KTH Industrial Engineering
and Management

Combustion of sludge in Fortum's plants with possible phosphorus recycling

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Abstract

The management of waste is by all means a great challenge to any society. In Sweden, the past decades has seen legislation progressing in congruence with concerns over environmental stress from inefficient waste management. The legislative changes aim primarily to promote waste reduction and better waste utilization. Sludge is a waste-type from different industrial processes and is unfortunately of limited reuse and recycling-value, but sludge combustion for energy recovery appears promising. Also, the oftentimes high phosphorus content in sludge strengthens the potential of extracting phosphorus from combustion ashes.

The heat and power industry has shown great interest in sludge combustion. Fortum has a set of different sludge types to choose from as well as many different options available based on where and how the sludge can be incinerated. Yet there are many inherent problems, but also operational benefits, of combusting sludge. These factors combined make the venture multifaceted and therefore not straightforward. Based on this, this thesis is a preliminary study aiming to assess the possibility of combusting sludge in Fortum's existing or future facilities, along with possible phosphorus recovery from the combustion ashes.

The study was based on applying either sludge mono- or co-combustion. The scenarios evaluated were; firing 70000 tonnes of digested sewage sludge, 50000 tonnes of fibrous sludge and 26400 tonnes of digestate which all are pertinent sludge amounts in this study. Co-combustion involved firing these together with the base fuels fired in Fortum's grate furnace and fluidized bed boilers in Brista and Högdalen CHP plants. The mixing yielded new characteristics of the combustion input, such as a lower heating value, which were vetted against the boilers' capability to handle these. Mono-combustion was compared economically with co-combustion to assess investment profitability. The phosphorus concentration in the ashes from the mixes was determined as well in order to assess the possibility for viable extraction. In addition, proper sludge pretreatment methods were examined.

The results showed that co-incineration of 70000 tonnes digested sewage sludge was possible in boiler P6 in Högdalen and B2 in Brista. These generated an economic gain with an internal rate of return of 96,3 % and 96,4 % respectively. It was possible to co-incinerate 50000 tonnes of fibrous sludge in boilers B1 and B2 in Brista as well as P6 although economic gains were only seen in B1, where the internal rate was 87,5 %. Co-incinerating 26400 tonnes of digestate was possible in all boilers except P3 assuming that the similar boilers P1 and P2 in Högdalen can incinerate the sludge in tandem. The incineration of digestate yielded an economic gain for these boilers with an internal rate ranging from 25,7 % for P1 and P2 in tandem to 102,6 % for B1. Although mono-combustion is a practical solution it was found not to be an economically feasible alternative under prevailing economic conditions.

The results also indicated that NO_x and SO_x formation increased in the raw flue gases when co-firing sludge, as also was the case with flue gas volume flow and flue gas water vapor. Fossil CO_2 emissions decreased for all waste fired boilers when co-combusting sludge. Digested sewage sludge and digestate increased combustion ash amounts in all cases, whereas fibrous sludge only did this in B1. All sludge types were found to be beneficial for reducing the risk of corrosion and agglomeration, but digested sewage sludge was remarkably more so than digestate and fibrous sludge. The phosphorus concentration in the co-combustion ashes was deemed insufficient for viable phosphorus extraction, but was promising when firing digested sewage sludge in B1. The concentration was sufficient in a mono-combustion application when firing digested sewage sludge and digestate. Overall environmental impacts are however dubious. There needs to be further investigation in order to properly assess these.

Sammanfattning

Hanteringen av avfall är en stor utmaning i alla samhällen. I Sverige har lagstiftningen de senaste decennierna utvecklats i takt med ökad oro över miljöbelastningen från ineffektiv avfallshantering. I första hand syftar lagändringarna till att främja avfallsminimering och bättre avfallsutnyttjande. Slam är en typ av avfall från olika industriprocesser och har dessvärre begränsat värde för återanvändning och återvinning, men slamförbränning för energiutvinning verkar lovande. Även den i många fall höga fosforhalten i slam ger en potential att utvinna fosfor ur förbränningsaskorna.

Kraft- och värmeindustrin har visat stort intresse för slamförbränning. Fortum har olika slamtyper att tillgå och många olika alternativ gällande var och hur slammet ska förbrännas. Det finns också problem, men även förbränningstekniska fördelar, kopplat till slamförbränning. Tillsammans gör dessa faktorer satsningen mångfacetterad och därför inte helt självklar. Detta examensarbete är en förstudie som syftar till att bedöma möjligheten att förbränna slam i Fortums befintliga eller framtida anläggningar, tillsammans med eventuell återvinning av fosfor från förbränningsaskorna.

I studien undersöktes slamförbränning, antingen monoförbränning eller förbränning tillsammans med andra bränslen. Scenarierna som utvärderats innefattar förbränning av 70000 ton rötslam, 50000 ton fiberslam och 26400 ton rötrest vilka är relevanta mängder för denna studie. Samförbränning innebär att dessa blandas och eldas tillsammans med basbränslena i Fortums rosterpannor och fluidiserade bäddar i kraftvärmeverken i Brista och Högdalen. Slamblandningen ger upphov till nya egenskaper hos det inmatade bränslet, till exempel ett lägre värmevärde, vilka jämförs mot pannornas kapacitet att hantera dessa. Monoförbränning jämfördes med samförbränning för att bedöma dess ekonomiska konkurrenskraft. Fosforhalten i askan från blandningarna bestämdes även för att bedöma fosforutvinningspotentialen. Dessutom har lämpliga förbehandlingsmetoder för slam undersökts.

Resultaten visar att samförbränning av 70000 ton rötslam var möjlig i panna P6 i Högdalen och B2 i Brista. Dessa gav en ekonomisk vinst med en internränta på 96,3 % respektive 96,4 %. Det var möjligt att samförbränna 50000 ton fiberslam i panna B1 och B2 i Brista samt panna P6 även om ekonomiska vinster bara visades i B1, där internräntan blev 87,5 %. Samförbränning av 26400 ton rötrest var möjligt i alla pannor förutom P3 förutsatt att pannorna P1 och P2 i Högdalen kan förbränna slammet i tandem. Förbränning av rötrest gav en ekonomisk vinst i dessa pannor med internräntor mellan 25,7 % för P1 och P2 tillsammans och 102,6 % för B1. Även om monoförbränning kan vara en praktisk lösning är det inte ett ekonomiskt försvarbart alternativ under rådande ekonomiska förhållanden.

I studien gavs det även indikationer på att uppkomsten NO_x och SO_x i rågaserna ökade vid samförbränning med slam, samt att även rökgasvolymflöde och mängden vattenånga i rökgaserna ökade. Fossila CO_2 utsläpp minskade för de avfallseldade pannorna vid samförbränning. Rötslam och rötrest gav en ökning av mängden aska i alla pannor, medan fiberslam endast ökade denna i B1. Alla slamtyper var fördelaktiga att förbränna för att minska risken för korrosion och agglomerering men rötslam var anmärkningsvärt bättre i det avseendet jämfört med rötrest och fiberslam. Fosforhalten i samförbränningsaskorna bedömdes vara för låg för lönsam fosforutvinning, men var lovande vid rötslamsförbränning i panna B1. Koncentrationen var tillräckligt hög vid monoförbränning av rötslam och rötrest. Det är dock oklart vad den totala miljöpåverkan blir vilket skulle behövas utredas vidare.

Acknowledgement

We would like to thank Eva-Katrin Lindman for giving us the opportunity to work on this project and for all the help and advice she has provided. To be out in the industry and see Fortum from the inside has truly been a fantastic experience. Additionally we would like to thank Mikael Ljung and Per-Eric Jacobsson for showing us the CHP plants in Högdalen and Brista during our study visits. We would also like to thank our supervisor at KTH, Reza Fakhraie, for being patient with us and giving us advice and help in this thesis.

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Nomenclature

Abbreviations

ar	As received
BFB	Bubbling fluidized bed
CFB	Circulating fluidized bed
CHP	Combined heat and power
daf	Dry, ash-free
db	Dry basis
DS	Dry substance
DSS	Digested sewage sludge
Eo1	Light fuel oil (Eldningsolja 1)
ESP	Electrostatic precipitator
WESP	Wet electrostatic precipitator
FB	Fluidized bed
FGR	Flue gas recirculation
GROT	Tree branches and tops (from Swedish "Grenar och toppar")
IRR	Internal rate of return
LFO	Light fuel oil
MSW	Municipal solid waste
NO_x	Nitrogen oxide emissions (NO and NO_2)
O&M	Operation and maintenance
PTP	Paper, wood and plastics (from Swedish "Papper, trä och plast")
PVC	Poly Vinyl Chloride
RDF	Refuse derived fuel
REACH	Registration, Evaluation, Authorization and restrictions of Chemicals
RT-chips	Chipped recycled waste wood (from Swedish "returträflis")
SC	Staged Combustion
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction
SO_x	Sulfur oxide emissions
Tonne	Metric ton (1000 kg)
wt-%	Weight percentage
WtE	Waste-to-Energy
öre	1/100 SEK

Symbols and parameters

α	Alpha value, produced electricity over total energy
$\beta_{bottom,ash}$	Fraction of total ash that becomes bottom ash
$\beta_{P,bottom,ash}$	Fraction of total phosphorus in ash that end up in the bottom ash
ΔAsh	Relative difference in ash, sludge mix over base fuel
$\Delta Ash_{disposal}$	Change in amount of ashes that will need to be disposed
$\Delta Base\ fuel$	Change in amount of base fuel needed for the sludge mix
Ψ	Mixing percentage on total weight basis
η_{boiler}	Boiler efficiency
η_{el}	Generator efficiency
η_{mech}	Mechanical efficiency (electricity generation)

η_{HEX}	Heat exchanger efficiency
Ash_{bottom}	Massflow of ashes ending up as bottom ash
Ash_{fly}	Massflow of ashes ending up as fly ash
C	Total annual costs
$C_{ash\ disposal}$	Total annual costs of disposing $\Delta Ash_{disposal}$ in co-combustion cases
$C_{base\ fuel}$	Annual cost of acquiring $\Delta Base\ fuel$ in co-combustion cases
C_{drying}	Costs for auxiliary drying of sludge
C_{inv}	Total cost of investment
C_{op}	Annual operational costs for a mono-combustion plant
$c_{base\ fuel}$	Per tonne cost for base fuel
$c_{bottom\ ash}$	Per tonne cost for disposing bottom ashes
$c_{fly\ ash}$	Per tonne cost for disposing fly ashes
c_{inv}	Investment cost per tonne of sludge to handle on a yearly basis
DR	Discount rate
e_{CO2}	Fossil carbon emission factor for waste fuels MSW and PTP
$Fossil_{CO2}$	Annual change in fossil CO_2 emission
h_{water}	Heat of vaporization for water
I	Total annual income
I_{DH}	Income from district heat sales
I_{el}	Annual income from electricity sales
I_{sludge}	Annual income/cost from sludge
i_{DH}	Per MWh income for district heating
i_{el}	Per MWh income for electricity sales
i_{P}	Per kg value for phosphorus
i_{sludge}	Per tonne income/cost for sludge
IR	Internal rate
LHV	Lower heating value
m	Mass
$m_{sludge,ar}$	Annual amount of sludge to be received
$\dot{m}$	Massflow
N	Economic lifetime of the investment
NPV	Net present value
P_{drying}	Power required for drying
P_{fuel}	Fuel power
P_{net}	Net power
P_{max}	Maximum phosphorus concentration in the total ash amount
$P_{max,bottom\ ash}$	Maximum phosphorus concentration in bottom ashes
$P_{max,fly\ ash}$	Maximum phosphorus concentration in fly ashes
R	Revenue
R_t	Total revenue year t
t_{op}	Yearly operational time of the boiler
u	Moisture content
V_P	Value of the phosphorus in the ashes
X	Wet mass fraction of a substance
Y	Dry mass fraction of a substance
Z	Component to be mixed on total or dry basis

Subscripts

base fuel	The base fuel for the investigated boiler
dry	Dry basis
mix	Mix of sludge and base fuel
sand	Bed sand for FB boiler
sludge	The investigated sludge
sludge,dried	Sludge after the dryer

1 Introduction

Human activities are affecting our natural environment now more than ever before. Growing public concerns over increasing greenhouse gas emissions has seen a significant surge recently, but much of what shapes energy politics today springs from energy security related concerns. The apprehension stems from the consequences of unsustainable energy systems, which disturb natural ecosystems and have led to alarming climate changes. Derived from this, social and socioeconomic systems may decay if solutions are not found and applied in the near future (Stigka, et al., 2014).

In April of 2013, an article written by a group of 15 environmental experts was published in Dagens Nyheter, one of Sweden's biggest newspapers. In it, they stressed the importance of a resource effective society as one of the most effective ways to reduce environmental impact, stating inter alia that *"The waste management sector also has a unique opportunity to not only reduce their own environmental impact, but also help other sectors reduce theirs through increased recycling and reuse."* (Finnveden, et al., 2013, English translation by Anton Marmsjö).

Waste management and heat and power production are in some aspects joint ventures where many waste products are combusted to produce heat and power. Though simultaneously, many are not. Amongst others, sludge from biogas production (digestate), sewage treatment plants and the pulp and paper industry (fibrous sludge) are potential combustible wastes whose current uses are not always ideal from a "closed-loop society" perspective. At present, large volumes are used as a final cover of landfill sites, but also for agriculture fertilization, for soil improvement etc. since they are often rich in soil nutrients. Granted, reusing and recycling for crop growth purposes are activities perhaps more desirable than combustion, but energy generation is preferred over any form of depositing.

Current trends indicate that the volume of produced sludge will increase in the future, primarily in the form of digestate from biogas production. Coupled with stricter farmland spreading and depositing regulations, sludge combustion will most likely become more and more common. Furthermore, the ability to extract plant-beneficial phosphorus from sludge combustion residue ashes reinforces this notion. In this way, sludge may be a source of energy as well as a source of phosphorus which is very beneficial, exploiting its usefulness to a high degree.

However, there are problems inherent with handling and combusting sludge that are significant. It is not clear how sludge moisture removal is handled best, nor is it evident which combustion methods are most advantageous, whether it be mono-combustion or co-combustion with other fuels. Methods for ash-phosphorus extraction are also not straightforward. This combination of moisture removal, combustion and phosphorus-extraction surely is unique from case to case. Finding feasible solutions to these issues is imperative to achieve a technically, economically and ecologically sound system of sludge pretreatment and combustion coupled with phosphorus extraction.

Fortum is one of the largest providers of heat and power to the greater area of Stockholm with a primary energy matrix featuring a high proportion of renewable energy sources. Recently, the company has gotten requests from the waste management sector of receiving and combusting sewage and fibrous sludge. A new biogas plant is under consideration as well, which would produce digestate for eventual combustion. With promising economic potential and in accordance with the company's ambition of strong competitiveness concerning environmental issues, a number of projects were set into motion, one of which is this thesis.

The main objective of this thesis is to assess the possibility of a technically, economically and ecologically feasible system of handling sludge. The study aims to provide a foundation which will recommend the best system for sludge pretreatment, combustion and phosphorus extraction based on Fortum’s conditions in Stockholm.

1.1 Objectives

The objectives of this thesis are to:

- Study different methods to combust sludge
- Study how Fortum's existing facilities in Stockholm can be used to combust sludge
- Study the possibility to recycle nutrients, primarily phosphorus, from sludge combustion ashes either by direct spreading on cropland or phosphorus extraction
- Develop a foundation that will aid in assessing the best method for pre-treatment and combustion of sludge, as well as assessing the possibility to recycle nutrients, particularly phosphorus. This will be discussed with regard to technical, economic and environmental impacts.

1.2 Method

To meet the objectives, a study of relevant information is performed and presented on sludge pretreatment, combustion and phosphorus extraction. Pretreatment will include drying and dewatering and combustion will be studied based specifically on two boiler types; fluidized beds and grate furnaces. Information on phosphorus extraction will be derived from available studies on the subject keeping in mind the commercial availability of the technologies.

Then, experiences on sludge treatment will be obtained from case studies on sludge handling and interviews with knowledgeable persons. This will be necessary since this is a theoretical study, that is, it does not include a separate experiment. This will make clear what aspects are important and how applicable they are to this case. Based on this knowledge, potential solutions will be assorted, discarding unfeasible solutions and testing attainable ones for viability.

The feasible solutions will be subjected to tests for technical viability, economic and ecological effects based on Fortum’s conditions in Stockholm.

1.3 Limitations

A number of limitations have been set for this work.

- The study is limited to the grate furnaces and CFB boilers at Högdalen and Brista.
- The fuels looked upon are MSW, PTP and biomass relevant for Högdalen and Brista. The sludge types used are from Himmerfjärdsverket sewage treatment plant, Holmen paper in Hallstavik and a biogas plant in Anneberg. These are considered representative of the types available to Fortum.
- The system boundary is limited to the reception of the sludge at the plant, sludge pretreatment, combustion and subsequent handling of the ashes. That is, any considerations falling outside of this system boundary, e.g. transports, prior or following treatment of material etc. will not be addressed.
- Spreading the sludge directly on farmland is not investigated in this thesis.
- The content of metals in the sludge mix will be calculated. Some of these will comprise the basis on which further evaluation will be done in the study. The metals of which the effects are not investigated are Hg, Pb, Zn, Cr, Ni and Cu but they can be used to evaluate the ashes’ quality.
- Some data used in the study has been excluded in the report for confidentiality reasons.

2 Background

In this chapter a literature review is presented. Topics which have been studied include boiler types, fuels, operational issues and flue gas cleaning processes. Additionally, information regarding sludge and different sludge types, sludge drying and dewatering and nutrients in sludge was gathered. Other relevant information on sludge incineration is presented as well.

2.1 Boilers

The conversion between the chemical energy of a fuel to useful energy such as heat and electricity is commonly done in an intermediate combustion process. These processes require boilers where chemical energy is converted into thermal energy in the furnace. This form of energy can be used directly, for example for space heating, or for further conversion to electricity using a steam turbine and a generator. For heat and power generation many different designs have been developed over the past centuries, each with its own distinct characteristics. The types relevant to this study will be discussed in this section along with typical boilers used for sludge combustion.

2.1.1 Fluidized bed

Fluidized bed, FB, technology was initially developed in the first half of the 1900s for other purposes than for generating energy. In the late 1920's it was developed as a method for gasifying lignite, and the technique was later on used for catalytic fracking of petroleum (photomemorabilia.co.uk, 2014). However, the modern day conventional use of fluidized bed combustion for energy production was first introduced in the 1970's and is today very common for both heat and power generation (Laboratory of Energy Engineering and Environmental protection, 2003).

The technology works according to the principle based on fuel-gas mixing using an inert bed material consisting of a layer of sand or sand-like media to which the fuel is injected. Combustion air is passed through the sand layer from the bottom, and the fuel is mixed with the bed material and combusted in the furnace. At a certain combustion air velocity the bed material starts behaving like a fluid, initially starting to bubble, and if the velocity is increased the bubbling becomes more energetic. At even higher air velocities the bed particles movement becomes very turbulent and are carried high above the material bed inside the furnace. At sufficiently high velocities it is necessary to recirculate particles carried away from the bed. This is especially the case with CFB boilers, explained in more detail in section CFB below (Laboratory of Energy Engineering and Environmental protection, 2003). The relative velocity between the air and bed particles, or slip velocity, will also increase as the air is passed at higher speeds until it reaches the transport phase where the gap starts to diminish (Martin, 2013). In Figure 1 the effects of air velocity on the bed material can be seen.

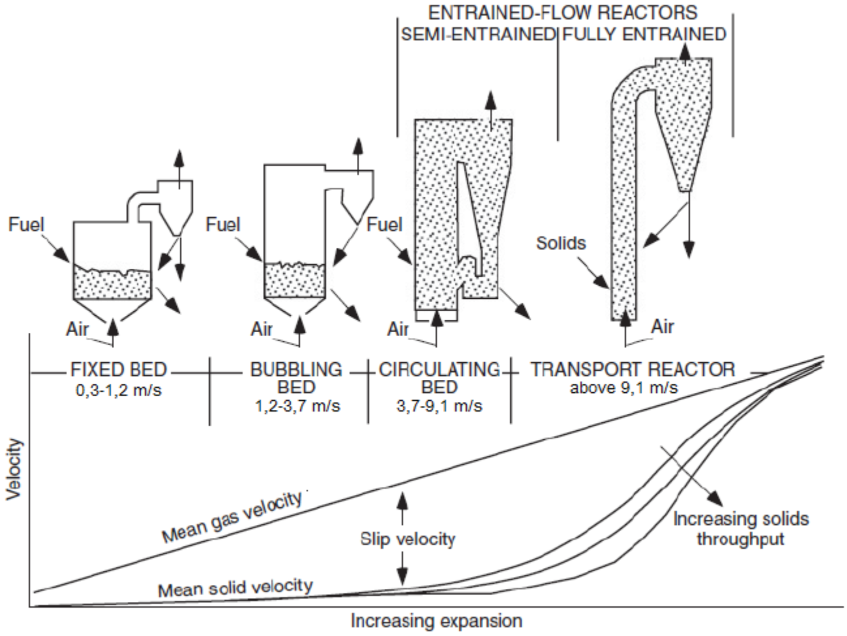


Figure 1: The effects of increased air velocity in a fluidized bed (Martin, 2013).

Fluidized bed boilers have several merits (Laboratory of Energy Engineering and Environmental protection, 2003) (Basu, 2006):

- Relatively low combustion temperature (800-900 °C) which reduces NO_x emissions (but increases N_2O emissions)
- High fuel flexibility; many different fuels can be combusted
- Allows for efficient control of SO_x emissions; desulfurization is made possible by injecting limestone into the bed material
- Wide range of acceptable fuel particle sizes which bypasses the need for preemptive fuel pulverization
- High combustion efficiency

The vivid movement of the bed material presents several benefits. It ensures a good mixing of air and fuel, as well as enhances the heat transfer in the combustion process, resulting in higher combustion efficiency and an even bed temperature distribution (Thermopedia, 2010). This also helps to reduce NO_x emissions since the bed normally does not have any “hot spots”. The bed material will also, as it scrubs the fuel particles, remove CO_2 and char which normally establish around the particles. This will enhance the efficiency and the rate of the combustion process as oxygen more easily can reach the combustible material (ASME, 2012).

BFB – Bubbling fluidized bed

Bubbling fluidized beds (BFB) are FB type boilers where the combustion air is kept at such a velocity to cause the bed material to bubble but still have a well-defined surface level. Little or no particle recirculation of bed material is generally needed. BFB boilers can be divided into three sections: bed, freeboard and backpass or convective section, shown in Figure 2. In many cases, particularly for deep bed BFBs, heat transfer surfaces are embedded in the bed which ensures efficient heat transfer. As much as 40-55 % of the total heat transfer from the boiler can be achieved in such cases. However this also increases the risk of erosion on these surfaces. Heat transfer surfaces are also found in the freeboard section and the backpass section (Statens energiverk, 1987) (Basu, 2006).

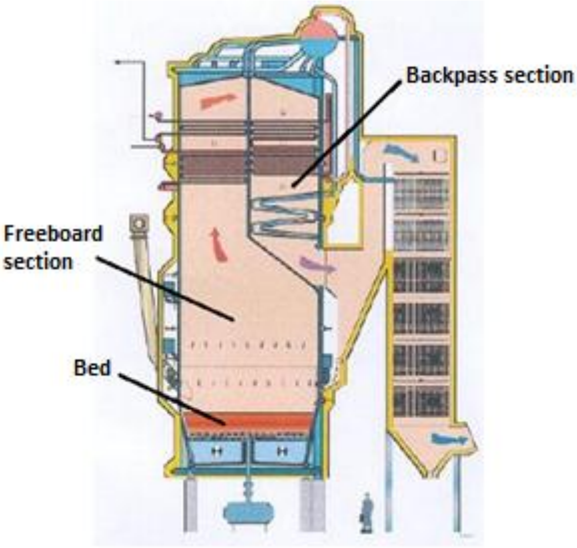


Figure 2: A Foster Wheeler BFB boiler (Eija & Flyktman, 2001).

CFB – Circulating fluidized bed

CFB technology involves a recirculation of particles in the furnace carried away with the combustion air back to the bed during operation. Like a BFB, the incoming combustion air fluidizes the bed material but the air velocity is greater, causing some of the bed material, combusted particles and ash to be transported away from the bed with the airflow. To avoid depletion of the bed material and hinder larger particles from going into the flue gas cleaning system a cyclone is adopted. The cyclone is essentially a gas-solid separator which separates larger particles from the flue gases. The larger particles are returned to the bed for further use, either for completing combustion (fuel particles), to restock the bed (bed material) or for rejection (bottom ash). The flue gases are sent to the flue gas cleaning system. The principal components of a CFB are shown in Figure 3.

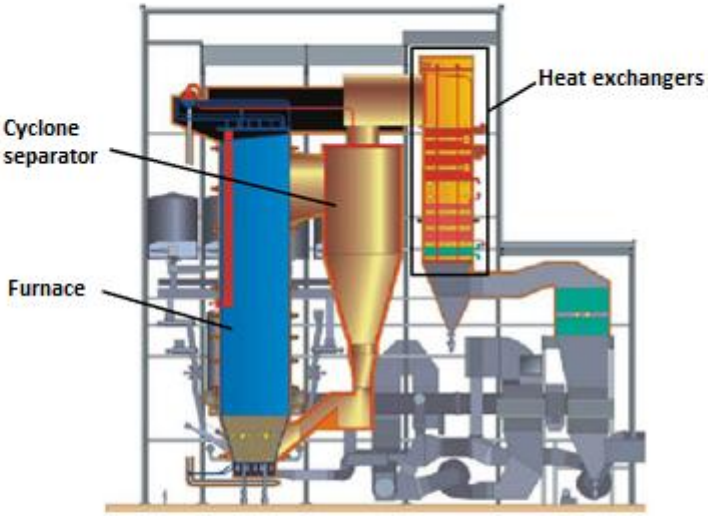


Figure 3: Alholmens Kraft's CFB boiler in Pietarsaari, Finland (Laboratory of Energy Engineering and Environmental protection, 2003).

What characterizes CFB boilers is that they have a higher grate heat release rate, 3-4,5 MW/m^2, compared to BFB which feature the range of 0,5-1,5 MW/m^2. This effectively means that they have a smaller grate area for a given thermal output, making it more compact. A smaller grate area, along with better mixing and an extended combustion zone also means that the boiler requires fewer fuel feed points. CFB boilers are less sensitive to load changes than BFB boilers due to easy control of heat absorption, and they generally feature a shorter startup time than pulverized coal fired boilers. Heat exchangers (economizers and superheaters) can also typically be found downstream in the flue gas flow after the cyclone (Basu, 2006).

2.1.2 Grate furnace

Since the beginning of industrialization the grate furnace has been the most common method for burning solid fuels. Grate furnaces are usually built with a nominal heating power within the range 15 kW to 100 MW (van Kuijk, 2008) (Laboratory of Energy Engineering and Environmental protection, 2003). The majority of the plants combusting MSW in Sweden utilizes grate furnace boilers (Gyllenhammar, et al., 2013).

Grate furnace boilers work by the principle that fuel is supplied onto a grate where the combustion takes place. The grate is designed so that the fuel is transported over its extension where the fuel's volume gradually decreases during the combustion process. The fuel volume decrease occurs in three steps. Firstly, the moisture in the fuel is evaporated i.e. the fuel is dried. Secondly, a pyrolysis takes place and the volatile matters released are combusted. Finally the remaining char is combusted on the grate. The necessary heat for the three steps is taken from the preheated combustion air and the heat in the boiler. At the end of the grate all fuel should ideally be converted so that ash and other inert materials are the only remains. This residue, which nevertheless also contains unburnt fuel from the combustion process, is then brought out from the boiler (van Kuijk, 2008) (Laboratory of Energy Engineering and Environmental protection, 2003).

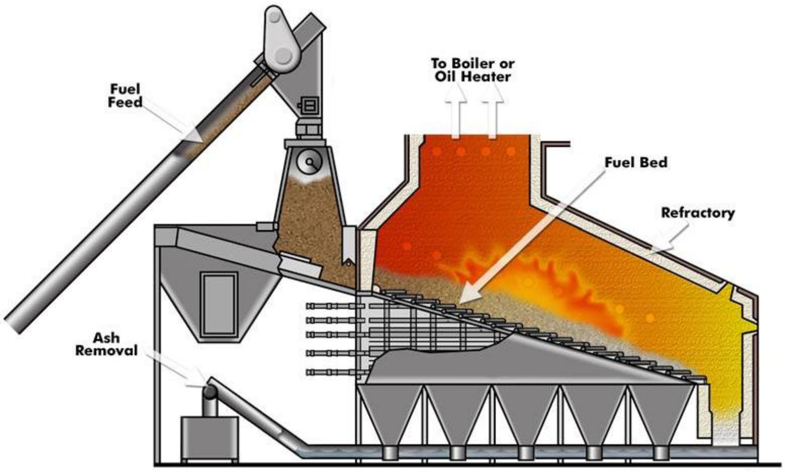


Figure 4: A schematic diagram of a sloped grate furnace for biomass combustion (Wellons Fei corp, 2012).

To assure that the fuel is transported along the grate different designs can be employed. The grate can be sloped or horizontal. One type of horizontal grate, called a traveling grate, is constructed as a conveyor belt which continually transports the fuel as it combusts until it reaches the ash removal system in the furnace. A sloped grate can rely on gravity to transport the fuel but often a type known as a moving grate is used. This type of grate is designed as a set of stairs where some of the stairs are fixed and the others are moveable. By translating the movable steps they push the fuel forward and downward along the grate. The grate can also be constructed so it is vibrating and thereby aiding the sliding of the fuel on the slope. In Figure 4 the layout of a biomass fired sloped grate furnace is depicted. For all different types of grates the primary air is supplied from beneath through the fuel bed and secondary air is supplied above the fuel bed to ensure burnout of the volatile gases emitted from the pyrolysis (van Kuijk, 2008) (Laboratory of Energy Engineering and Environmental protection, 2003).

2.1.3 Boilers for sludge combustion

Co-firing of sludge is commonly applied using both FB technology and grate furnaces. Mono-firing on the other hand is virtually uniquely allotted to fluidized bed boilers (PURE, 2014). But there are instances where other types of boilers are utilized. Most common for sludge combustion are multiple hearth and rotary kiln furnaces.

