

Alternative designs of waste fired combined heat and power plants allowing for improvements in steam data

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The use of ash-rich fuels is projected to increase in the near future, to substitute for fossil fuels in our ambition to reduce CO₂ emissions and encourage a circular economy. The combination of a more dynamic plant operation and the use of fuels with higher ash content will increase aerosol formation. This may potentially result in reduced lifetime and efficiency of the plants due to ash deposition. Avoiding deposition damage is critical and may lower maintenance and increase efficiency in several industrial sectors. The competition between chlorine and sulfur to react with alkali (sodium or potassium) to form either chlorides or sulfates is an important part of deposition related problems.

In this work the potential for increasing the electrical efficiency in bio- and waste fired

combined heat and power (CHP) plants is analyzed. Different plant configurations and operational strategies have been investigated using a thermodynamic modelling tool. The models are based on an existing waste fired CHP as a reference plant. Input data is gathered from the plant based on measurements at several different locations in the boiler. The result shows that a substantial increase in electrical efficiency can be obtained without increasing the steam temperature by implementing steam reheating. An even greater increase can be obtained by combusting a secondary fuel in a separate boiler interconnected with the primary boiler on the steam side. This will maximize the utilization of fuels.

1 Introduction

In line with the global goal of reducing the impact of climate change, several countries have set national goals. These goals vary in both ambition and time frame but will all require a transition with respect to energy consumption and conversion technologies. [1] As an example, the national goal for Sweden is set for all sectors to be independent of fossil fuels to achieve a net zero annual emission of CO₂ before 2045. In addition, Sweden also aims to become a nation with net-negative CO₂ emissions after 2045. [2] The biogenic and waste-derived resources will play an important role as a resource for production of materials, chemicals and as an energy resource for fuel, heat, and power generation. Biogenic resources from forest, agriculture, and maritime environments can be used assuming a sustainable production and harvest.

An important step in reaching a society that can rely only on renewable resources in a sustainable way is to have a high resource efficiency. This does, however, not imply that it necessarily is the best idea to maximize the efficiency of every individual process. The production of different materials, energy carriers and chemicals will be related to indi-

vidual properties of the raw material and one source will not be suitable for all purposes. Also, different parts from the same source, e.g. stem wood, bark and branches from a tree, will most likely also be suitable for different purposes. Stem wood has the highest value and could be used for lumber, pulp and paper production. This means that, for example, a heat and power plant that can operate with a flexible fuel intake and still maintain a relatively high energy efficiency will be a better option from a system perspective than if it would have run solely on high quality fuel that can be used for other purposes.

The quality of a fuel reflects its properties, heating value and composition. There are large variations in quality, i.e. composition, between different biogenic fuels even though they as a group are considered to have a low quality compared to for example coal. [3, 4] One of the main parameters to consider is the ash and its composition. Ash particles may deposit upon surfaces inside the boiler which will reduce the heat transfer but could also corrode the surface material. This type of corrosion is often referred to as high-temperature corrosion (HTC). The probability for an ash particle to be deposited depends on its physical properties, especially the melting point. A molten ash particle becomes sticky which increases the probability for the particle to deposit on a surface after impaction. One group of especially problematic species related to HTC are the alkali (sodium and potassium) chlorides. [5, 6] These species have a relatively low melting point, increasing the risk of deposition, and are also highly corrosive. [7, 8] Some of the highest alkali and chlorine contents in biomasses are found in residues from both land- and sea-based cultivation. Also waste streams, both household and industrial, are also generally high in alkali and chlorine. [9-12] A commonly used strategy to reduce the risk of deposition and HTC is to operate the boiler with heating surfaces temperatures kept below the melting point

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of the expected ash components. Such a strategy will reduce the demand for cleaning and maintenance of the unit but will also put a limit to the temperature of produced steam. Keeping the steam temperature low will lower the potential for power generation. This makes these fuels more suitable for generation of heat rather than for power generation.

This paper aims to investigate the possibility to increase the electricity generation from low-grade biogenic and waste derived fuels. Both single and dual fuel systems are included looking at the potential when biomass and waste-fired steam systems are combined; new biomass boilers can be connected to the steam cycle of existing waste-fired systems, depending on existing infrastructure conditions, to enhance capacity but also to improve fuel efficiency and this work aims to identify potential improvement in fuel efficiency for such hybrid systems. The plant Lillesjöverket in Uddevalla, Sweden, will be used as a reference plant for experimental and process modeling purposes.

2 Methodology

As mentioned, the Lillesjö CHP located in Uddevalla, Sweden, is used as a reference plant. The boiler is of moving grate type. The plant has a generating capacity of 36MW of heat and 10MW of electricity. The waste is a mixture of approximately one third of municipal solid waste and two thirds of industrial waste at a maximum rate of 14.8 ton/h. A schematic drawing of the boiler is shown in Figure 1. The boiler has an approximate height and depth of 23 m and 4.5 m respectively. The primary air is fed through the moving grate and the secondary air is fed to the boiler four meters above the grate. The distribution between primary and secondary air is 60/40. The boiler produces steam at 400 °C and 40 bar that is fed to the steam turbine. Heat for district heating is extracted in two steam condensers, operating at two different steam pressures, and a flue gas condenser.

