WtE Feasibility study, Pontiac, Canada - DRAFT

15 December 2023

Bright ideas.
Sustainable change.

Introduction

It is considered establishing a Waste to Energy (WtE) facility for treatment of residual, mixed waste from Pontiac and the neighbouring areas. Introduction of WTE divert waste from landfill, prevent methane emission and generate renewable energy to the local society.

In order to support decarbonisation of the local society the project is planned to introduce carbon capture to avoid emission of CO_2 emission, which is a natural product from the combustion process. The captured CO_2 can be stored underground or used for generation of E-fuels and prevent the usage of virgin fossil fuels (oil/natural gas). The plant will be designed for high energy efficiency to recover most possible energy from the waste.

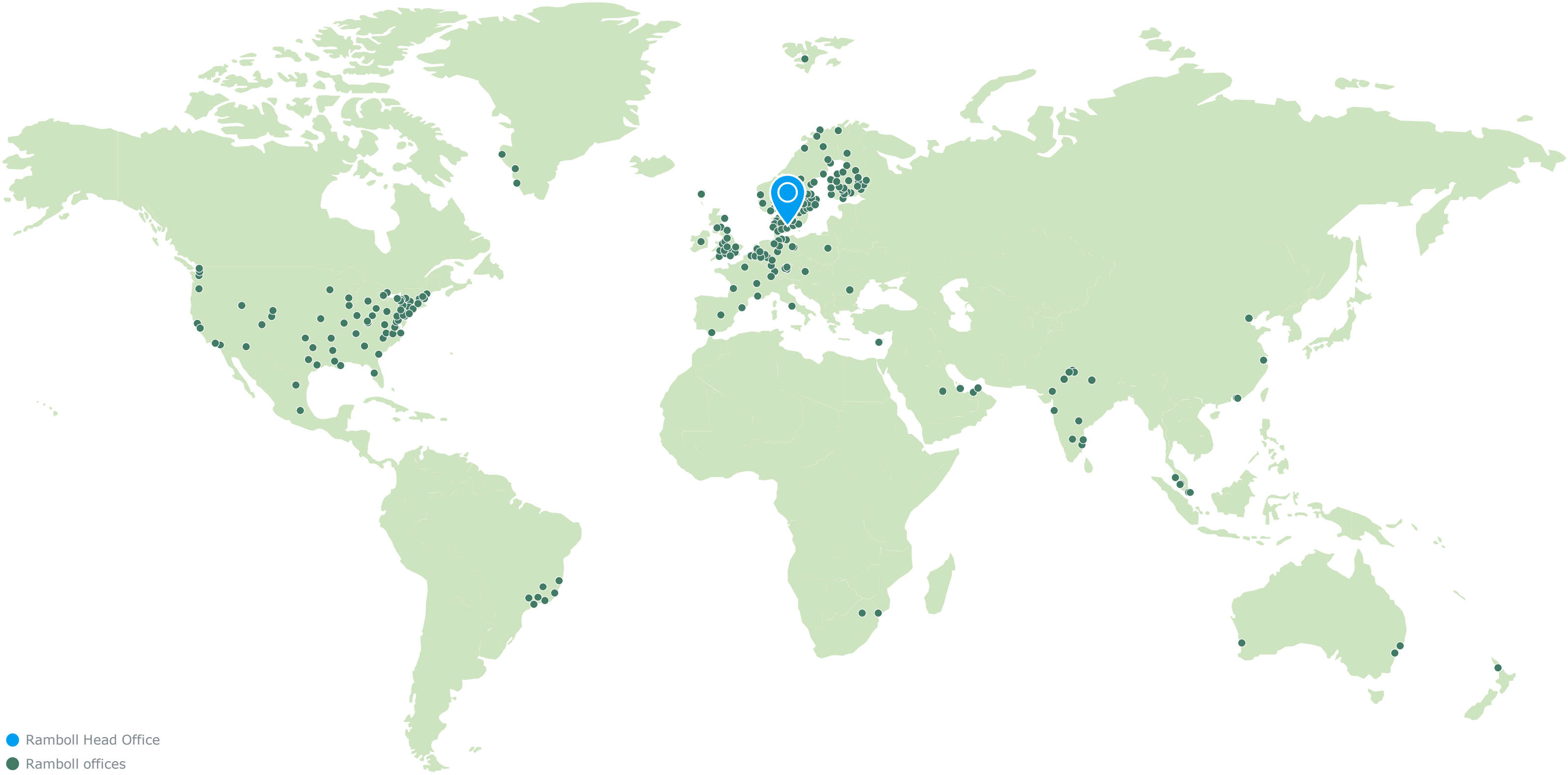
The WTE facility is planned to be equipped with an advanced flue gas cleaning component. The most modern technology will be used to ensure low emission limit values to the atmosphere.

The current project is carried out based on preliminary design data achieved specifically for this project or, where data are not available, based on data from similar projects primarily in Canada and Ramboll’s huge data base of similar projects Worldwide.

The overall purpose of the project is to develop a preliminary concept for the plant with a sufficient detail to support the preliminary business case. The technical report will present the choice of technology for the thermal treatment, the energy recovery, the flue gas treatment and the carbon capture and will recommend the conceptual design to form the basis for the preliminary business case. Based on the recommended scenario a mass- and energy balance is carried out. A brief scenario assessment is also provided

The technical input and the technical concept is developed by Ramboll. Ramboll is shortly presented below to allow the reader to understand the background of the technical consultant.

Ramboll’s 18,000 experts work globally across nearly 300 offices in 35 countries



Across the world, Ramboll combines local experience with a global knowledgebase to create sustainable cities and societies.

We combine insights with the power to drive positive change to our clients, in the form of ideas that can be realised and implemented.

We work multidisciplinary across our seven markets:

- Buildings
- Transport
- Energy
- Environment & Health
- Water
- Architecture & Landscape
- Management Consulting

World-leading waste-to-energy consultant

Thermal treatment of waste has since the 1970s been a special area of expertise in Ramboll and today Ramboll is a globally renowned consultant within Waste-to-Energy.

We have obtained this position throughout a long list of significant Waste-to-Energy projects, where we have been responsible for the planning, engineering, procurement, and contract management of Waste-to-Energy facilities. Indeed, we would suggest that our experience, expertise, and staff resources make us probably the most experienced and qualified consultant within Waste-to-Energy in the World.

We are more than 125 dedicated Waste-to-Energy project managers and specialists serving the market through our centre of excellence in Copenhagen with main regional hubs in Zürich, United Kingdom, Singapore, and Australia.

Globally in Ramboll, we have more than 2,500 specialists working with energy production, energy efficiency, renewable energy, power transmission, and district energy.

Ramboll has worked on Waste-to-Energy projects in more than 55 countries, providing consulting services for at least 200 new Waste-to-Energy lines.

12	125	>2,500
Global offices in 7 countries	WTE experts	WTE projects

Ramboll Energy from Waste, project references

Americas: Argentina, Bermuda, Brazil, Canada (British Columbia, Kuujjuaq/Quebec, Ontario, Price Edward Island), Falkland Island, US (Florida, Georgia, Maryland, Michigan, Pennsylvania, Utah)

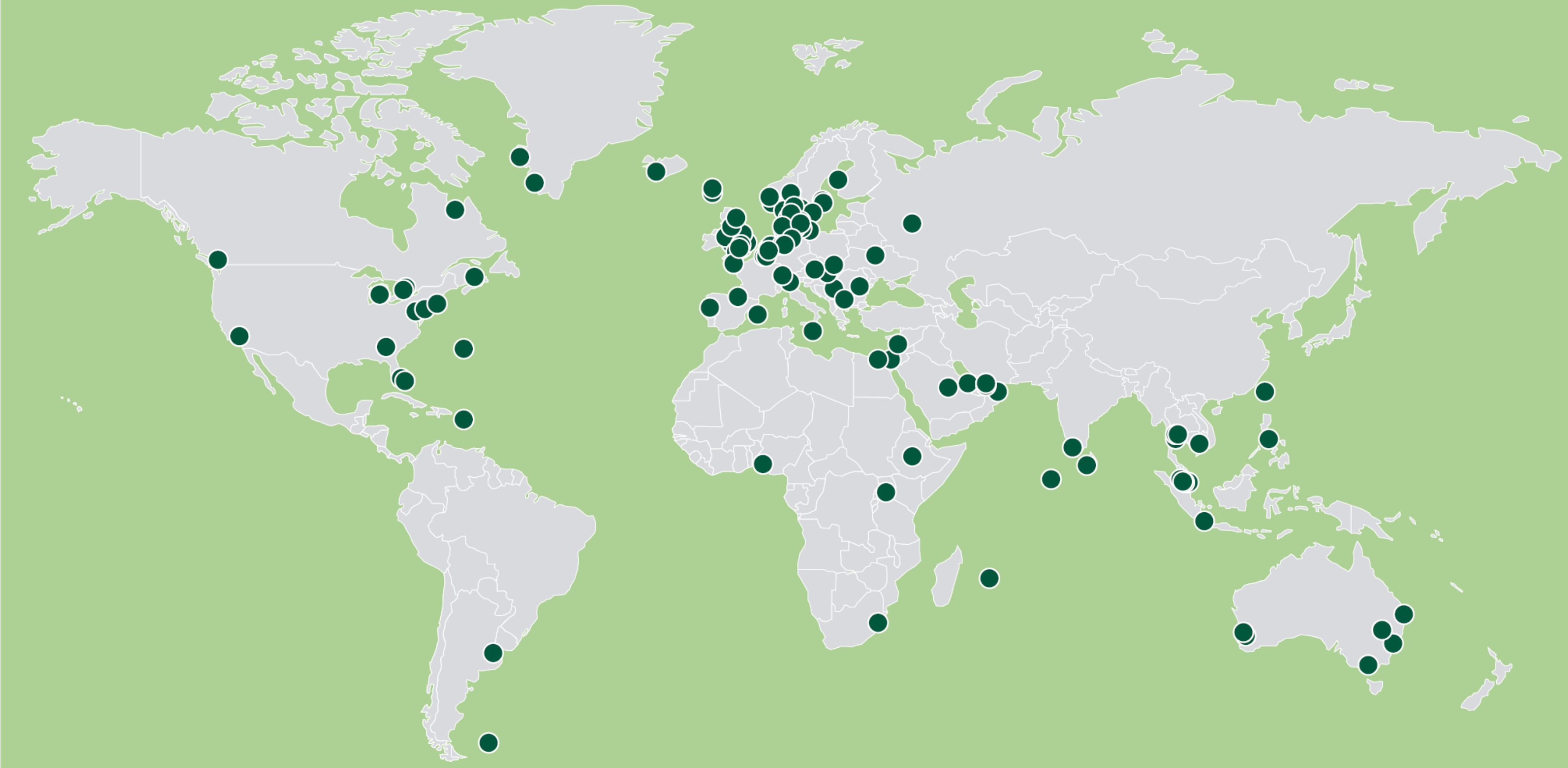
Europe: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Faroe Islands, Finland, Italy, Germany, Gibraltar, Greenland, Hungary, Iceland, Ireland, Lithuania, Netherlands, Norway, Portugal, Romania, Russia, Serbia, Spain, Sweden, Switzerland, Turkey, UK, Ukraine

Africa: Egypt, Ethiopia, Marroco, Mauritius, Nigeria, Uganda

Middle East: Israel, Lebanon, Oman, Qatar, Saudi Arabia, UAE

Asia: Cambodia, China, Hong Kong, Indonesia, Malaysia, Maldives, Mongolia, Philippines, Singapore, South Korea, Sri Lanka, Taiwan, Thailand

Australia: Brisbane, North Queensland, Perth, Sydney

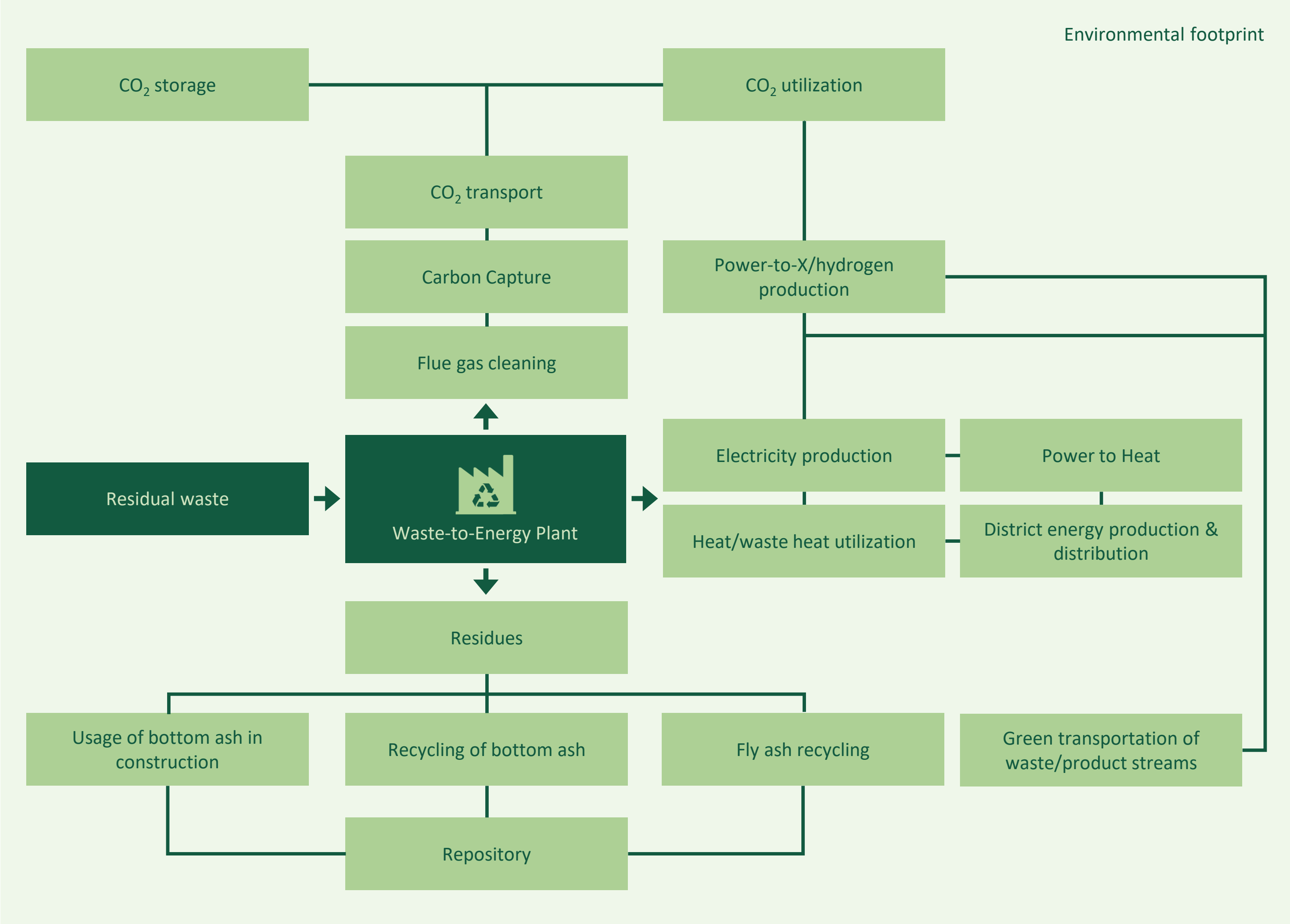


A range of sustainable solutions can be achieved through Waste to Energy

There are a **broad range of technological possibilities** that can be realized in the interconnection of processes related to waste-to-energy as presented in the general flow chart to the right.

Sustainability can be increased though **maximizing the energy efficiency** of the overall system and finding the most sustainable solution ensure integration with the local society, protect biodiversity, ensure high degree of resource recovery from the bottom ash and control the emissions as briefly presented at the next slide.

Possible concepts are presented in the techncial report below based on Ramboll's experience are presented in the report below.



Where it is uneconomic or unsound to recycle, residual waste becomes a valuable local source of energy

A waste-to-Energy facility is the cornerstone of most modern waste management systems

Waste can become a resource by turning it into energy.

A waste-to-energy facility may generate **a range of energy outputs:** electricity, district heating, steam for industrial processes, desalinated seawater or district cooling.

Superior to many alternative waste treatment processes

A waste-to-energy facility can be a valuable local source of secure, stable and **climate-friendly energy.** It will substitute fossil fuels and contribute to national energy self-sufficiency and will in many cases fully **eliminate the need for landfilling.**

The location of the Waste-to-Energy facility is decided based on specific and local conditions.

Waste-to-Energy facilities are typically placed near cities and towns to **supply the surrounding areas with energy outputs such as heat and electricity.** This means that waste does not have to be driven long distances, which **significantly reduces transportation costs.**

Waste-to-Energy as an integrated part of our societies

A waste-to-energy facility can have a large influence on the townscape and many Waste-to-Energy facilities are designed with **amazing architecture to become beacons for cities** and to welcome citizens as an integrated part of our societies.

Glossary

Abbreviations	Explanation
CC	Carbon capture
CHP	Combined heat and power
DH	District heating
FGT	Flue gas treatment
HHV	High heating value
IBA	Incineration bottom ash
LHV	Low heating value
LP	Load point
MSW	Municipal solid waste
RDF	Refuse derived fuel
SAF	Sustainable aviation fuel
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
TRL	Technology readiness level
WtE	Waste to energy

Waste amount and characteristics

Overview

Due to the early stage of the project and lack of detailed studies, it has been agreed to take certain assumptions in order to carry out mass and energy balances and to size the plant.

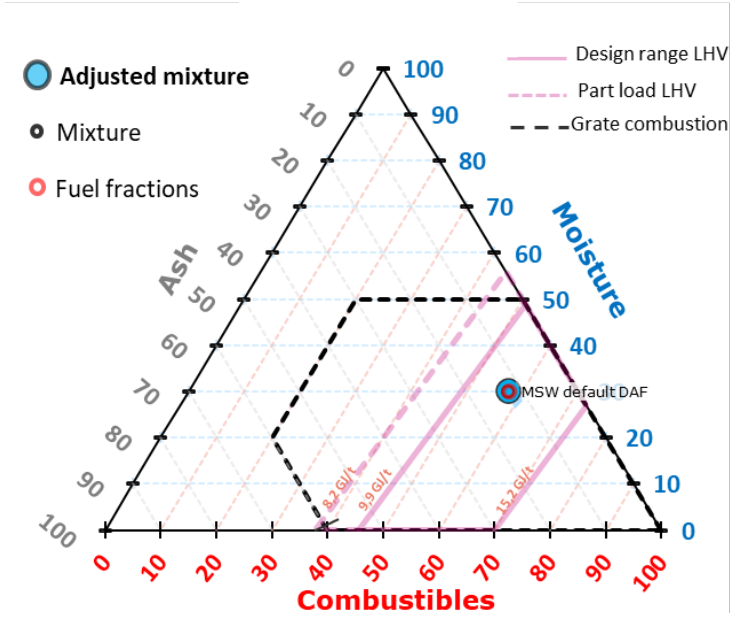
We have based the assessment on data from similar projects and on preliminary waste amounts.

