Technical And Economical Aspects Of Thermal Efficiency Of Grate-Fired Waste-To-Energy Plants

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EXECUTIVE SUMMARY

National price subsidies for the delivery of electricity from municipal solid waste, whereas subsidies are motivated by the assessment of being 40-60% of the municipal solid waste attributed to originate from biogenic sources (EIA (2007)), are pushing today the Waste-to-Energy industry towards higher thermal efficiency (Wandschneider (2007), Gohlke (2007)). It remains however a sensible issue whether the technically achievable performance is also reasonable on economic grounds.

Starting from a basic analysis on efficiency of the thermal power plant process, the paper discusses measures to increase the efficiency of a Waste-to-Energy plant that is conceived to produce electricity only. These measures are analysed for their technical feasibility discussing the particular limitations imposed by the particular fuel. The most promising measures are evaluated with regards to their economical benefit in terms of a net present value investment appraisal. The highest effect on the generated electrical output can be achieved by increasing the steam parameters of the live steam. Due to technical limitations of the turbine technology an increase in steam pressure must be accompanied by an increase of steam temperature. The latter may have a rather strong impact on the reliability of the plant in terms of reduced lifetime of the boiler. In order to keep the lifetime on reasonable levels additional provisions are to be made that (usually) increase the costs of a plant.

As Von Roll Inova is a leading plant constructor for thermal Waste-to-Energy plants, they have the necessary data in order to feed properly an investment model for an economical evaluation. The model is applied to different cases of increased steam parameters. Compared to a base variant with steam parameters of 40bara and 400°C the paper shows that the financial benefit from this measure can be increased up to a certain level of steam parameters before it falls off again due to the increased influence of the technical drawbacks.

INTRODUCTION

Waste-to-Energy (or Energy from Waste) is the step from simple disposal of residual municipal solid waste to a proper and sustainable use of waste materials that cannot be efficiently recycled or reused. Having identified Waste-to-Energy as an effective way to treat residual waste the question remains how it may be done most efficiently in order to reach an optimum CO₂ mitigation.
The proven and reliable waste treatment technology is the chemical conversion of waste by combustion in a grate-fired furnace. The recovery of the released heat in a steam boiler and the use in a water-steam-cycle producing electricity and (eventually) exporting usable heat is the thermal power plant process that is highly developed for rather simple fuels, like coal or gas. Municipal solid waste, instead, is a fuel producing highly corrosive flue gases and its utilisation in a thermal power plant process imposes technical restrictions that have an impact on the efficiency of the process.

Efficiency is defined as the ratio of benefit to expense or, technically spoken, usable output to input. A reasonable definition of the thermal efficiency of a thermal power plant relates the usable output, i.e. the gross electrical power plus the usable heat, to the input, i.e. the waste flow $B$ times the lower heating value $H_u$ of the waste plus any auxiliary power. The Figures 1 and 2 illustrate this definition on the basis of a simplified energy balance of a thermal Waste-to-Energy plant for two essential conceptual design cases A) and B) and the table 1 presents the proportions of the different energy streams for realised designs for cases A) and B).

The following principle findings on efficiency can be deduced from these simplified representations:

1. From an energetic viewpoint gross electric power and usable heat are equivalent.
2. Energy efficiency of a thermal Waste-to-Energy plant may be identified as a matter of reducing the direct heat release to the environment via the condenser.
3. In this respect the highest potential to increase the overall efficiency of Waste-to-Energy plant is a plant conception where a part or all steam produced can be finally exported as usable heat to appropriate consumers (e.g. in a district heating net).
4. In case of pure electricity production the potential to increase the efficiency of a Waste-to-Energy plant lies in the optimisation of the water-steam-cycle and a reduction of the amount of heat rejected with the flue gas at the stack.

