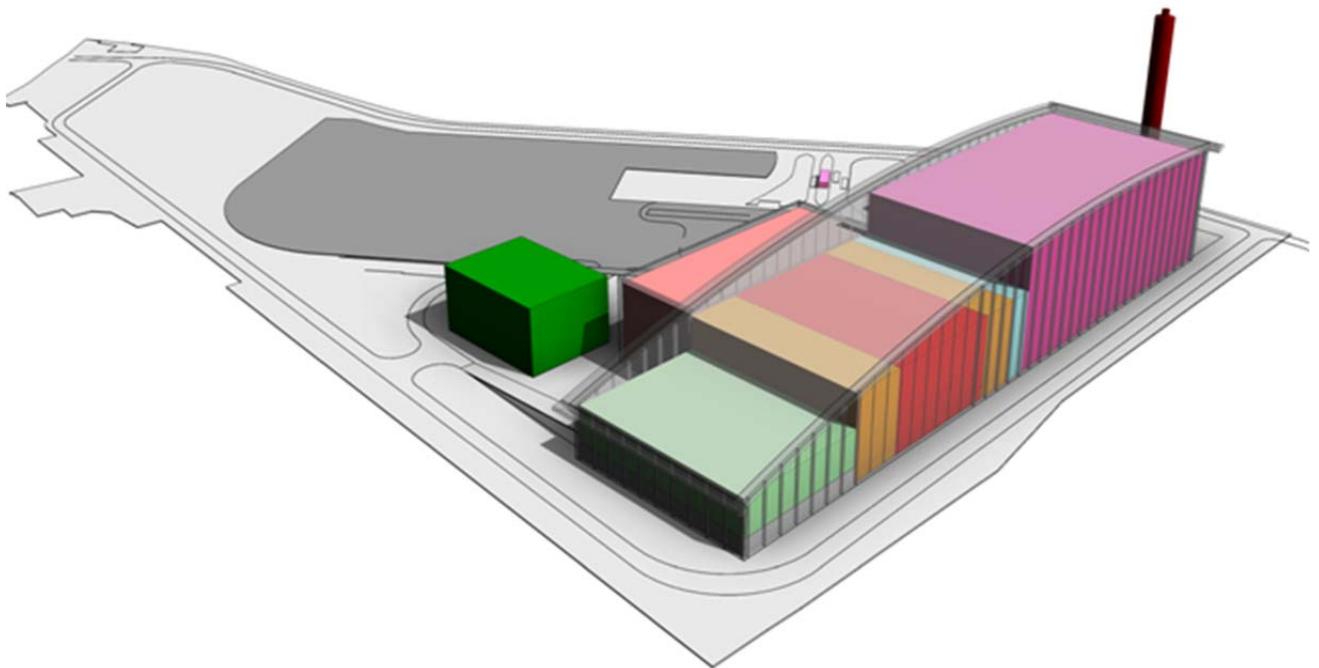


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# NORTH LONDON HEAT AND POWER PROJECT – FLUE GAS TREATMENT PLANT OPTIONS



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## 1. EXECUTIVE SUMMARY

### Introduction

The combustion of solid fuels, including waste and waste derived fuels results in the production of gases consisting water vapour, carbon dioxide and excess air. This mixture of combustion gases is termed "flue gas" and carries components including acid gases, organic substances, heavy metals and fly ash particles that can have adverse health and environmental impacts. Although these components represent a much smaller part than water, carbon dioxide or excess air, thermal process/power plants, including Energy Recovery Facilities (ERFs), treat flue gases to mitigate the impact of pollutants.

Water vapour is harmless but contributes to a visible plume at the stack outlet. Depending on waste properties, water vapour concentration typically lies in a range between 10% and 24% of the flue gas flow.

Carbon dioxide is the universal end product of combustion, but also the product of biological aerobic metabolisms. Carbon dioxide concentration of combustion gases is approximately 10% of the total volume, as an order of magnitude.

The major part, approximately 75%, of the flue gas is excess air, consisting of unburned oxygen and atmospheric nitrogen as well as argon (Ar) and other atmospheric components. This is harmless and does not require treatment.

This document provides an overview of flue gas treatment (FGT) technologies together with key criteria for technology selection and the drivers that impact technology choice. The document concludes with recommendations for NLWA's proposed new ERF at Edmonton, London.

Waste processing volumes and waste composition are key drivers for FGT plant technology selection and design. Waste to be processed is assumed to comprise municipal solid waste (MSW) derived from household waste, some commercial and industrial (C&I) waste, and residual waste from Household Waste Recovery Centres (HWRC's). Any other waste, such as solid recovered fuel (SRF), is assumed to be the product of sorted MSW that will, when combusted, give rise to similar flue gas.

FGT system selection and operation requirements need particular attention due to the content of sulfur and chlorine in waste fractions. These are the sources of sulfur dioxide (SO<sub>2</sub>) and hydrogen chloride (HCl) in the raw gas resulting from the combustion process and they have a key influence over the design of a FGT system.

### Site Factors

Site specific factors that influence FGT choice include restriction to nitrogen oxide (NO<sub>x</sub>) emissions if a local area is regarded as a "high NO<sub>x</sub>" region. Furthermore, restriction on the discharge of wastewater containing chlorine will preclude the ability to select a wet scrubbing system.

### Environmental Factors

Environmental permits set limits on the allowable concentration of pollutants in gaseous emissions from ERFs. Similarly there are specific requirements on the condition of wastewater discharged to a water course. Discharge condition limit values for air emissions and discharge of wastewater from ERF plants in the UK are determined on the basis of the parameters set in the European Union Directive 2010/75/EU on Industrial Emissions (IED). However, in some cases the permitted emission limits are more stringent than IED limits with reference to the principles of using Best Available Techniques (BAT) as defined in the Best Available Technology Reference Documents (BREF) documents and specific local conditions such as air quality.

BREF documents do not provide specific guidelines on the choice of technology, and both wet and dry systems can be considered as BAT. There are guidelines in the documents on the choice of reagent for pollutant abatement.

### Residues

Flue gas treatment using a reagent such as lime results in the production of solid residues. This is regardless of the FGT plant system in place. Residues are classified as hazardous waste and are disposed of at suitably licenced facilities. These can be hazardous landfill or underground storage. Some treatment techniques stabilise residues and reduce the potential for leaching. Residue production per tonne of waste combusted is a reflection of the pollutant removal efficiency of the FGT system. Residue amounts and composition will depend on the choice of FGT process, raw gas pollutant content, untreated flue gas and other process conditions.

### Flue gas treatment technologies

Basic FGT systems treat raw combustion gas after it has passed through the boiler to limit the emissions to air of dust, acidic gases (hydrogen chloride (HCl), hydrogen fluoride (HF) and sulphur dioxide (SO<sub>2</sub>)), heavy metals, nitric oxide/nitrogen dioxide (NO<sub>x</sub>) and dioxins.

NO<sub>x</sub> is treated in a separate system, within the combustion chamber or thereafter. Carbon monoxide (CO) and total organic carbon (TOC) content limits are addressed by control of the combustion in the furnace.

FGT plants are categorized into distinct systems: dry, semi-dry, and wet systems.

'Dry' systems use a dry reagent and reaction process, residues leave the facility as a dry product, and no wastewater is produced. This system is commonly employed in the UK.

'Wet' scrubbing systems have several processing stages. These include a wet scrubber producing a solution containing the majority of the chloride released from the combusted waste, thereby limiting the generation of solid residues.

### Dry systems (bicarbonate or lime)

Traditionally dry FGT systems have been the most commonly employed system worldwide and still widely used today. Dry bicarbonate and lime based systems are technically very similar. The dry system is relatively simple to install and operate. Space requirements are low. Therefore, the associated capital investment and maintenance costs are relatively low.

The dry process has limited capability when treating elevated levels of pollutants and the process is not suited for reaching very stringent emission values unless a large excess of hydrated lime is used. Significant quantities of residue generation increase disposal costs and make the process expensive from an operating perspective.

Ramboll's FGT system comparison below assumes a bicarbonate system.

### Semi dry systems

Semi-dry systems were introduced to optimise the chemical reaction between acidic combustion gases and lime added to the flue gas stream. This is achieved by introducing water to control flue gas temperature and humidity. Water may be injected directly into the flue gas stream or hydrated lime may be added as slurry.

Semi dry systems are relatively simple to install and operate. Furthermore, space requirements are moderate. The systems are more efficient than dry process. The process produces significant quantities of flue gas treatment residues, although somewhat less than dry, lime based treatment systems.

### Wet scrubbing systems

Wet scrubbing systems have not been installed at ERFs in the UK. This is believed to be due to higher capital cost requirements than alternative technologies and no readily available effluent outlets. However, the system is common in Europe e.g. Germany and Switzerland. Although the system is not common in UK, the concept is included in this report as a valid alternative representing an option to assess the most beneficial FGT solution.

In the wet FGT system hydrogen chloride (HCl) is separated simultaneously with hydrogen fluoride (HF) and mercury (Hg) in an acidic scrubber. Sulfur dioxide (SO<sub>2</sub>) and the remaining hydrogen fluoride (HF) contents are removed in a caustic or neutral scrubber. Wet FGT systems produce wastewater that requires treatment before discharge.

Wet FGT plants can achieve efficient flue gas cleaning, are robust with respect to changes in raw gas composition and have the flexibility to meet more stringent emission limits than currently in place. Low consumption of consumables results in low volumes of residue generation.

A wet scrubbing system includes many process steps, hence requiring high capital investment, is more complex to operate, and requires specialist staff. The treatment of wastewater is an additional process. The cost of liquid effluent disposal can be significant. There is significant plume visibility unless the flue gas is reheated prior stack exit.

A wet system can be combined with a semi dry system to avoid effluent discharge needs. Such a combined system archives high pollutant removal efficiency and reduces residue generation.

### FGT Technology Costs

The operational costs for FGT plants include consumables, the management of the resulting residue, staffing and maintenance. The following is Ramboll's cost rankings for the FGT systems detailed. The wet process yields much smaller amounts of residues, but requires more specialised staff and resources to operate. This is due to the high complexity of the plant. The advantages and disadvantages of the plant are balanced and consequently operating costs of the system are favourable over other systems.

The operating cost estimates below take account of wastewater treatment costs for the wet system.

*Note: 1 equates to lowest cost and 4 equates to highest cost*

Cost	Dry Bicarbonate	Semi-dry	Combined	Wet
<b>Capital Cost Ranking</b>	1	2	3	4
<b>Operating Cost Ranking</b>	4	2	3	1
<b>Overall Lifetime Cost Ranking</b>	4	1	3	2

**Table 1: FGT Plant Capital, Operational and Lifecycle Cost Rankings**

### De-NOx systems

Waste combustion in grate fired systems results in the production of nitrogen oxides (NO<sub>x</sub>) with typical flue gas contents of around 350 mg/Nm<sup>3</sup> with a reference condition of 11 % O<sub>2</sub>, dry. The current permitted NO<sub>x</sub> emission level from ERFs is 200 mg/Nm<sup>3</sup> (dry flue gas at 11% O<sub>2</sub>). A dedicated deNO<sub>x</sub> process is required to meet this requirement. The process options are:

- Selective Non-Catalytic Reduction (SNCR)
- Selective Catalytic Reduction (SCR).

The SNCR process entails ammonia water injection in the upper part of the combustion chamber. Suppliers of SNCR systems are usually willing to provide nitrogen oxides (NOx) emission guarantees in the range 100 – 150 mg/Nm<sup>3</sup>.

The SCR process entails ammonia injection upstream of a catalyst. SCR can achieve nitrogen oxides (NOx) emission levels lower than 25 mg/Nm<sup>3</sup> and limit ammonia consumption to a greater extent than the SNCR system.

The costs of deNOx by SCR are much higher than SNCR systems due to higher capital requirements. SCR systems can also have higher operating costs if there are heating requirements. Therefore, SNCR is usually the preferred deNOx technology in the UK due to its cost benefit advantages and the fact that the system enables compliance with current IED emission limit requirements. However, more stringent NOx emission limits i.e. 100 mg/Nm<sup>3</sup> or lower requirements may be set in the coming years. Modern plant designs using SNCR systems often make space allowance for the future retrofit of an SCR system to meet possible more stringent NOx emission requirements.

DeNOx System Costs

Operational costs for deNOx technologies include consumables, staffing and maintenance. The following are Ramboll’s cost rankings for deNOx systems. The cost estimates, considering both operational and capital cost estimates, conclude the SNCR 150 option as the most beneficial from a cost perspective. In general the SNCR process is much more attractive than the SCR perspective from a total cost perspective.

*Note: 1 equates to lowest cost and 4 equates to highest cost*

Cost	SNCR 150	SNCR 120	SNCR 100	SCR after semi-dry	Front-end SCR
<b>Capital Cost Ranking</b>	1	2	3	4	5
<b>Operating Cost Ranking</b>	2	3	5	4	1
<b>Overall Lifetime Cost Ranking</b>	1	2	3	5	4

**Table 2: deNOx System Capital and Operational Cost Rankings**

The SCR process captures much more NOx than the SNCR process. Therefore, the SCR process is more cost efficient if evaluated from a perspective of cost per kg of NOx captured. The SCR process is likely to compare favourably from a financial perspective where NOx taxes are in place i.e. Scandinavia.

Energy recovery options

Process design of the plant looks at energy efficiency across all components. The design of the FGT system and the adjoining equipment offers opportunity for energy recovery and improvements in overall plant efficiency. These include:

- Economiser design

The use of economisers in connection with flue gas treatment plants is frequently an opportunity to increase the overall energy efficiency of the plant. This is achieved through greater heat recovery from the flue gases emitted by the plant. An impact of this is increased possibility of plume visibility.

- Flue gas condensation

Flue gas condensation is primarily aimed at the recovery of latent energy contained in wet flue gases. When cooling flue gas to temperatures below water dew point, a part of the water vapour content condenses, releasing heat. The recovered heat can then be transferred by heat

exchanger to a consumer such as district heating. A disadvantage of cooled saturated flue gases is increased plume visibility above the stack and the need to avoid droplet precipitation.

Assessment of FGT technology options

The table below presents a high level comparison of the different FGT systems with a range of evaluation criteria. No single flue gas treatment concept is advantageous under all the evaluation criteria. The importance of each criterion needs to be weighed up for the specific project in hand.

