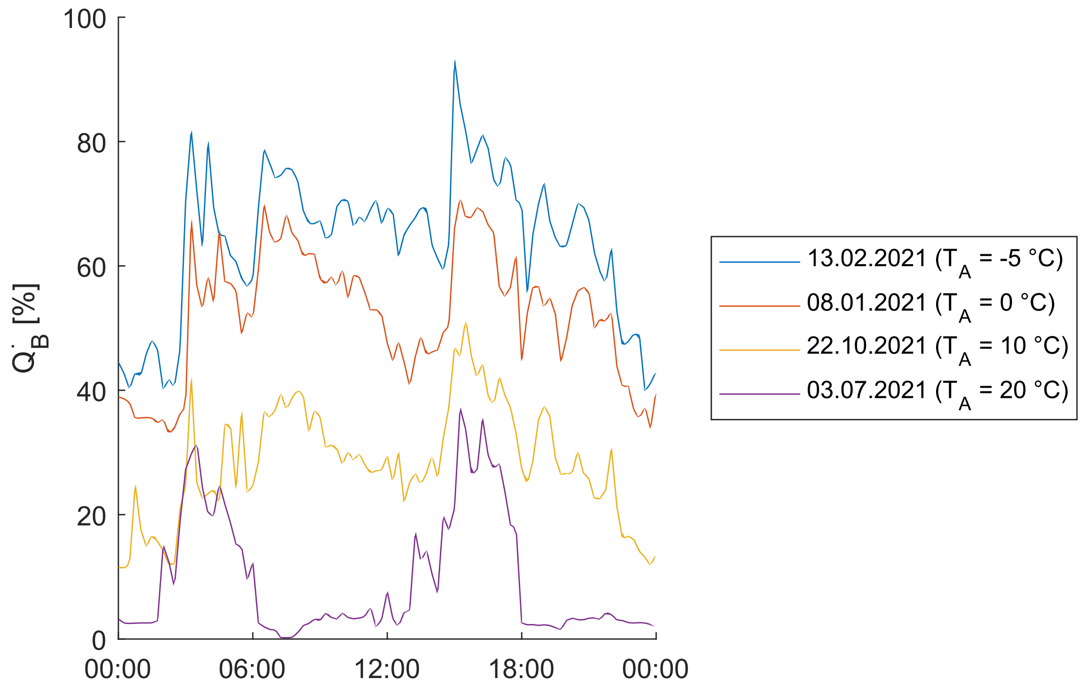


Figure 15 Measured daily load profiles of a district heating network in the Swiss midlands to calculate the current heat demand. T_A = Daily mean value of the ambient temperature.

The load profiles show load peaks before 6:00 h and before 18:00 h, which are caused by the provision of hot water and place high demands on the cascade and power control of the heat generation. Four daily profiles at ambient temperatures between -5 °C and 20 °C are used for the model and daily profiles are interpolated using the ambient temperatures known from meteorological data over a year [11]. Figure 16 shows the load curve and Figure 17 the simulated annual heat output profile.