These principles are known from thermal power plant technology resulting in combined heat and power (CHP) schemes, and are reflected by the discussed efficiency criteria as result of the revised European Waste Framework Directive adopted in 2008. Regions, where such CHP schemes in connection with Waste-to-Energy plants are common, are Scandinavia, Germany, the Netherlands and Switzerland, what may explain the very high acceptance and broad use of the thermal Waste-to-Energy technology in these regions. In many other regions, a steady export of heat is however difficult to implement although the problem of a proper and reliable waste treatment, that may be effectively done applying thermal Waste-to-Energy technology, remains the same. In order to achieve, beyond effective waste treatment, gross electrical efficiencies above 26% possible technical improvements for the Waste-to-Energy plant process are discussed in the following.

**MEASURES TO INCREASE THE THERMAL EFFICIENCY**

As said the efficiency potential lies in the reduction of heat loss via the flue gas at the stack and the improvement of the water-steam cycle that consists, simply said, in the reduction of the heat released to the environment via the steam condenser. However, the true origin of losses is the processes in the furnace and boiler. Their causes are attributed to the exergy losses by the irreversible combustion process and heat transfer that is taking place at very different temperature levels between the flue gas and the water-steam-cycle.

**Increase of Enthalpy of Live Steam (= Increase of Steam Parameters)**
The increase of the live steam enthalpy, i.e. pressure and temperature, leads to a decrease of the amount of steam that is produced with a given amount of heat supplied, and hence, the amount of steam that is to be condensed again.
In Waste-to-Energy plants the increase of the temperature of the boiler tubes beyond certain limits may lead to severe corrosion effects. The processes leading to boiler tube corrosion are fairly complex and are not linked only to the steam temperature. However, temperature appears to be crucial to separate designs with mild or acceptable boiler corrosion from designs that may be subject to substantial corrosion. The separating temperature for superheating of steam is anticipated to be at about 420 - 430°C. Typically applied protective measures to grate/boiler plants are:

- Use of high-alloy tubes or tube cladding, like Inconel®, for superheater bundles
- Spacious boiler design for low velocities in empty and convective boiler passes
- Provisions for quick super-heater bundle exchange (superheater bundle as wear part)

The increase of the steam pressure is less critical compared to a temperature increase. However, higher steam pressures may also demand for additional corrosion protection measures of the evaporator sections. Another technical limitation is the increase of the moisture content at the turbine outlet when increasing the live steam pressure at the turbine inlet. In order to overcome this drawback, for Rankine systems at increased pressures intermediate steam superheating is applied. However, intermediate steam superheating leads to losses due to additional pressure drop.

When choosing increased steam parameters, pressure and/or temperature, compared to the conventional design case of 40bara/400°C, the boiler as main part of the investment costs becomes substantially more expensive and boiler operation becomes more susceptible for increased wear.

**Decrease of Enthalpy of Expanded Steam at Turbine Outlet**

In case of a lower enthalpy at the outlet of the turbine the amount of heat to be transferred to the atmosphere for complete condensation decreases. The enthalpy at the outlet of the turbine can be lowered by:

- Expanding the steam to a lower outlet pressure, i.e. a lower condenser pressure/temperature. However this increases the moisture content in the outlet steam.
- Increasing the inner efficiency of the turbine.

The limiting moisture content of the steam at the turbine outlet depends on the particular design and the maximum acceptable values may vary between 10 up to 14%. The higher the limiting moisture content the higher the demand on design and material quality of the low pressure stages at the outlet of the turbine.

A possible increase in inner turbine efficiency aims on a reduction of the frictional heat produced by the turbine. This heat increases the enthalpy at the turbine outlet and must be finally transferred to the environment. The inner efficiency results from the turbine supplier’s design and ranges between 70 and 90%. Differences in the turbine design may have an important impact on the plant efficiency and may justify additional expenses for improved systems. This parameter is not further discussed herein.

**Regenerative Combustion Air and Feed Water Pre-heating with Steam or Flue Gas**

The further approach to optimise in particular the heat transfer between the flue gas and the water-steam-cycle is regenerative preheating of combustion air and feed water. Regenerative preheating is done by extracting partially expanded steam from the turbine for the preheating, thus producing a higher amount of live steam. Since the extracted steam flows are in total higher than the live steam flow additionally produced the steam flow to the condenser is thus reduced.

