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Opportunities to Improve the Energy Efficiency of Energy-from-Waste Plants

Gert Riemenschneider, Thomas Maghon and Walter Schäfers

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Originally, waste incinerators had the sole function of reliably burning the waste while meeting the statutory emission limits. In the meantime, however, there has been growing awareness of the waste's recoverable energy potential. These days it is imperative to optimize energy recovery from waste not only to meet the efficiency criterion and thus secure the recovery status of the operation as defined by the European waste hierarchy but also to further reduce CO₂ emissions in line with the climate protection targets. In this respect, thermal waste treatment plants are at an advantage in that more than fifty percent of the waste to be treated is of biogenic origin and therefore classifies as climate-neutral.
EfW plants typically use a conventional water-steam circuit for energy conversion and recovery as known from other power generation processes. However, energy optimization through raised steam parameters – the typical approach adopted in the power plant sector – has limited applicability for EfW plants because of the highly corrosive nature of the combustion flue gases from waste incineration. Nevertheless, optimization measures are worthwhile consideration as they not only provide ecological benefits but also generate additional income from increased energy sales. Some of the potential options will be presented below.

1. Options for energy optimization

1.1. Optimization of the water-steam circuit

The majority of the EfW plants currently in operation is designed for live steam temperatures in the range of 380 °C to 420 °C and pressures between 40 bar and 60 bar. For the purpose of the subsequent presentation, a reference plant with the following parameters will be used as a base line:

- Steam parameters 400 °C / 40 bar
- Feedwater temperature 130 °C
- Boiler outlet temperature 190 °C
- Flue gas oxygen content 8.0 %, dry basis
- Condensation pressure 70 mbar

For ease of understanding, the thermodynamic cycle is visualized by a T-s diagram. In this diagram, the heat inputs and outputs are characterized by the areas underneath the respective curve sections. The thermodynamic cycle for the reference plant is illustrated in Figure 1. The red line (or the area underneath) stands for the heat transferred from the flue gas to the water and/or steam. The blue line at the bottom designates the energy losses to the atmosphere on condensation of the exhaust steam in the air condenser at a low temperature level. The green line in turn describes the mechanical energy recovered through steam expansion in the turbine for electricity generation. Energy efficiency improvements are identified, inter alia, by a larger bounded area.

Figure 1: Reference plant with standard steam parameters
1.1.1. Higher steam parameters

Higher steam parameters, i.e. increasing the live steam temperature and pressure, translate into improved efficiency. For a comparison, this is illustrated in Figure 2 by the example of the water-steam circuit of the reference plant. The individual energy flows are again presented in different colours. The blue line represents the thermodynamic cycle with the higher steam parameters. The efficiency improvement is proportional to the larger area bounded by the curve.

Live steam parameters up to temperatures of approximately 520 °C and pressures of up to approximately one hundred bar are technically feasible in EfW plants. This would translate into a twenty percent increase in power production compared to the standard process.

The main limiting factor for higher steam parameters is the corrosion risk posed by corrosive components present in the combustion gases. Corrosion problems increase disproportionally with rising live steam temperatures. For this reason, special measures are needed to protect the heating surfaces located in the high-temperature zone. Protection of the heating surfaces is provided in the form of ceramic lining or overlay-welded metallic coatings with elevated nickel and chromium contents. The implementation of higher steam parameters requires a careful trade off between higher profit due to improved efficiency and the cost of the additional protective measures including increased maintenance requirements.

1.1.2. External superheater

Where steam at high temperatures is required – which is frequently the case at power plant and industrial sites – and the corrosion risk is to be kept at bay, the use of an external superheater may be a viable option. Using external superheaters, live steam temperatures of 530 °C and higher can be achieved. If the additional firing system is fuelled with natural gas or EL-grade fuel oil, the combustion flue gas can be released to the atmosphere without any further treatment. When using biomass as a support fuel, by contrast, flue gas cleanup will be needed.