Evaluation criteria:	Dry	Bi-carbonate	Semi-dry	Combined (Wet and Dry)	Wet
<b>Operational availability</b>					
- Performance history of reliable operation	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓
<b>Capability</b>					
- Ability to handle changes in raw gas composition	✓	✓✓	✓✓	✓✓✓	✓✓✓
<b>Flexibility</b>					
- Ability to meet more stringent future emission limit	✓	✓	✓✓	✓✓✓	✓✓✓
<b>Health and safety</b>					
- Reduced contact with hazardous material	✓✓	✓✓✓	✓✓	✓✓	✓✓
<b>Sensitivity to local conditions</b>					
- Limited plume visibility	✓✓✓	✓✓✓	✓✓✓	✓	✓
- Discharge of treated wastewater	N/A	N/A	N/A	N/A	✓
<b>Other environmental issues</b>					
- Low chemical consumption	✓	✓✓✓	✓✓	✓✓✓	✓✓✓
- Low electricity consumption	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓
- Low residue production	✓	✓✓✓	✓✓	✓✓✓	✓✓✓

✓✓✓ = attractive feature, ✓✓ = neutral feature, ✓ = existing but less attractive feature

## Conclusion

The semi-dry FGT system is the most attractive option for NLWA for the following reasons:

- The system is optimal for ERFs processing MSW where waste pollutant content will not vary notably in future years;
- There is no production of wastewater requiring specialist treatment and discharge;
- Flue gas condensation is not envisaged to be beneficial for NLWA due to the absence of adequately low cold water return temperatures from a potential district heating network;<sup>1</sup>
- There are relatively simple operational requirements; and
- There is a relatively low capital investment requirement.

A wet flue gas treatment system can reduce some emission limits to lower levels. However, this system produces effluent requiring treatment at the plant and its discharge as wastewater. If an outlet can be secured for wastewater, a wet flue gas treatment plant could be used to reduce emissions to lower levels than can be achieved by a semi dry system. Wet flue gas treatment systems are attractive for the following reasons:

- System flexibility to meet potentially more stringent future emission requirements;
- Capability to accept changes in waste composition, thus raw gas composition; and
- The amount of reagents used and resulting by products can be optimized to a higher degree.

'Advanced' SNCR systems can achieve NO<sub>x</sub> emission guarantees of around 100 mg /Nm<sup>3</sup>. This corresponds to 50% of the current daily average emission limit set in the IED. It is noted that the Edmonton region is recognised as a high NO<sub>x</sub> area. SCR systems can reduce NO<sub>x</sub> emissions to 25 mg NO<sub>x</sub>/Nm<sup>3</sup> or lower. NLWA's air quality modelling should consider the emission limits that can be achieved with SNCR 100 and SCR systems to facilitate an informed consultation and decision on the deNO<sub>x</sub> system choice. Furthermore, financial considerations should also form part of the decision making process. This may include a consideration of a tax on NO<sub>x</sub> emissions. ERF plants in Scandinavia are taxed on NO<sub>x</sub> emissions and this may also be introduced in the UK in the coming years or over the plant life.

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<sup>1</sup> It is believed, that the main option for heat supply (outside the FGT system) is the use of medium or low pressure steam extraction from a suitable turbine.

## 2. INTRODUCTION

This document provides an overview of the health and environmental risks posed by Energy Recovery Facility (ERF) emission to air, flue gas treatment (FGT) technologies available to mitigate risks, key criteria for technology selection and the drivers that impact technology choice. The document concludes with recommendations for NLWA’s ERF at Edmonton.

Ramboll’s evaluation criteria for flue gas treatment technology selection is presented and discussed in **Figure 1** below:



Figure 1: FGT Plant Evaluation Criteria

### 3. HEALTH AND ENVIRONMENTAL RISKS OF ERF EMISSIONS TO AIR

#### 3.1 Introduction

The combustion of solid fuels, including waste and waste derived fuels results in the production of gases consisting of water vapour, carbon dioxide and excess air. This mixture of combustion gases is termed "flue gas" and carries components including acid gases, organic substances, heavy metals and fly ash particles that can have adverse health and environmental impacts. Although these components represent a much smaller part than water vapour, carbon dioxide or excess air, thermal process/power plants including ERFs treat flue gases to mitigate impact of pollutants.

Water vapour is harmless but contributes to a visible plume at stack outlet. Depending on waste composition, water vapour concentration typically lies in a range between 10% and 24% of the flue gas flow.

Carbon dioxide is the universal end product of combustion, but also the product of biological aerobic metabolisms. Carbon dioxide concentration of combustion gasses is approximately 10% of the total volume, as an order of magnitude.

The major part (approximately 75%) of the flue gas is excess air comprising unburned oxygen and atmospheric nitrogen as well as the noble gas argon (Ar) and other atmospheric components that are harmless and do not require treatment.

The flue gas components that require treating and their potential impacts, if untreated, are discussed below.

#### 3.2 Acid Gases

##### 3.2.1 General

Sulfur dioxide ( $\text{SO}_2$ ), hydrogen chloride (HCl), hydrogen fluoride (HF) and nitrogen oxides ( $\text{NO}_x$ ) are acid gases. Solutions of acid gases and water have a low pH-value, thus acidic, and can have negative impacts on vegetation. Acidic gases released into atmosphere are converted into sulfuric acid, hydrochloric acid and nitric acid as they dissolve in water droplets and precipitate onto soil and into water basins.

Emission of acidic gases can result in acid rain impacting vast amounts of vegetation and areas of the natural habitat by acidification. The deposition of acid gases can also have corrosive effects on buildings.

##### 3.2.2 Sulfur Dioxide ( $\text{SO}_2$ )

Sulfur dioxide ( $\text{SO}_2$ ) health concerns include effects on the respiratory system. People with asthma or bronchitis are most vulnerable to these adverse health effects. Combustion processes that lead to high concentrations of sulfur dioxide ( $\text{SO}_2$ ) generally also lead to the formation of sulfur trioxide ( $\text{SO}_3$ ). This in turn leads to the formation of fine sulphate aerosol particles in the atmosphere, imposing health risks, as they penetrate into the lungs and over time causing potential respiratory disease.

##### 3.2.3 Hydrogen Chloride (HCl)

Hydrogen chloride (HCl) is gaseous and forms hydrochloric acid when in contact with humidity or water droplets and deposit on to the ground. Flue gas treatment measures to reduce sulfur dioxide ( $\text{SO}_2$ ) emissions also lead to a significant reduction in hydrogen chloride (HCl) emissions.

Exposure to highly concentrated hydrogen chloride (HCl) may affect human health; causing throat irritation and in extreme cases severe swelling of the throat. Inhalation of hydrogen chloride (HCl) can also lead to asthma. However, hydrogen chloride (HCl) at normal background levels is unlikely to have any adverse impacts on human wellbeing.

### 3.2.4 Nitrogen Oxides (NO<sub>x</sub>)

The components nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) are together termed nitrogen oxides (NO<sub>x</sub>), because over time nitric oxide (NO) is transformed into nitrogen dioxide (NO<sub>2</sub>).

Nitrogen dioxide (NO<sub>2</sub>) can contribute significantly to the formation of ozone near ground level and contribute to the formation of photochemical smog. Excess ozone (O<sub>3</sub>) concentrations are believed to cause increased respiratory symptoms and asthma. Nitrogen dioxide (NO<sub>2</sub>) is in itself toxic and reacts with ammonia, moisture, and other compounds to form small particles. The health effects of nitrogen dioxide (NO<sub>2</sub>) are similar to that of sulfur oxides.

### 3.3 Nitrous Oxide (N<sub>2</sub>O)

Other oxides of nitrogen include nitrous oxide (N<sub>2</sub>O). Nitrous oxide (N<sub>2</sub>O) is not a direct hazard to health, but a greenhouse gas with a significant global warming potential.

### 3.4 Ammonia (NH<sub>3</sub>)

Ammonia (NH<sub>3</sub>) is a volatile gaseous component originating as excess from the injection of ammonia water or urea in the nitrogen oxide (NO<sub>x</sub>) cleaning processes.

Ammonia (NH<sub>3</sub>) deposition to ground has effects on biological conditions through nitrification.

### 3.5 Heavy Metals

#### 3.5.1 General

Heavy metals are metallic elements with a greater density than iron and are generally of environmental concern. These metals, with the exception of mercury (Hg), are released in their oxidized form during combustion. They are discharged from the plant with either incinerator bottom ash, fly ash or the residual FGT products. Heavy metals from fly ash can leach into a watery phase and thereby enter the environment. Therefore, fly ash is sent to safe/hazardous landfills.

#### 3.5.2 Mercury (Hg)

Mercury (Hg) is the most prominent heavy metal and a naturally occurring element that is found in air, water and soil. The tendency of mercury to stick to fly ash particles is low.

Mercury (Hg) may have toxic effects on the nervous system and organs. Even at low concentrations mercury (Hg) can cause serious health problems and is a threat to the child development. Human activity is the main cause of mercury release. Once in the environment mercury (Hg) can be accumulated in the food chain.

Mercury must be specially taken care of in the flue gas treatment plant, either by application of activated lignite coke as an adsorbent or by absorption in an acidic reactor.

### 3.6 Dioxins and Other Organic Compounds

#### 3.6.1 General

Organic compounds, as a rule, are only generated when there is incomplete combustion e.g. lack of combustion air or insufficient combustion temperatures. Organic compounds are molecules that contain carbon (C) and typically hydrogen (H), oxygen (O) and other elements. Simple molecules like carbon dioxide (CO<sub>2</sub>) are regarded as inorganic, whereas methane (CH<sub>4</sub>) is classified as organic. Organic molecules can form long molecule chains, rings, and combinations hereof. A well-known class of such molecules are polycyclic aromatic hydrocarbons (PAH's) which can be toxic and can influence hormonal balance. Organic compounds and PAH's are unlikely to form or survive under normal combustion conditions.

#### 3.6.2 Dioxins

Dioxins are highly toxic and relatively stable organic compounds with a polycyclic structure. The presence of chloride (Cl) is a precondition for the formulation of dioxins. During typical waste

combustion processes dioxins are generated in the boiler in trace amounts and mostly segregated and conveyed away with fly ash. In the FGT dioxins are further reduced by injection of activated carbon or lignite coke or alternatively by catalytic reduction.

Dioxins entering the environment are persistent pollutants and can accumulate in the food chain, mainly in the fatty tissue of animals. Dioxins can cause reproductive and development problems, damage to the immune system, interfere with hormones and also cause cancer. Human exposure is mainly through food consumption, thus food supply is monitored by relevant agencies/organisations to detect concentrations and prevent human consumption.

People have background exposure to dioxin levels that does not impact health. However, efforts are undertaken to reduce current background dioxin exposure levels through limiting emissions from sources. ERFs are often claimed as being a significant source of dioxins. This is not the case when the dioxin emission levels are limited with flue gas treatment.

### 3.7 Particles

Particulate matter and dust mainly originates as fly ash from the combustion process. The introduction of powdery reagents and reaction products in FGT plants also adds to particulate matter presence in the flue gas. Particulate filters limit particulate matter and dust emissions from ERFs. The absence of a particle filter at an ERF would result in a dark exhaust plume from the stack.

### 3.8 Development Conclusions

The historical development of emissions from ERFs has been assessed in the separate study "Health Impact Literature Review". Emissions from ERFs have significantly reduced over the last 40 years. Substantial reductions have been achieved since the 1990s. Emissions of main pollutants under the current regulation (IED and BREF) have reduced by a factor of around 10 compared to the mid-1990s and by a factor of around 100 compared to previous decades before any regulations were implemented. This applies to key pollutants such as particulate matter, hydrogen chloride (HCl), dioxins and most trace heavy metals. Other pollutants such as sulphur dioxide (SO<sub>2</sub>) and mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NO<sub>x</sub>) have also reduced significantly. Technical developments now offer the potential to reduce NO<sub>x</sub> emissions even further.

## 4. CONSIDERATION FOR FLUE GAS TREATMENT DESIGN

### 4.1 Plant Capacity and Waste Input

Waste processing volumes and waste composition are key drivers for FGT technology selection and design. This document outlines FGT systems for concept selection. The types of flue gas treatment systems discussed are applicable to the industrial scale ERF plant NLWA is considering.

### 4.2 Waste Composition

The waste to be processed is Local Authority Collected Waste (LACW) assumed as primarily comprising municipal solid waste (MSW) derived from household waste with some (minor) contribution from commercial and industrial (C&I) waste. Similarly any/possible waste derived fuels i.e. solid recovered fuel (SRF) that may be processed is assumed to be the product of treating MSW waste streams, thus resulting in similar composition flue gas.

MSW typically has an approximate net heating value of 9 to 10 MJ/kg. The heating value and pollutant content of waste streams such as C&I are generally higher than that of household waste. C&I waste typically has an approximate calorific value of 11 to 12 MJ/kg.

FGT system selection and operations at ERFs requires particular attention due to sulfur and chlorine in waste fractions. These are the respective sources of sulfur dioxide (SO<sub>2</sub>) and hydrogen chloride (HCl) in the raw gas resulting from the combustion process and they have a key influence over the design of a FGT system. Usually almost all chlorine is converted to hydrogen chloride (HCl) whilst only a proportion of sulfur is converted to sulfur dioxide (SO<sub>2</sub>), i.e. some 30-70%.

Chlorine in household waste occurs at moderate levels (typically 0.1 - 0.3%, excluding the effect of PVC), predominantly from normal household salt. PVC with a chlorine content of circa 50% is a key source of chlorine in waste treated at an ERF plant. Even small amounts of PVC in waste would generate high hydrogen chloride (HCl) levels in raw flue gas. Thus, the indicative waste specification reflects a certain amount of PVC or similar waste fractions. The nature of waste types delivered to EfW plants has a significant influence when selecting a FGT concept due to the need to meet specified hydrogen chloride (HCl) emission limits.