The effect of regenerative preheating is maximised by optimising the temperature levels at which heat is transferred. In Waste-to-Energy plants typically one to two extractions are made at different steam pressure levels. The feed water to the boiler is, thus, usually heated to or above 130°C and the combustion air, depending on the waste quality, to about 80 to 130°C.
Preheating the feed water to higher temperature levels prior to the boiler should result in further increased efficiency. However, increased feed water temperatures may restrict to cool the flue gas within the boiler down to an optimum temperature. The remaining flue gas heat can be still used to preheat the condensate water, taking care of the limitations imposed by the acid dew point.

**Reduction of Heat Released by the Flue Gas at the Stack**

From the heat balance according to table 1 the losses attributed to the flue gas flow at the stack are significant and the potential for efficiency increase is, hence, high. For plants with combined heat and power production it is even the main significant source of heat losses in the process. The flue gas heat losses can be reduced by following measures

- Decrease of flue gas temperature at the outlet of the boiler, i.e. increase of boiler heat surface.
- Decrease of excess combustion air, i.e. by means of flue gas recirculation and minimisation of parasitic air flows, i.e. leakage or transport airs, respectively.
- Utilisation of the remaining flue gas heat after boiler for internal or external use, i.e. internally for instance for condensate preheating by flue gas heat instead of steam.

In particular, flue gas recirculation has been early adapted by Von Roll Inova for the Waste-to-Energy technology and optimised in order to control reliably the possible risks related to corrosion and fouling in the recirculation lines and at the injection nozzles. Effectively it has been applied in several plants increasing the overall efficiency of the plant due to the increased boiler efficiency and the reduced size of the flue gas treatment downstream the extraction point.

The flue gas boiler outlet temperature is subject to constraints: it is selected due to the chosen flue gas treatment process and the use of flue gas heat at or below dew point of the vapour contents requires more costly protective measures to cope with acid condensates.

**Further Possible Measures**

Further possible and applied energetic optimisation measures not specifically discussed herein are:

1. Reduction of energy consumption of the plant, e.g. use of energy-efficient machinery.
2. Reduction of heat losses by heat radiation, e.g. application of efficient insulation.
3. Reduction of losses from residues exiting the process, e.g. improved burnout of bottom ash.
4. Reduction of fouling effects leading to necessary oversizing of the boiler and substantial efficiency loss during the service time of the boiler.

A reduction of plants energy consumption is less a matter of the design of the thermal cycle but must be viewed within the overall plant design. Reduction of heat losses by radiation and from residues have a direct impact on the efficiency of the water-steam-cycle but, taking into consideration the typical low energy streams of the related losses and anticipated expenses for further improvement, their remaining potential to contribute substantially to an efficiency increase appears to be low.

**EVALUATION OF DIFFERENT EFFICIENCY MEASURES**

The influence of different efficiency measures on the generator output is presented in the following for a Waste-to-Energy plant with condensation turbine dedicated for electricity production only. A base case scenario is defined as benchmark. In each calculation only one parameter will be varied while the other parameters are kept constant according to the base case scenario. The result of the variation is the increase in generator output power compared to the base case scenario. Table 2 shows the applied data for the base case scenario as well as the varied parameters including the range of variation applied.
Increase of Enthalpy of Live Steam (= Increase of Steam Parameters)
Obviously, as derived from Figure 3, the increase of the steam pressure appears to have a more significant impact on the generator output than the steam temperature. Thus, at constant live steam temperature the generator output increases for instance by 3% when increasing the pressure from 40bara to 50bara or by 2% when increasing the pressure by 10bars from an initial pressure of 60bara, respectively. In contrast, the generator output increases only by about 0.4% when increasing the steam temperature by 10K at constant steam pressure.

Decrease of Steam Enthalpy at Outlet of Turbine
It appears from the Figure 4 that lower condensation pressures/temperatures have a fairly reasonable influence on the generator output such that the condensation of the steam should be generally done as close as possible to the low temperature of the close-by available heat sink in the environment. For air cooled condensers a reasonably achievable pressure level may be thus at 0.08bara in regions of a moderate climate leading to a generator output increase of about 1.9% compared to a technically more modest solution with 0.1bara.