The water-steam circuit of an EfW plant equipped with an external superheater is directly comparable with the thermodynamic cycle at elevated steam parameters presented in the previous section. It differs from the latter only in that the higher live steam temperature is attained by the input of external energy (shaded area in Figure 3). Due to the lower flue gas and radiation losses of the external superheater, the required thermal energy input is lower compared to the boiler, translating into a further increase in electrical generation efficiency.
Basically, there are two concepts for integrating the external superheater into the overall plant. On the one hand, the external superheater can be installed in the immediate vicinity of the boiler in such a way that the flue gases from the additional firing system are directly led to the boiler after having passed through the superheater, united with the main flue gas stream and routed to the stack via the flue gas cleaning system.

An alternative concept that has rendered excellent service is to install the superheater as a stand-alone component in the boiler house. As already mentioned, flue gas cleaning is not needed when using natural gas-fired systems. Discharge of the flue gas to the atmosphere occurs exclusively via the natural draft of the stack. The superheater is provided with additional economizer heating surfaces to utilize the energy content of the flue gas and to lower the flue gas temperature to roughly 150 °C.

1.1.3. Steam reheat configuration

Where high electrical generation efficiencies are the objective, steam reheating as known from thermal power plants is an interesting alternative. With the steam reheat configuration, the live steam is returned to the boiler after partial expansion through the first turbine stage and once again heated to live steam temperature by heat exchange with the hot flue gases. The reheat steam is then led to the second turbine stage followed by condensation in the air condenser. The process is depicted in Figure 4 and relates to the conditions at a realized plant. With a moderate live steam temperature of 420 °C but an elevated live steam pressure of 90 bar, this plant optimized for exclusive electricity generation achieves efficiencies of some thirty percent.

Steam reheating makes it necessary to install heating surfaces in the high-temperature zone. At the same time, the high live steam pressure results in a correspondingly higher temperature of the evaporator heating surfaces. In either case it is necessary to provide both the evaporator waterwalls and the superheater heating surfaces with effective corrosion protection.
1.1.4. Feedwater preheating

The feedwater can be preheated with steam extracted from the turbine. The resulting energy savings for feedwater heating translate into an increased live steam rate and ultimately into an improved electrical generation efficiency.

Below, both the feedwater and the condensate preheaters will be assessed. In EfW plants, it is common practice to preheat the condensate returned to the feedwater tank. However, for the energy optimization of a plant, it makes sense to also include the preheating stage downstream of the feedwater tank – more precisely downstream of the feedwater pumps – into the picture.

In order to elucidate the effect of condensate and feedwater preheating, two different steam parameter combinations are examined in Table 1: the standard parameters at 400 °C/40 bar and high steam parameters at 500 °C/90 bar.

Without any feedwater or condensate preheating, the reference plant attains a gross electrical generation efficiency of 25.2 percent. Condensate-side preheating increases the gross electrical generation efficiency to 26.3 percent. Installation of a feedwater preheater on the high-pressure side contributes another 0.3 percent-points.

A look at the scenario with the assumed high steam parameters shows a significantly improved picture. Because of the higher energy requirement for feedwater preheating under these conditions, the energy savings are more pronounced for this scenario. The electrical generation efficiency attained without any preheating is 29.4 percent (gross) and increases by one percent-point when using a condensate preheater. In contrast with the lower steam parameter scenario, the high-pressure feedwater preheater contributes another efficiency increase of 1.0 percent-point.

Depending on the steam parameters, it would also be possible to double the number of condensate and high-pressure feedwater heaters as against the variant here presented. Whether this is feasible ultimately depends on the capacity of the plant and/or the turbine that must have a sufficient number of tapping points for the feedwater heating stages.

