

Waste Heat Recovery for District Heating – a Hot Topic at a Low Temperature –

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Heating and cooling for households accounts nearly for 50 % of annual EU´s energy consumption. Space heating and residential hot water generation are the main contributors in the overall households consumption, accounting 79 % of final energy use [1]. Domestic gas heating accounts 69 % of overall natural gas import because the buildings are not well insulated and existing boilers inefficient. Despite the significant share in overall energy consumption, heating and cooling sector was particularly overlooked by EU´s government and the main focus was always given to the electricity production. This has been changed in February 2016 where EU has proposed District Heating & Cooling Strategy (DHC) as a first initiative to make this area more sustainable and energy efficient. Amongst other measures it involves reusing the waste energy from different industrial processes and energy efficiency improvements in general. DHC strategy is a follow up of EED (Energy Efficiency Directive) which sets binding targets for different EU countries (updated in 2016) as 30 % improvement in energy efficiency compared to 2012 until 2030. Such legal framework gives a solid basis for utilizing the waste heat otherwise be lost in the atmosphere.

The main scheme where to pay attention is a combined heat & power generation (CHP). CHP exists and being used almost for a century. It brings significant advantage in the fuel energy utilization, where besides electricity generation the heat is recaptured in different forms. It could be process steam, district heating water, chilled water or combination of those.

This article focuses on recovering the waste heat from flue gases generated by either Waste-to-Energy or Biomass unit by recapturing its sensible and latent heat into district heating (DH) networks for units working in CHP mode. Heat recovery for district heating generally uses low-pressure (LP) steam from steam turbine extraction to preheat returning district heating stream to a final forward temperature. Usage of LP steam is reasonable due to the fact that live steam is fed into steam turbine to release its energy for electricity generation. District heating system is therefore heated by a steam with reduced temperature and pressure closer to a heated media. This conventional concept is applied in most heating plants across Europe.

Currently, when the fuel is becoming more valuable resource than ever before and CO₂ ticket prices are climbing, it is worth to think about the solution how to improve the overall plant efficiency and performance. Many of us already knows that installation of flue gas condenser could bring substantial increase in district heat generation, together with less CO₂ generated. In Nordic countries, flue gas condenser is present on a number of heating plants. Contrary to that, quantity of condensers installed in Western part of EU is close to zero. But what is the reason for? The key aspect is in district heating operating temperatures, especially the return one. Denmark, for example, has typical return DH temperature around 38 – 42°C. This is caused by a year-long mild climate and district heating system architecture in general. In Germany, typical return district heating temperature is around 60 – 65 °C. On a first insight the numbers looks pretty similar, 20K temperature difference in the area 450 – 30 °C where the steam-water cycle operates seems negligible, but opposite is the truth.

Understanding the major impact of the return district heating temperature to the overall plant performance equipped with flue gas condenser is essential for forward-looking planning to the district heating scheme of the future.

This paper outline the main physical principles of GE 's integrated aCHP (Advanced Combined Heat and Power Generation) solution with the aim to improve overall plant efficiency by increasing district heating production, together with significant reduction of CO₂ production and greater unit flexibility.

1. Understanding the fuel efficiency

In order to understand how waste heat recovery from flue gases works it is necessary to see the logic behind the fuel efficiency calculations. In EU it is common that fuel energy input is expressed as LHV (lower-heating-value). Thus, efficiency factor for boiler or plant is typically based on LHV.

LHV is, however, not full amount of energy introduced into the process. The overall flow is based on HHV (higher-heating-value). The main difference between LHV and HHV is that LHV accounts water vapour in flue gases released into the atmosphere still in gas phase, but HHV consider full fuel input, including energy from water vapour condensation known as latent heat transfer. This is especially important for high humidity fuels such a municipal solid waste or biomass where the water content is high as of 40 – 55 % of moisture. In the boiler, this fuel needs to be evaporated to generate energy and hot flue gases. Flue gases therefore has quite signification water vapour share in the overall content and this energy is currently released unused into the atmosphere.

