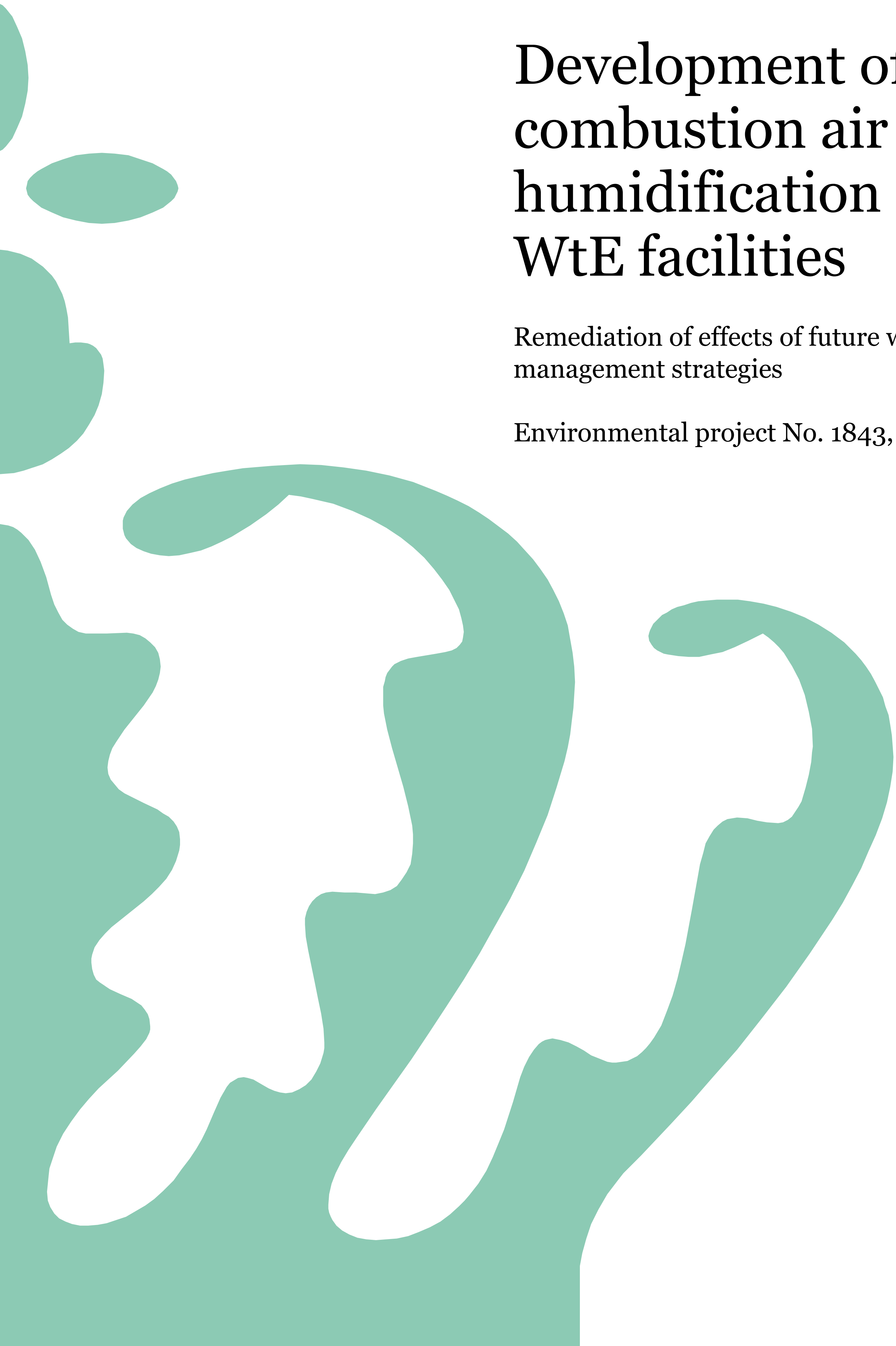
**Ministry of Environment
and Food of Denmark**
Environmental
Protection Agency

Development of combustion air humidification at WtE facilities

Remediation of effects of future waste management strategies

Environmental project No. 1843, 2016



Title:

Development of combustion air humidification at WtE facilities. Remediation of effects of future waste management strategies.

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Sources must be acknowledged.

Contents

1. Foreword

Many Waste-to-Energy (WtE) plants will experience a change in waste composition compared to the current situation as a result of implementation of increased recycling of waste. This change may influence the energy recovery and hence a major source of revenue for the facilities.

In this project a technology is suggested to compensate for the possible challenges foreseen by the separation of the organic fraction giving a dryer fuel for Waste-to-Energy facilities. The project has been carried out in co-operation between Rambøll Danmark A/S, Babcock & Wilcox Vølund A/S, I/S Vestforbrænding, AffaldPlus I/S and AffaldVarme Aarhus.

The project has been carried out from January 2014 to December 2015 with the following steering committee for the project:

- Lennart Gustafsson (Götaverken Miljö AB)
- Ole Andersen (AffaldPlus)
- Ole Holmboe (I/S Forbrænding)
- Kenneth Egeskov (AffaldVarme Aarhus)
- Jens Dall (Dall Energy)
- Christian Riber (Rambøll Danmark A/S)
- Thilde Fruergaard Astrup (The Danish Environmental Protection Agency)

Rambøll Danmark A/S has contributed with resources for project management, waste composition analysis and energy system analysis. Babcock & Wilcox Vølund a/s (including Götaverken Miljö AB) has contributed with resources for technology development, layout evaluation and energy system analysis. The three WtE facilities have contributed with resources for innovation and assessment of the technical solutions.

For the report Rambøll has produced the text with the exception of the chapter on furnace/boiler effects which was produced by B&W Vølund headed by Thomas Norman. The report has been reviewed by all members of the steering committee in the production process.

This project was managed by the engineering consultant Rambøll Denmark A/S and was supported financially by The Danish Environmental Protection Agency through the Programme for Green Technology 2013.

1.1 Reading guidance

The report reflects the work done in the way that assessments were made in the same order as presented in the report. The problem in the way of future changes in waste composition was studied and remediation options assessed. The preferred solution (combustion air humidification) was studied and its potentials, advantages and disadvantages were evaluated. The perspective of the technology was studied and hence the way was paved for the next stage in implementing a solution for the problem at hand.

2. Conclusion and Summary

The Danish resource strategy, “Danmark uden affald” ("Denmark without waste"), sets new guidelines for the handling of waste within the Danish municipalities. The new handling includes more waste separation, which, in the future, will result in a changed composition of the waste to be used for energy recovery in Waste-to-Energy (WtE) facilities, compared to the composition today. Segregation of the organic waste will be important to meet the 50% recycling target set out and with the high moisture content of this fraction this will reduce the moisture content of the waste mixture, and the flue gas and, in turn, reduce the energy recovery from flue gas condensation systems. As true as this is the modelled average Danish waste composition only changes slightly as both low and high calorific waste fractions are sorted out. However it is concluded that regional differences are likely to be much larger and hence the individual WtE facilities are anticipated to see much higher differences in waste received than observed on the national average.

This project focuses on introduction of combustion air humidification in the WtE industry to generate more energy and prepare the facilities for future challenges introduced due to the increased focus on resource recovery upstream the facility in the waste management system. Combustion air humidification was found as the most energy efficient system in comparison with other alternatives such as waste humidification and water injection into the furnace.

Major advantages and disadvantages of introducing combustion air humidification technology have been studied and assessed and the following can be concluded to be the most important:

Advantages:

- Fuel water content fluctuation can be counteracted (furnace and boiler will see a constant water content)
- Significant district heat production without a backpressure turbine (and even possibly without a turbine bleed)
- Cost effective district heat production (even with a backpressure turbine)
- Enabling district heat production by condensation with district heat return temp. in the range 55 to 70^{o}C
- Lower temperatures before the super heaters (with boiler modifications significant lower temperatures)
- Short payback periods of 5 to 8 years

Disadvantages:

- More complexity added to the facility
- New boiler regulation might be needed and new operator instructions
- Cold flue gas might need reheating to ensure sufficient dispersion, avoid droplet formation and to avoid plume visibility
- Project might need to include a lining of the stack to accommodate the wet environment
- Plant layout might be challenged with the space need for scrubbers, pumps and piping

It is concluded that the major disadvantages encountered have been solved during the project and that the disadvantages remaining (above) are without major significance.

The potential for the technology is great since a major part of the facilities with present flue gas condensation can benefit from the technology and so can a majority of facilities without a present condensation unit but with some district heat production and a higher demand than the production capacity. The market covers primarily countries located in climates where heating of homes is required and accommodates district heating systems.

3. Konklusion og resumé

Den nationale ressource strategi, "Danmark uden affald" giver nye retningslinjer for kommunernes affaldsplaner med hensyn til genanvendelse og genanvendelsesmål. Mest gennemgribende er genanvendelsesmålet på 50% for husholdningsaffald, der sandsynligvis medfører, at udsortering af organisk affald til genanvendelse vil finde sted i de fleste kommuner. Dette betyder, at restaffaldets sammensætning vil blive påvirket, hvilket har betydning for de danske affaldsforbrændingsanlæg. Især vil udsorteringen af det organiske affald med højt fugtindhold betyde, at det resterende affalds fugtindhold reduceres, hvorfor røggassens fugtindhold reduceres og energiudbyttet fra røggaskondensering reduceres. Det er imidlertid sandsynligt, at den gennemsnitlige affaldssammensætning på landsbasis kun ændres lidt, da både fraktioner med høj og med lav brændværdi udsorteres. Men det er også sandsynligt, at der vil være store regionale forskelle, og at der mellem forbrændingsanlæggene vil være meget større forskelle, end det konstateres på landsgennemsnittet.

Dette udviklingsprojekt har fokuseret på introduktion af forbrændingsluftbefugtning på affaldsforbrændingsanlæg for at øge anlæggenes energieffektivitet og give anlæggene en mulighed for at håndtere fremtidige ændringer af affaldet. Forbrændingsluftbefugtning erblevet sammenlignet med andre metoder så som befugtning af affaldet eller indsprøjtning af vand i ovnen og er blevet evalueret som den mest energieffektive metode til at modvirke effekterne af udsortering af øgede mængder organisk affald.

De største fordele og ulemper ved introduktion af forbrændingsluftbefugtning fundet i dette projekt er listet herunder:

Fordele:

- Udsving i affaldets vandindhold kan modvirkes (ovn og kedel vil se et konstant vandindhold)
- Betydelig fjernvarmeproduktion uden modtryksturbine (og muligvis uden et turbineudtag) gennem brug af røggaskondensering
- Omkostningseffektiv fjernvarmeproduktion (uanset turbinekobling)
- Mulig fjernvarmeproduktion ved røggaskondensering uden brug af varmepumpe, når fjernvarmereturtemperaturen er høj, fx i intervallet 55 til 70 °C
- Lavere røggastemperaturer før overhedere i kedlen (og med kedelmodifikationer betydelige lavere temperaturer)
- Korte tilbagebetalingstider på 5 til 8 år

Ulemper:

- Mere kompleksitet tilføjet til anlægget
- Ny kedelregulering kan være nødvendig og evt. nye operatørinstruktioner
- Kold røggas udledt fra skorstenen skal måske genopvarmes for at sikre tilstrækkelig spredning, undgå dråbedannelse og for at undgå synlig røgfane
- Materialer, der anvendes til røgrør i skorstenen skal kunne tåle det våde miljø
- Anlæggets layout kan blive udfordret, da der skal skaffes plads til skrubbere, pumper og rør

Det konkluderes, at de største ulemper er blevet løst i løbet af projektet, og at de tilbageværende ulemper (ovenfor), er uden større betydning.

Potentialet for teknologien er stort, da både anlæg med og uden eksisterede røggaskondenseringsanlæg kan drage fordel af denne teknologi. Markedet dækker primært lande med et klima, hvor der er et rimeligt behov for boligopvarmning, og hvor eksisterende fjernvarmesystemer findes.

4. Introduction

All over the world recycling is on the agenda and governments and decision makers are looking into the waste management systems to see if fractions like plastic, metals and organics could be routed to recycling as an alternative to the current route of treatment or disposal. These efforts of increasing recycling rates in the waste management systems will lead to changes in the remaining residual mixed waste which will be a signature of the waste management system in effect. When Waste-to-Energy (WtE) facilities treat the residual waste they are likely to experience a change in composition of the feedstock. In a Danish context this means that when the expected effects of the Danish resource strategy, “Danmark uden affald” ("Denmark without waste") are realized, potentially causing separation of 50-60% of the organic waste, many Waste-to-Energy (WtE) plants will experience a change in waste composition and heating value compared to the current situation. This change may influence the energy recovery and hence a major source of revenue for the facilities.

WtE facilities with flue gas condensation will be challenged most by high recycling rates on the organic fractions as the potentially reduced content of water in the waste will significantly reduce the energy recovery by flue gas condensation.

In effect capacity is made available in the flue gas condensation systems that may be exploited for boosting the total energy efficiency of the plants by addition of water vapour. It is not advantageous for the overall energy efficiency or economically feasible (or environmentally or politically appropriate) to use water from waterworks to replace the water “missing” in the waste. A system is therefore needed where process water from the WtE process or other places in the plant is used as substitute for the “missing” water. Additionally a number of challenges must be taken into account following the character of the combustion air, the composition of the waste, the facility’s accessibility and the potential health risk.

These opportunities are investigated in the shape of using combustion air humidification (CAH), which has not hitherto been used at WtE plants in Denmark.

In addition, the potentially increased heating value (due to lowering of water content) can be a challenge for some plants, which could lead to a number of operational problems and the risk of damage, particularly to older refractory protected furnaces. Furthermore, the increased heating value can lead to increased flue gas temperature in the boiler, which will increase the corrosion rate, thereby increasing maintenance costs considerably. A very dry fuel will result in the formation of a very dry flue gas. A boiler designed for a normal wet flue gas, may face problems to superheat the steam. Consequently the plant's electrical efficiency will decrease, while energy production by flue gas condensation drops as well.

In this project the CAH-technology is suggested to compensate for the possible challenges foreseen by the separation of the organic fraction giving a dryer fuel.

This technology is first of all relevant for already highly energy optimised WtE systems having installed flue gas condensation, as it is a means of increasing the energy output from this equipment, and hence, further improve the energy efficiency of the facility. Other WtE facilities may also in principle benefit from the humidification to reduce the combustion temperature, but it is not equally attractive for the energy balance and the financial result without the contribution from the improved energy recovery.

4.1 Flue gas condensation and combustion air humidification

Flue gas condensation is an energy recovery process by which the heat of condensation of water vapour contained in the flue gas is recovered for use as heat. This may add 20% to the total energy efficiency of a WtE facility. The condensation heat is carbon neutral because it can be obtained without use of fossil fuel except for a modest indirect contribution through the use of electricity to drive pumps etc. This is therefore a climate friendly form of energy.

Flue gas condensation is widely used at WtE facilities in particularly in Denmark and Sweden, and it can be used in other areas where the facilities have a large sale of heat, e.g. through a district-heating (DH) network. DH is already extensively used, particularly in large parts of Eastern Europe and its use is increasing throughout Europe, as DH is considered climate friendly because it can be supplied at low cost and low fuel consumption from cogeneration plants and waste heat sources.

At the energy facility, flue gas condensation may be achieved by so-called “direct condensation” where relatively cold DH water is heat exchanged with a warm flue gas scrubber liquid, by which the DH water is heated and the scrubbing liquid is cooled. As the scrubbing liquid is cooled water vapour in the flue gas condenses and thereby releases the heat of condensation, in turn heating the scrubbing liquid circulating back to the heat exchanger. Only circulation pump energy is needed for this kind of energy recovery.

If the DH return water is warmer than the scrubbing liquid (which peaks around 60 °C), a heat pump is needed to recover the energy. This so-called “heat pump condensation” is associated with investment in a heat pump system and the use of driving energy for the heat pump, equivalent to an electricity consumption of around 15-25% of the recovered heat. Direct condensation and heat pump condensation may be combined to maximise heat recovery.

An inventory of installed flue gas condensation systems shows that roughly one third of the WtE capacity in Denmark used this technology in 2015 and that this figure will double to around 60% in 2017 when several systems currently under construction commence operation.

There are few reports of use of CAH for WtE facilities except for three plants with past experiences in Sweden.

In relation to energy recovery in flue gas condensation CAH has two important potentials:

- CAH can significantly increase the output from direct condensation and thereby make a supplementary heat pump fully or partly redundant, in turn saving investment and driving energy for the heat pump system
- CAH can enable district heat production by condensation with DH return temperatures in the range 55 to 70°C that would otherwise require a heat pump.

4.2 Objectives and methodology

The first objective of this project is to identify the most efficient counter measure to changes in the waste compositions, most likely in the form of lower water content of the waste, being a result of increased recycling of the organic waste fraction. With a technology identified as the most efficient measure the second objective is to study the thermodynamic modelling of the complete energy process system of WtE facilities with steam boiler, cogeneration turbine/generator set and flue gas condensation. A third objective is to identify process configurations to be optimised with respect to energy efficiency, while keeping system complexity low, i.e. minimise the direct and indirect electricity consumption and maximise the heat output and keeping the systems attractive from the points of view of investment, construction and operation.

