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DIPLOMARBEIT

State-of-the-art and comparison of
incineration and gasification of residues and waste

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs
unter der Leitung von

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(Veronika Wilk)

Danksagung

Corpus omne perseverare in statu suo quiescendi

vel movendi uniformiter in directum,

nisi quatenus illud a viribus impressis cogitur

statum suum mutare.

Ein Körper verharrt im Zustand der Ruhe

oder der gleichförmigen Translation,

sofern er nicht durch einwirkende Kräfte

zur Änderung seines Zustands gezwungen wird.

(Isaak Newton: Philosophiae naturalis principia mathematica)

Kurzbeschreibung

In der Europäischen Union fällt von Jahr zu Jahr mehr Müll an, der entsorgt werden muss. Da es eine gesetzliche Verpflichtung gibt, Müll vor der endgültigen Deponierung zu behandeln, gewinnt die thermische Nutzung von Rest- und Abfallstoffen immer mehr an Bedeutung.

In dieser Arbeit werden zwei thermische Abfallnutzungsverfahren, Müllverbrennung und Müllvergasung, verglichen. Dazu wird der Stand der Technik beider Technologien erhoben und zusammengefasst. Der Vergleich zeigt die Stärken und Schwächen der beiden Verfahren und zukünftige Potentiale.

Müllverbrennung ist das wichtigste thermische Verfahren zur Abfallbehandlung und ist in Europa Stand der Technik. Dabei werden Schadstoffe sicher zerstört und der thermische Energieinhalt des Mülls kann genutzt werden. Eine Müllverbrennungsanlage besteht aus einer Feuerung, in der Müll verbrannt und die chemisch gebundene Energie als Wärme freigesetzt wird. Das heiße Abgas gibt die Wärme an das Wasser in den Heizflächen im Dampferzeuger ab. Die Energie, die im Abfall gespeichert war, kann zur Heißwasser-, Dampf- oder Stromerzeugung verwendet werden. Das Rauchgas muss anschließend gereinigt werden. In der trockenen Rauchgasreinigung wird Staub und Flugasche abgeschieden. HCl und HF werden im sauren Wäscher abgetrennt, im basischen Wäscher reagiert SO_2 zu Gips. In der katalytischen Rauchgasreinigung werden Dioxine und Furane zerstört und NOx Emissionen verringert. Durch die Müllverbrennung wird das Reststoffvolumen, das deponiert werden muss, auf ein Zehntel reduziert.

Der zweite thermische Verwertungsweg für Rest- und Abfallstoffe ist die Müllvergasung. Dabei werden aus kohlenstoffhaltigen Stoffen brennbare Gase durch die Reaktion mit dem Vergasungsmittel erzeugt. Durch die Erzeugung eines Gases kann nicht nur der thermische Energieinhalt des Abfalls genutzt werden, es eröffnen sich auch neue Anwendungsmöglichkeiten. Das Gas kann in einem konventionellen Dampfprozess zu Strom und Wärme umgesetzt werden, aber auch in Gasmotoren oder Gasturbinen mit höherem Wirkungsgrad verstromt werden. In einem Gas- und Dampfprozess kann das heiße Abgas der Gasturbine in einem Abhitzekessel nochmals zur Strom- und Wärmegewinnung verwendet werden. Nach weiteren Gasreinigungsschritten kann das Gas auch in chemischen Synthesen eingesetzt werden, um so daraus flüssige Treibstoffe, synthetisches Erdgas oder andere Chemikalien herzustellen.

Es wurden in der Vergangenheit verschiedene Müllvergasungsprozesse entwickelt, die aber auf Grund von technischen und/oder wirtschaftlichen Problemen wieder eingestellt wurden. Auf dem Gebiet der Biomassevergasung jedoch wurde in den letzten Jahrzehnten intensiv geforscht und die Vergasungstechnologie dadurch deutlich weiterentwickelt. Der Wirbelschichtvergaser in Güssing ist eines der erfolgreichen Beispiele dafür. Diese Technologie steht nun am Sprung zur Kommerzialisierung.

In Anbetracht dieser Entwicklungen gibt es nun sicherlich großes Potential für die Müllvergasung. Die Entwicklung eines neuen Müllvergasungsprozesses, basierend auf den Erkenntnissen der Biomassevergasung, wird Gegenstand weiterer Forschungsarbeiten sein.

Abstract

More and more waste is generated every year, which has to be disposed. There is a legal obligation to treat waste before it can be landfilled in the European Union. Thus, thermal waste treatment is a very important issue.

In this work two pathways of thermal waste treatment, incineration and gasification, are compared. For this purpose, literature on both technologies has been reviewed and the state-of-art technology for waste incineration and gasification is presented. The comparison highlights the strengths and weaknesses of both technologies and identifies future potentials.

In Europe waste incineration is the state-of-the-art technology ensuring destruction of the pollutants and allowing recovery of the energy content of the waste. A waste incineration plant consists of a furnace, where the waste is incinerated and the chemically bonded energy of the waste is discharged as heat. The hot flue gases pass the heat to the water in the heating surfaces of the steam generator. The energy of the waste can be used for the generation of hot water, steam of electrical power. Then the flue gas has to be cleaned in the air pollution control system. Dust is precipitated, HCl and HF is removed in an acid scrubber and SO_2 in an alkaline scrubber. A catalytic reaction destroys dioxins and furans and reduces the emissions of NOx. Due to waste incineration the volume of the residues, which have to be landfilled, is reduced by 90%.

The second pathway of thermal waste treatment is waste gasification, where solid carbonaceous materials are converted into combustible gases by reaction with gasification agents. Due to gas production, not only the energy content of the waste can be recovered but the product range is extended. The producer gas can be converted into heat and power in a conventional steam boiler but also combusted in gas engines or turbines with higher efficiencies. In a combined cycle plant the hot exhaust gas of the turbine can be used in a heat recovery steam generator to increase the efficiency even more. After further cleaning the producer gas is also a suitable feedstock for synthesis of liquid fuels, synthetic natural gas and other chemicals.

Waste gasification processes have been developed in the past, but the plants have been shut down because of economic reasons and/or technical problems. However, important research has been done in the field of biomass gasification and thus gasification technology has been improved markedly. The fluidised bed gasifier in Güssing is one of the most successful examples; this technology is about to be commercialised.