The indicative waste amount and composition for the ERF is assumed to be as stated in **Table 3**:

Parameter	Unit	Nominal waste	Proposed range <sup>2</sup>
Waste flow	ton/h	43.75	
Annual hours of operation	hrs/yr	8,000	
Annual waste throughput per line	ton/yr	350,000	
Annual waste throughput by a 2 line plant	ton/yr	700,000	
Lower heating value	GJ/t	10	7-12
Thermal energy input per line	MW	122	
Ash content in waste	%	20	
Moisture content in waste	%	31	
Sulfur in waste, S	%	0.13	0-0.5
Chlorine in waste, Cl	%	0.64	0-1.5

**Table 3: Waste specification for FGT-technology selection**

<sup>2</sup> The range maybe exceeded for individual waste loads/samples, but it shall be possible to mix the waste fed to the furnace to fit within the range, e.g. by efficient mixing of waste in the bunker. The nominal values are derived from the waste analysis and recommendations. The nominal point is the design point for the plant. A range is stated for Lower Heating Value, sulfur and chlorine contents to reflect the possible values with waste compositions variations.

Ramboll reviewed the “Waste Composition Analysis for NLWA” report prepared by Entec, dated September 2010. The study supports the assumption of an average lower heating value of 9.5 GJ/t. However, sulfur content (around 0.1%) seems to be lower than usually assumed for MSW, but chlorine content (0.8%) is higher than that usually assumed for MSW.

It is believed that supplementary waste fractions such as bulky waste will contribute to the waste volumes to be processed, thus a typical blended (mixed) waste is assumed. In our experience typical sulfur concentrations for such mixed waste would be 0.2% and chlorine would be 0.5%. Thus the nominal sulfur content has been elevated to 0.13 % and the chlorine has been lowered to 0.6% in order to take the uncertainties into account.

Ramboll’s analysis assumes that there will be no pre-treatment of MSW received at the ERF.

Based upon current operations at the existing Edmonton plant, NLWA have advised a calorific value of 10 GJ/t for preliminary ERF design and sizing.

Ramboll recommends that further waste sampling is undertaken as part of the detail design process to better inform the waste composition the ERF will be designed to process. Information such as raw gas properties at the existing Edmonton could also be monitored to provide information to support new ERF design.

### 4.3 Flue Gas Flow and Composition

The MSW sulfur and chlorine contents discussed above are considered appropriate to evaluate the FGT concept options for NLWA.

The flue gas flow rate and composition for a 350,000 tpa line is provided below in **Table 4**.

Parameter	Unit <sup>4)</sup>	Nominal value	Min - max. (½-hr mean values) <sup>5)</sup>
O <sub>2</sub> content in flue gas, dry basis	% O <sub>2</sub> , dry	8.5*	6-10
Flue gas flow, actual O <sub>2</sub> and H <sub>2</sub> O	Nm <sup>3</sup> /h	235,000*	160,000 – 260,000
Flue gas flow (dry, 11 % O <sub>2</sub> )	Nm <sup>3</sup> /h	244,000	170,000-270,000
Flue gas temperature @ boiler exit	°C	170	160-200 <sup>1)</sup>
Flue gas moisture content	%	17	10-24
<b>Emission components at 11 % O<sub>2</sub>, dry (reference state)</b>			
CO	mg/Nm <sup>3</sup>	10	0-40
TOC	mg/Nm <sup>3</sup>	1	0-30
Dust	mg/Nm <sup>3</sup>	2,100	500-5000
HCl	mg/Nm <sup>3</sup>	1000	50-2500
SO <sub>2</sub> and SO <sub>3</sub> (as SO <sub>2</sub> )	mg/Nm <sup>3</sup>	200	0-1200
HF	mg/Nm <sup>3</sup>	20	0-50
NO <sub>x</sub> (as NO <sub>2</sub> ) without SNCR	mg/Nm <sup>3</sup>	350	250-500
NO <sub>x</sub> (as NO <sub>2</sub> ) with SNCR <sup>2)</sup>	mg/Nm <sup>3</sup>	120	100-300
NH <sub>3</sub> <sup>2)</sup>	mg/Nm <sup>3</sup>	10	0-20
Σ 9 metals <sup>3)</sup>	mg/Nm <sup>3</sup>	10	50
Hg	mg/Nm <sup>3</sup>	0,2	0,5
Cd+Tl	mg/Nm <sup>3</sup>	1	2
Dioxins and furans, TEQ	ng/Nm <sup>3</sup>	2	5

**Table 4: An example of raw, untreated flue gas flow rate and composition (1 x 350 ktpa line)**

\*) : Dependent on furnace/boiler guaranteed performance.

1) : Dependent on boiler optimisation and choice of FGT-concept

2) : Assuming SNCR for deNO<sub>x</sub>

3) :  $\Sigma$  9 metals is the sum of concentrations for: Sb, As, Pb, Cr, Co, Cu, Mn, Ni and V

4) : Nm<sup>3</sup> are cubic meters at standard conditions at 0 °, 101,325 Pa.

5) : Range applies for normal operation under which all guarantees shall be fulfilled. The range may be exceeded on occasions i.e. for a short term basis or during abnormal operations, e.g. during water spraying for removal of ash deposits.

#### 4.4 Site Specific Factors

Site specific conditions at Edmonton as well as the priorities of NLWA may have a strong impact on the choice of FGT system. For instance, plant location may mean it is not possible or permitted to discharge wastewater with elevated content of salt in solution (non-hazardous calcium chloride) to a recipient or sewage system, e.g. foul drain. In such cases FGT plants comprising wet scrubbing systems as a rule are not suitable. A typical wastewater specification at a water treatment plant outlet is presented in **Table 8**.

## 5. ENVIRONMENTAL REQUIREMENTS

### 5.1 General

Environmental permits set limits on allowable concentration of pollutants in gaseous emissions from ERF plants. Similarly there are specific requirements on the condition of wastewater discharged to a water course. Discharge condition limit values for air emissions and discharge of wastewater from ERF plants in the UK are determined on the basis of the parameters set in the EU Directive 2010/75/EU on Industrial Emissions (IED). However, in some cases the resulting emission limits for the permit are more stringent than IED limits with reference to the principles of using Best Available Techniques (BAT) as defined in the BREF documents. These aspects are discussed below.

### 5.2 IED Directive

The air emission limit values set out in the IED are listed in **Table 5** below.

Parameter	Unit, ref. dry flue gas at 11% O <sub>2</sub>	Air emission limit values , cf. IED-directive	
		Daily average	½-hour average 97 % / 100 %
Dust	mg/Nm <sup>3</sup>	10	10 / 30
HCl	mg/Nm <sup>3</sup>	10	10 / 60
HF	mg/Nm <sup>3</sup>	1	2 / 4
SO <sub>2</sub> + SO <sub>3</sub>	mg/Nm <sup>3</sup>	50	50 / 200
NO <sub>x</sub> as NO <sub>2</sub>	mg/Nm <sup>3</sup>	200	200 / 400
Result of spot sampling			
Cd + Tl	mg/Nm <sup>3</sup>	0.05	
Σ 9 metals <sup>1)</sup>	mg/Nm <sup>3</sup>	0.5	
Hg	mg/Nm <sup>3</sup>	0.05	
Dioxin, TEQ	ng/Nm <sup>3</sup>	0.1	

**Table 5: Emission limit values within the EU**

<sup>1)</sup> Σ 9 metals include the metals and their compounds: Sb, As, Pb, Cr, Co, Cu, Mn, Ni and V

Emission limit values for carbon monoxide (CO) and total organic carbon (TOC) are not included in **Table 5**. These parameters are not notably affected by the flue gas treatment processes. However, they are controlled by waste combustion conditions and there are specific regulatory requirements for these.

### 5.3 BAT Requirements and BREF-Document

Best Available Techniques (BAT) has been introduced in the Integrated Pollution Prevention and Control (IPPC) directive and subsequently into the Industrial Emissions Directive (IED). This requires the EU commission to issue BAT reference documents (BREF).

The preamble of the IED reads (item 13),

*'In order to determine best available techniques and to limit imbalances in the Union as regards the level of emissions from industrial activities, reference documents for best available techniques (hereinafter "BAT reference documents") should be drawn up, reviewed and, where necessary, updated through an exchange of information with stakeholders and the key elements of BAT reference documents (hereinafter "BAT conclusions") adopted through committee procedure. In this respect, the Commission should, through committee procedure, establish guidance on the collection of data, on the elaboration of BAT reference documents and on their quality assurance. BAT conclusions should be the reference for setting permit conditions. They can be supplemented by other sources. The Commission should aim to update BAT reference documents not later than eight years after the publication of the previous version.'*

The BREFs are supplemented by the research institute of the EU Commission in Seville, Spain. Thirty different BREFs are issued, all with a standard table of contents of which chapter 5 is on BAT. The BREF on waste incineration has 5 subsections. Section 5.1 of these is on “Generic BAT” for all waste incineration and 5.2 is “Specific BAT for municipal waste incineration” that contains 63 recommendations of particular interest in this context.

The IED-directive includes a clause (Article 15, 3) stating:

*‘The competent authority shall set emission limit values that ensure that, under normal operating conditions, emissions do not exceed the emission levels associated with the best available techniques as laid down in the decisions on BAT conclusions...’*

It remains to be seen how this clause will be implemented in practice and we await a new edition of the BREF that will detail conclusions.

The latest update of the BREF on waste incineration was issued in 2006, and a new edition including “BAT conclusions” is due “no later than 2016” according to the wording of the preamble:

*The latest BREF BAT 35 is the closest one that gets to the BAT conclusions. BAT 35 reads: ‘the use of an overall flue-gas treatment (FGT) system that, when combined with the installation as a whole, generally provides for the operational emission levels listed in **Table 6** for releases to air associated with the use of BAT.*

Parameter	Unit	BATOEL	
		daily average	½-hour average 100 %
Dust	mg/Nm <sup>3</sup>	1-5	1-20
HCl	mg/Nm <sup>3</sup>	1-8	1-50
HF	mg/Nm <sup>3</sup>	<1	<2
SO <sub>2</sub> + SO <sub>3</sub>	mg/Nm <sup>3</sup>	1-40	1-150
NO <sub>x</sub> as NO <sub>2</sub>	mg/Nm <sup>3</sup>	120-180 <sup>1)</sup> 40-100 <sup>2)</sup>	3-350 <sup>1)</sup> 40-300 <sup>2)</sup>
<b>Result of spot sampling</b>			
NH <sub>3</sub>	mg/Nm <sup>3</sup>	<10	
Cd + Tl	mg/Nm <sup>3</sup>	0.005-0.05	
Σ 9 metals	mg/Nm <sup>3</sup>	0.005-0.5	
Hg	mg/Nm <sup>3</sup>	<0.05	
Dioxins, TEQ	ng/Nm <sup>3</sup>	0.01-0.1	

**Table 6: BAT intervals (BAT Operational Emission Levels)**

<sup>1)</sup> With SNCR. <sup>2)</sup> With SCR

BREF-documents do not provide specific guidelines on the choice of technology, hence both wet and dry systems can be considered as BAT. There is no guideline in the documents with respect to the choice of consumables for pollutant abatement, e.g. use of quick lime, hydrated lime or sodium hydroxide (NaOH) for sulfur dioxide (SO<sub>2</sub>) absorption.

#### 5.4 Expected Future Air Emissions Limit Values

This document considers FGT system options with respect to their flexibility towards meeting future emission limit values. This is somewhat helped by providing margins over the existing emission limits set out in **Table 6**. Therefore, the actual emission limits achieved by plants should not exceed the current daily average value requirements set in detail in **Table 7**.

Future limit values and the BAT conclusions are not known, thus any attempt to suggest future limit values shall be considered as Ramboll’s best estimate based upon currently available information. Ramboll cannot be held liable for actual future requirements different from our professional opinion at this time.

Our estimate considers the following, amongst other, factors:

- The above cited clause of Article 15, 3 of the IED-directive.
- The actual implementation of the IED-wording into permits remains to be seen when the revised BREF note is published with new BAT Conclusions.
- The conflicting basis of limit values that should not be exceeded anytime, and “operational emission levels” achieved under “normal” operation”.
- The limit values for waste incineration are already low for most pollutants, compared to other combustion sources i.e. coal and biomass.
- Extensive tightening of limit values may necessitate relatively costly additional equipment, and the socio-economic benefit of reduced emissions may not be a reasonable proportion to the additional cost.
- Emissions of particulate matter, sulphur dioxide (SO<sub>2</sub>), hydrogen chloride (HCl), hydrogen fluoride (HF) and dioxins are already reduced to environmentally less significant levels by current limit values.
- BAT Operational Emission Levels (BATOEL) for hydrogen fluoride (HF) is close to detection levels, further reducing the Emission Limit is difficult. The neutralization of hydrogen fluoride (HF) follows the same mechanisms as hydrogen chloride (HCl), thus effective hydrogen chloride (HCl) removal yields effective hydrogen fluoride (HF) removal. Therefore, in some cases continuous hydrogen fluoride (HF) measurements are substituted by continuous hydrogen chloride (HCl) measurement and supplementary periodic hydrogen fluoride (HF) spot measurements.
- The current emission limit value for mercury (Hg) is less stringent when compared with other pollutants, considering the severe environmental consequences of its emission. This is particularly the case for human toxicity and some European countries, e.g. Germany, have already tightened the mercury (Hg) limit value and require continuous monitoring.
- The current emission limit value for mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NO<sub>x</sub>) allows a significant environmental impact considering the range of impacts of their emissions (e.g. SMOG-formation, acidification, eutrophication and human toxicity) and associated socio-economic cost.
- The local air quality objectives may necessitate lower emissions at specific locations, particularly for mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NO<sub>x</sub>), as many cities have challenges in meeting the EU air quality requirements, particularly for nitrogen dioxide (NO<sub>2</sub>). Indications are that the Edmonton site falls into this category.
- Ammonia has no limit value in the IED-directive, but its frequent use in SNCR-systems makes a limit value obvious.
- Nitrous oxide (N<sub>2</sub>O) may be introduced in the revised BREF because it is a common by-product from the use of urea in the SNCR process.