As basis for modelling the current and anticipated future composition of waste for WtE facilities are used, which in turn are based on the frames given by the objectives of the Danish resource strategy. Modelling includes a separate furnace/boiler model in order to identify positive and negative effects of CAH on the operation of the furnace/boiler and identify potential beneficial constructional changes.

Modelling is done for a typical example plant and the results are applied in modelling of 3 specific WtE facilities. The possibilities of retrofitting CAH at these facilities are investigated with the specific requirements and availability of space, DH return temperatures etc.

5. Future waste outlook

5.1 Introduction

The Danish resource strategy, sets new guidelines for the handling of waste within the Danish municipalities. The new handling includes more waste separation, which, in the future, will result in a changed composition of the waste to be used for energy recovery, compared to the composition today. There may be differences in the way the strategy is implemented in different municipalities why some WtE facilities may experience a drop in heating value and wetter waste while others may experience increasing heating value and waste with lower moisture content.

Changes in the heating value and moisture content of the waste will affect the combustion temperatures and the moisture content of the raw flue gas. The underlying data for some typical cases consisting of the composition of waste and the raw, untreated flue gas for Danish WtE facilities before and after the completion of the resource strategy are presented here. These sets of data shall form the basis of subsequent process calculations and assessments on effects of changes. While the sets of data represent different cases for average waste there may be large local and temporal variations not covered by the data sets.

The cases evaluated are shown in table 1:

TABLE 1 CASES OF WASTE COMPOSITION EVALUATED IN THIS STUDY

Case	Description
2011	Typical waste (estimated average) before completion of the resource strategy using reference year 2011.
2022	Typical waste (estimated average) after completion of the resource strategy using reference year 2022.
2022L	Local implementation gives waste with a low heating value
2022H	Local implementation gives waste with a high heating value

The listed cases are used in different technology modelling scenarios in subsequent chapters to assess the response of the technology to changes in waste composition.

5.2 Assumptions on Waste and Recycling

To be able to evaluate the future waste composition the expected effects of future strategies must be defined. The Danish government made their expectations to the effects of the resource strategy available and these effects are reproduced in table 2 below:

TABLE 2 ESTIMATIONS OF FUTURE EFFECTS OF THE RESSOURCE STRATEGY, TRANSLATED FROM (DANISH MINISTRY OF THE ENVIRONMENT (MILJØMINISTERIET), 2013)

Expected effects of the Resource Strategy						
SOURCE	**Expected effects**			**Present day destination (2011)**		
		2018	**2022 goals**	**Recycling**	**Energy recovery**	**Landfills**
	Type of material (waste fraction)	**Min %**	**Min %**	**%**	**%**	**%**
Domestic waste*	Recycling of organic waste, paper, cardboard, glass, wood, plastic and scrap metals.		50	22	75	0
	Collected electronic waste	75		68**		
Service sector	Recycling of paper, cardboard, glass, metal and plastic.	70		53	47	0
	Recycling organic waste	60		17	83	
All	Energy recovery of garden waste*	25		87	4	4
	Collected electronic waste	65				
	Collected batteries	55		47		
	Recovery of waste from shredder	70		0		
	Recycling of phosphor in sewage sludge	80		-		

* A small amount is used for temporary storage and special treatment and is not included in this table. Thus the three types of treatment do not add up to 100%.
**Average of the marketed amounts over the last 3 years.

For the evaluation of the heating value and chemical composition of basis-waste in 2011 and 2022 in Table 5, a preliminary model has been set up for the Danish waste flows and the distribution of recycling and incineration of main fractions. Among these, alternative fuels for WtE facilities are included to compensate for the reduced waste flow to the energy facility. The percentages for recycling listed below are used among others.

Waste led to WtE facilities in Denmark amounted to around 3.5 million tonnes in 2011. It appears from Figure 1 that household waste made up over 40 % of the waste for WtE facilities and commercial waste and industrial waste around almost 50 %. Approximately 10 % of the treated waste was reject from recycling activities, wood waste (excluding impregnated wood), imported waste (refuse derived fuel, RDF), shredder residues and garden/park waste. Note that the data represent a national average and it is a simplified presentation of selected data of the Resource Plan (Environmental Protection Agency of Denmark, 2014a) supplemented with information on 2011 from the waste statistics 2012 ”Affaldsstatistik 2012” (Environmental Protection Agency of Denmark, 2014b). From these sources data is selected for waste led to Danish WtE facilities. Relatively large differences are noted between the two sources. The differences are probably caused by introduction of a new data collection system taken into operation in 2011. For instance there could be differences in the allocation of the waste led to recycling centres. These deviations are estimated to have insignificant impact on the present study of waste composition, the main purpose of which is to address changes from 2011 to 2022. The rejects from recycling activities are estimated by Ramboll assuming recycling activities to occur in Denmark.

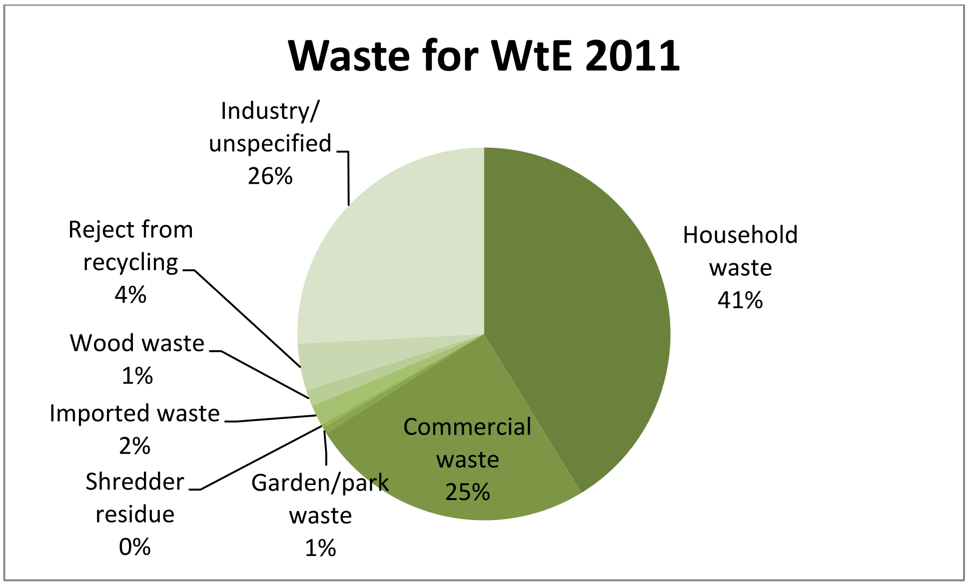


FIGURE 1 ESTIMATED BREAKDOWN OF AVERAGE WASTE LED TO WTE FACILITIES IN 2011, CF. TEXT.

Recycling rates for 2011 and 2022 (basis), Table 3, are roughly equivalent to percentages listed in table 1 of the Resource Strategy. For 2011 a recycling rate is chosen a little higher than that of table 1 in the Resource Strategy (30% instead of 22% for paper, cardboard, metal, glass and organic waste from households). The reason is that official waste statistics for 2011 show a significantly larger number for the overall recycling from households than listed in the table, 38%, even without recycling from municipal waste recycling centres being included. The confusion on recycling percentages is probably caused by the introduction of a novel waste data system in 2011.

TABLE 3 CHOSEN RECYCLING RATES FOR THE EVALUATED CASES.

Recycling	2011	2022 Basis	2022, High Heating Value	2022, Low Heating Value
Domestic Waste:				
Paper, cardboard, plastics, metals, glass, organic waste	30%	60%	69%	46%
Hereof organic waste alone	10%	50%	80%	10%
Commercial waste:				
Paper, cardboard, plastics, metals and glass	53%	72%	52%	80%
Organic waste	17%	60%	80%	30%
Other				
Garden waste, recovery (energy)	4%	30%	20%	30%

For the 2022-basis it is assumed that the lacking waste flow for the WtE facilities to a certain extent is compensated by imported waste and wood waste with a relatively high heating value which is the main cause for the modest increase in the average heating value compared to 2011.

The mentioned cases with respectively high and low heating value are examples of possible consequences of local development depending on the local priority of recycling initiatives between the dry fractions with high heating value and the wet fractions with low heating value. Other effects are included to compensate for the reduced fuel supply. Examples of this include the reception of wood waste with a relatively high heating value. Similarly, fresh and excavated shredder waste contributes with respectively high and low heating value.

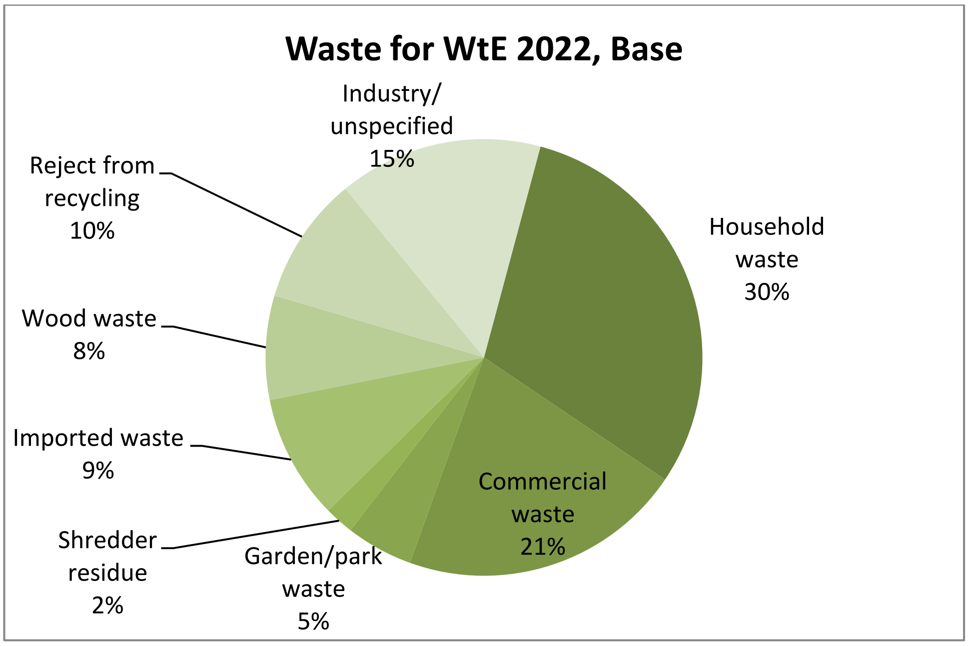


FIGURE 2 ESTIMATED BREAKDOWN OF AVERAGE WASTE LED TO WTE FACILITIES IN 2022, CF. TEXT.

The assessment of breakdown for 2022, Figure 2, shows that other waste sources are anticipated to be incinerated as more recycling happens of particularly household waste. Sources that are expected to increase are for instance imported waste (RDF), biomass (wood waste), shredder residues, garden/park waste and rejects from recycling activities. The base case should be considered a typical example. There may be large local and temporal variations experienced by the individual WtE facility. Also the composition of household waste may change as the result of implementation of the resource strategy. For instance some municipalities may choose to focus on segregation of organic waste with low heating value while others may target fractions with high heating value such as plastic and paper.

The future waste composition and heating value may therefore vary. The likely range is illustrated by the cases for 2022 with low and high heating value, respectively, in figure 3 and 4. These cover quite large variations in consequential changes for WtE facilities and it is likely that most facilities will experience waste compositions within the range represented by these two cases.

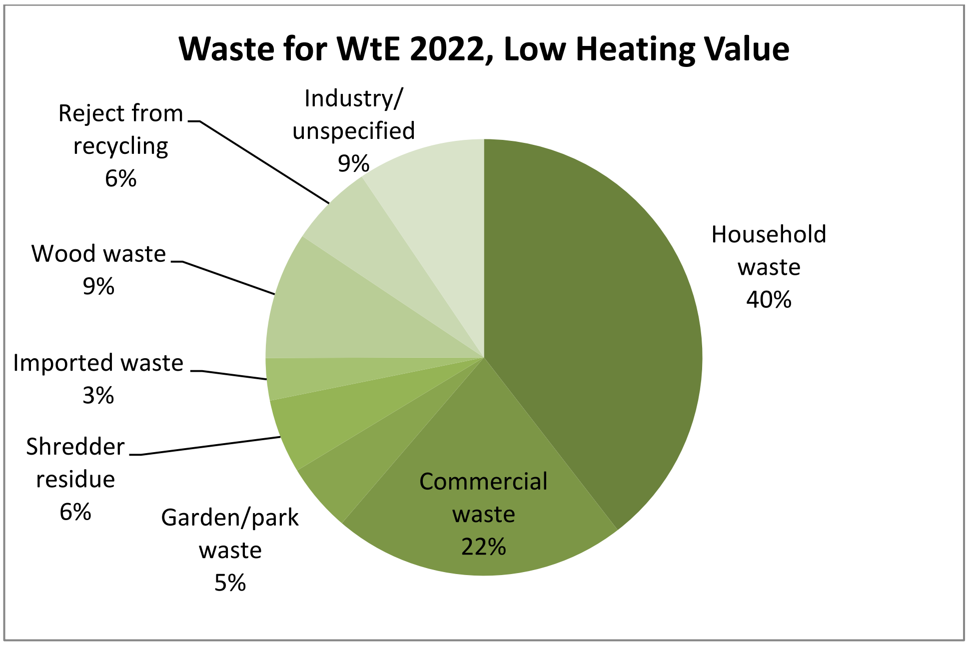


FIGURE 3 ESTIMATED BREAKDOWN IN THE LOW HEATING VALUE CASE FOR WASTE LED TO WTE FACILITIES IN 2022, CF. TEXT.

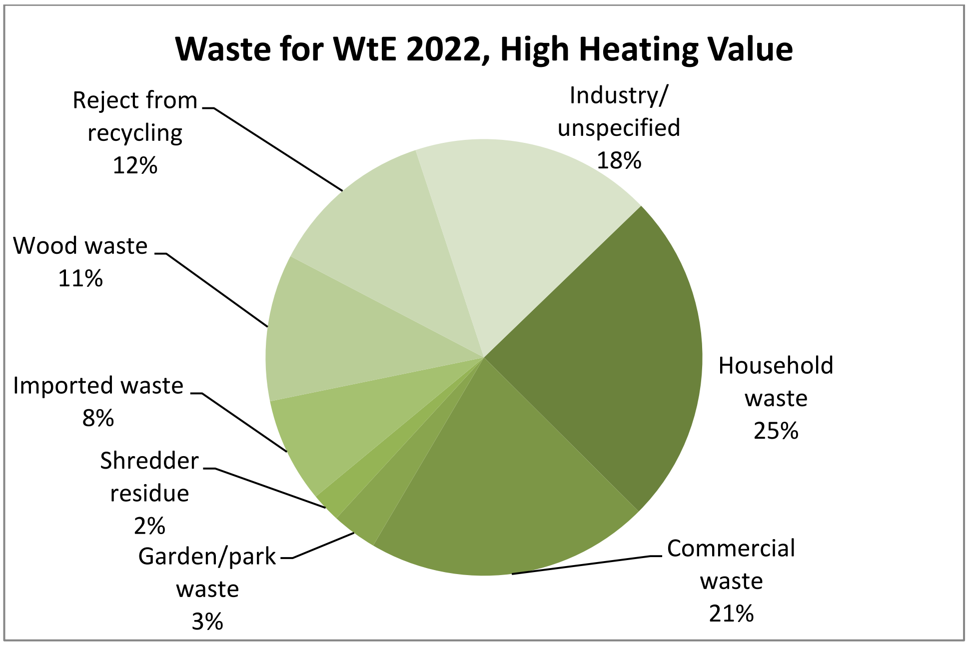


FIGURE 4 ESTIMATED BREAKDOWN IN THE HIGH HEATING VALUE CASE FOR WASTE LED TO WTE FACILITIES IN 2022, CF. TEXT.

5.3 Cases

Typical waste (estimated average) before completion of the resource strategy using reference year 2011 is listed in Table 4 based on the breakdown of Figure 1, and the composition of waste of all cases is listed in Table 5.

TABLE 4 ASSUMPTIONS BASED ON TYPICAL WASTE BEFORE IMPLEMENTATION OF THE RESSOURCE STRATEGY, 2011. ESTIMATED AVERAGE

Composition, main constituents		As Received	Dry Basis	Dry and Ash-free
Lower Heating Value	GJ/tonne	10.50	17.07	22.52
Water	Fraction	0.3365	0	0
Ash	Fraction	0.1606	0.2421	0
C	Fraction	0.2748	0.4142	0.5464
H	Fraction	0.0384	0.0578	0.0763
O	Fraction	0.1779	0.2682	0.3538
N	Fraction	0.0056	0.0085	0.0112
S	Fraction	0.0017	0.0025	0.0033
Cl	Fraction	0.0045	0.0068	0.0090
Sum	Fraction	1.00	1.00	1.00
Higher Heating Value	GJ/tonne	12.16	18.33	24.18
Calculation, Schwanecke Formula:				
Lower Heating Value	GJ/tonne	10.47	17.03	22.46

TABLE 5 HEATING VALUE AND MAIN CONSTITUENTS OF WASTE FOR THE DIFFERENT CASES.