Multiple hearth furnaces are constructed as cylinders, and as the name implies consists of several circular hearths stacked onto each other. The fuel is supplied from the top and a vertical rotating shaft mounted in the center of the furnace equipped with rubble arms stir and move the fuel on each hearth. The fuel is pushed, alternately inwards and outwards, towards openings on each hearth and falls down to the next one. As the fuel travels downward in the furnaces; drying, pyrolysis, char combustion and ash cooling takes place. The ashes are then extracted from the bottom of the furnaces (FGC Group LLC, 2010). A schematic diagram of a multiple hearth furnaces can be seen in Figure 5.

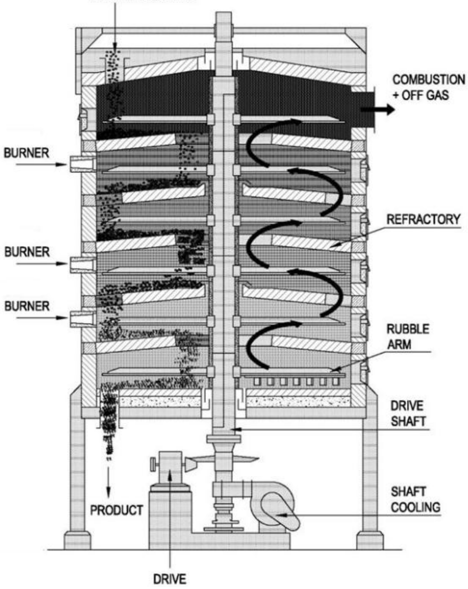


Figure 5: A schematic diagram of a multiple hearth furnace (Aselaide Control Engineering, 2013).

Rotary kiln is another furnace type that has frequently been applied for sludge combustion in Japan and is to a great extent utilized in cement production plants today. The high temperatures that can be achieved in the kilns can also be used to destruct medical wastes. The kiln is designed as a steel tube lined with fireproof ceramics. The tube is slightly sloped and rotates at a slow pace. The inclination and the rotating movement ensure material to be turned and conveyed from the inlet in the upper part to the outlet. The input material depends on what the rotary kiln is used for e.g. when producing cement the raw material is calcium carbonate and silica-bearing materials. The input material is heated to its sintering temperature and the product at the outlet is cement. The fuel, often pulverized coal, is blown into the center of the lower part of the kiln thus producing a large concentric flame inside the tube (Özek Makina, 2014) (Werther & Ogada, 1999). Sludge can be fed into the kiln with other raw materials to be captured in the product or fed alone into the furnace to reduce the volume of the sludge. The layout of a rotary kiln plant can be seen in Figure 6.

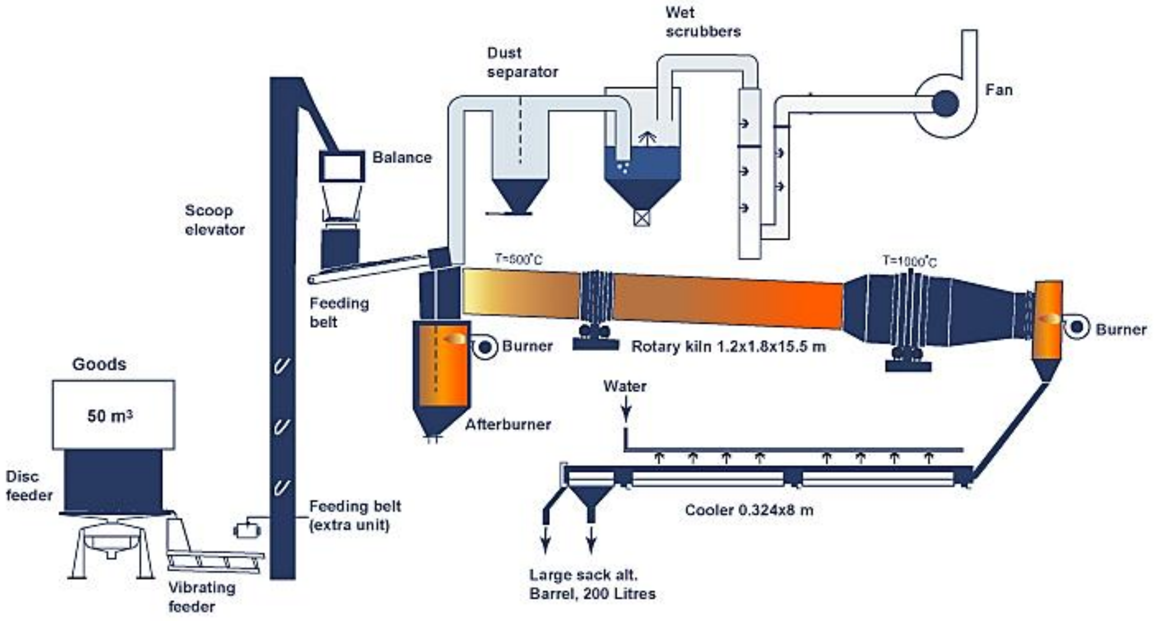


Figure 6: Layout of a rotary kiln plant from Minpro AB (Minpro AB, 2014).

In this study the choice of boiler for mono-combustion of sludge will be a fluidized bed since commercially available systems are predominately based on FB boilers.

2.1.4 Operational issues concerning boilers

Certain fuels can be troublesome due to the creation of chemical substances which cause wear and tear and can damage the boiler and heat transfer surfaces. Corrosion, erosion, fouling and deposits, slagging and agglomeration are recurrent issues.

There are two types of corrosion; low temperature and high temperature corrosion. Low temperature corrosion occurs at 100-150 °C and is caused primarily by sulfur compounds. High temperature corrosion can be induced by chlorine and sulfur compounds, metals such as lead, zinc and tin, as well as caused by oxidation (Svedenkrans, 2000).

Problems can also occur from fouling and deposits which arise when ash is collected on heat transfer surfaces. Collected deposits on surfaces exposed to predominately radiant heat are called slagging. These issues along with corrosion originate from the fuel ash and contents of sulfur and chlorine which ease the movement of alkali compounds. Among the alkali compounds, potassium and sodium form alkali silicates that melt at temperatures lower than 700 °C. The melted silicates act as an adhesive, thus increasing the depositions formed on surfaces. Biomass in general contains more inorganic material, where potassium and sodium is included, than for example coal. More inorganic material can increase the occurrence of fouling, slagging, depositions and corrosion (Saidur, et al., 2011).

Agglomeration is the sticking together of individual particles to one another to form a mass. Concerning FB, specifically two cases are relevant risks; the fusing together of bed particles at high temperatures, called sintering, and agglomeration caused by matter found in certain fuels (Khan, et al., 2009). Agglomeration is essentially a result of salts of potassium and phosphorus which melt at low temperatures and/or when silica in the FB bed material and calcium in fuel react to form a mass. The accumulated masses in the bed material eventually cause defluidization. Also, ashes rich in potassium can react with the bed material and cause agglomeration. It is therefore desirable to capture the alkali compounds or hinder the development of alkali silicates to protect the boiler. This is often done by using additives which raise the melting point of the alkali ashes. Additives used to prevent fouling and agglomeration are; dolomite limestone, lime, alumina, kaolinite or even sludge. The alkali materials will then react with the additive instead of chlorine which is beneficial due to the higher melting point of the compound (Saidur, et al., 2011). Agglomeration can naturally also occur in grate furnace boilers but the effects are not equally alarming.

Erosion is generally an issue coupled with higher combustion temperatures. Temperatures in FB boilers are relatively low, but an unfortunate consequence from using fine grained bed materials is the impact of particles on sensitive surfaces when the bed is in movement. This is however a more pressing issue when the air velocity is high (Statens energiverk, 1987). In any case, boilers are in general prone to erosion caused by the movement of particles, e.g. fuel ash, which grinds down sensitive surfaces. However, as discussed in sections 2.1.1 and 2.5.1, erosion may also be beneficial as it can erode unwanted coatings on surfaces and also scrub fuel particles for more efficient combustion.

2.2 Flue gas cleaning

One important process in an incineration plant is the flue gas cleaning system. Concerns over air quality in human settlements has historically been the driving force to adopt flue gas cleaning systems, and more recently, the recognition that greenhouse gases has a devastating effect on the environment. From an industry perspective the accumulated governmental regulations on emissions have steered further development of flue gas cleaning technologies. Common techniques that are used in Fortum's plants are presented below.

2.2.1 Nitrogen oxides (NO_x) reduction systems

Selective Non-Catalytic Reduction (SNCR), Selective Catalytic Reduction (SCR) and combustion based approaches such as staged combustion (SC), flue gas recirculation (FGR) and reburning are recurring techniques for NO_x reduction.

SNCR takes place in the furnace. Dry urea or ammonia as reductive agents is directly injected into the furnace, which reacts with the nitrogen oxide at 900-1050 °C to form nitrogen and water vapor. SCR takes place in a catalyst at 200-400 °C further downstream of the flue gas cleaning process. It must be installed after systems which remove particles and acidic gases in the flue gas cleaning chain. A mixture of ammonia and air is injected in the flue gas stream and reacts with the nitrogen oxide, producing water and nitrogen (Wtert, 2010).

SC entails combustion in essentially two zones. The first zone, being located below the second zone in the furnace, is where the combustion starts. In the first zone, rich combustion (deficit of air for stoichiometric combustion) takes place. The rest of the combustion air is introduced for complete fuel consumption in the second zone. The deficiency of combustion air in the first zone allows NO_x to react with unburnt hydrocarbons in the fuel, and the cool temperature of the second zone counteracts the formation of NO_x as well. Reburning is in essence SC applied after an ordinary combustion stage, however it may use a different fuel than the main fuel. FGR entails a portion of the flue gases to be led back to the furnace and mixed with secondary air entering the wind box. This lowers the flame temperature, diluting the oxygen and reducing NO_x formation (US Environmental Protection Agency, 2000).

2.2.2 Particle removal systems

The purpose of particle removal systems are, as the name suggests, to remove particles from the flue gases. Prevalent systems include cyclones, electrostatic precipitators (ESP), and fabric filters. In cyclones, the flue gases are swirled in a tube, forcing high inertia (high mass) particles to the wall and low mass flue gases to swirl near the center. The low mass flue gases exit through an opening in the center of the tube, and the large particles are collected in the bottom. ESPs electrically charge the particles in the flue gases using high voltage, which then move towards the precipitation electrode. After the process is finished, the electric charge is suspended and the particles are removed from the precipitator. Fabric filters use the same principle as vacuum cleaners. The flue gases are passed through fabric material where particles will be suspended and the remaining flue gases pass through (Wtert, 2010).

2.2.3 Scrubbers

The particle removal system precipitates solid particles from the flue gas stream but cannot hinder gaseous matter. To remove the gaseous contaminants the principles of absorption or adsorption are used i.e. transforming the reactants to nonpolluting products or capturing the pollutants on an additive respectively. Acidic and alkaline pollutants from the combustion process are evaporated and follow the flue gas. To remove these pollutants along with SO_x, mercury, dioxins and furans gas scrubbers are often used. Scrubbing can be done in three ways; wet, wet-dry and dry scrubbing (Wtert, 2010).

In wet scrubbers the flue gases are lead through or sprayed with water or hydrogen peroxide. The liquid can also contain a reagent if certain molecules are of interest to be cleaned out. The flue gases are exposed to a sufficient amount of scrubber liquid to saturate the flue gas stream. The scrubber solution is then exhaled from the cleaning system as a liquid for, if necessary, further cleaning (Wtert, 2010).

Wet-dry scrubbers utilize an aqueous absorption agent which is sprayed into the gas stream. The difference from wet scrubbers is that the gas stream is not saturated. When the water evaporates the pollutants in the flue gas react with the agent to form solid particles. The particles can then be separated from the stream with a filter or equivalent (Wtert, 2010).

A dry scrubber does not incorporate water in the process. Instead a dry and fine powder is added to the flue gases. The pollutants in the flue gases react with the powder and forms solid products, which can then be precipitated in a filter. The absorption agent is often lime and sodium bicarbonate. Lime is often used to reduce the SO_x content in the flue gas (Wtert, 2010) whereas activated carbon can be used to remove mercury, dioxins and furans (Chemviron Carbon, 2013).

2.2.4 Additional desulfurization for FB

SO_x reduction techniques described above can be applied to many types of furnaces. However, a method specific to fluidized bed boilers makes further desulfurization possible. A direct injection of lime into the bed (at a calcium/sulfur ratio of 1-3) will ensure a calcium surplus and achieve 80-95 % sulfur removal, where CFBs feature higher desulfurization efficiencies. The drawback of lime-injection is a larger ash amount (Bajpai, 2010).

2.2.5 Flue gas condensation

Flue gas condensation is primarily used to recover heat from the flue gases when combusting fuels with high moisture content. The condenser is used so that the latent heat energy emitted during condensation of the water vapor in the flue gases is recovered for heating purposes, often district heating. The flue gas condensation can also fulfill the purpose of removing pollutants from the flue gases. At temperatures around 200-300 °C dioxins condensate and are removed from the flue gases. Vitriol is also separated at temperatures around 110-170 °C. The water starts to condense at around

40-80 °C. Simultaneously, water soluble gases such as hydrochloric acid and mercuric oxide condensate, which cleans the flue gases further (Statens Energiverk, 1991). The flue gases will leave the condenser at a lower temperature and with a reduced amount of pollutants.

2.3 Fuels

The composition of a fuel, in general, is made up of moisture, ash, char and volatiles. All four make up the total substance. The dry content of the fuel, i.e. the total substance discounting the moisture, is denoted as the dry substance (DS). Excluding ash from the dry substance, the remaining volatiles and char constitutes the combustible substance, which is denoted as daf (dry and ash free).

The primary energy source i.e. the fuel used to produce heating and power in a combined heat and power plant can vary. It depends on several factors such as what technology is used in the plant, e.g. if the boiler is of fluidized bed or grate furnace type, as well as the availability and price of different fuels in the country or region the plant is operating in. The choice of fuel can also be affected by pertaining rules, regulations, taxes and other policy instruments.

In Sweden energy- and CO_2-taxation have been adopted to increase the cost of, and thus reduce the use of, fossil fuels for heat and power generation. There are excise duties put on electricity and fuels, on carbon dioxide and sulfur emissions and a levy system is also used for nitrogen oxide emissions. The use of untaxed biofuels has substantially increased since the taxes were introduced in the beginning of the 1990s (Government Offices of Sweden, 2012). In the following chapter fuels that are used today in Swedish CHP plants are presented. The main focus will be on the fuels that are used in Fortum's plants today.

The Swedish policies regarding energy related emissions consist of, as mentioned, different taxes and fees. For different fuels the energy tax and the excise duties vary. The taxes that applied 2013 for some fuels can be seen in Table 1 below.

Table 1: Taxes for different fuels in Sweden 2013 (Energimyndigheten, 2013).

	Energy tax	CO_2-tax	Sulfur tax	Total tax	Total tax öre/kWh
Heating oil SEK/m^3 (<0,05 % sulfur)	817	3093	0	3910	39,3
Heavy fuel oil SEK/m^3 (0,4 % sulfur)	817	3093	108	4018	37,9
Coal SEK/tonne (0,5 % sulfur)	621	2691	150	3462	45,8
LPG	1050	3254	0	4304	33,6
Natural gas	903	2316	0	3219	29,2
Crude tall oil SEK/m^3	3910	0	0	3910	39,9
Peat SEK/tonne 45 % moisture (0,3 % sulfur)	0	0	49,5	49,5	1,8

The figures in Table 1 are based on the general tax for different emissions and the fee for nitrogen oxide emissions. The levels applied in 2013 can be seen in Table 2.

Table 2: General energy related tax levels and fees 2013 (Energimyndigheten, 2013).

	Cost (SEK/kg)
Carbon dioxide tax	1,1
Sulfur tax	Coal and peat 30 Oil 27 (for every 10 wt-% sulfur content)
Nitrogen fee	50

2.3.1 Biomass and biomass derived fuels

Biomass in an ecological sense refers to material derived from living plants or animals. The accumulation of biomass in plants originates from photosynthesis. In energy conversion, biomass is often referred to as plant based material which can be utilized for energy production. There are also liquid and gaseous fuels which are derived from biomass, such as biogas and ethanol, often such fuels are referred to as biofuels.

In many developing countries people still rely on biomass, essentially wood from trees and bushes, as their main source of energy for cooking and lighting purposes. These uses are however a rare sight in industrialized countries. Biomass as an energy source was more or less abandoned on behalf of electricity produced from petroleum based fuels and coal. Today environmental issues regarding fossil fuels are, yet again, slowly shifting the energy matrix towards increased biomass utilization. The main difference today is that all kind of fuels derived from biomass are of interest, not only wood (Klass, 1998).

Table 3: Comparison between biomass and other fuels (KTH Department of Energy Technology, 2009).

Fuel	Water content %	MJ/kg	kWh/kg
Oak-tree	20	14,1	3,9
Pine-tree	20	13,8	3,8
Straw	15	14,3	3,9
Grain	15	14,2	3,9
Rape oil	-	37,1	10,3
Hard coal	4	30 - 35	8,3
Brown coal	20	10 - 20	5,5
Heating oil	-	42,7	11,9
Bio methanol	-	19,5	5,4

Table 3 shows the heating values and moisture contents for different biofuels and fossil fuels. Non-refined biomass has a lower energy content and also a higher moisture content compared to the fossil fuels, though some refined biomass based fuels such as rape oil have heating values of the same magnitude. It may, at first sight, seem like biomass is not an obvious alternative to conventional fossil fuels for heat and power production. Yet, the carbon neutral characteristic of biomass is a factor which suppresses the heating value difference in favor of mitigated climate change. Also, as is the case in Sweden, tax reliefs are often in place to encourage extended utilization of biomass. In this study the main focus is on the woody biomass fuel combusted at Brista CHP plant.

Table 4: Compositional analysis of the biomass fuel used at Bristaverket (Herstad Svärd, 2014).

Biomass fuel Brista		
Proximate analysis		
Moisture	wt-%	47,4
Ash	wt-% (db)	2,5
HHV daf	MJ/kg	21
HHV ar	MJ/kg	10,8
LHV daf	MJ/kg	19,6
LHV db	MJ/kg	19,1
LHV ar	MJ/kg	8,9
Ultimate Analysis		
C	wt-% (db)	50,5
H	wt-% (db)	5,97
N	wt-% (db)	0,33
S	wt-% (db)	0,02
O	wt-% (db)	40,54
Cl	wt-% (db)	0,11
Ash and trace elements analysis		
Lead, Pb	mg/kg (db)	0,94
Cadmium, Cd	mg/kg (db)	0,23
Copper, Cu	mg/kg (db)	2,69
Chrome, Cr	mg/kg (db)	3,38
Mercury, Hg	mg/kg (db)	0,02
Nickel, Ni	mg/kg (db)	0,91
Zinc, Zn	mg/kg (db)	62,6
Potassium, K	mg/kg (db)	1736
Sodium, Na	mg/kg (db)	182
Calcium, Ca	mg/kg (db)	5013
Phosphorus, P	mg/kg (db)	280

In Table 4 above a mean chemical composition of several fuel samples from Brista CHP is shown. More specifically the fuel consists of forest residues (GROT) and stem wood chips which Fortum pays for to acquire. It should also be mentioned that the composition of such a fuel varies depending on where the biomass was harvested as well as the type of trees used. The composition also depends on which parts of the tree that are used. For example, using either the stem or branches and tops will give slightly different compositions and heating values (Tilli, 2003). The moisture content of woody biomass varies between species, age and tree parts but generally around 50 % of the living tree is water (Werkelin, et al., 2005). The utilization of biomass fuels entails advantages and disadvantages compared to conventional fuels i.e. coal and oil (Saidur, et al., 2011):

- Advantages
    - Commonly low content of ash, C, S, N and trace elements.
- Disadvantages
    - Commonly high content of moisture, Cl, K, Na and low energy density.

Biomass can cause problems in boilers due to the high content of Cl, K and Na according to the reactions described in section 2.1.4. But also since biomass generates ash rich of potassium which reacts with the bed material in FB boilers, agglomeration is a problem occurring from biomass combustion (Saidur, et al., 2011).

2.3.2 Municipal solid waste – MSW

Municipal solid waste (MSW) denotes the waste type discarded from the public and industries in their everyday activities. Since societies differ from each other according to economic activity, location, living habits etc. the composition of MSW will often be location-specific.

The incineration of MSW has for a long time been applied as a practical way to deal with the large volumes of unwanted waste. This view on waste management was gradually revised as it was realized that it often contained recyclable materials and matter that was unhealthy to incinerate. Waste was thus divided, extracting materials for reuse, recycling, further treatment, incineration and landfill-depositing. It was also realized that MSW incineration could be used to generate useful energy, which today is a widespread practice. For example, a large share of the energy to Stockholm's district heating network is supplied by incinerating MSW in Fortum's CHP plants. However it must be said that waste has become subject to export, where it is often sent to countries with excess incineration capacity. For this reason, there may not always be a clear link between the MSW produced and the MSW incinerated at a given location.

A study was carried out by Avfall Sverige (2012) to determine the composition of MSW used for incineration at seven geographically spread combustion plants in Sweden. As can be expected, the analysis showed that although the fuel type is the same, they varied not only from plant to plant, but also between samples of the fuel taken. One plant under study was Fortum's CHP plant in Högdalen, described in more detail in section 2.4.1. The primary fractions that the waste was composed of in their study are shown in Figure 7.

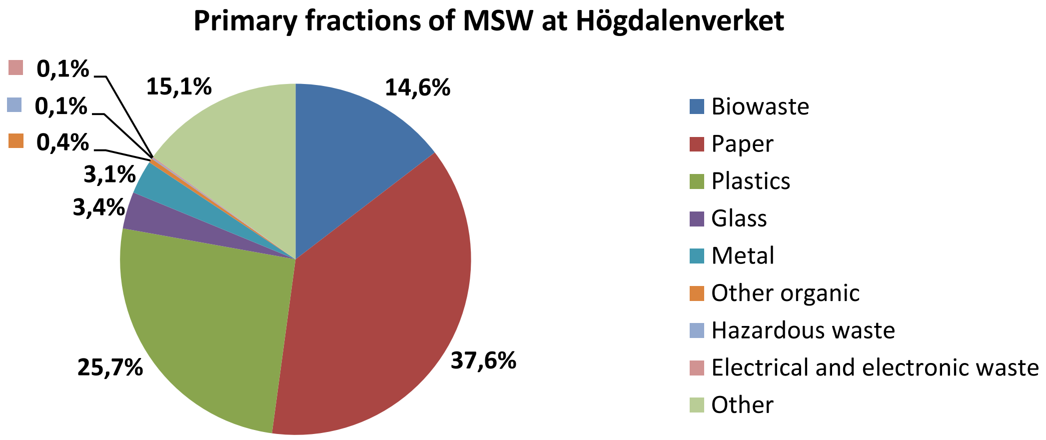


Figure 7: Primary fractions of MSW at Högdalenverket in Stockholm (Avfall Sverige, 2012).

Table 5 shows the analysis results of six fuel samples, calculated as a mean, from Högdalenverket analyzed in their study.

In addition, the table shows the composition of typical food waste found in MSW and also a resulting composition of MSW where the food waste has been separated for a prospective biogas plant, see more in section 2.4.1. This is based on the separation of 31000 tonnes of food waste annually for biogas production from the ordinary waste stream to Högdalenverket's boilers P1-P4 (Gustafsson, 2014). The total flow to these boilers amounts to ca. 444000 tonnes domestic waste plus 118000 tonnes industrial waste per year (Fortum, 2013). The food waste therefore corresponds to ca. 5,5 % of the total MSW amount. The increased heating value, albeit not much higher, means that the boilers would be able to operate with a lower MSW throughput for the same power output, but at the same time one of the boilers may have to accommodate the biogas byproduct digestate for incineration. Aside from an increased heating value the composition of the MSW is not affected to a high degree. Summarized, a slight increase of the metal and ash content and a decrease of moisture can be seen. Considerations such as these apply only to grate furnaces boilers at Högdalen and are necessary to consider only if the biogas facility will be built.

Table 5: Mean compositional analysis of MSW incinerated at Högdalenverket, food waste and a subsequent calculation of MSW without food waste (Avfall Sverige, 2012) (Bohn, et al., 2011).

MSW				
Proximate analysis		**MSW[1]**	**Food waste[2]**	**MSW w/o food waste****
Moisture	wt-%	45,4	75[3]	43,7
Ash	wt-% (db)	19,9	9,5	20,2
Ultimate analysis				
C	wt-% (db)	46,2	49	46,1
H	wt-% (db)	6,3	6,4	6,3
N	wt-% (db)	1,2	2,3	1,1
S	wt-% (db)	0,15	0,16	0,15
O	wt-% (db)	25,5	32,4	25,3
Cl	wt-% (db)	0,75	0,24	0,76
LHV dry	MJ/kg	19,4	19,7	19,3
LHV ar	MJ/kg	9,4	3,08	9,8
Ash and trace elements analysis				
Lead, Pb	mg/kg (db)	136	1,6	140
Cadmium, Cd	mg/kg (db)	0,6	0,07	0,6
Copper, Cu	mg/kg (db)	450	14,5	460
Chrome, Cr	mg/kg (db)	63,2	2,2	65
Mercury, Hg	mg/kg (db)	*	0,02	0
Nickel, Ni	mg/kg (db)	73,5	1,5	75
Zinc, Zn	mg/kg (db)	567	35,4	580
Potassium, K	mg/kg (db)	3630	2810	3660
Sodium, Na	mg/kg (db)	10600	1530	10840
Calcium, Ca	mg/kg (db)	29870	22700	30050
Phosphorus, P	mg/kg (db)	1570	3910	1506

**Not presented in data*

***Calculated by the authors, see section 6.1.1*

[1] (Avfall Sverige, 2012)

[2] (Bohn, et al., 2011)

[3] (Gustafsson, 2014)

Considering the nature of the fuel, it is very advantageous to allow MSW-incinerating plants constitute base load energy production. The constant supply stream, adequate heating value, and the inverse expense relation i.e. the plant owner obtains revenue from receiving the MSW makes the variable costs for energy production very low (Djurberg, 2011).

On the other hand, MSW contains high concentrations of chlorine, alkalis and heavy metals. Corrosion is therefore a more prominent issue than in conventional fossil fuel fired boilers. Typical solutions to serious corrosion are to select corrosion resistant tube material or to prepare tubes, e.g. by applying a protective coating, to reduce corrosion risks. Other solutions are also to apply a remedial additive or co-combust with sulfur rich fuels (Stålenheim & Henderson, 2004). In Sweden there are also regulations concerning MSW combustion, where an important imposition states that MSW must be burnt at a temperature of at least 850 °C for at least 2 seconds (Sveriges Riksdag, 2013). Co-combustion with sludge, which is a high moisture substance, should therefore be applied with this in mind since it affects the characteristics of combustion in the boiler.

2.3.3 PTP

MSW is a type of waste that has not gone through any prior treatment or separation. PTP on the other hand is a sorted waste fuel consisting of paper, plastics and wood. Incineration of PTP also falls under the same regulatory provisions as MSW i.e. the PTP has to be burnt at temperatures above 850 °C with a residence time of at least 2 seconds (Sveriges Riksdag, 2013).

In 2012-2013, a series of tests for fuel analysis were conducted to determine the composition of the PTP incinerated in P6 at Högdalen. A total of six samples were collected for analysis between the 12th of October and the 8th of March. The samples were in general equivalent in composition. A mean of the sample compositions is shown in Table 6. Compared to MSW the PTP fuel neither generates a significant income nor a significant expense for Fortum.

Table 6: Mean compositional analysis of the PTP combusted in P6 (Lindman, 2013a).

PTP fuel P6		
Proximate analysis		
Moisture	wt-%	28,3
Ash	wt-% (db)	16
Volatile matter	wt-% (db)	72,6
Fixed Carbon	wt-% (db)	10,2
Ultimate analysis		
C	wt-% (db)	45,2
H	wt-% (db)	5,8
N	wt-% (db)	0,82
S	wt-% (db)	0,56
O	wt-% (db)	29,9
Cl	wt-% (db)	0,42
LHV daf	MJ/kg	22,1
LHV dry	MJ/kg	18,3
LHV ar	MJ/kg	12,1
Ash and trace elements analysis		
Lead, Pb	mg/kg (db)	85,2
Cadmium, Cd	mg/kg (db)	0,56
Copper, Cu	mg/kg (db)	228,2
Chrome, Cr	mg/kg (db)	129,4
Mercury, Hg	mg/kg (db)	0,17

PTP fuel P6		
Nickel, Ni	mg/kg (db)	14,6
Zinc, Zn	mg/kg (db)	642,4
Potassium, K	mg/kg (db)	1990
Sodium, Na	mg/kg (db)	3260
Calcium, Ca	mg/kg (db)	25370
Phosphorus, P	mg/kg (db)	260

2.4 Fortum's plants

In this chapter some of Fortum Heat's plants in Stockholm will be described. These plants are assumed to be eligible for eventual sludge combustion. For each plant only the relevant blocks and boilers for the study, i.e. the ones combusting solid fuels, are described more in depth.

2.4.1 Högdalenverket

Fortum's CHP plant in Högdalen produces both heat and power using primarily MSW and PTP. It has permission to process 700000 tonnes of waste for incineration per year, a limit which is virtually met today. The plant constitutes the baseload supply to Stockholm's central and south district heating system, which was connected in 2008 to form the district heating system "City/Söder". It consists of four grate furnace boilers, one fluidized bed boiler, three oil fired boilers, and one electric boiler. The grate furnace boilers and the fluidized bed boiler are coupled with flue gas condensation units, installed for added energy extraction. These different plant components are presented in Table 7.

Table 7: Specifications of the blocks at Högdalenverket (Djurberg, 2011) (Fortum, 2013).

Unit	Type	Year of commission	Main fuel	Net power [MW]
P1 & P2	Grate Furnace	1969	MSW	2 x 17 (heat) 2 x 6 (electricity)
P3	Grate Furnace	1986	MSW	30 (heat) 10 (electricity)
P4	Grate Furnace	2004	MSW	61 (heat) 21 (electricity)
P5	Oil fired boiler	1979	LFO and Bio-oil	80 (heat)
P6	CFB boiler	2000	PTP	63 (heat) 26 (electricity)
P11 & P12	Oil fired boiler	1974	LFO	2 x 10 (heat)
P21	Electric boiler	1983	Electricity	25 (heat)
Flue gas condensation P1-P3	-	2000	-	10 (heat)
Flue gas condensation P4	-	2004	-	16 (heat)
Flue gas condensation P6	-	2000	-	10 (heat)

For the purposes of this study, boilers P1-P4 and P6 are of particular interest and will be discussed further.