<table>
<thead>
<tr>
<th>Live steam temperature</th>
<th>Live steam pressure</th>
<th>LPCH</th>
<th>HPFH</th>
<th>Gross electrical efficiency</th>
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<tr>
<td>°C</td>
<td>bar</td>
<td>–</td>
<td>–</td>
<td>%</td>
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<td>No</td>
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<tr>
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<td>No</td>
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<tr>
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<td>500</td>
<td>90</td>
<td>Yes</td>
<td>Yes</td>
<td>31.4</td>
</tr>
</tbody>
</table>

LPCH: low-pressure (condensate) preheater
HPFH: high-pressure feedwater preheater

Table 1: Electrical efficiency with condensate and feedwater preheating
1.2. Other optimization options

Aside from the optimization of the water-steam circuit presented above, there are further opportunities for efficiency improvements. These relate in particular to improved energy utilization or a combination of measures which can best be explained with the aid of a Sankey diagram. Figure 5 illustrates such a diagram for the reference plant (400 °C/40 bar) defined in section 1.1.

This diagram is based on the assumption of an energy content of one hundred percent of the waste delivered to the plant. If this energy is used exclusively for power production, the principles of thermodynamics will result in energy losses of around 73 percent attributable to the condensation of the turbine exhaust steam.

1.2.1. District heat generation

The heat loss by condensation can be minimized or avoided altogether if there is a demand for district heat. With such a combined heat and power concept, i.e. the co-generation of electricity and heat, the turbine exhaust is condensed at a higher temperature level than would be the case with exclusive power production. The condensate obtained at a higher temperature level gives off its heat content to a district heating system that supplies adjacent residential buildings or industrial plants with heating and process energy.
In the example shown in Figure 6, the complete thermal energy recovered from exhaust steam condensation is fed to the district heating grid. The temperature level needed for an effective use of the waste heat goes, however, at the expense of a lower electrical output. Energy losses mainly account for the remaining thermal content of the flue gas.

For such plant configurations with integrated district heat generation, a number of prerequisites must be satisfied. On the one hand, the plant must be located in the vicinity of heat consumers, on the other, there should be a year-round demand for district heat. This is frequently the case in the Scandinavian countries with a low average annual temperature. This is why this type of plant is frequently encountered in these countries. In Southern European countries, district heat is only needed in special cases. Consequently, the energy content of the waste is more or less exclusively converted to electricity in these countries. In order to achieve improved energy use despite the unfavourable climatic conditions, the utilization of the waste heat for the operation of absorption absorption chillers supplying a district cooling grid has been discussed in recent years.

1.2.2. Reduction of the flue gas O$_2$ content at the boiler outlet

The EfW plants currently in operation are typically operated with a flue gas O$_2$ content of about eight percent (STP, dry) corresponding to an excess air factor of approximately 1.6. The flue gas oxygen content is controlled via the combustion air rate. When treating low-calorific waste, the O$_2$ reduction potential is limited because of the need for sufficient primary air to dry and burn the waste. Above calorific values of about nine MJ/kg, such limitations no longer play a role.

Figure 7 shows another Sankey diagram of the reference plant where the flue gas losses are separately presented. As can be seen from the diagram, the flue gas losses decrease with decreasing flue gas O$_2$ content due to the lower combustion air rate. Figure 8 illustrates the influence of the flue gas oxygen content in figures. The flue gas losses of the reference plant operated with eight percent O$_2$, STP, dry basis amount to about 11.6 percent and vary by some three percentage points in the region examined. A reduction of the oxygen content in the reference plant to e.g. five percent O$_2$ (STP, dry) translates into an approximately 1.9 percent-points increase in gross power production.
Care must however be taken to ensure that lowering the flue gas oxygen content and the associated reduction of the combustion air rate does not compromise the air-flue gas mixing conditions in the area of the secondary air ports. Here, suitable measures are needed. Frequently, flue gas recirculation is used to improve mixing and control the flue gas temperature in the radiation pass.

1.2.3. Influence of the flue gas temperature at the boiler outlet

While the reduction of flue gas losses through a lowered flue gas $O_2$ content discussed above is based on a flow rate reduction, the flue gas energy content can also be influenced by a temperature reduction. The energy withdrawn from the flue gases is taken up by the boiler system. As the temperature gradient between the flue gas and the feedwater decreases towards the boiler outlet, the required heating surface area increases significantly with decreasing boiler outlet temperatures.