Considering these developments, there is definitely interesting potential for waste gasification now and the design of a new waste gasification process based on the findings in biomass gasification will be the scope of future research work.

Contents

Figures

Tables

Abbreviations and symbols

MSW	municipal solid waste
APC	air pollution control
ESP	electrostatic precipitator
NOx	nitrogen oxides
SCR	selective catalytic reduction
SNCR	selective non-catalytic reduction
PCDD	polychlorinated dibenzodioxins
PCDF	polychlorinated dibenzofurans
TCDD	2,3,7,8-tetrachlorodibenzodioxin (Seveso dioxin)
TEQ	toxicity equivalent quantities
AC	activated carbon
FB	fluidised bed
BGBl	Bundesgesetzblatt (federal law gazette)
TOC	total organic carbon
R1, D10	classification of waste treatment according to the Waste Framework Directive
RDF	refuse derived fuels
EUP	EBARA-Ube process
PTIFG	pressurised twin-internally circulating fluidised bed gasifier
BGL	British Gas Lurgi
DEA	diethylamine
MDEA	N-methyl-diethanolamine
MTBE	methyl-tert-butylether
SNG	synthetic natural gas

LCV	lower calorific value	MJ/kg, MJ/Nm³
Nm³	standard volume at 273.15 K and 101 325 Pa	m³
λ	excess air ratio	-
η	efficiency	-
ΔH	enthalpy of reaction	kJ/mol
α	ratio of moles of NH_3 and moles of NOx	-
E	energy	GJ

Subscripts

B	boiler
el,g	gross electrical efficiency
el,n	net electrical efficiency
th	thermal
CG	cold gas
HG	hot gas
P	annual energy produced
F	annual energy input
i	additional imported energy
W	energy content of the waste

1 Introduction

Thermal waste treatment is gaining markedly in importance nowadays as more and more waste is generated every year, which has to be treated or disposed. In Europe a large percentage of waste is valorised in the form of electricity and heat. In North America, however, there are only few thermal treatment facilities; the major part of the waste is still being landfilled, which is about to change in the years to come.

In Europe waste incineration is the most common technology of thermal waste treatment. In contrast to that, waste gasification has been taken into consideration in North America too and several gasification processes have been presented in the past. Because of the heterogeneous nature of waste only fluidised bed gasifiers and rotary kilns are suitable therefore. In terms of fluidised bed gasification Austria is among the leading countries in Europe. Two gasifiers using biomass as feedstock with a nominal capacity of 10-20 MW are already operating; three more plants are under construction and will be commissioned in the next two years.

The scope of this diploma thesis is to evaluate the two pathways of thermal waste treatment. The state of the art of waste incineration and gasification is investigated and presented. It is taken as a basis to compare the two technologies and to highlight the strengths and weaknesses of the different processes.

2 Thermal waste treatment

2.1   Waste as fuel

Any substance or object the holder discards, intends to discard or is required to discard is waste under the European Waste Framework Directive. [12]

Waste is an inhomogeneous fuel with varying composition depending on its origin. There are household wastes, industrial wastes, hazardous wastes, commercial wastes, etc.

Household waste is generated by household activities, including food preparation, cleaning, fuel burning, old clothes, and packaging, newspaper and garden wastes. Three different categories of household waste can be distinguished. A part of the waste is collected separately in order to be recycled, such as paper, glass, metals and plastics. Old furniture, obsolete utensils and equipment are bulky wastes because of size and shape. They are also collected separately. The remaining part of household waste is generally referred as municipal solid waste (MSW).

Industrial waste is a very general term as the composition of industrial waste depends on the kind of industries involved. Apart from components comparable to household and commercial waste, hazardous chemical substances can be found there. Hazardous waste has to be collected and treated separately. [57]

Commercial waste comprises waste from shops, offices, restaurants and similar commercial establishments. It mainly consists of packaging, office supplies and food wastes. [57]

According to the Directive 2000/76/EC of the European Parliament and of the Council on the incineration of waste, commercial, industrial and institutional wastes are also considered as mixed municipal solid waste, if the nature and composition is similar to waste from households. [11]

Other waste streams are street sweepings, which mainly contain dust, construction and demolition waste and excavated soil.

2.1.1   Municipal solid waste

Austria

58 million tons of waste were generated in Austria in 2007. In Figure 2.1 the different origins of waste are illustrated. The major part is excavated soil, which is explained by an increased number of building sites of the national railway company in 2007. Household wastes represent 6% or 4 million tons of the total amount of waste in Austria. [67]
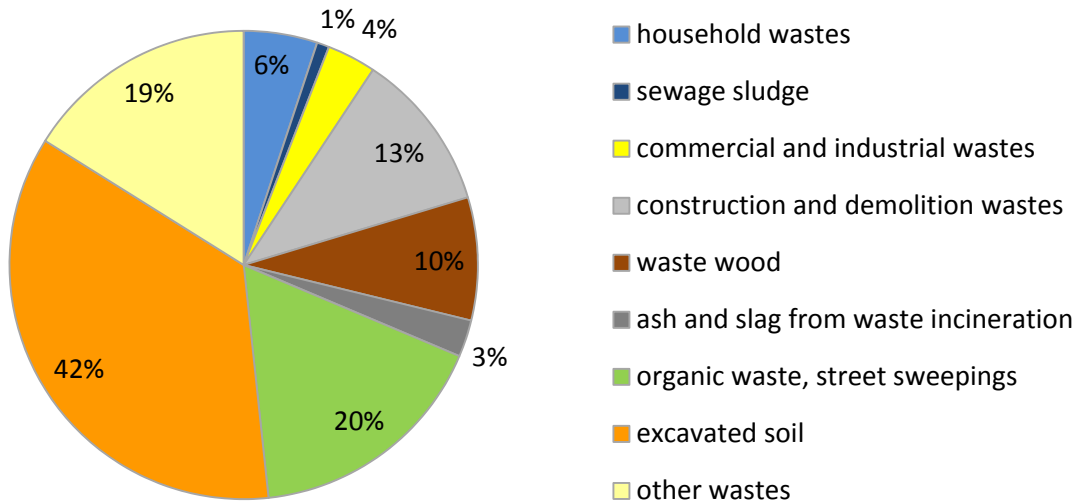
Figure 2.1: Waste in Austria in 2007 characterised in respect to fuel, adapted [67]