2.1 Measurements

Figure 1 indicates the seven measurement positions (M1 to M7) used in this work. M1 to M3 are located along the burnout zone above the grate and M4 to M6 are located along the super heater section. The last position, M7, is positioned at the boiler flue gas exit before the flue gas cleaning. These ports were used to measure flue gas temperature and composition. The temperature was measured using a suction pyrometer at a depth of 2 m. Gas composition measurements were carried out using a heated extractive sampling probe, also reaching 2 m into the flue gas stream. The sampled gas was subsequently analyzed using an FTIR and a paramagnetic oxygen analyzer. This system is moved around to be able to measure in the different measurement ports M1 to M7. This means that the concentration can only be measured in one port at a time. How-

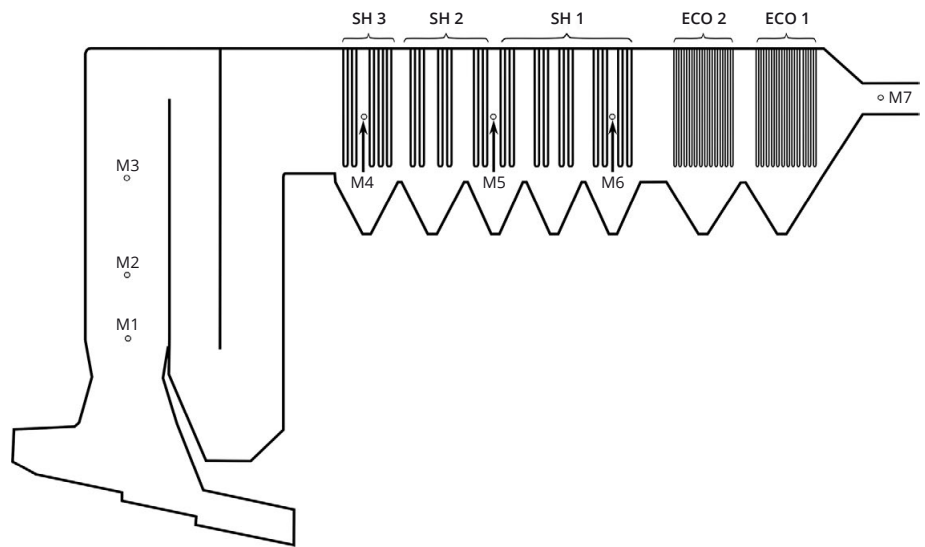


Fig. 1: Positions at the Lillesjö combined heat and power plant used for measurements in this work.

ever, next to M7 (50 cm downstream) is another measurement position (not shown in Figure 1) used for continuous flue gas measurements for control purposes. The measuring principle is the same with the flue gases being extracted via a heated sampling line connected to an FTIR and a paramagnetic analyzer for oxygen. This system is used to follow any eventual variation while measuring with the other system throughout the boiler. The two systems were compared when the movable system measured in M7. The comparison showed a good agreement for all components of interest in this work.

2.2 Plant simulations

Different plant configurations are evaluated thermodynamically using the software Ebsi-

lon Professional. A detailed model based on the Lillesjö CHP plant is used as a reference model (see Figure 2) that also acts as the base model from which the models for different configurations are derived. As mentioned earlier, the Lillesjö CHP plant produces steam at 400 °C and 40 bar that is used for electricity generation and has two steam condensers operating at two individual pressures. The heat released in the steam condensers is used to generate hot water for the local DH-system. The temperature of the DH-water coming into the plant is increased prior to the steam condenser utilizing heat from the flue gases in a flue gas condenser. It should be mentioned that the plant is operated slightly different depending on season and heat demand. The data of the generated steam re-

Tab. 1. Some temperatures and pressures used in the reference model.

Primary steam		Pressure levels [bar]			Flue gas temperature after FG-condenser [°C]
Pressure [bar]	Temperature [°C]	Feed water heater	Steam condenser 1	Steam condenser 2	
40	400	11	0.85	0.39	55

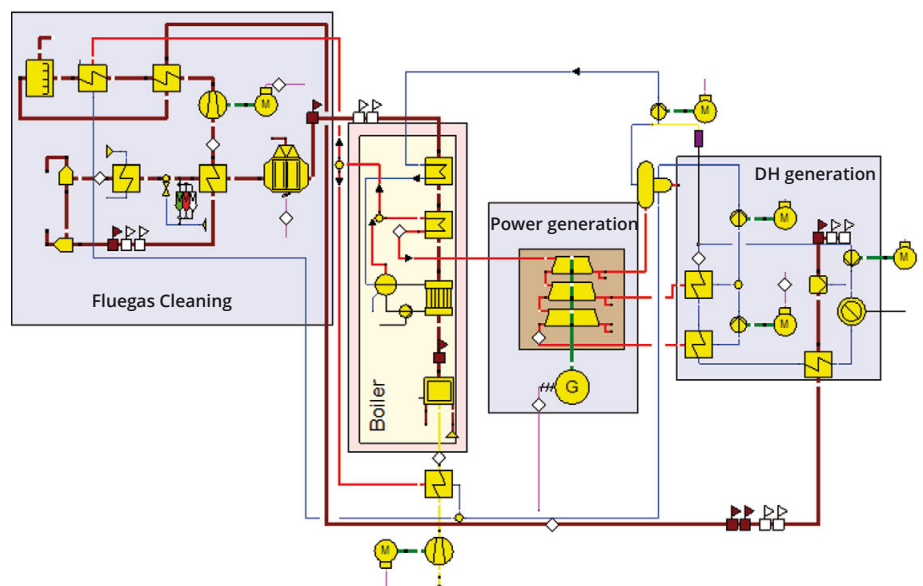


Fig. 2: Schematic overview of the reference model created in Ebsilon Professional.

mains the same but during periods with low heat demand the flue gas condenser is bypassed and the steam condenser pressures are lowered. This will naturally influence the plant efficiency. However, the relative difference between the different configurations investigated in this work will remain the same independent of operation mode. All models and results shown in this work are therefore only representing the operational mode during the months with a high heat demand with the flue gas condenser in operation. Some important operational data used in the model is summarized in Table 1.