Figure 8:
Influence of flue gas $O_2$ content on power production

Figure 9:
Influence of flue gas temperature on power production
The influence of the boiler outlet temperature on power production and the flue gas losses are illustrated in Figure 9. A reduction of the boiler outlet temperature from 190 °C – reference plant – to 150 °C, for instance, results in an energy efficiency gain of some three percent.

As mentioned before, operation with a lowered flue gas temperature at the boiler outlet necessitates an adapted larger boiler. Ultimately, the choice of the boiler outlet temperature will, however, be dictated by the planned flue gas cleaning concept. At 190 °C to 220 °C, wet flue gas cleaning systems with integrated evaporation of the scrubber effluent require significantly higher flue gas temperatures than dry processes operating at 140 °C to 180 °C.

### 1.2.4. Flue gas condensation

When using a wet flue gas cleaning system, the flue gas exiting the system has a high latent energy content in the form of condensable water vapour. The share of the latent energy accounts for approximately fifty percent of the total flue gas energy content. This energy can be recovered by condensation. This presupposes, however, a suitable infrastructure preferably with a district heating grid operated year-round and with return flow temperatures in the range of 40 °C to 60 °C as needed for condensation.

Systems available for recovering the heat of condensation from the flue gas include direct-contact condensers where the flue gas is directly contacted with the process water or systems consisting of one or several heat exchangers. The subsequent discussion proceeds from the use of a condenser scrubber arranged downstream of the actual flue gas cleaning system; see Figure 10.

The condenser scrubber is composed of two stages. In the first stage, the flue gas is quenched to saturation temperature by means of process water recirculated through the condenser. The process water is then cooled in heat exchange with the return flow from the district heating grid and enters the second stage where it trickles through
the scrubber packing in countercurrent with the flue gas. In the process, the moisture contained in the flue gas condenses and collects in the scrubber sump. As condensation occurs by direct contact, the return temperature of the district heating grid is the sole factor determining the water vapour condensation rate of the condenser scrubber. The latter increases with decreasing return temperature.

In the ideal case, the entire flue gas water vapour content can be condensed, i.e. the entire latent heat content can be recovered. This latent heat is considered in the gross calorific value or upper heating value. As, according to European practice, thermal efficiency calculations are based on the net calorific value, which does not include the latent heat, efficiencies of greater than one hundred percent can be achieved. This is illustrated in Figure 11. In the example here shown, the entire heat of condensation of the exhaust steam is transferred to a district heating grid so that energy losses occurring are restricted to the flue gas losses of 10.9 percent and minor further losses of 2.1 percent, corresponding to a total energy loss of 13.0 percent. In the condenser scrubber, the flue gas is first cooled to the level of the return flow from the district heating grid, thus being saturated with water vapour which is then condensed due to the lower return temperature of the district heating grid. The heat of condensation in turn raises the supply temperature of the district heating grid.

Figure 11:
Plant with district heat generation and flue gas condensation

Figure 12:
Heat recovery through flue gas condensation
Figure 12 shows the amount of heat transferred to the district heating grid as a function of the flue gas temperature downstream of the condenser scrubber. The flue gas temperature follows the return temperature of the district heating grid with a small differential. High rates of heat transfer to the district heating system are attained in particular in the transitional periods in spring and autumn when the return temperatures of the district heating grid are low. Here, major amounts of excess condensate may be generated that must be treated and discharged.

1.2.5. Combustion air preheating with low-pressure steam

Primary air preheating is used for waste with calorific values of less than about ten MJ per kilogram in order to improve the ignition and combustion behaviour of the fuel. At the same time, the energy input associated with primary air preheating increases the live steam rate going to the turbine. Preferably, low-pressure steam should be used as a heating medium for primary air preheating as it has already given off part of its energy content in the turbine.