Further optimisation may be reached by cooling towers (about 0.06bara) or water-cooled condensers (about 0.03bara), but for Waste-to-Energy plants these solutions are rarely implemented due to either non-availability of appropriate water sources close to the accepted site or environmental concerns in terms of plume visibility or heat impact on the available water source.

Regenerative Combustion Air Pre-heating with Steam
In Figure 5 air preheating with low pressure steam at 5bara is studied at different temperature levels or levels of heat transferred into the air. The calculations show that preheating of primary and secondary air has an effect of about 0.9% and 0.3%, respectively, of increase in generator output when increasing the respective air temperature by about 50K. Air preheating can however be done only within restricted limits since a high air temperatures may affect the stability of the combustion process in case of high calorific values of the waste.

Reduction of Heat Released by the Flue Gas at the Stack
The flue gas is cooled down within the boiler by about 1000K. In case the flue gas temperature at the boiler outlet is varied by +/-10K the heat transfer to the boiler is roughly changed by +/-10/1000 = +/- 1%. Due to an overlaying influence of the specific heat of the flue gas, the generator output power changes, as a general rule, only by about +/- 0.8% in case of a variation of +/-10K of the boiler outlet temperature. For the varied range of temperatures the linear effect is shown in Figure 6.

The effect of the reduction of the excess air is shown in Figure 7. It is non-linear but within the varied range of oxygen content in the dry gas it can be estimated, as a general rule, by +/- 0.7% in case of a variation of +/-1 vol.-% oxygen content in dry gas. As shown the impact of flue gas recirculation is quite substantial compared to a situation where, without such provision, the generator output is reduced by more than 1.5%. Conceiving a plant without flue gas recirculation the decrease of the oxygen content would lead to an increase of the adiabatic temperature by about 100°C, increasing, as well, the thermal load in the furnace. For the an adiabatic combustion temperature of 1175°C the oxygen content without recirculation would be about 9 vol.-% in dry gas.

Figure 8 presents the design results where the extracted steam at about 1.2bara and 5bara, respectively, which is usually used to preheat the condensate, is substituted by flue gas after the boiler and the extraction for the flue gas recirculation. Hence this steam can be completely expanded in the turbine and produce additional electricity while the flue gas heat is further used before leaving the plant at the stack.
Comparison of Different Efficiency Measures Discussed
The comparison of the effect of different efficiency measures, as presented in Figure 9 (Variants explained in Table 3), confirms that a selection of increased steam parameters, in particular steam pressure, is the most promising way to reach a high efficiency increase.

This result is not really surprising since several Waste-to-Energy plant developers have followed this route resulting in a plants conceived to operate at substantially increased steam parameters (e.g. Gohlke (2007)). However, there remain doubts concerning the financial viability of such developments in case of parameters exceeding values where corrosion effects and respective counter-measures may start to have a significant impact on the capital costs.

ECONOMICAL EVALUATION OF INCREASE OF STEAM PARAMETERS

Model Assumptions and Description of Variants
The financial benefit of increased steam parameters is compared to the base variant. The benefit is expressed as net present value of the power revenues during an assumed finance life time minus the difference of extra capital costs compared to the base variant. The plant assumed has a thermal power of 55.6MW and produces electricity only. The calculation is based on a yearly operation period of 8000hrs/a at 100% load. The investment model takes into consideration the capital cost aspects influenced by the modified design parameters, namely boiler design/dimensions and its effects on insulation, steel structure and platforms as well as civil works related to boiler house volume, boiler corrosion protection, thermal system design (turbine and condenser size, piping, feed water pumps), as well as the electrical system (transformers for export of electrical energy and increase of auxiliary power supply). An influence of different operational expenditures is made only for different parasitic electric consumption due to different feed water pumps. The four different variants are given in Table 4.