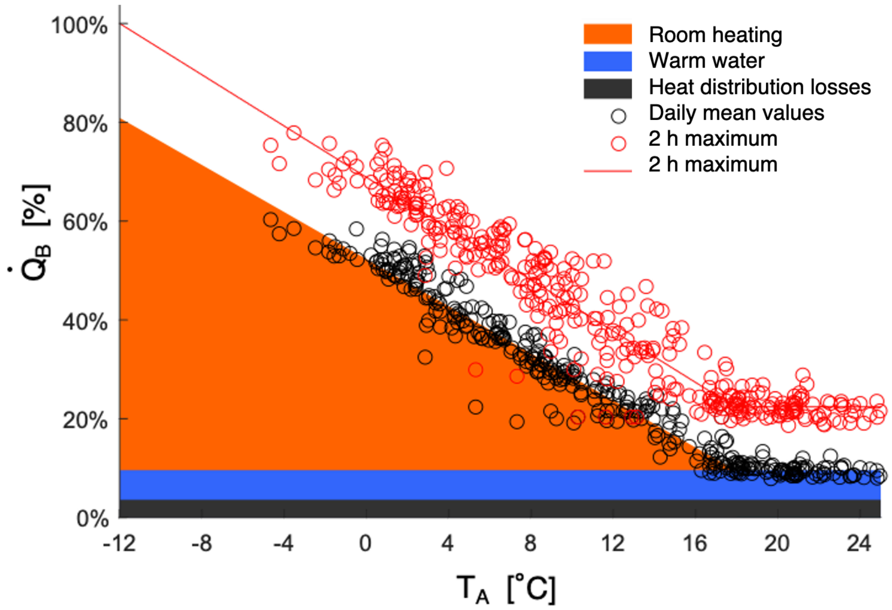


Figure 16 Stacked load characteristic of the average daily heat demand and the 2 hours maximum heat demand as a function of the daily average ambient temperature related to the installed boiler capacity. Points: Measured data.

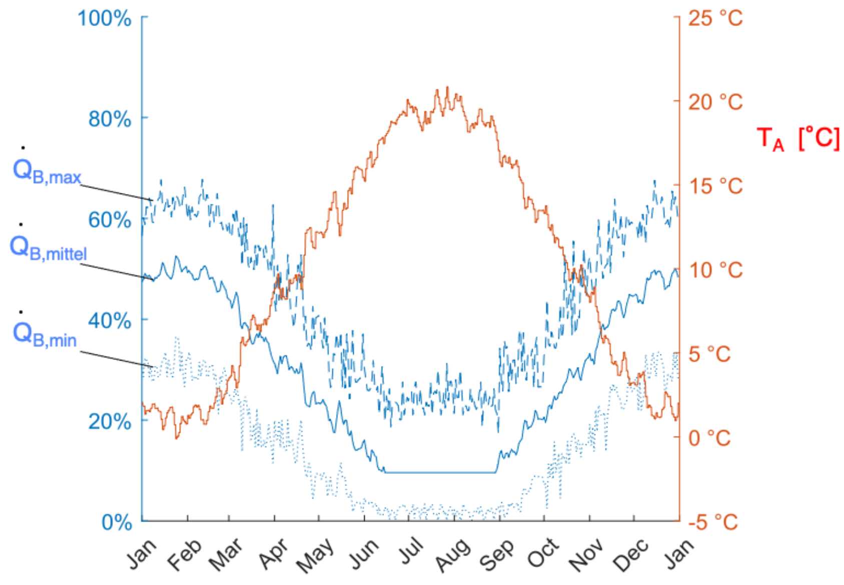


Figure 17 Heat demand and daily mean temperature during one year (simulation based on meteorological data for the investigated site).

The model was validated by measurements on a boiler with heat storage tank in different situations, e.g. the response on a step of the heat demand as shown in Figure 18 [15].