The study is based on a waste feed of 400,000 t/year, with a Lower Heating Value (LHV) of 11.7 MJ/kg (corresponding to a Higher Heating Value (HHV) of 13.4 MJ/kg).

The waste treated at the facility is assumed to have an ash content of around 12.5 % and a moisture content around 30%.

This mixture is indicated in Tanners Triangle in Figure 3. Tanners' triangle shows the relation between combustibles, moisture content and ash content in the waste. When the mixture is within the area defined by the dashed lines, it is deemed suitable for incineration.

Tanners triangle of assumed waste composition



Assumed waste elemental composition

Element	Unit	Composition
C	%(w)	30.7%
S	%(w)	0.2%
H	%(w)	4.2%
O	%(w)	21.1%
H_2O	%(w)	30.3%
N	%(w)	0.6%
Cl	%(w)	0.5%
Ash	%(w)	12.5%

Corresponding heating values

LHV	MJ/kg	11.7
HHV	MJ/kg	13.36

Capacity diagram: detailed review

Based on the stated assumptions, it is suggested that the WtE facility capacity diagram to be designed for an average calorific value of 11.7 MJ/kg and ranging from 8.2-15.2 MJ/kg to prepare for variations in the incoming waste. A relatively wide diagram has been considered given the scarce information available.

The **total amount of MSW to be processed is defined to be 400,000 tpa**, equivalent to **200,000 tpa per incineration line**. Given an annual availability of the facility of 8,000 h, the nominal capacity will be 25.0 t/h per line.

The capacity diagram indicates the connection between the input waste stream in t/h, the calorific value in MJ/kg and the thermal load in MW for the boiler. The capacity diagram indicates the operational area where all guarantees, environmental, and functional requirements must be met (blue line).

Continuous operation shall preferably be at 100% thermal load to have an efficiently operating facility. Continuous operation beyond the limits of the diagram is not possible (red line). The overload area enclosed by the red line, does not allow for operational set-point, however only ½-hour average conditions to allow for variations in the control system.

The proposed capacity diagram is seen in the figure to the right, for a single line.

According to the capacity diagram the nominal design point (Load Point, LP1) is 25 t/h at a calorific value of 11.7 MJ/kg, which equals a thermal input of 81.3 MW per line.

The line (LP2) – (LP5) represents 100% thermal load, and the facility shall preferably be operating along this line, in practice done by operating the boiler on a fixed steam flow rate set point. This implies that the amount of waste is reduced if the calorific value exceeds 11.7 MJ/kg and similarly increased if the calorific value decreases.

The diagram allows a range for the calorific value between 8.2 MJ/kg (line between (LP8) and (LP9)) and 15.2 MJ/kg (line between (LP5) and (LP6)).

The maximum waste throughput (100 % mechanical load) is 29.5 t/h represented by the line (LP2) – (LP9), corresponding to 118 % of the nominal throughput of LP1 (mechanical load), which is considered as being good industry practice.

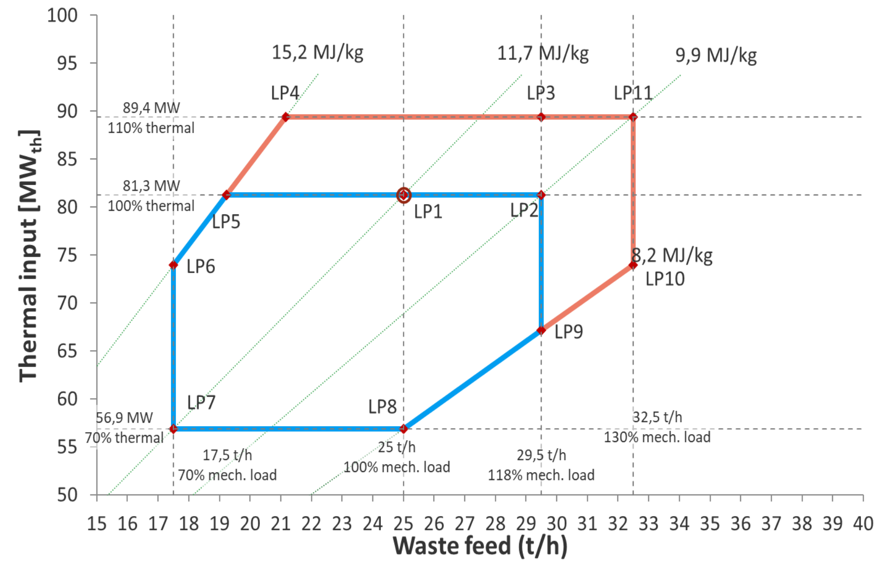
The minimum waste throughput is 17.5 t/h represented by the line (LP6) – (LP7), corresponding to 70 % of the nominal throughput of LP1 (mechanical load), which is considered as being good industry practice.

Inside the area made up by the lines (LP2), (LP1), (LP5), (LP6), (LP7), (LP8), (LP9) and (LP2) the facility shall be able to be in continuous operation.

The line (LP4) – (LP11) is the maximum thermal load (89.4 MW), which is 110 % of the nominal thermal load. The area constituted by the lines (LP2), (LP3), (LP4) and (LP5) represents a thermal load of 100–110 % of the nominal load, is designed to manage inevitable fluctuations from the preferred operational line (LP2) – (LP5). Continuous operation at thermal overload is not possible.

The line (LP7) – (LP8) is the minimum allowable thermal input where all guarantee-values have to be fulfilled without use of auxiliary gas/oil burners. The line is representing 70 % of the nominal thermal load (56.9 MW).

Capacity Diagram; Pontiac (1 out of 2 boilers)



[Source: Ramboll]

Loadpoint table (1 out of 2 boilers)

Loadpoint table	Unit	LP1	LP2	LP3	LP4	LP5	LP6	LP7	LP8	LP9	LP10	LP11
Calorific value LHV	MJ/kg	11.7	9.9	10.9	15.2	15.2	15.2	11.7	8.2	8.2	8.2	9.9
Waste feed	t/h	25.0	29.5	29.5	21.2	19.2	17.5	17.5	25.0	29.5	32.5	32.5
Thermal input	MW	81.3	81.3	89.4	89.4	81.3	73.9	56.9	56.9	67.1	73.9	89.4
Waste feed (daily)	tpd	600	708	708	508	462	420	420	600	708	780	780
Waste feed (yearly)	tpa	200,000	236,000	236,000	169,231	153,846	140,000	140,000	200,000	236,000	260,000	260,000

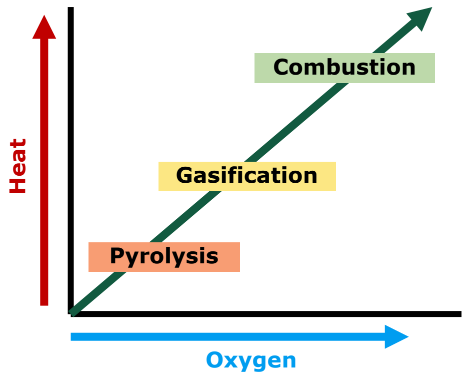
1. Introduction and background
2. Abbreviations
3. Waste amount and characteristics
4. **High level thermal treatment technology assessment**
5. High level flue gas cleaning options
6. High level carbon capture options
7. High level energy recovery
8. Plant description and preliminary sizing
9. Overall mass and energy balance
10. Layout and building volume
11. Overall architectural ambitions
12. CAPEX / OPEX
13. Life Cycle Analysis (LCA)

There are three main processes for the treatment of waste; controlled conditions can produce a desired output

Thermochemical conversion processes are used to produce heat, solid, liquid, and gaseous products and a wide variety of each type depending on reaction conditions.

Several thermal technologies are competing in the waste-to-energy industry. Grate based incineration (**combustion**) is dominant as the most versatile and robust technology, and the technology is continuously being optimized to improve environmental performance standards and increase resource recovery, as well operational availability (>8,000 hours a year). However, research and development in alternative technologies, (e.g. **pyrolysis** and **gasification**), is ongoing, and some of these technologies are offered however, still not on a commercial scale.

There are three basic processes for thermal treatment of MSW: Combustion, gasification and pyrolysis (and combinations hereof). Each of these thermal treatment processes is outlined below.



Heat and oxygen almost completely control what kind of thermal conversion will occur.

Pyrolysis	Gasification	Combustion
Feedstock is heated to high temperatures without adding air or steam. This produces a condensable, refinable ‘pyrolysis gas’ (including tars, methane, hydrogen, CO) that can be treated for energy/fuel production, and a non-condensable gas that can be combusted for heat. Solid carbon and ash are waste products.	Feedstock is heated with the addition of small quantities of oxygen, which react with the carbon to produce additional hydrogen and CO. The oxygen also reacts to breakdown some of the tar, producing a syngas composed primarily of methane, CO, water and hydrogen. Some ash as waste is produced.	Feedstock is heated with excess air supply, causing total combustion. This produces a flue gas composed of CO_2, steam and nitrogen, releasing all energy as heat in the hot flue gas. **This is the only process which can effectively process mixed MSW.**

Process comparison

Parameter	Pyrolysis	Gasification	Combustion
Reaction environment	Zero oxygen	Reducing, low oxygen	Oxidizing, excess stoichiometric oxygen
Oxidizing agent	None	Air (also O_2 and/or steam)	Air
Temperature	400-800°C	500-900°C (air) 1,000-1,500°C (other gasifying agents)	850-1,200°C
Main outputs	Liquids & solids	Gas	Heat
Produced gases	CO, H_2, CH_4 and other hydrocarobns	CO, H_2, CH_4 CO_2, H_2O	CO_2, H_2O
Pollutants	H_2S, HCl, NH_3, HCN, tar, particulates	H_2S, HCl, NH_3, HCN, tar, particulates	SO_2, NO_x, HCl, PCDD/F, particulates

Pyrolysis is an effective solution for hard-to-recycle waste, but an inefficient treatment of general MSW

Technology overview

Pyrolysis is a technology used to process hard-to-recycle waste, but is not available for MSW, and not considered by Ramboll as an attractive technology to pursue.

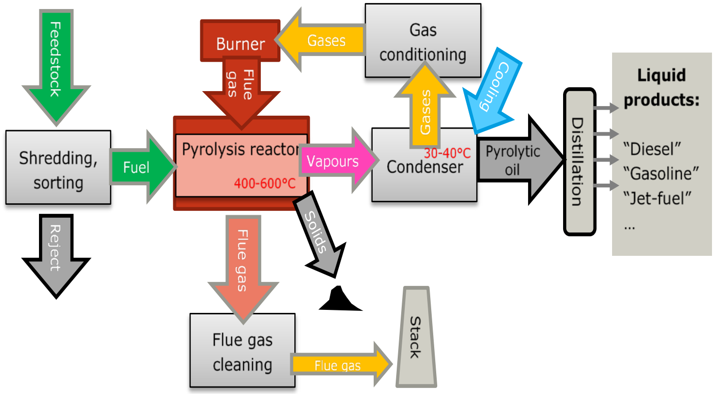
- Today no pyrolysis facilities for mixed waste (MSW/RDF) are known to be operating except possibly some of the old R21 plants in Japan. Pyrolysis technology for mixed waste is not available on the market anymore, however pyrolysis of separated tyres or plastic for recycling is evolving.
- Pyrolysis is a possible technology in chemical recycling processes for plastic and receives a lot of attention as a chemical recycling process to promote circularity and produce new plastics (production of fuel is not considered recycling in Europe). However, current worldwide installed capacity is very limited.

Process Description:

- The feedstock is sorted, shredded and heated to a high temperature (typically 400-600°C). Different types of externally heated pyrolysis reactors are used by different technology companies. Controlled temperatures and fast heating rates are desirable as they decrease polymerization (coking). Rotating kilns or conveyer screw reactors continuously move the feedstock particles to increase contact with heating surfaces. To sustain a stable vapor production batch reactors are usually operated as many units with separated cycles. Fluidized beds offer very high heating rates but require the product to be mixed with sand in the reactor.
- Pyrolysis produces a liquid fraction (condensable vapours or oil), solid fraction (char), and gasses (non-condensable). The relative yields of these products are determined by the process conditions as well as the type and composition of the feedstock. The selection of the reactor type and pyrolysis temperature are the two main factors that strongly affect product selectivity.

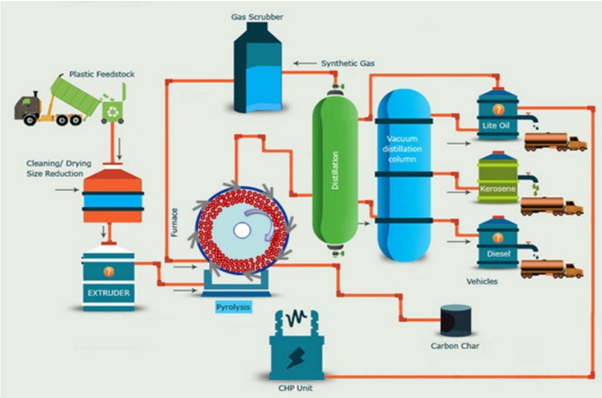
Tyre pyrolysis

- Several plants exist for separate pyrolysis of end-of-life tyres to produce recovered carbon black (rCB) and this industry is growing.
- Current main challenge is the development quality standards to ensure marketability of the rCB. Standardization work is ongoing.



Plastic pyrolysis

- Plastic pyrolysis facilities are at different levels of R&D, and few have operated for more than a few years due to technical and/or economical challenges. Fires and explosions have been common at the facilities so far, and existing companies still struggle with the scaling up of the facilities to commercial plants, postprocessing of the produced oils, and the profitability of the process. Several plants continue to be in the pipeline but plastic pyrolysis is a volatile industry with many project failures and short-lived facilities and suppliers.



The gasification process has moderately high temperatures and a controlled supply of oxygen/air

Gasification is a partial thermal oxidation, which results in a high proportion of gaseous products (carbon dioxide, water, carbon monoxide, hydrogen, and gaseous hydrocarbons), small quantities of solids, ash and condensable compounds (tars and oils).

Steam, air, oxygen or combinations of them are supplied as oxidising agents.

Different processes occur during gasification:

- **Drying** (100-150°C): moisture is removed by evaporation using the heat generated in the zones below.
- **Pyrolysis** (200-500°C): dried fuel from the drying zone is further heated to cause thermal degradation and partial volatilization.
- **Combustion/Oxidation** (800-1,200°C): the volatile gaseous products of pyrolysis are partially oxidised in energy releasing reactions resulting in a rapid rise in temperature. The heat generated is often reused to drive the upstream drying and pyrolysis of the fuel and the gasification reactions.
- **Reduction/Gasification** (650-900°C): the char is converted into product gas by reaction with the hot gases from the upper zones. The gases are reduced to form a greater proportion of H_2, CO, CH_4, C_2H_2 and C_2H_6.

Gasification

Drying

Moist feedstock + Heat → Dry feedstock + H_2O

Devolatilization

Dry feedstock + Heat → Char + Volatiles

Combustion

$C + O_2 \rightarrow CO_2 + Heat$

$C + 1/2O_2 \rightarrow CO + Heat$

$H + 1/2O_2 \rightarrow H_2O + Heat$

Char + Heat → Slag

Slag → Clinker + Heat

Gasification

$C + H_2O + Heat \rightarrow CO + H_2$

$C + 2H_2O + Heat \rightarrow CO_2 + H_2$

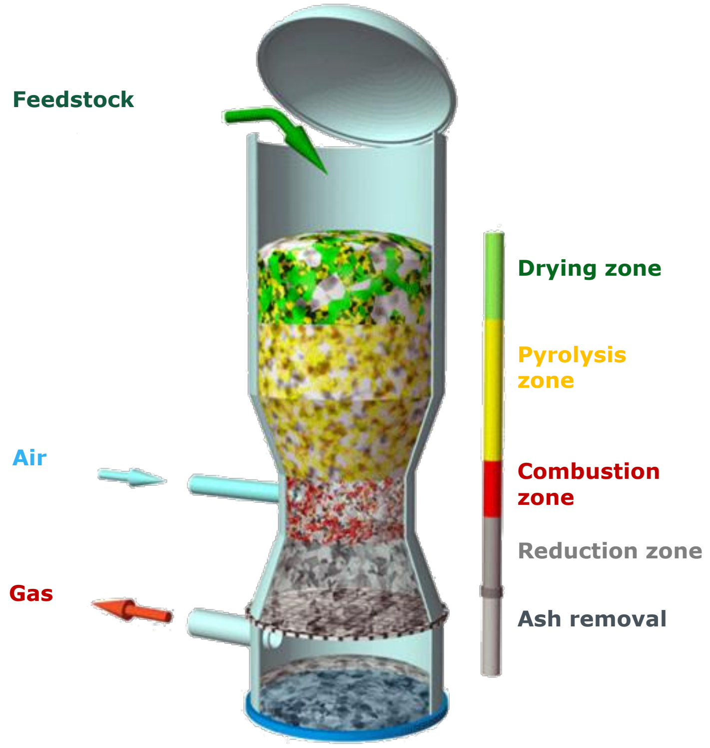
$C + CO_2 + Heat \rightarrow 2CO$

$C + 2H_2 \rightarrow CH_4 + Heat$

$CO + 3H_2 + Heat \rightarrow CH_4 + H_2O$

$CO + H_2O + Heat \rightarrow H_2 + CO_2$

Reactions in the different stages of gasification



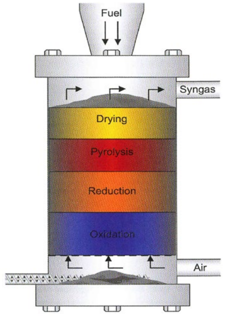
Different zones in a downdraft fixed bed gasifier

Various gasifier reactor designs accommodate different inputs and outputs (1/2)

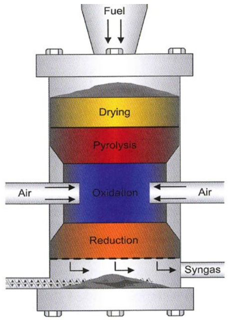
The principal design concepts, even though there are others available, can be classified in:

1

Fixed bed reactors are often considered a possible technology for small-scale plants of up to 10 MW. Within fixed bed reactors, it is possible to distinguish updraft and downdraft configurations. The main difference is that in downdraft gasifiers the decomposition products from drying and pyrolysis go through thermal cracking in the oxidation zone thus produce less tar and a higher quality gas than updraft gasifiers, where the pyrolysis gas go directly into the syngas. Fixed bed gasifiers are simple in construction, operate at low gas velocity with high carbon conversion and long residence time. However, they are not normally used on a large scale due to the low moisture content required in the feedstock, which is one of the limitations for the use of MSW and overheating spots in the reactor.