Parameter	Unit	daily average	½-hour average 100 %
Dust	mg/Nm <sup>3</sup>	5	20
HCl	mg/Nm <sup>3</sup>	8	40
HF	mg/Nm <sup>3</sup>	<1	<2
SO <sub>2</sub> + SO <sub>3</sub>	mg/Nm <sup>3</sup>	30	100
NO <sub>x</sub> as NO <sub>2</sub>	mg/Nm <sup>3</sup>	40 - 150	100 - 200
NH <sub>3</sub>	mg/Nm <sup>3</sup>	5	20
N <sub>2</sub> O	mg/Nm <sup>3</sup>	5	30
<b>Result of spot sampling</b>			
Cd + Tl	mg/Nm <sup>3</sup>	<0.02	
Σ 9 metals	mg/Nm <sup>3</sup>	<0.1	
Hg	mg/Nm <sup>3</sup>	<0.02	
Dioxins, TEQ	ng/Nm <sup>3</sup>	<0.05	

**Table 7: Possible Minimum Future Emission Value Requirements**

### 5.5 Wastewater Discharge

Flue gas treatment processes entailing wet scrubbers generate wastewater that requires treatment and discharge. For further explanation refer to **Section 6.6 - Wet Scrubbing Systems**.

Wastewater discharged from the plant should, as a minimum, fulfil the requirements of the IED directive, ref **Table 8**. The relevant authorities may choose to tighten these requirements as a result of local conditions with a view to the BAT emission levels as guided by BREF documents.

### 5.6 Solid FGT Plant Residues

Flue gas treatment using reagents such as lime result in the production of solid residues. This is regardless of the FGT plant in place. Some of the residues produced are classified as hazardous waste. Such residues are treated at approved facilities. Management practices of these in the UK are usually either underground storage at licensed facilities or blending in a concrete mixture to stabilise hazardous substances and landfilling the resulting non-hazardous mixture. The amount of residue production is a reflection of the pollutant removal efficiency of the FGT system and how much additional reagent is required to treat the hazardous component.

For UK based ERFs, fly ash from the boiler is usually diverted into the bottom ash collection stream. However, a change in legislation may require its management as hazardous waste. In this event fly ash can be diverted into the FGT residue stream and managed accordingly. The treatment costs for hazardous waste is many times that of non-hazardous waste.

Parameter	Unit	IED	Chloride wastewater (wet FGT only)	Condensate (flue gas condensation only)
Flow	m <sup>3</sup> /tonne waste	-	0.1-0.2	0-0.5
Chloride	mg/l	-	30 000	200
Sulphate S	mg/l	-	1,500	800
Suspended matter (95 %)	mg/l	30	10	5
Ammonium-N	mg/l	-	10	5
Cyanide, CN	µg/l	-		
Mercury, Hg	µg/l	30	3	0.2
Cadmium, Cd	µg/l	50	5	1
Thallium, Tl	µg/l	50	3	2
Arsenic, As	µg/l	150	20	5
Lead, Pb	µg/l	200	50	5
Chromium, Cr	µg/l	500	50	5
Copper, Cu	µg/l	500	50	5
Nickel, Ni	µg/l	500	50	5
Zinc, Zn	µg/l	1500	300	50
Antimony, Sb	µg/l	-	100	10
Cobalt, Co	µg/l	-	30	10
Manganese, Mn	µg/l	-	-	-
Vanadium, V	µg/l	-	50	15
Tin, Sn	µg/l	-	50	10
Silver, Ag	µg/l	-	10	3
Molybdenum, Mo	µg/l	-	100	30
Selenium, Se	µg/l	-	-	-
Dioxins and furans, TEQ	ng/l	0.3	0.05	0.02

**Table 8: Expected flow rate and concentrations of wastewater from an optimised WWT facility**

## 6. FLUE GAS TREATMENT TECHNOLOGIES

### 6.1 General

FGT refers to a ranges of processes imposed on raw (untreated) combustion gas to limit harmful pollutants such as emissions of dust, acidic gases, heavy metals, and dioxins to levels well below legal emission limits.

Mono-nitrogen oxides (nitric oxide and nitrogen dioxide) ( $\text{NO}_x$ ) are treated in a separate system within the ERF. The options for this are described in detail in **Section 7**.

Carbon monoxide (CO) and total organic carbon (TOC) content requirements are addressed by controlling the combustion conditions in the furnace.

FGT plants are categorized into distinct systems: dry, semi-dry, wet systems and combinations hereof.

- 'dry' systems are where the chlorine and sulfur content of the waste leaves the facility as a dry product, and no wastewater is produced. This system is commonly employed by UK based ERFs.
- 'wet' scrubbing systems have several processing stages. These include a wet scrubber that produces a solution containing the majority of the chloride released from the combusted waste, thereby limiting the generation of solid residues.

It is possible to combine the above concepts as a 'dry-wet' process. The concept of the combined system is to remove the majority of the pollutants in an upstream dry system and include a downstream polishing scrubber to improve the overall efficiency of the flue gas treatment. Effluent from the scrubber is withdrawn as a bleed to control the salt level in the scrubber and is evaporated in the upstream 'dry' process step. Therefore, the combined dry-wet system is wastewater free.

Below are examples of typical FGT technologies. There are many specific variations for each of the systems presented.

### 6.2 Principles of Dry and Semi-dry FGT Systems

Dry and semi-dry flue gas cleaning concepts are characterized by the reaction of the acid flue gas components (hydrogen chloride (HCl), sulphur dioxide ( $\text{SO}_2$ ), and hydrogen fluoride (HF)) with the reagents forming dry cleaning products or FGT residues.

Residues are typically collected with the dioxin / furan loaded activated carbon (AC) or lignite coke, usually added to flue gas alongside with dry basic reagents. Heavy metal contents are simultaneously removed from flue gas.

Dry and semi-dry systems are less complicated compared to equivalent wet systems, because the cleaning process is performed in one common step.

Dry and the semi-dry flue gas cleaning processes usually function through the injection of hydrated lime into the flue gas stream. This leads to the neutralization of the acid flue gas components.

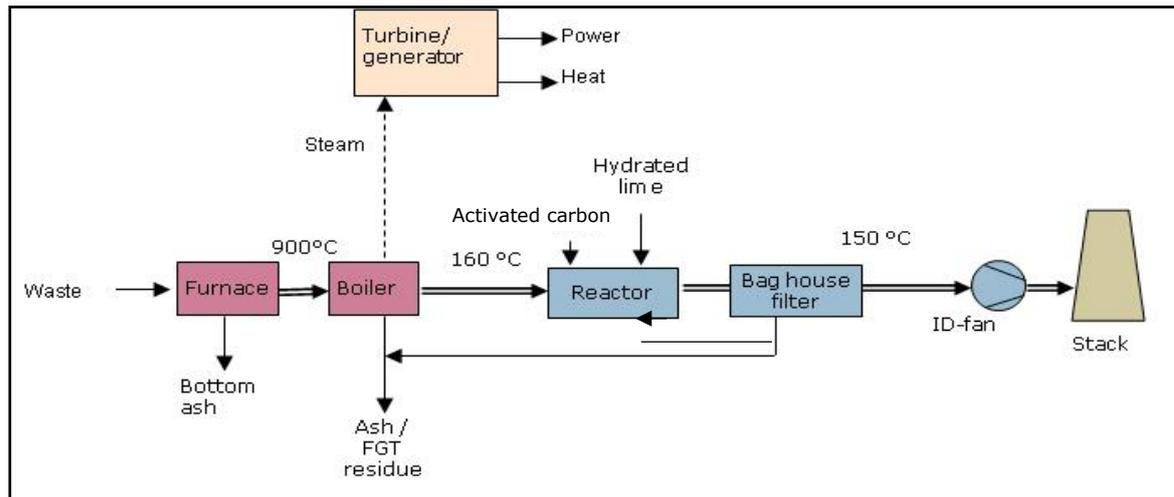
The process is called dry if hydrated lime is used as a dry pulverized reagent without adding water. It is called semi-dry if lime is moistened with water before injection into the system. In both cases the reaction product and a surplus of unreacted reagent is collected in a dry powdery form by bag house filters. There are numerous commercially available dry FGT systems. Similarly, there are some alternatives to hydrated lime as a reagent e.g. sodium bicarbonate.

### 6.3 Dry Lime Based Systems

#### Introduction

Dry lime based systems have traditionally been the most common FGT system and are still widely used.

The key components of the dry lime based system, flue gas and material flows together with conditions such as typical flue gas temperatures at various stages of the plant are shown in **Figure 2**.



**Figure 2: Lime based dry absorption system**

The solution comprises the following main components:

- Reactor for the addition of hydrated lime and activated carbon
- Bag house filter for separation of the reaction products and fly ash
- Induced draught fan (ID-fan) and stack

For energy recovery purposes an economiser might be integrated downstream, after the main components of the FGT. The drivers and possibilities are further described in **Section 8 - Energy Recovery**.

The flue gas temperature at boiler exit is typically 160 ° C. The process works in a range of lower temperatures, 160 ° C down to approximately 140 ° C. At higher temperatures efficiency is often reduced, corrosion and clogging can be an issue at lower temperatures.

An absorbent in the form of powdered hydrated lime ( $\text{Ca(OH)}_2$ ), is blown into the reactor where a reaction between hydrated lime ( $\text{Ca(OH)}_2$ ) and the gaseous flue gas impurities in the form of sulfur dioxide ( $\text{SO}_2$ ), hydrogen chloride (HCl) and hydrogen fluoride (HF) takes place on the surface of the lime particles. This results in the formation of gypsum ( $\text{CaSO}_4$ ), calcium sulphite ( $\text{CaSO}_3$ ), calcium chloride ( $\text{CaCl}_2$ ) and calcium fluoride ( $\text{CaF}_2$ ); all in the form of solid powdery residues. Activated carbon powder is applied as part of the process for the absorption of mercury and dioxins. FGT residues are treated as hazardous waste. The residues also comprise the activated carbon used in the treatment process.

The FGT residues may be recirculated for better reagent use. The reactivation of recirculated reagents can be by humidification or use of steam and depends on the FGT plant supplier. However, a certain excess of hydrated lime cannot be avoided. The consumption rates of hydrated lime for the dry concept are typically in the range of 2.0 to 3.0 times the theoretical minimum consumption rate for the assumed raw gas conditions and the clean gas composition required. Excess of hydrated lime injected into the process remains unused and is discarded as a mixture together with the reaction products.

The temperature drops slightly across the reactor unit due to heat loss and transport air use.

The reaction products, any unreacted powdered hydrated lime ( $\text{Ca(OH)}_2$ ) and remaining fly ash from the furnace/boiler are separated in the bag house filter. This residue is collected for storage in a silo and sent to disposal/treatment as hazardous waste.

A frequency controlled centrifugal induced draught fan (ID-fan) is applied to transport flue gas from the combustion chamber through the boiler, the FGT and to the stack. The fan is commonly located at the tail end of the plant and designed to overcome the complete pressure loss of the FGT plant and to maintain a defined vacuum in the furnace/boiler unit in all load cases. The flue gas temperature typically increases in the range of 5 °C up to approximately 145 °C as a result of the compression and friction within the induced draught fan. The ID-fan is the main FGT plant power consumer.

#### Advantages

The dry hydrated lime based FGT system is relatively simple to install and operate. The relative space requirements are low. Therefore, the associated investment and maintenance costs are also relatively low.

Efficiency of reagent usage may be improved by using a higher grade of lime with improved reactivity.

The process is used in many plants hence the wide availability of references and operational experience.

#### Disadvantages

The dry process has limited capability when treating elevated levels of pollutants, particularly sulfur dioxide ( $\text{SO}_2$ ) and hydrogen fluoride (HF). Therefore, the process usually results in some emission values which are higher than other systems. Dry systems are less flexible when handling flue gas from waste fractions with highly variable composition, particularly those rich in sulfur. Furthermore, elevated temperatures reduce the effectiveness of mercury capture and the ability to meet stringent mercury emission limits.

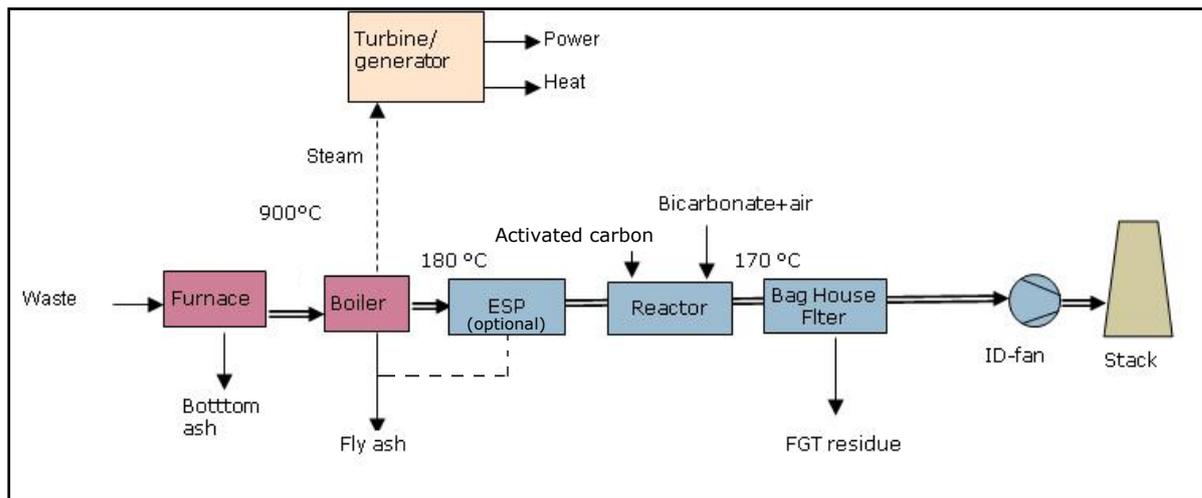
A significant excess of hydrated lime is required to treat flue gases to levels that comply with emission limits. This is typically 100 - 200% excess hydrated lime and this results in large quantities of residue generation. Using high volumes of hydrated lime generates high levels of residues because excess of hydrated lime remains unused and can only be discarded as a mixture with the reaction products. Consequently the treatment costs make the process expensive from an operating perspective.

## 6.4 Dry Bicarbonate Based Systems

### Introduction

Bicarbonate based systems are used at many plants in Europe, particularly in France. This system does not require injection of air or water to cool flue gas after the boiler stage because bicarbonate is effective at temperatures of 170 - 190 °C. These temperatures match the flue gas temperatures at boiler exit.

The key components of the dry bi-carbonate based system, flue gas and material flows together with conditions such as typical flue gas temperatures at various stages of the plant are shown in **Figure 3**.