Additionally, the possibility to build a biogas production facility in Högdalen is currently under investigation. If built, this would involve separating ca. 31000 tonnes of food wastes per year from the annual flow of MSW to the plant for biogas production, leaving a deficit of fuel for the boilers. The expected amount of digestate from the biogas production would then be ca. 26400 tonnes/year at 25 % DS (Gustafsson, 2014). The separation of food waste will also leave a possibility to receive more waste for incineration within the existing permit.

P1 & P2

Boilers P1 and P2 are in operation 8000 h/year. They are manufactured by the former company VKW, and are grate furnace boilers of the same type generating superheated steam to a joint steam system and steam turbine coupled to P1-P4.

The MSW is transported to the plant by trucks and tipped into a common waste bunker shared with P3 and P4. A grapple then feeds MSW from the bunker to the feed hoppers, one for each furnace. From the hoppers belonging to P1 and P2 MSW is fed into the furnaces at a rate of 10 tonnes/h each on a back-and-forth moving feed table. The fuel bed is then transported through the furnace where it is combusted along slowly rotating cylinders. Ash and slag falls down into a water filled extinguishing bath and is then conveyed to a slag bunker. The flue gases are cleaned together with the flue gases from P3 in a common flue gas cleaning system (Fortum, 2013).

Several actions are taken to reduce emissions in the flue gases. First, ammonia is added to the flue gases after the furnace (SNCR) to reduce NO_x emissions. After combustion, the flue gases are then taken through the flue gas cleaning system. These are listed in order from first to last in the process chain (Fortum, 2013):

- A limestone reactor where it is mixed with hydrated lime, recirculated fly-ash and water
- A fabric bag filter which separates reaction-products from the limestone reactor and other particles
- A scrubber divided in two stages; one acidic stage and one neutral stage
- A condenser unit where water vapor in the flue gases is condensed for additional energy extraction, and water soluble gases and particles are removed.

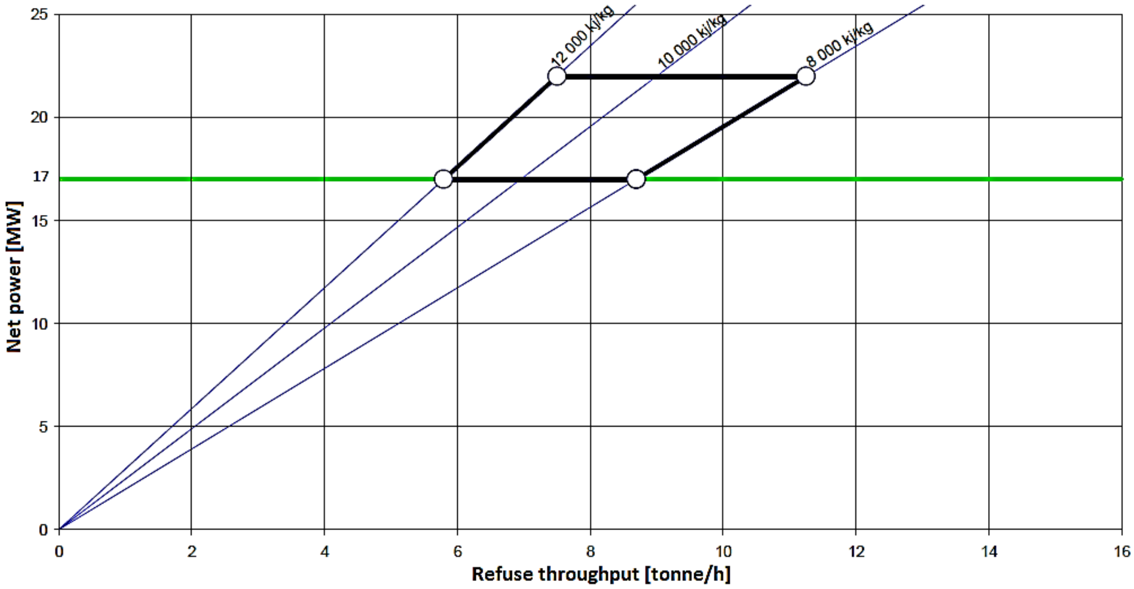


Figure 8: Stoker capacity diagram for P1 and P2 at Högdalenverket (Lindman, 2014).

In Figure 8 above a stoker capacity diagram for the boilers P1 and P2 can be seen. A stoker capacity diagram shows what the boiler is designed for in the sense of fuel mass flow and the power output at different heating values. The capacity diagram is only valid for the boiler and does not take the fuel feeding system, ash handling system and flue gas treatment equipment into consideration (Andersson, 2014). A boiler can be operated at conditions outside the area of normal operation but not continuously for prolonged periods. In continuous operation the boilers P1 and P2 can handle waste with a LHV of 8-12 MJ/kg. The maximum fuel feed rate is approximately 11,2 tonnes/h. When mixing the MSW with a substance with lower heating value, such as sludge, the increased fuel mass flow is a limiting factor since the mechanical stresses put on the grate otherwise becomes excessive (Andersson, 2014).

P3

Boiler P3 is a sloped grate furnace boiler in operation 8000 h/year manufactured by MARTIN GmbH with a nominal power of 44 MW. The fuel is fed from the hopper to the grate via three horizontal feeding tables. The grate consists of rods where every other rod moves in order to stir the fuel bed. Ash and slag falls down into a water filled extinguishing bath and is then transported to a slag bunker. The flue gases are cleaned together with the flue gases from P1 and P2 in a common flue gas cleaner. The flue gas cleaning system is comparable to the process applied for P1 and P2. One notable difference is that the cleaning system for P3 has two limestone reactors (Fortum, 2013).

Fouling and deposits on the superheaters are removed by a rapping system which is complemented by blast sooting performed every sixth week. If necessary, the empty pass can also be blast sooted. Funnels underneath the grate are sometimes clogged, caused by melted aluminum, which causes boiler shutdown. This must be removed manually (Avfall Sverige, 2008). The boiler has previously had problem with corrosion on the superheatears which have had to be replaced. Also, the SO_x emission control in flue gas condensing bypass mode currently operates at a critical level which makes it sensitive to an increase of flue gas volume flow (Andersson, 2014).

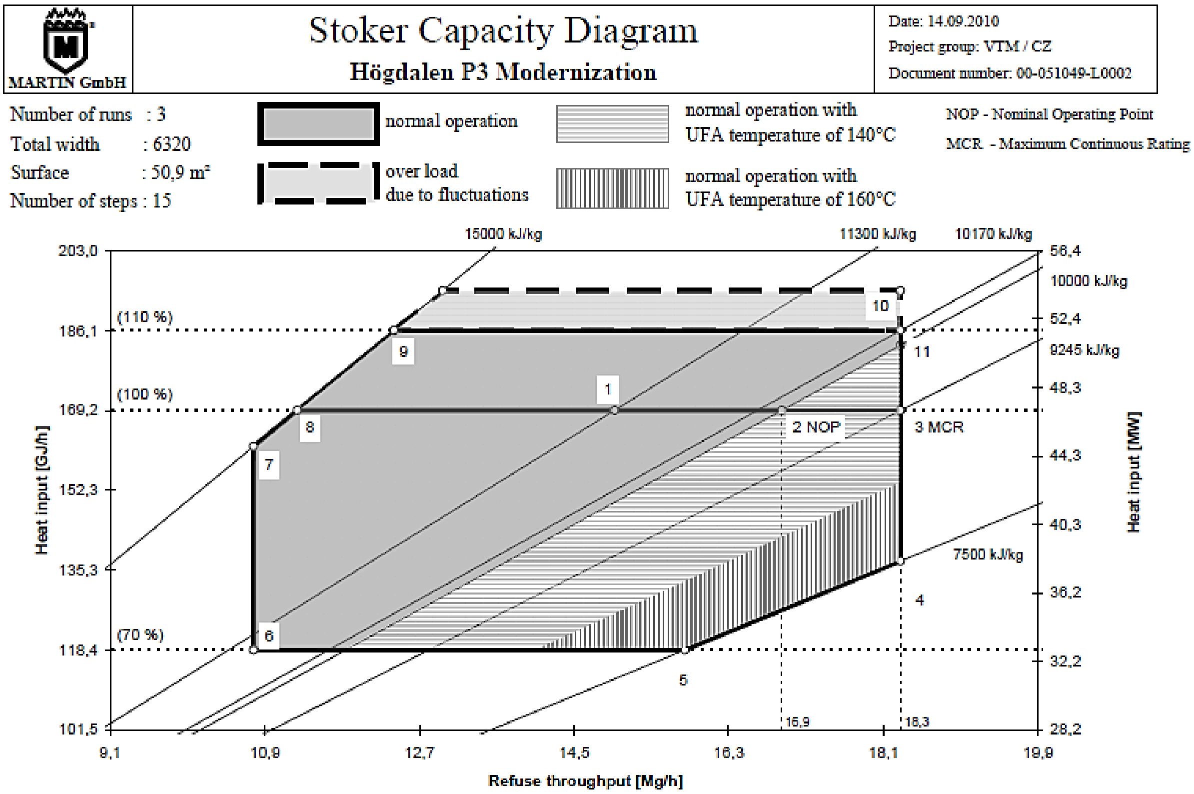


Figure 9: Stoker capacity diagram for P3 at Högdalenverket (Lindman, 2014).

In Figure 9 a stoker capacity diagram for P3 can be seen. The boiler can, according to the stoker capacity diagram, handle waste with a LHV between 10,17-15 MJ/kg and still operate at full capacity since recent modernization measures allows continuous 110 % operation. The fuel flow is limited to 18,3 tonnes/h and the lowest heating value with reduced load for continuous operation is 7,5 MJ/kg. But in actuality the MSW fuel at Högdalen has a LHV lower than 10,17 MJ/kg, see section 2.3.2, which means that the boiler operates outside the stoker capacity diagram at full load. The effective limit for the LHV will therefore be set to 9,44 MJ/kg in this study.

P4

P4 is a grate furnace boiler in operation 8000 h/year, built by Vølund, with a nominal power of 83 MW, where the grate has one water and one air cooled section. Fuel is fed to the grate from the hopper via nine feeding tables at a rate of 34 tonnes/h. The furnace is designed to be able to process fuels with high contents of chlorine and sulfur as well as bulky objects containing impurities. Ash and slag is transported by hydraulic pushers to a vibrating chute where they are transported to a slag bunker through holes in the furnace wall. P4 has its own flue gas cleaning unit (Fortum, 2013).

The flue gas cleaning system for P4 differs from the system used for P1-P3 and P6. The following process is applied, listed in order from first to last in the process chain (Fortum, 2013):

- An ESP where dust is separated
- Two scrubbers. Water and limestone is injected into the flue gases in the first scrubber, and activated coke and lye is injected in the second.
- A wet electrostatic precipitator (WESP) where dust is separated down to 2 mg/Nm^3. The condenser unit is placed after the WESP where the water vapor is condensed for additional energy extraction and to clean out some particles and water soluble gases.

The same problems as P3 concerning melted aluminum in the funnels underneath the grate have occurred repeatedly. The boiler also has problems with high moisture waste, resulting in unburnt materials in the ashes (Avfall Sverige, 2008). Apart from these, no notable operational issues have been reported.

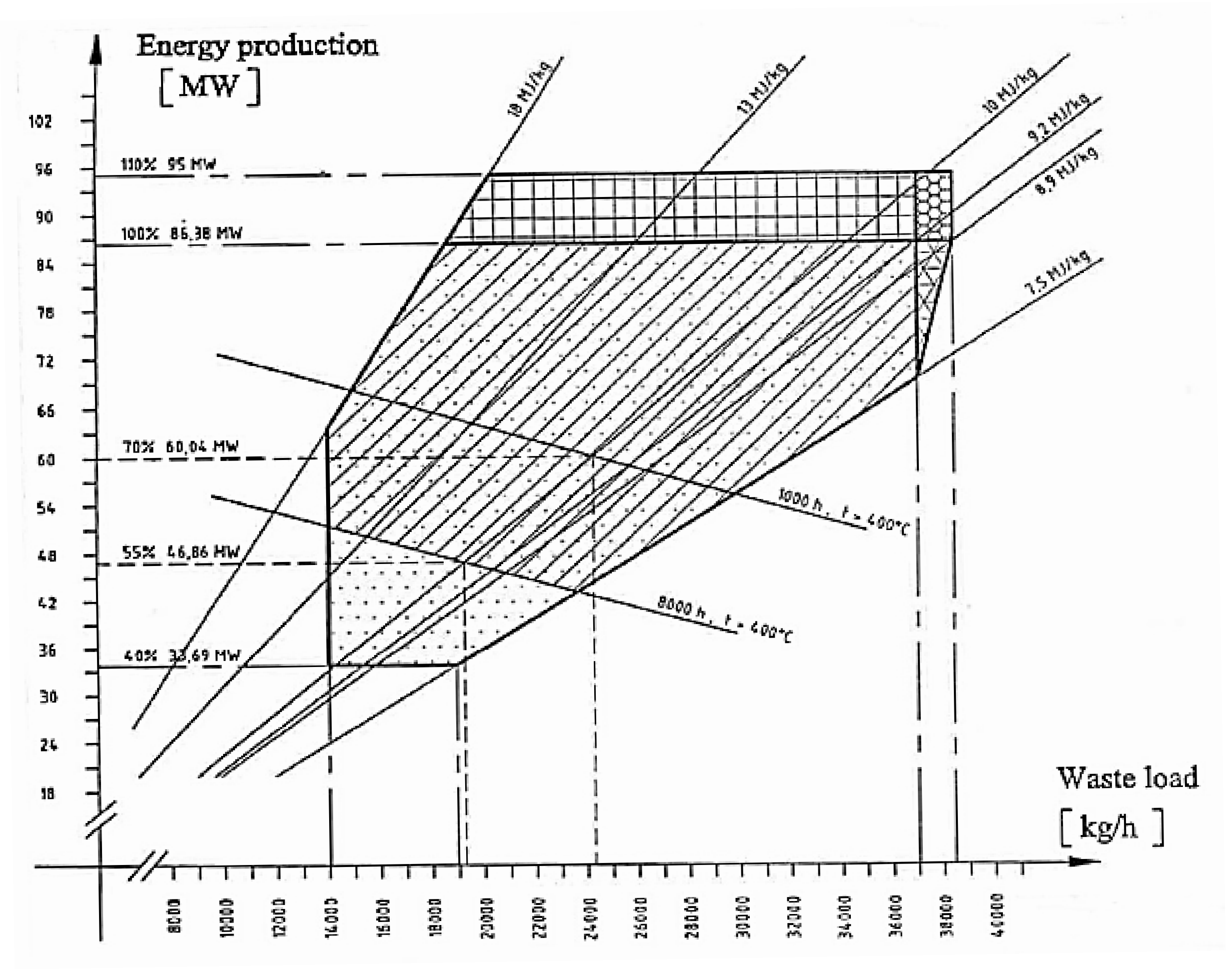


Figure 10: Stoker capacity diagram for P4 at Högdalenverket (Lindman, 2014).

The stoker capacity diagram for boiler P4 is shown in Figure 10. As can be seen in the diagram the lowest possible LHV of a fuel for full load operation at is 8,9 MJ/kg. The corresponding fuel feed rate here is 38,8 tonnes/h in P4.

P6

P6 is a PTP fired CFB boiler in operation around 7000 h/year with a nominal power of 90 MW built by Foster Wheeler. PTP arrives at the plant pre-shredded and is passed through a fuel transportation system from the fuel reception hall to the boiler. The transportation system is automatic and consists of a series of conveyors and several culling steps aimed at removing magnetic materials and bulky pieces of fuel. The bulky pieces of fuel are normally sent to the grate furnaces, although the system is also equipped with shredder mills which allow bulkier fuel to be added to the fuel stream. Intermediate storage silos in the system ensure a steady flow of fuel to the boiler, which is incinerated at a rate of 30 tonnes/h. Ash is extracted from the furnace via water cooled screws (Fortum, 2013).

The flue gases are passed through the same type of cleaning process as with P1-P3, with two exceptions. There is an additional step where activated carbon is mixed with the flue gases before the limestone reactor. Also, burnt lime as opposed to hydrated lime is used in the limestone reactor. The SNCR step is applied in the cyclone due to beneficial temperature conditions (Fortum, 2013).

The boiler is equipped with an effective bed material treatment and replenishing system which prevents agglomeration. Corrosion on tubes was previously recurrent, causing tube leaks 1-2 times a year but has since been corrected. Fouling and deposits are removed with a rapping system, coupled with blast sooting performed once a month (Avfall Sverige, 2008). An interview with Mikael Ljung, an on-site maintenance engineer, revealed that the main operational issues at present are erosion related (Ljung, 2014). The consumption of bed sand amounts to ca. 20 tonnes/day (Lindman, 2014).

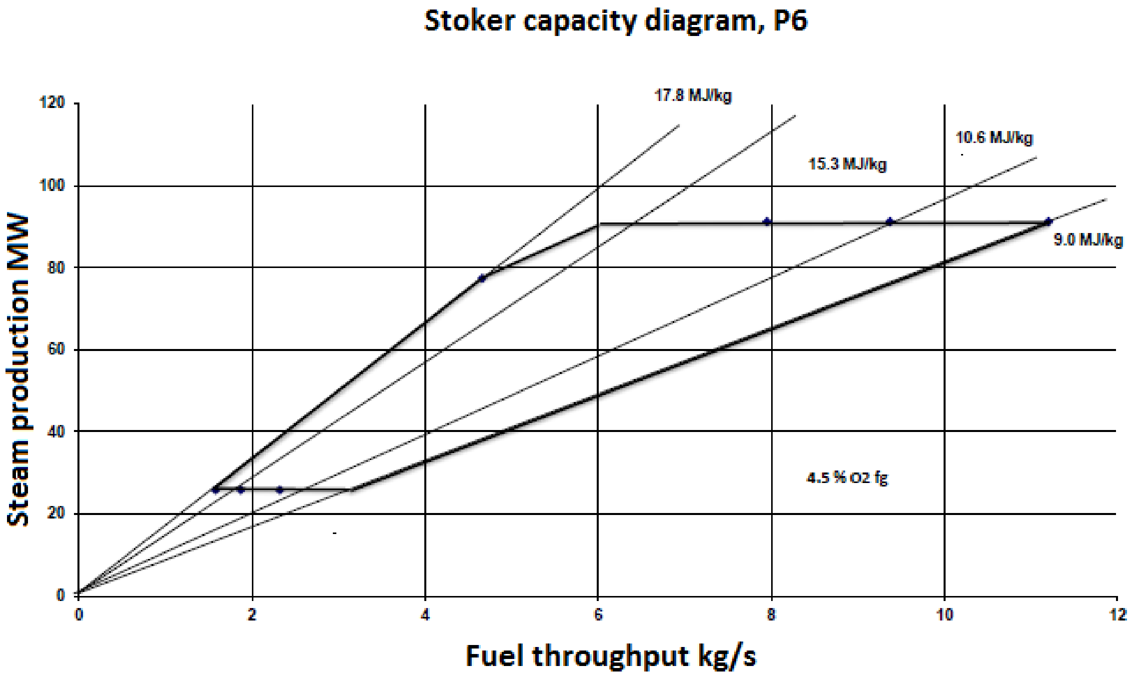


Figure 11: Stoker capacity diagram for P6 at Högdalenverket (Ljung, 2014).

Stoker capacity diagrams are most often used for grate furnace boilers incinerating waste and are not common for FB boilers. The capacity diagram shown in Figure 11 above has been constructed by personnel at Högdalenverket. As can be seen in the figure the lowest acceptable heating value of the fuel is 9 MJ/kg and the fuel feed rate is limited to approximately 11,2 kg/s.

2.4.2 Bristaverket

In the town of Märsta in Sigtuna municipality Fortum Heat has a CHP plant, Bristaverket, which primary supplies the municipalities Sigtuna and Upplands Väsby with district heating and electricity. The Brista plant was put into operation in 1997 and was then further extended with a new production unit in 2013. The older block, B1, uses primarily biomass as a fuel in a CFB boiler with the possibility to use light fuel oil Eo1 as a startup and backup fuel. The newly built block, B2, is constructed to incinerate MSW in a grate furnace. The plant is connected to the North-eastern district heating system and acts together with Fortum’s CHP plant Hässelbyverket as base load units. This connection was done to increase the flexibility of the heat production in the district heating system according to the most favorable operation conditions (Fortum, 2014) (Fortum Värme, 2013). The different blocks in the plant are presented in Table 8.

Table 8: Specifications of the blocks at Bristaverket (Fortum Värme, 2013) (Djurberg, 2011) (Jacobson, 2014).

Unit	Boiler type	Year of commission	Main fuel	Net power [MW]
B1	CFB	1996	Stem wood chips, GROT, forest residues	75 (heat) 41 (electricity)
B2	Grate furnace	2013	MSW	60 (heat) 20 (electricity)
Flue gas condensation B1	-	2002	-	30 (heat)
Flue gas condensation B2	-	2013	-	8-12 (heat)

Both of the two blocks are of interest for this study and will be discussed further.

B1

The first block consists of a CFB boiler in operation for approximately 8000 h/year from Foster Wheeler, but the operational time is expected to decrease as B2 will take over base load production. The boiler is fed with forest residues (GROT) and stem wood chips, either brought to the plant or from logs which are shredded on site. More specifically the fuel mix fed to the boiler consists of ca. 70 % GROT and ca. 30 % stem wood chips (Jacobson, 2014). The fuel is stored in a fuel silo and fed to the boiler via conveyor belts at a desired rate. At full production the annual fuel consumption amounts to ca. 350000 tonnes of biomass. As mentioned, in order to initiate the combustion process LFO is used which also can be utilized as backup fuel. The annual consumption of LFO amounts to ca. 200 tonnes. The boiler produces steam which is sent to a steam turbine coupled to a generator for electricity production. The steam is then condensed in a condenser cooled by district heating water. The plant in Brista is not designed to operate in cold condensing mode i.e. it can only produce electricity when there is a simultaneous demand for heat. The capacity factor is therefore limited. The emission reduction system consists of the following steps (Fortum Värme, 2013) (SWECO, 2009):

- Reduction of NO_x through stepwise air supply and limited excess air during the combustion in the bed. FGR is also used to help reduce the NO_x formation
- Cyclone separation of bed material and bottom ash from the flue gases
- Further reduction of NO_x by injecting ammonia in a SNCR stage
- Particles and soot are removed in an ESP
- The flue gases are condensed and the heat is recovered to the district heating network and some particles and water soluble gases are cleaned out
- No desulfurization, but the emissions must meet requirements (25 mg/Nm^3 dry gas at 6 % O_2)

Ash is removed from the bottom of the furnace via screws cooled by district heating water and dumped into containers. Soot is removed from heat transferring surfaces by steam soot blowing lances. The utilization of biomass has been granting the plant the Swedish electricity certificate support scheme. However, the support scheme is limited in time and the support for Bristaverket has recently ended. The boiler consumes, due to inadequate performance of the cyclone separator, more bed sand than what it was designed for, amounting to ca. 11 tonnes/day. The boiler operates with 20 % excess air (Jacobson, 2014).

A stoker capacity diagram for the CFB boiler at Bristaverket is not available. To determine the limiting values regarding sludge mixing, technical data sheets associated with B1 were employed. The limiting values on the fuel fed to the boiler can be seen in Table 9. Sludge mixing will be limited by maximum allowed moisture and ash content and the minimum heating value of 8 MJ/kg. At full load the fuel power amounts to 133 MW (Jacobson, 2014).

Table 9: Boiler design specifications based on fuel data (Jacobson, 2014).

Technical specification		**Min.**	**Max.**
Moisture content	%	40	55
Ash content	% db	0	5
Heating value (LHV ar)	MJ/kg	8	11

B1 is the only boiler in this study which does not combust waste. It currently only has permission to combust biofuels which implies that extended permissions would be necessary in order to add sludge to the fuel mix. Additionally, this will impose further requirements on the combustion process.

B2

The newly built second block consists of a grate furnace boiler built by MARTIN GmbH fed with MSW. It is similar to P4 in Högdalen and holds a permission to incinerate 240000 tonnes of waste annually (Fortum Värme, 2013). It is planned to be operational for 8000 h/year. Since the block is in its start-up phase no issues from continuous operation are known or are to be expected. A start-up issue that has appeared is low moisture content in the industrial waste used. The low moisture content results in a too high heating value causing high temperatures in the furnace. The LHV is expected to decrease as more household waste will be added to the fuel mix for future operation (Jacobson, 2014). An appropriate assumption in this study is to consider the fuel to have the same properties as the PTP fuel but the same monetary value as MSW.

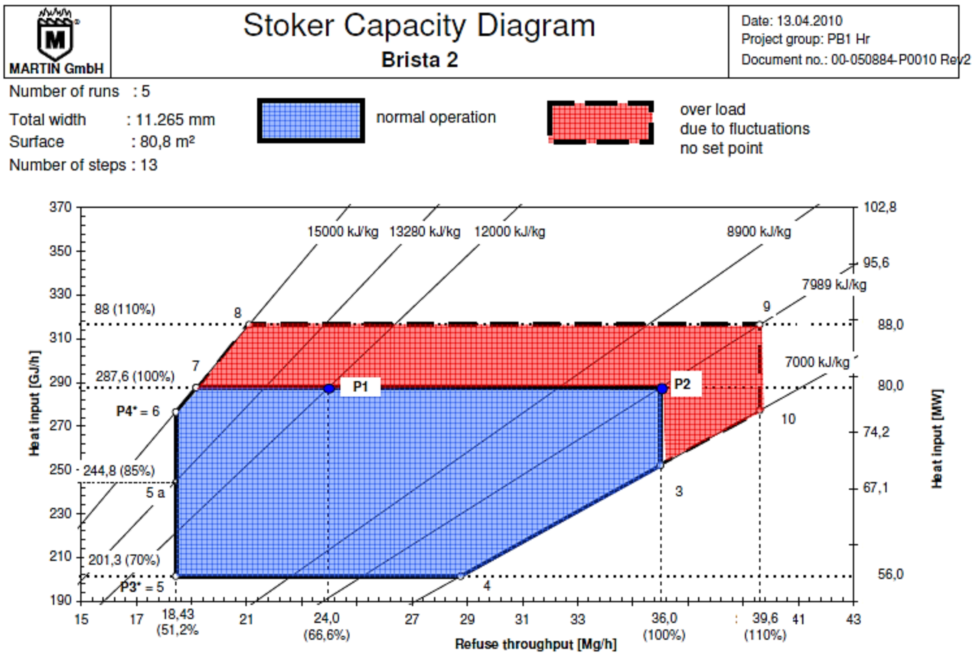


Figure 12: Stoker capacity diagram for B2 at Bristaverket (Lindman, 2014).

Figure 12 above depicts a stoker capacity diagram for the boiler. As can be seen in the picture the lowest acceptable LHV for full load operation is 7,989 MJ/kg and the maximum fuel feed rate in normal operation is 36 tonnes/h.

2.5 Sludge

Sludge generally refers to the semi-solid slurry which is a byproduct left from numerous industrial processes. The types of sludge which will be addressed in this report are sludge from sewage treatment processes, digestate from biogas production processes and fibrous sludge. There are several traits common to these types of sludge (Lindman, 2014):

- High water fraction (70-96 %)
- High ash content (12-50 % db)
- Low energy content (<4,1 MJ/kg as received)
- Generally contains high fractions of phosphorus and other soil nutrients
- May contain impurities e.g. heavy metals and pathogens

Sludge mainly varies in composition and moisture content according to production process from which it is a byproduct and the input substrate, but these can also vary from location to location and according to climate and season.

In Sweden it has historically been considered a waste byproduct and was commonly deposited on landfills. However, the treatment of waste in general has in the last 10-15 years been subject to reevaluation on a national and international level. An increased awareness of sustainability issues and “recycling thinking” have led to new policies concerning resource management being formed (Svenskt Vatten, 2013). Following directives from the EU and Swedish government, the ambition to make better use of waste for useful purposes, e.g. recycling, energy production etc., has led to landfill-depositing being increasingly regulated. In 2000 a landfill-deposit excise-tax of 250 SEK/tonne was brought into force, which was incrementally raised over the following years to 435 SEK/tonne in 2006. In 2002 a law prohibiting landfill-depositing of combustible materials was enacted, and in 2005 the deposit of organic materials, including sludge, in landfills was banned. These have resulted in a significant decrease of deposited waste on landfills (Arvidsson, et al., 2012). Yet this has increased the demand to find alternative ways and new solutions to waste management. This applies especially to sludge since its recovery potential for other uses is limited. The uses for other activities are also often restricted since sludge in many cases contains hazardous material.

In essence, the question facing stakeholders now is finding what new feasible uses sludge may have. It is often used as an agricultural fertilizer, but this practice is somewhat controversial. It is not well established how the substances accumulate in soil and crops or leach into groundwater. Long term ecological effects are difficult to determine, and the practice usually entails long transportation distances (Linder, 2001). Moreover, sludge for fertilization purposes is at present strictly regulated, see more in section 2.7.1, which already secludes a large portion of sludge, and more stringent regulations in the future would seclude even more (Hansson & Johansson, u.d.). Other uses for sludge include fertilizer for forest land, as well as a final cover for landfill sites, for the production of plant soil and for increasing soil humus content (Tideström, 2008). Another treatment, albeit not principally for a useful purpose, has been to incinerate it to reduce volume and to eliminate organic materials, enabling landfill depositing (Levlin, et al., 2001). By and large though, beneficial solutions are not common and finding new ones are in high demand.

What is noteworthy is that the increased need for alternative means of sludge disposal has affected the energy utility fuel market since sludge is showing potential as fuel to be combusted by itself, for co-combustion with other fuels or as a combustion additive (Naturvårdsverket, 2005). But depending on key factors, e.g. ash composition and moisture content, sludge is not always practical for the sole purpose of generating useful energy. Specifically, the high moisture content is problematic as fuel handling systems in most plants are designed for dryer fuels. But discounting useful energy generation, sludge may still be beneficial to use as an additive to reduce the occurrence of emission-compounds or to remedy boiler operational issues (Bäfver, et al., 2013). In any event, sludge typically requires some type of pretreatment before it is practical for incineration on an industrial scale.

2.5.1 Sewage sludge

Sewage treatment plants process incoming sewage produced by industries and people through several steps in order to clean it before returning it to the environment. A byproduct from the cleaning process is sludge which contains impurities generated in a community. Rules and regulations have in the past decades controlled and lowered the discharge of harmful matter from societal activities to sewage systems, as can be seen Figure 13 showing the presence of certain metals in sewage sludge from Henriksdal sewage treatment plant (Thuresson & Haapaniemi, 2005). It is evident that much has happened between 1981-2001, but the downward trend has since halted.