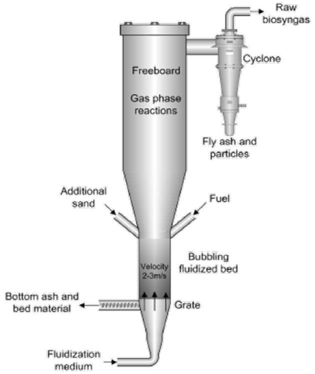
Updraft



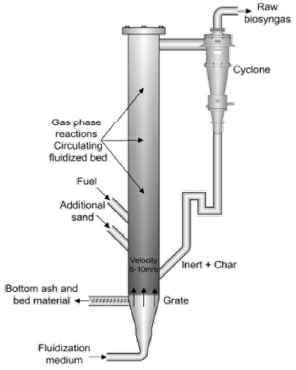
Downdraft

2

Fluidized bed reactors, including bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) reactors, are based on the principle of fluidization in which both the fuel and hot bed material (inert inorganic material and/or catalyst) is made to behave as a fluid by mixing the solid particle fuel material with a upward gas stream. The semi-suspended conditions are kept by controlling the gas velocity. These gasifiers provide an excellent gas-solid contact, a uniform temperature and solid/gas concentration in the entire bed. It is not possible to have separate reaction zones in a single reactor in fluidized bed systems (drying, pyrolysis, reduction and combustion) due to the intense gas-solid mixing. Fluidized bed gasifiers usually operate at relatively low temperatures (700-900°C) to prevent ash sintering and agglomeration and are the preferred option for large-scale plants due to superior scalability characteristics compared to fixed bed systems.



Bubbling fluidised bed (BFB)

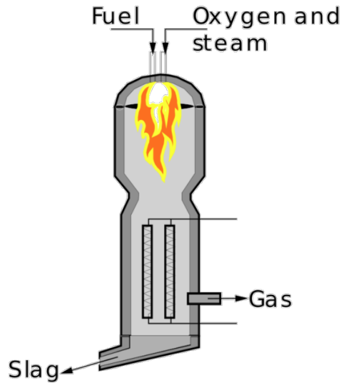


Circulating fluidised bed (CFB)

Various gasifier reactor designs accommodate different inputs and outputs (2/2)

3

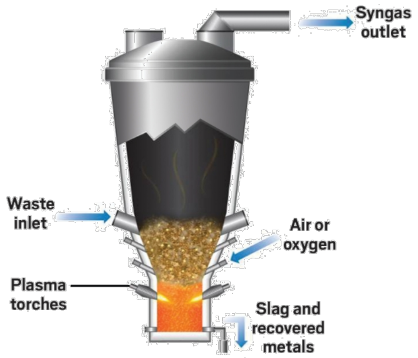
Entrained flow reactors operate at high temperatures (1,400°C) and high pressure (20-70 bar) by injecting powdered fuel into a high-speed stream of the gasifying medium and into the reactor. Thus, the gas stream entrains the fuel particles and directs the flow direction and speed through the reactor system. This technology is typically used for industrial-scale coal gasification because of its higher availability, higher throughput, and better product gas quality. Entrained flow gasifiers produce a very clean syngas but require a very uniform feedstock in the form of fine powder and is generally not suitable for mixed waste streams.



Entrained flow reactor

4

Plasma-assisted reactors which are designed with plasma zones generated by plasma torches. Plasma torches generate small zones of high energy intensity at up to 10,000 °C whereby gases come into an ionized state "plasma". The torches are energy intensive and can use various energy types such as electrical energy, combustion of high energy density fuels in pure oxygen, and intense UV light. Solids and tars in syngas that passes through the plasma zone is effectively broken down into simple gases. Also, the inorganic materials can be transformed into inert and vitrified slag. With MSW the development of plasma-assisted gasifiers have historically been troubled and experienced severe technical issues and project failures and is facing various techno-economical constraints such as high capital costs and energy consumptions.



Plasma reactor

Different gasification reactors have various levels of suitability for treating MSW

1 Fixed bed

- Limited scale-up options
- Suitable only for small-scale
- Uniformity and moisture content requirements for feedstock can be a problem for MSW type of feed
- The low fixed carbon content of some wastes makes gasification in updraft and downdraft reactors difficult
- Poor mass transfer and poor and non-uniform heat exchange between the feedstock and the gasification agent within the reactor.

Not suitable for treating MSW

2 Fluidized beds

- Good mixing and good gas–solid contact, resulting in more homogeneous temperature distribution in the gasifier, higher reaction rate and conversion efficiencies compared to fixed bed gasifiers
- Possibility to achieve a lower tar concentration in the gas product by using the bed material as a heat transfer medium and catalyst
- Often used at test gasification projects

Considered for treating MSW. However, extensive sorting (RDF) and pre-treatment required. No or limited full scale plants using MSW

3 Entrained flow

- Entrained flow reactors This technology is not suitable for waste conversion due to the short time of residence in the reactor, the requirement of the minimum size of the feedstock, and the economic perspective.

Not suitable for treating MSW

4 Plasma-assisted

- The most expensive application due to the cost of the operational process; yet it can be an appropriate gasification technology for the treatment of MSW.
- Plasma torches require large amounts of electricity, roughly 1200–2500 MJ per tonne of MSW.
- Historically plasma-assisted gasification projects for mixed waste have resulted in very significant technical and economical failures.
- Plasma-assisted “waste destruction” (without energy recovery) at small scales have been implemented for hazardous medical waste and military installations.

Not (or moderate) suitable for treating MSW

Source: Arena, U. (2012) Process and technological aspects of municipal solid waste gasification. A review, Waste Management 32 (4): 625-639,

Waste combustion is the dominant system for MSW

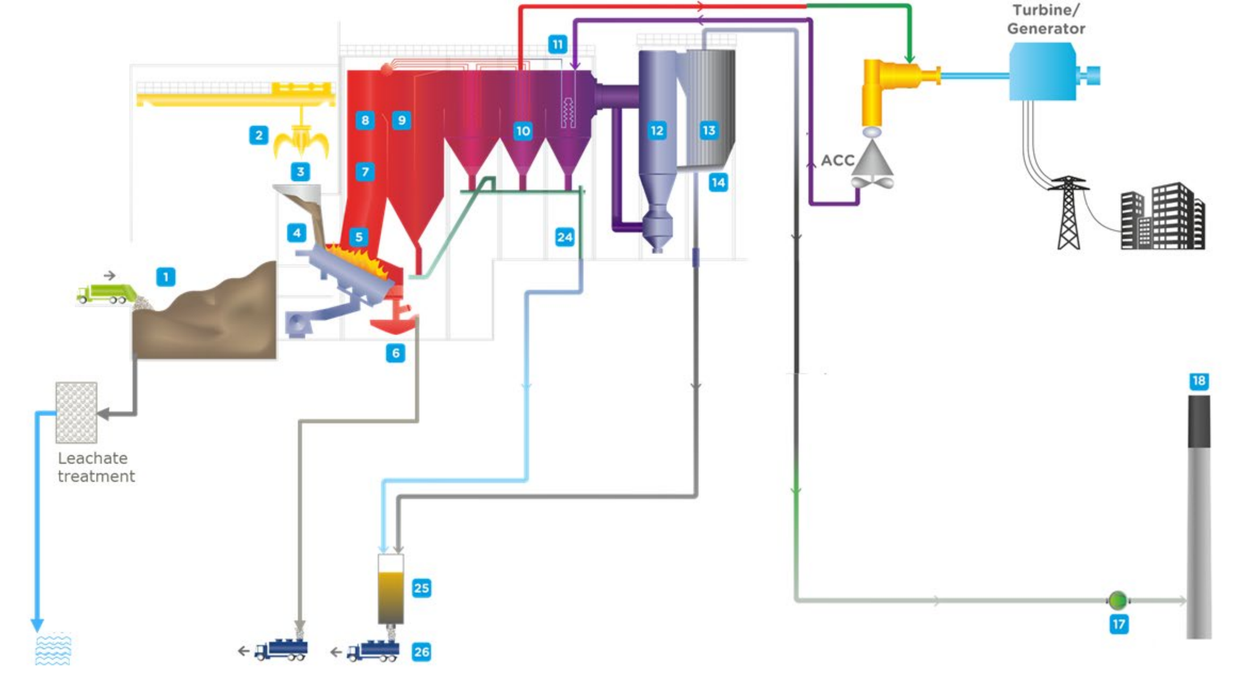
Technology overview

Input: Mixed waste, air, water, chemicals

Output: Power, heat, incineration ash, treated wastewater

- Waste incineration is one of the **most widely practised waste management technologies** worldwide.
- It is often coupled with energy recovery system (boiler and steam turbine-generator) for power production, and sometimes heat for district heating in cold climate, or process steam for industrial usage.
- Carbon capture technology can also be implemented, to reduce the impact of emissions to the atmosphere.
- Downstream flue gas treatment is installed to clean the flue gas to reach acceptable environmental standard before discharge.
- Wastewater treatment is also installed to treat the leachate and process wastewater.
- Incineration Bottom Ash (IBA) can be matured and used to produce aggregates for construction.
- Fly ash is considered hazardous in many countries and need to be disposed in licensed landfill.

Waste combustion process diagram

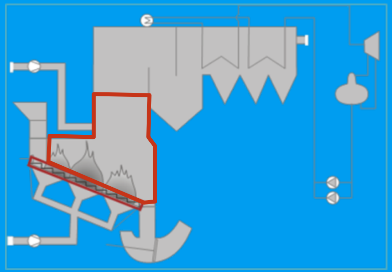


[Source: Ramboll]

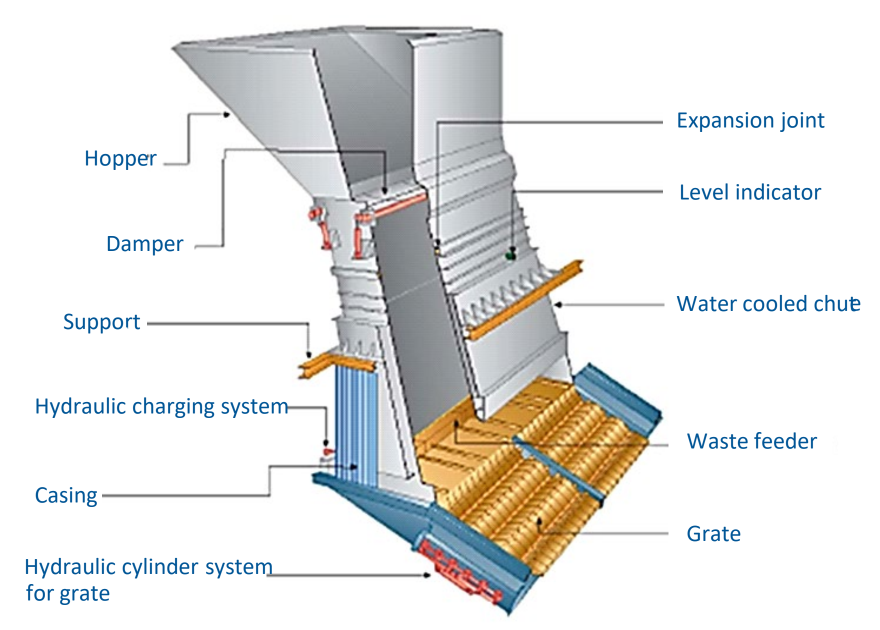
Advanced moving grate incinerator

Technology overview

Parameter	Advanced Moving Grate
Number of boiler lines in operation	>5,000
Waste limitation	Recommended to be shredded, if >1m
Reported annual availability	≥8,000 h/y
Proven, commercial operation >3 years	Numerous plants, well documented operation
Commercially available with a capacity >500 tpd	Yes
Require flue gas treatment	Yes
Compliant with the strictest air emission standards (EU)	Yes
Process residues	Bottom ash (inert waste) production depends on ash content of the incoming waste <40 kg/t waste, consisting of fly ash and flue gas treatment residues (hazardous waste)
Energy usage for pre-treatment	None



Moving grate process diagram



[Source: Ramboll]

Combustion with advanced grate is recommended as the most robust and proven thermal treatment technology

Comparative overview

The summary table below compares the performance and consumption parameters of three thermal treatment technologies. Combustion is assessed as the most beneficial waste process across all assessment criteria.

	Pyrolysis	Gasification	Combustion
Resource recovery (material recovery and recycling)	🟢	🟢	🟢
Energy recovery (efficiency, quantity)	🟡	🟡	🟢
Environmental performance (air, soil, water, GHG)	🟢	🟢	🟢
Land use	🟢	🟢	🟢
Track record and reliability	🟠	🟠	🟢
Cost efficiency	🟠	🟠	🟢

Assessment of benefit level: 🟢 High 🟡 Medium 🟠 Low

Recommendations

A **combustion waste treatment system** with an **advanced moving grate incinerator** is recommended as the most robust technology for the treatment of mixed MSW.

This is also the most proven and widely-used waste system, with numerous long-term commercial operations documented globally.

Combustion is the most dominant thermal treatment technology, as it can process the widest range of waste types. In the context of MSW treatment, this implies less sorting, selecting and pre-treatment of waste is required. Both pyrolysis and gasification are more volatile in their operation and have not been successful scaled to an operational extent such that installation of either of these technologies as the primary waste treatment facility for a community would be considered reasonable.

An **advanced moving grate incinerator** is recommended as it can accept large waste factions, with minimal pre-sorting of waste. A fluidized bed incinerator requires stricter limitations on waste input, with additional energy use for pre-treatment. The energy efficiency gained from fluidized bed incineration is not considered significant enough to offset this additional energy requirement. Furthermore, the technology produces a large volume of residue, and is generally a less proven technology.

The combustion technology is as mentioned in the slides above the most well proven technology with a long and reliable operational record. The **CAPEX/OPEX** is well known and foreseeable.

Alternative thermal technologies are not commercially available. It is often difficult to get competitive bids and most often proposals are conditioned and with very limited access to background data. The CAPEX/OPEX is not backed up by historical data and the technologies are typically still under development and thus investment cost may increase along with technical development of the technologies.

It is recommended to base the conceptual design and the business case for the Pontiac WtE facility on an advanced combustion technology.

Flue gas cleaning technologies

Advanced WtE facilities are equipped with high efficient flue gas treatment downstream the combustion process to clean the flue gases before being emitted. Various technical solutions are available on the marked with different efficiency, different investment cost and different operational expenses.

Mixed municipal solid waste from private households, from public and private companies contains various pollutants and unwanted materials. One of the main purposes of a WtE facility is to destruct pollutants and to sanitizing the society. Most pollutants are destructed in the thermal process and the remaining pollutants will be captured or destructed in the flue gas cleaning.

The choice will depend on the requested emission limit value as well as the quality of the incoming waste and especially which margins and peak loads are expected in the incoming waste.

In the following slides the main technologies will be described and Ramboll will recommend which solution fits best to the overall functional requirements and the incoming waste.

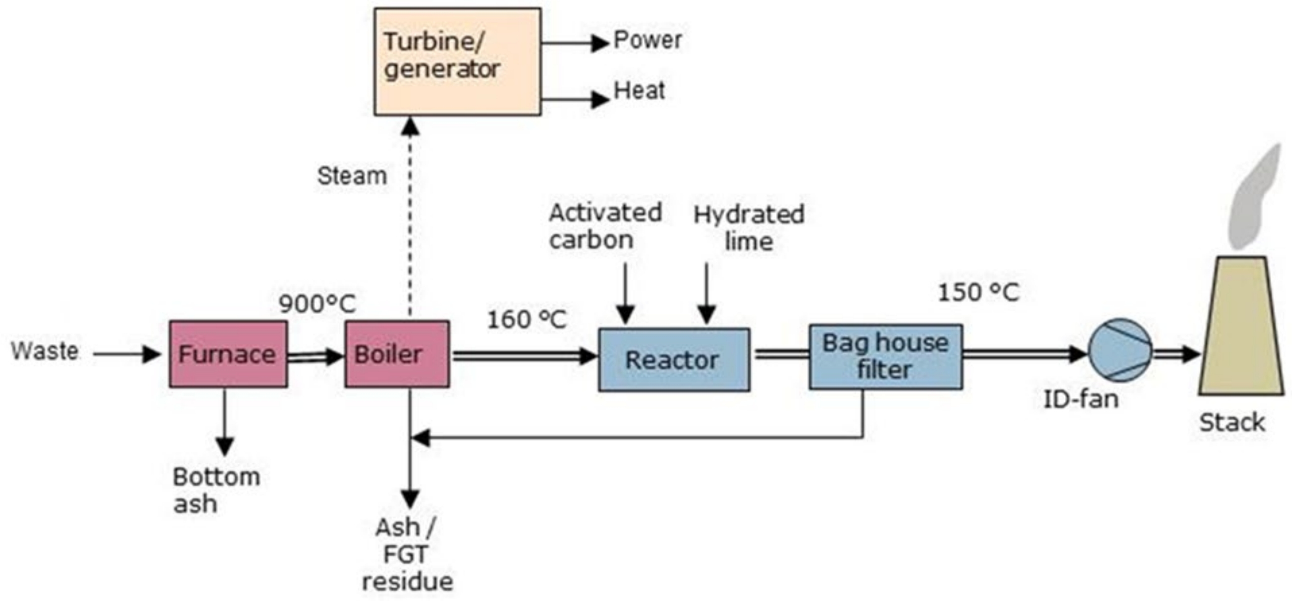
Furthermore, the WtE is planned to be equipped with carbon capture to ensure the emission of CO_2 is minimised. It has to be considered if the carbon capture should be designed for both fossil and biogenic CO_2. Waste consist approx. 50% fossil and 50% biogenic CO_2. The carbon capture technology is briefly discussed based on an amine technology which currently is the most proven technology for WtE facilities. The carbon ccapture is described in a separate section after the flue gas cleaning technology has been chosen.

Dry lime-based systems

Overview

Dry lime-based systems are the simplest type of FGT system and are still widely used.

The key components of the dry lime-based system and the flue gas and material flows together with conditions such as typical flue gas temperatures at various stages of the plant.



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, e.g. Sorbacal™ or similar products.

The process is used in many plants, particularly smaller facilities, 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 (SO_2) and hydrogen fluoride (HF). Therefore, the process is not suited for reach-ing very stringent emission values or for handling flue gas from waste fractions, 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 the 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.

The use of economisers to reach low reaction temperature in order to enhance the absorption process has limited number of references.

Given the difficulties in meeting low emissions, this system is not considered further for the plant at Pontiac.