**Figure 3: Bicarbonate based dry absorption system**

The plant comprises the following main components:

- Electrostatic precipitator - ESP (optional)
- Reactor for the injection of bicarbonate
- Baghouse filter
- ID-fan

For energy recovery purposes an economiser might be integrated downstream, after the main components of the FGT. The drivers and possibilities are further described in **Section 8 - Energy Recovery**.

Flue gas temperature downstream of the boiler is set to 170 - 190 °C. Compared to the dry lime process, the process needs a higher temperature than for example lime based dry systems to activate bicarbonate ("pop-corn-reaction").

In cases where fly ash and the residual product is delivered to different outlets, flue gas requires pre-cleaning by an electrostatic separator (ESP) before it enters the dry bicarbonate flue gas cleaning plant.

The use of an ESP facilitates the recovery/recycling of the bicarbonate by preventing fly ash contamination. Bicarbonate is collected separately and sent to recycling facilities. During the recycling process, undertaken at external supplier facilities, chlorides and the sulphates are "washed out" and the bicarbonate is regenerated. The process is common in France and Germany where used bicarbonate is collected from plants for treatment and reuse. Ramboll is not aware of this process currently being used in the UK.

The bicarbonate products from the reaction with sulfur dioxide (SO<sub>2</sub>) and hydrogen chloride (HCl), (the sodium salts) are dissolved in water and can be regenerated to bicarbonate before

being reused. "Inerts" like fly ash carried to the recycling plant impose extra cost to recycling or can even make it impossible. Therefore, a precondition for the bicarbonate concept is often that the fly ash is separated beforehand and is not mixed together with the bicarbonate product in a common silo.

ESPs are effectively used in operations where bicarbonate is captured for recycling. However, given that there are no known ERF plant bicarbonate recycling schemes in the UK, our analysis assumes no primary ESP filtration.

An absorbent in the form of powdered sodium bicarbonate is injected into the reactor. The bicarbonate in the reactor is activated and reacts with flue gas impurities in the form of sulfur dioxide (SO<sub>2</sub>), hydrogen chloride (HCl) and hydrogen fluoride (HF). Activated carbon, which adsorbs mercury and dioxins, is injected at the same time. These reactions occur effectively at high temperatures, thus no flue gas pre cooling is required. In addition, because bicarbonate is more reactive than hydrated lime, less bicarbonate is needed than in lime based solutions. However, when compared to dry or semi-dry systems, activated carbon consumption increases with higher temperatures. This is because mercury adsorption is more effective at lower temperatures.

The resulting reaction products, used activated carbon and unused sodium bicarbonate residues are filtered in the bag house filter and sent to the residue silo. Residues are subsequently sent to landfill or to recycling plants, where bicarbonate recycling schemes are in place.

A frequency controlled centrifugal induced draught fan (ID-fan) is applied to transfer flue gas from the combustion chamber, through the boiler, flue gas cleaning plant and subsequently to the stack. The flue gas fan is most commonly located at the tail end of the plant and designed to overcome the complete pressure loss of the FGT-plant, maintaining a defined vacuum in the furnace/boiler in all load cases. The flue gas temperature typically increases in the range of 5 °C to 175 - 195 °C due to compression and friction within the induced draught fan. The ID-fan is the main FGT plant power consumer.

#### Advantages

The bicarbonate based FGT system is relatively simple to install and operate. The use of an ESP before the main process results in a chemical residue at the bag filter, which can in principle be recycled. Bicarbonate consumption is moderate because approximately only 20% excess reagent use is required. This reduces the amount of residues produced when compared to a lime based flue gas treatment plant. The process is advantageous if a selective catalytic reduction system is subsequently used to remove oxides of nitrogen (NO<sub>x</sub>) because the SCR-catalyst can be installed downstream of the bag house filter without the need to reheat the flue gas to temperatures required for this process.

#### Disadvantages

The dry bicarbonate process has limited capabilities where there are elevated pollutant levels, particularly sulfur dioxide (SO<sub>2</sub>) and hydrogen fluoride (HF). Furthermore, elevated temperatures are not ideal for the capture of mercury, and this is of concern where there are more stringent emission limits.

Bicarbonate is relatively expensive and there are a limited number of suppliers. This can cause uncertainty over the security of supply and delivery related issues. It is important that the supplier also provides recycling capability and transport distances are not excessive.

## 6.5 Semi-Dry System

### Introduction

Semi-dry systems were introduced to optimise the chemical reaction between the acidic gases and lime added to the flue gas stream. There are two distinct forms of semi-dry systems:

- Hydrated lime added as slurry. This increases the efficiency of the chemical reaction between the acidic gases (sulfur dioxide (SO<sub>2</sub>), hydrogen chloride (HCl), hydrogen fluoride (HF) etc.) and the lime; or
- Recirculation of the residue to reuse un-reacted lime. The residue is typically humidified by water to 'reactivate' the re-circulated lime.

Semi dry systems have two advantages. Firstly an increase in reaction efficiency reduces lime overdosing requirements compared to dry systems, hence savings in consumables costs. Secondly there are less FGT residues generated due to reduced lime use and recirculation of unreacted lime.

The key components of the semi-dry system, flue gas and material flows together with conditions such as typical flue gas temperatures at various stages of the plant are shown in **Figure 4**.

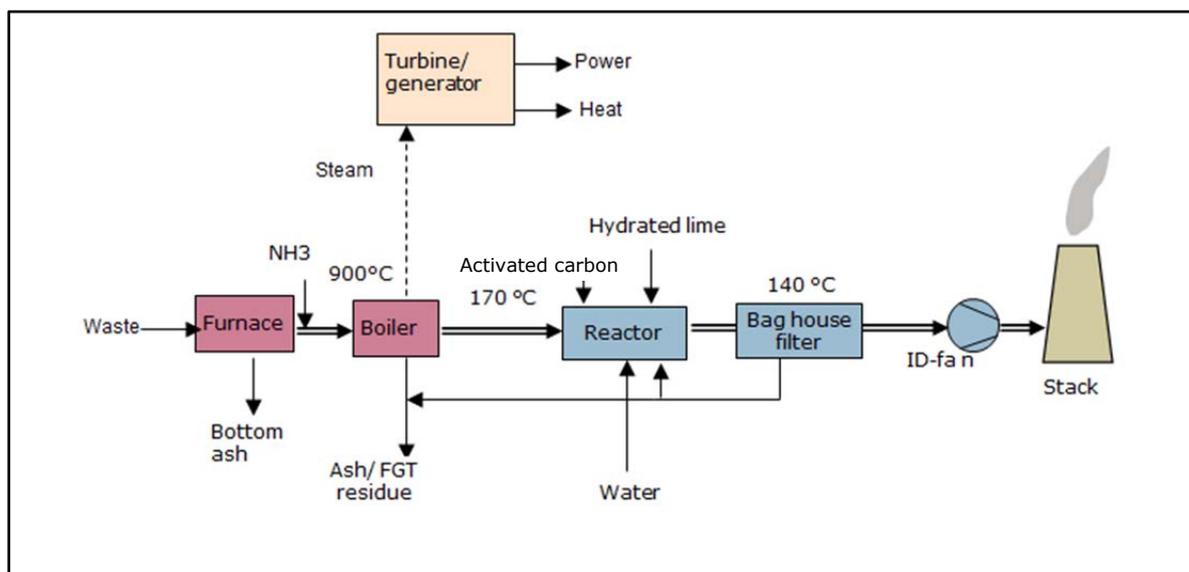


Figure 4: Semi-dry system

The plant comprises the following main components:

- Reactor for the injection of hydrated lime and activated carbon
- Baghouse filter
- ID-fan

For energy recovery purposes an economiser might be integrated downstream, after the main components of the FGT. The drivers and possibilities are further described in **Section 8 - Energy Recovery**.

The process works in a range of temperatures, 200 °C to approximately 170 °C. The amount of acid components in the raw gas and the water content of the injected lime slurry determine the quantity of water to be evaporated in the reactor, thereby defining the requirement for a minimum inlet temperature. Both the water content of the injected slurry as well as the optimal reaction temperatures depend on the system supplier.

### Advantages

Semi dry systems are relatively simple to install and operate. Furthermore, space requirements for the plant are relatively moderate.

There are many semi-dry FGT plants in operation. Hydrated lime is a common commodity produced by a range of different suppliers and is easy to source.

### Disadvantages

The process is limited in its ability to treat high sulfur dioxide (SO<sub>2</sub>) levels in raw flue gas streams, and this needs to be considered where there are more stringent emission requirements.

The system requires an excess of hydrated lime dosing, typically 50 - 130%. Therefore, the process produces significant quantities of FGT residues, although somewhat less than the dry, lime based treatment systems.

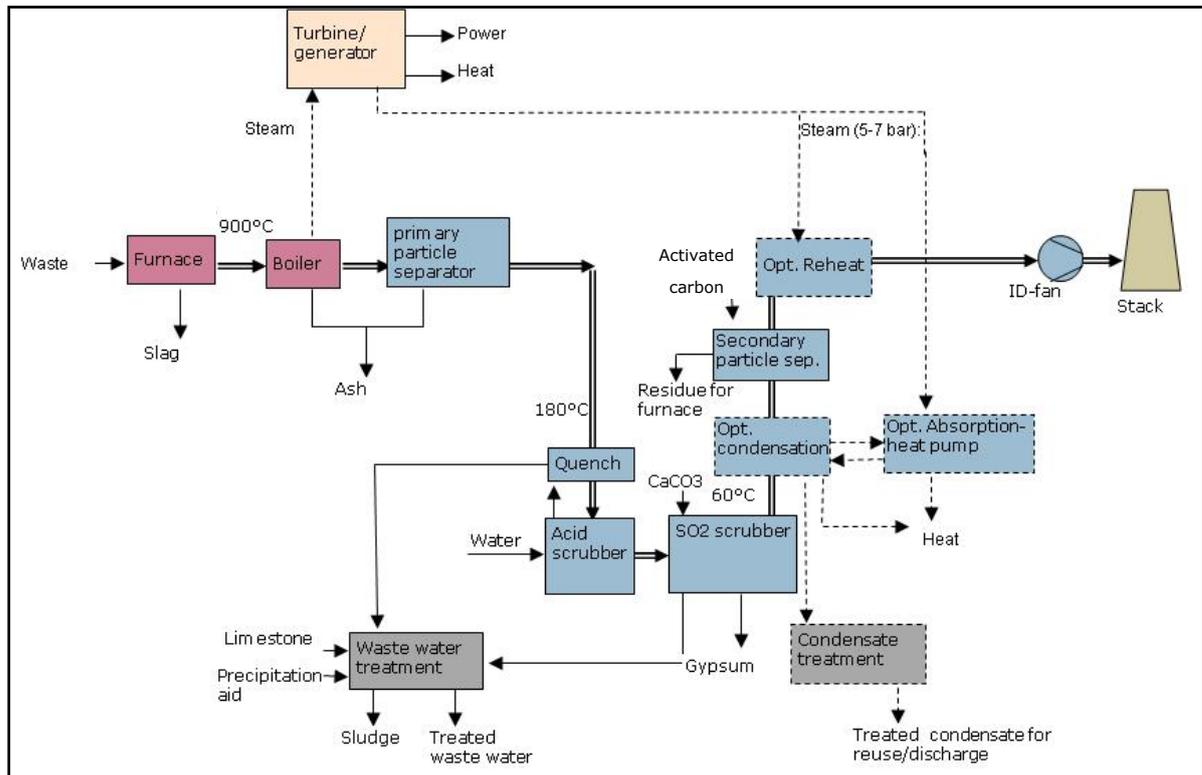
Hydrated lime consumption and residues generation increase considerably where there are elevated or varying raw gas hydrogen chloride (HCl) and sulfur dioxide (SO<sub>2</sub>) contents.

The mixing system for water and lime requires daily maintenance; a task that entails risk of human contact with hazardous material. The system requires close monitoring to maintain performance.

**6.6 Wet Scrubbing Systems**

Wet scrubbing systems have not been installed in UK ERF plants. However, the system is common in Europe e.g. Germany and Switzerland. Therefore, the concept is included in this report as a reference and possible alternative solution.

The key components of the wet scrubbing system, flue gas and material flows together with conditions such as typical flue gas temperatures at various stages of the plant are shown below in **Figure 5**.



**Figure 5: Wet flue gas treatment with SNCR**

The solution contains the following main components:

- Primary particle separator
- Quench
- Acidic hydrogen chloride (HCl) scrubber
- Caustic sulphur dioxide (SO<sub>2</sub>) scrubber
- Condensation (optional)
- Secondary particle separator
- Reheater (optional)
- Induced draught fan (ID-fan) and stack
- Wastewater treatment
- Condensate treatment (optional)

Wet flue gas cleaning requires the removal of hydrochloric acid (HCl) contents as soluble salts via a wastewater drain. This is a key difference from the dry flue gas cleaning systems where salts are separated and removed in solid form.

In wet flue FGT system hydrochloric acid (HCl) is separated simultaneously with hydrogen fluoride (HF) and mercury (Hg) in an acidic scrubber. The sulfur dioxide (SO<sub>2</sub>) content and remaining hydrogen fluoride (HF) content is removed in a caustic or neutral scrubber. By recirculating the liquid in the scrubbers a close contact between the acid gas and the washing liquid is achieved. Depending on the supplier, the scrubber may include special nozzles and internal parts, which are designed to optimize the effectiveness of the process.

Wet FGT systems require dust in the flue gas to be removed in a primary particle separator (e.g. electrostatic precipitator (ESP) to minimize the particle load at the acid scrubber stage. Consequently wet flue gas cleaning systems always consist of at least two steps that can be optimised individually. The process stage for the removal of dioxins is a secondary particle filter (e.g. a bag house filter).

Wet FGT systems produce wastewater that requires treatment before discharge. Furthermore, a solid residue in the form of gypsum, a non-hazardous output, is produced. An additional residue is small amounts of dewatered hydroxide sludge which is considered as hazardous waste that can be mixed with fly ash. Hydroxide sludge contains high amounts of heavy metals in its precipitated form. Therefore, treatment of the small amounts of hydroxide sludge is usually not considered as an option and it is managed as a hazardous waste.

#### Advantages

Wet FGT plants can achieve efficient flue gas cleaning and are robust with respect to changes in raw gas composition and have the flexibility to meet more stringent emission limits than currently in place.

The consumption of absorption chemicals is low in terms of excess lime and sodium hydroxide use. Sodium hydroxide, though hazardous, is simpler to handle as it ends up in a mixed solution. Low consumption of consumables results in low volumes of residue generation.