Parameter	Unit	2011	2022 Basis	2022, High Heating Value	2022, Low Heating Value
Lower Heating Value	GJ/ton	10.5	10.8	12.5	9.0
Water	%	33.65	32.38	26.88	39.38
Ash	%	16.06	15.52	15.64	16.17
C	%	27.48	28.30	31.96	24.25
H	%	3.84	3.91	4.38	3.35
O	%	17.79	18.72	19.96	15.74
N	%	0.56	0.57	0.52	0.59
S	%	0.17	0.17	0.16	0.16
Cl	%	0.45	0.41	0.50	0.36

Parameter	Unit	2011	2022 Basis	2022, High Heating Value	2022, Low Heating Value
Sum	%	100	100	100	100
Higher Heating Value	GJ/ton	12.16	12.44	14.1	10.7

Most modelling in this report is made for a typical WtE facility with a nominal waste throughput of 20 tonnes per hour at the heating value of 2011 of 10.5 GJ/tonne, corresponding to 58.3 MW thermal input. Table 6 lists throughput data of the nominal case together with the 2022-cases. It is noted that the waste throughput in tonnes per hours is adjusted to yield the same thermal input of 58.3 MW in all cases, because the plant capacity is mostly determined by the thermal input unless the heating value is very low. The corresponding data of the raw flue gas (i.e. flue gas downstream the boiler and upstream flue gas treatment) is listed in Table 7. These are the data used for modelling in the respective cases in the following chapters, except when a specific facility is analysed. In such cases the raw flue gas composition of Table 6 is still used.

TABLE 6 DATA FOR TYPICAL WTE FACILITIES WITH A THERMAL INPUT OF 58.3 MW.

Parameter	Unit	2011	2022 Basis	2022, High Heating Value	2022, Low Heating Value
Waste Input	tonnes/h	20	19 .5	16 .8	23 .3
Annual Hours of Operation	hours/year	8 000	8 000	8 000	8 000
Annual Waste Flow	tonnes/year	160 000	155 618	134 270	186 578
Heating Value (lower)	GJ/t	10 .5	10 .8	12 .5	9 .0
Thermal Input	MW	58 .3	58 .3	58 .3	58 .3
Annual Input Energy	MWh/year	466 700	466 700	466 700	466 700

TABLE 7 RAW FLUE GAS DATA FOR TYPICAL WTE FACILITIES WITH WASTE SUPPLIED AS IN TABLE 2

Parameter	Unit4)	2011	2022 Basis	2022, High Heating Value	2022, Low Heating Value
Oxygen in Flue Gas	% O_2, dry	7 .5	7 .5	7 .5	7 .5
Flue Gas Flow (actual % H_2O, and O_2)	Nm^3/h	105 800	104 700	100 400	111 400
Flue Gas Flow (dry, 11 % O_2)	Nm^3/h	117 200	116 700	114 400	120 300
Boiler Outlet Temperature	°C	160-200 1)	160-200 1)	160-200 1)	160-200 1)
Moisture Content	%	17 .9	17	16	20
Pollutants at 11 % O_2, dry (reference state)					
CO	mg/Nm^3	10	10	10	10
TOC	mg/Nm^3	1	1	1	1
Dust	mg/Nm^3	2 300	2 200	2 000	2 700
HCl	mg/Nm^3	720	630	680	650

Parameter	Unit[4]	2011	2022 Basis	2022, High Heating Value	2022, Low Heating Value
SO2 and SO3	mg/Nm^3	280	280	220	310
HF	mg/Nm^3	20	20	20	20
NOx 2)	mg/Nm^3	150	150	150	150
NH3 2)	mg/Nm^3	10	10	10	10
Σ 9 metals 3)	mg/Nm^3	100	100	100	100
Hg	mg/Nm^3	0.15	0.15	0.14	0.16
Cd+Tl	mg/Nm^3	2	2.0	2.0	2.0
Dioxins og furans, TEQ (gas phase)	ng/Nm^3	2	2	2	2

[1] Depending on boiler optimisation and the concept used for flue gas cleaning
[2] Assumed SNCR-system
[3] Σ 9 metals: Sb, As, Pb, Cr, Co, Cu, Mn, Ni og V
[4] Nm^3 is a normal cubic metre, i.e. cubic metre at standard temperature and pressure, 0 °C, 101,325 Pa

5.4 Conclusion on future waste

While it is clear that the changes to be expected on a national level as modelled above remains small the potential differences between scenarios that would potentially meet the future strategies are very large and probably larger than the differences observed today. Since municipalities in many countries, including Denmark, are free to choose the strategy they find fit to meet the national strategic goals, the variations in composition and physical characteristics of feedstock for WtE facilities, could be very large. Even though the changed heating value and composition is likely to be in the design range of the WtE facilities the changes would call for optimisation to get the best out of the waste with the WtE facility in question. One particular challenge will be high heating value of the waste for WtE in cases where wet, organic waste with low heating value is diverted, causing elevated furnace temperature and reduced energy output of flue gas condensation systems.

6. Remediation options

Equipment that will secure the same or higher energy production despite the reduced moisture content in the waste and the increased calorific value as a possible consequence of the resource strategy have been studied. A low moisture content of the fuel is often considered an advantage in boilers, but when the system is designed to cope with high moisture content and equipped with flue gas condensation the low moisture content has some negative effects. For instance, in the furnace the combustion temperature may become too high causing damage to refractory and increase corrosion exposure, and in flue gas condensation energy recovery relies on condensation of the moisture content of the flue gas and a low moisture content reduces the energy production.

During the project all the relevant possibilities to counteract the negative effects has been evaluated, including:

- Pre-treatment of the waste before energy recovery, including for instance sorting and segregation
- Conditioning of the waste before energy recovery, including humidification or drying
- Moistening of combustion air
- Water injection in furnace

The possible solutions have been evaluated according to certain measures of success including:

- Other means of recovery of the reduced energy production in the flue gas condensation system
- Possibility of an increased overall plant efficiency
- Improved energy quality (e.g. larger power production or higher district heating temperature)
- Possibility of increased recycling (metals, waste products, water)

Two methods that fulfil the measures are humidification of the combustion air or waste. Both methods demand the development of new processes, new principles and a new plant design. New boiler calculations, mass and energy balances and new layout are all needed for existing installations. There will be a certain focus on the development's importance of operating existing and new district heating systems significantly. Therefore the solution in mind is the development of an actual product that can be bought and installed in existing plants that experience a decrease in energy production as a consequence of reduced moisture content. The product must also be capable of being implemented in new plants so that they become capable of coping with changed waste compositions in the future.

Humidifying the waste in the bunker before it is fed into the boiler is very straight forward and simple to implement. It will reduce the furnace temperature to its normal level and bring the situation for the flue gas condensation system back to the original state and ensure that the condensation system on a plant is able to work at full capacity supplying district heating. The solution will create simple practical problems with effluent water from the bunker and problems with water drainage from the fuel feeding system.

Nevertheless the dry fuel offers an opportunity to obtain a better efficiency for the plants. In the solution where the water is added as liquid water to the waste the evaporation of the water is done internally in the energy system with high value energy at high temperatures. To obtain a better energy efficiency the water should be added to the combustion process as evaporated water in the combustion air. The evaporated water could be added in a process where the combustion air is humidified driven by low value heat from the low temperature flue gas downstream of the flue gas condensing system and in some cases also by the return water from the district heating system.

In conclusion, addition of liquid water is a viable solution but less energy efficient compared with humidification of the combustion air, which is why this project onwards focuses solely on the option where combustion air is humidified.

7. Humidification technology

7.1 Introduction

The development of the humidification technology for Waste–to-Energy facilities has been performed in three stages briefly described below:

1. **Initial development**
   Firstly an assessment of what is possible with existing technologies and combinations of these, secondly a brain storm and evaluation of how to best overcome challenges identified in the first assessment
2. **Primary development**
   The goal of this stage is to further perform technology development and optimisation in terms of energy efficiency and ability to operate without adverse effects on the combustion process or bringing down the plant availability
3. **Technology assessment**
   This stage includes an economical assessment, and an layout and process assessment will conclude if the technology should be further developed. In case of a positive outcome a draft plan for further development and market preparation will be proposed

In the following chapters the results of completing the steps will be described. The “Combustion air humidification” chapter describes the technology and the challenges faced specifically for WtE facilities. The chapter “Modelling the optimal system” describes how modelling has been used as development tool to test ideas for solving challenges and optimizing the process and hence making it feasible. In the chapter “Implementation of the technology” and “The simple business case” the technology assessment step is described.

Modelling in the initial and primary development is done based on a model plant with a nominal waste input of 20 tonnes per hour at a lower heating value of 10.5 GJ/tonne (cf. Table 6), and changes in the composition of waste and flue gas are based on the data of Table 5 and Table 7.

Further modelling and technology assessment is done from a general approach and based on three specific WtE facilities in Denmark:

- Aarhus Line 1
- AffaldPlus (Næstved) Line 3
- Vestforbrænding (Copenhagen) Line 5

7.2 The Swedish experience

CAH systems have successfully increased the heat recovery at several biomass-fired power plants in Sweden during recent decades, typically using a combined unit for both water vapour recovery and air humidification (Axby, Gustafsson, & Johansson, 2000) and (Jeppesen, Hansson, & Axby, 2007). Some Swedish Waste-to-Energy facilities had combustion air humidification systems installed in the period before 2007. We have been able to locate these facilities with operational experience:

- Linköping
- Halmstad
- Lidköping

Only very limited information about the present experience was available during this project, however the following was concluded:

In Linköping and Halmstad a solid rotor heat transfer technology was used. It was taken out of operation due to the high maintenance costs associated with keeping the rotor clean from particles otherwise clocking the channels allowing the heat transfer. In Lidköping a system using a scrubber to handle the humidification (as suggested in this project) was implemented, however due to problems with burnout and corrosion of the air preheater eventually caused the system to be taken out of operation.

Our literature search found no research on CAH implementation at solid fuel boiler plants, and very limited coverage of flue gas condensation (Oravainen, 1998). Hence even though manufactures and users claim benefits by these systems and thermodynamic theory supports this, no systematic evidence has been collected to document that it is in fact the case, and more importantly document the use of the potential of flue gas condensation systems. Further information on the experience gained could with advantage be retrieved in a later phase, when more time is available than in the present project.

7.3 WtE plant

The basis for the study is a WtE plant based on a steam boiler connected to a back pressure steam turbine and additional district heat heat production by way of flue gas condensation. This system is briefly described below.

7.3.1 Steam cycle

In a WtE plant, chemical energy in the waste is converted to thermal energy in the furnace and boiler. The waste moisture is evaporated and enters the flue gas. The hot flue gases produced are cooled in a steam boiler, where the energy is used to produce high temperature steam for the steam cycle. The flue gas temperature at the boiler outlet is typically in the range of 150-200 °C.

The high pressure and temperature steam is piped from the boiler to the turbine for the production of heat and power. In the turbine, the superheated steam is expanded, converting some of the thermal energy to mechanical energy and further on to electrical energy in the generator. The expanded low temperature steam is condensed in two turbine condensers, where district heating (DH) water is used as coolant. As a consequence the DH water is heated to reach the required temperature on the flow side of the DH network.

The produced condensate from condensation of the steam from the turbine is returned to the boiler closing the steam cycle.

7.3.2 Flue gas condensation

Heat used to evaporate the water content of the waste may be recovered from the flue gas by flue gas condensation, if installed. In its simplest form, the moist flue gas downstream of the boiler is cooled by the DH water in a scrubber condenser, tube condenser or steel plate condenser. Provided that the DH return temperature is lower than the saturation temperature of the flue gas, water will condense and the condensing heat transferred to the DH net. The amount of recovered energy is strongly favoured by low DH return temperatures.

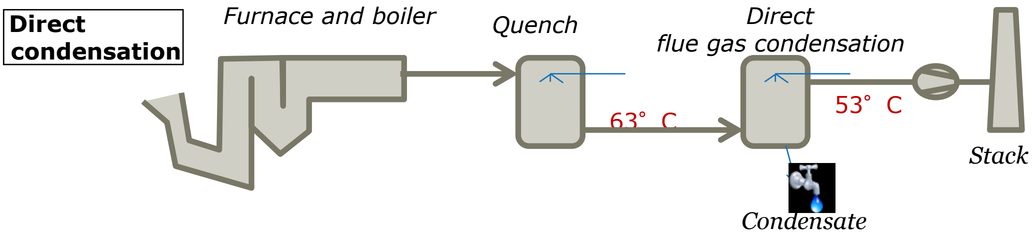


FIGURE 5. WTE PLANT WITH FLUE GAS CONDENSATION. TEMPERATURES ARE EXAMPLES FOR A DIRECT CONDENSATION STAGE COOLED BY 50°C DH WATER.

Figure 5 shows an example of the flue gas path for a plant equipped with one direct flue gas condensation stage cooled by 50 °C return water from the DH system. After a quench, the flue gas is saturated with water at 63 °C. Cooling the flue gas from 63 to 53 °C causes condensation of significant amounts of water, releasing low temperature heat energy, which is recovered to the DH system. It appears that the DH return temperature is limiting the energy recovery by this so called “direct condensation” where DH water is heated by simple heat exchange. Had the connected DH return temperature been even lower, e.g. 40 °C, the yield would increase significantly, as it would cause more water to condense.

In order to increase the heat recovered by flue gas condensation, a heat pump can be installed to recover heat from the flue gas at even lower temperatures than the available DH water, thereby increasing the amount of condensation heat recovery. The temperature raise comes at the cost of the consumption of driving steam in the case of an absorption type heat pump (AHP) or electricity in a compression heat pump (CHP). Such a system typically comprises of one or two stage flue gas condensers, where the gas is first cooled directly by the DH return (“direct condensation stage”). Subsequently the flue gas is further cooled down with the aid of the heat pump, which heats the DH water further after the initial direct condensing stage.

Flue gas condensation does have a negative influence on the power production at the turbine, because the cooling water temperature (DH return water) is increased, when it is used for condensation of the turbine outlet, and the warmer water reduces the efficiency of the turbine. The power loss is however much smaller than the additional DH energy recovery, as only approximately 5% of the added heat is lost as power in a regular two-condenser system. In direct condensation 1 MWh of heat comes at the expense of around 50 kWh of electricity, equivalent to a coefficient of performance (COP) of around 20 (=1000 kWh/50 kWh).

In heat pump condensation the use of driving energy for the heat pump represents a significant electricity consumption and therefore gives a much lower COP, being in the range 4-6, depending on the extent of optimisation of the entire system. The electricity consumption is roughly the same for an AHP or CHP, but in AHP the consumption is indirect because it is the reduced electricity production by use of driving steam for the AHP. The COP optimisation relies on for instance the required DH flow temperature and the required temperature and pressure of driving steam (in case of an AHP).

7.3.3 The model WtE plant

If nothing else is noted, the modelling in this report will be based on a typical model WtE plant with the following features as shown in table 8:

Parameter	Value
Fuel feed	20 t/h
Fuel type	2011 (Basis at 10.5 GJ/t LHV) **Variations:** 2022H (High Heating Value) or 2022L (Low Heating Value)
Flue gas temperature after boiler	180 °C
O_2 in flue gas after boiler	7.5 % (dry)
Ambient air	15 °C, RH 40%
Air preheating	None
Flue gas cleaning type	Wet
Location of flue gas condenser	Downstream ID-fan
Flue gas condenser dT (DH return water – cooled flue gas)	3 °C
Available DH return temperature	45, 55 or 65 °C
Saturated flue gas after quench *(calculated from above conditions for 2011-fuel)*	63,7 °C

TABLE 8. MODEL PLANT BEFORE COMBUSTION AIR HUMIDIFICATION.

The DH return temperatures are chosen to represent the conditions at three Danish WtE plants. In Figure 6 the potential for flue gas condensation at the WtE model plant is shown as a function of flue gas temperature downstream the condenser. For a DH return temperature of 45 °C, a direct condensation stage can cool the flue gas to 45+3=48 °C, recovering 9.2 MJ/s heat. With DH return temperatures of 45 °C, 55 °C and 65 °C, the direct condensation stage can recover 9.2, 4.2 and 0.0 MJ/s respectively.

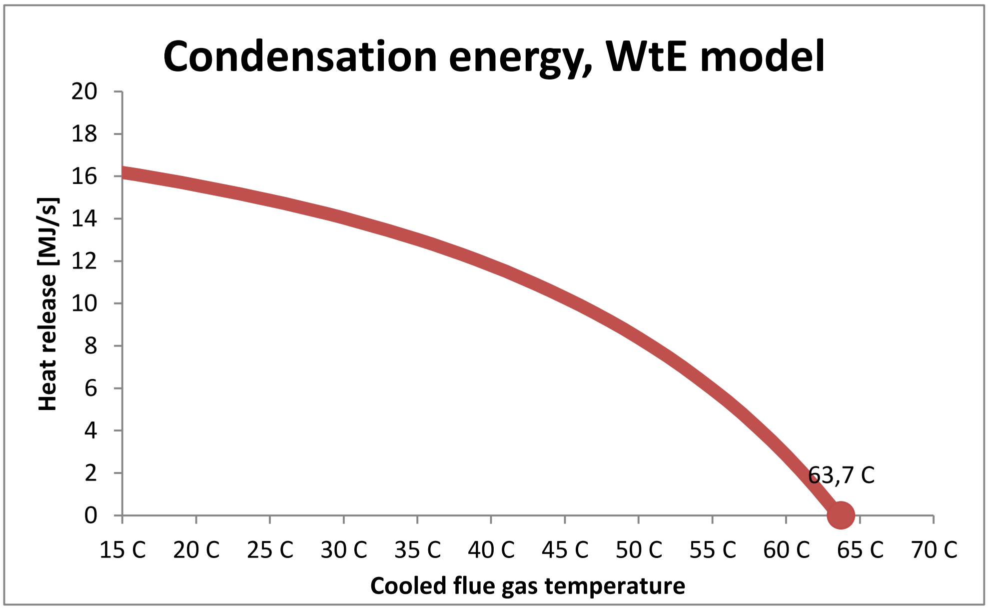


FIGURE 6. FLUE GAS CONDENSATION POTENTIAL AT MODEL PLANT.