Semi-dry system

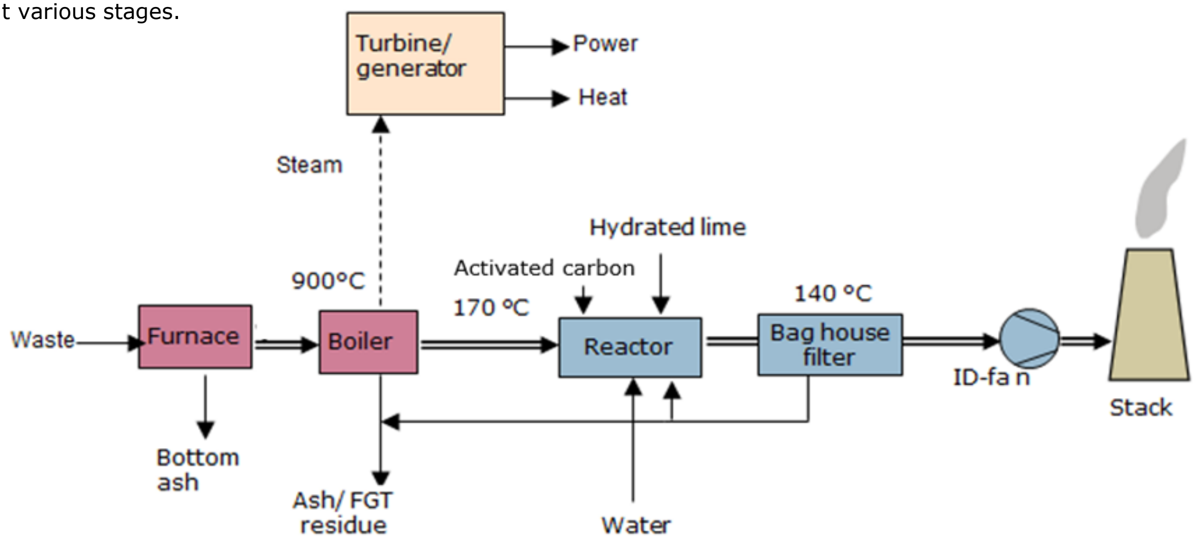
Overview

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 (SO2), 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. Different suppliers have different ways of injecting water for humidification and for introducing and mixing recirculated lime and new 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 figure shows key components of a semi-dry system, flue gas and material flows together with conditions such as typical flue gas temperatures at various stages.



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_2) 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_2) contents.

The mixing system for water and lime requires daily maintenance. The system requires close monitoring to maintain performance.

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Wet scrubbing systems

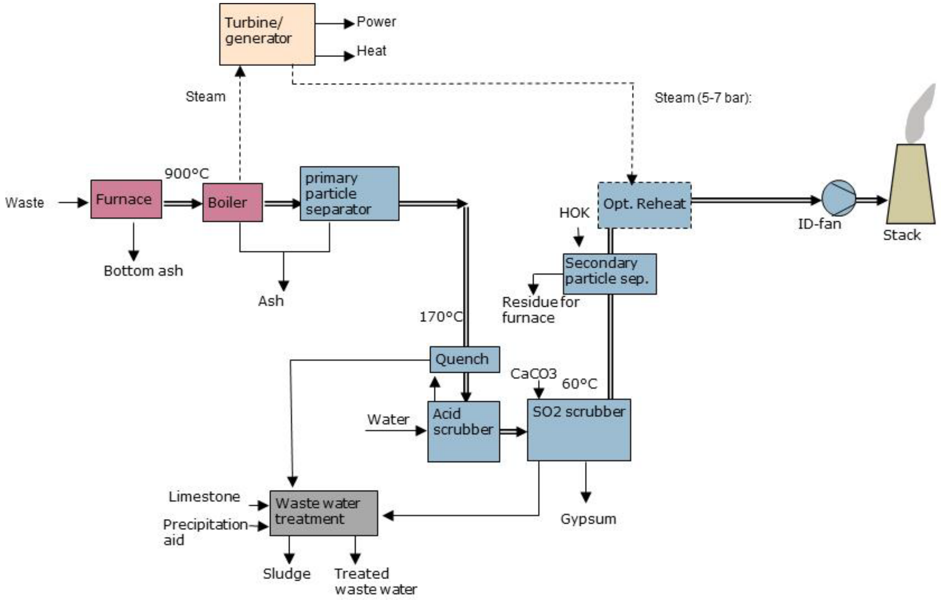
Overview

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_2) content and remaining hydrogen fluoride (HF) content is removed in a caustic or neutral scrubber. Limestone or NaOH may be used in the SO_2-scrubber.

Wet FGT systems require dust in the flue gas to be removed in a primary particle separator (e.g. electrostatic precipitator) 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.



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 further reduces residue generation.

There are many reference plants employing wet FGT systems, 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 with-out such systems. It may be a challenge to get the necessary permits for discharge of wastewater, which represents a risk for the time schedule. Furthermore, wastewater discharge is not a component desired by the client.

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

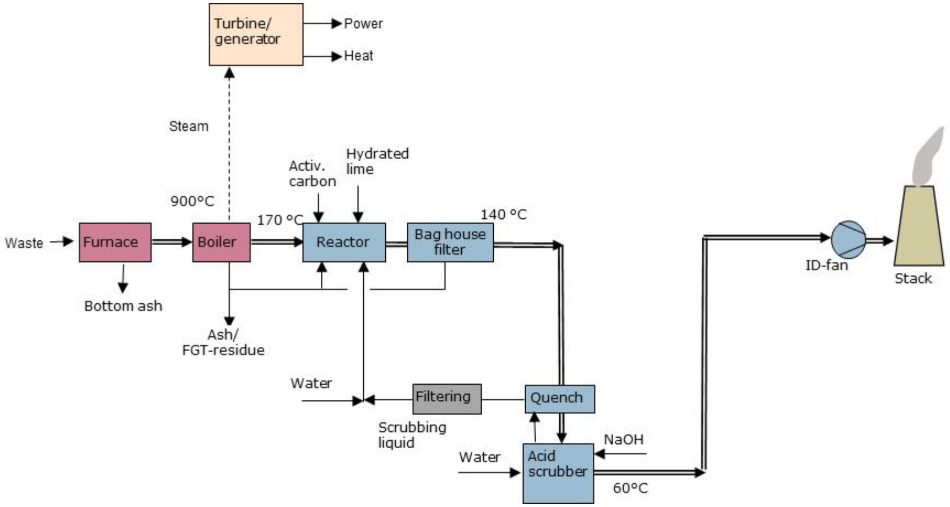
‘Combined Dry-Wet’ System

Overview

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 reach the same very low emissions of HCl and SO_2 as the wet scrubbing system while avoiding wastewater handling and discharge. It also reduces 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 figure shows key components of a combined system and the flue gas and material flows together with conditions such as typical flue gas temperatures at various stages



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_2). 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 waste-water produced by the system.

There are many operational WtE 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. This also applies if burnt lime (CaO) is selected for hydration on site, as part of the process.

Installation of flue gas condensation is straight forward with the scrubbing system already planned/installed. This may be done in the same scrubber tower by adding an additional circulation stage and a heat exchanger.

Furthermore, the wet scrubber is the first stage in a carbon capture treatment process and thus a wet scrubber will be introduced when the plant is designed for carbon capture.

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.

Despite savings in lime consumption (and residue generation), limited, if any, savings in operational cost should be expected when compared to semi-dry systems due to the additional power consumption associated with the scrubber.

This system will have high plume visibility unless the 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, for instance by cleaning water injection nozzles. This may be in a separate mixer or water injection nozzles in the reactor in the flue gas path. The system also requires close monitoring to maintain performance.

This is the flue gas treatment system recommended to best meet the requirements of a WtE facility in Pontiac.

Emission limit values (ELV) at stack – examples

Parameter	Ontario A7	Unit	Durham York	Unit	Average period
Total Suspended Particulate Matter	14	mg/Rm^3	9	mg/Rm^3	4 h avg.
Hydrochloric acid (HCl)	27	mg/Rm^3	9	mg/Rm^3	24 h avg.
Sulphur dioxide (SO_2)	56	mg/Rm^3	35	mg/Rm^3	24 h avg.
Nitrogen oxides (NO_x)	198	mg/Rm^3	121	mg/Rm^3	24 h avg.
Organic matter	33	mg/Rm^3	33	mg/Rm^3	10 min avg.
Carbon monoxide	40	mg/Rm^3	40	mg/Rm^3	4 h avg.
Cadmium	7	µg/Rm^3	7	µg/Rm^3	Spot sampling
Lead	60	µg/Rm^3	50	µg/Rm^3	Spot sampling
Mercury	20	µg/Rm^3	15	µg/Rm^3	Spot sampling
Dioxins and furans	0.08	ng/Rm^3	0.06	ng/Rm^3	Spot sampling

Rm^3 reference conditions are dry flue gas at 11% O_2, 25 °C and 1 atm (101.3 kPa).

Expected emission to the air (annual average)

Parameter	Unit	Semi-dry	Combined	Wet
Water vapour	% vol.	18	22	22
CO [1]	mg/Rm^3	9	9	9
TOC [1]	mg/Rm3	1	1	1
N_2O [1]	mg/Rm^3	2	2	2
NH_3 [2]	mg/Rm^3	5	0.5	0.1
Dust	mg/Rm^3	1	1	1
HCl	mg/Rm^3	6	1	1
SO_2	mg/Rm^3	18	1	1
HF	mg/Rm^3	0.5	0.1	0.1
Cd + Tl	mg/Rm^3	0.001	0.001	0.001
Hg	mg/Rm^3	0.007	0.004	0.004
Σ9 metals	mg/Rm^3	0.03	0.03	0.03
Dioxins or furans, TEQ	ng/Rm^3	0.005	0.005	0.005

Rm^3 reference conditions are dry flue gas at 11% O2, 25 °C and 1 atm (101.3 kPa).

Notes: [1] Not affected by the flue gas treatment system; [2] Originating from ammonia slip from an SNCR process, assuming 5 mg/Rm^3 ammonia slip

Flue gas treatment technology evaluation

Evaluation criteria[1]:	**Semi-dry**	**Combined**	**Wet**
Operational availability			
Performance history of reliable operation	✓✓✓	✓✓✓	✓✓✓
Capability, emissions			
Ability to reach very low emission levels (as a minimum like current facility) and to handle changes in raw gas composition	⚠[1]	✓✓✓	✓✓✓
Flexibility			
Ability to meet more stringent future emission limit (official limits)	✓✓	✓✓✓	✓✓✓
Health and safety			
Reduced contact with hazardous material	✓✓	✓✓	✓✓
Consumables and residues			
Low chemical consumption	✓✓	✓✓✓	✓✓✓
Low electricity consumption	✓✓✓	✓✓	✓✓
Low residue production	✓	✓✓	✓✓✓
Discharge of treated wastewater	N/A	N/A	⚠

✓✓✓ *attractive feature* ✓✓ *improved feature* ✓ *acceptable feature* ⚠ *NOT acceptable feature*

Notes: [1] Concept can fulfil the stated emission requirements, but is not likely to reach the desired low levels of Pontiac;

DeNox systems

NOx emissions require a dedicated system to be abated:

Waste combustion in grate fired systems results in the production of mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NO_x) with flue gas contents of typically around 350 mg/Nm³ with a reference condition of 11% Oxygen (O_2), dry.

- 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.
- NO_2 is toxic and reacts with other compounds to form small particles, potentially causing respiratory disease over time.

The deNOx process options are:

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

Both systems are based on the injection of either ammonia (NH_3) or urea (carbon acid diamide, $(NH_2)_2CO$) in an aqueous solution.

SNCR

- Takes place in the combustion chamber by injection of ammonia-water solution.
- Suppliers of SNCR systems are usually willing to accept NO_x guarantees in the range **100 – 150 mg/Nm³** at new facilities.
- Lower values down to **70 mg/Nm³** can be achieved with significant ammonia slip.
- Cleaning unreacted ammonia out of the flue gas is best done in a wet scrubbing system, there are no viable alternatives.

SCR

- Needs separate system where ammonia is injected upstream of a catalyst at a temperature of 180 - 300 °C.
- SCR tail end systems require large gas/gas heat exchangers and a significant amount of steam to heat the flue gas to these temperatures.
- SCR front end systems require tailored flue gas treatment system (e.g. high temperature particulate removal)
- For both SCR types, plant own power consumption is increased (e.g. additional systems to run and pressure loss in the flue gas path)
- SCR use can achieve NOx emission levels lower than **25 mg/Nm³**, 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/Nm³ depending on the NOx emission requirement.

DeNOx system technology evaluation

Evaluation criteria:	**SNCR**	**SCR**
Operational availability		
Performance history of reliable operation	✓✓✓	✓✓✓
Capability, emissions		
Ability to reach very low emission levels and to handle changes in raw gas composition	✓	✓✓✓
Flexibility		
Ability to meet more stringent future emission limit (official limits)	✓✓	✓✓✓
Consumables and residues		
Low chemical consumption	✓	✓✓
Low electricity/steam consumption	✓✓✓	✓*
Costs		
CAPEX	✓✓✓	✓
OPEX	✓✓	✓✓✓
NPV	✓✓	✓

*Front-end SCR would mitigate this significantly, but cannot be implemented in a simple semidry-system

✓✓✓ *attractive feature* ✓✓ *improved feature* ✓ *acceptable feature*

- Both SNCR and SCR can achieve lower emissions than the stated limits.
- SNCR is easily implemented in a semidry system and does not require additional large components.
- SCR can reach even lower NOx emissions but require significant additional CAPEX and footprint.

SNCR deNOX process is recommended to best meet the requirements of a WtE facility in Pontiac.

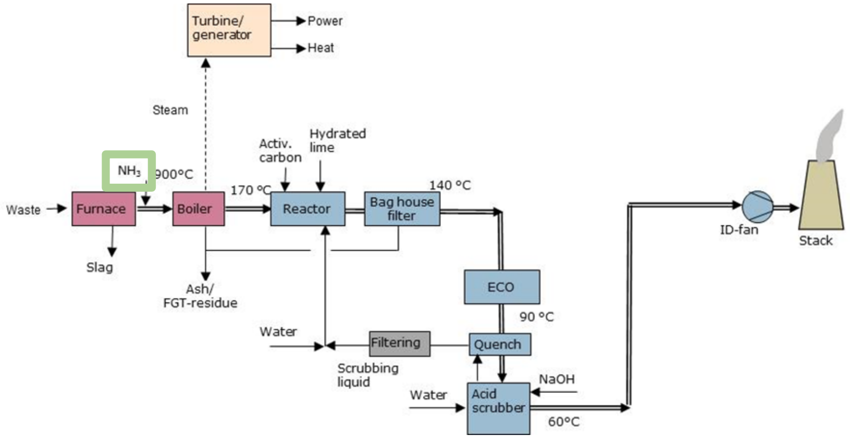
Recommended Flue Gas Treatment technology

Base case:

- SNCR-system for DeNOx
- Semi-dry system composed by a reactor with injection of hydrated lime, activated carbon and water, followed by a bag house filter
- Economiser for energy recovery for district-heating
- Wet scrubbing system, including quench, wet scrubbing with NaOH neutralisation, and bleed water transfer to semi-dry system

The combination has the advantages of having a relatively low CAPEX. It has many references for the sub-systems, SNCR, semi-dry, and wet scrubbing. It meets the environmental expectations for all pollutants including dust, HCl and SO2.

The main disadvantage apart from the increased chemical consumption and solid residue production, is that if pushed to reach NOx emissions below 100 mg/Nm3, there may be ammonia slip at an elevated level which will require an ammonia stripper for the bleed water of the scrubber.

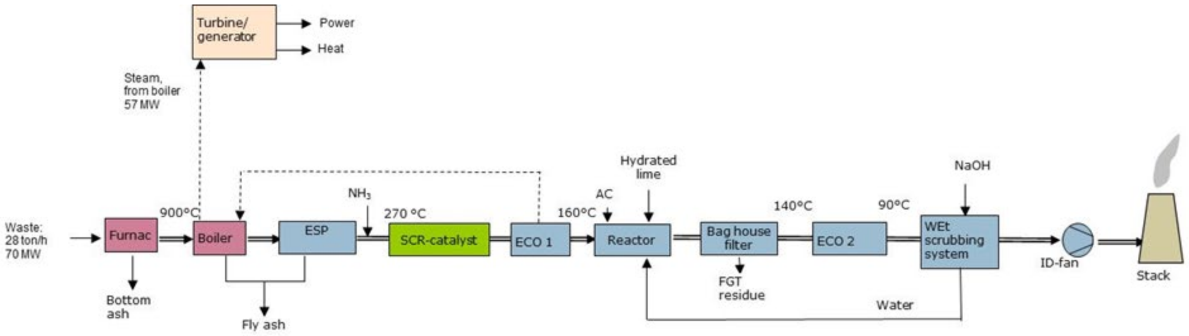


SCR alternative:

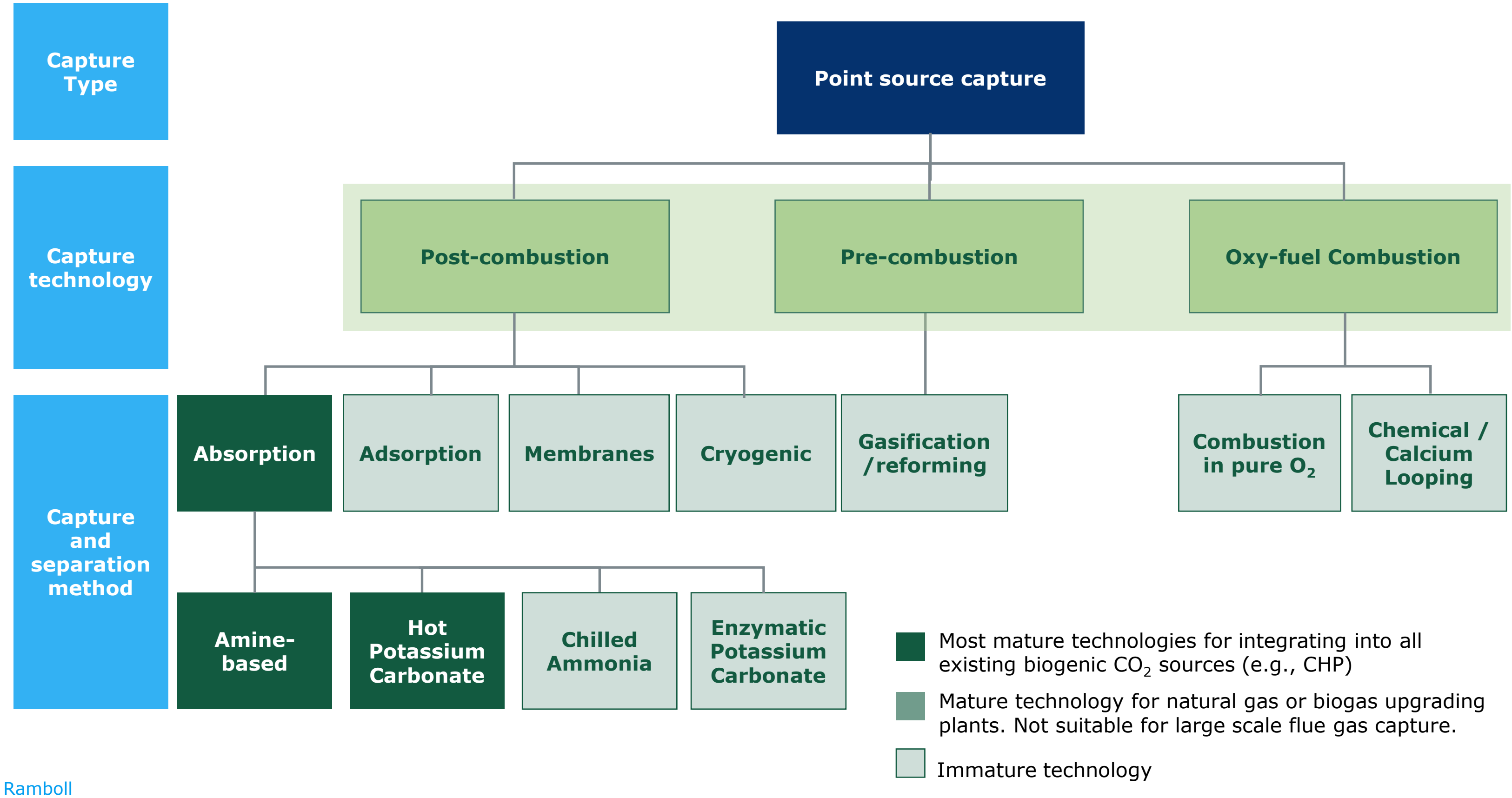
- Front-end SCR-system:
  - Electrostatic precipitator for particle removal, ammonia injection and catalyst
- Economiser 1 (part of the high-pressure boiler system)
- Semi-dry system composed by a reactor with injection of hydrated lime, activated carbon and water, followed by a bag house filter
- Economiser 2 for energy recovery
- Wet scrubbing system, including quench, wet scrubbing with NaOH neutralisation and bleed water transfer to semi-dry system

The combination has the advantages of having many references for the sub-systems, semi-dry, and wet scrubbing. It meets the environmental expectations with good margin. It will reach NOx emission levels of around 30 mg/Nm³, which is well below current regulations, and it provides very low emissions of all pollutants including dust, HCl and SO_2.