Chlorides are transferred to the water phase instead of a solid phase which reduces residue generation.

There are many reference plants employing wet FGT systems outside the UK. Therefore, there are several suppliers and long term operational experience to draw from.

#### Disadvantages

A wet scrubbing system includes many process steps, hence requiring high capital investment, it is more complex to operate, and requires specialist staff.

The treatment of wastewater is an additional process requiring skilled wastewater treatment plant operators. A wastewater discharge stream is required. This is additional to plants without such systems. The total cost of disposing liquid effluent can be significant.

There is significant plume visibility where flue gas is not reheated prior to stack flow and exit.

## 6.7 'Combined Dry-Wet' System

The 'Combined Dry-Wet' System comprises the combination of a semi-dry or a conditioned dry FGT-system with a reduced wet FGT system.

The combined ('dry-wet') concept aims to reduce the overdosing of lime in the bag house filter compared to the semi-dry or conditioned dry system, especially in periods with peak concentrations of acidic gases. Flue gas polishing treatment takes place in a wet scrubber. This approach is very efficient for the removal of pollutants during peak flows.

The key components of the combined system, flue gas and material flows together with conditions such as typical flue gas temperatures at various stages of the plant are shown in **Figure 6**.

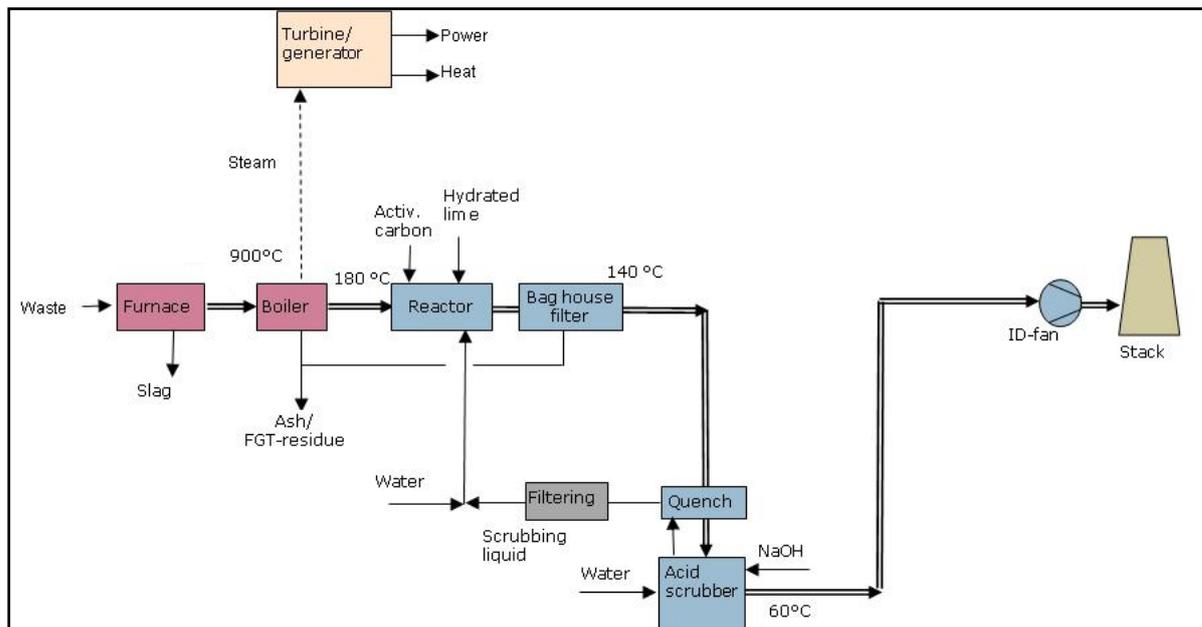


Figure 6: Combined 'dry-wet' system

Details of semi-dry, dry and wet system are described in the respective sections of this study, i.e. **Section 6.3 Dry Lime Based Systems** and **Section 6.6 Wet Scrubbing Systems**. Semi-dry and conditioned dry systems operate in a range of temperatures, 200 ° C down to approximately 170 ° C. A temperature of 180 ° C is assumed to be sufficient for the necessary evaporation of recirculated water from the acid scrubber, but is dependent on the system supplier.

### Advantages

The hydrated lime based semi-dry system is simple to install and operate compared to wet systems.

The addition of a scrubber ensures relatively low excess lime use and offers the capability to handle fluctuating raw gas pollutant contents. The system has the ability to meet even more stringent emission limits than currently in place, particularly for hydrogen chloride (HCl) and sulfur dioxide (SO<sub>2</sub>). The amount of wastewater produced in the wet scrubber is reduced compared to the dedicated wet systems. The wastewater produced is used within the overall process, either for humidification of reagent, recirculate or other media. The net impact is that there is no wastewater produced by the system.

There are many operational ERF plants (worldwide) using semi-dry FGT technology with wet scrubber systems.

Hydrated lime, one of the main reagents, is produced by a range of different suppliers and is easy to source.

#### Disadvantages

Hydrated lime dosing is still significant in spite of the scrubbing system. Therefore, a fairly large amount of residue is generated, though slightly less than the dry and semi-dry systems.

Generally limited, if any, savings in operational cost should be expected when compared to semi-dry systems due to the additional power consumption and manpower requirements associated with the scrubber.

This system will have high plume visibility unless treated flue gas is reheated – e.g. in a gas-gas heat exchanger - downstream of the bag house filter prior to the emission through the stack.

The mixing system for water and hydrated lime requires daily maintenance; a task that entails risk of human contact with hazardous material. The system also requires close monitoring to maintain performance.

## 6.8 Expected Air Emissions Levels with the FGT Systems Considered

The performance in terms of emission levels for each FGT system is shown in **Table 9** and **Table 10**. The tables show that, in general, all systems are capable of achieving emission limit values that are much lower than IED requirements. The main difference between the FGT technologies is that systems incorporating the use of a scrubber ('combined' and 'wet' systems) can reduce the emissions of hydrogen chloride (HCl) and sulfur dioxide (SO<sub>2</sub>) by factors of 10 and 5 times below the EU IED requirements respectively. Therefore, these systems provide significant margins should the need arise to meet more stringent requirements for these emissions.

All systems have very efficient dust removal capabilities with emission levels reduced from 1,000 - 1,500 mg dust/Nm<sup>3</sup> to around 1 mg dust/Nm<sup>3</sup> during normal operation and with good maintenance. Heavy metals – except mercury (Hg) - are bound on the surface of the dust particles. Therefore, equal removal efficiencies are achieved for heavy metal removal as all systems have the same dust removal efficiency.

Expected emissions under normal operation are listed in the tables below.

*Note: Values apply under normal operation, and are not limit values.*

Parameter	Unit	Bicarbonate	Semi-dry	Combined dry-wet	Wet
Water vapour	% vol.	17	18	22	22
CO	mg/Nm <sup>3</sup>	10		10	10
TOC	mg/Nm <sup>3</sup>	1		1	1
N <sub>2</sub> O	mg/Nm <sup>3</sup>	2		2	2
NH <sub>3</sub>	mg/Nm <sup>3</sup>	5		0.5	0.1
Dust	mg/nNm <sup>3</sup>	1		1	1
HCl	mg/Nm <sup>3</sup>	6		1	1
SO <sub>2</sub>	mg/Nm <sup>3</sup>	20		10	10
HF	mg/Nm <sup>3</sup>	0.5		0.1	0.1

**Table 9: Expected emission to the air (daily average)**

Reference conditions are dry flue gas at 11% O<sub>2</sub>.

Parameter	Unit	Bicarbonate	Semi-dry	Combined dry-wet	Wet
Cd + Tl	mg/Nm <sup>3</sup>	0.001	0.001	0.001	0.001
Hg	mg/Nm <sup>3</sup>	0.012	0.008	0.004	0.004
Σ9 metals	mg/Nm <sup>3</sup>	0.030	0.030	0.030	0.030
Dioxins or furans*, TEQ	ng/Nm <sup>3</sup>	0.010	0.005	0.005	0.005

**Table 10: Expected indicative concentrations of heavy metals and dioxin**

Reference conditions are dry flue gas at 11% O<sub>2</sub>.

(\*) Values based on SNCR. Emission of dioxins and furans may be reduced further as a side effect of catalytic processes (SCR). However levels are low and difficult to measure.

## 6.9 FGT Technology Costs

### 6.9.1 Operational Costs

Relative FGT plant operational costs considering consumables, residues and energy use are detailed in **Table 11**.

The bicarbonate process appears to be the least favourable concept from an operating cost perspective. Even though the reactivity of the reagent can be assumed to be close to the theoretical optimum, raw material costs and costs for the regeneration of the residual product are significant disadvantage for this process.

The lime based semi-dry process is shown to be the most advantageous system from an operational cost perspective.

The combined dry-wet process appears to be less attractive than the semi-dry process. This is due to the maintenance of a relatively complex system. The reduction of costs for residue disposal is marginal when compared to the semi-dry system. This cost saving does not compensate for the maintaining the complex dry-wet system.

The wet process yields much smaller amounts of residues, but requires more specialised staff and resources to operate. This is due to the high complexity of the plant. The advantages and disadvantages of the plant are balanced and consequently operating costs of the system are favourable over the other systems considered.

*Note: 1 equates to lowest cost and 4 equates to highest cost*

	Dry Bicarbonate	Semi-dry	Combined	Wet
<b>Operating Cost Ranking</b>	4	2	3	1

**Table 11: FGT Plant Operational Cost Ranking**

6.9.2 Capital Costs

Relative FGT plant capital costs are detailed in **Table 12**.

The capital costs for bicarbonate and semi-dry processes are comparable. This is with the exception of the equipment required for humidification of the reagent in the semi-dry process. However, the bicarbonate process requires mills (typically hammer mills) for bicarbonate preparation, thus almost balancing the cost difference.

The wet process requires a variety of sub-systems and machinery, e.g. scrubber circulation pumps, wastewater system, gypsum-dewatering and filtrate system, bleed tanks, etc. and requires the highest capital investment. The combined process usually reuses wastewater in the treatment process and this avoids wastewater treatment/discharge.

Building/housing cost needs are evaluated by excess investment needs compared to the smallest plant, which is typically the semi-dry process.

*Note: 1 equates to lowest cost and 4 equates to highest cost*

T	Bicarbonate	Semi-dry	Combined	Wet
<b>Capital Cost Ranking</b>	1	2	3	4

**Table 12: FGT Plant Capital Cost Rankings**

6.9.3 Lifetime Cost

FGT plant capital and operational costs are evaluated to determine lifecycle costs over a period of 20 years

The outcome of this evaluation is set out in the table below.

*Note: 1 equates to lowest cost and 4 equates to highest cost*

	Bicarbonate	Semi-dry	Combined	Wet
<b>Overall Lifetime Cost Ranking</b>	4	1	3	2

**Table 13: FGT Plant Lifecycle Cost Rankings**

Our evaluation supports semi dry system as the most attractive process from a financial perspective. This is owed to the simplicity and efficiency of the systems.

## 7. DENOX SYSTEMS

Waste combustion in grate fired systems results in the production of mono-nitrogen oxides (nitric oxide and nitrogen dioxide) ( $\text{NO}_x$ ) with flue gas contents of typically around  $350 \text{ mg/Nm}^3$  with a reference condition of 11 % Oxygen  $\text{O}_2$ , dry.

Mono-nitrogen oxides (nitric oxide and nitrogen dioxide) ( $\text{NO}_x$ ) is one of the main reasons for acid rain and can also contribute to the formation of smog and ozone, which is believed to cause increased respiratory system issues, including asthma. In addition nitrogen oxide ( $\text{NO}_2$ ) is toxic and reacts with other compounds to form small particles, potentially causing respiratory disease over time.

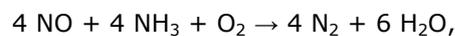
Optimisation of air injection for combustion, flue gas recirculation and other primary combustion control features can reduce mono-nitrogen oxides (nitric oxide and nitrogen dioxide) ( $\text{NO}_x$ ). However, these processes alone cannot meet the IED requirement to restrict emitted  $\text{NO}_x$  levels to  $200 \text{ mg/Nm}^3$  (dry flue gas at 11%  $\text{O}_2$ ). Therefore, a dedicated deNO<sub>x</sub> process is required to ensure compliance with IED regulations and fulfil plant permitting requirements. The deNO<sub>x</sub> process options are:

- Selective Non-Catalytic Reduction (SNCR)
- Selective Catalytic Reduction (SCR)

Both systems are based on the injection of either ammonia ( $\text{NH}_3$ ) or urea (carbon acid diamide ( $\text{NH}_2$ )<sub>2</sub>CO) in an aqueous solution.

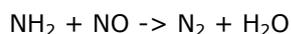
With an SCR process ammonia water is injected as reagent into the flue gas. The water is evaporated and ammonia reacts with  $\text{NO}_x$  on a catalytically active surface which enables reaction at much lower temperatures and at lower reagent consumption rate than compared to SNCR.

General the predominant chemical main reaction for DeNO<sub>x</sub> is:



where the nitrogen oxide (NO) content of flue gas is reduced to free nitrogen and water, two harmless by-products.

In case of urea usage the process entails an activation of urea ( $\text{CO}(\text{NH}_2)_2$ ) followed by the neutralizing reaction:



Where urea is used a side reaction generates significant amounts of nitrous oxide ( $\text{N}_2\text{O}$ ). This is different from nitrogen oxide (NO) and nitrogen dioxide ( $\text{NO}_2$ ) because it is a greenhouse gas and ozone depleting agent. Urea is more expensive, but is less hazardous than ammonia water. Usually, unless specific requirements apply locally, the use of ammonia water is recommended. The theoretical (stoichiometric) consumption is approximately 1.5 kg of 25 % ammonia water per kg  $\text{NO}_x$  removed.

### 7.1 SNCR

The SNCR process entails ammonia water injection in the upper part of the combustion chamber of the furnace where gases are at a temperature of 850 - 950 °C. These temperatures are suitable for ammonia to react with nitrogen oxide (NO) and nitrogen dioxide ( $\text{NO}_2$ ). Excess ammonia is needed at this stage to ensure contact between the ammonia decomposition products and  $\text{NO}/\text{NO}_2$ . More than twice the theoretical minimum ammonia consumption is needed for 70 %  $\text{NO}_x$  reduction, depending on actual process conditions and allowed emissions. Optimisation of the process requires careful control of ammonia injection, flow rates and stable combustion control.