The reviewed boilers are designed for an outlet temperature of 180°C after 8000hrs of operation. The objective was to design the boilers so that the corrosion risk is to be fairly the same for all boilers, and additional costs due to the higher corrosion risk are mainly reflected by the capital expenditures (and not in the operation costs). This means that the amount of corrosion protection (cladding) applied is steadily increased with increased steam parameters and the tube wall thicknesses and material are adapted to the steam pressure.

The financial model assumptions for the presented calculations are:
- discount rate for the NPV calculation : 6.5%
- finance life time of the investment : 20 years

These values are in the range of values as they are typically assumed by developers for Waste-to-Energy projects. The varied variable is the electricity revenue. On European electricity markets like Germany, UK, the Netherlands the revenues are today of the order 40 – 60 EUR/MWh. Taking into account subsidies these revenues may be substantially higher and reach values of 100 EUR/MWh or more.

Discussion of Economical Evaluation
The results of the simple financial model gives the clear indication that for European market based revenues for the sales of electricity the choice of increased steam parameters appears to be reasonable only to the extent where, from respective experience, more severe corrosion exposure is to be expected. Thus, the additional expenses for protective counter-measures counterbalance the benefit from the achievable efficiency increase. Very high steam parameters, i.e. steam temperatures above 430 - 440°C may become economically sensible at high subsidised electricity revenues. As such subsidies may be subject to changing political environments to rely and depend on subsidies in the plant design may not be favourable and impose additional risk on the operational business.
Due to this perception, Von Roll Inova is rather careful to promote the application of high steam parameters. Recent plants conceived by Von Roll Inova at increased steam parameters are located in Roosendaal (NL) and London, Riverside (UK) with steam parameters of 60 bara/420°C and 72 bara/427°C, respectively. Applying also other efficiency measures, as presented herein, the London plant is designed to reach a gross efficiency of about 30%. These plants are at present under construction by Von Roll Inova as EPC Contractor and are to come into operation in 2010.

CONCLUSION

Starting from an analysis on the effects of known energy efficiency measures on the generated electrical output, increasing the steam parameters of the live steam is identified as the measure with the highest efficiency potential for Waste-to-Energy plants. However, the drawbacks of this efficiency strategy, in particular a substantial increase of corrosion-related wear of the boiler, need a subtle assessment in order to decide on the extent of a reasonable design. Financial models based on a net present value investment appraisal of the additional capital costs, revenues and operation costs are necessary and helpful when executing such design assessment. The model applied and presented herein is still simple and does, in particular, not consider eventual negative effects on plant availability and operational costs for maintenance. Nevertheless, it may be concluded from the model results that exceeding steam temperatures of 430 - 440°C appears to be economically only viable in case revenues from electricity sales reach and remain at levels far above today’s typical market prices. Hence, a still more conservative plant design as rather promoted by Von Roll Inova may be a more sustainable design strategy for a long-term investment like a Waste-to-Energy plant.

REFERENCES


FIGURES

Figure 1: Design case A) a plant with condensation turbine and possible export of usable heat by steam extracted from the steam turbine

Figure 2: Design case B) a plant with backpressure turbine and complete use of steam at turbine outlet as usable heat
Figure 3: Influence of live steam parameters at turbine inlet.

Figure 4: Influence of steam pressure outlet turbine or condensation pressure on generator output.

Figure 5: Influence of regenerative combustion air preheating on generator output (PA: primary air, SA: secondary air).

Figure 6: Influence of flue gas temperature at boiler outlet on generator output.
Figure 7: Influence of excess combustion air on generator output.

Figure 8: Influence of use of flue gas instead of steam for condensate preheating on generator output.

Figure 9: Comparison of different efficiency measures for specific design cases.

Figure 10: Results of financial model calculation for different levels of electricity revenues. Variants are according to Table 4.
Table 1: Energy outputs for design cases A) and B) in realised Waste-to-Energy plants.