The layout of the reference model is shown in Figure 2 and can be divided into four parts: steam generation, electricity genera-

tion, heat generation and flue gas cleaning. Both the layout and process parameters such as the temperature and pressures are based on the Lillesjö CHP plant.

The reference model is one of three different plant configurations investigated in this work. A simplified layout of each of these configurations is shown in Figure 3. The layouts only show the main steam and water flows of the steam cycle. The flue gas cleaning and heat generation parts are the same in all configurations and are therefore omitted from these figures focusing on what is different between them. The original configuration is shown in Figure 3a with steam being generated at 40 bar and 400°C, which is expanded in the turbine, and condensed be-

fore being fed back to the boiler again. The second configuration, with a reheat cycle, is shown in Fig. 3b. In this configuration the live steam pressure is increased to 200 bar, but the temperature is kept at 400°C. This allows for the addition of a high-pressure turbine stage where the steam is expended before being reheated. The pressure levels in the high-pressure turbine are chosen to give an inlet pressure of 40 bar in to the second turbine. With a reheat temperature of 400°C the steam going into the second turbine is the same as in the base model also keeping the streams downstream of the turbine the same in both configurations.

The third configuration, shown in Figure 3c, represents a plant with an addi-

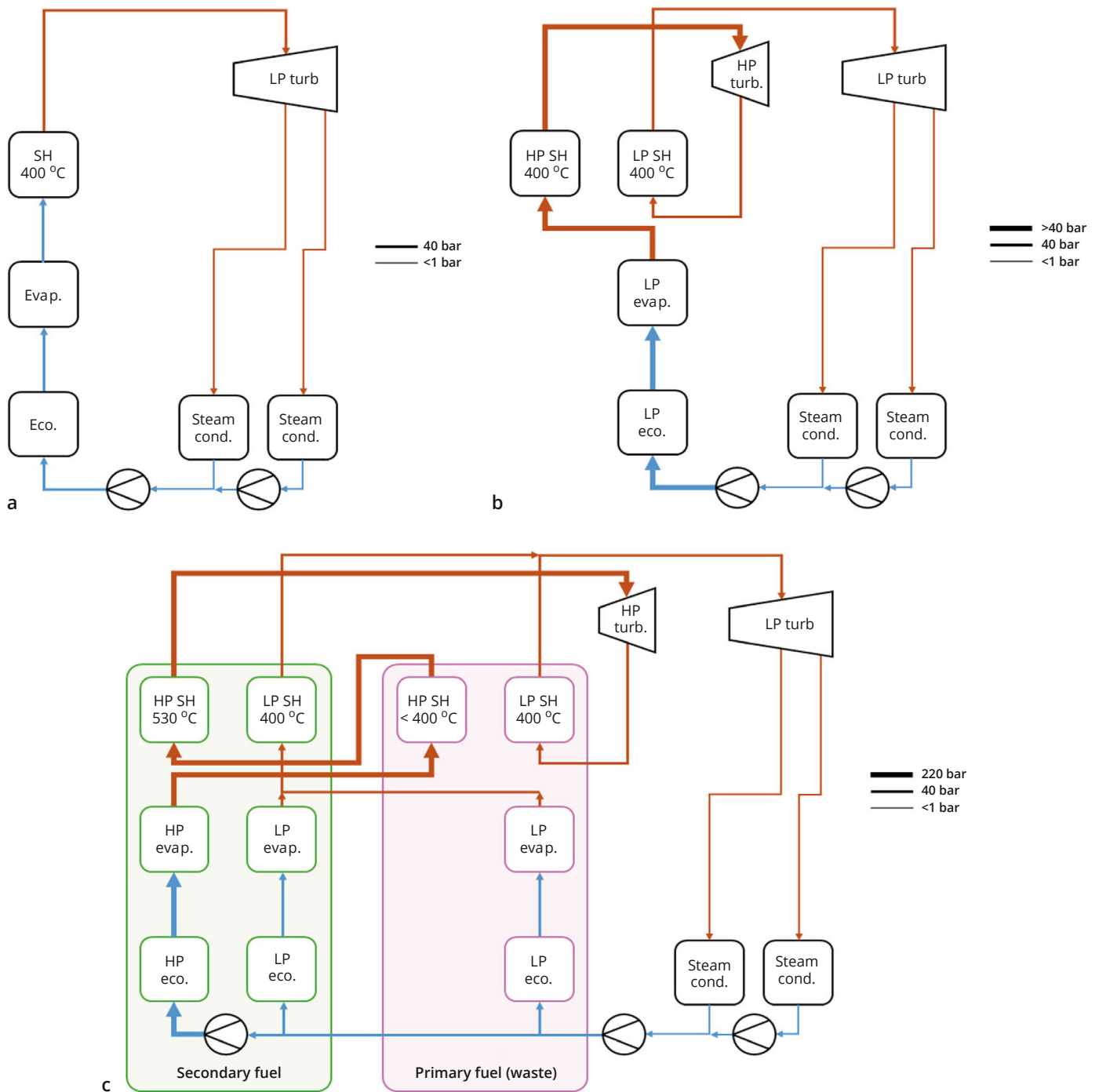


Fig. 3: Simplified layouts of the three different plant configurations investigated in this work; a) reference model, b) reheat cycle, and c) parallel co-combustion.