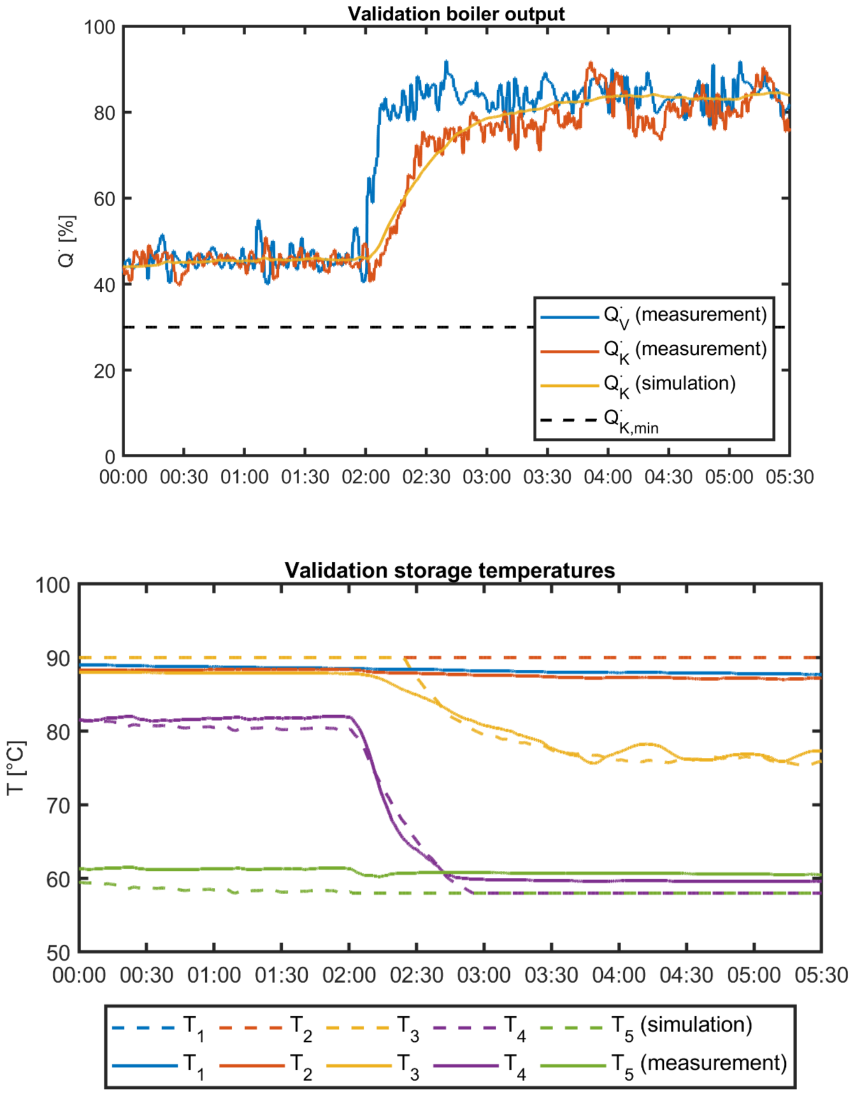
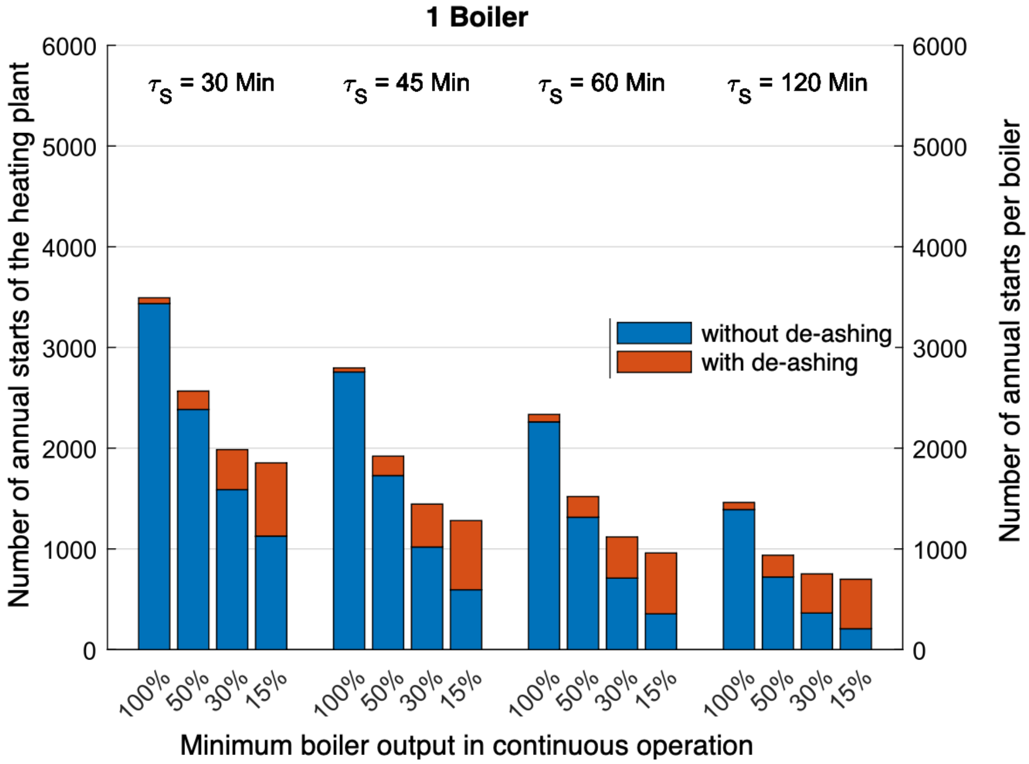