<table>
<thead>
<tr>
<th>Input</th>
<th>%</th>
<th>Output A)</th>
<th>%</th>
<th>Output B)</th>
<th>%</th>
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<tbody>
<tr>
<td>B x Hu</td>
<td>97</td>
<td>Usable heat</td>
<td>0</td>
<td>Usable heat</td>
<td>73</td>
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<tr>
<td>Auxiliary power</td>
<td>3</td>
<td>Gross electric power</td>
<td>26</td>
<td>Gross electric power</td>
<td>17</td>
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<tr>
<td></td>
<td></td>
<td>Heat release at condenser</td>
<td>59</td>
<td>Heat release at condenser</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rejected heat at stack</td>
<td>11</td>
<td>Rejected heat at stack</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Losses by residues</td>
<td>2</td>
<td>Losses by residues</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Losses by radiation</td>
<td>2</td>
<td>Losses by radiation</td>
<td>2</td>
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<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
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Table 2: Energy outputs for design cases A) and B) in realised Waste-to-Energy plants.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base case data</th>
<th>Variation data</th>
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<tbody>
<tr>
<td>Waste Thermal Power MW</td>
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</tr>
<tr>
<td>Turbo-Generator Generated power MW</td>
<td>14.48</td>
<td></td>
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<tr>
<td>Flue gas O2 content Vol.% dry</td>
<td>7.2</td>
<td>3.2 - 9.1</td>
</tr>
<tr>
<td>Temperature outlet boiler °C</td>
<td>180</td>
<td>160 - 220</td>
</tr>
<tr>
<td>Feed water Temperature °C</td>
<td>130</td>
<td>130 - 145</td>
</tr>
<tr>
<td>Live steam Temperature °C</td>
<td>400</td>
<td>360 - 500</td>
</tr>
<tr>
<td>Pressure bara</td>
<td>40</td>
<td>40 - 90</td>
</tr>
<tr>
<td>Temperature increase by</td>
<td>0</td>
<td>35 - 180</td>
</tr>
<tr>
<td>intermediate superheating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded steam Pressure exit turbine bara</td>
<td>0.1</td>
<td>0.06 - 0.14</td>
</tr>
<tr>
<td>Air preheating Pressure of steam bara</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Heat of extracted steam kW</td>
<td>0</td>
<td>0 - 3'200</td>
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<tr>
<td>Condensate Steam pressure bara</td>
<td>1.2</td>
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<tr>
<td>preheating Steam pressure de-aerator bara</td>
<td>5</td>
<td>3.5 - 8</td>
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<tr>
<td>Heat from flue gas kW</td>
<td>0</td>
<td>0 - 2200</td>
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Table 3: Design cases as compared in Figure 9.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Base case data</th>
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<tbody>
<tr>
<td>1 Life steam parameters</td>
<td>40 bara / 400°C</td>
<td>60 bara / 420°C</td>
</tr>
<tr>
<td>2 Life steam parameters</td>
<td>40 bara / 400°C</td>
<td>70 bara / 440°C</td>
</tr>
<tr>
<td>3 Steam reheating</td>
<td>None</td>
<td>HP: 90bara/400°C; LP 16bara/310°C</td>
</tr>
<tr>
<td>4 Condensation parameters</td>
<td>0.1 bara / 45.8°C</td>
<td>0.08 bara / 41.5°C</td>
</tr>
<tr>
<td>5 Flue gas temperature boiler outlet °C</td>
<td>180°C</td>
<td>160°C</td>
</tr>
<tr>
<td>6 Oxygen concentration in flue gas (dry)</td>
<td>7.2 vol.-%</td>
<td>3.9 vol.-%</td>
</tr>
<tr>
<td>7 Flue gas cooling by condensate preheater</td>
<td>None</td>
<td>30K</td>
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Table 4: Variants considered for financial net-present value assessment. Variant 4 includes intermediate steam reheating.

<table>
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<th>Variant</th>
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<tr>
<td>Life steam parameters</td>
<td>Pressure</td>
<td>40</td>
<td>60</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Temperature °C</td>
<td>400</td>
<td>420</td>
<td>440</td>
<td>460</td>
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<tr>
<td>Thermal efficiency</td>
<td></td>
<td>26.1</td>
<td>27.8</td>
<td>28.6</td>
<td>29.3</td>
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