The main disadvantages are limited reference base for the front-end SCR, and the CAPEX are relatively high for the combined FGT and SCR-system. In the presented concept, the ESP is included for no other purpose than to protect the catalyst, which adds to the cost of the concept.



Many carbon capture technologies exist, but only a few are mature enough to be implemented in full-scale



Capture Type

Point source capture

Capture technology

Post-combustion

Pre-combustion

Oxy-fuel Combustion

Capture and separation method

Absorption

Adsorption

Membranes

Cryogenic

Gasification /reforming

Combustion in pure O_2

Chemical / Calcium Looping

Amine-based

Hot Potassium Carbonate

Chilled Ammonia

Enzymatic Potassium Carbonate

■ Most mature technologies for integrating into all existing biogenic CO_2 sources (e.g., CHP)

▨ Mature technology for natural gas or biogas upgrading plants. Not suitable for large scale flue gas capture.

□ Immature technology

Point source capture takes advantage of a high concentration of carbon emissions (from a WtE plant, CO_2 concentration in flue gas are typically 10-15%),

Point source **capture technologies** have been developed to remove the carbon at different stages of the process:

- **Post-combustion**, after CO_2 has been formed in a traditional combustion process
- **Pre-combustion**, removing the carbon from the fuel before the combustion
- **Oxy-fuel combustion**, which changes the combustion to obtain a flue gas with very high concentration of CO_2 directly

The only mature technologies applicable to Waste to Energy plants are Post-combustion chemical absorption technologies.

Post-combustion capture is the most mature carbon capture technology

Technology overview:

- Post-combustion capture involves the capture of CO_2 from boiler flue gases after combustion occurs

Most common CO_2 capture methods:

- Absorption: most advanced method, flue gas is captured by flowing through the chemical or physical sorbent
  - Typically uses solvents that can be thermally regenerated (requires high energy input, which is typically taken from the steam produced in the power plant, leading to a loss in the plant's power production)
  - Chemical solvent types: Amines most widely used, hot-potassium carbonate (HPC) and chilled ammonia process (CAP) also in advanced development
  - Physical absorption: uses physical absorbents (usually Rectisol or Selexol) in which CO_2 dissolves under high pressure. Not applicable for flue gas and better suited when feed gas is already in a higher-pressure condition, >6 bar.
- Membrane: least common post-combustion capture method which captures CO_2 by flowing the flue gas through membranes which retain the CO_2 due to a pressure difference or from micropores on the membrane. Typically combined with other methods to enhance the capture process.

Parameter	
Testing with biomass fuels	Tested and demonstrated with heterogeneous biomass fuel inputs and MSW
Biogenic CO_2 sources compatibility	WtE, Biomass CHP, Pulp and paper mills, biogas upgrading plants
General technology readiness level (TRL)	9 for post-combustion capture through chemical absorption with amines
Cost[1]	Highly dependent on the capacity. Estimate is around 70-170 CAD/tCO_2 captured for amine post combustion capture.
CO_2 capture rate	85-95%
Energy used (Amine)	2.6-3.8 GJ/tCO_2

Benefits

- Most mature capture technology (TRL of 9 for chemical absorption with amines) with several carbon capture plants operational worldwide, though this is primarily in relation to fossil fuel generation plants
- Possible to retrofit into existing combined heat and power generation plants (WtE, biomass CHP, pulp and paper mills)

Drawbacks

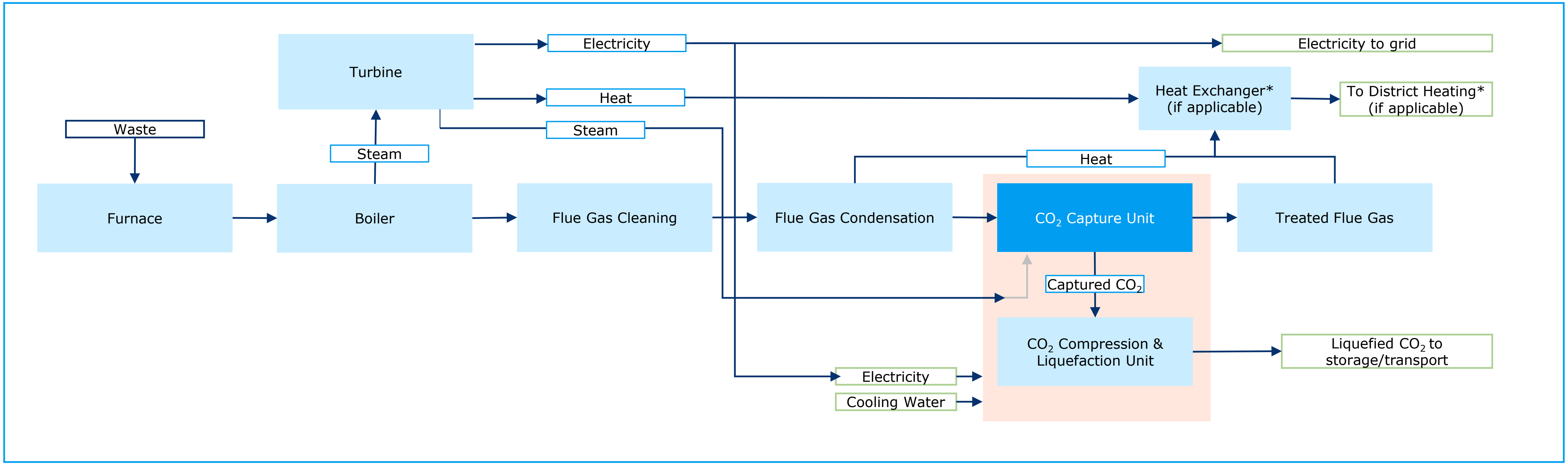
- A high energy requirement (in the form of steam) for the regeneration of the chemical solvents (i.e., amines) which causes a reduction in plant power/heat output

Key Conclusions

The compatibility and maturity of this technology make it the most suitable for biogenic CO_2 sourcing, even though it is energy intensive.

Waste-to-Energy plant retrofitted with carbon capture

Energy and CO_2 flows at a typical WtE with post combustion capture[1]



Source: [1]Adapted from Bisinella et al. (2021) "Environmental assessment of amending the Amager Bakke incineration plant in Copenhagen with carbon capture and storage"

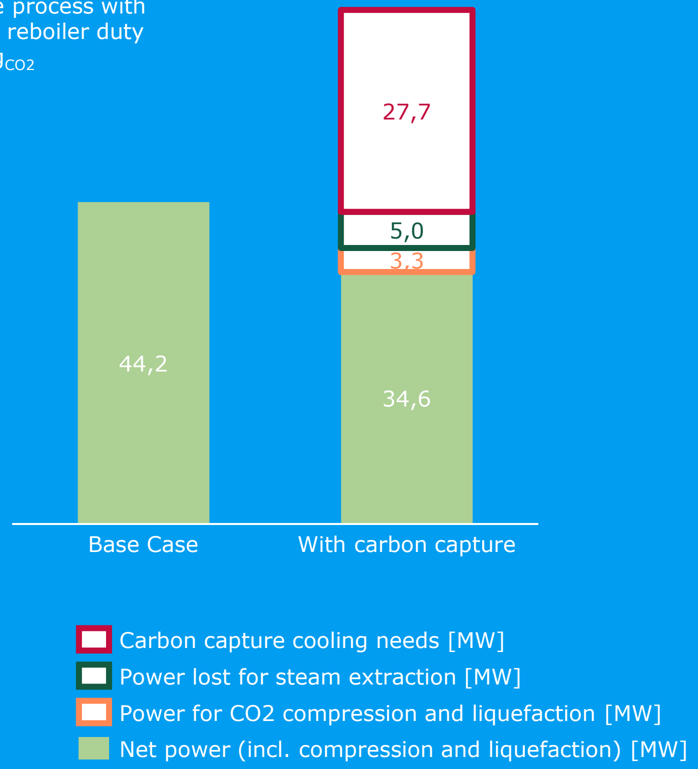
Waste-to-Energy plant with carbon capture

Impact of carbon capture integration on energy production at Pontiac WtE

Capturing 50% of the CO_2 emissions for the base case plant:

- Steam is used for the CC process, hence decreasing power production.
- Power is used to run the CC plant.
- Power is used for liquefaction and compression of CO_2 (assumed to -30°C and 17 bar).
- Additional cooling capacity is needed to reject heat from the CC plant, compression and liquefaction, and cooling of the flue gas before the absorber.

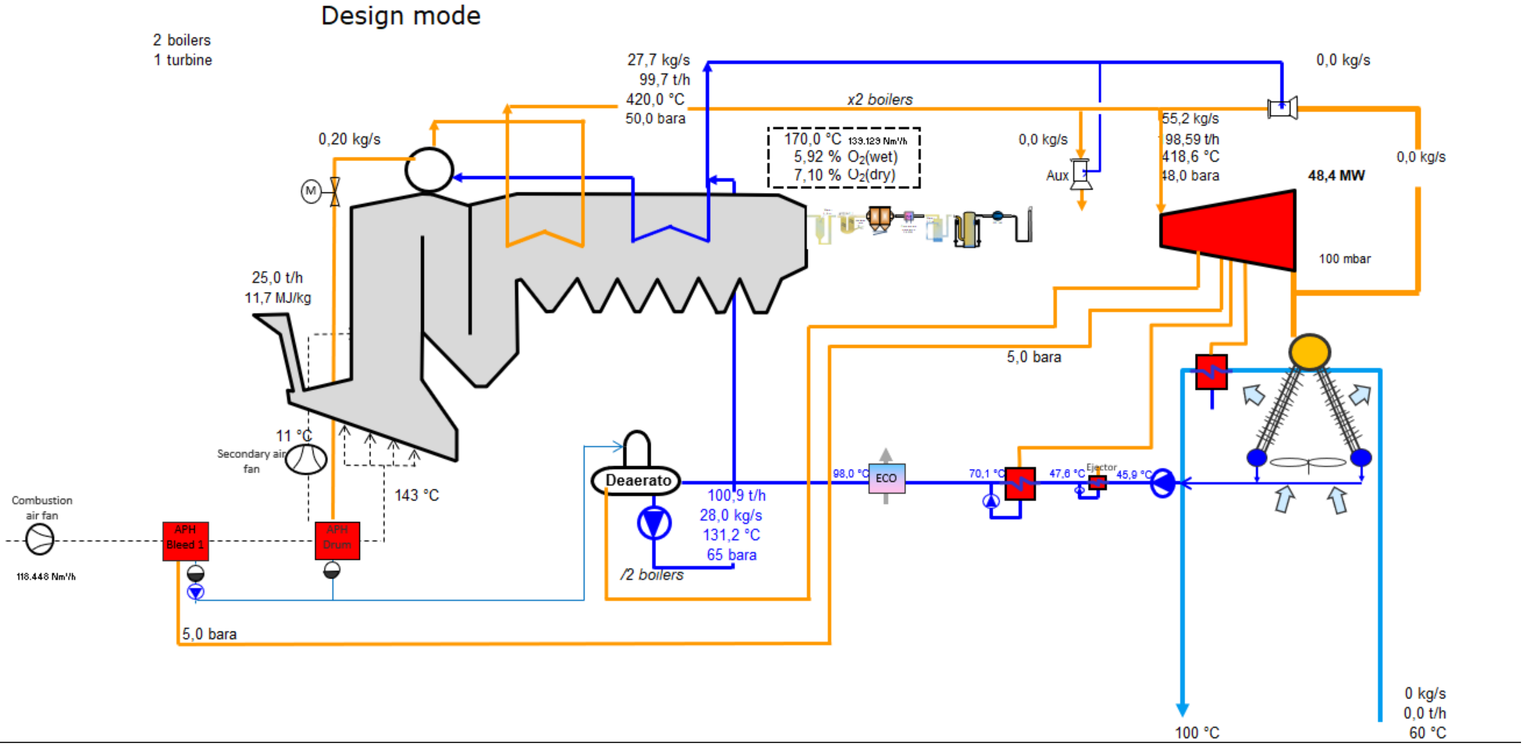
Due to the large amount of heat rejected, there is good synergy for plants exporting heat, e.g. for a district heating network.



Figures shown are based on an amine process with an assumed reboiler duty of 3.6 MJ/kg_{CO2}

Energy recovery: Process overview

Pontiac WtE



[Source: Ramboll]

Energy production

- Heat is transferred from the boiler to the water/steam cycle.
- The steam is expanded in a turbine to produce electricity.
- The turbine has several ports to bleed some of the steam (e.g. for condensate preheating and combustion air preheating).
- District heating can be supplied by a low-pressure bleed in the steam turbine with relatively low impact on the power production.

Energy recovery:
Heat and power production

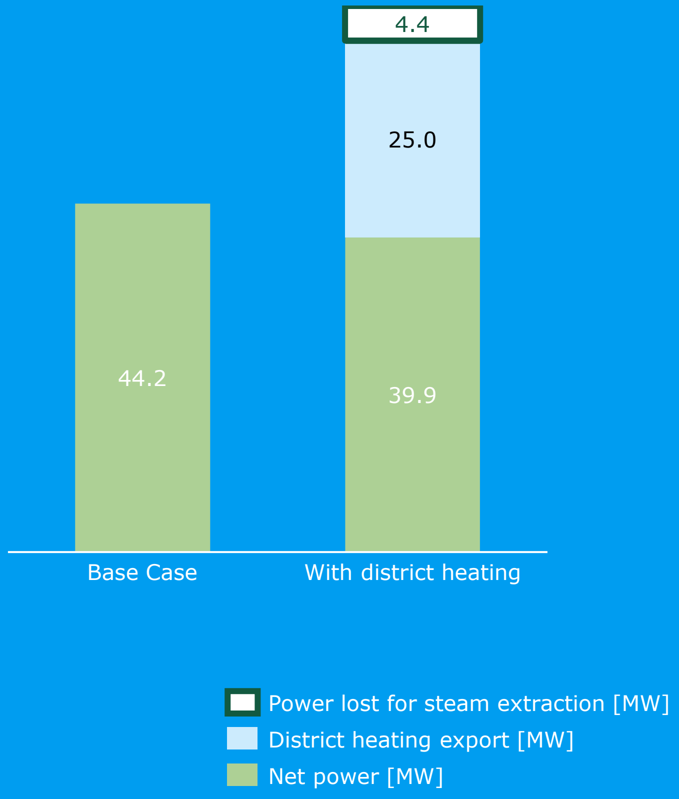
Potential for additional energy recovery systems:

- Water is added to the flue gas in the scrubber, cooling it down to its dew temperature.
- Introducing an economizer before the scrubber reduces the amount of water needed and makes it possible to recover part of the heat from the flue gas:
    - This heat can be employed for condensate preheating.
    - The availability of district heating consumers provides a very efficient alternative use case for the recovered heat.

Energy input and outputs summary for the base case scenario, with and without heat export

	Unit	Power only	Heat and Power
Waste input	t/y	400,000	400,000
Lower heating value	MJ/kg	11.7	11.7
Total energy input	MWth	162.5	162.5
Estimated end power output	MWel	44.2	39.9
District heating export	MWth	-	25.0 [1]

Power output comparison with district heating scenario



Notes: [1] Return/forward temperatures of 60/100°C - 5 bar turbine bleed

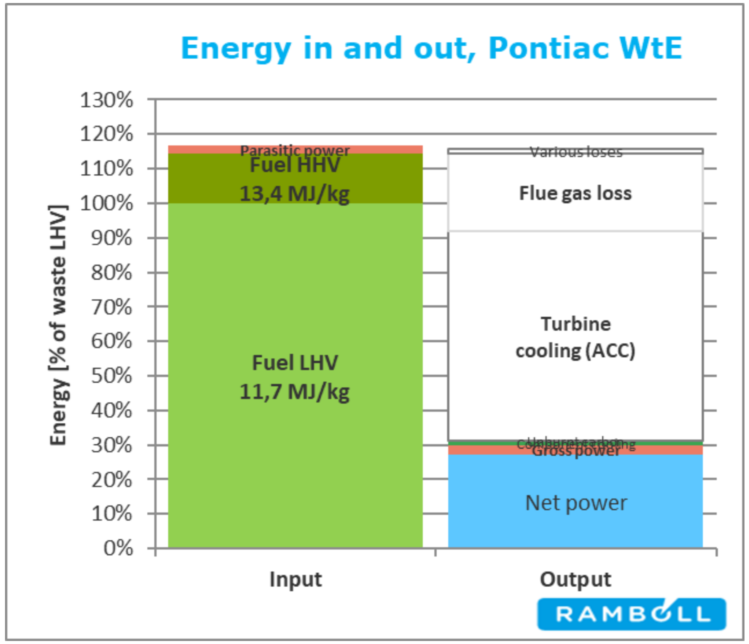
Energy recovery:
District heating network impact

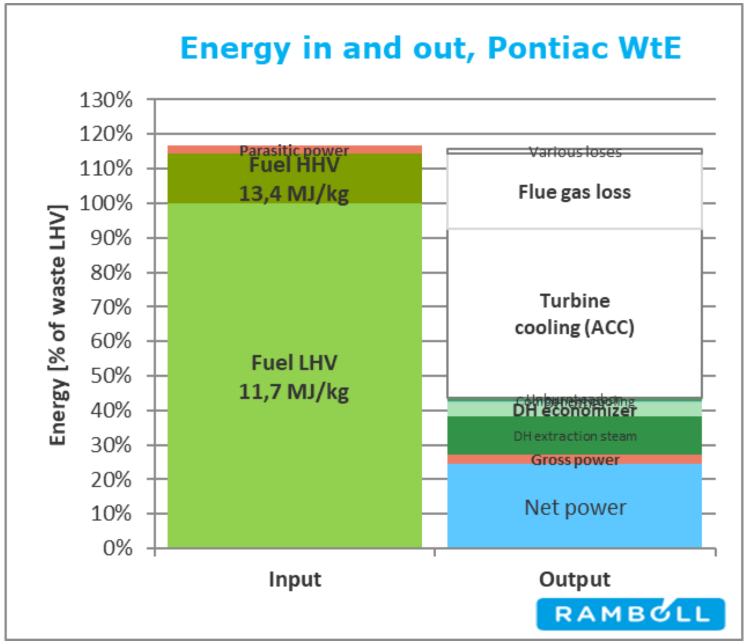
Availability of heat consumers in the area would have a prominent role in designing the plant

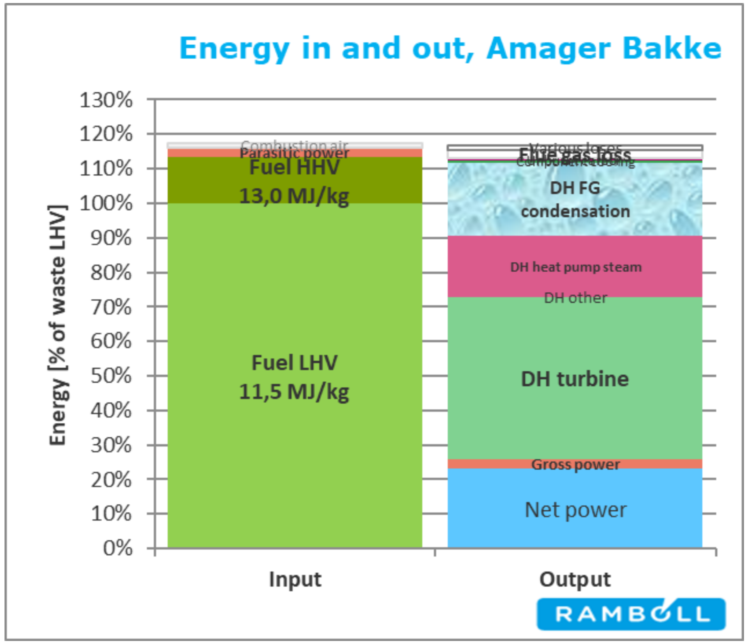
- A large district heating network capitalizes on the opportunity for very efficient utilization of the energy released during the waste incineration process.
- Integration of carbon capture rejects large amount of heat at low temperature, which can be recovered through district heating if such network is available. Below is illustrated how the energy is recovered in a power generating Pontiac WtE plant and in a situation where the plant deliver some energy to a local district energy system. For comparison is illustrated the plant in Copenhagen which has the most efficient district energy and is connected to the World's largest district energy system. It is not likely that such district energy system can be developed in Pontiac.