Depending on the level of optimisation, the process causes some un-reacted ammonia to leave the boiler with the flue gas. This is known as ammonia slip. Excess ammonia (NH<sub>3</sub>) can deposit to the ground and adversely impact biological conditions e.g. through nitrification of soils.

In dry and semi-dry FGT-systems a certain amount of the ammonia (NH<sub>3</sub>) slip is caught by the residue in the bag house filter. The remaining ammonia leaves the plant with the clean flue gas. A typical requirement for the maximum ammonia slip would be 5 - 10 mg/Nm<sup>3</sup>, though the slip is not indicated as a limit value in the EU-directive.

Where the FGT system includes a wet scrubber, ammonia will be absorbed in the scrubbing liquid. This is why the resulting wastewater will contain ammonium, which may be removed in an ammonia stripper to fulfil discharge requirements.

**7.2 SCR**

The SCR process entails ammonia injection upstream of a catalyst at a temperature of 180 - 300 °C. The reaction between nitrogen oxide (NO) and ammonia (NH<sub>3</sub>) occurs on the catalytic surface. Most suppliers prefer a reaction temperature close to 250 °C, because higher reaction temperatures reduce unwanted and hindering condensation of salts on catalytic surfaces. The temperature requirement must be observed during the design and operation of the ERF plant.

SCR use can achieve NO<sub>x</sub> emission levels lower than 25 mg/Nm<sup>3</sup>, and limit ammonia consumption close to the theoretically optimal ratios. Ammonia slip is usually very low, i.e. in the range of 0 - 5 mg/Nm<sup>3</sup> depending on the NO<sub>x</sub> emission requirement, due to even distribution of ammonia over the flue gas cross section and catalyst activity.

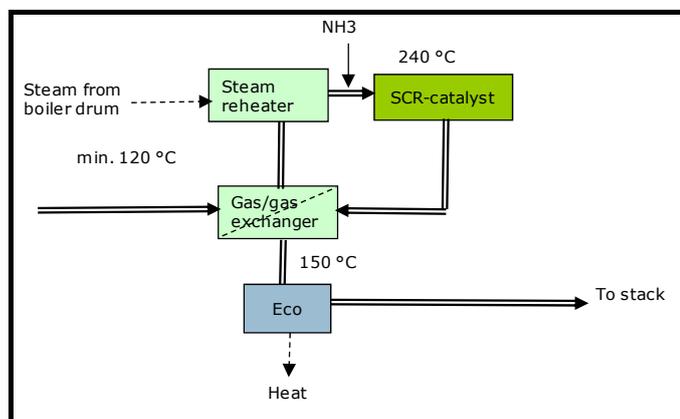
Ammonia consumption may be calculated from the NO<sub>x</sub> content of the raw flue gas and the NO<sub>x</sub> emission limits to be adhered to. The reduction of the NO<sub>x</sub> level from 400 mg/Nm<sup>3</sup> to 20 mg/Nm<sup>3</sup> requires less than 4 kg of 25 % ammonia water per tonne of waste processed.

SCR systems are incorporated into FGT plants as either tail end or front end systems.

**Tail-end SCR**

The catalyst is placed after the first FGT stages with tail-end SCR systems. This requires reheating flue gas. Usually a combination of heat exchangers is used for reheating i.e. a gas/gas exchanger followed by a steam re-heater, if steam is available at the required catalyst temperature. Steam boilers with exit steam parameters of 400 °C and 40 bar yield suitable drum steam temperature for SCR-reheat to about 240 °C, as illustrated in **Figure 7**. If steam is not available, a gas or oil fired duct burner may provide the air heating required.

There are examples of SCR catalysts operated at lower temperatures (190 °C). However, in these cases in-line regeneration is needed together with a periodically fired burner.



**Figure 7: Typical tail-end SCR-system**

### Front-end SCR, boiler integrated

In pulverized coal fired plants, the SCR-catalyst is usually integrated as high dust catalysts in a boiler section where the temperature range is optimal for the process, thus evading the need for reheating. This system is rarely used in waste incinerators due to the risk of catalyst deactivation, wear and clogging.

### Front-end SCR, after ESP

In these systems ammonia injection and the catalyst is placed downstream of an ESP operating at some 270 °C. The high pressure economiser of the boiler is located externally, after the catalyst. This combines the advantage of not requiring reheating with a dust free flue gas downstream of a particle filter. This does not save much investment costs compared to the tail-end SCR system. However, the ERF operation benefits from the avoidance of steam consumption for reheating flue gas.

## 7.3 Performance of deNOx Systems

The performance of the deNOx systems presented is evaluated below.

Three SNCR variants achieving different nitrogen oxide (NO<sub>x</sub>) emission levels are assessed; i.e. Nox emissions of 150, 120 and 100 mg/Nm<sup>3</sup>. The use of ammonia water depends on the NO<sub>x</sub> emission levels achieved. The three variants of SNCR are compared with the two variants of the SCR. The resulting performance is summarised in **Table 14**.

In general ammonia water consumption of the catalytic process (SCR) is close to the theoretical optimum, whereas the SNCR consumes significantly higher amounts of ammonia water. SNCR system ammonia consumption increases from SNCR 150 to SNCR 120 and to SNCR 100. Higher ammonia consumption achieves lower NO<sub>x</sub> emission levels in the SNCR systems. The SCR process removes the most amount of NO<sub>x</sub>.

Ramboll's experience of the optimal operational range is provided in **Table 14** below for each system.

The process values shown in **Table 14** will also depend on the detail of the chosen process and on the capabilities of the supplier to optimise the process (es).

Consumption, emission	Unit	SNCR 150	SNCR 120	SNCR 100	Tail-End-SCR	Front-End-SCR
NO <sub>x</sub> in raw gas without deNO <sub>x</sub> **	mg/Nm <sup>3</sup> *	400	400	400	400	400
NO <sub>x</sub> -emission, expected	mg/Nm <sup>3</sup> *	150	120	100	20	20
NO <sub>x</sub> Removed	tonnes/year	490	550	580	740	740
Optimal operating range of NO <sub>x</sub> -emission	mg/Nm <sup>3</sup> *	80-160	80-160	80-160	10-70	10-70

**Table 14: DeNOx, Indicative ammonia consumption and NOx-reduction (350 ktpa line)**

\*) dry flue gas at 11% O<sub>2</sub>

\*\*) for evaluation purposes the calculation is executed with the conservative figure of 400 mg/Nm<sup>3</sup> NO<sub>x</sub> in raw gas instead of 350 mg/Nm<sup>3</sup>

#### Emission level 150 mg/Nm<sup>3</sup>

If the permitted emission levels are in the range of 150 mg/Nm<sup>3</sup> SNCR 150 would be the preferred option.

Emission level 100 mg/Nm<sup>3</sup>

If the anticipated and permitted emission levels are in the range of 100 mg/Nm<sup>3</sup> SNCR 100 would be the preferred option. However, in the range of 100 mg/Nm<sup>3</sup> and below the quantity of bidders, who are willing to guarantee emissions limits with SNCR technology are limited. Although technical installations are very similar, the capital investment costs will increase with decreasing emission levels from 150 to 100 mg/Nm<sup>3</sup>.

Emission level 20 mg/Nm<sup>3</sup>

At low emission levels the amount of NO<sub>x</sub> captured by the catalytic processes exceeds the capability of the SNCR. In this case the SCR would be the preferred option. The amount of NO<sub>x</sub> removed is considerably higher and it has to be underlined that the NO<sub>x</sub> footprint is lowered significantly in this case. This somewhat mitigates higher capital cost requirements.

**7.4 Cost of DeNO<sub>x</sub> Systems**

7.4.1 Operational Costs

Operational costs for deNO<sub>x</sub> technologies include consumables, staffing and maintenance. The following are Ramboll's cost rankings for deNO<sub>x</sub> systems. The cost estimates, considering both operational and capital cost estimates, conclude the SNCR 150 option as the most beneficial from a cost perspective. In general the SNCR process is much more attractive than the SCR perspective from a total cost perspective.

*Note: 1 equates to lowest cost and 4 equates to highest cost*

Cost	SNCR 150	SNCR 120	SNCR 100	SCR after semi-dry	Front-end SCR
<b>Operating Cost Ranking</b>	2	3	5	4	1
<b>Overall Lifetime Cost Ranking</b>	1	2	3	5	4
<b>Capital Cost Ranking</b>	1	2	3	4	5

**Table 15: deNO<sub>x</sub> System Capital and Operational Cost Rankings**

The SCR process captures much more NO<sub>x</sub> than the SNCR process. Therefore, the SCR process is more cost efficient if evaluated from a perspective of cost per kg of NO<sub>x</sub> captured. The SCR process is likely to compare favourably from a financial perspective where NO<sub>x</sub> taxes are in place i.e. Scandinavia.

**7.5 Conclusions of deNO<sub>x</sub> System Considerations**

SCR deNO<sub>x</sub> systems achieve far lower levels of nitrogen oxide (NO<sub>x</sub>) emissions than SNCR systems. SCR systems also consume less ammonia than SNCR systems.

The costs of deNO<sub>x</sub> by SCR are higher than SNCR systems due to higher capital requirements. This is to an extent due to the fact that SNCR systems are incorporated into boiler plant and limited additional plant footprint is required. SCR systems require the installation of a separate plant. Front-end SCR systems are susceptible to wear and tear, clogging and deactivation and are rarely used in newer plants. Tail-end-SCR systems have higher operating costs due to heating requirements.

SNCR was often the preferred deNO<sub>x</sub> technology due to its cost benefit advantages and the fact that the system enables compliance with current IED emission limit requirements.

However, more stringent NO<sub>x</sub> emission limits i.e. 100 mg/Nm<sup>3</sup> or lower requirements may be set in the coming years. Local requirements with respect to NO<sub>x</sub> acceptance and the NO<sub>x</sub> footprint in the region may also be a decisive factor in the choice of technology. Furthermore the expected NO<sub>x</sub> concentration may be decisive for the determination of the stack height. If a 100 m stack allows for 100 mg/Nm<sup>3</sup> of emissions, a lower height may be allowed at lower NO<sub>x</sub> concentrations.

Furthermore, some countries could follow Scandinavian countries and also introduce NO<sub>x</sub> taxation. Therefore, modern plant designs using SNCR systems often make space allowance for

the future replacement with a SCR system to meet more stringent NO<sub>x</sub> emission requirements, should they come into force.

## 8. ENERGY RECOVERY

### 8.1 General

Energy recovery characteristics are based on the different requirements of the FGT concepts. This provides the variety of opportunities outlined below.

### 8.2 Economiser Use

The use of economisers in connection with flue gas treatment plants is frequently an opportunity to increase the overall energy efficiency of the plant. The economiser is a heat exchanger located in the flue gas path, and it transfers heat from the hot flue gas to a suitable heat carrier, typically water. The heated water is used to improve overall energy efficiency e.g. by pre-heating combustion air. The description below is based on the conditions prevailing in a dry lime FGT process. However, the technical principles can be adapted to any type of FGT system.

The energy content of the flue gas specified in **Table 4** is circa 70 kW/°C. This represents the potential energy recovery in an economiser located somewhere in the flue gas train.

In a bicarbonate system the flue gas energy content may be recovered in an economiser located downstream of the bag house filter operated around 180 °C. The economiser may be part of the high pressure system, thereby increasing the total steam output of the boiler, thus the power produced by the plant.

Cooling flue gas as an example by a further 20 °C, has the potential to yield an additional 1.5 MWth steam that would correspond to some 0.45 MWe of power production.

It is possible to recover further energy from the flue gas by use of a corrosion protected economiser operating with its own water circuit at a relatively low pressure and temperature. The economiser can provide heat for condensate pre-heating, air pre-heating or similar low-temperature applications. Such heat would replace steam extraction from the turbine and represent additional power production. Cooling of flue gas by 40 °C would increase power production by some 0.3 - 0.45 MWe as an estimate, thus yielding significant returns over the project lifetime.

Savings in water consumption for cooling will be achieved in the wet and combined semi-dry and wet systems when the flue gas is cooled in an economiser upstream of the wet scrubber.

### 8.3 Position of the ID-Fan

A fan is applied to produce a draught and to transport the flue gas from the combustion chamber through the boiler, the flue gas cleaning plant and finally to the stack. The fan also ensures negative pressure in the furnace and flue gas path to prevent smoke escaping into the boiler hall. This induced draught fan or "ID-fan" is the central equipment of the ERF. The ID-fan can be located upstream or downstream of the economisers ("hot" or "cold" position). When located in "cold" position at temperatures of approximately 80 °C the actual volume of the flue gas decreases, thus the ID-fan power consumption can be somewhat reduced. However, there is a need to consider protecting the ID-fan against corrosion e.g. by application of acid-proof steel.

### 8.4 Flue Gas Condensation

Flue gas condensation is primarily aimed at the recovery of latent energy contained in wet flue gases and secondly condensation may serve as a source of process water for the plant or other applications. Furthermore, the reduction of flue gas humidity tends to reduce the plume visibility to a degree, depending on actual weather conditions and flue gas exhaust temperature.

Flue gases from waste combustions typically contain a relatively high content of water vapour. When cooling the flue gas to temperatures below the water dew point, a part of the water vapour content condenses, releasing heat. The water leaves the system as condensate as the flue gas is dehumidified. Heat recovered can then be transferred by heat exchangers to a consumer e.g. a district heating network, air preheaters, a heat pump or another system. Basic principles of how flue gas condensation can be integrated into flue gas cleaning system, and how the produced condensate can be used at the facility are provided below.

Condensation may take place directly in a separate scrubber where circulating water is cooled in a heat exchanger. The condensate leaving the system should be as clean as possible. Therefore, it is recommended that any flue gas condensation step is introduced downstream of the primary cleaning steps, where dust, hydrogen chloride (HCl) and sulfur dioxide (SO<sub>2</sub>) is removed.

The condenser system can be integrated into a wet scrubber system, as depicted below, or it can be established as a stand-alone unit.