It is not suprising that the sole electricity production from municipal solid waste has quite low efficiency. The reason is that Waste to Energy units are operating with low steam temperature and pressure due to risks of high temperature chlorine corrosion etc. Typical steam parameters are around 400 °C at 40 bar(a). Convertibility of heat energy into electricity is therefore limited, resulting in low overall cycle efficiency around 22 – 26 %. Contrary to that, combined heat and power operation where the residual energy from electricity generation is recaptured in the district heating network increases the overall efficiency over 80 %. Both given numbers accounts the fuel based on LHV. But what are the results in case we use as a basis HHV instead of LHV? The difference illustrates the Figure 1.

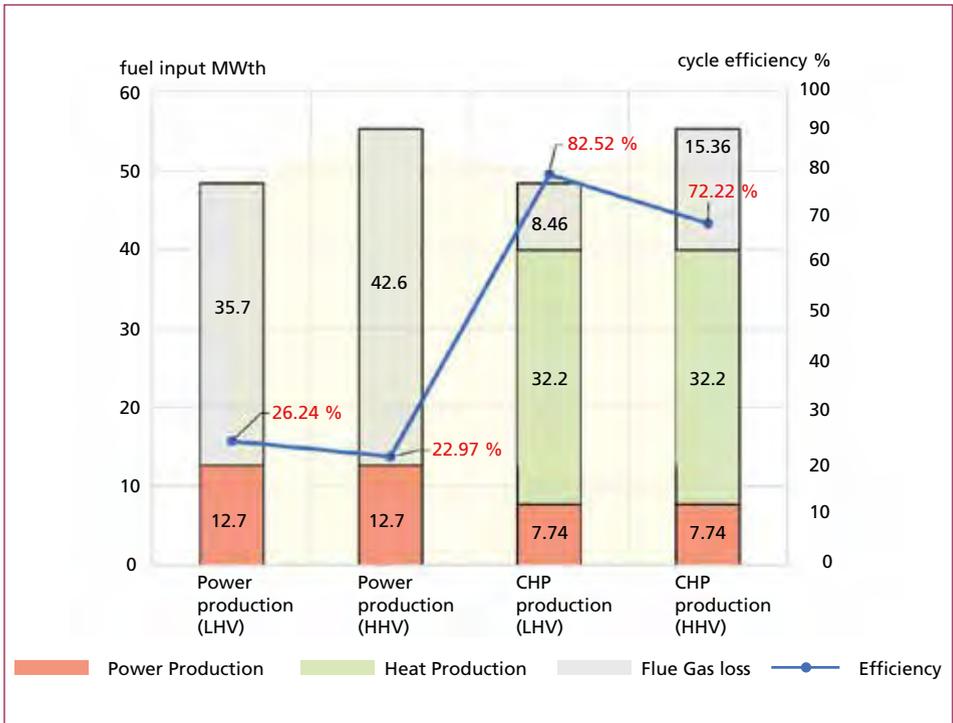


Figure 1: Fuel efficiency vs. losses for electricity and CHP production based on LHV and HHV. Conditions: 40 MWth boiler, Condensing turbine, 140 °C stack temp., fuel LHV 10 MJ/kg, H₂O in fuel gas 17.8 % vol. wet

Diagram given on the Figure 1 is quite useful as a graphical expression of the difference between lower and higher heating value for various operating modes. It is clear that CHP operation gives much better fuel utilization factor by reduced loss of waste heat (flue gas heat). Red numbers represent achievable efficiency and more importantly difference in cycle efficiency by changing the basis for the calculation. Despite reasonably good efficiency in CHP operation mode there is still a significant amount of energy coming out unused from the stack into the environment. The graph also explain how it is possible to reach miracle efficiency in gas-condensing boilers above 100 % - simply the basis for such efficiency is LHV.

2. The technology

This section is divided to a description of different streams which are essential for waste heat recovery. Each stream has its own specific conditions that can become a limiting factor in achievable energy recovery factor. The streams explained are: flue gases, district heating network and steam-water cycle.