If DH temperatures are too high to produce heat by direct condensation (e.g. 65 °C DH in this case), heat pumps can be applied to recover the energy at lower temperatures. Thus the Danish plant with this temperature set (Vestforbrænding) uses only a heat pump assisted flue gas condensation stage, cooling the flue gas to around 45 °C.

For a system with combustion air humidification, the recovered heat can also be predicted from Figure 6, by using the cooled flue gas temperature downstream the humidification condenser (H-condenser). In other words, the DH yield is defined by the cooled flue gas temperature whether or not humidification is installed.

7.4 Combustion air humidification

Combustion air humidification is a method to further increase the total efficiency at combined heat and power plants, historically mainly implemented at biomass fired plants. The idea is moving some of the residual energy in the flue gas back into the combustion air. Figure 7 shows the example from figure 5 extended with combustion air humidification.

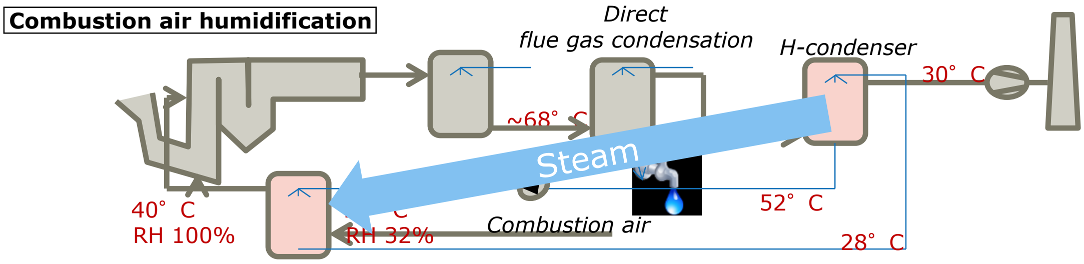


FIGURE 7. COMBUSTION AIR HUMIDIFICATION. TEMPERATURES ARE EXAMPLES, WHERE DIRECT CONDENSATION IS COOLED BY 50°C DH WATER.

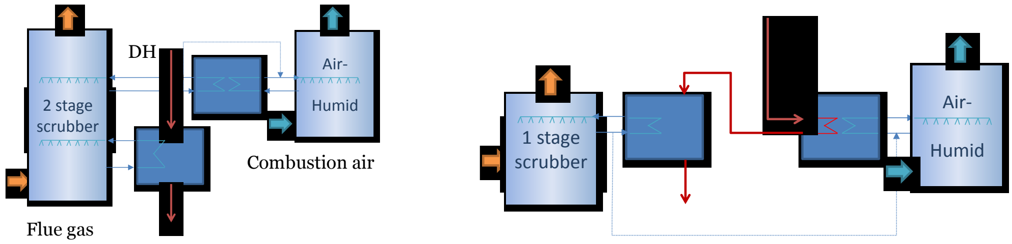
The combustion air is heated and humidified by exchange with the warmer flue gas downstream of a flue gas condensing. The water evaporated at low temperature (50°C) in the humidifier leads to higher enthalpy and saturation temperature in the flue gas at the boiler outlet, which increases the temperature and amount of heat transferred from the direct condensing stage to the DH return. In the example, the higher water content increases the water dew point after the quench so that the direct condensation stage can condense the water content from saturated flue gas from 68°C instead of just 63 °C.

Part of the low temperature water (50°C) input to the humidifier will not evaporate, but be recovered as cooled water (20-30°C) and used to cool the final flue gas condensation stage in order to cool and dry the flue gas even further.

The net effect is that energy in the flue gas not recovered by the direct flue gas condensation stage is returned back into the furnace, so that the amount of energy lost through the stack is decreased further. As a result, the total energy efficiency of the plant is increased without the significant energy consumption of a heat pump stage.

7.4.1 Humidification system details

Given an existing plant with flue gas condensation, the combustion air humidification system adds a humidification unit to the combustion air path upstream any air preheaters. The steam can be recovered upstream the stack either by means of a new separate condensation stage as indicated above, or by using the cooled water from the humidifier to further cool the existing condensation stage. Two implementations representing these two alternatives were chosen for further investigation. They are illustrated in Figure 8.



(x22) (x42)

FIGURE 8. HUMIDIFICATION SYSTEM DIAGRAMS FOR ENERGY RECOVERY IN: SEPARATE H-CONDENSATION STAGE (X22) AND BY PRECOOLING THE DH WATER (X42).

The first alternative (x22) corresponds to the system from figure 7 with one major adjustment to adapt it to WtE plants; the humidification water circuit is divided into two separated by a heat exchanger. Such a separation is not necessary on existing biomass fired plants, but prompted by the fact that most of the combustion air is drawn from the waste bunker hall to remove odours and contaminated dust. A single circuit would allow contaminated water to foul the condenser and the clean flue gas immediately before emission through the stack. When the heat transfer happens over a heat exchanger the supply of water could in principle be of virtually any source with a low salt content, but as the condenser circuit is nearby it is straight forward to use this as source of water. The condensed water is thus transferred from the clean final condenser circuit (H-condenser) to the dirty humidifier circuit to be evaporated into the combustion air. It is accompanied by the corresponding evaporation energy transferred through the heat exchanger. Both circuit circulation flows are much larger than the net transfer of water between them.

In the second alternative (x42), DH water is used to transfer the evaporation energy from the H-condenser to the humidifier. The humidifier draws low temperature heat by precooling the returned DH water. The existing flue gas condenser is supplied by the now colder DH water, and is thus able to cool the flue gas to lower temperatures. Due to the higher dew point of flue gas entering the existing flue gas condenser, the DH water is heated to a higher temperature than would be possible without the humidification system, causing the higher energy yield.

The precooling alternative (x42) is a simpler system than (x22), as no separate H-condenser stage is necessary. As we will see below, the energy yield potential is however somewhat lower for alternative (x42).

The necessary equipment for implementing combustion air humidification to a plant already equipped with direct flue gas condensation will be described below for each alternative.

7.4.2 Separate H-condenser alternative (x22)

The humidifier
The humidifier is a packed bed scrubber where warm water is sprayed in at the top and it is falling downwards in countercurrent flow with dry air. The water is heating up the air and partly evaporating into the air.

The residual water is cooled in the process to a temperature approaching the wet bulb temperature of the incoming air, i.e. the temperature that would be reached if the air is cooled by evaporation of water into it to reach the saturation point (100% relative humidity). This cold water is pumped from the bottom of the scrubber.

Other humidifier types exist, in particular the Ljungstrom type “enthalpy exchanger” integrating the humidifier and H-condenser in a single unit. Although it is used successfully at several biomass plants, it does not provide sufficient separation between the fouled combustion air and the cleaned flue gas at WtE plants, and has thus not been considered here.

Flue gas condensers
The H-condenser is equivalent to usual flue gas condensers used for direct condensation. It can be implemented as either a scrubber based solution or as a heat exchanger located in the flue gas stream cooled directly by the condensation water circuit.

The flue gas condensation requires one or more condensation stages with separate liquid circuits. The number of stages depends on the humidification implementation and the possible inclusion of a heat pump stage.

Internal water circuits and heat exchanger
The heat exchanger separating the humidification water circuit from the H-condenser circuit is foreseen to be a plate heat exchanger with a grädichkeit around 2-3 °C similar to those applied in many scrubber based flue gas condensation systems.

The humidification circuit will accumulate dust and impurities from the fouled air steam. It is thus necessary to include a continuous filtration as well as a blow-down stream to remove particles and minerals. It is expected that the filter can be implemented as a sand filter, and that the removed particles as well as the blow-down water can be disposed of in the furnace.

If the H-condenser is implemented as a condensing heat exchanger in the flue gas, it may eliminate the need for an additional separating heat exchanger, as the cooling water is not in contact with the clean flue gas. The condensing water/water heat exchanger would then need to be able to operate on the fouled water from the H-condenser without blockages or corrosion issues.

DH system
In principle, no changes are needed for the DH system, as the additional heat will be recovered in the existing flue gas condensation stage. Additional DH flow may be needed in order to collect the increased amount of heat. This may require changes in the DH supply piping.

Optionally, a DH forward pipe may be led to the humidification heat exchanger in order to boost humidification using the higher temperature. This would not increase the overall energy efficiency, but could be used to enhance the combustion control range offered by the humidification, which is described later.

7.4.3 DH precooling alternative (x42)

The humidifier

The humidifier is similar to that needed for alternative (x22).

Flue gas condensers

No new flue gas condenser is required for this alternative.

Humidification circuit and heat exchanger

A heat exchanger is needed to transfer heat from the DH return flow to the humidifier circuit. This is foreseen to be a plate water/water heat exchanger type.

The humidification circuit will need filtration and a bleed as described for alternative (x22)

DH system

For the DH precooling alternative, additional piping of the DH return is needed in order to direct it through the humidifier heat exchanger.

A DH forward supply may optionally be piped to the humidifier circuit to allow boosting the humidification as described for alternative (x22).

7.4.4 Equipment overview

Table 9 lists the necessary main mechanical equipment to be added to an existing WtE plant with flue gas condensation in order to implement combustion air humidification.

Required equipment	(x22) Separate H-condenser	(x42) DH precooling
Humidifier with water circulation, pumps, continuous filter and blow-down.	X	X
Heat exchanger separating circuits	X	
New H-condensation stage with water circulation and pumps	X	
Heat exchanger DH / humidification circuit		X
New DH pipes to humidifier heat exchanger		X
Water supply (e.g. condensate pipe from H-condenser to humidifier circuit)	X	X
Water treatment for additional condensate	X	X

TABLE 9. EQUIPMENT NEEDED TO APPLY HUMIDIFICATION TO AN EXISTING WTE PLANT.

8. System evaluation

8.1 Performance calculations

In order to assess to actual heat potential from a humidification system, it is necessary to consider the balance of the whole flue gas path of the plant from the combustion air inlet to the stack.

Several conditions and balances must be considered:

- The combustion air will be heated to a temperature approaching the incoming water from the H-condenser.
- The combustion air is assumed to be near water saturation at the humidifier outlet.
- The amount of heat that can be recovered in the H-condenser is determined as the heat added as sensible and evaporation energy into the combustion air in the humidifier.
- The amount of water recovered in the H-condenser is available to the humidifier.
- The volume flow of dry flue gas is approximately equal to that of dry combustion air.

It will be assumed that the flue gas temperature at the boiler outlet is unaffected by the installation of the humidification system, and that the O_2 content in the flue gas on dry basis is unchanged. To illustrate the full potential, it is assumed the both primary and secondary air is humidified with high efficiency (to just 4 °C below the H-condenser inlet flue gas temperature).

To enable development and evaluation of the optimal system for combustion air humidification we have used three modelling tools for different tasks and for reconfirming the results:

1. The Thermoflex® energy system modelling software was used to initially develop the systems, do the initial calculations and to assess the consequences within the boiler.
2. An excel-based model developed by Ramboll was used to explore and illustrate the theory of the system.
3. A modelling tool developed by Götaverken Miljö was used to calculate the different system setups at the three plants cases.

8.1.1 System impact of humidification

In this section, we will illustrate the impact of combustion air humidification on the plant energy balance. Figure 9 shows the calculated results for the model plant with direct condensation only, and with x22 humidification implemented. The separating heat exchanger is not shown. The balances show that the DH output from the flue gas condensation is tripled from 4.2 MJ/s to 13.2 MJ/s due to the humidification.

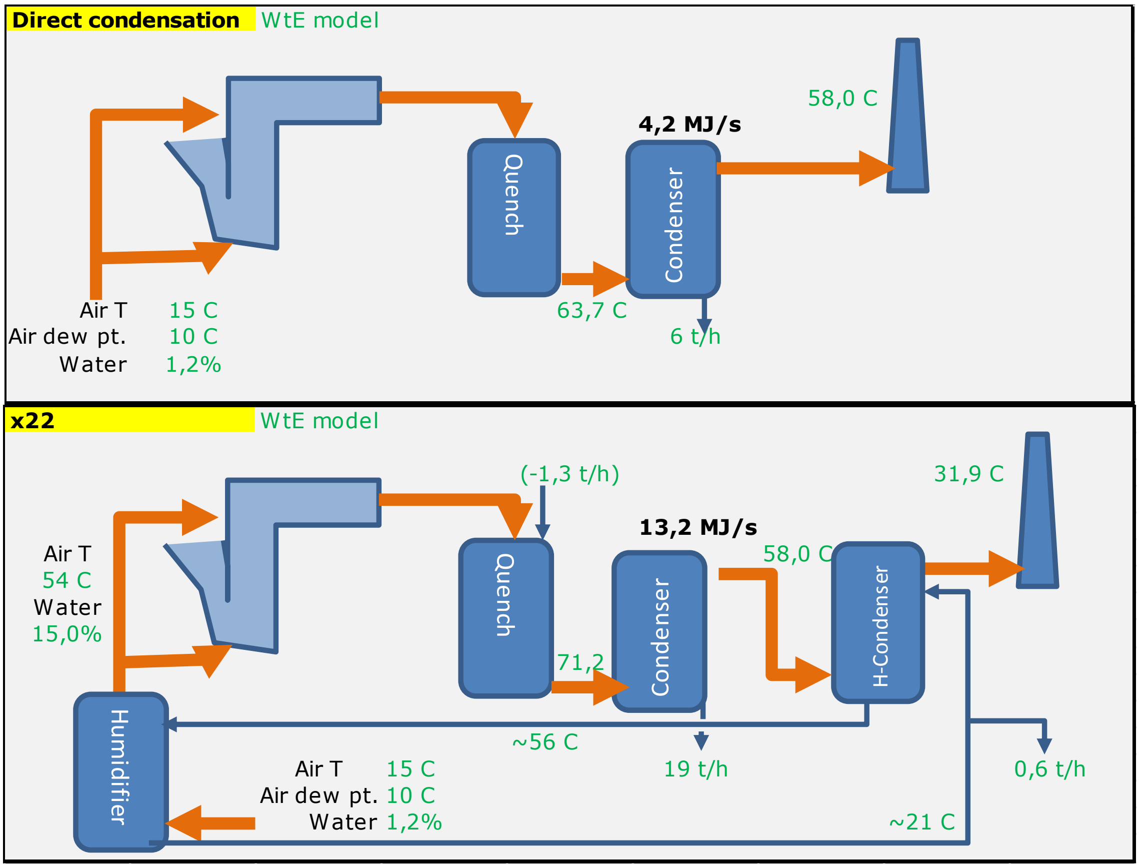


FIGURE 9. ENERGY BALANCE, AND TEMPERATURE AND HUMIDITY OF COMBUSTION AIR AND FLUE GAS AT 55 °C DH RETURN TEMPERATURE (X22)

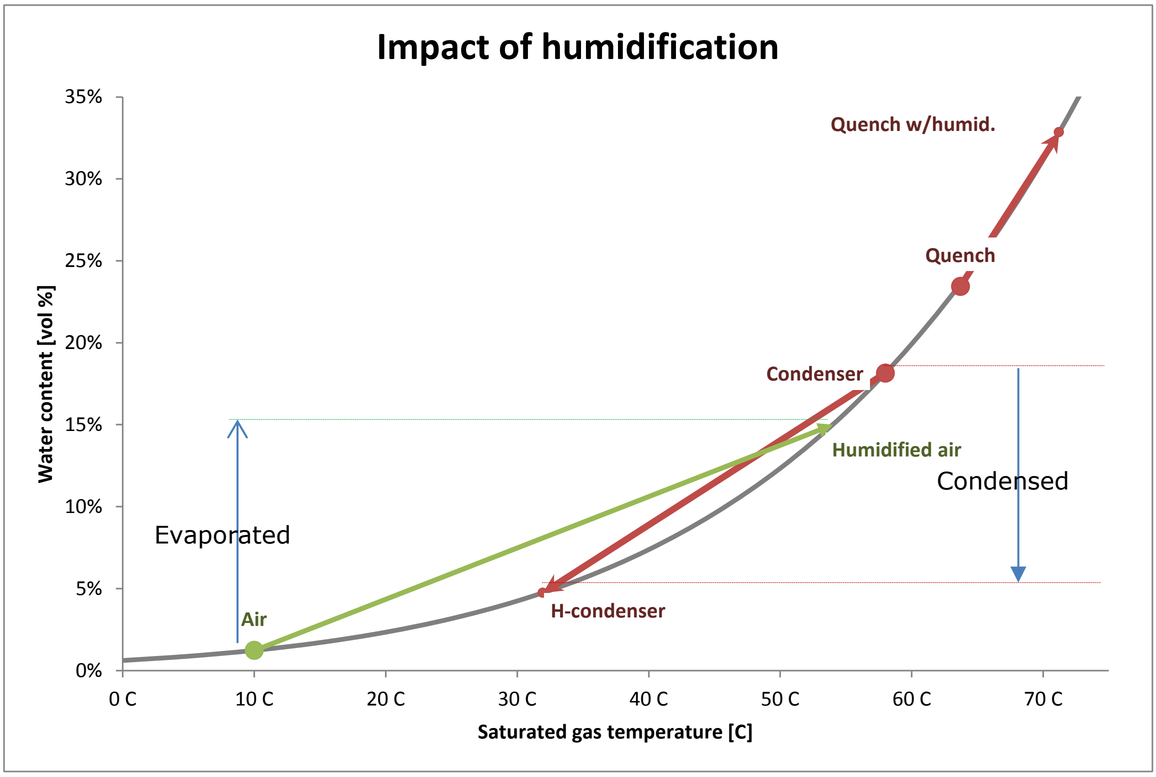


FIGURE 10. THE WATER SATURATION CURVE AND THE IMPACT OF HUMIDIFICATION ON THE TEMPERATURE AND HUMIDITY OF COMBUSTION AIR AND FLUE GAS AT 55 °C DH RETURN TEMPERATURE (X22), REFER TO TEXT FOR EXPLANATION

In the diagram of Figure 10, the temperature of the combustion air and flue gas is illustrated on the water saturation line. As the gas is assumed to be water saturated at the points shown, the actual water contents will stay at the saturation curve as shown. The indicated water contents (in volume %) are assuming the gases to be at standard pressure of 101,3 kPa.