tional boiler used for parallel co-combustion. In this comparison the primary fuel is always waste but with different fuels being used as secondary fuel in the additional boiler. These two boilers are connected to the same steam cycle as can be seen in the figure. This configuration also has a reheat cycle but in this case both the temperature and pressure into the high-pressure turbine is increased. The exact numbers will depend on the fuel properties of the secondary fuel. The layout will, however, remain the same, independent of fuel. Steam generation is divided between the two boilers to maximize the potential in high quality steam production. The primary boiler will mainly produce 40 bar steam. Only a small amount of the heat released in this boiler will be used for super heating the high-pressure steam, but not at temperatures over 400 °C. Most heat is provided to the high-pressure stream by the secondary boiler, also allowing for temperatures above 400 °C. This configuration is simulated in two different versions, keeping either the steam generation or the waste consumption the same as in the reference model.

2.3 Steam temperature estimation

The maximum temperature of the steam generated in a boiler is often a trade-off between electrical efficiency and the risk of deposition and HTC related problems. This is often something that is set based on combustion tests of a specific fuel. Testing the combustion characteristics of different fuels is, however, not within the scope of this work. Instead, the maximum steam temperature used for different fuels in the plant modelling is determined based on a scoring system. This scoring system uses known data for two fuels; the average waste composition combusted at the Lillesjö reference plant, and a coal used in a boiler generating steam at 600 °C. The scoring evaluates all fuel and ash components but are weighted with focus on the alkali, chlorine, and sulfur content. Each fuel is given a score between zero and one which is used in the equation below to determine the temperature used for the specific fuel in the plant models.

$$T_{fuel} = 400\text{ °C} + Score_{fuel} * 200\text{ °C}$$

The result from the fuel scoring is complemented using a two stage FactSage simulation. FactSage was used to determine equilibrium composition based on minimizing Gibbs free energy. For this the databases FactPS, FToxid and FTSalt were used due to their large collection of solids and solutions for a combustion environment with high levels of sulfur, chlorine and alkali. For the calculations pure gases and pure solids, as well as solution phases where ash melts and slags are included were considered. For the solution phases the following base-phases were applied FToxid-SLAGA, FTSalt-B1, FTSalt-oP28D, FTSalt-hP22, FTSalt-hP14 in accordance with other studies [13, 14]. In the first simulation stage the composition of each

fuel was individually set as input for a simulation run at 1400 °C. The same temperature was used for all fuels and supposed to represent the combustion environment. The part of a fuel that is not coming out from the first simulation in gas phase is assumed not to reach the superheaters. The remaining part, found in the gas phase, is used as input from the second simulation. In this stage the temperature is set to whatever temperature a fuel received based on its score. The result from the second stage of the simulation is used to estimate the amount of molten ash for each fuel at its steam temperature.

3 Results and discussion

3.1 Flue gas measurements

The flue gas temperature as well as HCl and SO₂ concentration is shown in Figure 4 for six different locations in the boiler. These measurements were performed using the same set up, which is why it could only be measured in one position at the time. The numbers within parenthesis show the concentration measured in the M7 position during the same time as the measurement in each specific position was performed.

The result does not show a clear trend in SO₂ variations between positions. The concentration is going up and down in every second position. The variation in concentration is relatively small, only 70 ppm in difference between the lowest and highest concentration. For comparison, the difference is almost 400 ppm for HCl. HCl does also show a clearer trend, increasing from the first to the second position with a following continuous decrease in concentration. This could indicate that HCl is still being released between location one and two. The decrease in concentration that follows after position two suggests that HCl reacts to form other chlorine containing species, e.g. alkali chlorides. The reduction in HCl concentration contin-

ues all the way to the convection section and stabilized first when it enters the second superheater section. This is in agreement with the reaction kinetics for chlorination of alkali species which slows down with decreasing temperature. [15 to 17]

3.2 Long term variations

Data from the M7 position located in the boiler flue gas exit (see Figure 1) is used to look at long term variations in SO₂ and HCl concentrations. The data is obtained from the local measurement system used for operational control of the boiler and measures continuously as the boiler is running. A five-year long period was examined to see if there are any obvious variations due to e.g. season. To give an idea of the variations over time, a 180-day period is presented in Figure 5. The figure shows the variations in SO₂ (top) and HCl (middle) concentration together with S/Cl-ratio (bottom) in the flue gas during approximately half a year. The data is presented in two different time scales. The grey line represents one minute average values, and the black line corresponds to a 24-hour running average based on the one-minute values. Figure 5 show that there are relatively large variations on a shorter time scale. For SO₂ the concentration changes from 100 ppm to 400 ppm within a few minutes. For HCl the span is 500 ppm to 800 ppm in the same time frame. The running average does, however, show that these quick variations oscillate around a relatively stable level of approximately 200ppm and 650ppm for SO₂ and HCl respectively. This results in an S/Cl ratio that most of the time remains lower than 0,5 and only a few times briefly exceeds one.