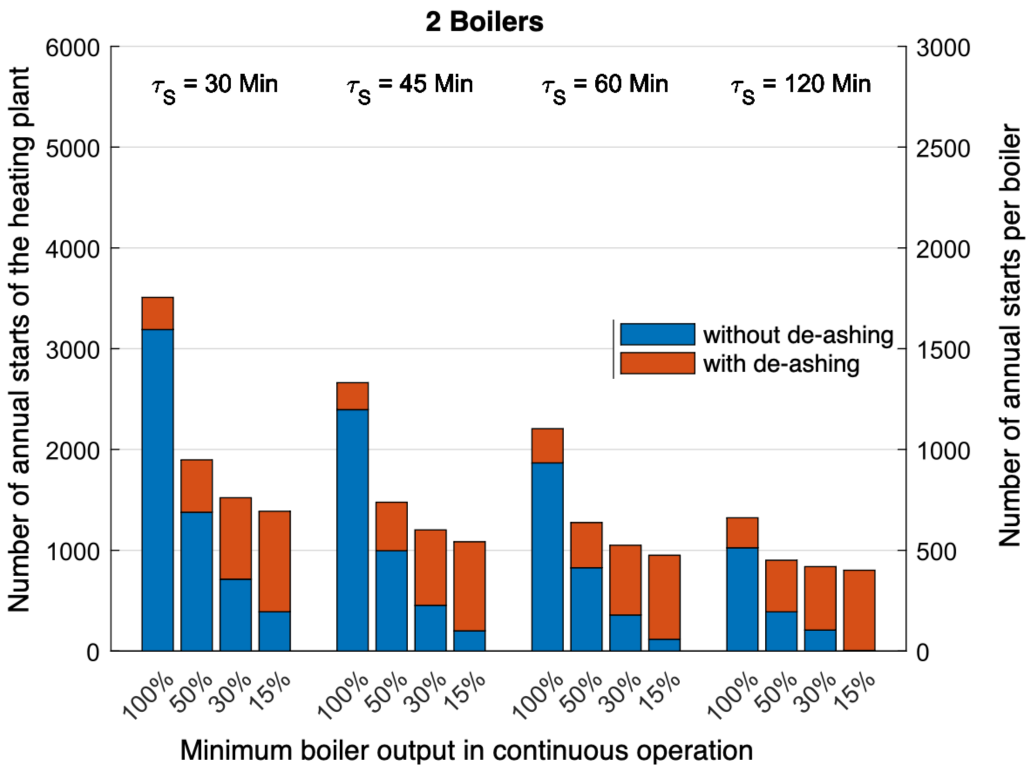
Figure 18 Validation of the model by comparison of measured data and simulation results. Above: Measurements of the boiler output as function of time during a step of the heat demand. Below: Temperatures in the heat storage tank during a step of the heat demand [15].

4.2 Results 1: boiler starts and plant dimensioning

Figure 19 shows the number of boiler-starts resulting from the simulation over 365 days for systems with one, two, three and four wood boilers. The plants with one and two wood boilers serve to visualise the theoretical limits and the corresponding requirements for the modulation capability of boilers. However, the focus of the present investigation are cascades with three and more boilers.
The total values of the starts are divided into the number of starts that would occur without automatic ash removal to cover the varying heat demand and such starts that are caused by the boiler shutdowns for the periodic de-ashing cycles. The results shown here and further calculations [11] show the following trends:

- For cascade systems with three boilers, periodic de-ashing, 60 minutes of storage capacity and power modulation from 50 %, the model results in around 1500 annual starts of the system or around 500 starts per boiler.
- Without power modulation, the values are about 40 % higher.
- In plants with two boilers, ash removal causes less than a third of the starts, with three or four boilers about half.
- Two instead of three boilers cause more starts per boiler but fewer starts of the entire plant. With four boilers, both, the starts per plant and the starts per boiler increase.
- Doubling the storage capacity to 120 minutes reduces the number of starts by about 25 %, reducing it to 40 minutes increases it by about 20 %.
- Reducing the load peaks to smooth the demand profile at a maximum of 60 minutes of storage capacity can reduce the number of starts by around 25 %. At 120 minutes of storage capacity, there is no longer any discernible influence.