2.1. Flue gas stream

Flue gases from municipal solid waste has around 18 % of water share. The level of water share in flue gases is determined by the fuel humidity as a main contributor and flue gas cleaning technique. For example, unit where wet flue gas desulphurisation is installed has higher water content due to spraying the water into the process in a different

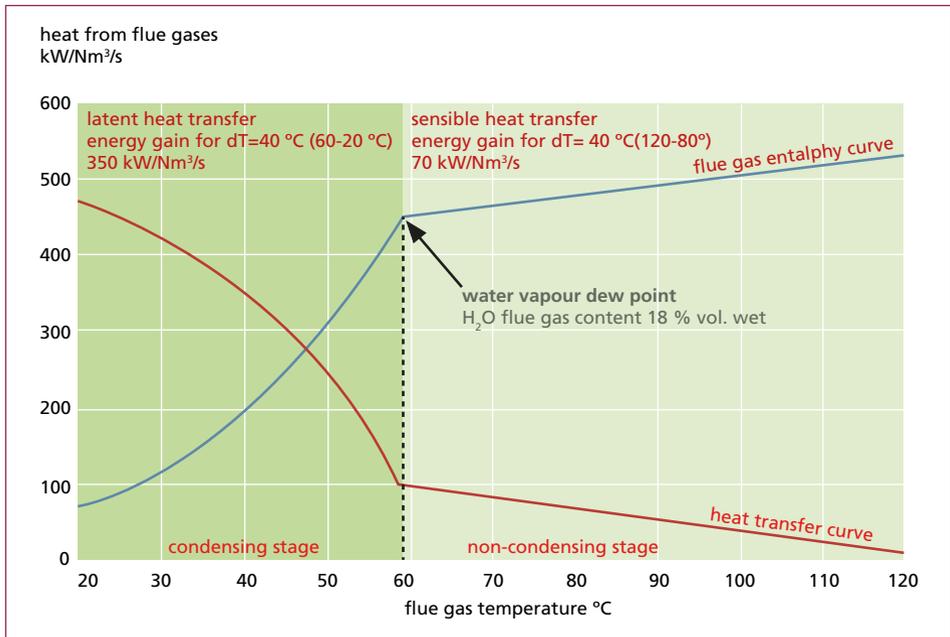


Figure 2: Sensible and Latent heat transfer potential for 18 % H_2O content in flue gases

absorber sections. Typically the stack flue gas temperature is lower than with dry cleaning techniques, because the water introduced into the process needs to be evaporated by sensible heat resulting in lower outlet temperature. The opposite effect occurs in case of need for preheating the flue gases downstream absorber to a suitable temperature for selective catalytic reduction (SCR). This energy, typically taken from low pressure steam is another part of stack loss resulting in lower overall plant efficiency. That being said, any technique which allows to recapture both sensible (from steam reheater) and latent (from evaporated water) heat from the flue gases at the stack is of a great help for energy recovery. To see the potential of sensible and latent heat recovery from flue gases see Figure 2.

From this diagram it is obvious that sensible heat transfer takes place when the flue gas temperature is above the water vapour dew point. Water vapour dew point is determined by H₂O content in the flue gases. 18 % H₂O is typical for 50 % fuel humidity and dry flue gas cleaning technique resulting in water vapor dew point around 58 °C. Latent heat transfer (when water vapour condensing on a cold surface and releasing its latent heat) occurs only below dew point temperature. Latent heat transfer is approximately 5x more efficient than sensible heat transfer at given temperature level. Our main goal is therefore to reach the dew point as soon as possible in order to start with condensation.

The level of heat recovery is determined by a temperature of flue gases outflow. Cooling down the flue gases is possible by a cooling stream at suitable temperature level. It is typically return district heating water or water from a heat pump. The dependency on how the heat recovery is changing by boundary conditions is shown in Figure 3.