In the last three years the amount of household wastes has increased by 9%. This is due to the fact, that the population has augmented and the number of people living together in a household is reduced. The increasing demand for convenience and disposable products generates more and more waste. Because of the partly low bulk density of household waste, a volume of 28 million m³ has to be treated. [67]

Household waste consists of municipal solid waste and waste, which is collected separately in order to be recycled and reused, such as paper, glass, metals and plastics. Municipal solid waste represents about 40% of household waste and is mainly composed of organic waste, paper and cardboards, toiletries and plastics. Figure 2.2 shows the shares of the different species of waste.
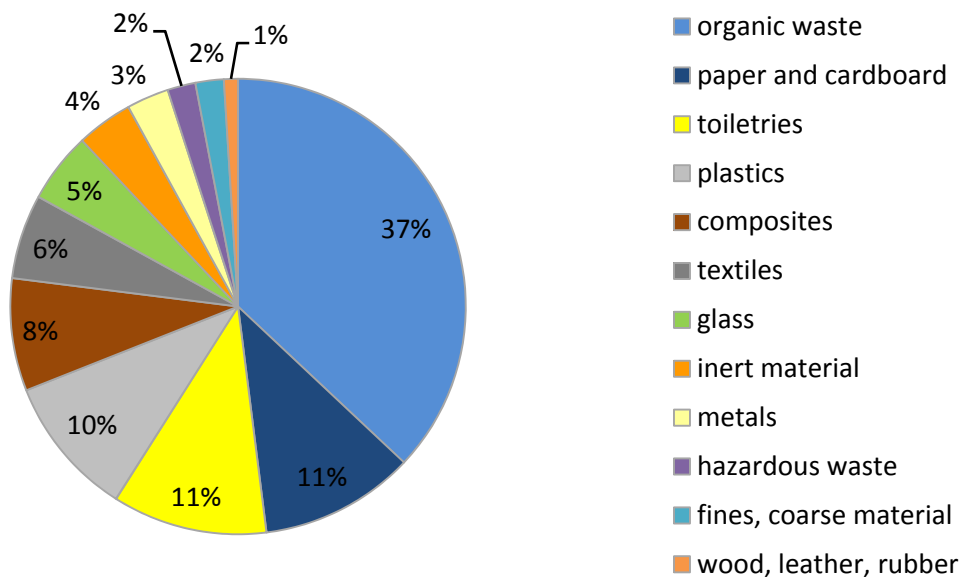
Figure 2.2: Municipal solid waste in Austria 2007, adapted [67]

Organic and hazardous wastes are also part of household wastes. In Figure 2.3 treatment of all those household waste streams is illustrated.
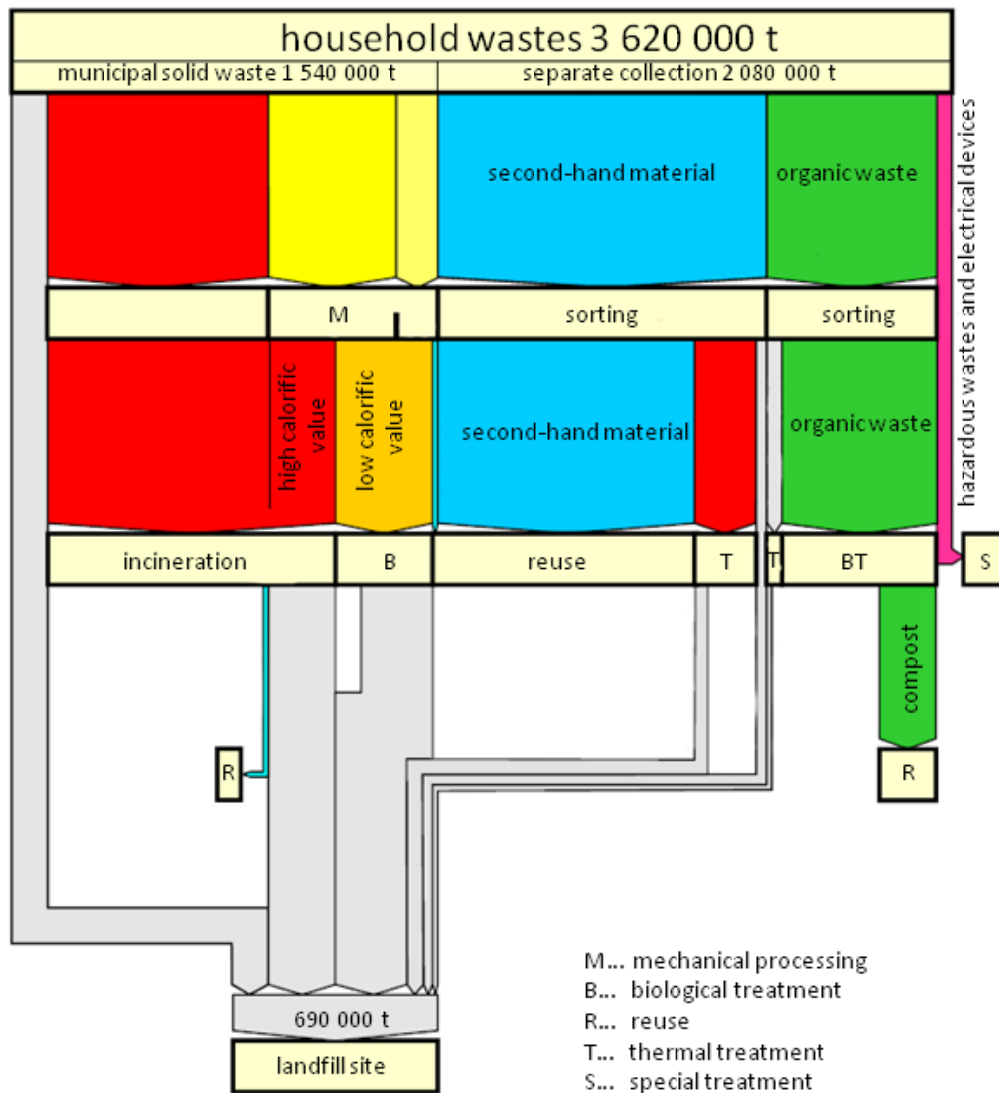
Figure 2.3: Treatment of household waste in Austria, adapted [67]