No District Heating

>70% output as District Heating







Energy recovery: District heating and carbon capture

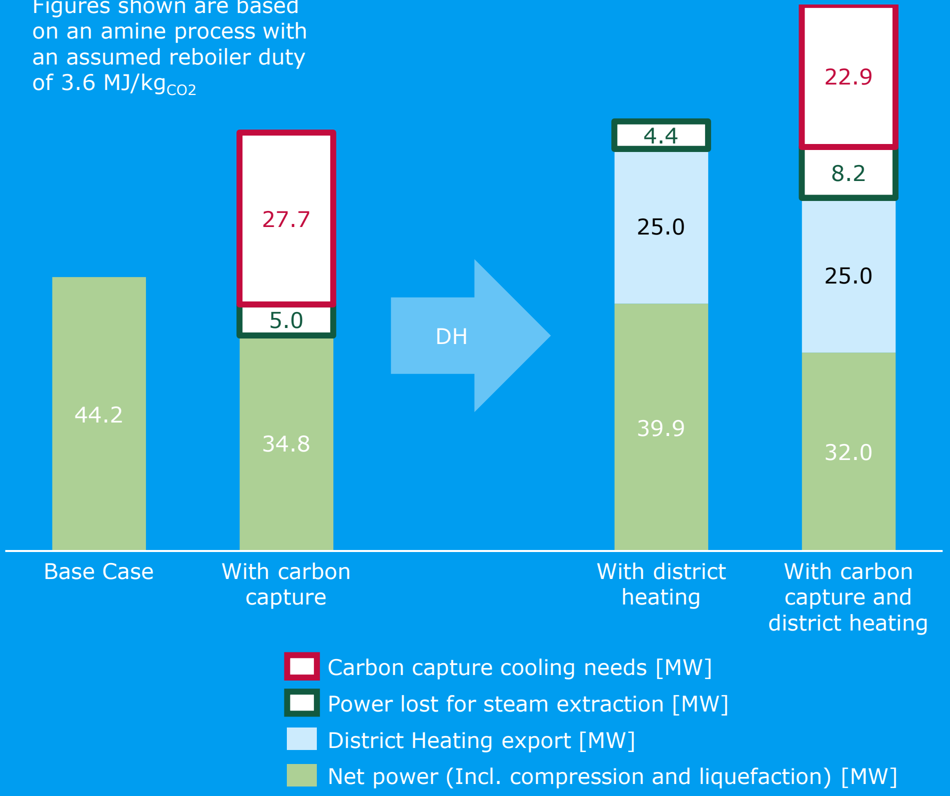
Key Takeaways

Lower penalty on power production due to Carbon Capture (CC) can be achieved when a combined use case with district heating is available:

- Part of the low-grade heat from the CC plant can be used to deliver district heating.
- As part of the heat is rejected this way, less heat needs to be taken away by coolers.
- Since part of the heat export is conducted by the CC plant, less steam is extracted from the turbine for heat production (e.g. the power lost due to steam extraction is lower than the sum of the cases with only DH and only CC)

Power output comparison with stand-alone and combined carbon capture and district heating scenarios

Figures shown are based on an amine process with an assumed reboiler duty of 3.6 MJ/kg$_{CO2}$

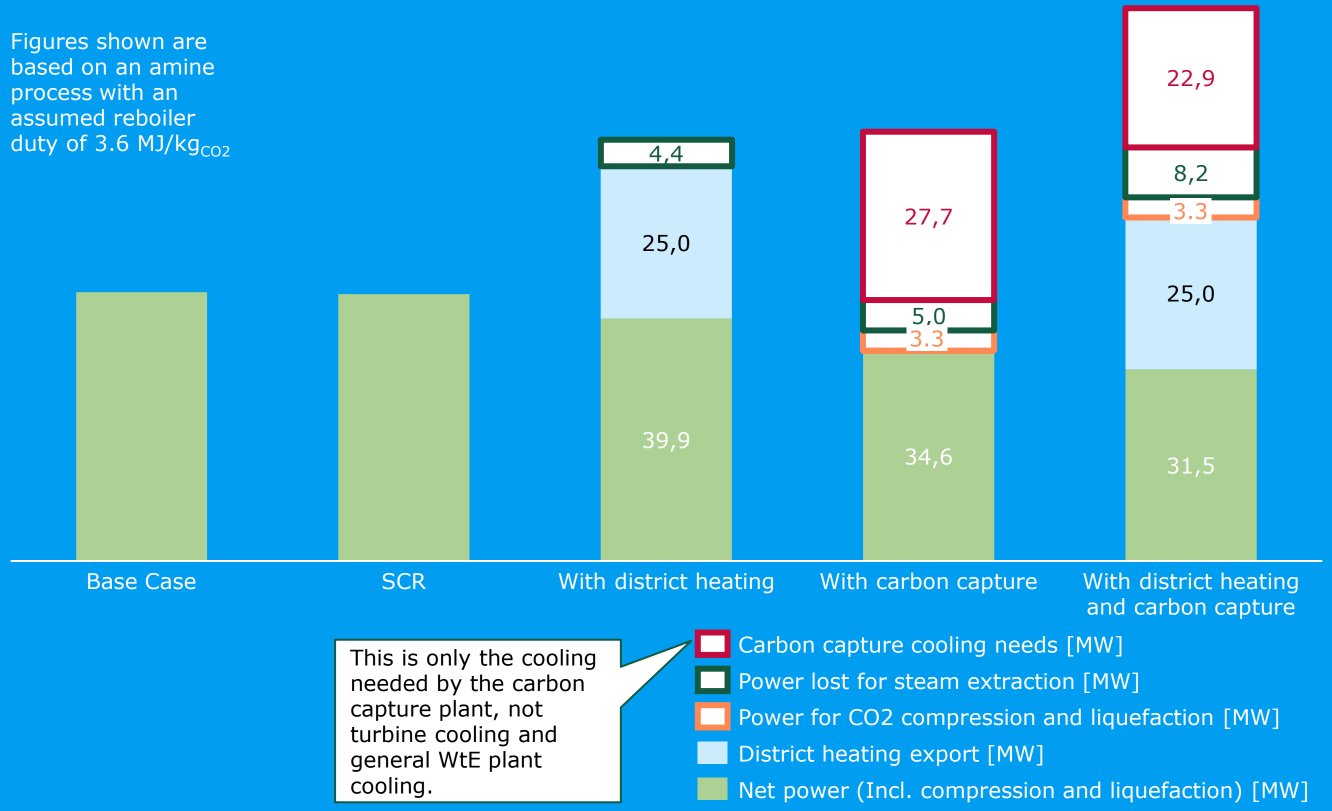


Review of scenario possibilities

Key takeaways

- From an energy recovery point of view, SNCR (base case) and SCR based systems perform similarly, with similar net power output values.
- Integration with a district heating network reduces the net power production but increases significantly the overall plant efficiency.
- The addition of a carbon capture system with capacity to capture 50% of the CO_2 emissions would decrease the power export significantly, depending on the specific technology employed, and require significant added cooling capacity.
- The combined integration of both carbon capture and district heating systems presents **optimized overall synergies**, reducing both power penalty and cooling required.

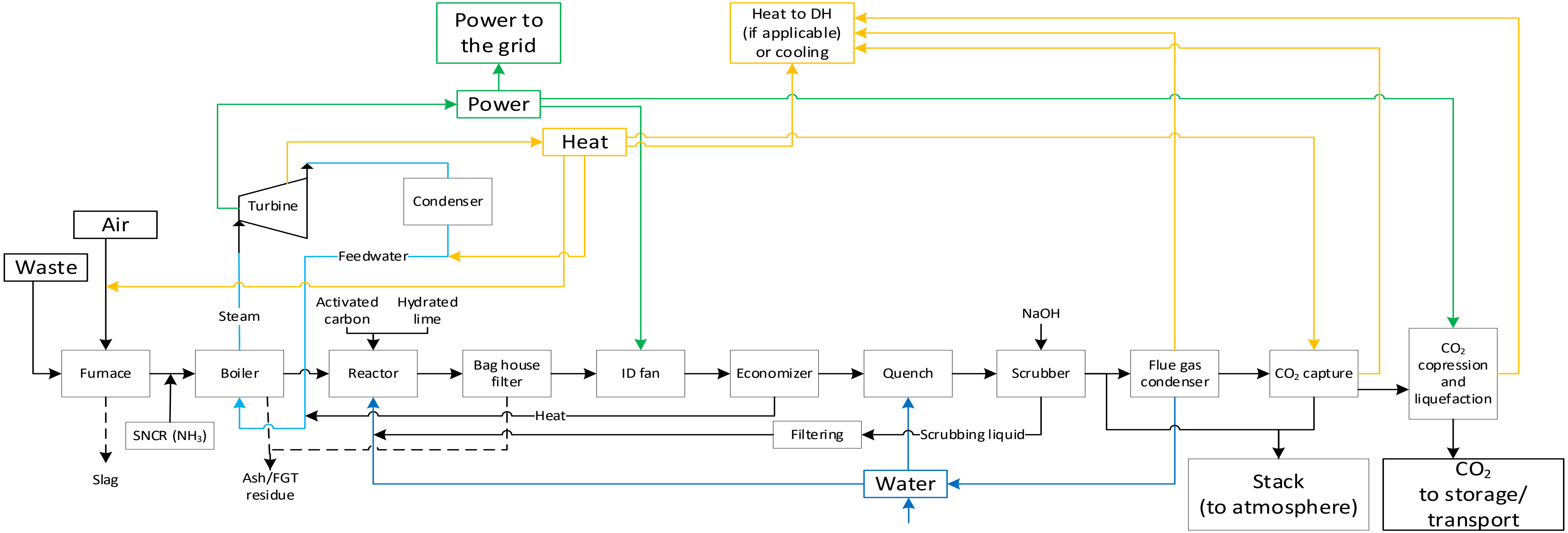
Comparative overview: Efficiency can be gained through combined heat and power production, which synergizes well with carbon capture integration.



Figures shown are based on an amine process with an assumed reboiler duty of 3.6 MJ/kg_{CO2}

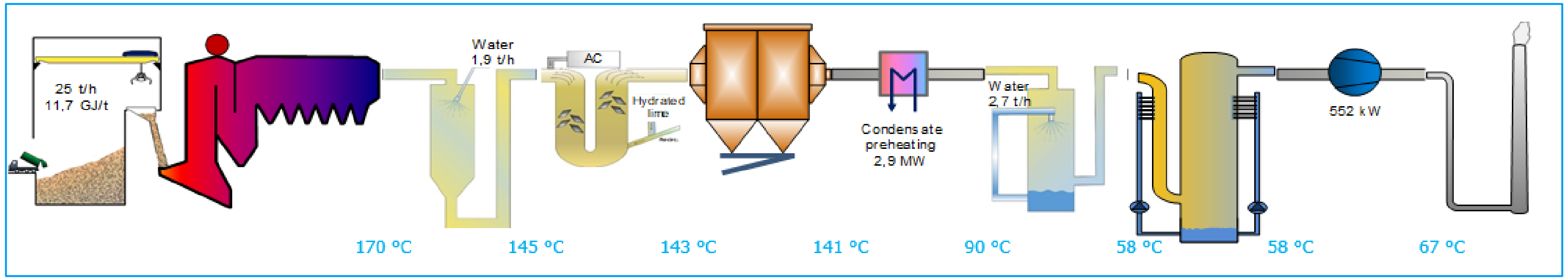
This is only the cooling needed by the carbon capture plant, not turbine cooling and general WtE plant cooling.

Ramboll proposed plant design



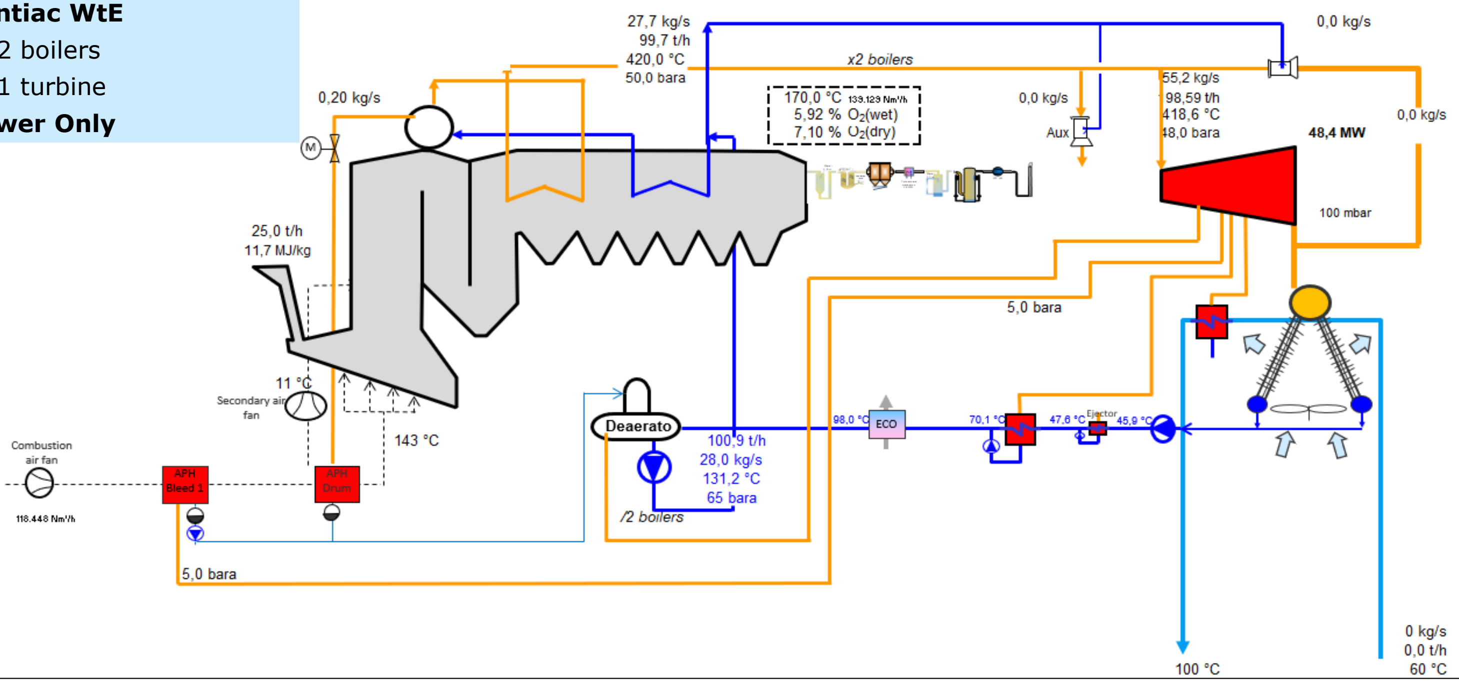
- Two line moving grate waste incineration boilers, with air preheating and SNCR system.
- Each line with its own semidry flue gas treatment with energy recovery and polishing scrubber.
- Single steam turbine for power production and heat supply to Carbon Capture plant and possible users.
- Flue gas condensation and Carbon Capture plant, with compression and liquefaction according to CO_2 supply chain.