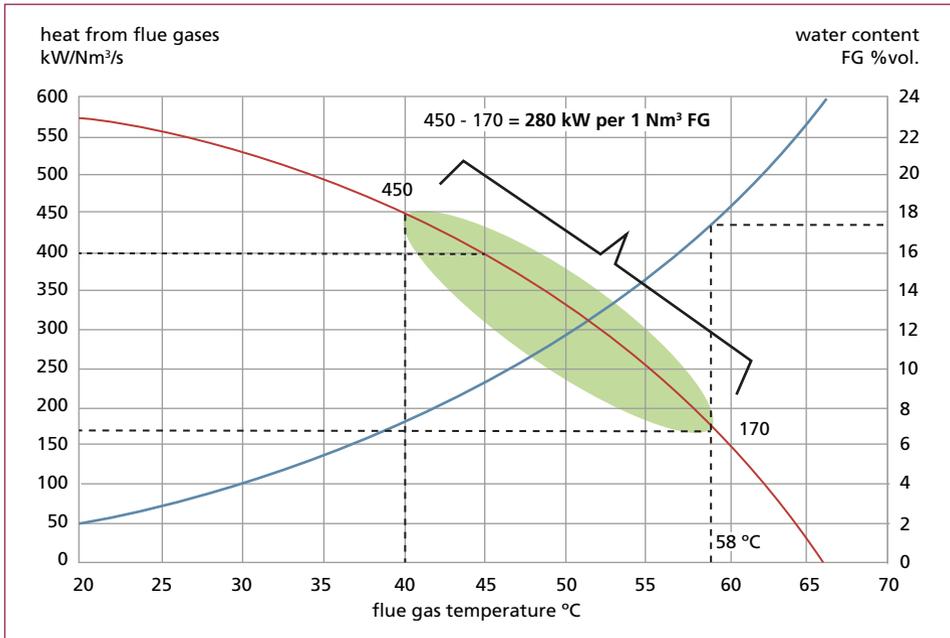


Figure 3: Heat recovery potential based on different H₂O content in flue gases and final flue gas temperature

We clearly see that in order to start with condensation we need a cooling media with as low as possible temperature, definitely below the dew point. On figure 3 flue gases are cooled down to 40 °C which is hardly achievable with existing district heating network.

2.2. District heating network

Beginning this article we stated the importance of return district heating temperature on the overall performance and comparison of such for Nordic and non-Nordic countries (42 °C vs. 65 °C). Once the return district heating temperature is above the dew point it is thermodynamically impossible to start with condensation and no latent heat transfer occur. Therefore it does not make sense at all to install a sole flue gas condenser, since no latent heat transfer will be provided.

A gamechanger in the overall waste heat recovery equation is installation of an industrial size heat pump. Heat pump essentially providing temperature lift with usage of external energy. This article covers mainly absorption heat pump technology, as long as it seems to be more suitable for CHP plant because it operates with heat only (with minor electricity consumption). For sake of clarity, the absorption heat pump described here is based on a working pair of lithium bromide and water, where LiBr ensures essential temperature lift and heat transfer is provided via water. Global warming potential (GWP) of this heat pump type is zero. Heat pump works at three temperature levels – high temperature providing driving heat for thermo-physical reaction, medium temperature for releasing the energy from the process and low temperature generating cold (chilled) water as cooling media for flue gas condenser.

Cold water is of a great interest, because it is a media which determine the final flue gas temperature. If the heat pump can generate chilled water at around 35 °C there is a possibility to reach the flue gases temperature around 40 °C (accounting reasonable dT on flue gas condenser). Chilled water temperature from heat pump is, however, determined by another two factors. The first criteria is return district heating temperature. Typically, for return temperature 60 °C achievable chilled water temperature is around 40 °C and flue gases can therefore be cooled to approximately 45 °C. In case the return district heating temperature goes lower, the heat recovery potential goes up and vice versa. Next criteria is available steam pressure. Necessary steam pressure is predominantly given by a district heating outlet temperature from a heat pump (typically limited to 90 °C) which is a function of return district heating temperature and available DH water flow. One could look into Dühring chart for solubility of lithium bromide with water to understand more about the topic.

In order to visualize the big differences around couple °C in district heating network we shall have a look how the system performance is changing with different district heating temperatures.