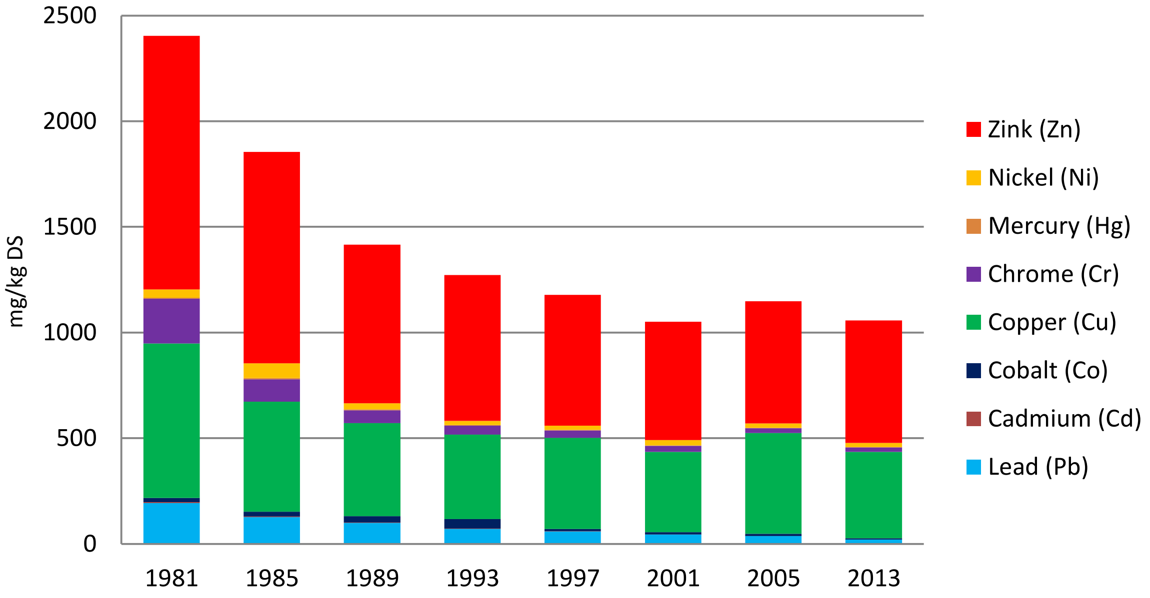


Figure 13: Presence of metals in sludge from Henriksdal sewage treatment plant between 1981-2013 (Thuresson & Haapaniemi, 2005) (Haglund & Olofsson, u.d.).

Sewage from greater Stockholm is treated in two plants in Bromma and Henriksdal. Like in many other plants, raw sewage sludge is a byproduct from the treatment process in these plants which arises from two steps in the cleaning process (Stockholm Vatten, 2010a):

- Chemical cleansing; after an initial mechanical filtration, iron sulfate is added to the sewage water which flocculates the phosphorus. The phosphorus flocculates sink to the bottom in a primary sedimentation basin and forms into sludge (primary sludge).
- Biological cleansing; microorganisms are added to the sewage water which break down organic material and produces nitrogen gas. The sludge residue sinks to the bottom in a secondary sedimentation basin (bio sludge).

The sludge which has formed is then collected, a process which is called thickening. It is mixed with grease sludge delivered to the plant from external sources, and the mix is taken to an anaerobic digester for stabilization (Borggren, 2007). The primary output products are biogas and digested sewage sludge (DSS) as a byproduct. The DSS is then taken to a centrifuge for dewatering. This process is relevant for sewage sludge treatment in the Stockholm area. The total flow of dewatered DSS from Henriksdal and Bromma is ca. 70000 tonnes annually. The plant in Bromma is planned to be shut down in 2018, but in any case, sewage sludge will in the near future be led to Henriksdal sewage treatment plant until a new plant is built in Sickla (Stockholm Vatten, 2014a). The flow of DSS is assumed to not be affected to a great extent.

Historically, the combustion of DSS has not been common practice in Sweden, neither for volume reduction nor energy generation (Naturvårdsverket, 2013). Only recently has the method been generating serious interest, which makes relevant data on DSS composition scarce. Bäfver, et al. (2013) refer to a compositional analysis of three samples of dewatered, digested sewage sludge from Himmerfjärdsverket sewage treatment plant south of Stockholm in their report *"Sludge fuel mixtures – Combustion and extraction of phosphorus"*. A mean composition has been calculated based on the analysis results and is shown in Table 10 below. Due to the similar treatment processes of Himmerfjärdsverket and the plants in Henriksdal and Bromma, this data will be considered representative of the DSS relevant to this study.

Table 10: Mean compositional analysis of dewatered digested sewage sludge from Himmerfjärdsverket (Bäfver, et al., 2013).

Digested sewage sludge		
Proximate analysis		
Moisture	wt-%	76,2
Ash	wt-% (db)	41,5
Ultimate analysis		
C	wt-% (db)	31,1
H	wt-% (db)	4,3
N	wt-% (db)	3,6
S	wt-% (db)	1,4
O	wt-% (db)	18
Cl	wt-% (db)	0,07
LHV dry	MJ/kg	12,6
LHV ar	MJ/kg	1,14**
Ash and trace elements analysis		
Lead, Pb	mg/kg (db)	23,3
Cadmium, Cd	mg/kg (db)	<0,5
Copper, Cu	mg/kg (db)	350
Chrome, Cr	mg/kg (db)	47,7
Mercury, Hg	mg/kg (db)	*
Nickel, Ni	mg/kg (db)	32,3
Zinc, Zn	mg/kg (db)	967
Potassium, K	mg/kg (db)	5633
Sodium, Na	mg/kg (db)	2700
Calcium, Ca	mg/kg (db)	29270
Phosphorus, P	mg/kg (db)	31570

**Not presented in data*
***Calculated by the authors, see section 6.1.1*

As can be seen, DSS has a high ash content, moisture content, and oxygen concentration. These factors take away from the heating value. The moisture content makes ignition and combustion problematic. From a boiler combustion perspective, these are precarious qualities compared to other fuels that need to be given attention. But positive qualities can be seen as well as shown by Gyllenhammar et al. (2013). In summary, it has been proposed that the following qualities have a positive effect on the boiler in co-combustion with problematic fuels such as biomass and waste fuels (Gyllenhammar, et al., 2013):

- High sulfur content
- High content of aluminum silicates
- High concentration of ash particles in the flue gases which provides a lot of surface area for alkali chlorides to condensate on
- High erosion effect on deposits due to high concentration of particles in the flue gases
- High content of phosphorus

Sulfur compounds from the iron sulfates added during the treatment process can break up alkali chlorides during combustion in a process called sulphation. This has a counteracting effect on superheater corrosion (Aho, et al., 2010). It has also been seen that phosphates in the sludge can also react with alkali chlorides for the same effect as well. Also, the risk of agglomeration is reduced by the presence of kaolin, an aluminum silicate, which reacts with agglomeration-inducing alkalis (Gyllenhammar, et al., 2013).

2.5.2 Digestate from biogas production (from food wastes)

Food waste has been found useful to utilize for the production of biogas which is why the separation of household and food waste is becoming more common. Separated food wastes can be sent to a biogas plant where an anaerobic digester is used for an anaerobic digestion process. This process can be either dry digestion or wet digestion. The essential difference is that the substrate, the organic waste, used in the dry process is stackable and has a moisture content of 75-80 % and the wet process is done with wet pumpable substrates where the water fraction is higher (Bioenergiportalen, 2012). In 2009, wet digestion was the only method used for biogas production in Sweden (Göteborg Energi, Innovatum Teknikpark, 2009).

The main product from a digestion process is biogas (Biogasportalen, 2014). The byproduct from wet digestion is a digestate which can be divided by dewatering at the plant into a liquid and a solid fraction. Ca. 97 % of the liquid digestate is made up of water, and the solid digestate has a moisture content of ca. 70 % (Baky, et al., 2006). The amount of water in the solid digestate can however vary according to the biogas plant’s dewatering or drying equipment. Also, the retting process and the type of substrate used will affect the moisture content and the chemical composition of the digestate. Dry digestion will eventually result in a dryer digestate which can reduce or eliminate the need of dewatering or drying on site. But further auxiliary drying of the dry digestion residue will enhance the digestate’s feasibility as a combustion additive or fuel and also reduce the need for transports. In any respect, water is generally an undesirable component which is why, although wet digestion is the established method in Sweden, dry digestion has been generating more and more interest in recent years (Göteborg Energi, Innovatum Teknikpark, 2009).

Digestate generally contains a high proportion of plant available nitrogen and other nutrients. In fact, it contains the same amount of soil nutrients as the substrate since the nutrients remain during the digestion process. The composition, especially the content of nutrients, will therefore to a great extent reflect the waste input composition to the biogas production (Makádi, et al., 2012). In Sweden the total amount of digestate produced 2012 was 725970 tonnes of which nearly 100 % was used as a bio-fertilizer in the agricultural sector (Avfall Sverige, 2013). Below in Table 11, compositional analyses of digestates from food wastes from a biogas plant in Linköping and a pilot plant in Anneberg can be seen. The heating value of the Linköping digestate at 95,6 % moisture content is negative ca. -1,65 MJ/kg (BELAB AB, 2014), whereas the table presents the heating value at 75 % moisture content which is what can be expected after mechanical dewatering or from a dry digestion process.

Table 11: Compositional analysis of a digestate from a dry digestion process using food wastes from NSR AB as substrate (Bohn, et al., 2011) and an analysis of a sample taken by the authors from Tekniska Verken's biogas plant in Linköping (BELAB AB, 2014).

Digestate			
		Anneberg, dry digestion[1]	**Linköping, wet digestion[2]**
Proximate analysis			
Moisture	wt-%	76,4	95,6
Ash	wt-% (db)	22	30,1
Volatile matter	wt-% (db)	78	*
Ultimate analysis			
C	wt-% (db)	45,8	38,5
H	wt-% (db)	5,7	5,0
N	wt-% (db)	2,5	5,6
S	wt-% (db)	0,21	0,55
O	wt-% (db)	23,5	15,9
Cl	wt-% (db)	0,34	4,3
LHV dry	MJ/kg	18,8**	15,5
LHV ar	MJ/kg	2,58**	2,05***
Ash and trace elements analysis			
Lead, Pb	mg/kg (db)	3,7	6,6
Cadmium, Cd	mg/kg (db)	0,13	0,49
Copper, Cu	mg/kg (db)	30,6	55
Chrome, Cr	mg/kg (db)	8,4	23
Mercury, Hg	mg/kg (db)	0,035	0,045
Nickel, Ni	mg/kg (db)	7,6	26
Zinc, Zn	mg/kg (db)	99,1	170
Potassium, K	mg/kg (db)	3970	27230
Sodium, Na	mg/kg (db)	1980	26560
Calcium, Ca	mg/kg (db)	32500	34730
Phosphorus, P	mg/kg (db)	9170	13220

**Not presented in data*

***Calculated by the authors, see section 6.1.1*

****Based on a moisture content of 75 %, which is relevant to this study*

[1] (Bohn, et al., 2011)

[2] (BELAB AB, 2014)

It has been noted that the composition of different digestates based on food waste vary between cases, test samples and retting processes. The two samples in Table 11 originate from different retting processes and different pretreatment process of the substrates. The food waste used as a substrate at Anneberg has prior to the dry digestion process been shredded and mixed with water to wash it from heavy impurities and then mechanically dewatered in screw presses (Bohn, et al., 2011). The substrate at Linköping is shredded, removed of plastic material, mixed with water and then taken to the wet digestion process. The variances in composition between these two digestates are most likely attributed to the different pretreatment and retting methods. For example, the lower content of alkali metals and chlorine in the Anneberg digestate is probably due to the dewatering process where these dissolved in the water and were removed with the wet fraction. Other notable differences are that the Linköping digestate has a higher ash fraction, nitrogen content, higher contents of metals and lower contents of carbon and oxygen on dry basis. Since it is unclear what is removed from the solid fraction during dewatering it would be dubious to use the Linköping digestate and merely convert content data based on 75 % moisture content without consideration of how dry matter content in actuality may be affected. For this reason the Anneberg digestate, where the analysis was based on a more relevant moisture content, will be used instead for further investigation.

Similarly to DSS, digestate generally has a high ash content, moisture content, and oxygen concentration. But there is no presence of iron or aluminum sulfates, assuming food waste containing these are not added, since the retting process itself does not incorporate these. An outcome from this is that the sulfur content is much lower in the digestate than that of DSS. This may insinuate that the reduced risk of wear in co-combustion that can be seen from using DSS is absent. But the high phosphorus content may still yield remedial effects when co-combusting digestate with troublesome fuels such as biomass.

2.5.3 Fibrous sludge

Fibrous sludge is a residue from the pulp and paper industry. During the production of pulp and paper residues follow the process water to the sewage system. The sewage therefore has to consecutively go through the following steps; sedimentation, biological treatment and/or chemical precipitation to reduce the amount of impurities. All three of these cleaning steps produce different sludge types, named primary sludge, bio sludge and chemical sludge (Eklund, 2003). These three sludge types are often mixed at the paper mill. Whether or not the sludge types are mixed and depending on the process used at the mill will result in different properties of the sludge (Henriksson, et al., 2012). It is therefore important to investigate the specific sludge when assessing the combustion feasibility. Fibrous sludge will in this study be used as the notation for the mixed sludge residues from a paper mill. More specifically, sludge from a paper mill owned by Holmen in Hallstavik will be used and a compositional analysis of the sludge can be seen in Table 12. One key difference compared to DSS and digestate is that the fibrous sludge has not gone through any digestion process. The fibrous sludge has the highest LHV as received among the different sludge types and the lowest dry content of alkali metals and phosphorus. Additionally, fibrous sludge has the lowest ash and moisture content. The high amounts of sulfur is a result from the perception chemical, iron sulfate. The amount of fibrous sludge from Holmen paper mill is ca. 50000 tonnes/year.

Table 12: Compositional analysis of fibrous sludge from Holmen paper mill in Hallstavik (Herstad Svärd, 2014).

Fibrous sludge		
Proximate analysis		
Moisture	wt-%	69,9
Ash	wt-% (db)	12,3
Ultimate analysis		
C	wt-% (db)	47,9
H	wt-% (db)	6
N	wt-% (db)	2,24
S	wt-% (db)	0,62
O	wt-% (db)	30,95
Cl	wt-% (db)	0,04

Fibrous sludge		
LHV daf	MJ/kg	21,7
LHV dry	MJ/kg	19,03
LHV ar	MJ/kg	4,02
Ash and trace elements analysis		
Lead, Pb	mg/kg (db)	4,37
Cadmium, Cd	mg/kg (db)	0,99
Copper, Cu	mg/kg (db)	14
Chrome, Cr	mg/kg (db)	9,2
Mercury, Hg	mg/kg (db)	0,04
Nickel, Ni	mg/kg (db)	2
Zinc, Zn	mg/kg (db)	607
Potassium, K	mg/kg (db)	946
Sodium, Na	mg/kg (db)	2435
Calcium, Ca	mg/kg (db)	7805
Phosphorus, P	mg/kg (db)	2010

2.6 Drying and dewatering of sludge

The moisture content in fuels affects the combustion and boiler characteristics to a great extent. For example, the heating value of a fuel is negatively linearly correlated with the fuel moisture content and the fuel moisture will be very influential in the location and characteristics of heat transfer in the boiler. Wet fuels can be hard to ignite or impossible to burn on their own. Drying and dewatering are, even though they are energy demanding, alternatives to increase the heating value and the flammability of wet fuels which can result in a net energy gain. With sufficient moisture removal even substantially wet materials such as sludge can be burnt without additional fuel.

In broad terms, sludge consists of solids surrounded by and containing water. Water in sludge exists in different forms, illustrated in Figure 14. These are (Linder, 2001):

A. Cell-bound water
B. Water bound to sludge particles by adhesive and cohesive forces
C. Capillary bound water in the particles’ pores
D. Water inside flakes of sludge particles
E. Unbound water

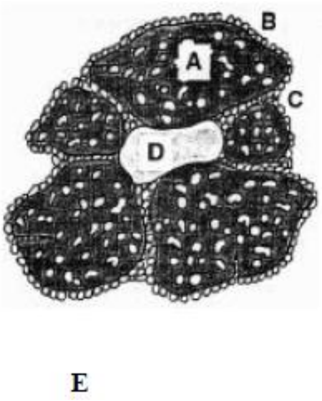


Figure 14: Schematic image of different forms of water in sludge (Linder, 2001).

After thickening, water removal can in principle be done in two ways, dewatering or drying. Dewatering refers to the removal of the moisture as a liquid and drying is the removal of moisture as water vapor. A process which lowers the moisture content of a fuel can also be a combination of these two. Water in the forms of E, C and B can be removed using mechanical dewatering, and to a certain degree, also forms D and A. However, water forms D and A require an addition of polymers and/or polyelectrolytes which cause a change in the surface tension of the cells in order to be released by dewatering. For complete water removal of sludge a drying process is needed (Flaga, u.d. a).

Several measures can be adopted to lower the water content in sludge. Common mechanical ways of reducing the moisture content are; screw presses, belt presses, press filters and centrifuges (The AD centre, 2014). As was mentioned in section 2.5.1, sludge from the sewage treatment plants, Henriksdal and Bromma (and Himmerfjärdsverket), are centrifuged to ca. 25 % DS before it is transported away from the plants. This is within the dewatering DS range, see Figure 16, and can be expected from most mechanical dewatering techniques (Flaga, u.d. a).

Drying is often done by heating the sludge in order to evaporate the water. Heat can be supplied directly from a heat source or, if accessible and sufficient, waste heat from another process. Except in cases where solar heat, waste heat or any other “free” heat source is used, drying processes are in general much more expensive to operate than dewatering processes but may still be beneficial. By using a thermal drying process over 90 % of DS can be achieved (Flaga, u.d. a). Drying of sludge is often done in drum dryers and belt dryers (Rehl & Müller, 2011).

The difference between drying and dewatering is that dewatering is in essence a mechanical removal of water, whereas drying involves evaporating water by using thermal energy. This means that water soluble material may also be removed during dewatering which affects the dry content whereas drying removes water only. In essence, dewatering can lower the concentration of material on a total mass basis, in contrast to drying which concentrates them. For example, most of the nitrogen is removed with the water during dewatering (Tamm & Ossiansson, 2009), and possibly also water soluble alkali chlorides. Water from dewatering may thus require cleaning. From a combustion perspective it is therefore important to consider the sludge pretreatment process in order to avoid exposing the boiler to unnecessary risks of corrosion, agglomeration and deposits.

The role of dewatering and drying is essential for practical sludge combustion. High water fraction sludge such as digestate has a very low effective heating value, which in extreme cases of very high moisture contents (higher than 90 %) is even negative. This is due to the heat of vaporization needed to turn the water into gas phase. Indeed, fuel moisture content levels will determine combustion suitability and performance, but these are also determined by the content of ashes and volatiles. The mono-combustion requirements can be seen in Tanner’s triangle in Figure 15. Though this triangle was developed based on research on communal waste incineration, it has been shown to be applicable on sludge combustion as well. The darkened area marks the limits on moisture content, ash content and content of volatiles required for mono-combustion (Flaga, u.d. b).

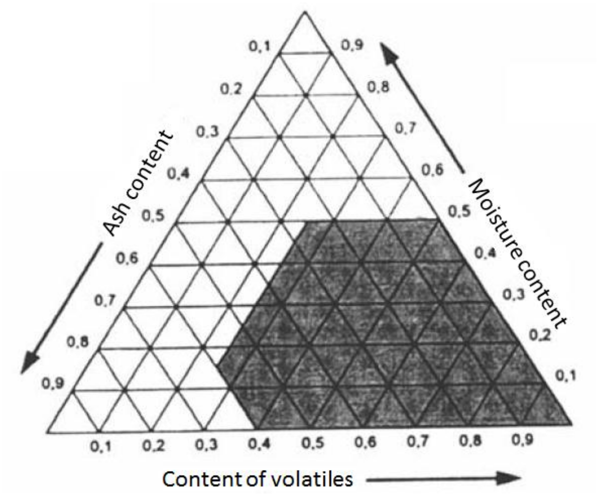


Figure 15: Tanner's triangle (Flaga, u.d. b).

From the perspective of co-combustion, successful combustion may be achieved at higher sludge moisture contents. This will naturally require complementary fuels with better combustion properties. The fuel-sludge mixture ratio will, amongst other factors, be determined largely by the sludge moisture content. The sludge water removal steps and subsequent combustion application are shown in Figure 16.

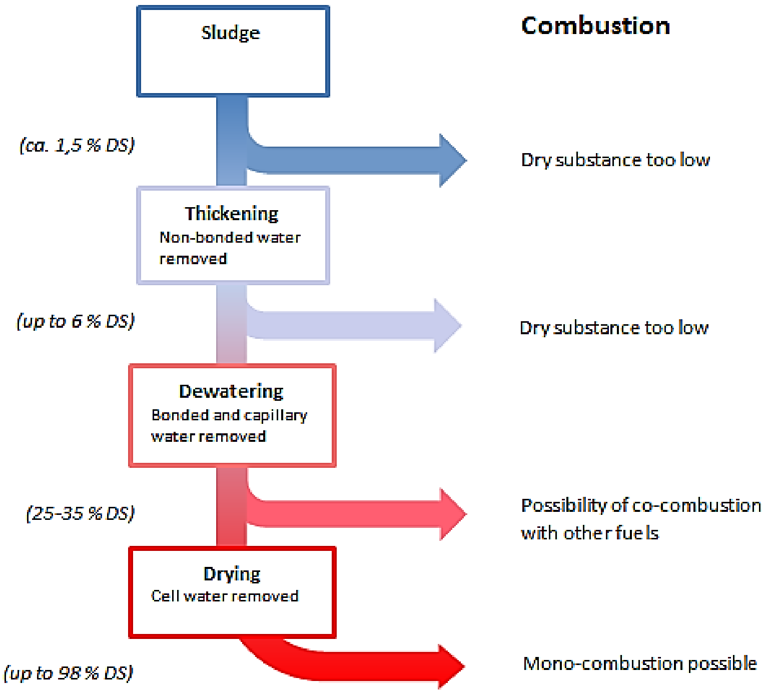


Figure 16: Sludge water removal process (Flaga, u.d. b).

Sludge changes in consistency during the shift from liquid form to a paste form. This change occurs during both dewatering and drying processes. Dewatering does not entail any special precautions regarding this phase change but drying does. Sludge, in particular DSS, will in the range of 45-65 % DS be in the so called sticky phase. This phase makes the sludge troublesome to handle and can cause dryers to clog or even break (Flaga, u.d. a). In a combustion process this can also result in a blocking of the fuel feeding system causing an inevitable shutdown of the boiler.

2.7 Soil nutrients in sludge

Plant nutrients consist of macro- and micronutrients, see Table 13. Macronutrients are nutrients that plants need in large quantities, and micronutrients are needed in small quantities. Today, plant nutrients are artificially manufactured and sold to farmers as fertilizers who then spread them on their fields (Hansson & Johansson, u.d.). Minerals used for manufacturing artificial plant nutrients must be mined, which is problematic since the resources are finite. For example, some researchers believe that the world's phosphorus reserve will be depleted within the next 50-100 years (Evans, 2011). Additionally, mining entails an environmental burden. Nutrient recycling is therefore desirable to the extent it is possible.

Table 13: Macro- and micronutrients (Hansson & Johansson, u.d.).

Macronutrients	Micronutrients
Nitrogen (N)	Copper (Cu)
Potassium (K)	Manganese (Mn)
Phosphorus (P)	Iron (Fe)
Calcium (Ca)	Boron (B)
Magnesium (Mg)	Zinc (Zn)
Sulfur (S)	Molybdenum (Mo)
	Chlorine (Cl)
	Nickel (Ni)

The phosphorus that plants need is in the form of chemical compounds called phosphates. An essential characteristic of the phosphate compound is its ability to be assimilated by plants. Fertilizers usually contain high quality phosphates, usually monocalcium phosphate or tricalcium phosphate, which are superior to phosphates found in sludge (Linder, 2001). Nevertheless, sludge is a waste product. Any usefulness from sludge is essentially justified from an ecological viewpoint, which is why it is often used as a fertilizer. But spreading it directly on cropland precludes its potential to be combusted for generating useful energy. For this reason a lot of resources are presently being invested in research and development of methods for phosphorus extraction from sludge combustion residue ashes. Finding profitable methods could be groundbreaking since the practical and economic uses of sludge would in essence double, i.e. it could be used for both power and heat generation *and* for agriculture fertilization.

However, it must be stated that the combination of the two is not without issues. For example, nitrogen and humus-forming substances are lost during the combustion process whilst the fuel-phosphorus remains in the ashes. Available technologies for phosphorus extraction exist but are uncommon. It is also recommended that sludge be combusted separately i.e. by mono-combustion, since the mixture with other fuels may increase the presence of harmful metals. Furthermore, there is little to no experience of sludge combustion combined with phosphorus extraction in Sweden at present (Naturvårdsverket, 2013).

Aside from this, the use of sludge is subject to a conflict of interests. The conflict is whether it is better to spread the sludge directly on farmland for a high utilization of crop nutrients or to use it for generating useful energy coupled with complementary phosphorus extraction. The former does not take advantage of sludge as a source of energy, and the latter makes energy retrieval possible but at a cost of losing some of the nutrients beneficial for crops. It is not yet clear what method is most beneficial in a broad perspective. But whatever the case, both methods need to be evaluated in light of existing regulations concerning agricultural fertilizers.

2.7.1 Regulations on sludge as an agricultural fertilizer

Fertilizers are regulated to ensure that concentrations on certain heavy metals and compounds are kept at a level that is deemed safe for the environment and humans. According to Naturvårdsverket (2012), sludge may be used as a fertilizer if it contains little or no pathogenic microorganisms, heavy metals, drug or pesticide residues and other harmful substances (Naturvårdsverket, 2012). Nonetheless, it is not always clear what constitutes a safe concentration, what compounds and heavy metals are harmful or what short and long term effects they may have. The matter is complicated further due to "cocktail effects" when chemicals mix with each other to produce new compounds (Hansson & Johansson, u.d.).

That being said, there are detailed studies on the negative effects of many chemicals, but regulations adhere to different forms of sludge depending on its origin. Based on regulations from the Swedish environmental code and environmental protection agency, sewage sludge may legally be used in conventional agriculture if it complies with the established limits on seven heavy metals, see Table 14. A significant portion of sewage sludge does not qualify, especially based on the restrictions on cadmium concentrations, which is why only a portion of sewage sludge is spread on farmlands today (Hansson & Johansson, u.d.).

Table 14: Regulations concerning sewage sludge to be used on farmland (Hansson & Johansson, u.d.).

Metal	Maximum concentration for use on farmland	Maximum supplied per year (average over 7 years)
Lead	100 mg/kg db	25 g/ha year
Cadmium	2 mg/kg db	0,75 g/ha year
Copper	600 mg/kg db	300 g/ha year
Chrome	100 mg/kg db	40 g/ha year
Mercury	2,5 mg/kg db	1,5 g/ha year
Nickel	50 mg/kg db	25 g/ha year
Zinc	800 mg/kg db	600 g/ha year

Digestate generally has a lower concentration of harmful heavy metals than sewage sludge. It is perceived that the digestate substrate, e.g. food wastes, for anaerobic digestion is "cleaner" than sewage sludge which is why it is more appropriate to use for fertilization than sewage sludge. But a definitive answer to its fertilizer-eligibility requires a digestate-specific analysis. A voluntary certification system exists which, if the limits are met, allows the digestate to be labelled a certified bio fertilizer (Naturvårdsverket, 2012). What is interesting to note is that all heavy metals limits for this certification are less stringent than the restrictions set for sewage sludge.

Using ashes as a fertilizer may be advantageous since the combustion process destroys many harmful materials and chemicals in the sludge, however many of the soil nutrients are combusted as well, making the overall outcome hard to determine. Another drawback is that spreading untreated ashes from sludge combustion yields limited crop benefits since the ash phosphorus is not plant available (Ottosen, et al., 2013). Overall, the effects of using combustion ashes for fertilization are not well documented at present. In 2010, the primary ash utilization was for construction material at landfills, and only ca. 1 % was used for soil improvement. The Swedish Thermal Engineering Research Institute, Värmeforsk, has set up a program called the "Ash Programme" in order to expand the body of knowledge concerning uses of ashes in Sweden. A conclusion from the "Ash Programme" is that more research is needed in order to establish potential gains and harms of using ashes in agriculture (Strömberg, 2012a). A body of regulations is therefore not in place as of yet.

Regarding the aspect of classification i.e. waste versus product, ashes tend to fall in between. An example is if an ash can be considered to have a legal and safe deposition it can be considered a byproduct. But based on waste directives from the EU there is the “End of Waste” criteria which determines when waste may cease being categorized as a ‘waste’ and instead be identified as a ‘product’. As of yet no “End of Waste” criteria regarding ashes exist. Another requisite to denote ash as a product, if the use to a large extent depends on the chemical properties, is that it needs to be registered according to the chemicals legislation REACH. At present there are ashes from Swedish plants registered in REACH (Strömberg & Herstad Svärd, 2012).

2.8 Waste classification

Fibrous sludge, DSS and digestate contains a high fraction of organic matter and burning it can be considered a CO_2-neutral process. One might therefore expect it to be classified as biomass in most applications, which indeed is the case when they are used as fertilizers. This is however not the case for incineration where instead DSS, fibrous sludge and digestate are classified as wastes (Bäfver, et al., 2013). One criteria to determine if a material, substance or object is classified as waste is if it fits into a waste category. Wastes are in the EU categorized and classified according to different codes in the European Waste Catalogue (EWC). In this catalogue there are some codes concerning sludge, listed below:

- 19 06 Waste from anaerobic treatment of waste
- 19 06 04 Digestate from anaerobic treatment of municipal waste
- 19 06 06 Digestate from anaerobic treatment of animal and vegetable waste
- 19 08 Waste from sewage treatment plant that is not otherwise specified
- 19 08 05 Sludge from treatment of urban wastewater
- 03 03 Wastes from pulp, paper and cardboard production and processing
- 03 03 05 De-inking sludge from paper recycling
- 03 03 07 Mechanically separated rejects from pulping of waste paper and cardboard
- 03 03 10 Fiber rejects, fiber-, filler- and coating-sludge from mechanical separation
- 03 03 11 Sludge from on-site effluent treatment other than those mentioned in 03 03 10

All of these EWC-codes are listed as wastes eligible for incineration in Högdalen and in boiler B2 in Brista (Environmental Protection Agency, 2002) (Miljödomstolen, 2010) (Miljödomstolen, 2002). This may be interpreted as sludge combustion using DSS, fibrous sludge and/or digestate is possible without legal hindrances in these boilers.