The main disposal routes for household wastes are waste incineration, mechanical-biological processing, sorting, and biological processing. 31% of household waste are treated thermally, which corresponds to 70% of MSW. A part of the residues of mechanical processing is also incinerated. 36% of waste generated by household activities are recycled and reused and only 3% are landfilled without being treated. [67]

Generation of waste in the European Union

In the European Union households and businesses produced 2011 million tons of waste in 2006. In Figure 2.4 the intensity of the blue colour indicates the amount of waste per person and year in 2007. In the map a west-east divide is visible. The average value for the European Union is 522 kg of waste per year and per inhabitant. Every Austrian generates 597 kg of waste per year, which exceeds the average value. The amount of waste per person correlates with prosperity but is also influenced by tourism and density of population. [18]
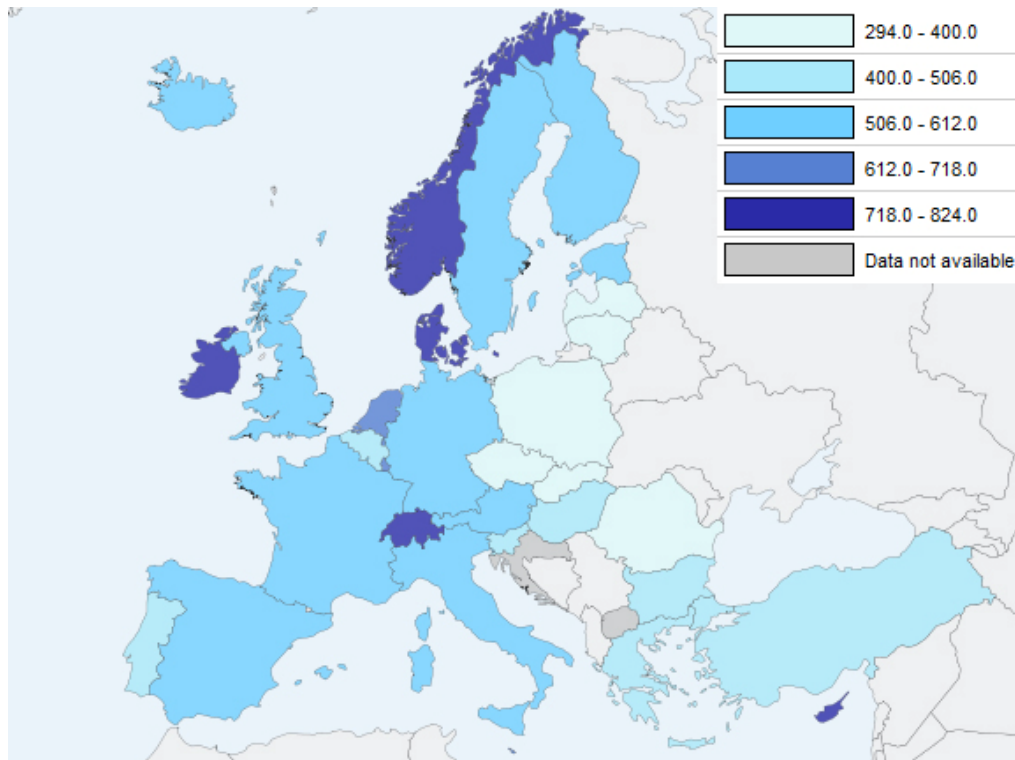
Figure 2.4: Kg waste per capita per year in the European Union 2007, [18]

The pathways of waste treatment differ in the European Union. Eurostat provides data on the amount of waste incinerated and landfilled per person and year. The rest of the waste is recycled, composted or treated in another way. On European average 19% of municipal waste are incinerated and 41% are dumped. Denmark is the leading country in waste incineration attaining a value of 53% if the ratio per inhabitant is taken into account. In Austria, Belgium, Germany, Netherlands, Luxembourg, France and Sweden 30% and more of the waste are incinerated. In contrast to that, landfilling is the major way of waste treatment in Rumania, Bulgaria, Poland and Greece. [18]

The west-east divide is highlighted in Figure 2.5, where the energy production from renewable solid waste is shown. The green column represents the primary electricity production in kilotons of oil equivalent (ktoe) and the red one the gross electricity production in GWh. Part of the waste is considered to be renewable, for example paper, food residues and waste wood. Thus, the renewable share of energy production by waste incineration depends on the composition of waste. If the renewable content is not measured, the International Energy Agency IEA recommends a 50% share. In 2007 14 TWh of renewable electricity were generated from waste in the European Union. [16]
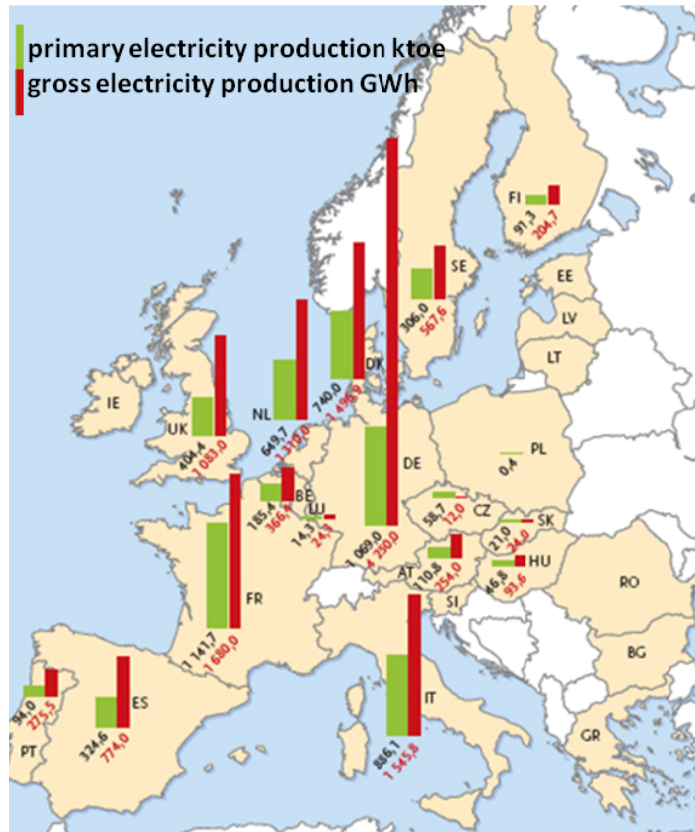
Figure 2.5: Energy production from renewable MSW in the EU 2007, adapted [16]