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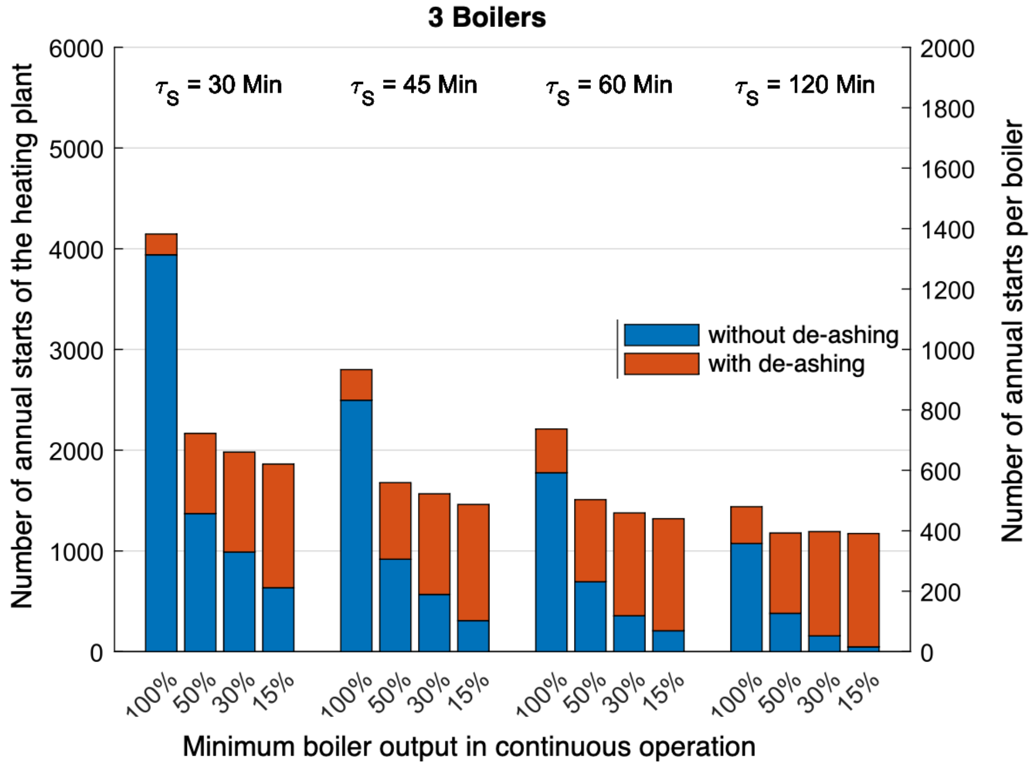