The S/Cl-ratio gives a good indication of what to expect of the alkali chemistry. It has been shown many times, even though the exact numbers vary from case to case, that a low S/Cl-ratio favors the formation of alkali

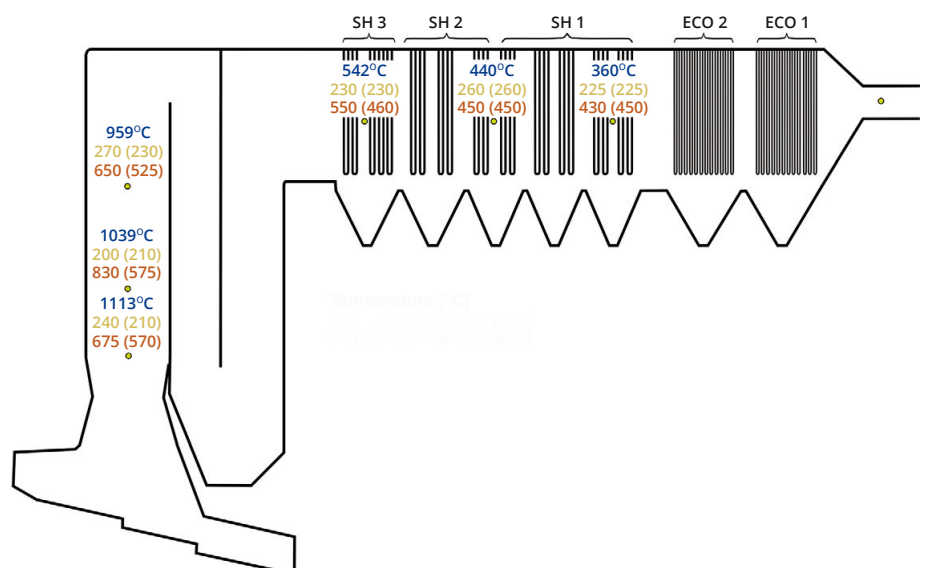


Fig. 4: Measured temperature, SO₂, and HCl concentration at different positions in the plant. Concentrations given within parenthesis the measured concentration in position M7 at the same time.

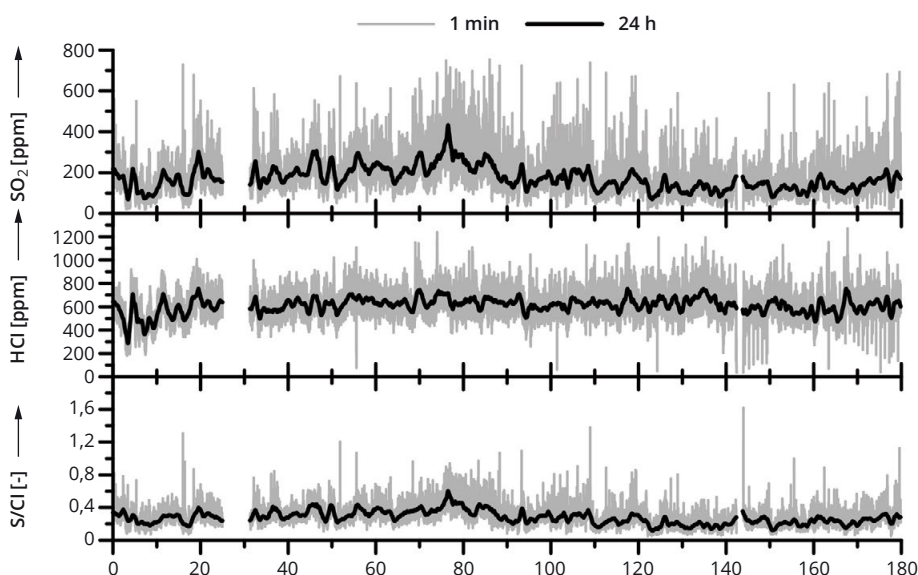


Fig. 5: Example of long term variations in SO_2 and Cl concentration as well as S/Cl-ratio in boiler flue gas exit during a period of 180 days. The figure shows one minute average values (grey) and a running 24 h average (black).

chlorides over alkali sulfates. [16-20] It is also the case that the S-Cl-ratio should be well above one to achieve any significant amount of sulfation. As an example, according to the work by Ekvall et al. with a S-/Cl-ratio of one only result in less than 30% of the alkali being sulfated and a ratio over four is required to reach 50%. [18, 19] A plant running on a similar fuel as Lillesjö will, in other words, never experience conditions that are favorable for sulfation of alkali metals. In addition, the variations in S/Cl-ratio are too fast to make any adjustment with respect to steam production realistic.

3.3 The effect of adding a reheat cycle

One or more re-heat cycles are commonly implemented in powerplants with high steam data. That is, however, not the case for waste or biomass fired combined heat and power plants where focus often is put on heat production. The limitations in steam data due to the HTC related problems for these fuels result in modest electrical efficiencies. The results from this work does, however, show that a reheat cycle could increase the electrical efficiency without increasing the steam temperature. A modified model was created based on the reference model with the only addition that a reheat cycle was added as shown in Figure 3b. The temperature of the steam entering the new high-pressure turbine was kept at 400°C to avoid increased risk for HTC. The pressure on the other hand was increased to 200 bars. The steam was expanded in the high-pressure turbine so that the inlet steam to the second turbine had a temperature and pressure of 400°C and 40 bar, respectively, after re-heating the steam. In this way the configuration of the low-pressure turbine and its condensers remains identical to the reference model.