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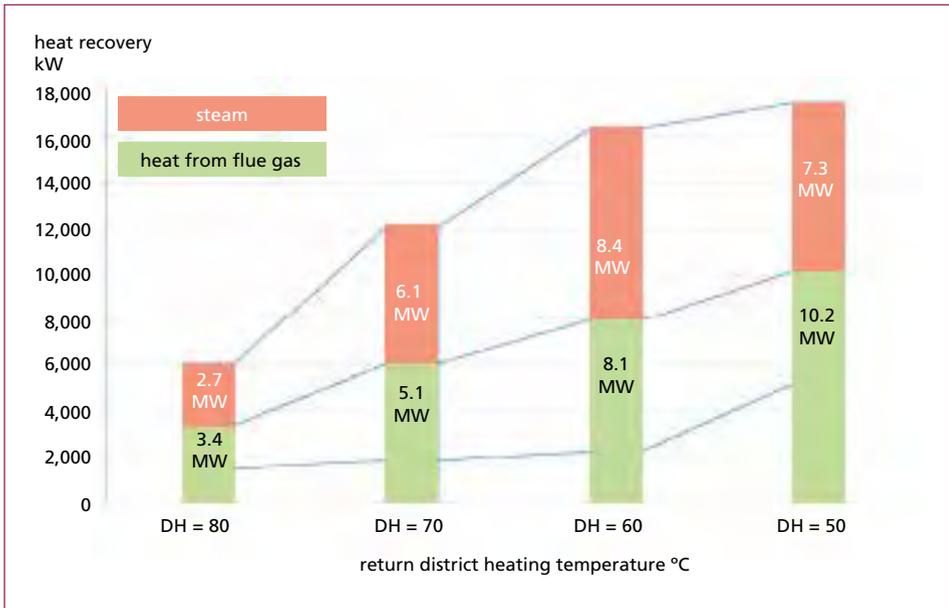


Figure 4: Flue Gas Condenser performance based on different return district heating temperature Conditions: 40 MWth boiler, flue gas inlet 140 °C, 45 °C stack temp., H₂O in flue gas 17,8 % vol. wet, same unit size for all cases

Example above is just for illustration about the impact of returning water temperature. For 40 MWth (LHV) boiler input and return district heating water at 60 °C, approximately 8 MW of heat could be recovered in addition to the existing unit’s performance. In case no heat pump is installed heat recovery and return temperature is kept at 60 °C no latent heat transfer will occur and recovered heat is only 2.2 MW instead of 8.1 MW (27 % of overall potential). Given rationales forces us to think about integration of the heat pump into the overall schematics to recapture as much as possible heat from flue gases even in case the return district heating temperature is above the dew point.

One could admit that the system consume steam. It is definitely an odd wording since all heat coming from the steam is introduced into district heating water with no/minor losses. As any other comparable system, also aCHP works with a certain efficiency. Consumption of low pressure steam around 5 – 7 bar(a) would reduce the electricity production in case aCHP is switched on. This is a true statement, but it is worth to think about this aspect in a wider context.

2.3. Steam-water cycle

Efficiency of electricity generation is determined mainly by a quality of a media providing mechanical and kinetic force for the steam turbine blades. Decreasing the steam parameters (temperature, pressure) reduce the convertibility potential of heat into electricity. Recent studies shows that steam at temperature around 174 °C (which

relates to steam condensing pressure 7,5 bar(a)) has the convertibility factor only 28 %. It means that 1MW of heat at such temperature level could generate approximately 280 kW of electricity if cooled down to 30 °C in conventional steam-water condenser. Convertibility factor is a general value and steam turbine arrangement needs to be taken into account as well on a case by case basis, so the results for a specific plant might differ. Heat to power convertibility is very important aspect to be understood and brings a main differentiation between mechanical heat pumps (electrically driven) and absorption heat pumps (heat driven). Let us have a look back to the example with different return temperature and take a case with 60 °C return. aCHP could generate 8.1 MW of heat from flue gases and consequently, heat pump need a driving heat in amount of 8.4 MW. Overall, the system generates 16.5 MW of heat to the district heating network with need of steam which normally being converted into electricity at 28 % efficiency. That being said, the coefficient of performance (COP) for such system, using slightly modified equation for COP calculation is as follow (System COP for absorption heat pump integrated with flue gas condenser):

$$\text{COP} = \frac{\text{heat from flue gas} + \text{heat from steam}}{\text{heat from steam} \cdot \text{convertibility factor}} = \frac{8.1 + 8.4}{8.4 \cdot 0.28} = 7.01 \quad (1)$$