The following example proceeds from the assumptions that the primary air temperature is raised to 115 °C and that the primary air accounts for sixty percent of the total combustion air at the given plant parameters. This increased primary air temperature results in a 3.4 percent increase in the steam flow rate. If the secondary air temperature is also raised to 115 °C the steam generation rate will go up by 5 % in total. Depending on the site-specific conditions, air preheating is therefore also used for energy efficiency improvement. In the example here presented, gross power production increases from 26.9 percent (reference plant) to 27.9 percent.

1.2.6. Plant optimization by combining several measures

For ease of comparison, only the effect of an individual measure or, at most, two measures has been discussed so far. A question still to be answered is what can be achieved by combining several measures, while bearing in mind that not all the options presented can be combined with one another.

To attain as high an electrical generation efficiency as feasible, the following measures have been selected:

- Condensate preheating to 105 °C
- Combustion air preheating to 170 °C
- Steam parameters 470 °C / 90 bar
- Oxygen content at boiler outlet 6 %, dry basis
- Flue gas temperature at boiler outlet 160°C
- Flue gas cooling by 50 K (first air preheater stage)
Individually, all these optimization measures have already been implemented in diverse plants and are therefore feasible. An interesting question is what electrical generation efficiency can be achieved through the combination of these measures. The thermal and thermodynamic cycle calculations yielded the following efficiencies:

- Boiler efficiency 92.4 %
- Gross – electrical generation efficiency 33.8 %

The electrical generation efficiency of 33.8 percent is equivalent to a 25.6 percent increase in power production as compared with the reference plant defined in section 1.1.

2. Examples of realized energy-optimized plants

In the following, some of the energy optimization measures described above will be presented by the example of realized plants.

2.1. Reduced excess air level

A new furnace and boiler unit was installed at the EfW plant in Hameln/Germany in 2006, Figure 13, replacing an existing unit from the year 1977. The flue gas cleaning and steam/condensate system remained unchanged. The old unit was designed for an excess air level of 1.9, allowing for increasing the thermal power of the new grate and boiler unit from thirty to forty MW at an excess air level of 1.39 without any changes to the flue gas cleaning system.

The flue gas temperatures in the furnace and after-burning zone were adjusted by means of flue gas recirculation to preclude slagging of the membrane walls. The furnace membrane walls and after-burning zone are lined with SiC plates for corrosion protection. Inconel 625 cladding is used in the zone directly above the grate and on the membrane walls in the first boiler pass above the refractory lining over a height of 6 m.

The furnace unit consists of a two-track forward moving Fisia Babcock grate system, each track with five independent
zones over the grate length and two integrated steps. Good burn-out of the flue gases and CO emission levels of less than twenty mg/m³ – STP, dry – were achieved with staged supply of secondary air and ten percent recirculated flue gas, taken from the electrostatic precipitator exit duct.

Since the first start-up to the present day, no significant corrosion was observed in the furnace and the radiation boiler passes, whether on the protected or unprotected membrane walls. All superheater surfaces are arranged in the third vertical pass and cleaned by steam-operated soot blowers. So far no corrosion or erosion has been observed on the boiler tubes in superheaters 2 and 3 directly exposed to the soot blowers due to protection with tube shield elements.

Compared to the baseline solution, the boiler efficiency is raised to 87.6 percent and gross power production to 27.3 percent by furnace excess air reduction to 1.39.

### 2.2. Optimization of boiler outlet temperature

As described above, the boiler efficiency can also be boosted by reducing the flue gas temperature at the boiler outlet (flue gas cooling). Depending on the boiler outlet temperature, the temperature level of the additional heat so recovered is such that it can only be used for primary air and/or secondary air preheating.

Such a concept was realized at Line 4 in Aarhus/Denmark – Figure 14. The flue gas temperature at the boiler outlet is 180 °C at one hundred percent load before the flue gas is admitted to a baghouse filter. After this dedusting stage, an external economizer is used for further flue gas cooling to 140 °C at a boiler feedwater temperature of 130 °C. The design of this external economizer for dedusted flue gas is compact compared to economizers located inside the boiler.