3 Burning sludge separately (mono-firing)

Mono-combustion is today used to handle sludge, primarily for volume reduction. This way of combusting substantially wet materials can be troublesome but with sufficiently dry sludge mono-combustion is an option. The main factor to suggest mono-combustion is the high availability of soil nutrients in the ashes; co-combustion with other fuels produces ashes where these would otherwise have been diluted. This in turn will improve the ability to recover the nutrients from the ashes and using them as a fertilizer. But with regard to Fortum’s case, one considerable drawback of mono-combustion is that a completely new plant or block has to be built, resulting in large investments and years of planning and construction. Case studies of existing mono-combustion plants and issues regarding mono-firing of sludge will here be discussed along with companies involved in the selling and building of sludge incineration plants.

Commercially available concepts for sludge combustion exist. Available turn-key solutions incorporating sludge drying, a bubbling fluidized bed boiler, electricity generation equipment and flue gas treatment equipment can be bought from a company named Outotec. This solution can also incorporate ash phosphorus extraction by using the Ash Dec technique, which is discussed more in chapter 5.

Sludge2energy is another company which also sells a concept and offers turn-key solutions for mono-combustion of sludge, also based on a BFB boiler. Their solutions can be complemented with suitable equipment to utilize the excess heat and an ash phosphorus extraction process.

Buying a complete sludge to phosphorus system from Outotec may not be necessary if one already holds some equipment such as a steam turbine and flue gas cleaning equipment on site. This can reduce the investment costs if existing blocks can be incorporated with the sludge mono-combustion unit. But on the other hand maintenance and warranty issues can be facilitated if all equipment is bought from one supplier.

Sludge mono-combustion in practice

Today sludge is being mono-combusted at several locations in Europe and all over the world. Many sludge incineration plants are currently in operation. A few existing and upcoming plants are mentioned here.

In Bad Vöslau, Austria, a sludge incineration plant was built by the company KAOLGEO in 2005. The plant is based on a bubbling fluidized bed boiler. About 30000 tonnes DSS with approximately 25 % DS is annually delivered to the plant. A portion of the incoming sludge is dried to 75 % DS in a contact dryer heated with steam from the boiler. The dried sludge is then mixed with the dewatered sludge to form a mixture of 47 % DS with a LHV of ca. 4,2 MJ/kg. The flue gases are cleaned with a dry and a wet scrubber and a filter to remove particles. The plant is in operation for 8000 hours per year and can deliver 1,3 MW of heat with flue gas condensation running and 0,3 MW without (KAOLGEO, 2014) (CEBC, 2014).

One of Europe's largest sewage sludge incineration plants is located in Moerdijk in the Netherlands. The plant has a self-sustained incineration process in a BFB which can be in operation more than 8000 h/year handling ca. 400000 tonnes of DSS annually at 22-30 % DS. The incoming DSS is dumped into a sludge bunker from which it is transported by a crane to screw conveyors and then to an intermediate sludge silo. From the silo the sludge is transported through a steam dryer before it is fed to the FB boiler with another screw conveyor. The sludge is dried to 35-45 % DS and ammonia is cleaned out from the vaporized water in an ammonia stripper to be used in the plant's SNCR. In addition to the SNCR the plant has a two-stage scrubber system, injection of a mixture consisting of limestone and activated carbon and bag filters to clean the flue gas. The plant produces electricity with a steam engine with an output of 300 kW. The low output is probably a result of the low steam data of 180 °C and 10 bar delivered at a rate of 11 tonnes/h (Outotec, 2013a).

In Zürich, Switzerland a sewage mono-combustion plant is under development. The plant has been ordered from Outotec and will work according to the same process as the previously mentioned plant in Moerdijk, except for some differences. The Swiss plant will handle 100000 tonnes of sludge at 22-30 % DS annually which is dried to 35-45 % DS. The steam produced in the boiler will have a higher temperature and pressure, 450 °C and 60 bar respectively. The steam will be delivered to a steam turbine, as opposed to a steam engine, at a rate of 9 tonnes/h. The electrical output from the plant will be 900 kW with the capability of producing district heating as well (Outotec, 2013b).

The Avedøre Spildevandcenter plant in Denmark couples sewage treatment with mono-combustion of byproduct DSS. The DSS is dried to 32 % DS and is injected into a FB boiler for combustion (ForskEl, 2010). The plant combusts ca. 7700 tonnes DS (ca. 35000 tonnes on total basis) per year with continual operation 5 days a week. Total investment costs amounted to 154 million DKK, corresponding to ca. 200-220 MSEK adjusted for inflation since the year 2000 (Balmér, et al., 2002).

3.1 Concluding remarks on sludge mono-combustion

Some general remarks regarding mono-combustion on sludge based on the facts mentioned in the previous chapters will be mentioned here. There are both advantages and disadvantages when investigating the possibilities to implement mono-combustion in the case of Fortum. These are:

- There are self-sustained mono-combustion plants which can operate with DSS with as low as 32-45 % DS. This does not concur with the Tanner diagram discussed in section 2.6. It can be interpreted that mono-combustion is possible with higher moisture contents than 50 %.
- Drying of the dewatered sludge is obliged for a self-sustaining combustion process.
- Thermal energy for drying is most often taken from heat generated during the combustion.
- Low power output due to energy demanding drying equipment and low energy content of the sludge, but the power produced can be used to reduce the operational costs of the mono-combustion plant.
- High investment cost will ideally require high revenues from sludge disposal and an income from the recycled phosphorus to ensure economic feasibility.
- Effective and simple method for volume reduction if this is the primary purpose.
- May not replace an existing block in Fortum’s plants. Could act as an auxiliary unit producing only heat.
- Mono-combustion systems from Outotec are capable to produce steam with temperatures and pressures similar to that of the grate furnace boilers P1-P4 and B2.

4 Mixing sludge with other fuels (co-firing)

Co-combustion of sludge is the easiest way to combust the types of sludge discussed in this study. Ignition problems and other problems connected with high moisture content and low heating values can be evaded by mixing it with higher energy fuels commonly used in the industry. Sludge has in certain cases even been shown to be beneficial to evade risks of corrosion, deposits and other operational issues normally associated with certain boilers and fuels. In this chapter, studies of previous experiments and existing sludge co-combusting plants will be presented, aimed at showing the effects of mixing sludge with other fuels and how this is applied in reality. Co-combustion with digestate is virtually unexplored, which is why these cases are all based DSS fired with different waste-types and biomass fuels. The different case studies are divided according to the boiler used i.e. one section for FB boilers and one section for grate furnace boilers.

4.1 FB combustion

Co-combustion in FBs is a promising method for successfully integrating sludge in a fuel mix due to the boiler’s high fuel flexibility. On the other hand, the bed sand in the residue ashes speaks against its suitability for practical phosphorus recycling. This aspect must be taken into consideration. Previous experiments and experiences will be discussed below which have been aimed at illuminating what may be expected from DSS co-combustion in a CFB boiler. The DSS used in these studies can be considered comparable to each other.

One study was an experiment, part of a Värmeforsk-project called *"Agglobelägg 3"*, on DSS from Himmerfjärdsverket and RDF/bark co-combustion by Herstad Svärd, et al. (2011) performed in 2009, using a 12 MW CFB boiler at Chalmers University of Technology to study the occurrence of corrosion, agglomeration and deposits in 6, 12 and 24 h test trails. The boiler featured a separate sludge feeding system feeding the boiler with DSS corresponding to 14 %, 25 % and 33 % on total mass basis via feeding screws, mixing it with the base fuel which was a 20/80 % RDF/bark fuel mixture. The DSS used had a moisture content of ca. 70 %. These high DSS concentration-mixtures were possible due to the low moisture content (ca. 10 %) of the RDF/bark mix.

Ljungdahl & Zintl, (2001) studied the effects on thermodynamic properties, emissions and effects on agglomeration from DSS co-combustion in a laboratory scale boiler. One of their experiments used chipped recycled waste wood or RT-chips as a base fuel. The DSS used was in this case dried to a moisture content of 40 %, and the fuel consisted of 50 % RT and 50 % DSS on total mass basis. Worth noting is that this study showed that the amount of sludge possible to mix with another fuel is limited by the subsequent adiabatic combustion temperature, increase of flue gas volume and the increased formation of ash.

Petterson, et al. (u.d.) performed similar tests to the Värmeforsk-project, studying corrosion and deposition effects from co-combustion of DSS at 75 % moisture content. Händelöverket's 75 MW CFB was used for one short term (24 h) and one long term (1000 h) trail. The tests featured a separate sludge handling/feeding system which fed the boiler with DSS via feeding screws. The boiler is normally fired with a 40/60 % mix of household and industrial waste. The short term test was carried out feeding ca. 6 tonnes/h of DSS and the long term test used 3 tonnes/h, corresponding to ca. 20 % and 10 % DSS mix on total mass basis respectively.

Deposits

Herstad Svärd, et al. (2011) showed that the occurrence of alkali chlorides in the deposits decreased as the amount of DSS in the mix increased. But compared to an earlier experiment (*"Agglobelägg 2")* they performed where 8 % DSS on dry basis from Ryaverket in Gothenburg was mixed with wood, straw and PVC, the reducing effect was not as prominent, see Figure 17 (Herstad Svärd, et al., 2011). The probable explanation to this is the high amount of calcium in the RDF/bark fuel which sufficiently replaced the alkali metals in reaction with the sulfur and phosphorus (see section 6.1.1). This was evident in the total amount of deposit accumulated. The 9,2 % DSS fuel mixture on dry basis produced a larger amount of deposits than the reference case, i.e. no DSS in the mix, and contained a large amount of sulfur. Only at the 13 % DSS mix on dry basis was the alkali reducing mechanism effective, where the amount of alkali chlorides was virtually eliminated and the amount of deposits were cut by more than half. This is seen in Figure 17 under "Agglobelägg3".

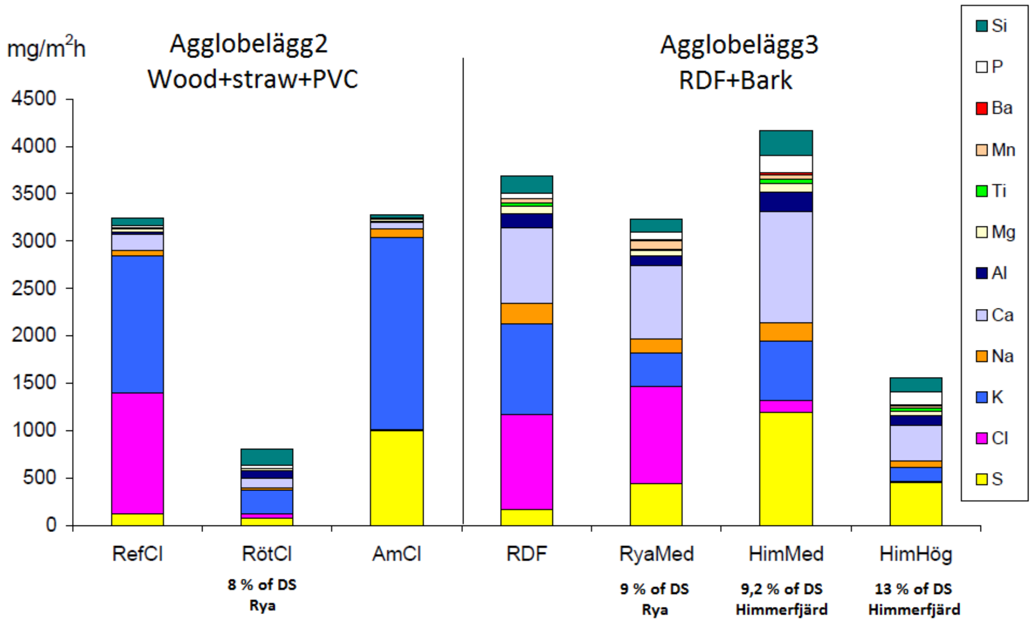


Figure 17: Results on amount of deposits from the projects Agglobelägg 2 and Agglobelägg 3 (Herstad Svärd, et al., 2011).

The tests by Petterson, et al. (u.d.) exclusively show higher deposit formation rates than the reference case where only waste was fired. The deposit accumulation tended to be higher on higher temperature testing probe surfaces. The difference between these findings reveals the significance of the base fuel and DSS contents as well as DSS mixing ratios. In other words one cannot draw any definite conclusions on the effects on deposit accumulation when co-combusting DSS.

Corrosion

According to Herstad Svärd, et al. (2011) there is no clear indication that sludge will be beneficial since the high content of sulfur adds to the corrosion risk. But the results from super heater corrosion probe measurements can overall be summarized as positive, showing a general decrease of corrosion with higher concentrations of DSS. These test were however performed at temperatures up to 700 °C, providing no clear indication of corrosion tendencies at higher temperatures when sulfur induced corrosion becomes significant. This higher content of sulfur is also evident as demonstrated by Ljungdahl & Zintl, (2001) where it was seen that the SO_x emissions increased by a factor of ca. 7 from the reference case (100 % RT-chips). NO_x emissions increased as well by a factor of 4-5 when compared to firing only RT-chips whereas there was no increase in the CFB boiler in Chalmers.

The long term tests by Petterson, et al. (u.d.) revealed that the DSS had a remarkable reducing effect on the presence of alkali chlorides in the flue gases. This in turn led to a reduction of corrosion (ca. 80 % reduction) on high-temperature (550 °C) material. At lower material temperatures the remedial effect was in essence lost, but the short term test showed that DSS mitigated the initial corrosion attack.

Agglomeration

Herstad Svärd, et al. (2011) found that the bed agglomeration temperature was increased when DSS was added, where aluminum-flocculant rich DSS raised the temperature further than iron-flocculant rich DSS. A higher DSS dosage resulted in a higher agglomeration temperature, meaning that the formation of agglomerates was in essence counteracted. This notion is supported by Ljungdahl &

Zintl, (2001) where agglomeration issues were eliminated during their DSS-mix experiment trails (Herstad Svärd, et al., 2011) (Ljungdahl & Zintl, 2001) (Pettersson, et al., u.d.).

Experiences in Industry

Although sludge co-firing in CFB boilers is commonplace in the industry, coal is the dominating base fuel used in such applications. In Germany alone, 18 hard coal-fired power plants and 8 brown coal-fired plants apply sludge co-firing (Wasielewski, et al., 2013). Cases where other base fuels are used have not been found, making it difficult to assess the potential on an industrial scale.

4.2 Grate furnace combustion

Grate furnaces are more commonly used for combustion of wastes. Corrosion, deposits and other issues are however still recurrent problems, which seem to be specific from plant to plant due to unique designs, fuel mixes etc. Coupled with a limited ability to thoroughly investigate these problems, universal solutions are inconceivable. What may be collected from the research community instead are general rules and guidelines giving an idea of what happens when boiler operation changes. Two case studies showing what effects sludge co-combustion may have on a waste-fired grate furnace boiler are discussed below.

Bäfver, et al. (2013) performed a co-combustion experiment primarily to assess the potential of phosphorus extraction from ashes when firing sludge together with biomass, though reports on emissions, agglomeration and operational observations are also presented. The experiment entailed co-combustion with RT-chips and DSS (ca. 76 % moisture content) in a 55 MW grate furnace run at 50 % capacity in Enköping, owned by ENA Energi. The DSS and RT-chips were mixed in two different compositions, one 35/65 % DSS-RT mix and one 45/55 % DSS-RT mix on total mass basis.

Another similar experiment using DSS co-fired with domestic/industrial waste and SLF (shredded light fraction) was carried out in 2011 by Gyllenhammar, et al. (2013). The aim of this study was to examine corrosion effects and the formation of deposits on heat transferring surfaces. Mixes containing 17 %, 23 % and 26 % DSS on total mass basis mixed with varying compositions of domestic/industrial waste and SLF were fired in a 15 MW grate furnace boiler.

Bäfver, et al. (2013) experienced some difficulties in handling the increase of NO_x emissions. The fuel moisture cooled the boiler which meant that the ammonia injection had to be decreased. NO_x emissions therefore increased by a factor of ca. 1,5-2,5 in the treated flue gases, where a higher DSS mix resulted in higher NO_x emissions. SO_x emissions in the treated flue gases increased remarkably, at least by a factor 9, but this is uncertain since the sampled data exceeded the instrument's measurement range. Other notable increases of emissions were of N_2O and HCl. Comparable observations on SO_x emissions were made by Gyllenhammar, et al. (2013), although these only increased by a factor of 2,5-3,5. HCl emissions doubled in the extreme case. NO_x were higher than the reference case, but no clear correlation could be detected when the amount of DSS added in the mix varied. The authors hypothesized that this was due to the subsequent lower combustion temperature when firing DSS, but also that the urea injection varied between tests. MARTIN and Vølund, the manufacturers of boilers P3 and P4 at Högdalenverket respectively stated that, via Christer Andersson (2014), a consultant at ÅF, an increase of SO_x and NO_x emissions is not guaranteed with sludge co-firing (Andersson, 2014). The data seems to support this notion.

Gyllenhammar, et al. (2013) also found that adding DSS proved beneficial for reducing the concentration of corrosives in deposits. However, an important aspect is that tests using a mix of DSS, domestic/industrial waste and SLF caused more deposits to form than tests using solely domestic/industrial waste. In fact, using SLF in the fuel mix increased deposit accumulation rates remarkably. That being said, a general conclusion that can be drawn is that adding DSS counteracts the formation of alkali chlorides but increases the concentration of sulfur in deposits, similar to tests performed on FB boilers (Bäfver, et al., 2013) (Gyllenhammar, et al., 2013). Also, different fuels will result in different accumulation rates of deposits.

Experiences in industry

Plants currently in operation in the industry today using grate furnaces with continuous co-combustion are found mostly in continental Europe. Large scale facilities include the Bamberg WtE plant in Bamberg, Germany (6,3 MW_{el}, 23 $MW_{heating}$). There, sludge is dewatered to a DS of ca. 30 % and mixed with limestone to form a granular mix which is then scattered in the waste bunker together with household, commercial and bulky waste. The plant processes 12600 m^3, corresponding to ca. 12600 tonnes, DSS per year (Hitachi Zosen INOVA AG, u.d.a) (Gyllenhammar, et al., 2013). The plant has successfully been using this method for at least 12 years, and no negative effects on incineration, burnout, smell and emissions have been detected (Hall, u.d.).

Similar to the Bamberg plant, the Thun WtE plant in Switzerland (12 MW_{el}, 25 $MW_{heating}$), operational since 2003, allows for co-incineration of sewage sludge at 20-40 % DS together with domestic and commercial waste. The grate can operate using a flow of sewage sludge of up to 10 % of waste throughput (Hitachi Zosen INOVA AG, u.d.b), amounting to an annual capacity of 10000 tonnes of DSS (Khalil, et al., 2007).

Other plants include the Würzburg and Göppingen plants in Germany which apply pre-drying processes before combustion. The plants make use of thermal energy generated on site for drying sludge which in the Würzburg plant is separately spread directly on the grate. In Göppingen the sludge is premixed and dried together with the other waste before combustion (Gyllenhammar, et al., 2013).

To summarize, there are grate furnace plants currently in operation that incinerate typical waste fuels, but have the capacity to add sludge in the fuel mix as well at no critical expense in modified plant design. This supports the notion that a system of continuous sludge co-incineration is readily attainable, at least in grate furnace boilers. Undoubtedly, one must be precarious when comparing different plants and boilers to each other. Incineration systems are designed and developed over time according to a plant's specific premises, but the fact that it is tried and tested in many plants today suggests that a similar system is possible to implement in Fortum's plants.

4.3 Concluding remarks on co-combustion

Based on the cases discussed above, and findings by Linder (2001) on other similar cases, conclusions that can be drawn from co-combustion of sludge with other wastes are as following (Linder, 2001):

- There is an impending risk of increased NO_x and SO_x emissions. Some cases have reported a considerable upsurge in SO_x emissions but NO_x emissions have not been shown to increase as drastically.
- The effects on corrosive deposits and agglomeration are predominately positive. The reason for this is mostly attributed to the high content of phosphorus and sulfur in the sludge which counteracts the formation of alkali chlorides.
- There are different methods by which sludge is injected into the boiler:

    - For grate furnaces sludge may either be dumped in the waste bunker, dosed onto the fuel in the feed hopper, injected in the chute or sprayed directly onto the fuel bed in the furnace.
    - FB boilers typically require a separate, dedicated sludge feeding system which injects the sludge directly into the sand bed. Many types require the sludge to be “pumpable” which means that the dry content should preferably not exceed 25 %.
- Both Herstad Svärd, et al. (2011) and Petterson, et al. (u.d.) experienced difficulties with the sludge feeding system to the CFB boiler. Rocks and other impurities in the DSS often caused the screw feeders to break down. Tests using grate furnaces did not have as many problems.
- The type of base fuel plays a critical role in determining what may be expected from adding sludge to the fuel mix. As previously shown, a high content of calcium is detrimental to the formation of alkali sulfates and alkali phosphates, leaving a greater possibility for corrosive alkali chlorides to form. This affects the nature of deposit accumulation and corrosion.
- High water content sludge may increase the amount of unburnt material in the ashes.
- A large amount of water in the fuel mix may change the heat transfer distribution in the boiler system. This can in turn affect corrosion characteristics and influence the efficiency of certain flue gas cleaning equipment, for example the SNCR system.
- The water amount can also affect the combustion temperature, which is critical when incinerating wastes. This may imply the need for support firing to ensure that the combustion temperature does not fall below 850 °C.

A new sludge firing system will obviously be unique in character. Firing digestate is virtually unheard of even. The total combination and interplay of the different factors, i.e. type of sludge, boiler, base fuel etc., will not resemble any other system. The new system will instead have a distinct set of features and produce its own set of operational issues.

Consequently, experiences from previous cases can at most be used as guiding principles to be used in further discussions. To the extent this is possible this will be done when hypothesizing on possible solutions for incinerating sludge in Högdalen or Brista.

5 Phosphorus recycling

The main soil nutrient remaining after combustion is phosphorus which is found in the post-combustion ashes, but spreading untreated ashes directly on farmlands is legally ambiguous and anyway not beneficial, as mentioned in section 2.7.1, and therefore not considered a viable alternative. Additional treatment of the ashes is for this reason needed if it is to be used as a fertilizer. This chapter will include a discussion on companies with developed techniques for industrial scale purposes.

There are two techniques that have shown great potential in ash-phosphorus-recovery; Ash Dec (owned by Outotec) and CleanMAP (EasyMining Sweden’s method). The Ash Dec process is commercially available while the CleanMAP technology is expected to be market-ready in the near future. CleanMAP has as of yet only been tested on a laboratory scale (Fahlström, 2014).

The Ash Dec technique is applicable in industrial scale activities and is based on a thermo-chemical process which removes toxic heavy metals from sludge combustion ashes. A mix of the ash, chlorine and other additives is sent to a thermal reactor and kept at a temperature around 1000 °C for 20 minutes. Heavy metals, such as mercury and lead, evaporate with the additives. In an optional last step the remains can be enriched with other nutrients to become a multi-nutrient fertilizer adapted for cropland (SSWM, 2010).

In brief, EasyMining's process incorporates five steps. Dissolving of the ashes with acids is the first followed by filtering to precipitate sand and gypsum. After filtering, the CleanMAP technology is used where a separation incorporating ammonia extracts the phosphorus in the form of ammonium phosphates. After this step two more separation steps are used to precipitate metals such as aluminum and iron, and lastly, heavy metals. The process can be applied to ashes both from mono-combustion and co-combustion of sludge. In the sense of this study ashes from the sludge types mentioned in chapter 2.5 can be used in the process (EasyMining Sweden, 2013). This method has successfully been tested in the co-combustion experiment conducted by Bäfver et al., (2013) mentioned previously.

A crucial condition to both methods is the concentration of phosphorus in the residue ashes. Previous experiences using the EasyMining technique have shown that a phosphorus concentration of at least 5 % is needed for an economically viable system (Fahlström, 2014) and the Ash Dec technique requires sludge mono-combustion ashes also with at least 5 % phosphorus content (Naturvårdsverket, 2013). Moreover, these facilities are designed with a capacity to receive ashes in the range of 10000-30000 tonnes per year (TYRÉNS, 2013).

Naturally, both techniques benefit from an even higher phosphorus concentration since the end product needs to be able to compete with conventional fertilizers on the market, and regulations on harmful materials are often based on the relative amount of phosphorus, e.g. mg cadmium per kg phosphorus (Dornisch, 2013). It is therefore evident that co-combustion ashes make the methods less effective since the phosphorus is diluted when sludge is burned with a phosphorus-poor fuel. For this reason, ash-phosphorus recovery techniques are most commonly, but not exclusively, coupled with mono-combustion.

6 Sludge combustion in Fortum's case

Firing sludge, either by mixing it with other fuels or burning it separately, is evidently a tried and tested activity. Fortum, which owns many different plants, will firstly want confirmation if it is possible in the first place to integrate sludge incineration into their systems, and then arguably want to know the best method out of a variety of methods. In order to assess the best method of combusting sludge in Fortum's plants many scenarios can be considered, but to limit the extent of the study the evaluation was based on four different scenarios. The following scenarios were considered:

- Scenario 1: Combust ca. 70000 tonnes/year DSS from Stockholm Vatten
- Scenario 2: Combust ca. 26400 tonnes/year digestate from a biogas plant in Högdalen
- Scenario 3: Combust ca. 50000 tonnes/year fibrous sludge from Holmen paper
- Scenario 4: Mono-combustion of the different sludge types

The scenarios will be evaluated from an overall broad perspective, assessing the activity of sludge combustion as a general system. This means that the specific system design is irrelevant, e.g. whether Fortum or third party actors own and operate the system components or how the system components are related to each other. A consequence of this is that system specific practicalities such as transports and business agreements are not taken into consideration.

A sludge feeding system can only be installed for one boiler due to economical limitations, except for the case of using P1 and P2 together. Since they are next to each other and similar in design it will be assumed that these can be used in tandem with a feeding system portioning sludge evenly between them. The scenarios will therefore be based on the assumption that only one boiler, except P1 and P2 together, may incinerate all the sludge. Additionally, it will be assumed that storage is needed but not necessarily on site, meaning that the storage can be placed at the sludge supplier which probably already has such storage. An intermediate sludge storage at the plant would be considered sufficient.

The method by which sludge is fed into the boiler would in reality be specific to each individual boiler. Issues such as spatial ability, sludge moisture content massflow and smell etc. would be important to take into consideration. Admittedly, this would require further evaluation than is attainable. In this study it will be assumed that CFB boilers will need a separate, dedicated sludge feeding system which injects sludge directly into the furnace. For the grate furnaces the sludge feeding system can, apart from injecting directly into the furnace, allow the sludge to be added to the base fuel in the ordinary fuel feeding system. It may be fed into the feed hopper or injected in the chute. The limit for these methods (feeding grate furnaces) are mixtures of ca. 15 wt-%, based on information from Völund and MARTIN via Christer Andersson (2014). It is difficult to determine which of these methods will be best. In general though, spreading directly on the fuel bed is recommended for higher sludge mixing amounts. Dumping directly into the fuel bunker is disregarded as this would lead to odor issues and complicate accurate dosing (Andersson, 2014).

Sludge drying is, although beneficial for combustion, too energy demanding to be viable in a co-combustion application. Furthermore, maintaining 100 % net steam power from the boiler for heat and power production will not be possible if thermal energy for drying is taken from the steam cycle. For a mono-combustion plant, drying is however strictly necessary. It will therefore be assumed that drying is not incorporated in the co-combustion scenarios, whereas it will be dried to 55 % moisture content in the mono-combustion scenario. This is deemed sufficient for self-sustained combustion whilst still avoiding the sticky phase, see section 2.6.

In all scenarios, an effect of firing a sludge mixture is that the total amount of base fuel needed will decrease slightly. Depending on the type of base fuel, this can be interpreted as an avoided cost or loss of income.

In Scenario 2, the economic effects of firing a sludge mix in Högdalen will be compared to a case in which the base fuel is MSW without food waste. The reason for this is that there is digestate to combust only if a biogas facility is there to produce it, which means that there would already be a system in place in which food waste is being separated from the ordinary MSW. It is assumed that MSW without food waste has the same monetary value as MSW. Technical considerations concerning the grate furnaces in Högdalen in Scenario 2, such as relative change in water vapor in the flue gases, will be compared to firing only MSW (the current base fuel) in order to give data that is relatable.

Operational costs will be presented as a difference from firing the base fuel only. This means that some factors in a co-combustion case such as income from heat and electricity sales will not be included since the power output is assumed to not change when firing a sludge mix. A mono-combustion plant will however be contributory to Fortum’s heat capacity which is why heat incomes will be included in scenario 4.

6.1 Calculation models

The different calculation models used to examine and evaluate the different boilers when assessing the sludge combustion potential are presented here. Relevant assumptions and limitations are also discussed. The calculation procedure and evaluation was based on an interactive excel document made by the authors for the purposes of this study. The document allows the user to select sludge type and sludge amount, in total weight percent, to add to the base fuel for each boiler. Mono-combustion of the different sludge types can also be evaluated using the same excel document.

6.1.1 Sludge mix and LHV determination

The mixing procedure is calculated in a way where the ultimate analysis and the ash and trace elements analysis of the fuel and the sludge are mixed based on a chosen weight percentage of sludge into the fuel. The generic equation for finding the mix's composition is

$$Z_{mix} = Z_{base\ fuel} \cdot (1 - \Psi) + Z_{sludge} \cdot \Psi. \qquad (1)$$

Z denotes the component of interest, either on dry or wet basis, e.g. C, H, moisture content etc. Ψ is the total weight percentage of sludge to add to the fuel. This equation is also used to find the mix's LHV.

In reality, a mixing procedure would not result in a homogenous blend and the mix's composition would vary. But by assuming a homogenous mixture and using analyses provided in section 2.3 and 2.5, the mix's composition can be calculated. The amount of sludge possible in the mix is limited by the resulting heating value. That is, the mix must be able to maintain 100 % boiler power whilst still being within the boiler's fuel feeding capacity. These limitations are given in the stoker capacity diagrams found in section 2.4. Ψ is chosen in order to cover the amounts of sludge in the different scenarios. If the boiler at hand can handle these amounts, further analyses are carried out.