Representing the results in a correct way the unit would generate 16.5 MW of heat of which 8.1 MW is extra from flue gases and, at the same time, electricity reduction is approximately 2.3 MW resulting in overall efficiency factor of 7.01. Worth to mention that we have used a single stage absorption heat pump with COP 1.7. If we compare the similar arrangement with mechanical heat pump which consume electricity directly, the results differs by efficiency of a particular heat pump. Mechanical heat pumps at such temperature level could achieve COP around 3.2 – 4.2. Simply comparing efficiency factor the flue gas condenser with integrated absorption heat pump has nearly double the efficiency than the same condenser integrated with mechanical heat pump. Obviously, with lower district heating temperature the better COP can be achieved. Limiting design factor is available steam pressure and flow at suitable extraction level. Close to 7 bar(a) is an optimal value and higher pressure (for example live steam) gives worse results, mainly on electricity side. These aspects needs to be investigated case by case to find the best possible scenario.

2.4. GE solution for waste heat recovery

As shown in the chapters before, an enabling technology for waste heat recovery for district heating is a flue gas condenser integrated with absorption heat pump. Downstream of the existing cleaning process equipment, just upstream of the stack, the flue gases are taken into a standalone CHP to start the cooling procedure. The flue gases flows through the low-temperature economizer which is cooled directly by return DH water and the flue gas condenser integrated with an absorption heat pump (AHP). The AHP produces chilled water to cool down the flue gases well below

the water dew point, extracting a large portion of the latent heat. The gained energy is then transformed in the AHP into a quality which is sufficient to be re-used in the cycle – for preheating the return district heating water stream. Depending on stack arrangement, optional flue gas reheater could be installed. Reheater is designed to eliminate the droplets formation in the stack and related corrosion issues potential. System is equipped with integrated booster fan which allows to overcome the extra pressure loss provided by heat recovery system. This is a first fully integrated, standardized and modularized unit for waste heat recovery named aCHP (Advanced Combined Heat and Power Generation). It combines latest development in corrosion-resistant materials, together with well optimized system performance, excellent operational flexibility and low maintenance costs. The system essentially consisting of flue gas condenser, absorption heat pump, droplet separator, booster fan, silencer, connection to the existing flue gas system and related piping, instrumentation & control and electrical scope. We paid a lot of attention to shrink the system footprint to the smallest possible, but taking into account easy maintenance and accessibility. Standardized design is suitable for boiler sizes 25, 40 and 50 MW thermal input (LHV) with good scalability options. Boiler size relates to aCHP size 5, 8 and 10 MW of recovered energy, based on site specific boundary conditions. Cycle arrangement is apparent from the diagram Figure 5.

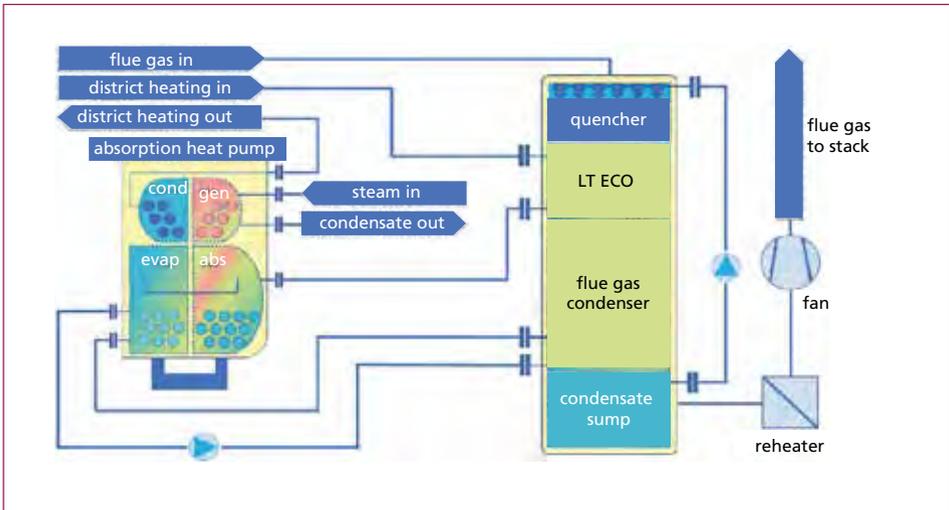


Figure 5: aCHP cycle arrangement

2.5. Layout arrangement

Overall arrangement is apparent from Figure 6. 5 MW unit has a footprint 120 m² and 10 MW has 180 m² respectively. Both condensing and heat pump module works as a separate package and can easily be displaced each other. This is especially suitable for the case where existing building can be used or district heating connection is far from the flue gas system.