The green arrow shows the heating and humidification of the combustion air. The vertical difference indicates the amount of water evaporated.

The red arrows indicate how the gas properties downstream the quench and downstream the condenser/H-condenser is changed by the humidification. Downstream the quench, the higher water content results in an increase in the adiabatic water saturation temperature from 63.7 °C to 71.2 °C. The resulting cooled flue gas temperature is decreased from 58.0 °C to 31.2 °C. The resulting DH yield increase from 4.2 to 13.2 MJ/s is consistent with Figure 6.

There is a small net bleed from the humidification water circulation. This is because thermodynamically slightly more evaporation heat is spent at lower temperatures (in the humidifier) than is gained by condensation of the same amount of water at higher temperatures (in the H-condenser). As the energy transferred must be identical, slightly more water is condensed than evaporated in the circulation.

The x42 alternative (DH precooling) for the same 55 °C return temperature conditions is shown in Figure 11. In order to reach the optimal yield, the DH flow was carefully controlled to match the following criteria: The resulting DH temperature from the flue gas condenser must equal the incoming flue gas saturation temperature less the assumed minimum temperature difference of 3 °C between the DH flow temperature and the saturation temperature of the quench (70.3-3=67.3 °C).

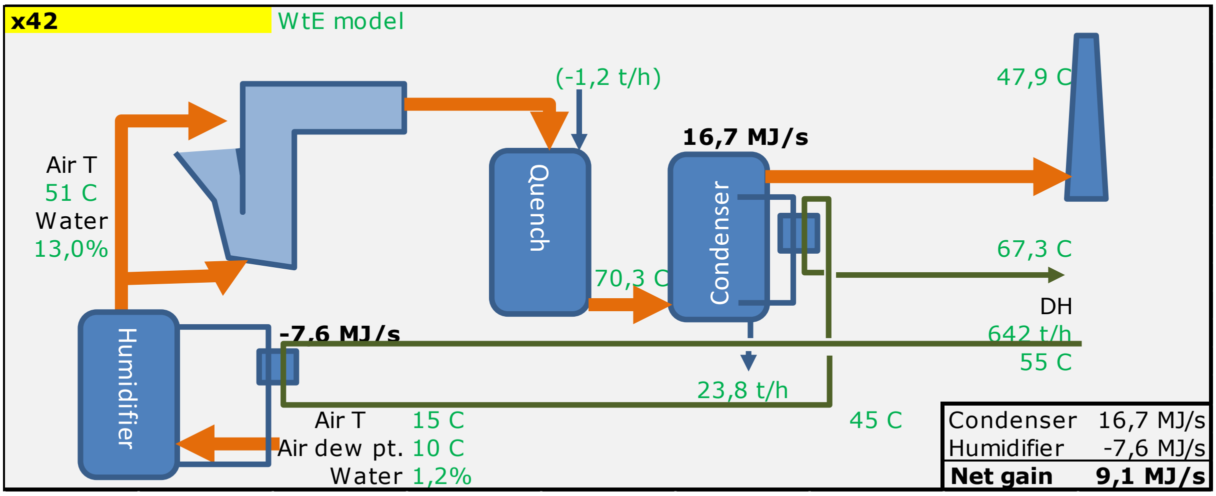


FIGURE 11. ENERGY BALANCE FOR THE X42 ALTERNATIVE AT 55 °C DH RETURN TEMPERATURE (COMPARE TO FIGURE 9).

It can be seen that the DH precooling delivers 7.6 MJ/s to the humidification, while 16.7 MJ/s is recovered in the flue gas condenser. The net yield is thus 9.1 MJ/s, which is a gain of 4.9 MJ/s caused by humidification. Note that the heat transfer in the flue gas condenser is fourfold higher with humidification, which may necessitate the existing flue gas condenser capacity to be upgraded when implementing the x42 humidification alternative on an existing system.

8.1.2 Results

The DH yield from humidification systems depends strongly on the system configuration as well as the available DH return temperature. In Figure 12, the condensation yield from the model WtE plant is shown as a function of the available DH return temperature. The green curve shows the yield from direct condensation, and is identical to Figure 6. The blue curve is with humidification using a separate H-condenser (x22), while the purple curve shows the yield from the simpler humidification implementation using DH precooling (x42). The temperature levels at the three example plants are indicated as pink areas. The “A+” plant with 55 °C temperature corresponds to the balances shown in Section 8.1.1.

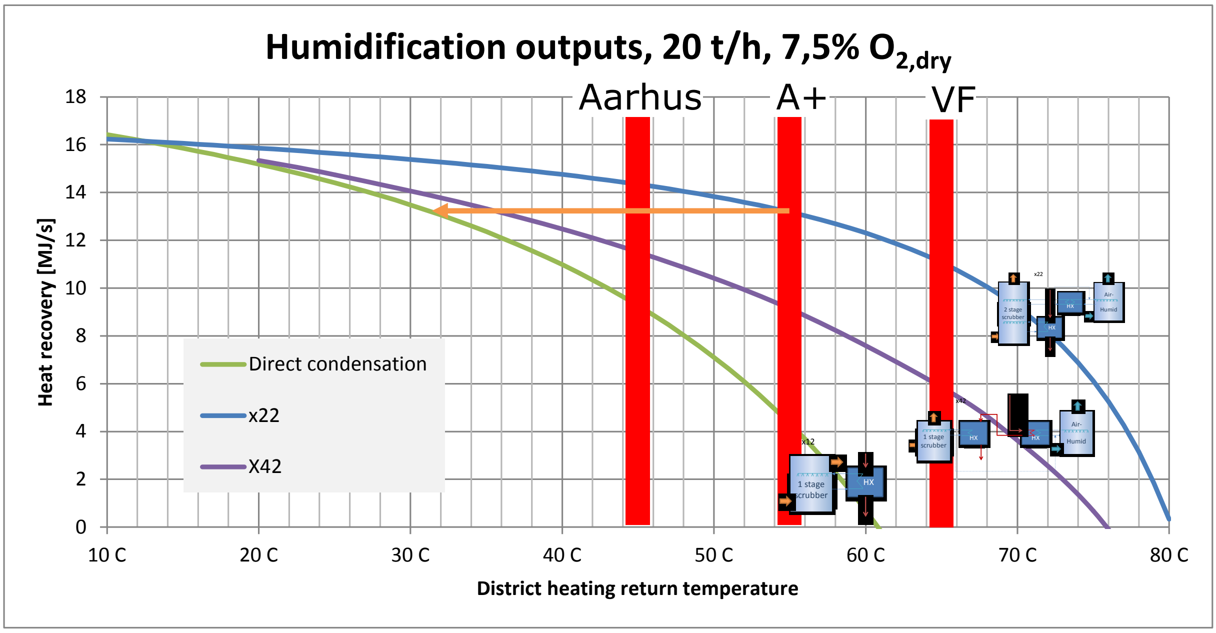


FIGURE 12. CONDENSATION DH YIELD AT MODEL WTE PLANT CONDITIONS WITH DIRECT CONDENSATION AND HUMIDIFICATION BY THE X22 AND X42 ALTERNATIVES

The simpler x42 alternative results in a lower potential DH gain than x22. Still both configurations produce significant amounts of heat at and above 61 °C which is the threshold temperature for any heat recovery by direct condensation without humidification.

The stack temperature can be read from the diagram as the temperature where direct condensation produces the same amount of DH heat. E.g. (orange arrow), the x22 implementation with 55 °C DH temperature results in a flue gas temperature of 32 °C, which is consistent with Figure 9.

8.1.3 Specific implementations

The calculation of the specific probable implementations at the three plant cases were done assuming the same model plant boiler as above when it comes to flue gas composition and temperature levels, but adapting the actual DH temperature and including a existing heat pump, whenever available. The modelling was done using Götaverkens modelling tool and a more conservative assumption regarding the efficiency of the humidification unit; the temperature difference between the incoming flue gas at the H-condenser and the humidified combustion air was assumed to be around 14 °C instead of 4 °C in the above calculations.

Existing case plants	Aarhus L1	AffaldPlus L3	Vestforbraending L5
DH return temperature	45 °C	55 °C	65 °C
Direct condensation stage	Yes	Yes	-
Heat pump condensation stage	-	Yes	Yes

TABLE 10. EXISTING FLUE GAS CONDENSATION CONFIGURATIONS AT THE CASE WTE PLANTS.

The heat pump configurations for the flue gas condensation at the three existing case plants are determined by their respective DH temperature levels, as it is seen from Table 10; Aarhus has the lowest DH temperature, and can thus provide a high energy recovery in direct condensation without a heat pump. AffaldPlus has a rather high return temperature with limited energy recovery potential in the direct condensation stage. A heat pump driven condensation stage therefore adds significantly to the energy recovery. At AffaldPlus the system is thus designed to recover the energy that can be recovered in a direct condensation stage, then use a heat pump to increase the yield in a separate stage. At Vestforbrænding the temperature is too high to produce any heat by direct condensation. Thus Vestforbrænding relies on heat pumps for all of their flue gas condensation heat recovery.

At the Aarhus plant, where only a direct condensation stage exists, the humidification solutions could likely be as already described for the x21 and x41 configurations.

At plants already equipped with a heat pump enabling flue gas condensation at low temperature, a humidification system can still be advantageous; Either it can take over some of the cooling work from the heat pumps saving driving energy, or the cooling capacities can be combined to condense to even lower temperatures. Figure 13 shows how humidification is could be implemented at plants in combination with heat pumps. At Vestforbrænding, where direct condensation is not possible with the present system, it could become possible with humidification due to the higher water content in the flue gas when the combustion air is humidified. At the same time cold water from the circuit would be available to recover more condensation heat in the heat pump stage, or decrease the need for driving energy for the heat pump.

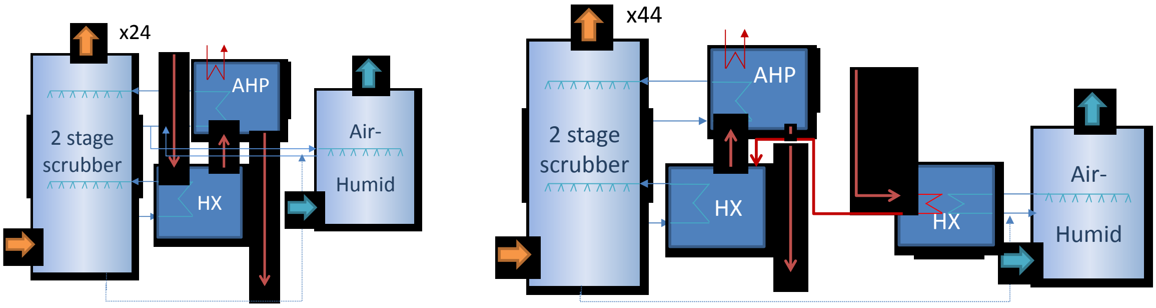


FIGURE 13. THE HUMIDIFICATION IMPLEMENTATION ALTERNATIVES FOR SYSTEM WITH A HEAT PUMP. EQUIVALENT TO THE ALTERNATIVES SHOWN FOR DIRECT CONDENSATION IN FIGURE 8.

If a humidification system is installed and used to simply replace all or some of the cooling work of a heat pump so that the flue gas is cooled to the same temperature as before, the total energy recovery is unchanged. But as driving steam or electricity for the heat pump is saved, the result is that more energy can be exported as electricity instead of heat. The calculated results in Figure 14 illustrate this.

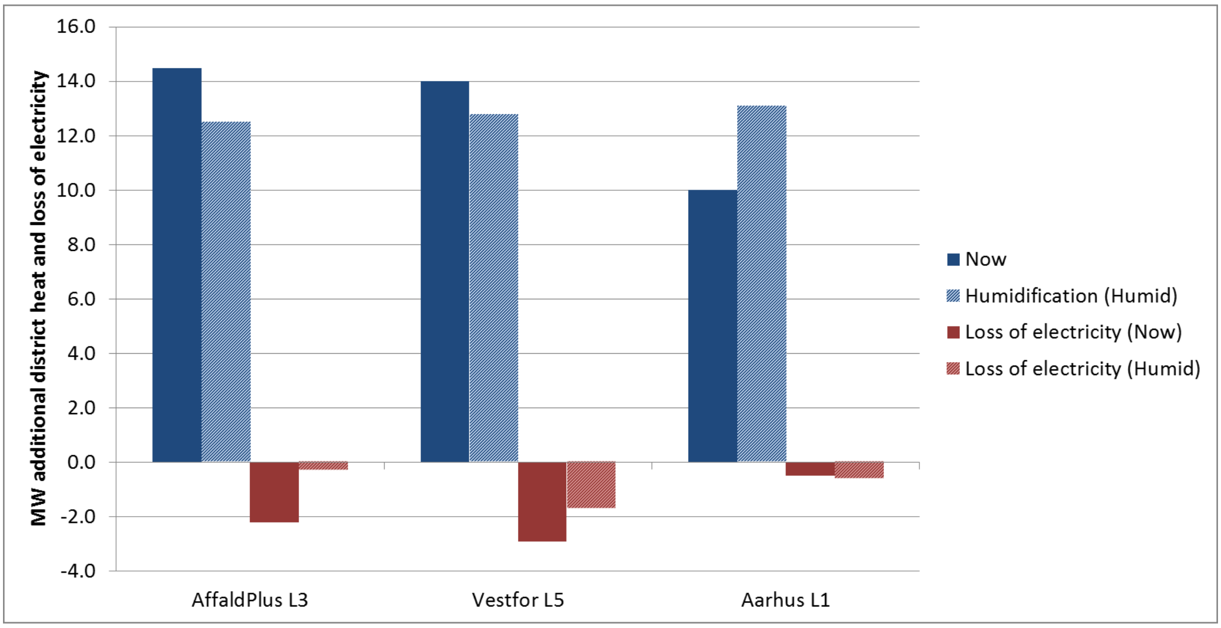


FIGURE 14 DEVELOPMENT IN CONDENSATION ENERGY AND ELECTRICITY CONSUMPTION WHEN THE THREE PLANTS INTRODUCE HUMIDIFICATION BUT DO NOT CHANGE THE COOLING TEMPERATURE OF THE HEAT PUMPS.