![Diagram of EfW Aarhus, Line 4](image)
Next is a further cooling step down to 100 °C. This flue gas heat exchanger has an enamel tube surface and PFA-foil protection. The heat from the flue gas is transferred to a cooling cycle which also takes up the heat from the grate bar cooling system. This PFA foil-covered heat exchanger is routinely water-cleaned to preclude condensation and settling of ammonia salts from the SNCR. The wash water is used as makeup water in the FGC scrubber. This re-gained heat from the flue gas is used in the process for primary and secondary air preheating.

Temperature optimization at the boiler outlet to 100 °C compared to the baseline solution increased the boiler efficiency from 86.3 percent to 92.7 percent and the gross power production from 26.9 percent to 28.9 percent.

The EfW plant Aarhus/Denmark has been in operation since the beginning of 2005. No major corrosion has been observed so far. The complete furnace and the after-burning zone in the 1st boiler pass are protected with Inconel 625 cladding. After nine years of operation, there was no need for repair work on the cladding due to wear and tear.

The Fünen (DK) and Jönköping (SE) EfW plants operate with similarly low flue gas temperatures of about 100 °C at the boiler outlet. In these plants as well, the low-grade heat recovered from the flue gas is used for combustion air preheating.

### 2.3. High steam parameters

Due to statutory regulations, the Naples plant (IT) was designed for a high electrical output. Steam parameters of 500 °C and 90 bar have been realized. The plant has been in operation since the beginning of 2009 and consists of three lines each designed for a gross furnace heat release rate of 113 MW.

![Figure 15: Naples EfW plant with technical data](image)
As can be seen from Figure 15, the plant was configured with a vertical pass boiler using platen heating surfaces for final superheating. Due to the high steam temperatures, these superheater platens had to be installed in the high-temperature zone with flue gas temperatures greater than 800 °C. The plant achieves a gross electrical generation efficiency of 30.8 percent related to the baseline conditions.

Given these temperature conditions, there is a high corrosion risk for the superheater platens. For this reason, the heating surfaces have been provided with monolithic SiC concrete protection. This concept had already proved successful in previously built plants where service lives of several years were attained. A long service life of the platen heating surfaces under these conditions presupposes, however, routine inspection of the refractory coating for cracks and other irregularities, and prompt repair before metal attack occurs.

2.4. External superheater

The use of an external superheater to boost the electrical generation efficiency has been described in section 1.1.2. Such a plant was commissioned by FBE in Heringen (GER) in 2009. The plant consists of two incineration lines for presorted waste, each designed for a thermal generating capacity of 58 MW. The live steam parameters are 400 °C/85 bar. Using the external gas-fired superheater, the steam temperature is raised to 520 °C as required to meet the steam specifications for the existing steam infrastructure.

The EfW plant as such is designed for the treatment of municipal waste, commercial waste of a similar composition and industrial waste with a net calorific value of 12 MJ per kilogram and a throughput of 17.5 Mg per hour; Figure 16. Its boiler system is composed of three empty passes followed by a horizontal pass accommodating the heating surfaces for superheat duty and the economizers.
In the external superheaters, the gas burner is arranged in the floor of the combustion chamber made up of radiant heating surfaces. These are followed by convective heating surfaces. To limit the flue gas temperature to approximately 150 °C, an economizer is provided as final heating surface. Figure 17 shows the water/steam-side integration of the external superheaters installed next to the incineration lines. The economizer needed to limit the flue gas temperature is supplied with feedwater by a parallel circuit.

The live steam temperature is controlled by load control of the natural gas burner of the external superheater rather than by spray attemperators normally used for this purpose. During startup operation already, the turbine inlet temperature can be controlled within an accuracy of +/- 4 K without any restrictions.

At conditions comparable to the parameters defined in section 1.1, this variant with external superheater achieves a boiler efficiency of 87.2 percent and a gross electrical generation efficiency of 31.1 percent. The contribution of the gas firing system to the total energy input corresponds to about 13.5 percent.