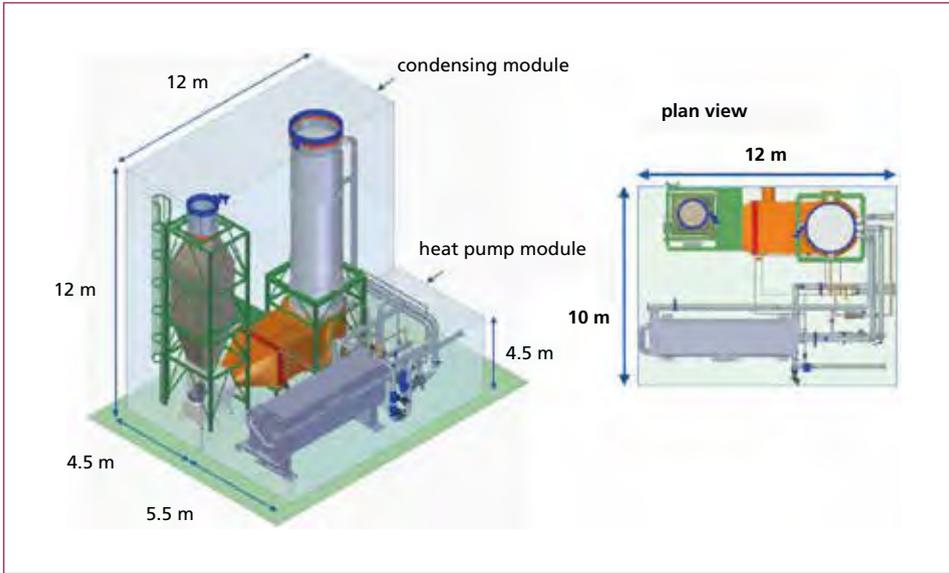


Figure 6: aCHP layout arrangement

Benefits

- significant heating capacity increase,
- substantially reduced CO₂ production,
- greater flexibility towards power market,
- optimized for higher DH temperatures,
- standalone product = zero boiler impact,
- exceptional coefficient of performance,
- attractive return of investment,
- long equipment lifetime (25 years),
- low own consumption & maintenance.

3. Case study

3.1. Customer's problem statement

We burn waste as fuel, which we burn for both power and heat production, whether the electricity prices are favorable or not. We can utilize more heat in the district heating network we are connected to, but our unit has limited capacity. Increased heat production can bring us an additional revenue stream which helps to improve our balance sheet.

An efficiency boost could enable us to positively contribute in the reduction of our town’s carbon footprint by decreased operating time from another conventional source (coal, gas) feeding the same heating grid. We also need greater plant flexibility to better react to market conditions.

3.2. Customer’s profile

An existing Waste to Energy facility has a capacity of 100,000 tons of waste per year and is equipped with a 40 MWth boiler. The unit generates 15 kg/s live steam 420 °C at 40 bar(a) into a condensing turbine with one controlled extraction at 5 – 7 bars. The steam turbine has a capacity of 13 MWe in condensing mode and the district heating production is 30 MWth. Overall district heating network has a peak capacity of 160 MWth with the heat being produced for > 6,000 hours per year. The unit has a heat dispatch priority and is running in a baseline operation mode > 8,000 hours per year. Electricity prices are given by the market conditions. Return district heating temperature is kept at ± 60 °C.