If the facilities operate the heat pumps to further increase the heat production instead of saving electricity as indicated on Figure 14 the heat production will be 26 to 39 % higher than today assuming that the heat pumps are able to deliver their cooling at lower temperatures without problems e.g. crystallization. A new additional heat pump can in many cases deliver further energy production by cooling the flue gas as low as 20 °C. As the condensation potential per °C is lower at lower temperatures, heat pump systems are often designed to cool the flue gas to around 30 °C. In the model results shown in Figure 14 the Vestforbraending facility improves its system cooling coefficient of performance (COP) from 4.8 to 7.5 where AffaldPlus improves its system cooling COP from 6.6 to amazing 41.7 proving that low temperature heat recovery with minimal electricity consumption is in fact possible. Loss of electricity in Figure 14 is due to the change in net electricity output from the facility, caused by the increased temperature of the DH-water at the inlet to the turbine condensers and the use of steam as driving energy for the heat pumps (Affaldplus and Vestfor, only)

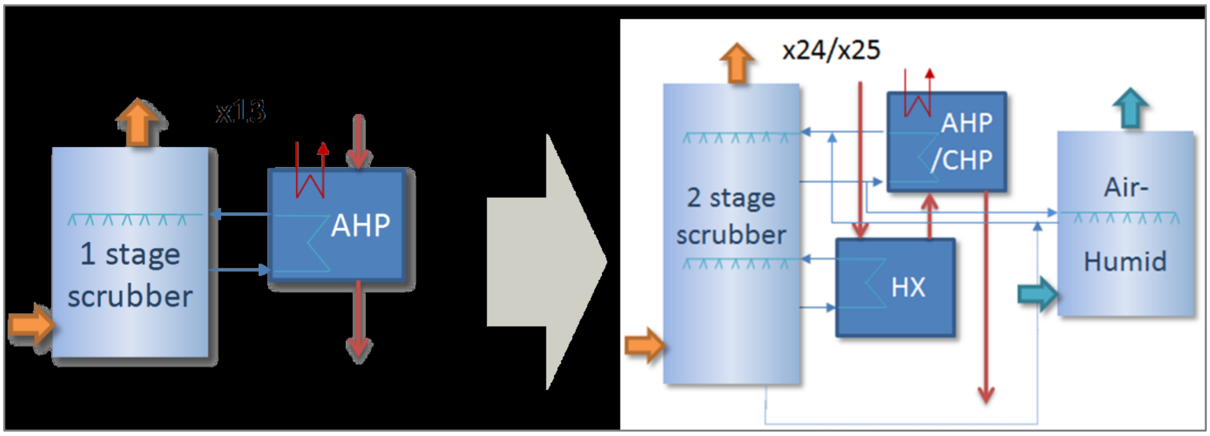


FIGURE 15 THE VESTFORBRAENDING LINE 5 SYSTEM TODAY AND AFTER IMPLEMENTATION OF A HUDIMIFICATION SYSTEM. (AHP/CHP ARE HEAT PUMPS)

8.1.4 Modelling the effects of changes in waste composition

If the water content of the waste is reduced, as it is likely to be in case organic waste is diverted from WtE facilities to e.g. biogas plants, the water content in the flue gas will decrease. This will cause the energy recovery in existing flue gas condensation installations to decrease. By enabling heat recovery from lower flue gas temperatures, combustion air humidification can reactivate the flue gas condensation capacity of affected plants.

To illustrate this, Figure 16 shows the energy recovery in the flue gas condensation at the conditions at the three case plants for different waste types: "Now" is the current basis 2011-type waste, while "2022H" is the situation if firing the drier 2022H-type waste in the existing systems. As expected, this will decrease the energy recovery from the flue gas condensation systems. The "2022H humid" columns show the potential heat recovery in the flue gas condensers based on the same dry waste as in 2022H, but with combustion air humidification systems installed.

As shown, it is possible to more than counteract the negative impact imposed on the flue gas condensation systems, if combustion air humidification systems are installed. In case the waste composition does not change, or even becomes more wet (e.g. by diverting plastics for recycling), humidification systems will still increase the potential heat recovery provided the flue gas condensers have spare capacity or their capacities are upgraded accordingly.

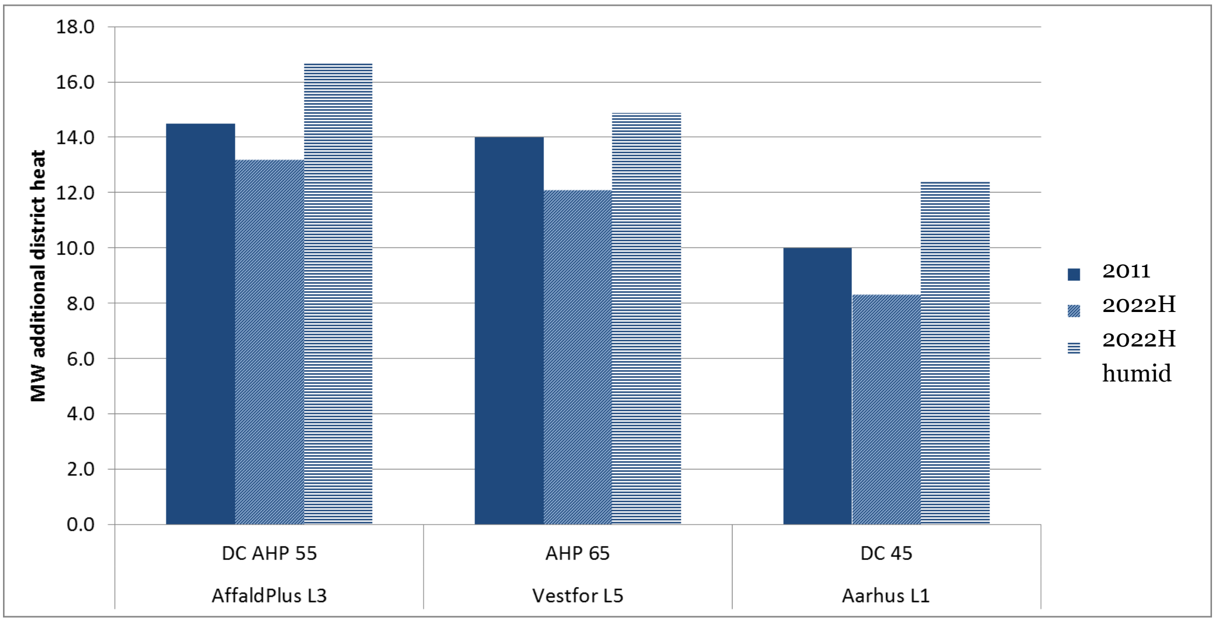


FIGURE 16 MODELLING THE EFFECTS ON FLUE GAS CONDENSATION YIELD AT THREE WTE FACILITIES FOR THE CURRENT WASTE (2011) AND TWO SCENARIOS:
2022H: WITHOUT ANY ACTION
2022H HUMID: WITH THE IMPLEMENTATION OF COMBUSTION AIR HUMIDIFICATION

8.2 Effects on the furnace/boiler system

Humidification of the combustion air affects the furnace/boiler system in several ways that may provide some benefits but may also limit the extent of humidification or operation range of furnace/boiler system. The following is a technical assessment of the impact of humidification of the combustion air on retention time, ash formation and corrosion. The assessment is carried out for the model plants according to the flue gas data of Table 8. Furthermore the modification that should be carried out on the boiler to compensate for the influence of humidification on the boiler operation is explained.

The considerations below are provisional, and hardly provide the full knowledge on effects without full-scale tests.

8.2.1 Calculation cases and criteria for these

Calculations are based on 21 cases, consisting of each of the three fuels (2011, 2022 and 2022H, cf. Table 5) in each of the following scenarios 7:

- No Humidification

- Moderate humidification, with three sub-scenarios. See criteria below.
    - Restrained heat input (and thus reduced net power).
    - Maintained net effect (and thus increased heat input).
    - Maintained net effect, combined with increasing heating surface radiation part and economiser

- Full humidification at 65 °C return temperature from the district heating system with three sub-scenarios:
    - Restrained heat input (and thus reduced net power).
    - Restrained net power (and thus increased heat input).
    - Restrained net effect, combined with the increase of heating surface in the radiation part and economiser

Moderate and full humidification are for instance realised through configuration x22 and x42, respectively, cf. Figure 8.

The scenarios and criteria are described on the basis of an unchanged fuel for all scenarios, i.e. a fuel composition and heating value that are close to the nominal values for the plant in question.

The immediate effect of humidification with unchanged fuel is that water vapour is added to the combustion air, thereby increasing the flow rate of combustion air. As a result the flow rate and moisture content of the flue gas are increased. But the actual effect will depend on the response of the furnace control system, including decisions of the operation staff on potential changes of set-points, e.g. on oxygen level.

For instance, another immediate effect is that the oxygen level (% of actual flue gas) drops as a consequence of increased water vapour content. At unchanged set-points for boiler load and flue gas oxygen percentage the flow of dry combustion air would usually increase to maintain the oxygen level (measured on actual flue gas), but a different response could easily be incorporated in the control of the furnace/boiler system. The three sub-scenarios represent two examples of control and one with boiler modifications. The choice will depend on the actual furnace/boiler design and dimensioning, as design parameters may allow, exclude or limit some possibilities.

In the case “restrained heat input”, the flue gas flow and oxygen set-point are maintained despite the humidification in order to have the least possible change for the boiler. The consequence is less waste throughput and hence reduced steam production from the boiler and, hence, reduced heat and power generation from the turbine/generator, but the potential for flue gas condensation increases due to the increased water vapour content.

In the second scenario where the net effect is maintained, the excess air level (i.e. dry oxygen level) is maintained. The increased flue gas flow rate by CAH then causes the flue gas loss[1] to increase, in turn necessitating a slight increase in waste input to maintain the steam output. The increased flue gas flow may also cause the boiler exit temperature to increase, which further increases the flue gas loss. The increased flue gas flow reduces the furnace temperature, and therefore it is also predicted to cause a drop in energy uptake in the first part of the boiler (the radiation passes) and a higher energy uptake in the super heater.

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[1] The flue gas loss is the energy content of the flue gas not recovered in the boiler, resulting in a loss from the perspective of the energy balance of the furnace/boiler system. It is calculated as the product of the mass flow of flue gas (kg/h), the specific heat capacity of the flue gas (kJ/kg/°C) and the temperature in excess of the reference temperature (°C).

This leads to the third scenario where additional heating surface is installed in the radiation passes in order to increase the energy uptake in this part of the boiler and reduce the energy uptake of the super heaters by lowering the flue gas temperature upstream the super heaters. The scenario also includes additional economiser surface to compensate for the larger flue gas flow. The necessity and extent of additional heating surface depends on the design and dimensioning of the boiler in question, and that is why the final evaluation is on project basis.

The criteria for increasing the heating surface have been:

- Heating surface of the radiation part is increased so much that the super heater performance is unchanged compared to the situation with the same fuel without humidification.
  (Explanation: When air is humidified, the flue gas flow increases. The flue gas before the units will be approximately unchanged, but because of the higher energy content of the larger amount of flue gas it unintentionally improves the superheating capability. By inserting additional heating surface in the radiation part, this improvement can be used to lower the flue gas temperature before the super heaters and thereby reduce the corrosion rates and ash buildup on the super heaters, in comparison with the situation without humidification.)

- Heating surface in economiser is increased so much that the ability to cool the flue gas is unchanged for the economiser compared to the situation with the same fuel without humidification.
  (Explanation: When air is humidified, it will increase the flue gas flow. Therefore, more heating surface is needed in the economiser to cool the larger amount of flue gas to the same outlet temperatures.)

In all cases the flue gas after the boiler is as far as possible maintained at 180 °C by means of preheating feed water before the economiser. The feed water preheating energy is taken from the boiler drum and is therefore energy neutral. The feed water preheating can only secure against flue gas temperature falling *below* the 180 ° C and does not prevent excess temperatures. Consequently in part of the calculation cases, the flue gas temperature is higher.

The criterion for determining the amount of water vapour addition when the fuel changes at moderate humidification has been that the flue gas flow by dry fuel (e.g. 2022H) with humidification should correspond to the flue gas flow at normal fuel (year 2011) without humidification. This means that this case corresponds to a full compensation for any future change from normal fuel to dry fuel.

8.2.2 Results

The presentation of the results focuses on three topics;

- The cases where moderate humidification is added without changing the fuel or boiler
- The case that the fuel changes from 2011 to a drier fuel (2022H) and humidification is done mainly to compensate
- Effects of extension of heat exchanger surface in the economiser and radiation part, when moderate or full humidification is added while the fuel is unchanged

Comparing the cases where moderate humidification is added without changing the fuel or boiler and the excess air level is unchanged, the consequences are summarised:

- The flue gas water vapour content increases.
- The furnace temperature drops.
- The flue gas flow increases.
- The flue gas velocities increase.
- The flue gas temperature in front of the super heaters drops.
- The flue gas temperature after the boiler increases. Alternatively the feed water preheating should be decreased equivalent to maintain unchanged flue gas temperature.
- If the boiler steam production is to be retained, the amount of fuel is increased in those cases where the flue gas after the boiler is maintained. Can the flue gas temperature not be maintained, the fuel amount is increased even more.
- The retention time over 850 °C drops.

- The super heating performance increases.
- The safety margin against boiling economiser drops.
- The potential for flue gas condensation increases considerably.

When the fuel is relatively dry with high heating value (i.e. drier than the nominal fuel), the humidification has the advantage of reducing the furnace temperature and the temperature upstream the super heaters. This relieves the load on the refractory in the furnace and reduces the primary NOx formation, and the lower temperature reduces the corrosion rates in the radiation passes and super heater. The boiler would be capable of coping with the elevated flue gas flow rate caused by moderate humidification without reducing the load because the boiler is designed for a lower heating value yielding the same, higher flue gas flow. In this case there are no significant negative consequences on the furnace/boiler system.

In case the furnace and boiler can accommodate an even higher flue gas flow, full humidification may be applied.

In case of a relatively wet fuel with low heating value humidification may add further to the condensation potential, but there may be negative consequences. For instance, the temperature of the afterburning chamber may drop to a level that makes it difficult to maintain the required 2 sec. retention time at minimum 850 °C.

In the scenario where the humidification only is used to compensate for the reduced flue gas flow from a drier fuel (i.e. normal fuel without humidification versus dry fuel with moderate humidification), there are no substantial differences. Flue gas velocities, temperatures, residence time and super heating performance can be considered as unchanged. However, the efficiency of the boiler will be higher than before, so that the steam production is maintained despite a lower fuel input, or alternatively the same thermal input from fuel achieves a higher steam production.

The effects of extension of heat exchanger surface in the economiser and radiation part, when moderate or full humidification is added while the fuel is unchanged could be summarised as:

- The flue gas temperature upstream the super heaters drops- causing the corrosion rate of evaporators and super heaters to drop
- The super heating performance is unchanged.
- The flue gas temperature after the boiler is unchanged.
- The safety margin against boiling economiser drops.
- Other consequences of the increased humidification are equal to those in the cases without additional area.

8.2.3 Assessment of impact on boiler

This section focuses exclusively on cases where humidification is used with an unchanged fuel, or where the humidification overcompensates for a drier fuel.

In cases where the humidification alone is used to compensate for the loss of flue gas from a drier fuel, there is no significant influence on the boiler.

Residence time

The calculations show that the flue gas residence time above 850 °C decreases. This may be critical with wet fuel has low heating value, partial load or when the boiler is clean, without insulating ash deposits. The cases with full load and fouled boiler are therefore not representative for a full verification of the residence time, and the influence on the residence time should not only be quantified from these cases. Moreover, the furnace calculation in the used calculation tool is very simple, why residence time calculation can only be considered as indicative. It is recommended to make an individual, CFD[2]-based retention time calculation of relevant cases on the specific boilers where humidification is installed.

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[2] Computional Fluid Dynamic

Flue gas flow velocities

In the performed calculations for moderate humidification flue gas flow velocities in the boiler are increased by up to 7%. This increase will almost always be acceptable to the boiler.

In the performed calculations for complete humidification is observed up to 17% increase of the flue gas velocities. This increase will in many cases be acceptable after a specific assessment of each individual boiler.

Note:
The usual effects of high flue gas velocity is increased particle entrainment in the first pass, increased corrosion on turbulence affected heating surfaces and increased pressure drop through the boiler and flue gas cleaning system, which can cause excessive negative pressure or excessive load of the induced draft fan.

Super heating performance

The humidification increases boiler super heating performance. Although the flue gas temperature before the super heaters decreases, the energy content of the larger amount of flue gas is higher.

The immediate consequence of this is that there must be a larger amount of injected feed water into the steam between the super heater sections in order to maintain the desired outlet temperature of the steam from the boiler. It can in some cases be necessary to increase the capacity of the injectors.

However, it will be obvious instead to take the opportunity to maintain super heating performance and achieve a reduction of corrosion stress on the super heater and evaporator surfaces as compared to the situation before humidification. This is explained in the section entitled "Consequences of corrosion on the super heaters". To achieve this improvement heating surface area upstream the super heaters is increased.

Flue gas temperature after the boiler

The flue gas temperature after the boiler would usually increase, which reduces the energy efficiency of the boiler. It also changes the conditions for the flue gas treatment system, which is, however, not normally a problem.

On some boilers the economiser will have so much excess capacity that the flue gas temperature can be maintained at the original level by reducing feed water preheating before the economiser but this must be considered as a special case. For most boilers it will be necessary to build in additional heating surface in the economiser.

Risk of low-temperature corrosion of economiser

Complete humidification will result in a water content in the flue gas, which substantially exceeds the water content, which occurs without humidification. The higher water content leads to higher dew point temperature in the flue gas and thus an increased risk of low-temperature corrosion.

In the calculations of wet fuel (e.g. 2022L) the dew point for sulfuric acid in the flue gas rises from 125 ° C to 130 ° C and the water dew point from approx. 60 °C to approx. 70 °C when adding full humidification. In general, calculations of the dew point for sulfuric acid in flue gas are always regarded with some uncertainty, and a fairly large safety margin is usually included. Consequently the economiser may be able to cope with the increased corrosion stress. However, if the economiser today is close to having low-temperature corrosion, low temperature corrosion will probably occur on the coldest rows in the economiser if the feed water temperature before the economiser is maintained. As the metal temperature of a typical economiser rises about 1 °C per tube row, it must be assumed that the problem is limited to the coldest 5 rows. These rows must either switch to a more resistant material, or else one have to accept an increased corrosion rate. Alternatively, the feed water temperature could be raised 5 ° C, to move away from the dew point, but this will increase the boiler exit temperature, and hence impair the efficiency of the boiler.