The addition of the reheat cycle increased the electrical efficiency from 20,5% in the

reference model up to 26,8% in the model with re-heat with the overall plant efficiency remaining at 107%. It should be noted that the model was configured to keep the heat production constant in both models. This means that the increased electricity generation caused the total steam production and fuel consumption to increase slightly to compensate for the additional energy requirement in the cycle. The required pump work did of course also increase due to the higher boiler inlet pressure. These changes are included in the efficiency calculations.

Increasing the pressure and including a re-heat cycle does make the plant configuration more complex and most likely also more expensive to build. However, with an increasing demand for electricity and maybe also higher electricity prices it could be an economically beneficial concept to apply also to waste and biomass fired CHP plants. Especially if renewable resources are to be used as efficiently as possible. It should also be noted that this modeling work was based on the reference plant Lillesjöverket. It would most likely be

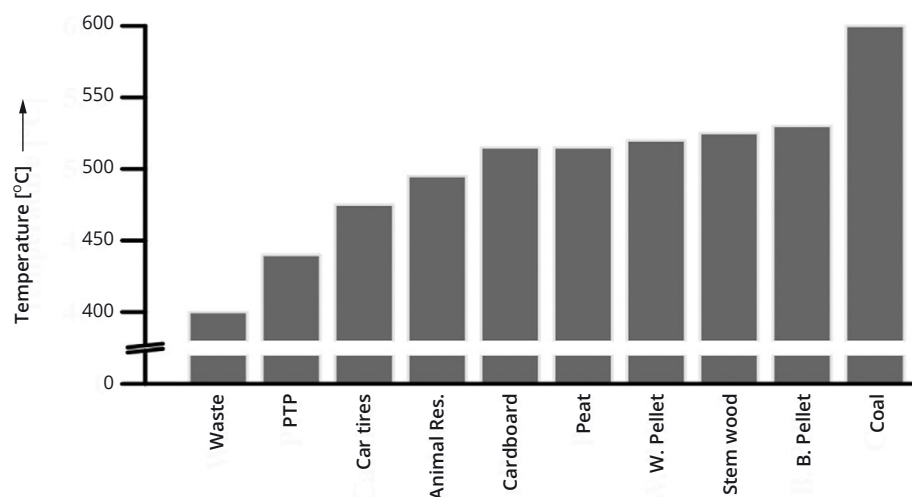


Fig. 6: Estimated steam temperatures based on fuel characteristic focusing on alkali, sulfur and chlorine content.

possible to increase the electrical efficiency further if the limitations of the existing plant would have been omitted. Neither such modelling work nor economical estimations are, however, within the scope of this study.

3.4 Fuel scoring system

As mentioned, what steam data that can be used in a plant is connected to the properties of the fuel combusted. High quality fuels, such as high rank coals, are usually among the fuels that can result in the highest steam data, up to 600°C or even higher, without suffering too much from deposition and corrosion. Municipal solid waste is, on the other hand, considered to be a low-quality fuel where steam data often is limited to 400°C . In this work fuel analysis from the waste combusted at the Lillesjö plant and a high-quality coal has been used as reference fuels. Other fuels have been given scores based on how similar they are to the two reference fuels. The scoring includes several components but similarities in alkali, sulfur and chlorine content have been rated higher than other components. This gives a fuel rating system that is focused upon corrosion rather than overall deposition.

The estimated steam temperature for 8 different fuels is shown together with the reference fuels in Figure 6. That woody biomasses would be among the fuels with the highest temperature rating was expected, especially pre-treated ones. Car tires that sometimes are used as a sulfur source to reduce HTC problems were, on the other hand, expected to end up higher compared to some of the others. And the opposite was expected for animal residues which is known to be a problematic fuel and was therefore expected to be lower in comparison to the other fuels.

Equilibrium composition calculations were made as a complement to the temperature rating system. The result for some of the fuels is shown in Figure 7. Figure 7a shows the estimated total amount of fly ash normalized to the amount found for coal at 600°C . It can be seen that cardboard has

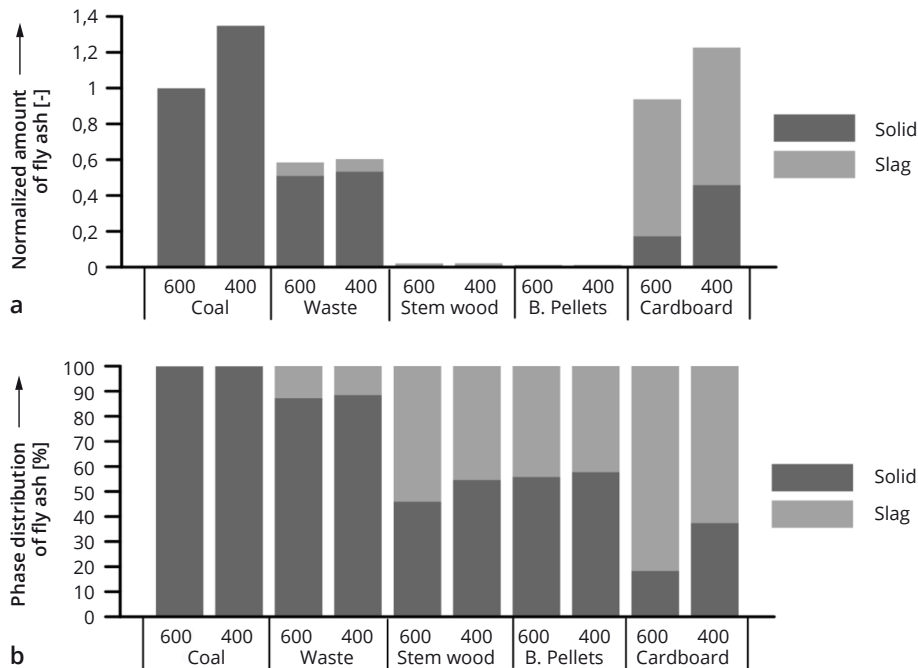


Fig. 7: Results from equilibrium calculations done in FactSage. Figure a presents total amount of fly ash relative to coal at 600 °C, and fig. b shows the distribution between fly ash in solid and slag phase.