### 2.5. Steam reheat configuration

A plant with steam reheat configuration was commissioned by FBE in Rüdersdorf (GER) at the beginning of 2008. As the plant supplies the adjacent cement mill with electric power, it was designed for maximum power production. The water/steam-side configuration can be seen from the water-steam cycle diagram in Figure 18. As the partially expanded steam at about 25 bar is reheated to live steam temperature, the heating surfaces for superheat and reheat duty are located in the same flue gas temperature zone and must take up large amounts of heat. Like in Naples, the platen superheater heating surfaces are therefore arranged in the second boiler pass; Figure 19. While direct steam reheating in the flue gas stream is common practice in coal-fired power plants, this concept has been applied for the first time to an EfW plant in Rüdersdorf.
Unlike in the Naples plant, the platen heating surfaces are not provided with a monolithic coating for corrosion protection but with Inconel cladding. Here, the lower final steam temperatures allow the use of Inconel 625.

Regarding steam reheat concept, it should be noted that commissioning of the turbine island involves greater complexity. Due to steam recirculation to the boiler, three line sections instead of only one continuous line have to separately blown out. The required steam blowing equipment has to be provided in due time. Since its first startup, the turbine has been operating reliably and trouble-free. The plant achieves a (gross) electrical generation efficiency of 30.5 percent.
3. Conclusion

Table 2 presents a comparison of the efficiencies of the energy-optimized example plants presented above with the values of the reference plant.

The calculations are based on standard conditions regarding

- waste composition
- turbine outlet pressure
- feedwater temperature
- isentropic turbine efficiency, and
- condensate preheating

as well as other parameters.

The most pronounced efficiency gains were achieved with an external steam superheater, high steam parameters and steam reheating. However, each variant is associated with additional costs: either the cost of the additional energy needed for the external superheater or the cost of the extensive corrosion protection required in view of the high steam parameters or the increased equipment requirements (heating surfaces, piping, turbine) for the steam reheat concept. The final decision on the plant concept can only be made after a careful consideration of the specific site conditions, the operating reliability, availability, utility consumption figures and capital and maintenance costs.

Table 2: Comparison of the energy-optimized plants with the reference plant

<table>
<thead>
<tr>
<th>Kind of EFW Plant</th>
<th>Units</th>
<th>Reference Plant</th>
<th>Reduced Excess Air</th>
<th>Flue Gas Cooler</th>
<th>External Superheating</th>
<th>High Steam Parameters</th>
<th>Steam Reheating</th>
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<td>Excess Air</td>
<td>%</td>
<td>60</td>
<td>39</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Boiler Efficiency</td>
<td>%</td>
<td>86.3</td>
<td>87.6</td>
<td>92.7</td>
<td>87.2</td>
<td>86.3</td>
<td>86.3</td>
</tr>
<tr>
<td>Boiler Efficiency Related to Reference</td>
<td>%</td>
<td>100</td>
<td>101.5</td>
<td>107.4</td>
<td>101.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Gross Electrical Efficiency</td>
<td>%</td>
<td>26.9</td>
<td>27.3</td>
<td>28.9</td>
<td>31.1</td>
<td>30.8</td>
<td>30.5</td>
</tr>
<tr>
<td>Gross Electrical Efficiency Related to Reference</td>
<td>%</td>
<td>100</td>
<td>101.5</td>
<td>107.4</td>
<td>115.6</td>
<td>114.5</td>
<td>113.4</td>
</tr>
</tbody>
</table>
Individual optimization measures such as high steam parameters, air preheating, low flue gas temperature etc. can be combined with one another. When using a wet flue gas cleaning process, boiler efficiencies of over one hundred percent can be achieved when relating the efficiency to the net calorific value/lower heating value (LHV) as is common practice in Europe.

To illustrate the achievable boiler efficiency, known individual measures have been selected for an optimized plant. Using such a combination of measures, some of which have already been implemented in full-scale plants but with all other conditions remaining unchanged, a gross electrical generation efficiency of 33.6 percent can be attained.
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