For analyses where the heating value was not provided, the fuel's or sludge's dry content heating value was determined as

$$LHV_{dry} = 35 \cdot Y_C + 93{,}9 \cdot Y_H - 10{,}8 \cdot Y_O, \qquad (2)$$

where Y_c, Y_H and Y_O are the dry mass fractions of carbon, hydrogen and oxygen in the fuel (RET MJ2411, 2012). The lower heating value, as received, is calculated as a function of the dry content heating value as

$$LHV_{ar} = LHV_{dry} \cdot (1 - u) - h_{water} \cdot u, \qquad (3)$$

where

$$u = \frac{m_{water}}{m_{ar}}. \qquad (4)$$

h is the heat of vaporization for water, which is 2,443 MJ/kg (Strömberg, 2012b). The LHV is used to determine the massflow of the base fuel and sludge mixture as

$$\dot{m}_{base\ fuel} = \frac{P_{fuel}}{LHV_{base\ fuel}} \qquad (5)$$

and

$$\dot{m}_{mix} = \frac{P_{fuel}}{LHV_{mix}}, \qquad (6)$$

where P_{fuel} is the fuel power needed for the boiler under study to maintain 100 % load, see Table 15. $LHV_{base\ fuel}$ and LHV_{mix} are the LHV_{ar} for the base fuel and sludge mix respectively. $\dot{m}_{base\ fuel}$ is the massflow of the base fuel and $\dot{m}_{mix}$ is the subsequent massflow of the sludge mix.

Table 15: Fuel power required for each boiler to maintain 100 % load.

P1 & P2	P3	P4	P6	B1	B2
25,6 MW	51,7 MW	96 MW	100 MW	133 MW	80 MW

6.1.2 Distribution of fly ash and bottom ash

To evaluate the sludge mix's effect on the ash handling system both the change in ash content and the mass distribution between fly and bottom ash are of interest. Not only will the boiler need the physical capacity to handle more ashes from combustion, but a change in the ash amounts generated will have an impact on the ash disposal costs. There may also be regulations that limit the allowed amount of fly and bottom ash, which however will not be considered in this study. The division between fly and bottom ash is also important in determining the phosphorus extraction potential. The relative difference between the base fuel's and the mix's total ash amount is expressed as

$$\Delta Ash = \frac{X_{ash,mix} \cdot \dot{m}_{mix}}{X_{ash,base\ fuel} \cdot \dot{m}_{base\ fuel}} \tag{7}$$

$X_{ash,base\ fuel}$ and $X_{ash,mix}$ are the ash content on wet basis in the boiler specific base fuel and sludge mix, respectively. In the boiler, the ash divides into bottom and fly ash according to

$$Ash_{bottom} = X_{ash,mix} \cdot \beta_{bottom,ash} \cdot \dot{m}_{mix} \tag{8}$$

and

$$Ash_{fly} = X_{ash,mix} \cdot (1 - \beta_{bottom,ash}) \cdot \dot{m}_{mix}, \tag{9}$$

where $\beta_{bottom,ash}$ is a factor expressing the amount of the fuel ash ending up as bottom ash. It is assumed that the ash will only consist of the fuel ash, and that all fuel ash ends up as either bottom or fly ash. The factor $\beta_{bottom,ash}$ is of course unique for each boiler and can be found experimentally. Here it will be assumed as 0,5 for CFB boilers (Lindman, 2013b) and 0,85 for grate furnaces (Fortum, 2014b).

6.1.3 Combustion table for flue gas flow

Firing a sludge mixture will lead to a change in flue gas volume flow, emissions, and a change in moisture in the flue gases. This is important as it will affect the flue gas cleaning system downstream of the furnace.

The combustion products in the raw flue gases, flue gas flow, water vapor, CO_2 and SO_x emissions in the raw flue gases will be calculated using a combustion table, see Appendix 1. The combustion table shown is an example where the flue gases are evaluated based on the MSW discussed in section 2.3.2. The filled-in combustion table based on the original fuel is compared to the corresponding table for a fuel/sludge mixture. From a comparison the change in flue gas flow, water content in the gases and change in SO_x in the untreated flue gases can be found. In the combustion table complete burnout of C, H and S is assumed, N_2 is inert and the O in the fuel reduces the amount of ambient air needed for stoichiometric combustion. The combustion table includes some additional assumptions. The humid ratio in the ambient air is set to 0,009. The amount of nitrogen supplied via combustion air is given as 3,77 times the supplied oxygen. The numbers calculated from the combustion table are on a per kg fuel basis. To calculate the values on a per second basis these have to be multiplied by the massflow of the fuel/sludge mix. The relative change of flue gas flow is done at normal conditions 0 °C and 1 atm. This study is limited to examine this at normal conditions as a precise study needs a deeper investigation than this preliminary study.

6.1.4 Drying

Drying is necessary in a mono-combustion facility, which is why it will be applied in Scenario 4. The power required for drying is calculated from

$$P_{drying} = \frac{(\dot{m}_{sludge,ar} \cdot u_1 - \dot{m}_{sludge,dried} \cdot u_2) \cdot h_{water}}{\eta_{HEX}}, \qquad (10)$$

where $\dot{m}_{sludge,ar}$ is the massflow of sludge into the dryer, $\dot{m}_{sludge,dried}$ is the massflow of sludge out of the dryer. η_{HEX} is the efficiency of the heat exchange process between the steam and the sludge and it is set to 0,8. u_1 and u_2 are the moisture content of the sludge as received and after the dryer respectively. The moisture content after the dryer, u_2, is set to 55 % in order to avoid the sticky phase. It is assumed that energy to dry the sludge will be taken from steam produced in the process which implies that the cost for drying can be considered as a loss of income from power and heat production. The income from heat and electricity sold can be calculated according to

$$I_{DH} = P_{net} \cdot t_{op} \cdot i_{DH} \cdot (1 - \alpha) \cdot \eta_{HEX} \qquad (11)$$

for district heat and

$$I_{el} = P_{net} \cdot t_{op} \cdot i_{el} \cdot \alpha \cdot \eta_{el} \cdot \eta_{mech} \qquad (12)$$

for electricity on a yearly basis. The net power from the boiler, P_{net}, available for power production is calculated by

$$P_{net} = P_{fuel} \cdot \eta_{boiler} - P_{drying}. \qquad (13)$$

i_{el} and i_{DH} are the income from electricity and district heating sales respectively. The incomes are set to 311 SEK/MWh for electricity (Nordpool spot, 2014) and for heat from a medium sized plant 1-10 MW 499 SEK/MWh and large plants >10 MW 324 SEK/MWH (Nohlgren, et al., 2014). The mechanical efficiency of the steam turbine η_{mech} and the efficiency of the generator η_{el} are both assumed to be 0.98, and η_{boiler} is set to 0,9. α is the alpha-value i.e. the factor stating the share of produced electricity in relation to total produced energy and t_{op} is the yearly operational time of the boiler. A typical alpha-value for a WtE CHP plant coupled to a district heating network is 0,24 and 0,40 for a biomass-fired CHP plant (Nyström, et al., 2011). The mono-combustion facility will not produce any electricity i.e. the alpha-value is 0.

Drying the sludge can thus be interpreted as a loss of a potential income, C_{drying}, which corresponds to

$$C_{drying} = P_{drying} \cdot t_{op} \cdot (\alpha \cdot i_{el} \cdot \eta_{mech} \cdot \eta_{el} + (1 - \alpha) \cdot i_{DH} \cdot \eta_{HEX}). \qquad (14)$$

6.1.5 Combustion related key values for assessing effects on boiler operation

The chemical reactions happening during a combustion process and in the succeeding flue gases can be hard or impossible to follow. But a qualitative judgment of the reactions to be expected can be done by calculating and observing certain key values based on the chemical composition of the fuel/mix used. The chemical reactions of interest in this study are those contributing to and countering the tendency for corrosive compounds formation and agglomeration in the boiler. These key values (calculated on a molar basis) are presented and explained below (Gyllenhammar, et al., 2013) (Davidsson, et al., 2012):

Cl/(Na+K): Indicates theoretically if there is enough chlorine to react with the alkali. Alkali chlorides are highly corrosive compounds and are therefore unwanted. Ideal values are low (less than 0,3 (Brodén, 2008)).

2S/(Na+K): Indicates if there is enough sulfur to react with the alkali. Alkali sulfates are less corrosive than alkali chlorides. This value should therefore ideally increase.

2S/Cl: Indicates if there is enough sulfur to replace the chlorine, which counteracts alkali chloride formation. This value should therefore ideally increase.

(2S+3P)/(Na+K): Indicates if there theoretically is enough sulfur and phosphorus to react with the alkali. Phosphorus can also react with alkali metals to form alkali phosphates, which is less corrosive than alkali chlorides. This value should therefore ideally increase.

(2S+3P)/Cl: Indicates if there is enough sulfur and phosphorus to replace the chlorine, which counteracts alkali chloride formation. This value should therefore ideally increase.

Ca/(S+1,5P): Indicates the amount of calcium present for reaction with the sulfur and phosphorus. A high value indicates a stronger tendency to counteract the favorable reaction of sulfur and phosphorus with alkali metals. For FB ideal values are <1,5, but grate furnaces are less sensitive.

These expressions will not reveal how the reactions will transpire in actuality. For example, it is not known what ratio of sulfur will react with alkali metals as opposed to oxygen to form SO_2. The indicator that can be used is the relative change of these values when adding sludge to the fuel mix. By seeing if they become higher or lower compared to the base fuel, assuming that the original fuel does not show any severe operational issues, a qualitative judgment can be done. In essence, the risk for operational issues can therefore be assessed on an increased/decreased basis.

6.1.6 Phosphorus

The distribution of the components in the ashes such as P, Pb, Zn, Ca etc. do not necessarily distribute according to the mass distribution of the ashes. An ash compositional analysis should ideally be performed on the fly and bottom ashes in the boiler to determine where the ash components end up.

The concentration of phosphorus in the ashes is important in order to assess the feasibility of phosphorus extraction. The maximum concentration of phosphorus in the ashes for grate furnaces is calculated according to

$$p_{max} = \frac{X_p}{X_{ash}}, \tag{15}$$

where X_p and X_{ash} are the total mass fractions of phosphorus and ash in the mix. For the CFB boilers the sand will dilute the phosphorus based on the feed of fresh sand to the boiler. For CFB boilers the maximum concentration of phosphorus in the ashes is calculated according to

$$p_{max} = \frac{X_p \cdot \dot{m}_{mix}}{X_{ash} \cdot \dot{m}_{mix} + \dot{m}_{sand}}. \tag{16}$$

$\dot{m}_{sand}$ is the massflow of sand which amounts to 0,23 kg/s for P6 and 0,13 kg/s for B1.

In the boiler the ashes divide and end up as either bottom ash or fly ash. The concentration of phosphorus in the fractions are calculated as

$$p_{max,bottom\ ash} = \frac{p_{max} \cdot \beta_{P,bottom,ash}}{\beta_{bottom,ash}} \tag{17}$$

and

$$p_{max,fly\ ash} = \frac{p_{max} \cdot (1-\beta_{P,bottom,ash})}{(1-\beta_{bottom,ash})}, \qquad (18)$$

where $\beta_{P,bottom,ash}$ expresses the portion of fuel phosphorus that ends up in the bottom ash. It is assumed that all fuel phosphorus ends up in either the bottom or fly ash. The distinction between these is important since they cannot be mixed due to environmental regulations. If $\beta_{P,bottom,ash}$ is not known for the boiler under consideration it will be assumed to be 0,8 for grate furnaces and 0,24, which is taken from an experiment performed in boiler P6, for the CFBs (Bäfver, et al., 2013) (Lindman, 2013b). To assess if phosphorus extraction from the residue ashes is economically viable the concentration of phosphorus in any of the ash fractions must be 5 % or higher. This is based on the information retrieved in this thesis.

For further economic judgment it is not clear how the phosphorus recycling would be handled, i.e. if the recycling equipment will be at the same location as the combustion facility or at a central ash receiving site. In any case the phosphorus can generate a direct income or result as an avoided cost. For the cases where the concentration of phosphorus is higher than 5 % in an ash fraction it will be considered to have a monetary value. The value of the phosphorus, V_p, can be estimated as

$$V_P = (Ash_{fly} \cdot p_{max,fly\ ash} + Ash_{bottom} \cdot p_{max,bottom\ ash}) \cdot 0{,}9 \cdot i_P \cdot t_{op}, \qquad (19)$$

where i_p is the market price for pure phosphorus and amounts to 20 SEK/kg (KSLA, 2013) and 0,9 represents the expected degree of extraction.

6.1.7 Environmental considerations

Emissions of SO_x are found using the combustion table. Calculating NO_x emissions in the raw flue gases is not as straight forward since the mechanisms behind it are more complicated. It is nonetheless an important consideration since it affects the NO_x cleaning equipment and may lead to increased NO_x emissions to the environment and higher emissions charges. What could provide an indication on how NO_x emissions may be affected is the change in massflow of fuel-bound nitrogen, which contributes as fuel NO_x to the total emission of NO_x. This is calculated as

$$fuel - N = \frac{X_{N,mix} \cdot \dot{m}_{mix}}{X_{N,base\ fuel} \cdot \dot{m}_{base\ fuel}}, \qquad (20)$$

where $X_{N,mix}$ and $X_{N,base\ fuel}$ are the nitrogen content on wet basis in the sludge mix and base fuel respectively.

The sludge-carbon is biogenic which means that fossil CO_2 emissions will decrease if the MSW and PTP fuels are displaced since a fraction of their carbon content are fossil based. This decrease is found by

$$Fossil_{CO_2} = \Delta Base\ fuel \cdot e_{CO_2}. \qquad (21)$$

$Fossil_{CO2}$ is the change in fossil CO_2 emssions, expressed in tonne/year. *ΔBase fuel* is the change in the amount of base fuel to be incinerated expressed as tonnes/year, and e_{CO2} is the fossil carbon emission factor which is set to 0,54 tonne CO_2 per tonne MSW of PTP (Avfall Sverige, 2012).

Other issues related to environmental considerations are an increased use of chemicals for the flue gas cleaning and the phosphorus extraction process. These can only be discussed on a qualitative basis.

6.1.8 Economic calculations

The following economic calculations on costs and incomes are based on what affect integrating sludge combustion will have on total revenues as compared to base fuel operation. For Scenario 1, 2 and 3 this will entail an added O&M cost, income/cost from displacing the base fuel, income/cost for disposing more or less combustion ashes and income/cost from acquiring the sludge. Scenario 4 will entail income generated from heat and electricity sales, income/cost from acquiring sludge, cost for sludge drying and an O&M cost which includes ash disposal costs for running the mono-combustion plant. The net revenues from these calculations will have to carry their respective investment costs.

Receiving sludge may generate an income based on the amount of sludge received. This can be calculated according to

$$I_{sludge} = m_{sludge,ar} \cdot i_{sludge}. \qquad (22)$$

Where I_{sludge} is the annual income from receiving sludge, $m_{sludge,ar}$ is the annual amount of sludge to be received and i_{sludge} is the income per tonne from the specific sludge. The expected income per tonne for the different sludge types are presented in Table 16. Market prices for these do not exist. Instead these are estimated based on alternative prices for other uses.

Table 16: Income per tonne of sludge. Estimated based on alternative prices for other uses (Fortum, 2014b).

DSS	Digestate	Fibrous sludge
200 SEK/tonne	250 SEK/tonne	-50 SEK/tonne

Co-combustion

A change in the amount of combustion ashes will lead to increased or decreased costs for ash disposal. This is expressed as

$$C_{ash\ disposal} = \Delta Ash_{disposal} \cdot ((1 - \beta_{bottom,ash}) \cdot c_{fly\ ash} + \beta_{bottom,ash} \cdot c_{bottom\ ash}) \qquad (23)$$

where

$$\Delta Ash_{disposal} = X_{ash,base\ fuel} \cdot \dot{m}_{base\ fuel} \cdot t_{op} \cdot (\Delta Ash - 1). \qquad (24)$$

$C_{ash\ disposal}$ is the cost for disposing the increased amount of ashes. A negative $C_{ash\ disposal}$ would therefore be an avoided cost. $\Delta Ash_{disposal}$ is the change in the amount of ashes to be disposed expressed as tonnes/year, and $c_{fly\ ash}$ and $c_{bottom,ash}$ are the costs for transport and disposing of the ash fractions. These costs are hard to determine since they are classified. It is determined that reasonable costs are 900-1000 SEK/tonne for waste fuel fly ashes, bottom slag ashes 75-200 SEK/tonne, CFB bottom ashes 200-400 SEK/tonne. The CFB biomass ashes are cleaner and useful for reuse in forests which are therefore assumed cheaper. Reasonable costs are assumed as 200-400 SEK/tonne. For the calculations these have been actuated according to the values presented Table 17. Note that these costs may be influenced if the phosphorus extraction requirements of 5 % phosphorus in the ashes are met.

Table 17: Estimated costs for ash transport and disposal for the different boilers.

	P1-P4, B2	P6	B1
Fly ash, SEK/tonne	1000	1000	300
Bottom ash, SEK/tonne	150	400	300

As previously explained, displacing a portion of the base fuel in a sludge mix will lead to an avoided cost or loss of income, depending on the type of base fuel. This cost/income difference is calculated according to

$$C_{base\ fuel} = \Delta Base\ fuel \cdot c_{base\ fuel}. \tag{25}$$

$C_{base\ fuel}$ corresponds to the loss of income. A negative $C_{base\ fuel}$ would accordingly correspond to an avoided cost. $c_{base\ fuel}$ is the cost (price) for acquiring the base fuel. General market prices for the base fuels are shown in Table 18. For the economic calculations a future fuel price forecast from Fortum was used.

Table 18: General cost of base fuels combusted in P1-P4, P6, B1 and B2 (Fortum, 2014b)

MSW (P1-P4, B2)	PTP (P6)	Biomass (B1)
-300 to -400 SEK/tonne	Ca. 0 SEK/tonne	Ca. 500 SEK/tonne

The actual investment cost to retrofit a boiler for sludge incineration will depend on the type of boiler and the sludge feeding system etc. In this study the initial investment amounts to 10 MSEK, except in the case where P1 and P2 are used in tandem where the investment cost is set to 15 MSEK. The O&M costs amounts to ca. 2 % of the total investment for a grate furnace boiler (Gustafsson, 2014). This data was retrieved from investment details carried out by Fortum. For lack of related data, this will serve as the investment cost and O&M costs for retrofitting a CFB boiler as well.

Mono-combustion plant

The investment cost for a stand-alone sludge mono-combustion system including sludge drying and flue gas cleaning is based on data presented by Balmér et. al., 2002. The plant would probably be built close to a district heating network which is why district heating connection and equipment is assumed to only be a small share of the total investment, ca. 10 %. The total investment cost C_{inv} is for a mono-combustion plant calculated as:

$$C_{inv} = m_{sludge,ar} \cdot c_{inv}, \tag{26}$$

where $m_{sludge,ar}$ is the annual sludge handling capacity of the plant measured as tonnes on total mass basis. The factor c_{inv} is expressed as the cost of such a plant per tonne of sludge to be incinerated per year. A reasonable price range is 2600-4000 SEK/tonne as received. This is set to 3250 SEK/tonne in calculations (Balmér, et al., 2002).

The operational costs C_{op} for running a mono-combustion plant is based on data on operational costs of one of Fortum's FB boilers. These are calculated as a lump sum according to:

$$C_{op} = P_{net} \cdot t_{op} \cdot 56 + 0{,}025 \cdot C_{inv}. \tag{27}$$

C_{op} is the combined variable and fixed operational costs. The variable costs amount to 56 SEK per produced MWh of heat, which includes ash handling, electricity usage, maintenance cost and other variable costs. The variable ash handling costs may in reality be influenced by the ash-phosphorus extraction business. The fixed O&M costs is assumed to amount to 2,5 % of the total investment cost (Alsparr, 2014).

Net present value

The total revenue, R, constitutes the difference between all incomes and costs that follow from an investment as

$$R = \sum I - \sum C. \tag{28}$$

The net present value of an investment is the sum of its future costs and revenues in present value terms, providing an indication of the investment's profitability. It is calculated as (Skärvad & Olsson, 2013)

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+DR)^t} - C_{inv}. \tag{29}$$

Where *NPV* is the net present value for the investment, C_{inv} is the initial investment cost, *DR* is the discount rate set to 6 % and R_t is the annual revenue at year t. *N* is the economic lifetime of the investment, which for Scenario 1, 2 and 3 is set to 15 years and 25 years for Scenario 4 (Axelsson, 2014).

An internal rate of return calculation indicates an investment's strength by showing the consequential internal rate, *IR*, required for the net present value of an investment to be zero. A high internal rate indicates a favorable investment. It is calculated according to (Skärvad & Olsson, 2013)

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+IR)^t} - C_{inv} = 0. \tag{30}$$

The IRR should ideally be as high possible.

7 Results

In this chapter the results from the evaluation of the four scenarios are presented, along with a summary of the results. The evaluated scenarios are:

- Scenario 1: Combust ca. 70000 tonnes DSS from Stockholm Vatten
- Scenario 2: Combust ca. 26400 tonnes of digestate from a biogas plant in Högdalen
- Scenario 3: Combust ca. 50000 tonnes fibrous sludge from Holmen paper
- Scenario 4: Mono-combustion of the different sludge types

For Scenario 1, 2 and 3 the mix percentage, Ψ, was chosen to cover the amount of sludge in each case. Additionally the max sludge mixture for each boiler is presented. For Scenario 4 the size of the plant was determined from the yearly tonnes of sludge in each scenario.

The results were acquired from an excel model of each boiler made by the authors, where the complete range of possible mixtures for each boiler was looked upon. The results shown are adapted to the scenarios.

7.1 Scenario 1 – Combust all DSS from Henriksdal

Scenario 1 involves the combustion of the total annual amount, ca. 70000 tonnes, of DSS from Henriksdal. The DSS massflow and corresponding mix percentage is presented in Table 19 along with the consequential relative change of ash, flue gas water vapor, flue gas flow, SO_2 and fuel nitrogen as compared to firing the base fuel only. The table also includes the mass fraction of phosphorus in the bottom and fly ashes as well as the change of fossil-CO_2. Max mix possible and max DSS are only based on the highest possible fuel throughput according to the stoker capacity diagrams. Other factors may in actuality constitute the effective limit. The max mix P values are based on the max mix percentage. The results were produced using equations 1-9, 15-18, 20-21 and the combustion table in section 6.1.3.

Table 19: Technical results Scenario 1.

		P1 & P2	P3	P4	P6	B1	B2
Mix (Ψ)	%	-	0	-	26	-	28
DSS	tonnes/yr	-	0	-	70950	-	71553
Flue gas flow	Rel. change	-	-	-	11,3 %	-	10,2 %
Ash	Rel. change	-	-	-	**26 %**	-	**24 %**
H_2O in flue gas	Rel. change	-	-	-	**38,9 %**	-	**38,6 %**
SO_2	Rel. change	-	-	-	**25 %**	-	**23 %**
Fuel-N	Rel. change		-	-	**46,3 %**	-	**43,1%**
P in fly ash	wt-%	-	-	-	2,41 %	-	2,43 %
P in bottom ash	wt-%	-	-	-	0,76 %	-	1,71 %
Fossil-CO_2	tonnes/year	-	-	-	-3600	-	-3640
Max mix possible	%	17	0	6	**28**	11	37
Max DSS	tonnes/yr	15580*	0	18550	78260	52370	106150
Max mix P fly ash	wt-%	2,38 %	0	1,55 %	2,6 %	**4,8 %**	3,21 %
Max mix P bottom ash	wt-%	1,68 %	0	1,09 %	0,82 %	1,52 %	2,27 %

**Results for P1 and P2 on an individual basis. Multiply by 2 for total amount for P1 and P2 accumulated.*

The only boilers with the capacity to handle 70000 tonnes/year of DSS are B2 and P6, although B2's mixing percentage is high concerning sludge feeding systems. Notable values are the increase of ash, water vapor in the flue gases, SO_2 and fuel-N. The phosphorus yield appears too low for viable extraction, although max mix fly ash for B1 appears promising. Results on economic outcome for B2 and P6 are presented in Table 20. The results were produced using equations 1, 7, 22-25 and 28-30.

Table 20: Economic results Scenario 1.

		P6	B2
ΔBase fuel	tonnes/yr	-6680	-6740
Massflow DSS	tonnes/yr	70950	71553
$\Delta Ash_{disposal}$	tonnes/yr	6230	6380
Income DSS	MSEK/yr	14,2	14,3
Ash disposal	MSEK/yr	-4,4	-1,8
O&M costs	MSEK/yr	-0,2	-0,2
Present value base fuel revenue	MSEK	-1,7	29,5
Present value total revenues	MSEK	91,8	90,4

		P6	B2
Investment	MSEK	-10	-10
NPV	MSEK	81,8	80,4
IRR	-	96,3 %	96,4 %

B2 and P6 show very similar economic results. The key values, calculated according to section 6.1.5, for co-firing DSS in P6 are shown in Figure 18.

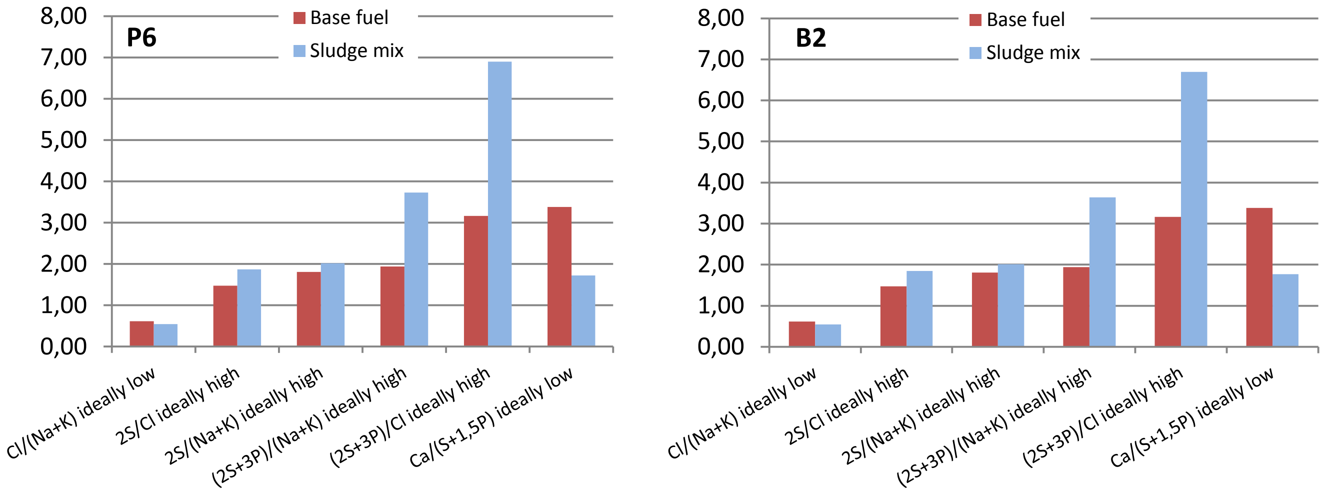


Figure 18: Key values for boiler P6 and B2. P6 Sludge mix: 26 % DSS, 74 % PTP. B2 sludge mix: 28 % DSS, 72 % industrial waste.

The key values move according to their respective favorable direction. There is an indication that the sulfur and phosphorus rich DSS has a remedial effect on corrosive compound formation and agglomeration, especially the high content of phosphorus which is evident in the last three bar-pairs.

7.2 Scenario 2 –Combust all digestate

Scenario 2 involves the combustion of ca. 26400 tonnes of digestate from a prospective biogas plant at Högdalen. The digestate massflow and corresponding mix percentage is presented in Table 21 along with the consequential relative change of ash, flue gas water vapor, flue gas flow, SO_2 and fuel nitrogen as compared to firing the base fuel only. The table also includes the mass fraction of phosphorus in the bottom and fly ashes as well as the change of fossil-CO_2. Max mix possible and max digestate are only based on the highest possible fuel throughput according to the stoker capacity diagrams. Other factors may in actuality constitute the effective limit. The max mix P values are based on the max mix percentage. The results were produced using equations 1-9, 15-18, 20-21 and the combustion table in section 6.1.3.

Since this case is based on combustion of digestate from food wastes from the usual MSW incinerated at Högdalen, the data in Table 21 for the grate furnaces P1 & P2, P3 and P4 represents a comparison between firing MSW and firing a mix of MSW without food waste together with digestate. This will assess the technical impacts based on experience from the operation of the boilers today. The base fuel, in which the sludge is mixed, will however change if food wastes are separated, this is considered in the economic results.

Table 21: Technical results Scenario 2.

		P1 & P2	**P3**	**P4**	**P6**	**B1**	**B2**
Mix (Ψ)	%	16	-	9	12	6	13
Digestate	tonnes/yr	13620*	-	27190	27640	26970	27620
Flue gas flow	Rel. change	8 %	-	5,2 %	4 %	2,1 %	3,4 %
Ash	Rel. change	4,4 %	-	3 %	3 %	23 %	3 %
H_2O in flue gas	Rel. change	14,9 %	-	7,6 %	14,3 %	5,3 %	13,9 %
SO_2	Rel. change	9,2 %	-	6,3 %	-1,2 %	**27,7 %**	-1,6 %
Fuel-N	Rel. change	8,3 %	-	2,9 %	10,5 %	**19,5 %**	9,3 %
P in fly ash	wt-%	1,36 %	-	1,19 %	0,49 %	1,72 %	0,51 %
P in bottom ash	wt-%	0,96 %	-	0,84 %	0,15 %	0,54 %	0,36 %
Fossil-CO_2	tonnes/yr	-1940*	-	-3870	-3190	-	-3190
Max mix possible	%	24	4	12	32	14	43
Max digestate	tonnes/yr	21900*	6260	37130	89200	66900	123910
Max mix P fly ash	wt-%	1,57 %	1,08 %	1,26 %	1,08 %	2,48 %	1,42 %
Max mix P bottom ash	wt-%	1,11 %	0,76 %	0,89 %	0,34 %	0,78 %	1,01 %

**Results for P1 and P2 on an individual basis. Multiply by 2 for total amount for P1 and P2 accumulated.*

Boilers P1 & P2, P4, P6, B1 and B2 have the capacity to handle ca. 26400 tonnes/year of digestate. P1 & P2's mix percentage is relatively high concerning feeding systems. There are no notable values except the relative change of SO_2 and fuel-N in boiler B1. In no boiler does the phosphorus concentration appear to be sufficient for viable extraction. Results on economic outcome for these boilers are presented in Table 22. The economic results for P1 & P2 and P4 represents a comparison between combusting a mixture of MSW without food waste together with digestate and combusting solely MSW without food waste. The results were produced using equations 1, 7, 22-25 and 28-30.