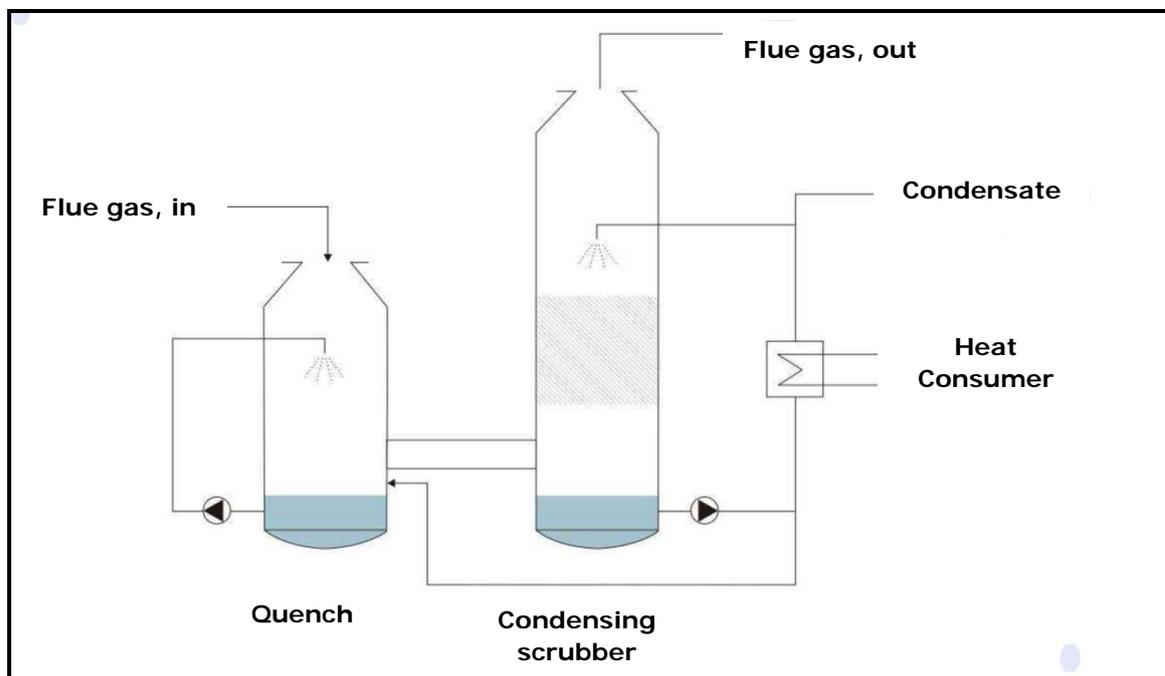


Figure 8: Flue gas condensation principle

Flue gas condensation may be carried out either in a scrubber, or by a heat exchanger. The former is considered to be the most reliable solution.

The principles in a condensing scrubber are as follows:

1. If not already saturated, flue gas is cooled down to dew point by injecting water into the quench
2. The gas is passed through the scrubber cooled by a heat exchanger on the recirculating scrubber liquid
3. The heated scrubber water is pumped through a heat exchanger and recirculated
4. Condensed water is removed from the scrubber circuit and is used as process water or discharged as wastewater
5. Cooled flue gas is passed to the stack

Flue gas condensation will produce approximately 1.0 MWth of heat for each 1.5 t/h of condensate recovered. Waste with a low net calorific value, burnt upstream (in the furnace), yields a high amount of energy recovery downstream (in the condenser).

In semi-dry and wet processes water is injected into the FGT process. Flue gas condensation facilitates the recovery of this water and the energy carried.

Flue gas temperature reduction reduces the actual flue gas flow. This reduces the power of the ID-fan, thus resulting in savings.

A disadvantage of cooled saturated flue gases is an increased droplet precipitation and plume visibility. This can be overcome by reheating or other counter-measures. However, these impact the net efficiency gains of flue gas condensation.

Flue gas condensation is sensitive to the external cooling temperatures. In Ramboll's experience flue gas condensation is rarely an option in the absence of a district heating network with suitable low return temperatures.

## 9. PLUME VISIBILITY

Plume formation is primarily the result of water vapour condensation when exhaust gas and ambient air mixes. Particles from the FGT plant processes i.e. the formation of salts or other sources only have a minor influence on the visibility of the exhaust gas leaving the stack and can be neglected. Possible water droplets carried through mist eliminators after wet scrubbers can cause droplet fall-out in a limited area around the stack, if the droplet separators are not properly designed. The risk of droplet fall-out can be eliminated, significantly or completely, if the exhaust gas is preheated before being released into atmosphere.

FGT plants using wet scrubbers or condensers are saturated with water (100% humidity). Therefore, unless reheating or dehumidification is applied there will be visible plumes in almost all weather conditions.

The temperature of flue gas derived from a dry or a semi dry FGT-system is significantly higher than flue gas from the wet systems and it is above the corresponding water dew point. As a result there is much reduced plume visibility with dry and semi dry FGT systems, compared to wet systems without flue gas reheating.

## 10. ASSESSMENT OF FGT SYSTEMS FOR DECISION MAKING

### 10.1 Flue Gas Treatment Plant

The assessment for decision making set out below is based on Ramboll’s experience from feasibility studies, other projects, development activities and operational plants.

**Table 16** presents positive, neutral and negative aspects of the FGT systems against the evaluation criteria set out in this document. No single flue gas treatment concept is advantageous under all the evaluation criteria considered. Therefore, the evaluation criteria needs to be weighed against the specifics of the project, according to the individual priorities and needs of the operator/owner.

Evaluation criteria:	Dry	Bicarbonate	Semi-dry	Combined	Wet
<b>Operational availability</b>					
- Performance history of reliable operation	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓
<b>Capability</b>					
- Ability to handle changes in raw gas composition	✓	✓✓	✓✓	✓✓✓	✓✓✓
<b>Flexibility</b>					
- Ability to meet more stringent future emission limit	✓	✓	✓✓	✓✓✓	✓✓✓
<b>Health and safety</b>					
- Reduced contact with hazardous material	✓✓	✓✓✓	✓✓	✓✓	✓✓
<b>Sensitivity to local conditions</b>					
- Limited of plume visibility	✓✓✓	✓✓✓	✓✓✓	✓	✓
- Discharge of treated wastewater	N/A	N/A	N/A	N/A	✓
<b>Other environmental issues</b>					
- Low chemical consumption	✓	✓✓✓	✓✓	✓✓✓	✓✓✓
- Low electricity consumption	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓
- Low residue production	✓	✓✓✓	✓✓	✓✓✓	✓✓✓

**Table 16: Assessment of base concepts for dry, semi-dry, combined and wet FGT technology**

✓✓✓ = attractive feature, ✓✓ = improved feature, ✓ = acceptable feature

Note: All base concepts are with SNCR for deNOx and without flue gas condensation.

When the key assessment criteria are considered, the following conclusions are drawn:

### **Most attractive concept**

The semi-dry FGT system is recommended as being potentially the most attractive option for NLWA. This is due to:

- The system is optimal for ERFs processing MSW where waste pollutant content will not vary notably in future years;
- There is no production of wastewater requiring specialist treatment and discharge;
- Flue gas condensation is not envisaged to be beneficial for NLWA due to the absence of adequately low cold water return temperatures from a potential district heating network;<sup>3</sup>
- There are relatively simple operational requirements; and
- There is a relatively low capital investment requirement.

A dry bicarbonate based system is considered to be a potential alternative subject to improved availability of reagent and the recycling of the residue thereafter.

### **Alternatives:**

Bicarbonate FGT is an option for NLWA due to:

- Similar investment costs to semi-dry systems
- Non-hazardous nature of the reagent
- Low costs of operation due to relatively simple injection system

However, on the downside;

- Higher cost for reagent and residue disposal

Combined dry-wet FGT is also an option for NLWA due to:

- Improved pollutant removal efficiency
- Lower operational costs due to reduced chemical consumption and residue production.

However, on the down side;

- Higher investment costs as well as higher operational costs due to additional power and additional maintenance.

Wet scrubbing systems are of interest where:

- Wastewater discharge is an option
- The waste pollutant load is high
- There are highly stringent emission requirements and exceptional environmental ambitions
- Low consumption of consumables and/or low residue generation are key factors

The drawbacks of the wet scrubbing system are

- Increased technical complexity
- Wastewater treatment is necessary
- Discharge of treated wastewater (containing salts and trace components) requires approval by the local authorities
- Increased plume visibility and
- Higher capital investment requirements.

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<sup>3</sup> It is believed, that the main option for heat supply (outside the FGT system) is the use of medium or low pressure steam extraction from a suitable turbine.

## 10.2 DeNOx System

The assessment set out below is based on Ramboll’s experience from feasibility studies, other projects, development activities and operational plants.

**Table 17** presents positive, neutral and negative aspects of the deNOx systems against the evaluation criteria set out in this document. No single deNOx treatment concept is advantageous under all the evaluation criteria considered. Therefore, the evaluation criteria in the future needs to be weighed against the specifics of the project, according to the individual priorities and needs of the operator / owner.

	SNCR 150	SNCR 100	SCR 20
<b>BAT (current)</b>	✓	✓✓	✓✓✓
<b>References</b>	✓✓	✓	✓✓
<b>NOx-Emissions</b>	✓	✓✓	✓✓✓
<b>Resilience (Pollutant abatement efficiency)</b>	✓	✓✓	✓✓✓
<b>Dispersion / Stack height</b>	✓	✓	✓✓✓
<b>Local Environment</b>	✓	✓	✓✓✓
<b>Consumables</b>	✓✓	✓	✓✓✓
<b>CAPEX</b>	✓✓✓	✓✓	✓
<b>NPV</b>	✓✓✓	✓✓	✓
<b>Risk</b>	Emission and dispersion requirements	Stringent emission requirements and supplier capability	

**Table 17: Assessment of concepts for DeNOx systems**

✓✓✓ = attractive feature, ✓ = neutral feature, ✓- = existing but less attractive feature

‘Advanced’ SNCR systems can achieve NOx emission guarantees of around 100 mg /Nm<sup>3</sup>. This corresponds to 50% of the current daily average emission limit set in the IED. However, space should be provided with such systems for future SCR installation to achieve lower emission limits. This is despite the wide belief that more stringent emission requirements for NOx levels well below 100 mg/Nm<sup>3</sup> are unlikely to be implemented by European authorities as doing so will have significant impacts on operational plants.

The Edmonton region is recognised as a high NOx region. SCR systems can reduce NOx emissions to 25 mg NOx/Nm<sup>3</sup> or lower.

NLWA’s air quality modelling should consider the emission limits that can be achieved with SNCR (to a level of 100 mg/Nm<sup>3</sup>) and SCR systems to facilitate an informed consultation and decision on the deNOx system choice.

It is assumed that no NO<sub>x</sub> taxation in the UK will be imposed in the near future, based on a professional judgement of regulatory means traditionally imposed to control environmental impacts in the UK. However, NO<sub>x</sub> taxation has been introduced for ERFs in Scandinavia and may be implemented in the UK. The introduction of such taxation will further enhance the case for a more efficient NOx reduction system.

### 10.3 Energy Recovery

Flue gas condensation is only relevant for NLWA's new ERF at Edmonton under certain circumstances. This is mainly due to the need for a suitable district heating system to be in place and the need for acceptance of increased plume visibility.

The use of economisers provides possibilities for further energy recovery without flue gas condensation. This is especially the case when economisers are integrated into the pressure part of the boiler as external economisers. This will somewhat reduce flue gas temperature to the stack and will increase plume visibility.

## 11. GLOSSARY

BAT	Best Available Techniques
BATOEL	BAT Operational Emission Levels
BREF	Best Available Technology Reference Documents
CaCl <sub>2</sub>	Calcium Chloride
CaF <sub>2</sub>	Calcium Fluoride
Ca(OH) <sub>2</sub>	Hydrated Lime
CaSO <sub>3</sub>	Calcium Sulphite
CaSO <sub>4</sub>	Gypsum
Catalyst	Term used in chemical reaction engineering. The catalyst facilitates an increased rate of reaction, usually by reducing the reaction temperature requirements.
Cl	Chlorine
Chloride	Ion of the Chlorine and present in salts or in a solution
CH <sub>4</sub>	Methane
C&I	Commercial and Industrial
CO	Carbon Monoxide
EU	European Union
ERF	Energy Recovery Facility
ESP	Electrostatic Precipitator
F	Fluorine
Fluoride	An ion of Fluorine and present in salts or in a solution
FGT	Flue Gas Treatment
HCl	Hydrogen Chloride
H <sub>2</sub> O	Water
HF	Hydrogen Fluoride
Hg	Mercury
IED	European Union Directive 2010/75/EU on Industrial Emissions
ID-Fan	Induced Draft Fan
IPPC	Integrated Pollution Prevention and Control
LACW	Local Authority Collected Waste
Lime	Common for hydrated lime, Ca(OH) <sub>2</sub> , or burnt lime, CaO
mg/Nm <sup>3</sup>	Milligram per Normal Meter Cubed
MSW	Municipal Solid Waste
MWe	Mega Watt Electric
MWh	Mega Watt Hour
MWth	Mega Watt Thermal
N <sub>2</sub>	Nitrogen Gas
(NH <sub>2</sub> ) <sub>2</sub> CO	Urea or Carbon Acid Diamide
ng/Nm <sup>3</sup>	Nanogram per Normal Meter Cubed (i.e.10 <sup>-9</sup> g/Nm <sup>3</sup> )
NH <sub>3</sub>	Ammonia
Nm <sup>3</sup>	Normal Meter Cubed, i.e. cubic meters of a gas recalculated to the standard temperature and pressure, 0 °C and the standard atmospheric pressure of 101,325 Pa.
NO	Nitric Oxide
NO <sub>2</sub>	Nitrogen Dioxide
NOx	mono-nitrogen oxides (nitric oxide and nitrogen dioxide)
NLWA	The North London Waste Authority
PAH 's	Polycyclic Aromatic Hydrocarbons
S	Sulfur
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO <sub>2</sub>	Sulfur Dioxide
Sulphide	Sulfur containing ion in solution or in salts, SO <sub>3</sub> <sup>2-</sup>
Sulphate	Sulfur containing ion in solution or in salts, SO <sub>4</sub> <sup>2-</sup>
SRF	Solid Recovered Fuel
t/h	Tonnes Per Hour
TOC	Total Organic Carbon