2.1.2 Industrial wastes

In industrial processes raw material is transformed into products. As the conversion is not complete, there are always undesired products (residues). After the recycling of the residues waste, which has to be treated, remains. The generation of waste in industrial processes is illustrated in Figure 2.6. In the following chapter several examples of industrial wastes are presented. [66]
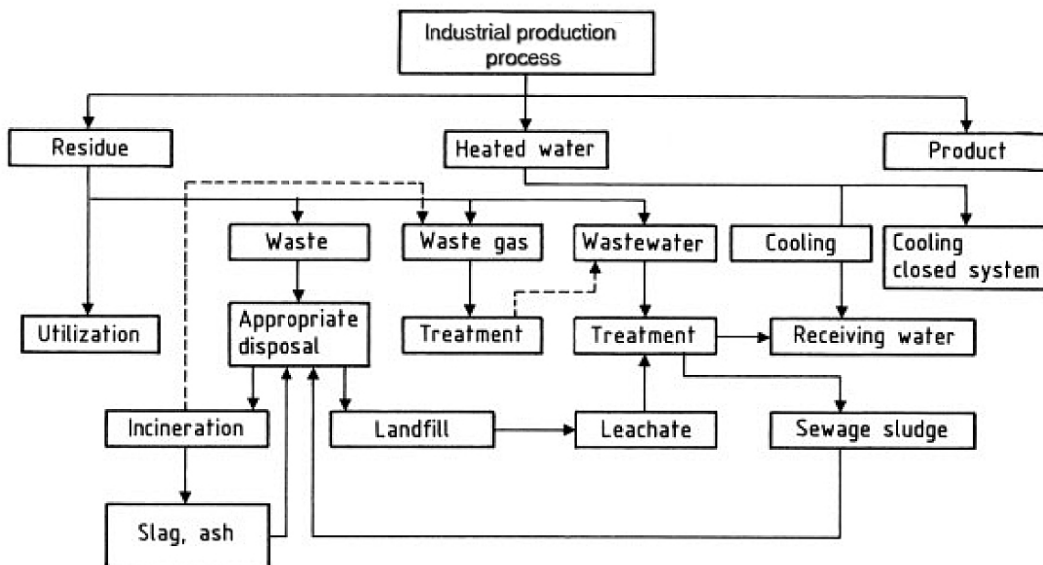
Figure 2.6: Generation of waste in industrial processes, adapted [66]

In the wood and wood processing industry wood residues are generated in the form of splints, wood shavings, sanding dust and bark. As a rule, material-sensitive recycling of wood residues creates more added value than energetic recovery. Splints, wood shavings and sanding dust are used for the production of chipboards. Wood shavings are also employed as raw material for the pulp and paper production. Bark is converted into mulch but may also be incinerated. Since there is a demand for process heat for drying processes in the wood processing industry, wood residues are also used as energy carriers. [32]

Organic waste is also generated in the food-processing industry. Usually, vegetable residues such as potato peelings contain a lot of water, thus they are not suitable as solid fuel but as substrate for biogas production by fermentation. Slaughter waste is manufactured into meat and bone meal, which serves as animal food. At the time of the mad cow disease (BSE) infected animals and slaughter waste were incinerated to achieve hygienisation. The technical and energetic use of meat and bone meal is increasing. [32]

In the pulp and paper production process residues are recovered thermally. Only a part of the wood, cellulose, can be converted into paper. Thus, wood is pulped in order to get cellulose as raw material for paper production. Black liquor contains the residual compounds such as lignin and resin. Since the paper machine requires large amounts of steam to dry the paper, black liquor is usually combusted in special furnaces to supply process heat. Other residues, such as fibre sludge, are also incinerated. [32]

In plastic processing plants waste is generated too. In contrast to plastic waste produced by the end-user, which contains all sorts of polymers and pollutants, plastic production waste is mostly homogeneous and unpolluted. That is why it can be returned to the production process or it can be reconditioned. Thermoplastics can be molten to produce new formed parts or regrind. Material-sensitive recycling is not possible for other types of polymers such as thermosetting plastic or elastomers because the polymer structure is destroyed by heat. However, their monomers can be recovered by hydrogenation, pyrolysis or gasification. These processes are also suitable for mixed and contaminated plastic wastes. Reclamation of thermoplastics cannot be repeated indefinitely without change in composition because the recycling process slightly alters the molecular structure. At the end of the recovery cascade there is usually energetic recovery. [63]

2.1.3 Other waste streams

Besides municipal solid waste and industrial wastes there are many other waste streams that are mainly composed of organic compounds.

Organic waste, such as trees that have been cut down, grass clippings and crop residues are usually turned into mulch, composted or ploughed back into the soil. Thus, the nutrient cycle is closed. Part of the organic waste, mainly wood, is also incinerated. Grasses and crop residues have unfavourable properties for incineration because of the high content of ash and the low ash melting temperature. [32]

Waste wood is wood that is not utilised anymore and which has to be disposed. Material-sensitive recycling or energetic recovery are applied depending on the pollution of the wood.