Table 22: Economic results Scenario 2.

		P1 & P2	**P4**	**P6**	**B1**	**B2**
ΔBase fuel	tonnes/yr	-7160	-7160	-5910	-7820	-5900
Digestate	tonnes/yr	27240	27190	27640	26970	27618
$\Delta Ash_{disposal}$	tonnes/yr	600	600	760	1290	665
Income Digestate	MSEK/yr	6,8	6,8	6,9	6,7	6,9
Ash disposal	MSEK/yr	-0,16	-0,17	-0,53	-0,39	-0,18
O&M costs	MSEK/yr	-0,3	-0,2	-0,2	-0,2	-0,2

		P1 & P2	**P4**	**P6**	**B1**	**B2**
Present value base fuel revenue	MSEK	-24,5	-24,5	-1,5	39,6	-25,8
Net present value total revenues	MSEK	37	38	58,5	99,4	37,5
Investment cost	MSEK	-15	-10	-10	-10	-10
NPV	MSEK	22	28	48,5	89,4	27,5
IRR		25,7 %	41,2%	61,9 %	102,6 %	40,8 %

All boilers yield a positive NPV. The IRR for P1 & P2 appears weaker than the others whilst B1 the strongest. The key values, calculated according to section 6.1.5, for co-firing digestate in P1 & P2, P4, P6, B1 and B2 are shown in Figure 19, Figure 20 and Figure 21.

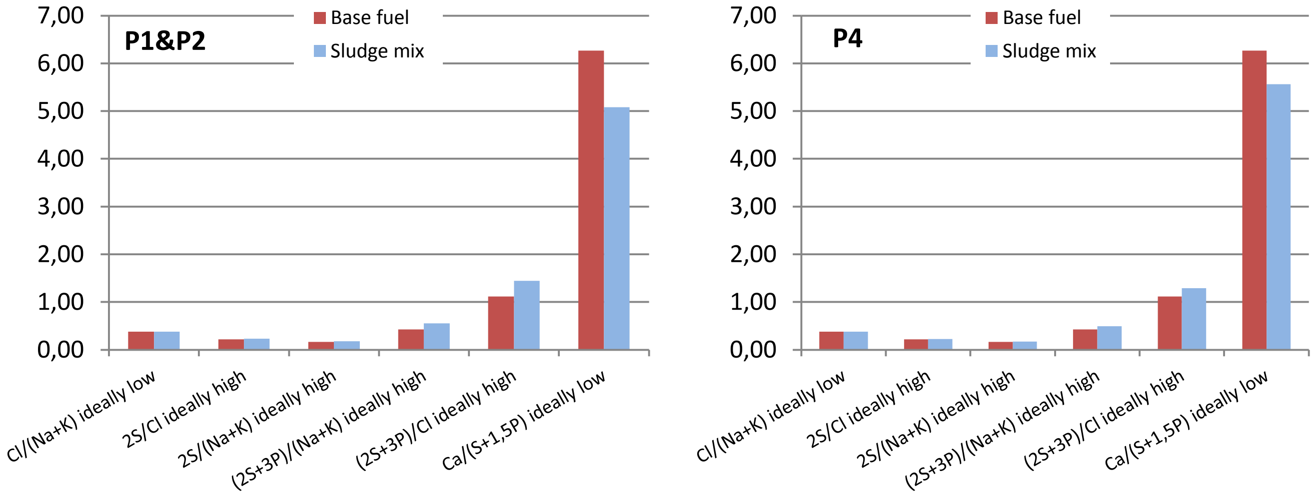


Figure 19: Key values for boiler P1 & P2 and P4. P1 & P2 sludge mix: 16% digestate, 84% MSW. P4 sludge mix: 9% digestate, 91% MSW.

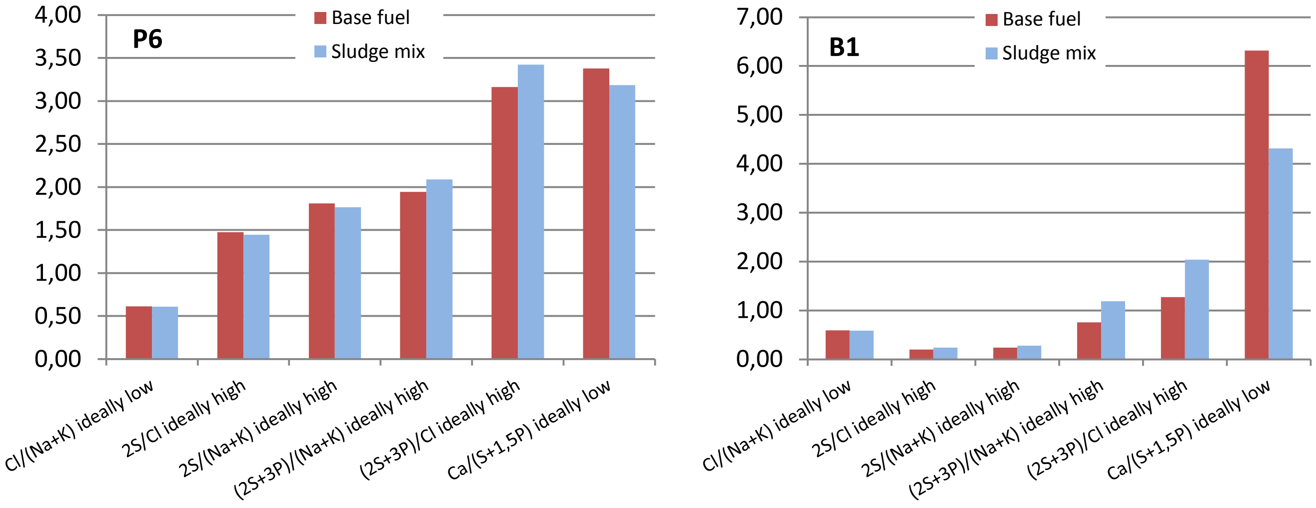


Figure 20: Key values for boiler P6 and B1. P6 Sludge mix: 12% digestate, 84% PTP. B1 sludge mix: 6% digestate, 94% biomass.

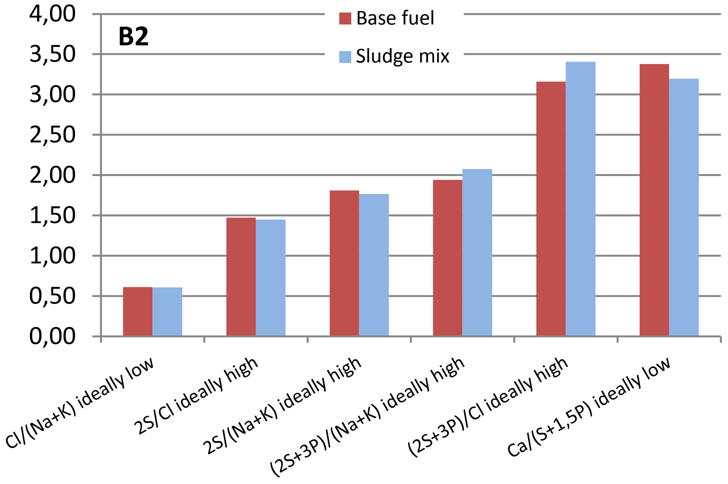


Figure 21: Key values for boiler B2. Sludge mix: 13% digestate, 87% industrial waste.

The key values suggest that digestate does not have the content of sulfur required to effectively neutralize alkali chloride formation in boilers P1 & P2, P4, B1 and B2. The increase of relative phosphorus content is however apparent which suggest that there may be remedial effects. P6 appears to marginally benefit from co-firing digestate with PTP as the change in key values is small compared to changes in the other boilers.

7.3 Scenario 3 – Combust all fibrous sludge

Scenario 3 involves the combustion of ca. 50000 tonnes of fibrous sludge from Holmen Paper. The annual amount of fibrous sludge and corresponding mix percentage is presented in Table 23 along with the consequential relative change of ash, flue gas water vapor, flue gas flow, SO_2 and fuel nitrogen as compared to firing the base fuel only. The table also includes the mass fraction of phosphorus in the bottom and fly ashes as well as the change of fossil-CO_2. Max mix possible and max fibrous sludge are only based on the highest possible fuel throughput according to the stoker capacity diagrams. The max mix P values are based on the max mix percentage. Other factors may in actuality constitute the effective limit. The results were produced using equations 1-9, 15-18, 20-21 and the combustion table in section 6.1.3.

Table 23: Technical results Scenario 3.

		P1 & P2	P3	P4	P6	B1	B2
Mix (Ψ)	%	-	0	-	21	11	23
Fibrous sludge	tonnes/yr	-	0	-	50950	50380	51820
Flue gas flow	Rel. change	-	-	-	6,4 %	3,1 %	4,9 %
Ash	Rel. change	-	-	-	-0,2 %	27,4 %	-2 %
H_2O in flue gas	Rel. change	-	-	-	**22,7 %**	7,8 %	**22,1 %**
SO_2	Rel. change	-	-	-	3,2 %	**202,4 %**	1,7 %
Fuel-N	Rel. change	-	-	-	19,9 %	**40,2 %**	17,5 %
P in fly ash	wt-%	-	-	-	0,34 %	1,26 %	0,37 %
P in bottom ash	wt-%	-	-	-	0,11 %	0,40 %	0,26 %
Fossil-CO_2	Tonnes/year	-	-	-	-9160	-	-9310
Max mix possible	%	26	0	9	38	18	50
Max fibrous sludge	tonnes/yr	23830*	0	27790	106200	85950	143102
Max mix P fly ash	%	1,17 %	0	1,09 %	0,5 %	1,39 %	0,64 %
Max mix P bottom ash	%	0,83 %	0	0,77 %	0,16 %	0,44 %	0,45 %

**Results for P1 and P2 on an individual basis. Multiply by 2 for total amount for P1 and P2 accumulated.*

Boilers P6, B1 and B2 have the capacity to handle ca. 50000 tonnes/year of fibrous sludge. B2's mix percentage is high concerning feeding systems. Notable values are the increase of water vapor in the flue gases for boiler P6 and B2 and the increase of SO_2 and fuel-N for B1. Results on economic outcome for these boilers are presented in Table 24. The results were produced using equations 1, 7, 22-25 and 28-30.

Table 24: Economic results for Scenario 3.

		P6	B1	B2
ΔBase fuel	tonnes/yr	-16960	-22760	-17250
Fibrous sludge	tonnes/yr	50950	50380	51820
$\Delta Ash_{disposal}$	tonnes/yr	-60	1560	-410
Income fibrous sludge	MSEK/yr	-2,5	-2,5	-2,6
Ash disposal	MSEK/yr	0,04	-0,47	0,11
O&M costs	MSEK/yr	-0,2	-0,2	-0,2
Present value base fuel revenue	MSEK	-4,3	115	-75,4

		P6	**B1**	**B2**
Present value total revenues	MSEK	-30,6	84,4	-102
Investment cost	MSEK	-10	-10	-10
NPV	MSEK	-40,6	74,4	-101
IRR		-	87,5 %	-

Only boiler B1 results in a positive net present value. The key values, calculated according to section 6.1.5, for co-firing fibrous sludge in B1 are shown in Figure 22.

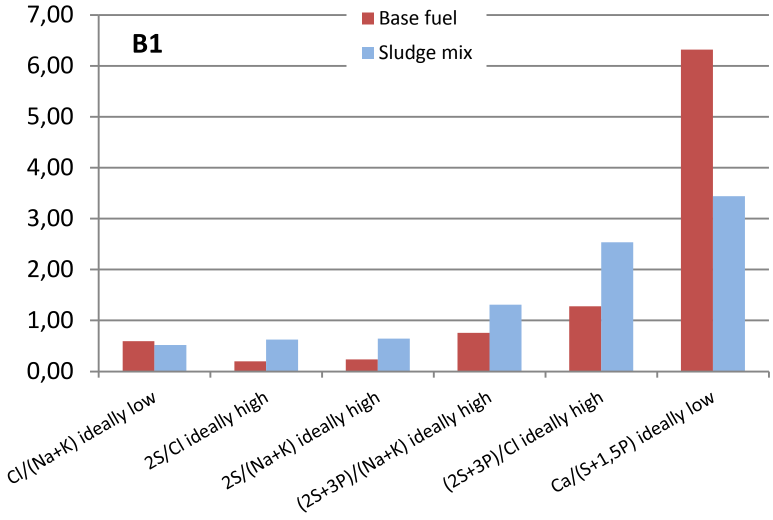


Figure 22: Key values for boiler B1. Sludge mix: 11 % fibrous sludge and 89 % biomass.

Firing fibrous sludge appears beneficial in preventing the occurrence of operational issues since all key values move according to their respective favorable direction. Specifically, the increased content of sulfur and phosphorus relative to calcium is prominent and is a very desirable characteristic in general when firing biomass fuels.

7.4 Scenario 4 – Mono-combustion

This scenario aims to compare the co-combustion alternatives against mono-combustion facilities. The capacity of the facility is set to the corresponding amount of sludge to handle, i.e. 70000 tonnes/year for DSS, 26400 tonnes/year for digestate and 50000 tonnes/year for fibrous sludge. The plant is assumed to be in operation 8000 hours per year. The sludge is dried to 55 % moisture content which should be viable for mono-combustion. The results on the phosphorus concentration in the ashes, incomes and costs along with the NPV and internal rate of return for the different sludge types can be seen in Table 25. The results were produced using equations 3-5, 7-19, 22 and 26-30.

Table 25: Results Scenario 4.

		DSS	Digestate	Fibrous sludge
Sludge amount ar	tonnes/yr	70000	26400	50000
Sludge to boiler	tonnes/h	4,6	1,7	4,2
Fuel power	MW	5,6	3,4	8,4
Drying power (ar to 45 % DS)	MW	3,5	1,3	1,8
P in fly ash	wt-%	11,56 %	6,34 %	2,48 %
P in bottom ash	wt-%	3,65 %	2,0 %	0,78 %
Income sludge	MSEK/yr	14	6,6	2,5
Heat	MSEK/yr	18,9	8,5	28,6
Drying cost	MSEK/yr	13,3	5	6,7
O&M costs	MSEK/yr	-7,8	-3,5	-7,3
Present value total revenues	MSEK	152	125	156
Investment cost	MSEK	228	86	163
NPV	MSEK	-75	39,5	-6,7
IRR		2,2 %	10,5 %	5,6 %
Value phosphorus	MSEK/yr	7,2	0,78	0

Mono-combustion can achieve a phosphorus concentration of more than 5 % in the fly ashes. The value of the extractable phosphorus, based on the current phosphorus world market price, is 7,2 MSEK for DSS, 0,8 MSEK for digestate. This could generate an income and improve the economic conditions of the investments but their profitability still appears doubtful. Fibrous sludge did however not yield the necessary concentration for extraction.

The results show that a mono-combustion facility for digestate is the most promising alternative amongst the mono plants. However it appears economically inferior in comparison to any co-combustion case. Mono-combustion of all three sludge types will lead to a phosphorus concentration sufficient for viable extraction in the fly ashes. The phosphorus extraction facility would most probably be handled by a third party actor since the investment could never repay itself.

8 Summary

The results from Scenario 1, 2 and 3 indicate that boiler B2 has the largest capacity to incinerate sludge. Based on other considerations, the data suggests that boiler B1 is most beneficial from an economic perspective. Co-combustion of digestate and fibrous sludge yielded the highest NPV in B1, which is due to the suppression of the expensive biomass base fuel. Mixing sludge with biomass does however cause the greatest variation in fuel sulfur, nitrogen and ash since the biomass fuel has a low content of these.

The phosphorus concentration is too low for viable extraction in any co-combustion case, although firing ca. 52500 tonnes of DSS in B1 did yield a phosphorus concentration of 4,8 % in the fly ashes. In general, the highest phosphorus concentration is found in the fly ashes for the CFB boilers, whereas the grate furnace boilers yield a fairly even phosphorus concentration between the fly and bottom ashes.

The key values indicate that no sludge type increases the risk of operational issues. Rather, they seem to dampen them. Digestate and fibrous sludge do not show this as assuredly as DSS, which indicates strongly that firing a mix with DSS would be beneficial in decreasing risks of corrosion and agglomeration.

Without phosphorus extraction, a mono-combustion facility does not appear favorable. Even with it, it is evident that mono-combustion cannot compete economically with co-combustion in any case. Although there is net positive revenue from the sales of heat and electricity and a phosphorus extraction scheme may generate additional income, these cannot cover the high investment costs for building a new facility. From a material recycling perspective though, mono-combustion is more beneficial.

It is evident that there is an economic potential in co-combusting DSS. The only boiler with the capacity to incinerate ca. 700000 tonnes is boiler P6, but a wide margin of error might exclude this boiler as well. Dividing the DSS amongst two or three boilers will be sufficient to receive all the sludge whilst still yielding a substantial income. Table 26 shows ca. 70000 tonnes DSS incinerated at either Högdalen or Brista. The results were produced using the same equations as for Scenario 1, 2 and 3.

Table 26: Economic results from dividing ca. 70000 tonnes DSS between two or three boilers.

		Högdalen			**Brista**	
		P1 & P2	**P4**	**P6**	**B1**	**B2**
Mix (Ψ)	%	12	4	15	8	15
DSS	Tonnes/yr	20920*	12140	36210	37010	33110
Base fuel	Tonnes/yr	-2520*	-1462	-3410	-4730	-3120
Income sludge	MSEK/yr	4,2	2,4	7,2	7,4	6,6
Ash disposal	MSEK/yr	-0,5	-0,3	-2,2	-1,1	-0,8
O&M costs	MSEK/yr	-0,3	-0,2	-0,2	-0,2	-0,2
Present value base fuel revenue	MSEK	-8,6	-5	-0,9	24	-13,6
Present value total revenues	MSEK	24,3	13,8	45,9	83,5	40,8
Investment cost	MSEK	-15	-10	-10	-10	-10
NPV	MSEK	9,3	3,8	35,9	73,5	30,8
IRR		14,7 %	11,6 %	48,1 %	86,1 %	43,1 %

**For P1 and P2 accumulated.*

This data indicates that there may be reasons to motivate retrofitting more boilers than one, or that it might still be economically beneficial to incinerate a smaller amount of DSS in only one boiler. The remedial effects on operational issues that DSS has support this notion.

9 Sensitivity analysis

Since the model has been designed based on a number of assumptions, it may be sensitive to changes in what could be critical parameters. The most decisive aspect in a possible potential sludge incineration system is the investment solidity.

It may be possible that all potential sources of income have been included, but many potential costs have been omitted in this study. A reasonable inquiry would be concerning how much margin there is for "unforeseen annual costs", e.g. higher O&M costs than expected, for the investments to yield a favorable IRR. Figure 23, Figure 24 and Figure 25 show how the IRR is affected when adding unforeseen costs to economic calculations for Scenario 1, 2 and 3. Note that only the positive NPV investment cases for each scenario are included which excludes boiler P3 and the mono-combustion cases from the table altogether.

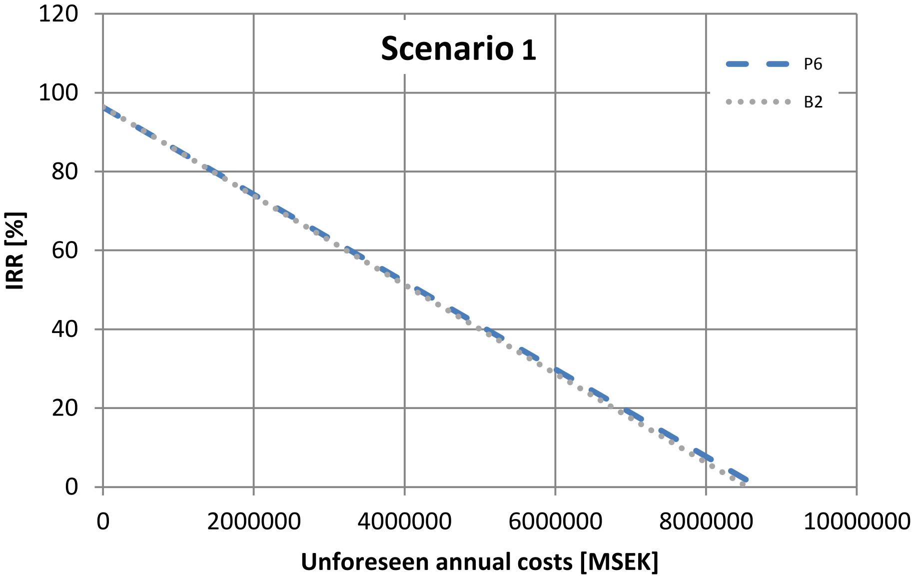


Figure 23: Effect on IRR when unforeseen annual costs are added to economic calculations in Scenario 1.

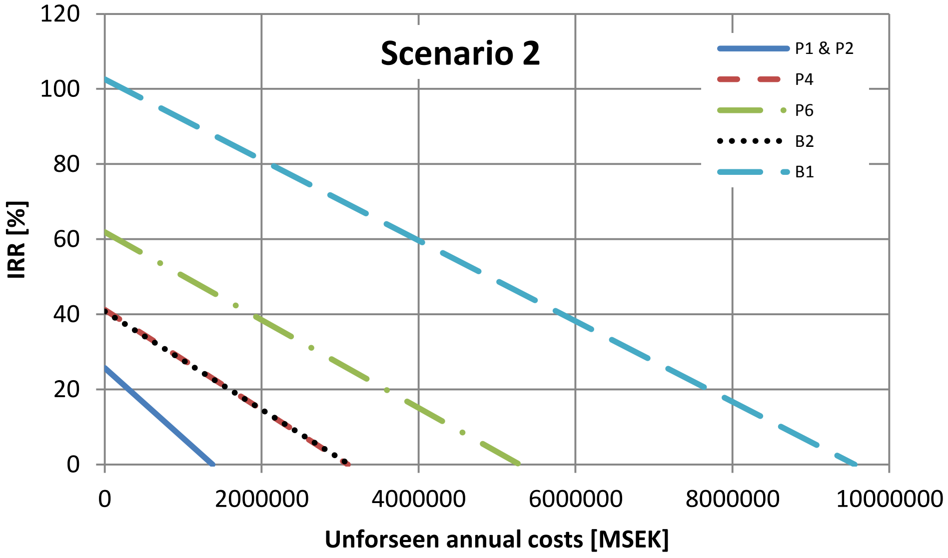


Figure 24: Effect on IRR when unforeseen annual costs are added to economic calculations in Scenario 2.

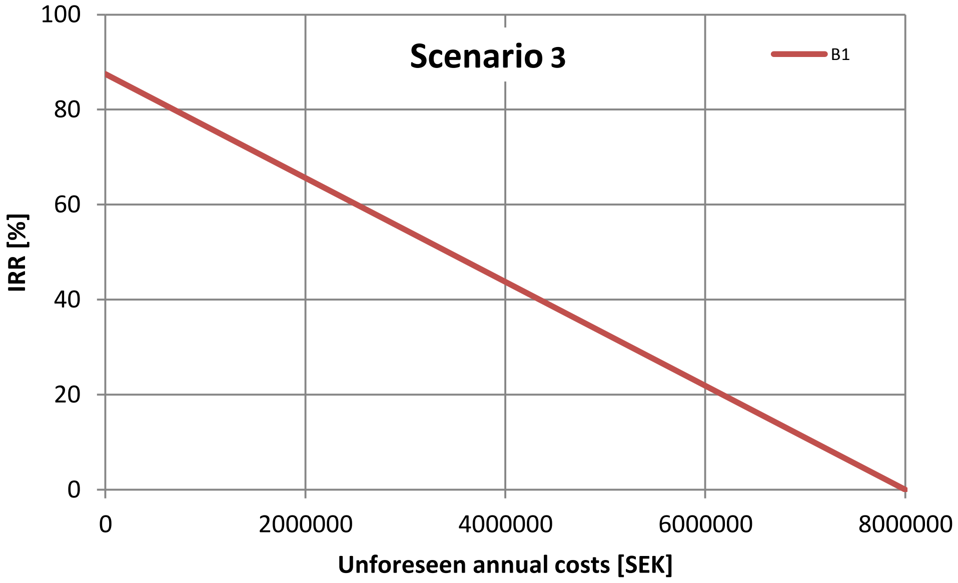


Figure 25: Effect on IRR when unforeseen annual costs are added to economic calculations in Scenario 3.

It can be interpreted from Scenario 2 that B1 has the largest margin, P6 the second largest, P4 and B2 are similar whilst P1 & P2 have the lowest. This would also be the case if the P1 & P2, P4 and B1 would have been able to incinerate DSS in Scenario 1. It is clear that the investments are relatively flexible, especially B1. The major factor for the economic profitability appears to be what base fuel the boilers operate with.

10 Discussion

Continual combustion of sludge on an industrial scale is relatively untested in Sweden. Many reports deal with short term experiments or cases and typically delve deep into a singular issue. It is for this reason that this thesis is broad and exploratory which has served to answer a question as much as inform of the question itself. At this point it is clear that determining the best boiler for sludge combustion is not straightforward.

It is indeed possible to combust sludge, either co-incinerating it with other fuels or firing it alone in a mono-combustion facility. Fortum does have the necessary resources to apply many different systems, but assessing the best method amongst many requires diligent consideration to many different aspects. It was found that dewatering was needed but drying shall be avoided if not strictly necessary. Also, the combustion of sludge may give rise to both beneficial and undesirable operational conditions and phosphorus extraction is virtually non-viable in co-combustion applications, which anyway is the only way possible to make good use of the ash-phosphorus.

The results show that boiler B2 has the largest capacity of all boilers to receive and incinerate sludge. This may be critical if the sludge flow is large, and the system is limited to only one boiler. Boiler B1 however showed the greatest economic potential, but is problematic in the sense that it has permission to only incinerate biofuels and the B1 ashes may be contaminated to the point of losing their bio-ash appellation. B1 also proved most promising in achieving a sufficient concentration of ash phosphorus but was most sensitive to changes in SO_x, NO_x and ash. Grate furnaces P1-P4 and B2 were technically suitable for incineration, but exchanging low quality, cheap sludge for higher quality, high revenue waste fuel gave discouraging red figures in economic calculations. It must however be pointed out that it is not a zero-sum game when it comes to increasing boiler throughput. That is, adding a tonne of sludge displaces only a fraction in weight of the base fuel. Granted, it may lead to exceeding the plants' incineration permissions, but it does not significantly disturb the capital flow as it is at present. This small change is beneficial concerning revenue generating waste, but less so when it comes to expensive biomass which ideally should be displaced more.

The environmental impacts in this study are based on the change of NO_x, SO_x and fossil-CO_2 emissions. The results from the model indicate an increase of NO_x and SO_x emissions, although one must be cautious not to interpret this as a guarantee. The formation reactions of these are complex, and SO_x formation has not been weighed against the likelihood of sulfur reacting to form other compounds, such as alkali sulfates. Total CO_2 emissions increase slightly, but depending on whether or not sludge is considered CO_2 neutral this may not be detrimental. One might instead consider a positive aspect in this as sludge carbon may have displaced fossil based carbon (from e.g. plastics in MSW) in CO_2 formation.

Overall, the premises were not favorable in achieving successful phosphorus extraction in co-combustion cases. It was possible for mono-combustion, but the economic gain seemed inadequate even under optimistic conditions. The true potential of the business in the future may have been underestimated however which is why it should definitely not be written off in future studies.

The findings of this thesis were based on a model in which a number of assumptions were made. All boilers were assumed to operate at 100 % constant load and be in operation 8000 h/year, except P6. The quality, type and annual amount of sludge for incineration were assumed static throughout the modelling time, as were the type and quality of the base fuels. The combustion process was also assumed stable, e.g. no temperature fluctuations, no effect on ash distribution etc. The water vapor content would most likely affect heat exchange characteristics of the boiler and open the possibility for expanded flue gas condensation capacity. None of these were considered in the model. Albeit not truly reflective of actual circumstances, these assumptions were considered justified in order to illustrate the principal outcomes of firing sludge in the boilers at Högdalen and Brista, and more to the point, the principal differences between the boilers themselves.

The model was consequently not detailed enough to provide a definitive answer to the main thesis objective. There is a strong indication that a technically, economically and ecologically feasible system for sludge combustion is possible, but a conclusive judgment has to await further and more detailed investigation.

The results of this study should therefore be used to identify key considerations when incinerating sludge, what effects can be expected, the principal differences between co-combustion and mono-combustion, between CFB and grate furnaces and between the individual boilers in Högdalen and Brista. Having these already mapped out makes way for future studies where each element can be deeper explored.

11 Conclusions

In this study the technical possibility to combust digested sewage sludge, digestate from food wastes and fibrous sludge was investigated. The investigation was carried out for the solid fuel fired boilers at Högdalenverket (P1, P2, P3, P4 and P6) and for the boilers at Bristaverket (B1 and B2). In addition, mono-combustion of the three sludge types was compared to the co-combustion cases for economic viability and phosphorus extraction potential.

From the study there may be drawn several conclusions. These are listed here:

- The combustion of 70000 tonnes of digested sewage sludge is technically viable in P6 and B2. P6 gave an IRR of 96,3 % and B2 96,4 %. Both of these had a wide margin of for unforeseen annual costs. Dividing the sludge between more boilers, or firing a lesser amount in one boiler, is still economically justifiable and could also be recommended considering the positive effects on boiler operation and maintenance (corrosion and agglomeration).
- The combustion of 26400 tonnes of digestate is applicable in P1 & P2, P4, P6, B1 and B2. The boiler with the largest economic gain is B1 with an IRR of 102,6 % and the greatest margin for unforeseen costs. Boiler B1 only has permission to incinerate biofuels i.e. the current permission has to be changed in order to combust digestate. On the other hand, the transport distance between Högdalen and Brista may lead to economic and environmental burdens. In that sense it is better to recommend a boiler at Högdalenverket. P6 gave the second largest economic gain with an IRR of 61,9 % and a wide margin for unforeseen annual costs.
- The combustion of 50000 tonnes of fibrous sludge is applicable in P6, B1 and B2. Only in B1 did this lead to a positive NPV, giving an IRR of 87,5 % with a very wide margin of unforeseen annual costs. Boiler B1 only has permission to incinerate biofuels i.e. the current permission has to be changed in order to combust fibrous sludge. However the increase of SO_x and potential increase of NO_x emissions must be taken into consideration.
- A mono-firing plant for digested sewage sludge or fibrous sludge is with the economic conditions (sludge prices, investment costs etc.) in the study clearly not a sound investment. Mono-firing of digestate gives a positive NPV but appears economically too weak to consider investing in.
- When firing B1's maximum capacity of digested sewage sludge, 4,8 % phosphorus concentration was achieved in the fly ashes. It was deemed not viable for recycling phosphorus, although it is still very favorable considering model uncertainties. Also, the phosphorus extraction technology can in the future be cost effective at even lower concentrations than 5 %. Firing digested sewage sludge in B1 is therefore the most promising co-combustion application for this purpose. Mono-combustion of digested sewage sludge and digestate gave the best conditions for economically viable phosphorus extraction.
- The plant in Högdalen operates near its current incineration permit of 700000 tonnes waste per year. This will have to be extended if fibrous sludge or digested sewage sludge is to be incinerated. The sorting out of 31000 tonnes food wastes for biogas production would leave a margin enough to incinerate the digestate within the current permission.
- When reducing the moisture content in digestate it is important that drying of digestate, from wet digestion, is preceded by a dewatering step. This is done in order to avoid concentrating water-soluble solids, e.g. alkali metals and chlorine.