When in connection with the addition of humidification one lowers the feed water temperature before the economiser to maintain the flue gas temperature after the boiler without adding additional heat exchanger in the economiser, the number of rows of pipes subjected to low temperature corrosion will be higher, since the humidification raises the dew point of sulfuric acid and the reduced feed water temperature decreases the metal temperature.

Risk for boiling in the economiser

The boiler water temperature after the economiser will increase as a result of humidification because the mass flow of flue gas, and hence, its energy content increase. On some boilers the temperature will come close to boiling depending on configuration of the boiler and the heating surface areas.

This issue will not always occur at full load. At part load the flue gas temperature after the boiler is maintained by increasing the feed water temperature in a heating loop in the boiler drum. Thereby, the water inlet temperature is so high that it only has to be supplied with a small amount of energy in the economiser to bring the water up to boiling temperature. Before the incorporation of humidification boiler it may be needed to analyse load data of the boiler to identify possible load cases with high risk of boiling.

If the problem occurs, the following options are possible:

- Cooling of some of the feed water energy in an air preheater via a water outlet between two economiser levels.
- Changing the feed water heating loop in the boiler drum to a bypass around the coldest part of the economiser.
- Increasing the heating surface in the radiation part, so the economiser receives colder flue gas.

Most boilers, however, have a large margin between the feed water temperature and the boiling point. Consequently such modifications will not be necessary.

8.2.4 Area increase of boiler

The calculation has identified two regions of the boiler, where it may be advantageous to increase the surface area. Area increase is only relevant in cases where humidification is used with an unchanged fuel, or where the humidification overcompensates for a drier fuel

- Radiation part.
  Here, additional surface area causes the flue gas temperature before the super heaters to decrease, thereby reducing the corrosion and ash build-up on the super heaters. Due to humidification this can be done without reduction of the super heating performance because of the increased flue gas flow holding a higher energy content. The increase in area is to be considered as an option. Also without increasing the surface area the humidification leads to a slight improvement of the situation of the super heaters, because the humidification reduces the flue gas temperatures. With the combination of humidification and increased surface area a significant improvement of the conditions for the super heaters can be achieved. If an area increase in the radiation part is omitted, the area increase in the economiser, however, should be larger.

- Economiser.
  Additional space is often necessary to maintain the current flue gas temperature after the economiser.

8.2.5 Improved corrosion conditions for super heaters

Background:

In the super heaters hot flue gas is heating the steam from the boiling point at the outlet of the boiler drum to the boiler outlet temperature, which is typically in the range 400-440 °C, the higher the temperature (and pressure) the higher the electricity production from the turbine. The metal surface temperature of the super heaters is, however, critical for the corrosion rates.

When designing a boiler the flue gas temperature upstream the super heaters should be selected so as to balance the interests of super heater performance (high flue gas temperature desired) and consideration for the super heater corrosion (low flue gas temperature desired).

By addition of humidification better super heater performance is obtained without increasing the flue gas temperature before the super heaters. The result is an opportunity to move the above balance and retain super heater performance with lower flue gas temperature upstream the super heaters. This is done in practice by increasing the heating surface area of the radiation portion before the super heaters so that the flue gas is cooled more before it reaches the super heaters.

Also without an area increase it can be expected that the humidification causes a reduction in corrosion rate of the super heaters. In this case, the reduction will, however, be significantly less.

Improvement of corrosion conditions

The improvement of the corrosion conditions for the super heaters is shown in Figure 17.

Explanation of the diagram:

- There are three super heater sections SH1, SH2 and SH3 numbered according to the flow direction of the steam. Seen from the flue gas flow direction, the SH2 comes first cooling the flue gas from around 560 °C to 520 °C, then SH3 cooling the flue gas from around 520 °C to 475 °C and finally SH1 cooling from 475 °C downwards. The steam flow direction in each super heater section is chosen for optimum surface temperature and performance.

- Each dotted line indicates temperature combinations which will have the same corrosion rate. A gap between two lines up and to the right corresponds to a 12% increase in the rate of corrosion - and if stepping down a 12% increase in the life span of the superheated.

- The red solid lines show the details of output case without humidification or added surface area.

- The blue solid lines show the details of the case with full humidification and unchanged heating surface. There is an improvement on the front of super heater number 2 (SH2), while SH3 is unchanged. On SH1 deterioration is seen in the front, but when this superheated has a lower absolute corrosion rate from the beginning, it will not necessarily have any impact.

- The green solid lines show the details of the case with full humidification and added heating surface. There is a much larger improvement of SH2 and SH3, which is typically the most vulnerable to corrosion. The improvement is approximately equivalent to two interlaced. Consequently life is increased about 25% for these super heaters. Also SH1 is improvement, but again it will not necessarily have any impact due to a lower absolute corrosion rate.

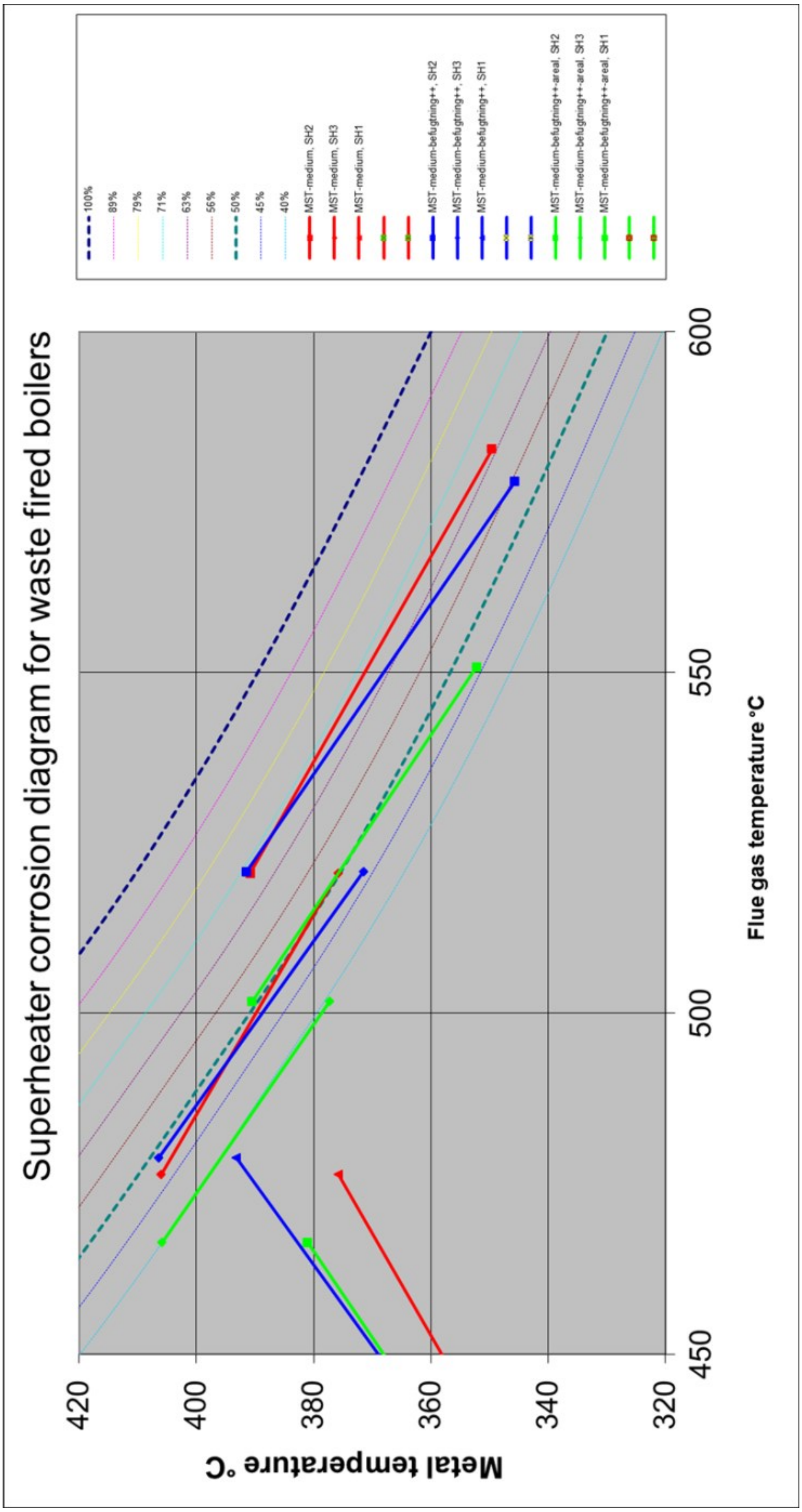

FIGURE 17 CORROSION DIAGRAM WITH SUPER HEATER CONDITIONS INDICATED WITHOUT AND WITH HUMIDIFICATION.

8.3 Implementation of humidification

A major challenge retrofitting an existing facility with the combustion air humidification system and required changes to the flue gas condensation units and other equipment relates to the space requirements of the humidifier and logistics of piping and ducting. The required space needs to be located and evaluated according to safety, environment and economy allowing an optimal location. However if for example no space can be found inside the facility an outside location would need evaluation taking into account the difference in surrounding environment and hence additional requirements on the equipment with regards to for example corrosion protection and condensing protection by insulation. The main focus will be on the location of the humidifier scrubber as it is the largest unit with the most location restrictions.

The major concerns when locating the humidifier is the following:

- Proximity to primary and secondary air ducts (to avoid pressure loss and excessive ductwork and piping)
- Proximity to the waste storage bunker and primary air inlet for the same reasons as above
- Possibility to bring down the weight (the humidifier has a significant water volume in the bottom)
- Proximity to district heating piping (to avoid excessive piping)
- Possibility for easy routing of pipe connections to the condensation unit

To illustrate the challenges related to install humidification an overall layout for a solution on the three plants involved in the project have been carried out. The focus has been on identifying space on the plants where it would be possible to install the humidifier unit. Consequently the layout on the plants is not handling the detailed routing of tubes, cables, pipes and ducts nor the changes to the flue gas condenser, the heat pumps or changes to the stack. The humidifier is assumed to be a glass fibre reinforced cylinder with an inlet on the side close to the bottom and an outlet also on the side in the top. Below in Table 11 provisional dimensions for the scrubber can be found.

TABLE 11 PROVISIONAL ESTIMATIONS OF THE SIZE OF HUMIDIFIER UNITS FOR THREE LINES AT THREE DIFFERENT FACILITIES

	AffaldPlus L3	Vestfor L5 One unit	Vestfor L5 Two units	Aarhus L1
Diameter (m)	3.1	5.9	2 x 4.2	2.9
Height (m)	12.1	14.3	14.3	12

8.3.1 AffaldVarme Aarhus

ON THE AARHUS FACILITY SPACE IS AVAILABLE ABOVE THE OLD WASTE BUNKER WHERE A LARGE CONCRETE DECK HAS BEEN MADE WHEN A NEW BUILDING ENCLOSURE WAS INTRODUCED SINCE IT IS HIGHER AND “CONTAINS” THE WASTE BUNKER IN ITS VOLUME. THE BUNKER ROOF CONCRETE DECK PROBABLY NEEDS TO BE REINFORCED TO CARRY THE HUMIDIFIERS BECAUSE IT IS NOT DESIGNED TO CARRY THE HEAVY LOADS OF THE COMPONENTS. THE SPACE IS CLOSE TO THE AIR FANS AND FURNACES AS CAN BE SEEN IN

Figure 18. Consequently the routing of the air ducts should be optimal.

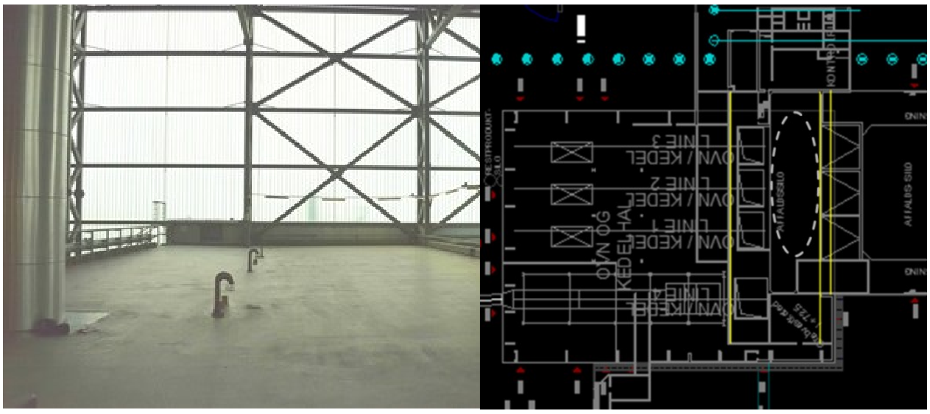

FIGURE 18 PICTURE OF AREA ABOVE BUNKER WHERE THE HUMIDIFIER CAN BE PLACED (LEFT) AND DRAWING SHOWING THE AREA (PUNCTURED LINE CIRCLE) ON AFFALDVARME AARHUS (RIGHT)

8.3.2 AffaldPlus

If the humidifier should be placed close to the combustion air system on line 3 on AffaldPlus, the humidifier probably needs to be placed outside the building as can be seen from the 3D layout in Figure 19. The outdoor location is not thought to be a problem as the humidifier has an internal heat source and hence frost problems are not foreseen. Some additional insulation should however be foreseen and some materials might need additional corrosion protection, however this is not very important to the overall economy.

Alternatively the humidifier could be placed in an adjoining building where a part of the flue gas cleaning system is located. This layout would generate some long air ducts but it would move the humidifier closer to the district heating installation used for the new flue gas condensation system.

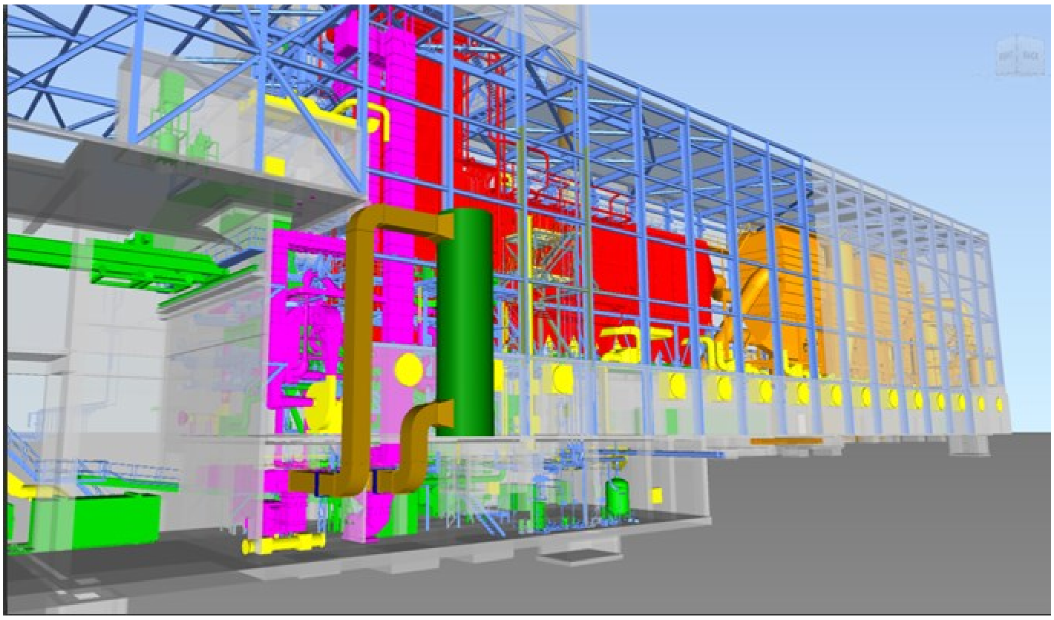

FIGURE 19 3D MODEL VIEW OF HUMIDIFIER (GREEN CYLINDER) PLACED OUTSIDE THE BOILER BUILDING AT THE WTE FACILITY AFFALDPLUS NÆSTVED

8.3.3 Vestforbrænding

The space available at Vestforbrænding line 5 does not easily allow for a humidifier with a diameter of 5,9 meters as estimated necessary. Consequently the humidifier needs to be split into two units with a smaller diameter.

With two smaller scrubber units the humidifiers can be located between the furnace and the bunker above the ramp feeder area as shown in Figure 20. This area is close to the present air ducts and air preheater, and consequently the re-routing of the ducts should be easy. As the location is very elevated a large steel structure is needed to support the humidifiers and to avoid oversizing this steel structure the water volume of the humidifiers can be located on the ground level in separate tanks.. This however needs to be studied in more detail.