For example wood in furniture has been painted and varnished; wood adhesives have been used. In Europe 38% of the waste wood were recycled and 34% were incinerated in 2006. [32]

Sewage sludge is produced in sewage treatment plants and it is a general term for all substances that can be separated from the waste water by physical, chemical or biological processes. It mainly consists of excrements, food residues, paper, sand, ash and activated sludge containing microorganisms and has a very high water content. [62] About 50% are organic compounds and 50% are inorganic compounds. Sewage sludge can be applied as fertiliser in agriculture, but this amount is decreasing constantly because sewage sludge is charged with organic pollutants and heavy metals. Thus, it is more likely to be utilized thermally in waste incineration plants, gasification plants or as substitute fuel in conventional coal fired power plants. [32]

Waste oil generally refers to used mineral or synthetic oil, oil emulsions and oily residues. They can be reconditioned if the oil is rather homogeneous and only slightly polluted. Depending on the amount and type of contaminants, they can also be used as substitute fuels in the cement industry or in blast furnaces in the steel industry. Heavily charged oils have to be treated as hazardous wastes, thus they are incinerated in rotary kiln waste incineration plants. [59]

2.1.4   Composition of waste

In Figure 2.7 the composition of waste is presented from a general point of view.
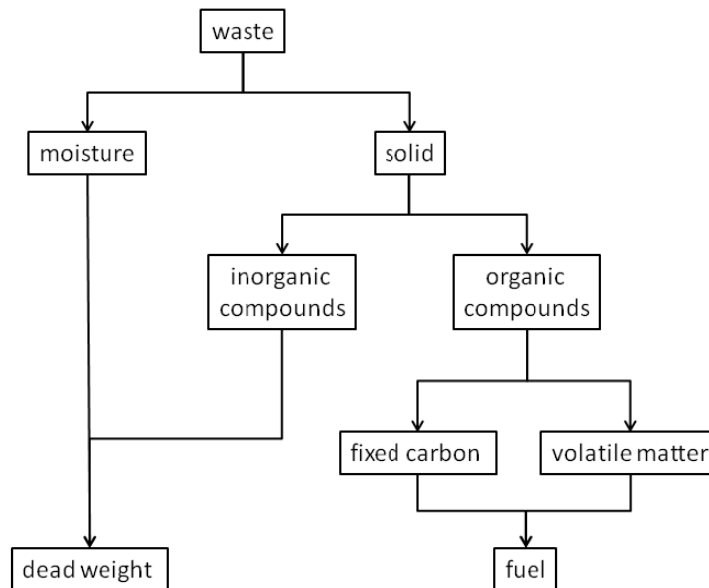
Figure 2.7: Composition of waste, according to [10]

Due to the heterogeneous nature of waste the concentration of the compounds varies and only ranges can be indicated as it is shown in Table 2.1 for household wastes.

Table 2.1: Chemical composition of household waste, [47]

element/compound		min	-	max
C	m%	28	-	40
H	m%	4	-	5
O	m%	16	-	22
N	m%	0.2	-	1.3
S	m%	0.3	-	0.5
Cl	m%	0.4	-	1
Cd	m%	0.0001	-	0.0033
Pb	m%	0.039	-	0.18
Cu	m%	0.006	-	0.21
Zn	m%	0.047	-	0.65
Cr	m%	0.003	-	0,27
Fe	m%	3	-	5
Hg	m%	0.00005	-	0.0011
dioxin	ng/kg	10	-	256
ash	m%	25	-	35
water	m%	15	-	35
combustible	m%	40	-	60
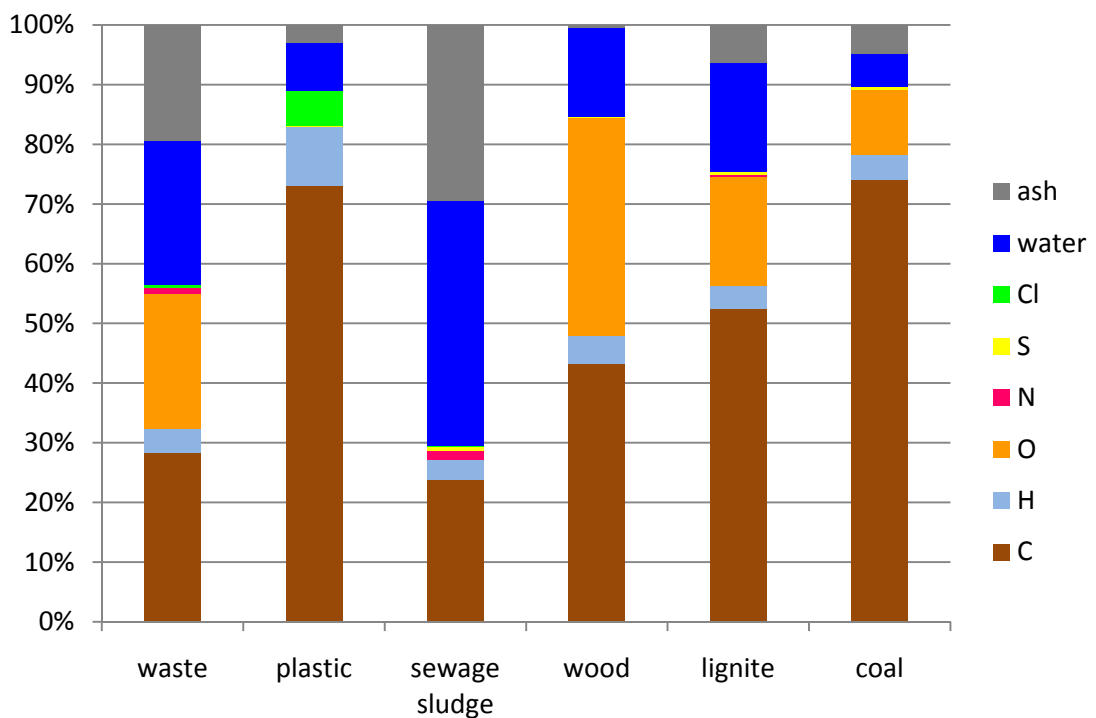
Figure 2.8: Comparison of MSW [47], plastic [37], sewage sludge [7], wood, lignite and hard coal [26]