Energy and mass balances: Power only scenario



Pontiac WtE
- 2 boilers
- 1 turbine

Power Only

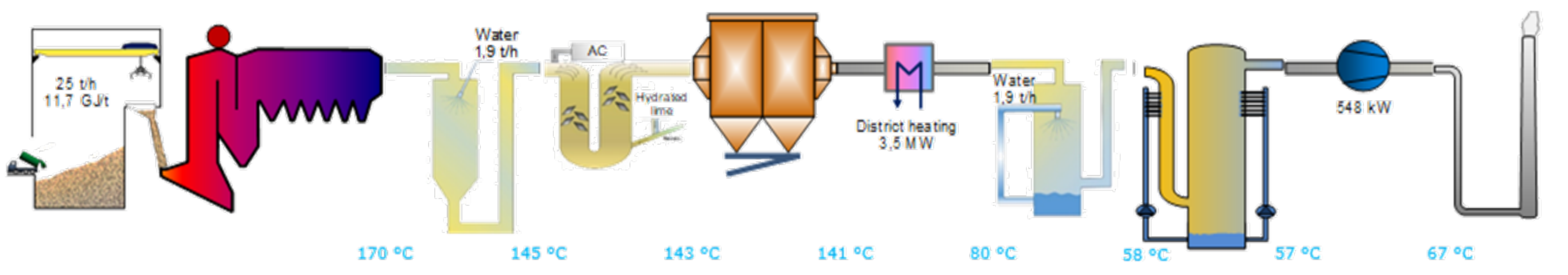


Inputs:
- Waste
- Combustion air
- Water
- Consumables, e.g. Ammonia, CaO, NaOH, Activated Carbon

Outputs
- Power (and/or heat)
- Ashes and FGT residue
- Flue gas (including CO_2)

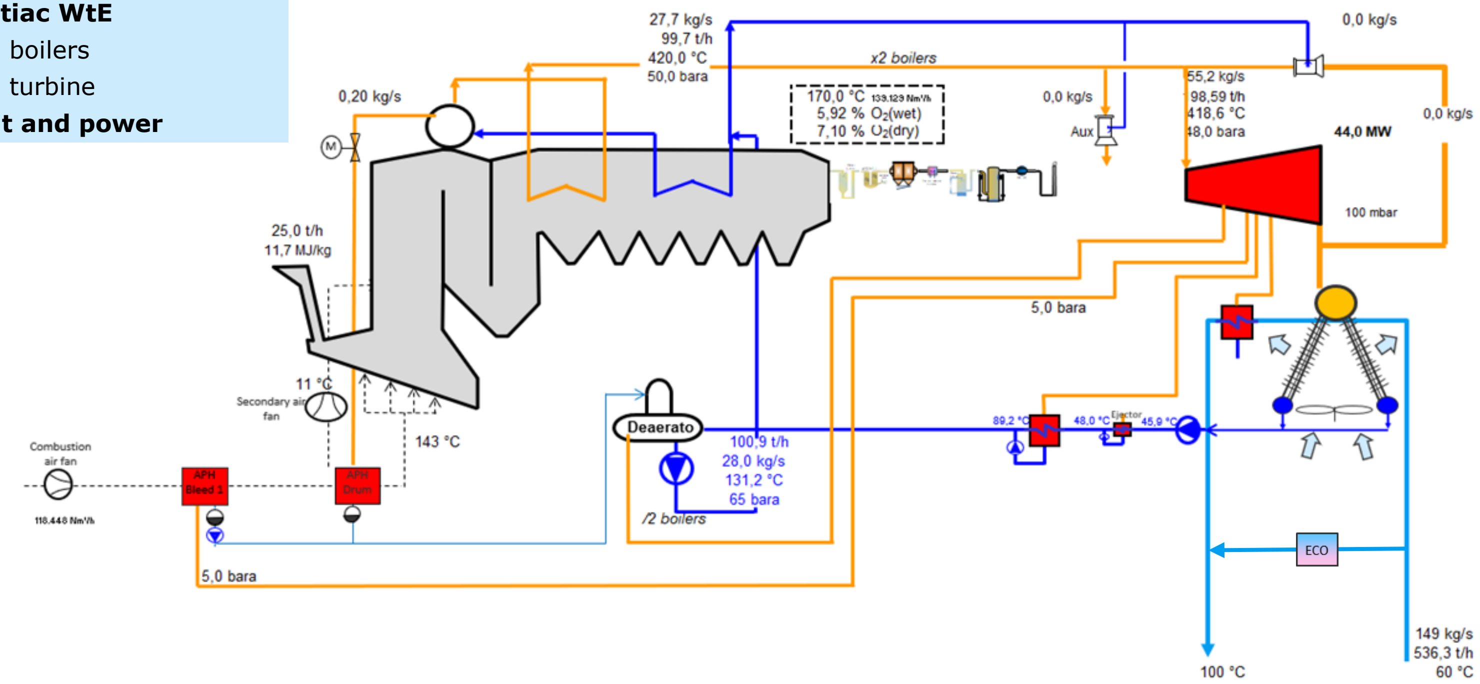
	Unit	Power only
Waste input	t/y	400000
Lower Heating Value	MJ/kg	11,7
Total Energy input	MWth	162,5
Gross power output	MWel	48,4
Net power output	MWel	44,2
District Heating export	MWth	-
Bottom ash (wet)	t/y	80000
Boiler ash	t/y	200
Residue from baghouse filter	t/y	13200
CO2 emissions	t/y	448000
Water consumption	t/h	12,4

Energy and mass balances: Heat and power scenario



Pontiac WtE
- 2 boilers
- 1 turbine

Heat and power

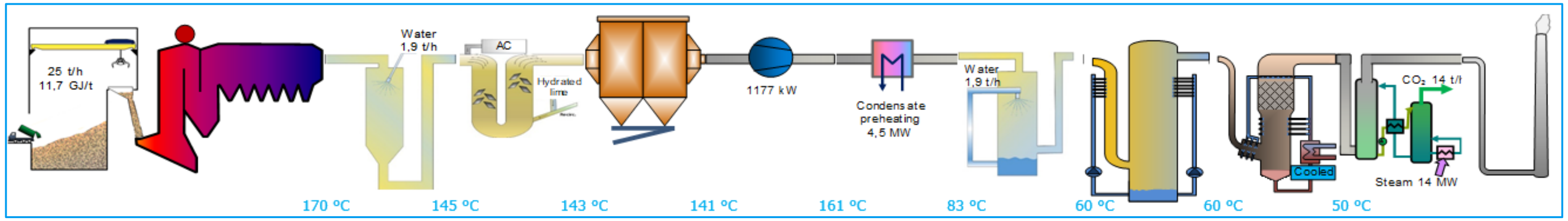


Inputs:
- Waste
- Combustion air
- Water
- Consumables, e.g. Ammonia, CaO, NaOH, Activated Carbon

Outputs
- Power (and/or heat)
- Ashes and FGT residue
- Flue gas (including CO_2)

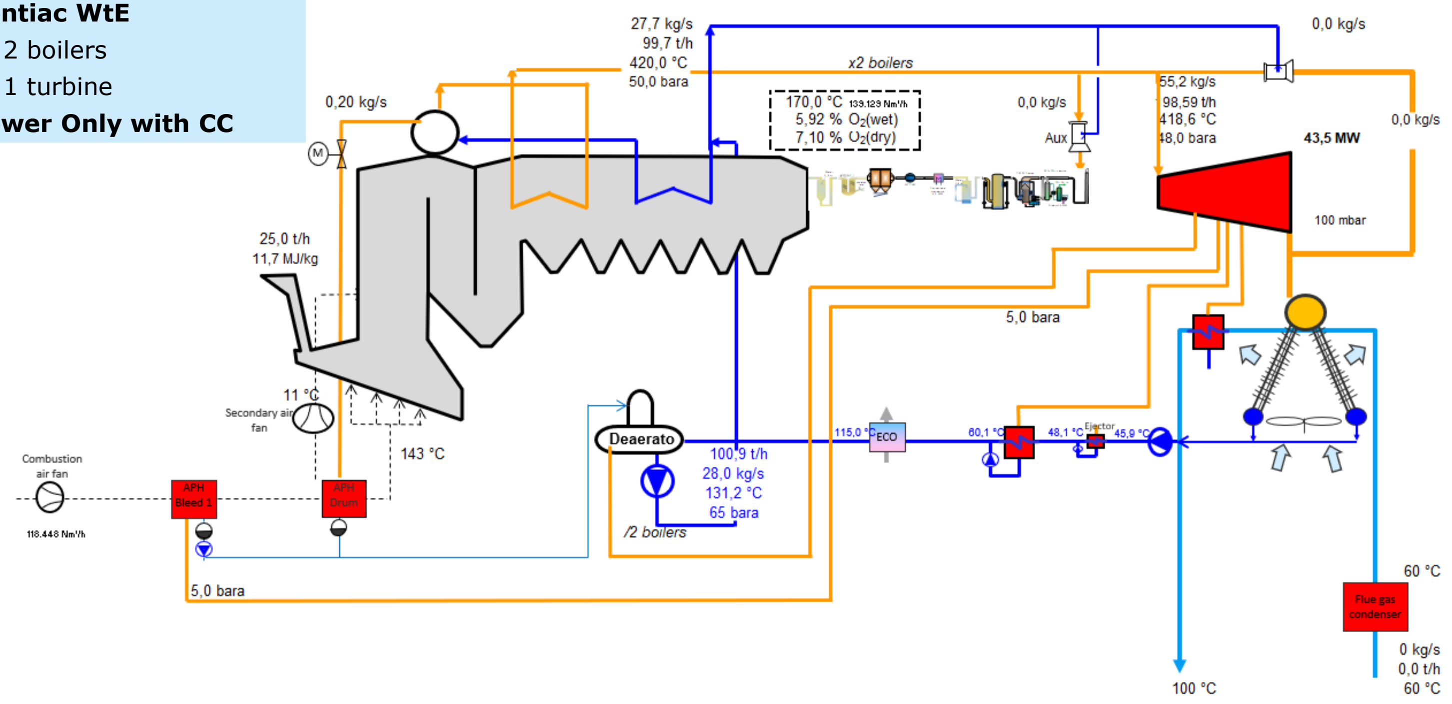
	Unit	Heat and Power
Waste input	t/y	400000
Lower Heating Value	MJ/kg	11,7
Total Energy input	MWth	162,5
Gross power output	MWel	44,0
Net power output	MWel	39,9
District Heating export	MWth	25,0
Bottom ash (wet)	t/y	80000
Boiler ash	t/y	2000
Residue from baghouse filter	t/y	13200
CO2 emissions	t/y	448000
Water consumption	t/h	10,8

Energy and mass balances: Power only with CC scenario



Pontiac WtE
- 2 boilers
- 1 turbine

Power Only with CC

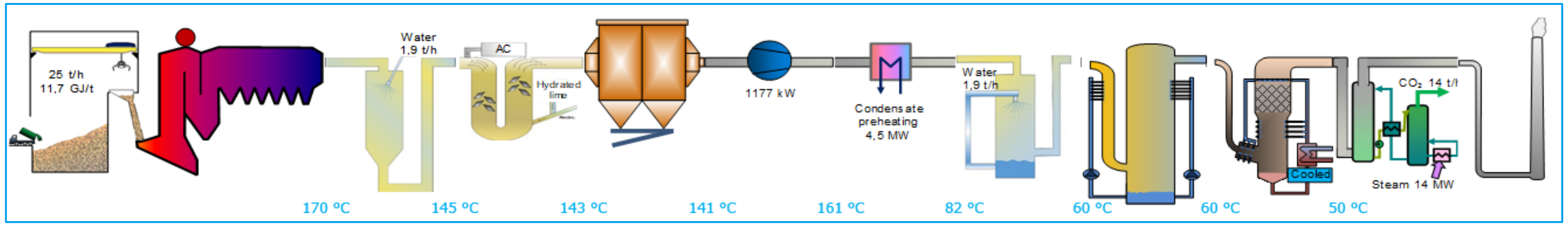


Inputs:
- Waste
- Combustion air
- Water
- Consumables, e.g. Ammonia, CaO, NaOH, Activated Carbon

Outputs
- Power (and/or heat)
- Ashes and FGT residue
- Flue gas (including CO_2)
- Captured CO_2

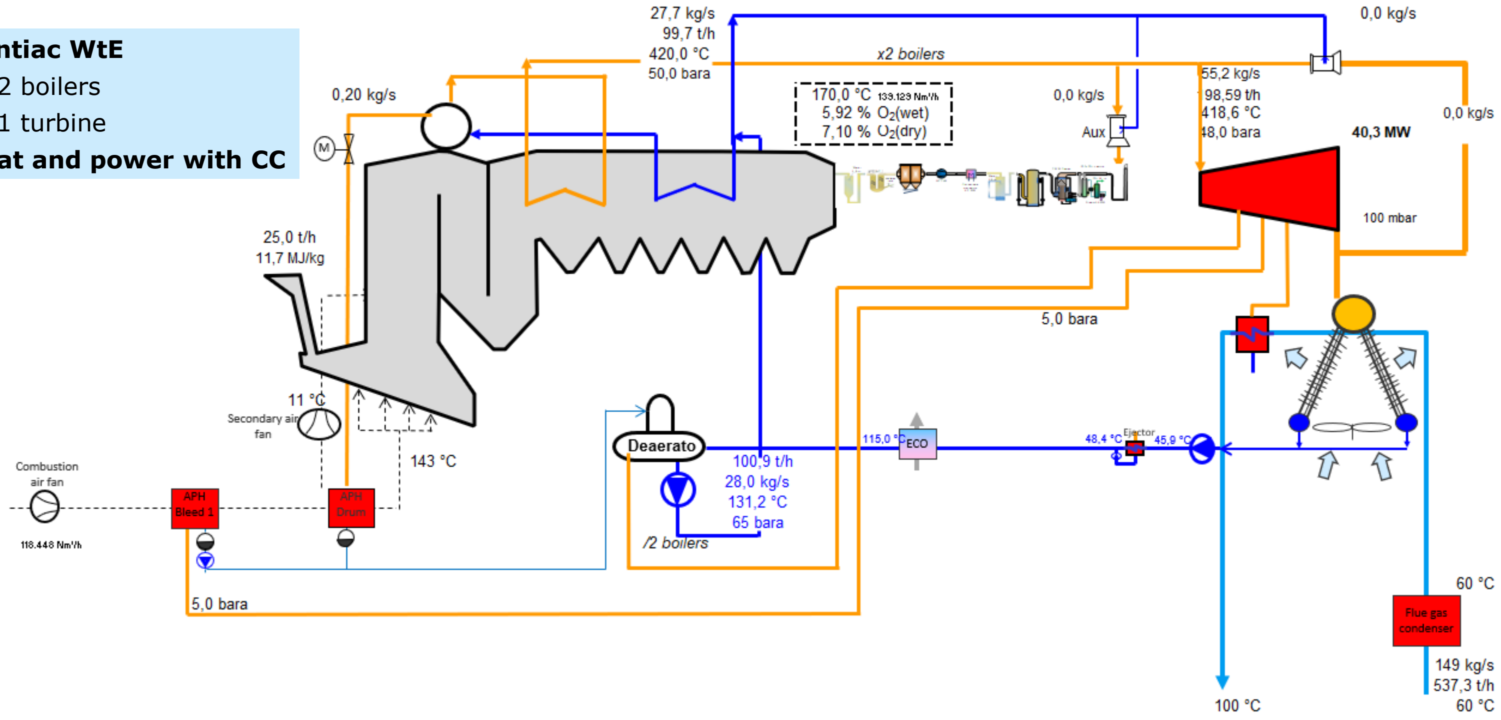
	Unit	Power only with CC
Waste input	t/y	400000
Lower Heating Value	MJ/kg	11,7
Total Energy input	MWth	162,5
Gross power output	MWel	43,0
Net power output	MWel	34,6
District Heating export	MWth	-
Bottom ash (wet)	t/y	80000
Boiler ash	t/y	2000
Residue from baghouse filter	t/y	13200
CO_2 emissions	t/y	224000
CO_2 captured	t/y	224000
Water consumption	t/h	1,0

Energy and mass balances: Heat and power with CC scenario



Pontiac WtE
- 2 boilers
- 1 turbine

Heat and power with CC



Inputs:
- Waste
- Combustion air
- Water
- Consumables, e.g. Ammonia, CaO, NaOH, Activated Carbon

Outputs
- Power (and/or heat)
- Ashes and FGT residue
- Flue gas (including CO_2)
- Captured CO_2

	Unit	Heat and Power with CC
Waste input	t/y	400000
Lower Heating Value	MJ/kg	11,7
Total Energy input	MWth	162,5
Gross power output	MWel	40,3
Net power output	MWel	31,5
District Heating export	MWth	25,0
Bottom ash (wet)	t/y	80000
Boiler ash	t/y	2000
Residue from baghouse filter	t/y	13200
CO_2 emissions	t/y	224000
CO_2 captured	t/y	224000
Water consumption	t/h	1,0

Residues from Waste Incineration

Management of WtE residues is very important as 1) the residues constitute a sizeable waste stream, 2) it involves high disposal costs for transport to and 'gate fee' at the landfill, 3) residues include hazardous waste, and 4) because the residues can be recycled as aggregate thereby maximizing sustainability of the waste management system

The majority of residues from waste incineration is made up of incineration bottom ash. This is classified as non-hazardous waste, typically disposed of at a sanitary landfill or recycled for construction aggregates:

- IBA for landfill typically will undergo removal of ferrous metal at the WtE plant by overhead magnets before transport to the landfill, where IBA can be used for cover materials and internal roads
- Recycling of IBA require maturation and sorting together with an extensive metal extraction, including removal of non-ferrous metals and - in few cases - extraction of rare metals (originating from electrical/ electronic waste). Recycling of IBA aggregate as course base layer material in road construction requires that a standard for the properties of IBA aggregates is adopted alongside other material standards used in construction

Fly ash and flue gas cleaning residue are classified as hazardous waste and typically will be landfilled at a hazardous waste facility after stabilization. Technologies for carbonization and aggregation of fly ash are available allowing this waste to be classified as non-hazardous waste or even used for recycling as aggregate in asphalt, but this is subject to regulatory approval in the jurisdiction of a WtE facility.

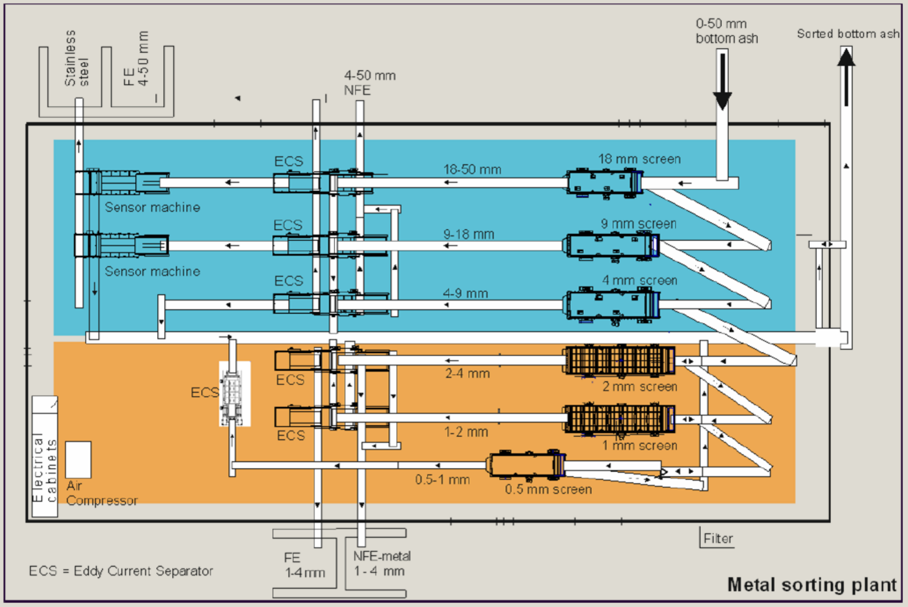
The estimated quantities of WtE residues from Ramboll's Ramsteam calculations are shown in the table below:

Residues amounts, approximate	t/y	kg/t_{WASTE}
Bottom ash, wet	80000	200
Boiler ash	2000	5
Fly ash and flue gas treatment residue	13200	33
Total	95200	238

WtE IBA aggregate used as sub-base material in road construction

Residues from waste incineration include the following residue types. Quantities will depend on waste types and the composition of the waste input (e.g. metals, inert waste and fines), waste that generates higher concentrations of contaminants in the flue gas, and the flue gas cleaning system employed:

- Grate sifting, which is material falling through the incineration grate, amounts to 0.2-0.5% of the waste input. This is usually fed into the incineration bottom ash (IBA)
- Boiler ash collected in the boiler/ economizer parts due to changes in velocity of the flue gas and settlement of ash particles. This is collected from the respective parts, and amounting to around 0.5% of the waste input
- Fly ash collected in dust filters, around 1-2% of the waste input
- Flue gas cleaning residue and reactants, around 1-2% of the waste input
- IBA discharged at the end of the incineration grate, around 90% of the waste ash content. Metals are discharged with IBA, for example:
  - 3% of the waste input as ferrous metal
  - 1% of waste input of non-ferrous metals
- The above amounts to around 15-25% in total.