more or less the same total amount of fly ash but a larger share is in slag phase compared to coal. Waste has about 40% lower total amount meanwhile logs, and black pellets only have a fraction. Figure 7b shows the distribution between solid and slag phase. Combining this with the temperature rating shown in Figure 6, it is most likely that Cardboard cannot be used at the suggested temperature without resulting in deposition problems. It is difficult to tell if e.g. black pellets should have a higher temperature rating than what was presented. On one hand, the total fly ash amount is lower compared to coal. But on the other hand, the amount of molten ash is still a bit higher compared to coal. So maybe not as high as for coal but potentially higher than the 530°C presented in Figure 6.

3.5 Parallel co-firing

Co-firing of different fuels can be done in different ways, either in a direct, indirect, or parallel configuration. In a parallel co-firing dual fuel system, the two fuels are combusted in separate boilers. The boilers are connected only via the steam cycle keeping the two combustion systems separated. This will result in a more complex system compared to applying direct co-combustion, but it allows you to fully utilize the potential of higher quality fuels. Both direct and parallel co-combustion have been investigated in this work. As expected, it was found that a parallel system has the potential in reaching the highest electrical efficiencies without increasing the risk of deposition and HTC related problems. It is therefore only the results from the parallel system that will be presented here.

Two different models for parallel co-firing have been constructed. One where the steam generation is set to be the same in all

cases. In the second version it is instead the amount of waste that is kept constant between the different cases. The two versions requires some different control strategies for steam flows etc which is why there are some differences in efficiency for the two versions as seen in Figure 8. The difference between the two models are, however, relatively small for each fuel. Looking at the numbers it is seen that the electrical efficiency can increase with more than 50% reaching electrical efficiencies over 31%.

There is a larger difference between the two versions of the parallel co-firing model with respect to total generation, see Figure 9. This is expected since the actual energy supplied to the system gets higher when you keep the mass flow of waste constant at the same time as an addition fuel is added. For this case, the electricity generation is 3 times higher than the reference case in the model

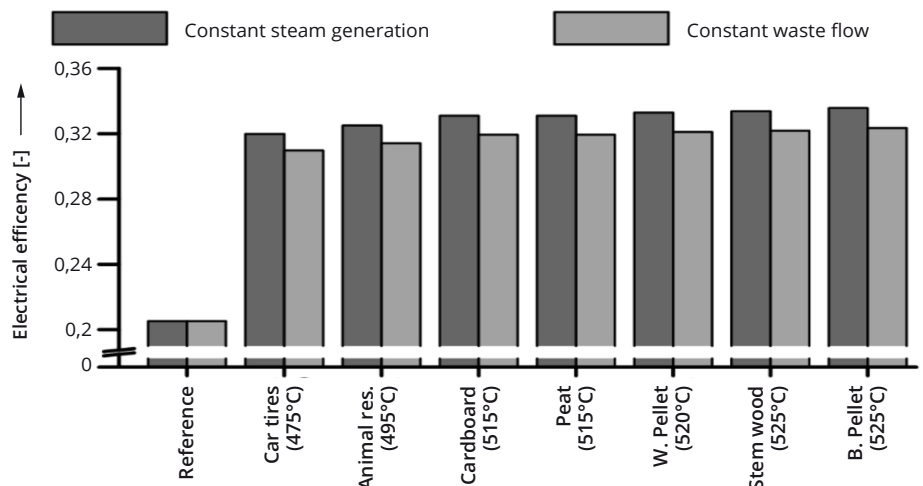


Fig. 8: Electrical efficiency when co-combusting different fuels with waste in two different parallel co-combustion systems. One keeping the steam generation constant, and one with constant feed of waste.

with constant waste flow. This is also about twice the electricity generated in the other version with constant steam generation. Note that there is also an increase in fuel consumption in this case. The higher fuel consumption is a result of a higher temperature and the addition of a reheat cycle at the same time as the mass flow of steam is kept the same as in the reference case. This increase in fuel consumption is however much smaller compared to the constant waste case. It is important to remember that it is assumed, in both cases, that there is a heat demand corresponding to the increased heat generation. Without the possibility to make use of (or cool) that heat it will not be possible to reach such a high electricity generation.

4 Conclusions

In this work different strategies for increasing the electrical efficiency in CHP-plants utilizing low quality fuels have been evaluated. The evaluation is partly based on gas composition and temperature measurements at the waste-fired Lillesjö CHP-plant located in Uddevalla, Sweden, which represents a typical state-of-the-art waste-fired CHP plant in northern Europe. The flue gas chlorine and sulfur concentration vary a lot within a timeframe of one hour. The same is true for the S/Cl ratio in the flue gas. The ratio does, however, never reach conditions that would clearly reduce the risk of problems related to high temperature corrosion.