Figure 2.8 presents typical elementary analyses of municipal solid waste, plastic, sewage sludge, wood, lignite and hard coal. There are certain basic requirements for waste used in incineration plants. The average lower calorific value has to be at least 6 MJ/kg. Because of the varying composition the calorific value of waste is not constant. It mainly depends on the moisture of raw waste, the ash content, which is made up of inorganic compounds, and the combustible fraction consisting of organic compounds. These three parameters (in percentage by weight) are necessary for a first indication of combustibility of waste by means of the Tanner triangle diagram. [57]
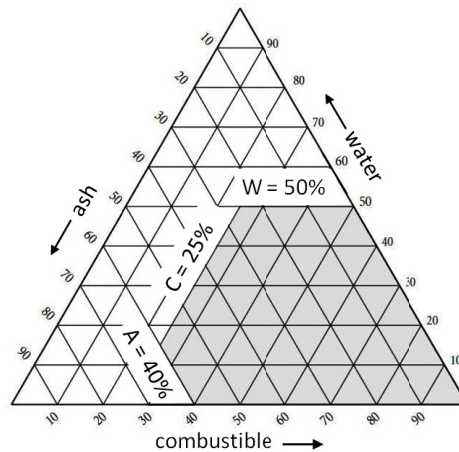
Figure 2.9: Tanner triangle diagram, adapted [57]

The shaded area in Figure 2.9 indicates that the fuel is theoretically feasible for combustion without auxiliary fuel. The limits are water content W < 50%, ash content A < 60% and combustible content C > 25%. [57]

Waste composition varies by cultural differences, climate and socio-economic conditions. It is also observed that there is a change with time. A comparison of the Tanner triangles in Figure 2.10 show that the ash and water content of European waste have declined and the combustible fraction has augmented due to the increasing standard of living. [64]
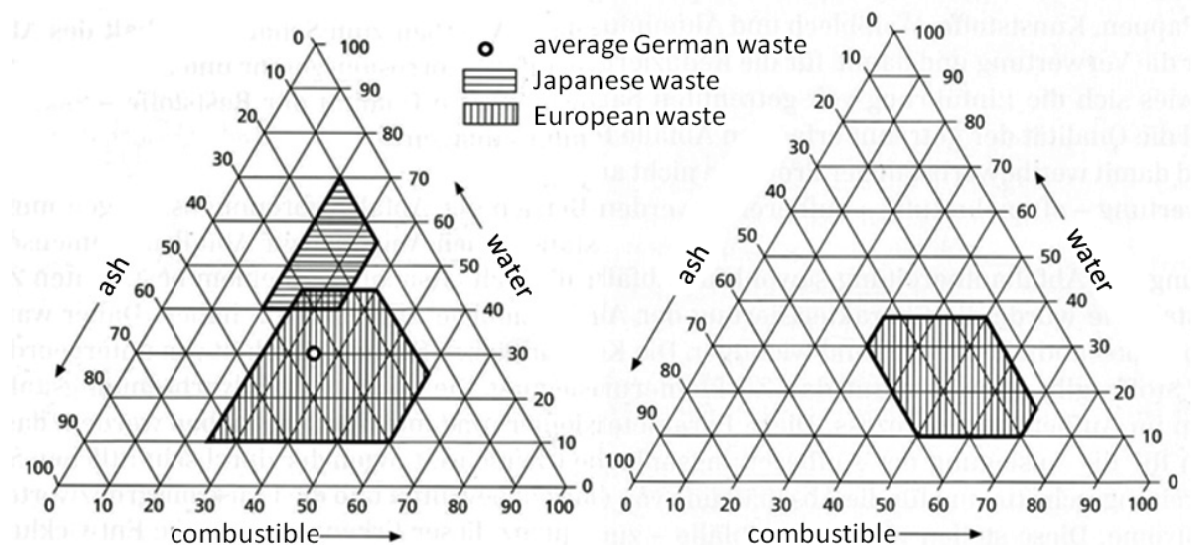
Figure 2.10: Tanner triangle 1992 and 1998, adapted [64]

2.2   Principles of thermo-chemical conversion

The objectives of thermal waste treatment are

- destruction of organic compounds
- concentration and lock out of inorganic compounds
- destruction and immobilisation of harmful pollutants
- reduction of deposition volume
- recovery of the thermal and/or chemical energy of the waste

The most important thermal waste treatment is waste incineration. It is the most highly developed method. There are also waste pyrolysis and waste gasification, which are still being developed. [58]

Thermo-chemical conversion aims to release the energy content of the waste. When waste is incinerated, the energy content is released directly in the form of thermal energy. It is also possible to convert waste into secondary energy carriers such as gaseous or liquid fuels and to release their energy later in a spatially divided oxidation. The production of secondary energy carriers diversifies the possible application of the energy content of the waste. [32]

Combustion consists of four sub-processes:

- heating and drying
- devolatilisation
- gasification
- char and volatiles combustion = oxidation

When waste is incinerated, all four sub-processes occur. Secondary energy carriers are obtained, when the process is interrupted after two or three sub-processes. To release the energy of these fuels they have to be further oxidised. Thus, the rest of the sub-processes take place. Regardless of whether the sub-processes occur in separated vessels or together, the final result is the complete oxidation of the waste.

As it is shown in Figure 2.11 and in equation 2.1, the sub-processes can be characterised by the excess air ratio λ that is defined as the amount of air used in the process in relation to the amount of air needed for a complete stoichiometric oxidation reaction. [32]

$$\lambda = \frac{m_{air}}{m_{air,stoichiom.}}$$
(2.1)
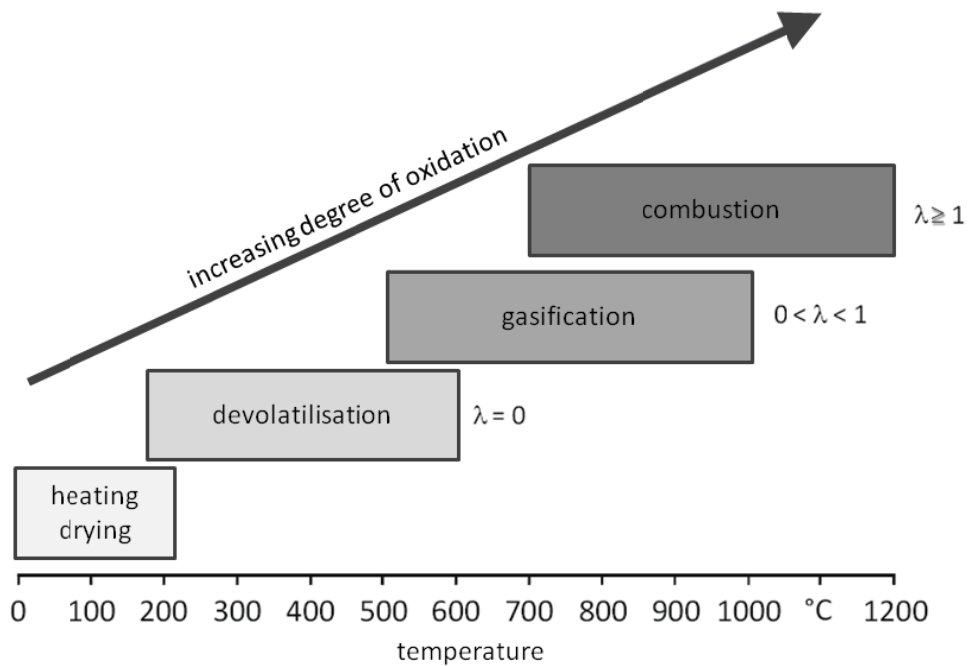
Figure 2.11: Sub-processes of combustion, adapted [32]