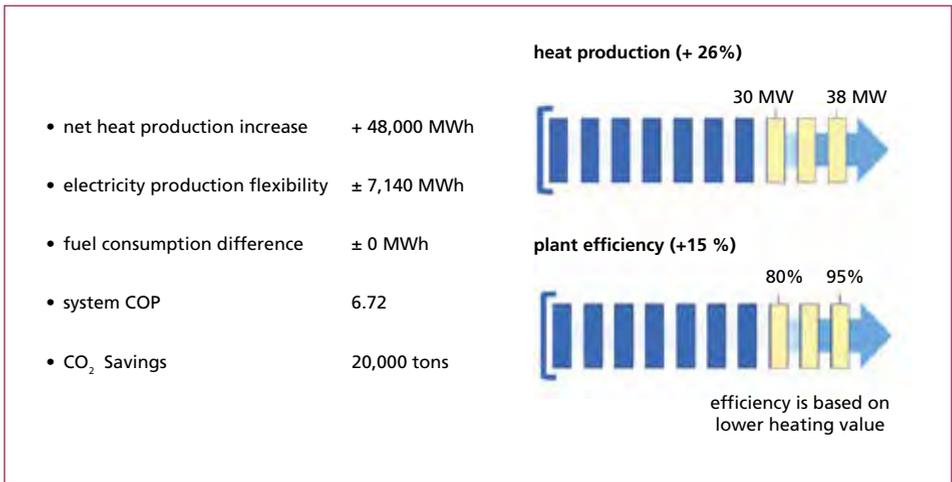


Figure 7: aCHP benefits; values are based on 6,000 hours in operation, CO₂ calculated for lignite

3.3. Contribution to the heat load diagram

Contribution of heat recovery solution to the heat load diagram is apparent below. The larger district heating network connection is, the more hours can be operated with aCHP. More hours of operation means shorter payback to monetize the investment. Recent calculations shows the great benefit from installing a flue gas condenser into the existing heating plant, both commercialy and environmentally.

Installing GE’s aCHP into the cycle allows the unit to either prioritize the heat or electricity for optimized operation. The heat optimized cycle can provide 8 MW of extra heat from the flue gases and therefore can improve fuel efficiency by approximately

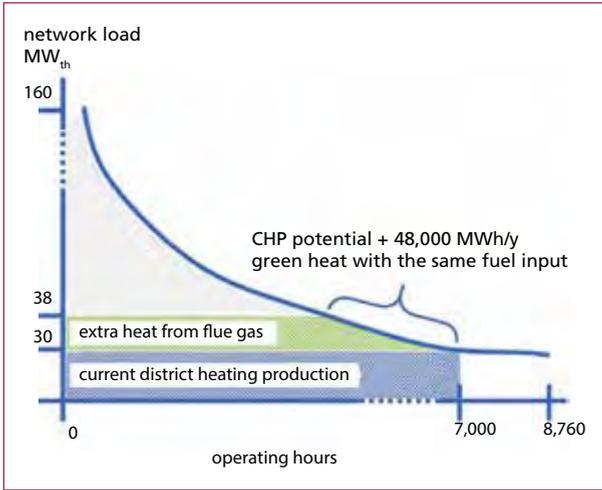


Figure 8:

Heat load diagram contribution of heat recovery measures

15 %. Simultaneously, the absorption heat pump uses low pressure steam from the existing steam turbine extraction as a driving heat. Extracted steam from higher pressure reduces electricity production, but none of this heat is lost. The full energy amount of the steam is transferred into the district heating network through the absorption heat pump. When the electricity prices become attractive, the heat pump can be stopped and steam from extraction sent to the condensing stage to increase the electricity production. For biomass units, the same heat production can be maintained with much less fuel consumption due to lower boiler load. aCHP enables the unit to run more flexible towards electricity market and get the most energy from the fuel in heat optimized mode. During transient periods (spring, autumn) the unit can run longer to avoid starting peaking gas boilers. GE has more than 30 years of experience with flue gas condensing system for waste to energy and couple installations are equipped also with a heat pump.

4. Conclusion

Waste heat recovery is becoming naturally a hot topic, because of great return-of-investment factor. Despite the fact this technology operates with relatively low temperatures, the potential of efficiency gain is substantial comparing other technologies. Steadily increasing prices of fuel and other commodities, together with widely accepted target to become more sustainable and environmentally friendly, nobody can overlook waste heat utilization which currently represent the most valuable untapped source of energy. We believe that state-of-the-art flue gas condensation is setting a new standard in energy efficiency for district heating segment. Integrated heat pump overcomes the main hurdle of high return temperature and enable to utilize much more energy from the fuel than before. Waste heat recovery projects could therefore be spread across the industrial segment. Local plants, municipalities and operators should investigate

such possibility of efficiency gain with respect to build a better society for the next generations. Waste heat recovery is the only measure of CO₂ footprint reduction with attractive payback.

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