- Dewatering of the sludge to ca. 25 % DS is a requirement prior to co-combustion. Drying in co-combustion cases is not recommended. It is not economical and should only be considered if strictly necessary.
- General indication of slight increase of total CO_2 emissions but the fossil CO_2 emissions decrease when MSW or PTP are co-combusted with sludge. Indications of increased NO_x and SO_x emissions in raw flue gases from all three sludge types. In B1 these increases are alarming. Digestate co-firing in P6 indicated lower SO_x in the raw flue gases.
- At high mixing ratios there is a risk of increased unburnt material in the ashes especially in the grate furnaces.
- Increase of ash amounts in all boilers when firing digested sewage sludge and digestate and when firing fibrous sludge in B1. Fibrous sludge co-combustion in P6 and B2 gave a less amount of ashes.
- B1 benefits the most economically from displacing the base fuel but the relative change in fuel sulfur, nitrogen and ash is most prominent when sludge is mixed with biomass. Since B1 does not have any sulfur cleaning at present, this may require lime injection in order to meet requirements (25 mg/Nm^3 dry gas at 6 % O_2).
- B2 has the highest incineration capacity. P6 also has a high incineration capacity, although in Scenario 1 it is still close to its maximum capacity which requires the boiler to operate at full load throughout the whole year. This inhibits the possibility of compensating low-mixing periods with high-mixing periods.
- Boiler B2’s current problem with too dry fuel could be solved by adding any of the three substantially wetter sludge types. This will reduce the high temperatures and could be beneficial in reducing other operational issues such as corrosion.
- The amount of base fuel displaced is relatively small (DSS displaced the least, fibrous sludge the most). This allows for flexible fuel mixing where boilers may run in base fuel operation and, when needed and available, injecting sludge without significantly affecting base fuel flow.
- Incinerating sludge on a smaller scale is justified from an operational standpoint. Especially DSS which is, independent of how it is incinerated, most favorable in decreasing operational issues whilst fibrous sludge and digestate have a lesser effect.
- If biogas is produced at Högdalen, incineration is a workable, economically justified and relatively easy way to handle the digestate without the need of transports.
- The mixing percentages for the grate furnaces were high concerning sludge feeding systems in some cases. This was especially the case for B2 in Scenario 1 and 3. A solution to be able to combust large amounts of sludge is spreading the sludge directly onto the waste in the bunker, though this can impair the working environment at the plant. Mixing the sludge with lime before spreading in the bunker, as done in Bamberg, could reduce such problems.

12 Future work

The comprehensive nature of this study has involved touching upon, and attempting to answer, many different topics and questions. Combustion is however a pervasive science and a working industrial-scale sludge combustion system is, as of yet, fairly novel in Sweden in any respect. Indeed, considering the economic pressure and the complex body of regulations placed upon the heat and power industry, this topic needs further attention.

Perhaps based on the findings of this study, it would be recommended to pick out promising boilers for further evaluation. In this regard it would be possible to look deeper into more detailed, but perhaps critical, effects of co-firing sludge with another fuel type. For example, a thorough understanding of potential emissions increase is necessary to take into consideration in order to plan for preventive measures. Also, the feeding system is a critical element in combustion design where continuous and effective fuel mixing is an outstanding consideration. Previous experiences of sludge combustion have shown that this can be troublesome.

A more detailed system scheme based on a single boiler would also further assess the economic implications. This study has been based on fairly static economic conditions, in many respects assuming non-variation in capital flow 15-25 years into the future, which of course rarely is the case. Specifically, the grey area of additional costs would be illuminated, one such example being the added running costs of flue gas cleaning which would surely increase.

The phosphorus extraction system needs to be given further attention. Assessing the profitability of such a system is crucial, not just for the economics of a mono-combustion facility, but also in a larger sense where a dwindling supply of mineral phosphorus will become felt in the future.

All in all, further studies should be done in light of the progressive nature of political policy dealing with the issue of waste management. If there are indications of great economic and environmental gain from firing sludge this should ideally be a matter which is explored in coherence with regulatory powers.

Bibliography

Aho, M. et al., 2010. *Reduction of superheater corrosion by co-firing risky biomass with sewage sludge,* Jyväskylä, Turku, Tampere: Elsevier.

Alsparr, J., 2014. *Asset Manager, personal contact.* Stockholm: Fortum Heat.

Andersson, C., 2014. *ÅF consultant* [Interview] (6 March 2014).

Arvidsson, L. et al., 2012. *AVFALL SVERIGES DEPONIHANDBOK - Reviderad handbok för deponering som en del av modern avfallshantering.* Malmö: s.n.

Aselaide Control Engineering, 2013. *Multiple Hearth Furnace.* [Online]
Available at: http://www.adelaidecontrolengineering.com/?q=content/multi-hearth-furnace
[Accessed 10 March 2014].

ASME, 2012. *Boilers: Fluidized-Bed Combustors for Biomass Boilers.* [Online]
Available at: https://www.asme.org/engineering-topics/articles/boilers/fluidized-bed-combustors-for-biomass-boilers?cm_sp=Boilers-_-Feataured%20Articles-_-Fluidized-Bed%20Combustors%20for%20Biomass%20Boilers
[Accessed 30 January 2014].

Avfall Sverige, 2008. *Intervjubaserad genomgång och sammanställning av korrosion och beläggningar i svenska avfallspannor,* Malmö: s.n.

Avfall Sverige, 2012. *Determination of fossil content in combustible Swedish municipal solid waste,* Malmö: s.n.

Avfall Sverige, 2013. *Svensk Avfallshantering 2013,* Malmö: Avfall Sverige.

Axelsson, O., 2014. *Asset Manager, personal contact.* Stockholm: Fortum Heat .

Bajpai, P., 2010. *Environmentally Friendly Production of Pulp and Paper,* Hoboken: John WIley & Sons Inc..

Baky, A. et al., 2006. *Rötrest från biogasanläggningar - användning i lantbruket,* Uppsala: SLU Service Publikationer.

Balmér, P. et al., 2002. *System för återanvändning av fosfor ur avlopp,* Stockholm: Danagårds Grafiska 2002/10.

Basu, P., 2006. *COMBUSTION and GASIFICATION in FLUIDIZED BEDS.* Boca Raton(Florida): CRC Press.

BELAB AB, 2014. *Certificate of analysis - rötrest Linköping,* Norrköping: Bränsle & Energilaboratoriet AB.

Bioenergiportalen, 2012. *Bioenergiportalen: Torrötning.* [Online]
Available at: http://www.bioenergiportalen.se/?p=3136&m=1640
[Accessed 12 February 2014].

Biogasportalen, 2014. *Biogasportalen: Från råvara till användning.* [Online]
Available at: http://www.biogasportalen.se/FranRavaraTillAnvandning
[Accessed 12 February 2014].

Bohn, I., Murto, M., Björnsson, L. & Rosqvist, H., 2011. *Torrötning av rejekt från förbehandling av matavfall,* Malmö: Svenskt gastekniskt centrum.

Borggren, C., 2007. *Mätning av metanpotentialen hos slam på Henriksdal och Bromma - Metodutveckling och utvärdering av labutrustningen "BCS-CH4 Biogas",* Stockholm: s.n.

Brodén, H., 2008. *FÖRBÄTTRAD ALKALI- OCH KLORIDKONTROLL GENOM SO2-STYRNING,* Nyköping: TPS Termiska Processer AB.

Bäfver, L. et al., 2013. *Sludge fuel mixtures – Combustion and extraction of phosphorus,* Borås: s.n.

CEBC, 2014. *Operational Experiences from Austrias First Medium Sized Sewage Sludge Mono-Incineration Plant in Großwilfersdorf,* Leobersdorf: KALOGEO.

Chemviron Carbon, 2013. *Chemviron Carbon: Flue gas treatment.* [Online]
Available at: http://www.chemvironcarbon.com/en/applications/air-treatment/flue-gas
[Accessed 14 February 2014].

Davidsson, K. et al., 2012. *Askans betydelse för rötslams goda samförbränningsegenskaper,* Borås: s.n.

Djurberg, K., 2011. *Systemdokument Fjärrvärme Stockholm.* Stockholm: s.n.

Dornisch, E., 2013. *Phosphorus recycling from sewage sludge ash - Comparison of the PASCH, Mephrec and Ash Dec processes -,* Graz: s.n.

EasyMining Sweden, 2013. *Fosforutvinning ur askor från förbränt avloppsslam.* [Online]
Available at: http://www.ksla.se/wp-content/uploads/2012/12/Patrik-Enfalt.pdf
[Accessed 13 March 2014].

Eija, A. & Flyktman, M., 2001. *Biomass CHP Technologies. Future Cogen,* Jyväskykä: VTT Energy Reports.

Eklund, A., 2003. *Vakuumtorkning av slam - En potentialstudie,* Stockholm: Värmeforsk Service AB.

Energimyndigheten, 2013. *Energiläget 2013,* Bromma: Arkitektkopia.

Environmental Protection Agency, 2002. *EUROPEAN WASTE CATALOGUE AND HAZARDOUS WASTE LIST,* Wexford: Environmental Protection Agency.

Evans, M., 2011. *fertilizer international blog.* [Online]
Available at: http://fertilizerinternationalblog.blogspot.se/2011/07/new-light-on-peak-phosphorus.html
[Accessed 12 February 2014].

Fahlström, J., 2014. *Ragn Sells consultant* [Interview] (19 March 2014).

FGC Group LLC, 2010. *Our products: Thermal processing equipment - Multiple hearth furnaces.* [Online]
Available at: http://www.fgcgroupllc.com/multiple_hearth_furnaces.html
[Accessed 10 March 2014].

Finnveden, G. et al., 2013, English translation by Anton Marmsjö. ”Regeringen måste satsa på resurseffektivt samhälle”. *Dagens Nyheter*, 01 April.

Flaga, A., u.d. a. *Sludge Drying,* Cracow: s.n.

Flaga, A., u.d. b. *THE ASPECTS OF SLUDGE THERMAL UTILIZATION,* Cracow: s.n.

ForskEl, 2010. *Working up phosphate from ashes,* Nyborg: Kommunekemi a/s.

Fortum Värme, 2013. *Miljörapport för Bristaverket 2012,* Stockholm: s.n.

Fortum, 2013. *Miljörapport 2012 Högdalenverket,* Stockholm: s.n.

Fortum, 2014. *Anläggningsblad Bristaverket,* Stockholm: Fortum Värme.

Fortum, 2014b. *General information.* Stockholm: s.n.

Government Offices of Sweden, 2012. *Government and ministries: Energy policy.* [Online]
Available at: http://www.government.se/sb/d/16022/a/190032
[Accessed 31 January 2014].

Gustafsson, K., 2014. *Project manager, personal contact.* Stockholm, Fortum Heat.

Gyllenhammar, M. et al., 2013. *Additiv för att minska driftproblem vid rostförbränning av avfall,* Göteborg: Waste Refinery.

Göteborg Energi, Innovatum Teknikpark, 2009. *FÖRSTUDIE Torrötningsutveckling,* Trollhättan: Innovatum Teknikpark.

Haglund, P. & Olofsson, U., n.d. *Miljöövervakning av slam - Redovisning av resultat från 2004, 2005 och 2006 års provtagningar,* Umeå: s.n.

Hall, J., n.d. *Ecological and economical balance for sludge management options,* Marlow: s.n.

Hansson, E. & Johansson, M., n.d. *Avlopp på våra åkrar - en rapport om miljögifter i slam,* s.l.: s.n.

Henriksson, G. et al., 2012. *Rätt slam på rätt plats,* Borås: SP Sveriges Tekniska Forskningsinstitut.

Herstad Svärd, S., 2014. *WSP consultant.* Stockholm: s.n.

Herstad Svärd, S. et al., 2011. *Ramprogram – Åtgärder för samtidig minimeringav alkalirelaterade driftproblem, Etapp 3,* Stockholm: s.n.

Hitachi Zosen INOVA AG, u.d.a. *Bamberg / Germany - Energy-from-Waste Plant,* Zurich: s.n.

Hitachi Zosen INOVA AG, u.d.b. *Thun / Switzerland - Energy-from-Waste Plant,* Zurich: s.n.

Jacobson, P.-E., 2014. *Study visit at Brista CHP plant* [Interview] (20 March 2014).

KAOLGEO, 2014. *Operational Experiences from Austrias First Medium Sized Sewage Sludge Mono-Incineration Plant in Großwilfersdorf / Austria.* [Online]
Available at: http://www.seiler.co.at/fileadmin/content/publications/iea_fb_conference_06.pdf
[Accessed 14 March 2014].

Khalil, R., Jonassen, O., Bugge, M. & Sørum, L., 2007. *Options for the treatment of organic sludge - The move towards thermal processing,* Trondheim: SINTEF Energy Research.

Khan, A., de Jong, W., Jansens, P. & Spliethoff, H., 2009. *Biomass combustion in fluidized bed boilers: Potential problems and remedies,* s.l.: Elsevier.

Klass, D. L., 1998. *Biomass for Renewable Energy, Fuels, and Chemicals.* 1st ed. London: Academic Press.

KSLA, 2013. *Slam och fosforkretslopp,* s.l.: Carl-Anders Helander, akademiens sekreterare och VD, KSLA.

KTH Department of Energy Technology, 2009. *CompEduHPT.* [Online]
Available at: http://www.energy.kth.se/compedu/webcompedu/WebHelp/index.html
[Accessed 10 February 2014].

Laboratory of Energy Engineering and Environmental protection, 2003. *Steam boiler technology.* [Online]
Available at:
http://www.energy.kth.se/compedu/webcompedu/ManualCopy/Steam_Boiler_Technology/index.htm
[Accessed 28 January 2014].

Levlin, E. et al., 2001. *Slamkvalitet och trender för slamhantering,* Stockholm: VAV AB.

Linder, K., 2001. *Sameldning av rötslam och energirika avfallsbränslen eller skogsbränslen,* Stockholm: Värmeforsk.

Lindman, E.-K., 2013a. *Bränsleanalyser P6 KME projektet.* Stockholm: s.n.

Lindman, E.-K., 2013b. *Asksammansättning P6 Högdalen 2013,* Stockholm: s.n.

Lindman, E. K., 2014. *Head of R&D, personal contact.* Stockholm: Fortum Heat.

Ljungdahl, B. & Zintl, F., 2001. *RT-flis och rötslam. Problemidentifiering relaterad till bäddsintring och emissioner vid eldning i FB,* Stockholm: Värmeforsk Service AB.

Ljung, M., 2014. *Study visit at Högdalen CHP plant* [Interview] (5 March 2014).

Makádi, M., Tomócsik, A. & Orosz, V., 2012. Digestate: A New Nutrient Source – Review. In: *Biogas.* Rijeka: InTech, pp. 295-310.

Martin, A., 2013. *Biomass Fundamentals 1.* Stockholm: s.n.

Miljödomstolen, 2002. *Miljödom Högdalen.* Stockholm: Stockholms Tingsrätt.

Miljödomstolen, 2010. *Miljödom Brista.* Stockholm: Nacka Tingsrätt.

Minpro AB, 2014. *Rotary kiln - technical plan.* [Online]
Available at: http://www.minpro.se/eng/storugn.htm
[Accessed 11 March 2014].

Naturvårdsverket, 2005. *Förbränningsanläggningar för energiproduktion inklusive rökgaskondensering,* s.l.: s.n.

Naturvårdsverket, 2012. *Biogas ur gödsel, avfall och restprodukter - Goda svenska exempel,* Stockholm: s.n.

Naturvårdsverket, 2013. *Hållbar återföring av fosfor-Naturvårdsverkets redovisning av ett uppdrag från regeringen,* s.l.: Arkitektkopia AB.

Nohlgren, I., Herstad Svärd, S., Rodin, J. & Jansson, M., 2014. *El från nya och framtida anläggningar 2014.* Stockholm, WSP.

Nordpool spot, 2014. *Elspot prices.* [Online]
Available at: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/ALL1/Hourly/
[Accessed 14 May 2014].

Nyström, O. et al., 2011. *El från nya och framtida anläggningar 2011,* Stockholm: s.n.

Ottosen, L. M., Kirkelund, G. M. & Jensen, P. E., 2013. Extracting phosphorous from incinerated sewage sludge ash rich in iron or aluminum. *Chemosphere,* 91(7), pp. 963-969.

Outotec, 2013a. *Sludge incineration plant - SNB Brabant - Moerdijk, Netherlands.* [Online]
Available at:

http://www.outotec.com/ImageVaultFiles/id_1104/d_1/cf_2/OTE_OiA_Sludge_incineration_plant_SNB_Brabant_Moer.PDF
[Accessed 14 March 2014].

Outotec, 2013b. *Outotec: Case studies.* [Online]
Available at:
http://www.outotec.com/ImageVaultFiles/id_1103/d_1/cf_2/OTE_OiA_Sludge_incineration_plant_ERZ_Zurich_Zuric.PDF
[Accessed 18 March 2014].

Pettersson, J. et al., n.d. *Evaluation of different fuel additives´ ability to master corrosion and deposition on steam superheaters in a waste fired CFB-boiler,* Stockholm: KME.

photomemorabilia.co.uk, 2014. *Fluidized Bed Combustion.* [Online]
Available at: http://www.photomemorabilia.co.uk/FBC.html
[Accessed 30 January 2014].

PURE, 2014. *Good practice in sludge management.* [Online]
Available at: http://www.purebalticsea.eu/index.php/gpsm:good_practices#ch_7
[Accessed 16 May 2014].

Rehl, T. & Müller, J., 2011. Life cycle assessment of biogas digestate processing technologies. *Resources, Conservation and Recycling,* 56(1), pp. 92-104.

RET MJ2411, 2012. *Lecture: An Introduction to Biomass Origin, Supply, and Conversion Technology,* Stockholm: KTH.

Saidur, R. et al., 2011. A review on biomass as a fuel for boilers. *Renewable and Sustainable Energy Reviews,* June, 15(5), pp. 2262-2289.

Skärvad, P.-H. & Olsson, J., 2013. *Företagsekonomi 100.* 16:1 ed. Malmö: Liber.

SSWM, 2010. *Sustainable sanitation and water management: Fertiliser from sludge.* [Online]
Available at: http://www.sswm.info/category/implementation-tools/reuse-and-recharge/hardware/reuse-urine-and-faeces-agriculture/ferti-0
[Accessed 13 March 2014].

Statens energiverk, 1987. *Fluidiserad förbränning - en översikt av teknikläget,* Örebro: Ljungföretagen.

Statens Energiverk, 1991. *Rökgaskondensering en översikt av teknikläget.* 1st ed. Stockholm: Sigtuna Tryck och Reklam AB.

Stigka, E. K., Paravantis, J. A. & Mihalakakou, G. K., 2014. Social acceptance of renewable energy sources: A review of contingent valuation applications. *Renewable and Sustainable Energy Reviews*, April, Volume 32, pp. 100-106.

Stockholm Vatten, 2010a. *Reningsprocessen.* [Online]
Available at: http://www.stockholmvatten.se/Vattnets-vag/Avloppsvatten/Reningsverk/Processer/
[Accessed 04 February 2014].

Stockholm Vatten, 2014a. *Miljösatsning för framtidens avloppsrening i Stockholm.* [Online]
Available at: http://www.stockholmvatten.se/Aktuellt/Nyheter/Miljosatsning-for-framtidens-avloppsrening-i-Stockholm/
[Accessed 25 February 2014].

Strömberg, B., 2012a. *Synthesis of Värmeforsk´s research programme “Environmenatlly correct utilisation of ashes 2009-2011”,* Stockholm: s.n.

Strömberg, B., 2012b. *Beräkningsbilaga A,* Stockholm: Värmeforsk Service AB.

Strömberg, B. & Herstad Svärd, S., 2012. *Bränslehandboken 2012.* 1st ed. Stockholm: Värmeforsk.

Stålenheim, A. & Henderson, P., 2004. *Corrosion in waste incineration facilities,* Stockholm: s.n.

SWECO, 2009. *Miljökonsekvensbeskrivning till ansökan om tillstånd till fortsatt och utökad verksamhet vid kraftvärmeverket i Brista.,* Stockholm: SWECO Vatten och Miljö.

Svedenkrans, C., 2000. *Mätningar och utvärdering avseende sambandet mellan bränslesammansättning, pannfunktion och materialkorrosion i en CFB-panna konstruerad för returbränsle,* Stockholm: s.n.

Svenskt Vatten, 2013. *Slamanvändning och strategier för slamanvändning,* s.l.: s.n.

Sveriges Riksdag, 2013. *Förordning (2013:253) om förbränning av avfall.* [Online]
Available at: http://www.riksdagen.se/sv/Dokument-Lagar/Lagar/Svenskforfattningssamling/_sfs-2013-253/
[Accessed 26 February 2014].

Tamm, D. & Ossiansson, E., 2009. *KONCEPTUTREDNING BIOGASANLÄGGNING MÖNSTERÅS – Biogasproduktion,* Lund: BioMil AB.

The AD centre, 2014. *Digestate processing.* [Online]
Available at: http://www.walesadcentre.org.uk/Technologies/DigestateProcessing.aspx
[Accessed 29 January 2014].

Thermopedia, 2010. *Fundamentals: Fluidized Bed.* [Online]
Available at: http://www.thermopedia.com/content/46/?tid=104&sn=1297
[Accessed 30 January 2014].

Thuresson, M. & Haapaniemi, U., 2005. *Slam från avloppsreningsverk - Mängder, kvalitet samt användning i Stockholms län under perioden 1981 till 2003,* Stockholm: Intellecta DocuSys AB.

Tideström, H., 2008. *Slamregler i korthet.* [Online]
Available at:
http://www.svensktvatten.se/Documents/Kategorier/Avlopp%20och%20milj%C3%B6/Slam/Slamregler%20i%20korthet%20-%20Kommentarer.pdf
[Accessed 29 January 2014].

Tilli, A., 2003. *Bioenergy,* Helsinki: Helsinki University of Technology.

TYRÉNS, 2013. *BEHANDLINGSMETODER FÖR HÅLLBAR ÅTERVINNING AV FOSFOR UR AVLOPP OCH AVFALL.* Stockholm: Thyréns AB.

US Environmental Protection Agency, 2000. *NOx Reduction Techniques and Control Measures,* s.l.: s.n.

van Kuijk, H. A. J. A., 2008. *Grate Furnace Combustion: A Model for the Solid Fuel Layer,* Eindhoven: Eindhoven University of Technology.

Wasielewski, R., Stelmach, S. & Jagustyn, B., 2013. SEWAGE SLUDGE AS A RENEWABLE ENERGY CARRIER AND CO2 ZERO EMISSION BIOMASS IN CO-COMBUSTION WITH COAL. *Environment Protection Engineering,* 14 February.39(2).

Wellons Fei corp, 2012. *Reciprocating grate.* [Online]
Available at: http://www.wellonsfei.ca/en/reciprocating-grate.aspx
[Accessed 29 January 2014].

Werkelin, J., Skrifvars, B.-J. & Hupa, M., 2005. Ash-forming elements in four Scandinavian wood species. Part 1: Summer harvest. *Biomass & Bioenergy,* Issue 29, pp. 451-466.

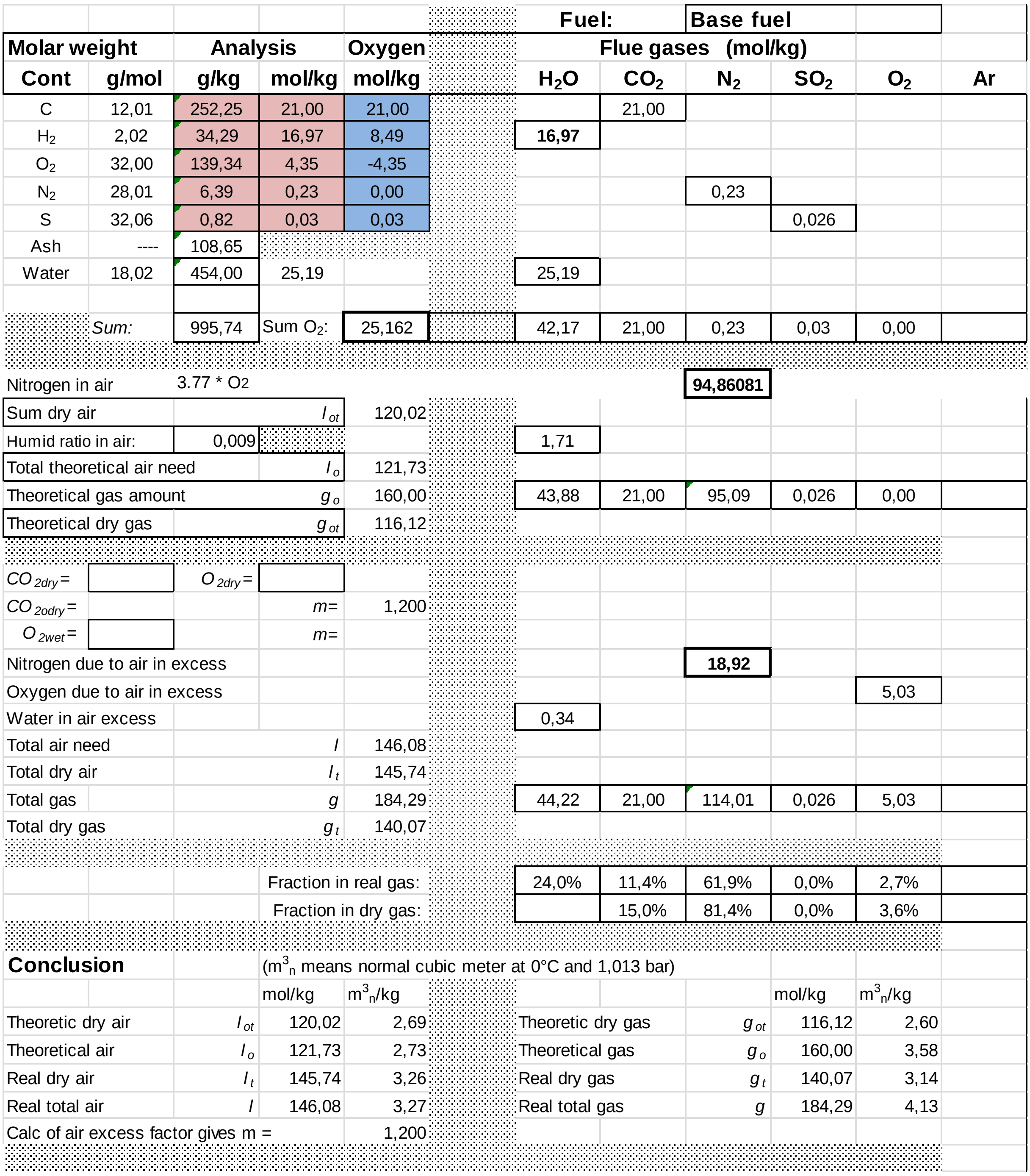
Werther, J. & Ogada, T., 1999. Sewage sludge combustion. *Progress in Energy and Combustion Science,* February, 25(1), pp. 55-116.

Wtert, 2010. *Flue gas cleaning.* [Online]
Available at: http://www.wtert.eu/default.asp?Menue=12&ShowDok=23
[Accessed 13 February 2014].

Özek Makina, 2014. *What is a rotary kiln?.* [Online]
Available at: http://www.rotarykiln.net/what-is-a-rotary-kiln/
[Accessed 11 March 2014].

Appendices

Appendix 1: Combustion table



						Fuel:		**Base fuel**			
Molar weight		**Analysis**		**Oxygen**		**Flue gases (mol/kg)**					
Cont	**g/mol**	**g/kg**	**mol/kg**	**mol/kg**		**H_2O**	**CO_2**	**N_2**	**SO_2**	**O_2**	**Ar**
C	12,01	252,25	21,00	21,00			21,00				
H_2	2,02	34,29	16,97	8,49		**16,97**					
O_2	32,00	139,34	4,35	-4,35							
N_2	28,01	6,39	0,23	0,00				0,23			
S	32,06	0,82	0,03	0,03					0,026		
Ash	----	108,65									
Water	18,02	454,00	25,19			25,19					
	Sum:	995,74	Sum O_2:	25,162		42,17	21,00	0,23	0,03	0,00	
Nitrogen in air		3.77 * O2						**94,86081**			
Sum dry air			l_{ot}	120,02							
Humid ratio in air:		0,009				1,71					
Total theoretical air need			l_o	121,73							
Theoretical gas amount			g_o	160,00		43,88	21,00	95,09	0,026	0,00	
Theoretical dry gas			g_{ot}	116,12							
CO_{2dry}=		O_{2dry}=									
CO_{2odry}=			m=	1,200							
O_{2wet}=			m=								
Nitrogen due to air in excess								**18,92**			
Oxygen due to air in excess										5,03	
Water in air excess						0,34					
Total air need			l	146,08							
Total dry air			l_t	145,74							
Total gas			g	184,29		44,22	21,00	114,01	0,026	5,03	
Total dry gas			g_t	140,07							
			Fraction in real gas:			24,0%	11,4%	61,9%	0,0%	2,7%	
			Fraction in dry gas:				15,0%	81,4%	0,0%	3,6%	

Conclusion (m^3_n means normal cubic meter at 0°C and 1,013 bar)

		mol/kg	m^3_n/kg			mol/kg	m^3_n/kg
Theoretic dry air	l_{ot}	120,02	2,69	Theoretic dry gas	g_{ot}	116,12	2,60
Theoretical air	l_o	121,73	2,73	Theoretical gas	g_o	160,00	3,58
Real dry air	l_t	145,74	3,26	Real dry gas	g_t	140,07	3,14
Real total air	l	146,08	3,27	Real total gas	g	184,29	4,13
Calc of air excess factor gives m =			1,200				