Proposed plant layout

The proposed plant layout includes the facilities required to accommodate the 2 x 200,000 tpa lines, within an available land area of approximately 9 hectares.

The layout is based on the preliminary concept described above. The proposed layout present a logic process flow and will allow for safe and easy operation and maintenance.

The location of the carbon capture facility allows for a possible later add on, should the business case conclude the it is not financially feasible to establish this unit from the very beginning.

The internal traffic, incoming waste trucks, trucks for collection of incineration bottom ash and flue gas residues and private vehicles for operation staff and guests is preliminary considered in the proposed layout.

The layout confirm that the available site provides sufficient footprint for the preliminary plant design.

The layout, the architectural appearance of the plant and landscaping need to be further assessed during the next stage. For inspiration we have included examples of existing or planned WtE projects worldwide.

Amager Bakke, Copenhagen, Denmark

"The inter-municipal waste management company, I/S Amager Ressourcecenter, has built a new flagship WtE facility, Amager Bakke, replacing their existing WtE facility. The plant is operated by the municipal company. The new facility is world-class in both energy efficiency and environmental performance and the skiing slope and café on the roof available for the public.

The facility is located in the city center, close to neighbours, close to the opera house and the Queen's castle. The plant is an architectural beacon for the city.

Capacity: 560,000 tpa

Commissioning: 2018"

Perth, Australia

"

Avertas Energy is building Australia’s first large-scale waste-to-energy facility in Kwinana, south of Perth. The facility will consist of two Waste-to-Energy lines.

The project is tendered as a DBOO project based on a long term concession contract.

Capacity: 400,000 tpa, two lines

Commissioning: 2023

"

IWMF WtE, Singapore

"

An integrated waste management facility (IWMF) with a WtE capacity of 7,200 tpd, a food waste capacity of 400 tpd and a sorting facility with a capacity of 250 tpd is planned to be established in 2024. Co-location synergies with a new sewage water treatment plant are investigated.

An important part of the integrated facility is an education center where local citizens can visit and learn about waste management. High energy efficiency and low emission has been important design criteria

Capacity: 2,600,000 tpa (WtE)

Commissioning: 2024

"

Greater Male, Maldives

"

The Ministry of Environment of the Maldives have awarded the Design Build Operate (DBO) contract for building and operating a Waste to Energy facility for a 15-year period to Urbaser.

Currently all waste is disposed at landfill and the key driver for implementing WtE has been landfill diversion together with generation of renewable energy.

Capacity: 200,000 tpa

Commissioning: 2025

"

Argo, Roskilde, Denmark

"

ARGO has established a new waste-to-energy unit. The facility produces power and heat to the greater Copenhagen district heating network. The challenging architectural design stands as a second landmark for the city of Roskilde after the city's grand cathedral.

The colour of the lighting can be changed – the orange on the picture matches an annual music festival taking place next to the plant and having the biggest scene called 'Orange Scene'.

Capacity: 200,000 tpa

Commissioning: 2013

"

NLWA, London, UK

"North London Waste Authority (NLWA) is planning to build a state-of-the-art Energy Recovery Facility (ERF) at the Edmonton EcoPark to replace an existing waste to energy facility that is reaching the end of its operational life after more than 50 years serving the local community.

The project is tendered as a BDO contract. Low emission, high power efficiency, large combustion units have been focus areas together with an attractive and affordable architecture.

Capacity: 700,000 tpa

Commissioning: 2027"

CAPEX – base case including carbon capture

Item	%	CAD M
Furnace/ Boiler System	25%	138
Turbine/ Generator/ ACC	7%	39
Flue Gas Treatment System	11%	61
Control Monitoring System (CMS)	2%	11
Electrical Key Installations	5%	28
Common Systems (Cranes, CCTV, etc.)	5%	28
Plant for Treatment of Combustion Ashes	3%	17
Balance of Plant	8%	44
Wear & Spare Parts	2%	11
Design, Documentation, Commissioning etc. (EPC scope)	5%	28
Civil Works and Buildings	24%	132
Transmission Power Connection	3%	17
Sub-Total WtE, EPC Contract Price		***550***
Carbon Capture Plant		200
Sub-Total WtE with Carbon Capture Plant		***750***
Project Development Cost & Miscellaneous Costs	10%	75
Total Project Costs		**825**

The investment estimate is based on similar WtE projects. The technology for WtE is based on international technology providers and local work forces construction and civil work.

The budget is based on the high level conceptual design and thus corresponding to AACE class 5 cost estimate.

The budget will be further detailed during the next stage. The current market is very volatile and the supply chain has been disrupted due to the international conflicts and the COVID19 in 2020-2022.

The cost level for civil works in Canada has shown a very high price level and the procurement strategy should be carefully assessed in order to keep the civil works at an acceptable level.

OPEX – base case with/without carbon capture

With carbon capture	**%**	**CAD**
Staffing		8.000.000
Average maintenance costs		20.625.000
Consumables		6.000.000
Landfill of incineration bottom ash		4.480.000
Landfill of flue gas residues		2.400.000
Sale of recovered metals		- 2.080.000
Insurance		2.800.000
Permitting and utilities		900.000
Sub-Total		***43.125.000***
O&M costs carbon capture		10.800.000
Sub-Total		***53.925.000***
Miscellaneous OPEX	10%	5.392.500
Total OPEX		**59.317.500**
Income from power sale		**22.176.000**

Without carbon capture	**%**	**CAD**
Staffing		8.000.000
Average maintenance costs		15.125.000
Consumables		6.000.000
Landfill of incineration bottom ash		4.480.000
Landfill of flue gas residues		2.400.000
Sale of recovered metals		- 2.080.000
Insurance		2.000.000
Permitting and utilities		700.000
Sub-Total		***36.625.000***
O&M costs carbon capture		**-**
Sub-Total		***36.625.000***
Miscellaneous OPEX	10%	3.662.500
Total		**40.287.500**
		28.320.000

The operational and maintenance cost is based on Ramboll's estimates and based on similar projects worldwide and using where possible unit costs from WtE projects in Canada.

The OPEX estimates will be further detailed during the next stage of the project.

As illustrated to the left the generation of power and thus the income from sale of energy will be significantly reduced in case of carbon capture. It should be noticed that the carbon capture is based on capturing the fossil based CO$_2$. Since biogenic CO$_2$ is considered climate neutral.

In the case that also biogenic CO$_2$ should be captured and hereby make the WtE facility carbon negative both CAPEX and OPEX will be significantly increased as well as the income from sale of energy will be significantly reduced. The cost calculation is not linear since there is an exponential increase should the last 10-15% CO$_2$ need to be captured.

The Carbon Impact of WtE versus Landfilling

- In addition to the technical and financial impact also the CO_2 emission is impacted by implementing WtE instead of landfill which takes place today.
- The WtE and carbon capture solution is based on the above technical descriptions.
- The comparison is based on:
  - WtE with power generation for treatment of 400,000 t/y (base case above)
  - Sanitary landfill for 400,000 t/y with bottom lining, leachate collection, landfill gas collection and utilization of the gas for power generation
- WtE is higher in the waste hierarchy than landfill of waste, but landfill of waste is still taking place in Canada, like in USA and in some member states of the European Union. Hence, the comparison is important
- Transport of waste is usually longer for landfills, and may involve several modes of transport such as trucking in semi-trailers, railway transfer, river barge transport and combinations hereof. Therefore, the comparison of the two scenarios takes into account a slightly longer transport for the landfill solution.

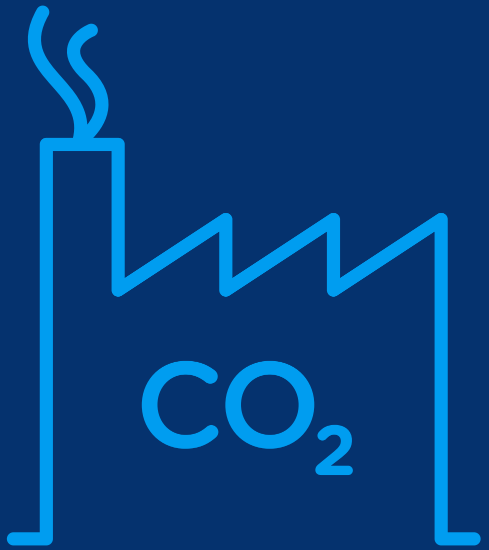
Large Power Generation Plant Operating on Landfill Gas (MSW Landfill in Buenos Aires)

Environmental Concern

- The key concern in the comparison is that landfill gas is rich in methane, which is a potent greenhouse gas counting 84 times that of CO_2 over a period of 20 years. The landfill gas may be used for power generation, however the efficiency is depending on how efficient the gas collection is done and is generally difficult to control due to the reasons mentioned below:
    - Methane is generated from anaerobic conditions in a waste layer, so primarily from compacted waste layers (immediate and careful compaction of waste is a practical ‘best landfill practice’)
    - Landfill gas generated in open cells will be released to the atmosphere until a cell is covered and the gas collection system is established
    - Landfill management aims to keep operational cells small, and a landfill is developed in multiple cells horizontally and vertically up to its final filling height. Hence, efficient collection of landfill gas require temporary gas collection in cells closed temporarily
    - Landfill gas collection systems are not fully efficient in the gas collection and, again, landfill gas and methane therefore will escape to the atmosphere from gas circumventing gas extraction pipes and pipe leaks.

The Carbon Impact of WtE

- The emissions from WtE are calculated as the sum of direct emissions and upstream emissions
- Direct impacts include the emission of CO_2 per ton of waste (403 kg CO_2) and minor impacts from methane (0.5 kg CO_{2e}) from waste storage and N_2O (1.6 kg CO_{2e}) from combustion of nitrogen in MSW and flue gas treatment
- Indirect emissions include consumables such as production of lime, ammonia and activated carbon (15 kg CO_{2e})
- The sum of direct and indirect emissions equal **420 kg of CO_{2e}** per ton of waste (only the fossil CO_2 emission is counted for, since the biogenic part is considered carbon neutral
- The offset emissions from the alternative production of outputs:
    - The substitute power production that is offset by the power generation from the WtE plant. For Pontiac, the life cycle emission from hydro power shall be used. Hydro power has an emission factor of 2-24 kg CO_{2e}/MWh, assumed as 20 kg CO_{2e}/MWh. The emission factor is highly dependent on the assumed energy mix, for example, the emission factor is 73 kg CO_{2e} per MWh for combined cycle gas turbine.
    - The net energy production from WtE is 884 kWh electricity per ton of waste combusted
    - Metals: ore extraction and processing that is offset by the metals recovered from combustion bottom ash (CBA) from the WtE plant
- The total offset from the WtE is the sum of the offsets from power (18 kg CO_{2e}), and IBA metals (39 kg CO_{2e}) and amounts to **57 kg CO_{2e}** per ton of waste, noting that the energy mix for production of substituted power is decisive for the result
- Hence, for WtE the total net emission calculates to **363 kg of CO_{2e}** per ton of waste
    - As an example, with substitute power production as combined cycle gas turbine, the offsets from power will be 330 kg CO_{2e} changing the impact of WtE to 51 kg of CO_{2e} per ton of waste
- With carbon capture installed, the CO_2-emission from WtE will reduce by 322 kg of CO_{2e} corresponding to a conservative capture rate of 80%. It can be argued that the contribution from substitute power production would remain largely unchanged at 18 kg CO_{2e} for hydropower electricity generation. Hence, the saving in CO_2 emission will be **41 kg of CO_{2e}** per ton of waste combusted. As example, the CO_2 emission will be **-271 kg of CO_{2e}** per ton of waste combusted with substitution of power generation from natural gas, and carbon capture at the WtE facility.



- As waste is combusted in the WtE plant, all of the carbon (biogenic and fossil) is **converted to CO_2**
- As a general **rule of thumb**, approximately one ton of CO_2 is emitted when one ton of waste is combusted
- As per the IPCC convention, only fossil CO_2 is considered to be derived from fossil fuels and counted towards global warming impacts
- Approximately **40% of the carbon input** is considered fossil and included in the CO_{2e} inventory
- **Emissions** are well controlled and understood in a WtE plant

Carbon Emissions from Landfills

The Carbon Impact of Landfilling

- Landfill gas produced will contain a mix of methane and carbon dioxide, approximately in a ratio of 1:1 by volume
- Approximately 50% of the landfill gas, and therefore 50% of methane by mass, is captured and burned. Some 5% will be oxidized to CO_2 before it is released into the atmosphere. The remaining 45% of the methane is released into the atmosphere without little or no control, including as diffuse channels
- The total of emissions and offset can be calculated to 2,175 kg of CO_{2e} per ton of waste using the multiplication factor of 84 for methane at 24 kg of CH_4 per ton of waste. It is here considered that 53 kg of CH_4 per ton of waste is contained in generated landfill gas of which 13 kg of CH_4 per ton of waste is used for power production resulting in offset CO_{2e} emission of 1.5 kg of CH_4 per ton of waste based on the emission factor for hydropower. 53 kg of methane in landfill gas is combusted with an emission of 2.7 kg of CO_{2e} per one kilo of methane giving a total emission of 143 kg of CO_{2e}
- The extra waste transport contributes 17.5 kg of CO_{2e} per ton of waste
- (Hence, 2,175 calculates as 2,016 +143 -1.5 + 17.5).

The Resulting Carbon Impact

- Hence, the WtE solution is better by 1,812 kg of CO_{2e} per ton of waste compared to sanitary landfill. As an example, this increases to 1,951 kg of CO_{2e} per ton of waste when substituting power generation from hydropower with power generated from natural gas.
- With carbon capture, the above reductions of CO_2 emissions will increase to 2,134 and 2,281 kg of CO_{2e} per ton of waste respectively
- Landfill may act as a sink for organic carbon (sequestration) estimated at 392 kg of CO_{2e} per ton of waste. If included, it would reduce the positive impact of the WtE facility with this number
- The recognized conclusions of the comparison are:
    - Significantly more low carbon energy is produced at the WtE plant compared to the landfill
    - Large global warming impacts can be avoided when diverting waste from landfill to WtE
- In case the district heating output from the WtE facility is also utilized, there will be also offset of emissions from heat production. This is counteracted by somewhat lower power production at the WtE facility. If the substituted heat generation is from a natural gas fired boiler (emission factor 236 kg CO_{2e}/MWh), this would result in an additional sink of around 60 kg of CO_{2e} per ton of waste, so further reducing the carbon emissions.
- The negative carbon impact of the landfill operation ranges from approximately 950 to 3,650 kg of CO_{2e} per ton of waste (compared with 2,175 kg of CO_{2e} in the adopted base case) when varying the landfill gas capture rate from 75% to 10% corresponding to a range from 'best case' to 'worst case' landfill operation. Seeing such wide spectrum in the actual operation of landfills is not unrealistic, for example as a result of using large working cells, slow pace in temporary and final covering of cells with gas extraction, and leaking pipe network/ poor efficiency in extracting landfill gas due to movement of gas in waste layers and settlements in layers
- The carbon impact from transportation is relatively modest, often around one percent of the impact of landfilling. Long transportation to remote landfills is more related to issues of costs, waste loading interfaces and traffic congestion.

Carbon Capture, Storage & Utilization

Carbon Capture

- The combustion of municipal solid waste releases CO_2, of which about 60% is of biogenic origin and therefore is considered CO_2-neutral. The remaining 40% is of fossil origin, mainly plastics, and thus contributes negatively to the climate balance
- As a rule of thumb, the combustion of one ton of municipal waste, releases about one ton of CO_2 (fossil and non-fossil CO_2)
- At this conceptual level an amine solution is considered
- A capture efficiency of CO_2 at 85-90% is assumed.

Carbon Storage & Utilization

- There are basically two options for the further treatment of CO_2:
- The first option is to transport the CO_2 into underground reservoirs. This method is often referred to as CCS, Carbon Capture and Storage. Underground reservoirs are typically depleted oil and gas fields onshore or offshore with suitable geological formations. CO_2 is already used in enhanced oil recovery and shale oil operations
- Another possibility is the use of CO_2, for example to produce synthetic fuels – a method often referred to as Carbon Capture and Utilization (CCU). Here, the CO_2 is in a catalytic process with hydrogen (H_2). This process is called Power-to-X (P2X).

Carbon Storage and Energy

The table below shows the approximate energy requirement for CO_2 capture of waste to energy plant for a capacity of 400,000 tpa waste.

Energy requirement for CO_2 – capture	**Quantity**	**Unit**
Power		
Power demand CO_2 capture per ton of CO_2	0.047	MWh_{el}/ton CO_2
Power requirement CO_2 compression per ton of CO_2	0.12	MWh_{el}/ton CO_2
Additional in-house requirements of the plant (400,000 tpa) in normal operation	4.6	MW_{el}
Heat demand (extraction steam 3.5 bar)		
Steam demand per ton of CO_2	1.0	MWh_{th}/ton CO_2
Steam requirement of CO_2 separation (400,000 tpa) in normal operation	28.0	MW_{el}

Energy Requirement for CO_2 Capture at a 400,000 tpa WtE Plant

- As presented under the technical section CO_2 capture system requires a considerable amount of electricity and steam which is supplied from the WtE plant.
- The electricity requirement consists of the requirements of the CO_2 separation (pumps, blowers, etc.) and the power consumption of the CO_2 compressors. The latter account for the largest part of the electricity.
- The energy consumption is mentioned in the technical section.
- The heat is typically supplied to the desorber as low-pressure steam (approx. 3.5 bar, 120 ^{o}C). In order to remove the CO_2 from the solvent, a heat requirement of about 1 MWh per ton of CO_2 is required.
- Part of the heat requirement can be recovered as district heating if such system exists.

Summary of CO_2 Emissions

CO_{2e} emissions from WtE (kg of CO_{2e} per ton of waste Combusted)	WtE, no Carbon Capture	WtE with Carbon Capture
Substituting Power from WtE with Hydropower (Base case)	363	41
Substituting Power from WtE with Combined Cycle Gas Turbine	51	-271

CO_{2e} emissions from Landfill of Waste Compared to WtE (kg of CO_{2e} per ton of Waste Landfilled or Combusted)	WtE, no Carbon Capture	WtE with Carbon Capture
Substituting Power from WtE with Hydropower (Base case)	1,812	2,509
Substituting Power from WtE with Combined Cycle Gas Turbine	2,134	2,281

In conclusion regarding CO_2 emissions:

WtE is significantly better than landfill of waste in terms of least carbon emissions. Furthermore, at the next level:

- The energy mix used for production of substituting power is significant for the CO_{2e} emission from WtE itself, but would seem having marginal impact for the comparison with landfill of waste
- Carbon Capture is significant for the CO_{2e} emission from WtE itself, but would seem having marginal impact for the comparison with landfill of waste