Four different plant configurations have also been evaluated using thermodynamic simulations with the Lillesjö CHP plant as reference plant. One alternative configuration tested was the addition of a reheat cycle. The simulation showed that by reheating the steam, while keeping the maximum steam temperature the same, could increase the electrical efficiency from about 20% to 26%. Another investigated configuration was parallel co-combustion. With a higher-quality fuel combusted in a separate boiler, but linked to the same steam cycle, allows for higher steam temperatures. The simulations show that an

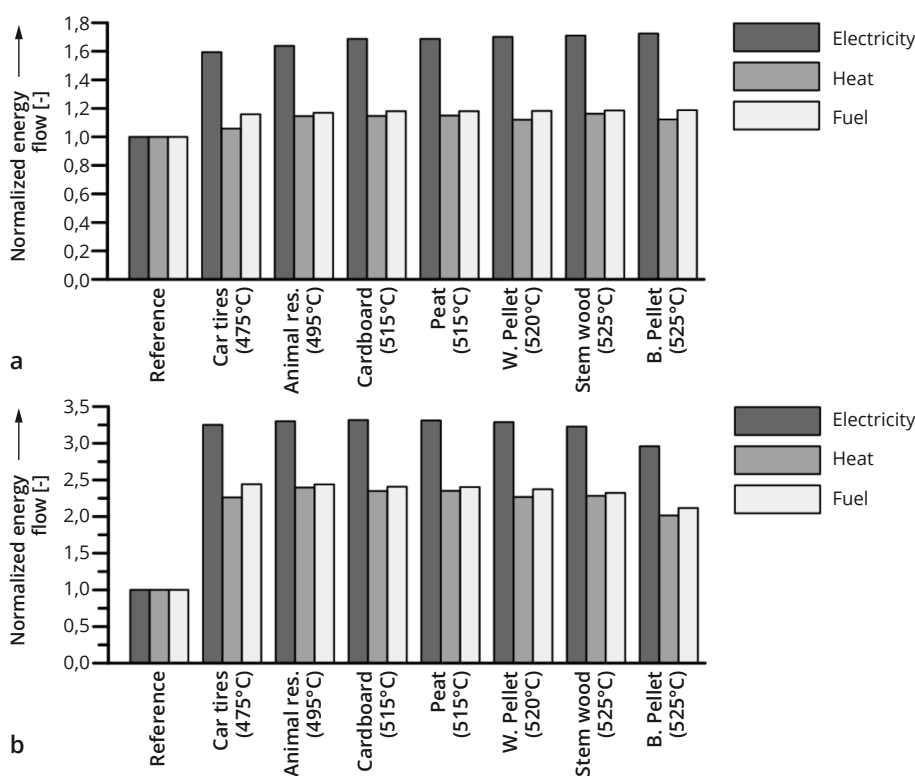


Fig. 9: Relative production when co-combusting different fuels with waste in two different parallel co-combustion systems. One keeping the steam production constant, fig a, and one with constant feed of waste, fig b.

electrical efficiency of almost 34% can be reached by co-firing waste and woody biomass in a parallel co-combustion system.

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Kurzfassung

Ausführungsvarianten von mit Abfall befeuerten Blockheizkraftwerken, zur Verbesserung der Dampfparameter

Es wird prognostiziert, dass die Nutzung aschehaltiger Brennstoffe in naher Zukunft zunehmen wird, um fossile Brennstoffe zu ersetzen und so unser Ziel der Reduzierung der CO₂-Emissionen sowie die Förderung einer Kreislaufwirtschaft zu erreichen. Die Kombination aus einem dynamischeren Anlagenbetrieb und der Verwendung von Brennstoffen mit höherem Aschegehalt wird die Aerosolbildung verstärken. Dies kann aufgrund von Ascheablagerungen möglicherweise zu einer verkürzten Lebensdauer und einem geringeren Wirkungsgrad der Anlagen führen. Die Vermeidung von Ablagerungsschäden ist von entscheidender Bedeutung und kann in verschiedenen Industriezweigen den Wartungsaufwand senken und den Wirkungsgrad steigern. Der Wettbewerb zwischen Chlor und Schwefel um die Reaktion mit Alkali (Natrium oder Kalium) zur Bildung von Chloriden oder Sulfaten ist ein wichtiger Aspekt bei Problemen im Zusammenhang mit Ablagerungen.

In dieser Arbeit wird das Potenzial zur Steigerung des elektrischen Wirkungsgrads in mit Biomasse und Abfall befeuerten Kraft-Wärme-Kopplungsanlagen (KWK) analysiert. Verschiedene Anlagenkonfigurationen und Betriebsstrategien wurden mithilfe eines thermodynamischen Modellierungstools untersucht. Die Modelle basieren auf einer bestehenden, mit Abfall befeuerten KWK-Anlage als Referenzanlage. Die Eingabedaten werden aus der Anlage auf der Grundlage von Messungen an verschiedenen Stellen im Kessel erhoben. Das Ergebnis zeigt, dass durch den Einsatz von Dampfüberhitzung eine erhebliche Steigerung des elektrischen Wirkungsgrads erzielt werden kann, ohne die Dampftemperatur zu erhöhen. Eine noch größere Steigerung lässt sich durch die Verbrennung eines Sekundärbrennstoffs in einem separaten Kessel erreichen, der auf der Dampfseite mit dem Primärkessel verbunden ist. Dadurch wird die Brennstoffausnutzung maximiert.