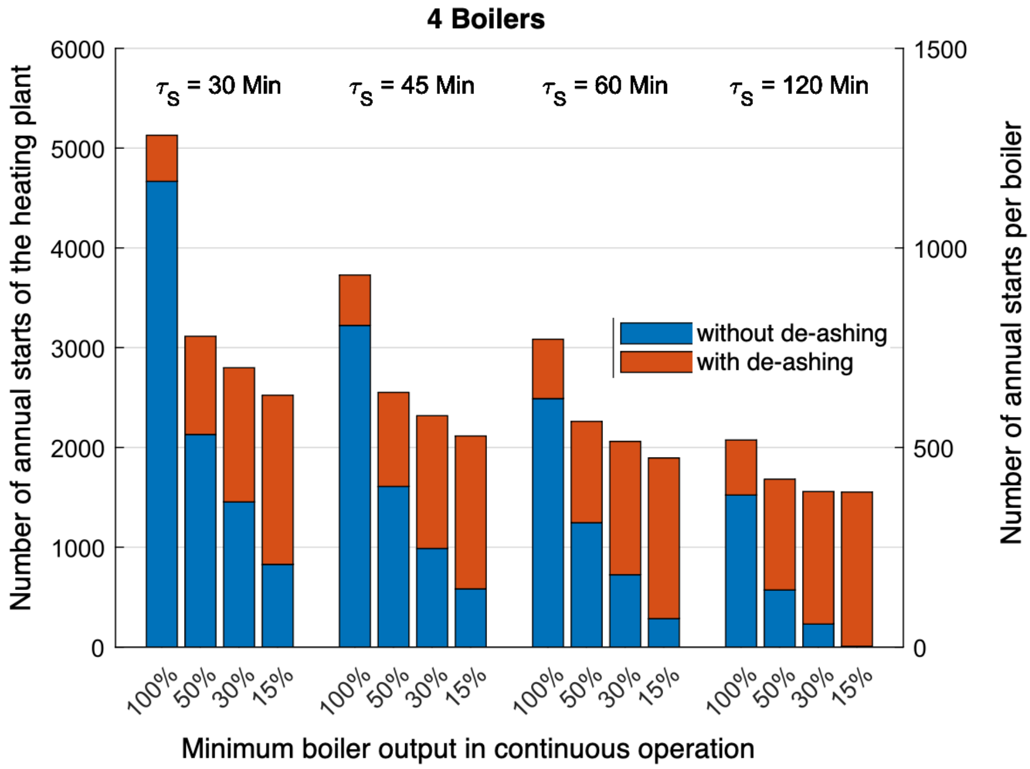

Figure 19 Number of annual starts as a function of minimum boiler output and storage capacity for cascades with one and two wood boilers (previous page), and three and four wood boilers (this page). Left scale: Number of starts of the system, right scale: number of starts per boiler.

4.3 Results 2: Influence of low-load operation

Since low-load operation can lead to increased pollutant emissions, QM recommends a minimum utilisation of 12 hours per day at minimum output for wood boilers. In the following simulation, this condition is assumed as given and the heat is generated using fossil fuels if the requirement is not met. The results in Table 4 show that the following configurations enable fossil-free operation: Single boiler systems with modulation from 10 %, two boiler systems from 30 %, three boiler systems from 40 %, four boiler systems from 60 %.

Table 4 Fossil share of annual heat demand with compliance with the low-load condition for wood-fired heating plants with one to four wood boilers for different control ranges. Green: 0 % fossil, blue: < 5 %, orange: < 15 %, red: ≥ 15%.

Power modulation	Number of wood boilers			
	1	2	3	4
100 %	97 %	27 %	17 %	12 %
90% – 100 %	66 %	24 %	16 %	11 %
80% – 100 %	53 %	22 %	15 %	11 %
70% – 100 %	44 %	20 %	13 %	3 %
60% – 100 %	35 %	18 %	12 %	0 %
50% – 100 %	26 %	16 %	2 %	0 %
40% – 100 %	19 %	14 %	0 %	0 %
30% – 100 %	13 %	0 %	0 %	0 %
20% – 100 %	10 %	0 %	0 %	0 %
10% – 100 %	0 %	0 %	0 %	0 %

5 Conclusions

The cascade systems investigated enable fossil-free heat production with energy wood. Before optimisation, the practical plants had more than 600 annual starts per boiler and over 1800 starts per plant. About half of these are a result of automatic grate de-ashing processes. One plant was optimised by taking the periodic de-ashing into account in the control system (e.g., by forced de-ashing after a boiler shutdown and before reaching the maximum operation period), reducing load peaks, changing the control concept and expanding the bandwidth of the power modulation. This reduced the number of starts to 350 per year and boiler.

The study confirms the benefit of a heat storage tank and QM's recommendation of one hour of storage capacity for two-thirds of the capacity installed in a two-boiler system. The analysis shows that the storage requirement does not decrease for three and four boilers and the storage dimensioning is therefore recommended even then. The following optimisation measures are also shown for the systems:

1. Conditions to switch-on the boilers should be based on a storage charging condition which corresponds to the high temperature level of the feedwater required by the consumers.

2. The switch-on condition for the first boiler should be selected high, while the switch-on condition for the last boiler should be selected low.

3. The power modulation should be enabled early after a boiler start and applied to all boilers and, if possible, start from approximately 50 % or lower of the nominal load.

4. With up to one hour storage capacity, operation can be improved by smoothing pronounced load peaks.

5. Gaps in heat production due to predictable boiler shutdowns for periodic de-ashing should be anticipated e.g., by a proactive increase of the heat output of the remaining boilers.

6. The control and parameter setting should be comprehensible and adjusted in case of changes in boundary conditions.

7. Since the periodic de-ashing cycles cause the majority of the starts during optimised plant operation, a further reduction of the starts would require an extension of the ash removal intervals.

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