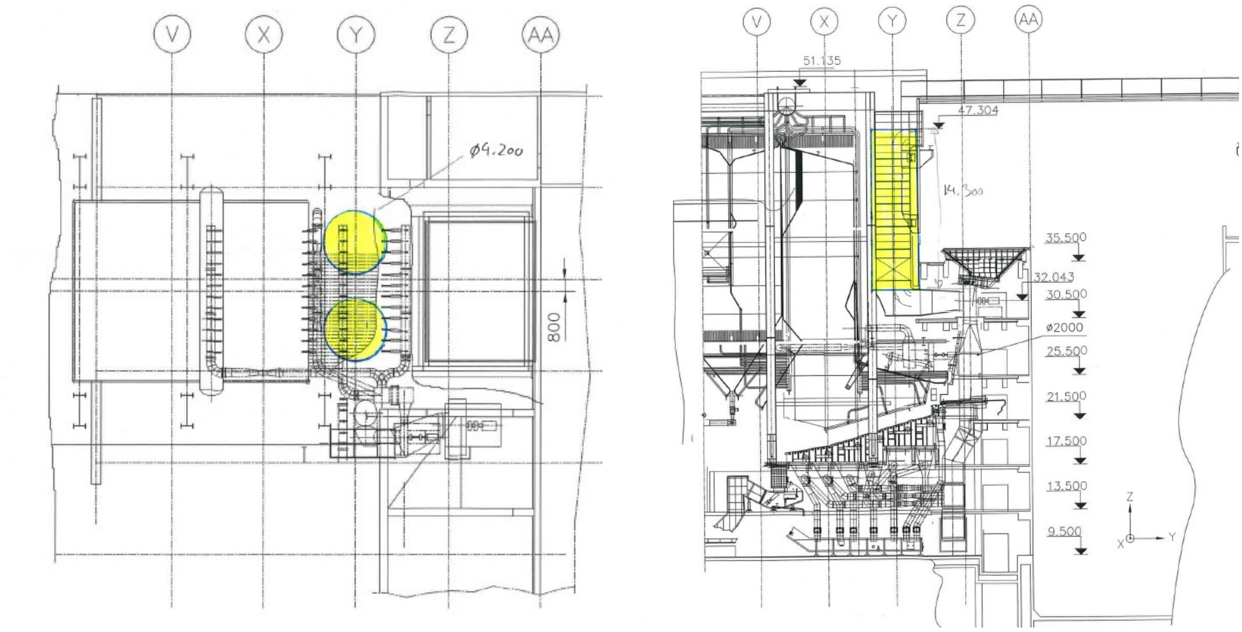

FIGURE 20 HUMIDIFIER ON VESTFORBRÆNDING PLACED IN A SECTION ABOVE THE FURNACE ALIGNED WITH THE FRONT WALL OF FIRST BOILER PASS

9. Simple business case

To calculate the business case of this new technology two of the three WtE plants previously evaluated have been used covering different sizes and starting points with the differences in present technologies.

The major driver in the economical calculations is the utility prices (energy, water and heat) and in this case we have calculated with a set of energy prices equivalent to a Danish scenario using 54 €/MWh for electricity (sales income) and 34 €/MWh for heat (sales income). The value of water has been neglected as the price in Denmark is very low. All scenarios have assumed 6000 hours of operational time a year for the condensation unit due to limitations in offtake by the grid during summer periods.

9.1.1 Direct scrubber no heat pump (45°C return)

The Aarhus case is based on a 45°C district heat return temperature grid. The facility will exchange a one stage direct scrubber system for a two stage system with humidification which has a total financial payback period of approximately 5 to 8 years. This is based on a € 0.63 million additional income from heat sales and a € 0.03 million loss of electricity sales.

9.1.2 Direct scrubber and heat pump (65°C return)

The Vestforbraending case is based on exchange of the present system with condensation in one stage using a heat pump due to the high return temperature of 65°C from the grid. The new two stage scrubber system consists of first a direct condensation stage and then a heat pump cooled stage. The heat pump circuit is first cooled by the humidification unit and the present heat pump and potentially the in the end a new heat pump. The new system has a total payback period of approximately 5 to 8 years. This is based on a € 2.4 million additional income from heat sales and a € 0.54 million loss of electricity sales.

9.1.3 General business case

Based on the two cases where simple business cases have been calculated it can be concluded that existing facilities with a heat market of 6,000 hours of heat sales available (34 €/MWh) can introduce this technology with relatively short payback times of 5 to 8 years.

New facilities would have even shorter payback times since the installation costs would be significantly lower.

The business cases do not take into account the advantages of lower temperatures before the super heaters or the positives effects of more smooth operation due to the possibility of controlling the furnace temperature through adjustment of the water vapour content.

10. Next steps

Further development and knowledge is needed before WtE facilities will consider implementation of optimized combustion air humidification to be a low risk project and hence there may be no projects started without further proofing. For optimized combustion air humidification to be implemented on a larger scale and gain the full market potential testing a full scale operational experience are needed. However, since the technology development level is still low further research is also needed for the technology to reach its full potential. Without research funding development will only happen slowly on a project to project basis as both facility owners and the suppliers will only take limited risks in each project, let alone overcome the challenges of being the first to realise a project.

10.1 Further work

At WtE plants the implementation of CAH will have to be adapted to overcome experienced and foreseen challenges. The required adaptions of the CAH system to WtE plants were studied and described in principle previously in this report, where other alternatives to obtain the same goals were also evaluated concluding that the CAH system is the altogether the most attractive. However, even though the main adaption challenges have been addressed, no practical experience or relevant tests are available to confirm that other challenges of importance do not exist. And more importantly no relevant research exists to show the operational problems specific for WtE facilities. It is expected that the majority of operational problems will be closely linked to the process downstream the humidification unit (placed on the combustion air inlet). The following likely primary consequences of implementing CAH at WtE plants were identified:

- Decreased maximum combustion temperature at the grate and in the furnace chamber
- Increased combustion air and flue gas flows, and increased water content in the flue gas in the boiler chamber
- A small relative increase in heat uptake in the convective section compared to the heat uptake in the radiant boiler chamber
- Decreased flue gas temperature upstream the boiler super heater banks
- Increased heat uptake in the economiser part

It is foreseen that these effects may cause the following impacts on individual systems:

- **The air preheaters** will receive the added water vapour with the air and thus increase the risk of corrosion in the first sections
- In **the furnace and afterburning chamber**, the decreased temperature and increased flue gas flow will impact the SNCR NOx abatement system if installed and challenge the legal requirement for WtE plants to subject the flue gasses to minimum 850 °C for two seconds
- In **the superheater banks**, two positive effects are expected from the decreased inlet temperature and increased heat transfer rate: The corrosion rate tends to be lower, while the superheating ability is increased
- In **the economiser**, the increased heat uptake will decrease the safety margin against boiling in the economiser and challenge its ability to cool the flue gases to the design outlet temperature. The higher flue gas moisture content will increase the dew point of sulphuric acid, and may increase the risk of low temperature corrosion
- **The flue gas treatment** system upstream the flue gas condenser will experience a higher flue gas flow and scrubber systems will experience a higher working temperature

A main change in the plant system is a decreased maximum combustion temperature in the furnace chamber and an increased flue gas flow. While most of the changes in operation conditions are relatively minor, the changes in local temperature and flow could be significant. How the changes affect plant operation is unknown and undescribed by present literature. It is believed that most of the waste boiler and flue gas cleaning equipment can proceed operation with only very minor modifications. However, the changes are believed to influence the SNCR unit responsible for NOx removal to keep emission limits. By injection of urea or ammonia in the furnace chamber, SNCR units work in a narrow temperature window around 1000°C (J.A. Miller C. B., 1989). Several detailed studies on SNCR unit performance in grate waste boilers have been conducted (J.A. Miller a. P., 1999), (Sarantuyaa Zandaryaa, 2001), (Thanh D.B. Nguyena, 2009), (Zengying Liang, 2010). However, the influence of using a CAH system on a waste boiler SNCR system has not been investigated before. When the furnace chamber flue gas temperature profile changes, the injection points and control strategy of the SNCR systems needs to be revised to maintain sufficient NOx reduction. In the planned measuring campaign some efforts will therefore be concentrated on determining the influence of the humidification system on the SNCR plant operation.

10.2 Research

Ensuring timely development of technologies to relieve the possible negative effects of the resource strategy on WtE facilities will definitely create a competitive advantage for Danish environmental technology in Denmark as well as the wider Scandinavian market, and parts of the European market. Research ensures that the activities are carried out on time with regards to the implementation of the upcoming resource strategy and it is ensured that the development supports the strategies.

By implementing more energy production flexibility this project could also prepare the WtE sector to take active part in the future smart grid where energy production must be driven both very strongly by production but also by energy producers with higher prioritization (RE like e.g.: wind, solar, wave and geothermal).

For further research the following will be the hypothesis:
The optimized CAH system can improve the energy efficiency significantly (several percent) at a co-generation WtE facility without significant loss of neither production availability nor reliability. The CAH system will lead to reduced temperatures in the furnace chamber and thereby influence the operation of the SNCR unit. The SNCR unit can be adjusted without extraordinary costs to counteract the influence of the CAH system.

Present experience transferred from biomass facilities make ground for the working hypothesis upon which a test WtE facility will invests in this system:
The standard CAH system can enable efficient condensation of the flue gas water content by heat exchange with the district heating return although the return temperature is too high for flue gas condensation when humidification is not applied in which case a heat pump would otherwise be necessary. The SNCR unit can be adjusted without extraordinary costs to counteract the influence expected on NOx levels by the CAH because of changed furnace chamber temperature profile.

The standard CAH technology is known from the biomass industry and has with little success been implemented at Waste-to-Energy facilities in Sweden based upon rotating mass technology (Ljungström disc). With modest further development into a wet system where heat transfer is made by contact with separate water circulation systems instead of one rotating mass most of the reported operational problems can be dealt with. The Swedish plants experienced limitations to the amount of humidification the furnace could handle. Releasing the full potential of the humidification system thus requires close integration into the boiler and furnace control systems.

10.3 Full scale testing

An important outcome of this project is that the technology is ready for full scale testing and that no intermediate step is neither needed nor beneficial in any way. A full scale test is very expensive when it comes to equipment and implementation risk but offers test opportunities and results that are unbiased in their results when it comes to evaluating the impact of implementation widely in the market. One drawback however is that the degrees of freedom when it comes to testing the theoretical limitations of the system as the system is expected to operate at max capacity as far as possible (due to size of the investment and consequence for the facility operation).

The objective of the full scale test is to verify the hypothesis by answer the questions:

1. How will thermal load changes influence the efficiency of the CAH facility?
2. What will be the likely maximum performance of CAH at a WtE plant, with acceptable production availability and reliability?
3. Can the energy efficiency and the district heating output be significantly increased with CAH installed at a WtE plant?
4. Will the CAH system lead to boiling problems in the economiser section of the boiler?
5. Can a control loop for the CAH be developed that will satisfy both high energy efficiency and stable energy production in all load points?
6. Should the control of the furnace and combustion air be adjusted for optimum performance (e.g. oxygen level)?
7. Will the CAH dampen temperature variations in the furnace?
8. Can the residence time requirement of 2 seconds at min. 850 °C be complied with at even the most adverse conditions?
9. Will the CAH system change boiler corrosion, erosion and deposits properties?
10. How does the CAH system influence the SNCR system and what may be needed to mitigate the changes?
11. What will be the best mitigation strategy for SNCR optimal performance after introducing CAH?
12. Will the CAH system change the thermal capacity of the furnace/boiler and can changes in boiling and superheating capacity be balanced?
13. How will the CAH system influence environmental performance?
14. Will the CAH system lead to more maintenance costs and will this influence the business case significantly?

The scheduled plant measurements will deal with the following issues:

- Changes in combustion temperatures will be registered with both permanently mounted equipment connected to the CMS system and with transportable diagnostic equipment. This will quantify the primary influence of the humidification system on the furnace chamber conditions.
- Parameters relevant for the de-NO_X SNCR system. Local gas compositions and temperatures will be measured before and after the ammonia injection area with probe equipment. It is believed that the humidification system will have some influence the operation of the SNCR system. The measurements will provide recommendation on how to appropriately compensate for the changes.
- Slag and fly ash collection for further analysis. Analysis of the fly ash to determine if good burn out is still obtained. Also, the Cl content in the fly ash could indicate if changes in fly ash induced corrosion may appear.
- Deposit registration. This will be done by simply making a photo registration on deposit levels in different areas of the plant during boiler outages. Because of the minor changes in the temperature and that the fly ash composition probably is only affected to a very minor degree deposits are believed not to be significantly affected. However, changes in furnace deposit may infringe plant operation and it is therefore important that it is observed.
- Emission level registration (mainly by the CMS system)
- Corrosion monitoring. This will be done by simple inspection when the boiler is stopped
- Monitoring of the humidification units. This will be done mainly by data collection using the CMS system. Furthermore measurements of the water and dust levels before and after the two humidification systems will be done to directly register the primary influence on the flue gas

Analysis of the complete data will include both the measurements done by moveable probes and by analyzing data from the SRO system.

Measuring campaigns:

- Campaign 1 Reference
  Reference measurements without installation of new humidification equipment to establish a base case for reference
- Campaign 2 Basic humidification
  Measurements with the humidification equipment in operation at standard conditions
- Campaign 3 Optimized humidification
  Measurements with the humidification equipment operation.

Operational changes will be investigated such as reduced humidification level and using district heating to stabilize humidity level in the exit flue gas. Before the reference measuring campaign is conducted the *combustion unit* will be modified with extra ports at relevant locations to make probe measurements possible. When the reference measuring campaign is finished the humidification system including SRO connected measuring equipment will be mounted.

The following will be the chronical sequence of events in the research project:

- Project planning, management and initiation
- Planning of measurements, modification of equipment at preparation of the measuring campaigns
- Measuring campaign 1, analysis and interpretation
- Measuring campaign 2, analysis and interpretation of campaign 2.
- Measuring campaign 3, analysis and interpretation of campaign 3.
- Overall results interpretation in collaboration with project partners and comparison with modelling
- Communication in articles and at conferences, conclusions and final project reporting

10.4 Fundraising

While it is clear that research is needed it is also clear that neither suppliers nor facility owners have the capacity to perform the research by themselves. Public funds must be provided to enable further research to avoid lost opportunities for the society and low pace development leading to lost market opportunities. Before the end of this project the Danish EUDP fund for test and demonstration of energy projects was applied for funding.

11. References

Axby, F., Gustafsson, J.-O., & Johansson, J. N. (2000). *Studie av rökgaskondensering för biobränsleeldade kraftvärmeanläggningar (Swedish for 'Study of flue gas condensation for bio fuel fired cogeneration plants").* Värmeforsk-rapport A9-815.

Danish Ministry of the Environment (Miljøministeriet). (2013). *Denmark without Waste (Danmark uden affald).* Copenhagen: Danish Ministry of the Environment (Miljøministeriet).

Environmental Protection Agency of Denmark. (2014a). *Denmark without Wasts, Resource Plan for Denmark 2013-18 (Danmark uden affald, Ressourceplan for affaldshåndtering 2013-2018).* Miljøstyrelsen.

Environmental Protection Agency of Denmark. (2014b). *Waste Statistics 2012 (Affaldsstatistik 2012).* København: Miljøstyrelsen.

J.A. Miller, a. P. (1999). Modeling the Thermal DeNOx Process: Closing in on a Final Solution. *Int. J. Chem. Kinet. 31*, 757-765.

J.A. Miller, C. B. (1989). Mechanism and Modeling of Nitrogen Chemistry in Combustion. *Prog. Energy Combust. Sci. 15*, 287–338.

Jeppesen, J., Hansson, H., & Axby, O. C. (2007). *Legionella i luftuppfuktare (Swedish for 'Legionella in air humidifiers').* Värmeforsk-rapport T06-603.

Oravainen, H. (1998). Flue gas condensing and heat recovery at biomass fired district heating plants. *Euroheat & Power 6, 26*, 28 - 30.

Sarantuyaa Zandaryaa, R. G. (2001). Nitrogen oxides from waste incineration: control by selective non-catalytic reduction. *Chemosphere 42*, 491-497.

Thanh D.B. Nguyena, T.-H. K.-I.-H.-J.-S. (2009). Application of urea-based SNCR to a municipal incinerator: On-site test and CFD simulation. *Chemical Engineering Journal 152*, 36–43.

Zengying Liang, X. M. (2010). Mathematical modelling of MSW combustion and SNCR in a full-scale municipal incinerator and effects of grate speed and oxygen-enriched atmospheres on operating conditions. *Waste Management 30*, 2520–2529.

Development of combustion air humidification at WtE facilities

This project focuses on introduction of combustion air humidification in the WtE industry to generate more energy and prepare the facilities for future challenges introduced due to the increased focus on resource recovery upstream the facility in the waste management system. Combustion air humidification was found as the most energy efficient system in comparison with other alternatives such as waste humidification and water injection into the furnace.

The potential for the technology is great since a major part of the facilities with present flue gas condensation can benefit from the technology and so can a majority of facilities without a present condensation unit but with some district heat production and a higher demand than the production capacity.

Dette udviklingsprojekt har fokuseret på introduktion af forbrændingsluftbefugtning på affaldsforbrændingsanlæg for at øge anlæggenes energieffektivitet og give anlæggene en mulighed for at håndtere fremtidige ændringer af affaldet. Forbrændingsluftbefugtning er blevet sammenlignet med andre metoder så som befugtning af affaldet eller indsprøjtning af vand i ovnen og er blevet evalueret som den mest energieffektive metode til at modvirke effekterne af udsortering af øgede mængder organisk affald.

Potentialet for teknologien er stort, da både anlæg med og uden eksisterede røggaskondenseringsanlæg kan drage fordel af denne teknologi.

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