2.2.1 Heating and drying

Below 200°C free or bonded water in the waste evaporates in an endothermic reaction. Hence, it is necessary to supply heat. As there is no air supply, the excess air ratio λ is equal to 0. Due to the high enthalpy of evaporation of water, the temperature of the waste is increasing very slowly during evaporation. The organic structure of the waste is maintained to a great extend. [32]

2.2.2 Devolatilisation

When waste is heated (with or without adding oxygen), devolatilisation starts in the temperature range of 150-220°C. It is an endothermic process with an excess air ratio λ equal to 0. Macromolecules are irreversibly destroyed by heat and form smaller molecules, which are gaseous or liquid. Devolatilisation is completed at approximately 500°C. The final products are combustible gases, vaporised liquid pyrolysis oils and char, which consists of carbon and ash. It is an important process to produce combustible gases and condensable organic compounds. [32]

2.2.3 Gasification

The aim of gasification is to convert solid pyrolysis residues (char) into combustible gases to be used as secondary energy carriers. A gasification agent containing oxygen such as air, steam, oxygen or carbon dioxide is added. The excess air ratio λ is in the range of 0 to 1. Gasification starts at temperatures exceeding 500°C and partly endothermic and partly exothermic reactions occur. The composition of the gas depends on the gasification agent, pressure and

temperature and the reactor design. The gas produced by gasification can be further oxidised during combustion. [32]

2.2.4 Combustion

With an excess air ratio λ = 1 stoichiometric combustion takes place. In general, the excess air ratio is above 1 to ensure complete combustion. When the reaction is completed, all species are oxidised and the chemical energy content is completely converted into thermal energy. [32]

3 Waste incineration

3.1 Physical principle of combustion

"Technically, combustion is the self-sustaining, exothermic interaction of a fuel with an oxidant through a series of chemical and physical events, ultimately resulting in the formation of water and carbon dioxide, which are the most stable reaction products." [50]

Combustion is the reaction of a fuel with an oxidant, usually oxygen. It is a very fast reaction at high temperatures, which emits heat and light in form of flames. The chemical reactions of combustion are mostly exothermic radical chain reactions. If fuel and oxygen react in a stoichiometric way, it is considered as complete combustion. If the fuel consists of hydrocarbons, the reaction products of complete combustion are CO_2 and water. A lack of oxygen leads to other products such as CO, other carbon compounds and soot. The use of aerial oxygen generates nitrogen oxides. [50]

Conventional combustion of solids comprises all four sub-processes described in chapter 2.2. Depending on the incineration technology, the sub-processes occur sequentially or spontaneously.

3.2 Combustion technology

The process of a waste incineration plant consists typically of five parts:

- waste receiving and preparation: bin, crane
- combustion: feeder, grate, air supply, combustion chamber
- heat recovery: boiler
- waste gas cleaning: fabric filter, multi stage scrubbing, DeNOx
- waste water treatment: HCl and gypsum recovery, precipitation of pollutants

3.2.1 Waste receiving and preparation

There are two broad categories: mass burning of inhomogeneous waste without pretreatment and burning of pretreated and homogenised waste. The feedstock requirements depend on the combustion system.

3.2.2 Grate firing

It is the most common process for thermal waste treatment and a thoroughly tested technology. Its core is a moving grate, where the waste is burned. The grate ensures the transport of the waste and rabbles it, so that the waste is distributed evenly. The movement of the grate uncovers new unburned surfaces of the waste. In addition to that, primary air is injected through the grate. [56]

There are several different grate designs that vary in how the charge is conveyed and rabbled:

- bar grate
    - reciprocating: the waste is pushed forward
    - reverse-acting: the waste close to the grate is pulled back, the waste on the top of the layer rolls downwards
- roller grate

In Austria only bar grate systems are employed; there are single- or multi stage arrangements. [6]

It is not necessary to pretreat the waste to be used in a grate firing, except for bulky waste, which is usually shredded beforehand. A grate firing is not sensitive to changes in composition and calorific value. The waste is gathered in the pit. As the plant is on permanent operation, the pit ensures the supply of waste during the night and on weekends and holydays, when there is no delivery. The waste is mixed and homogenised by overhead cranes controlled by an operator, who also removes inappropriate bulky waste. The overhead crane feeds the waste into the hopper. Via the chute the waste falls on the grate. Ash and slag leave the grate at the other end via the ash chute. [66] [10]

On the grate the sub-processes of combustion illustrated in Figure 3.1 take place.

Table 3.1: Combustion zones on a grate, [10]

	drying	devolatilisation	gasification	combustion
heat flux	endothermic	endothermic	endothermic/exothermic	exothermic
temperature range	50-150°C	250-500°C	> 500°C	> 850°C
gaseous products	water vapour	water vapour pyrolysis gas	water vapour hydrogen carbon monoxide carbon dioxide	water vapour flue gas
liquid products	-	pyrolysis oil	-	-
solid products	fuel	ash coke	ash slag	ash slag
excess air ratio	-	-	< 1	> 1
zone in figure	1	1-2	1-2	3

waste secondary air

after
burning

1

gases of the
primary combustion

grate

2

3

discharge varies by
rotational speed of
the roller and height

primary air

slag

1: drying, devolatilisation
2: drying, devolatilisation, gasification
3: combustion, complete burnout of the slag
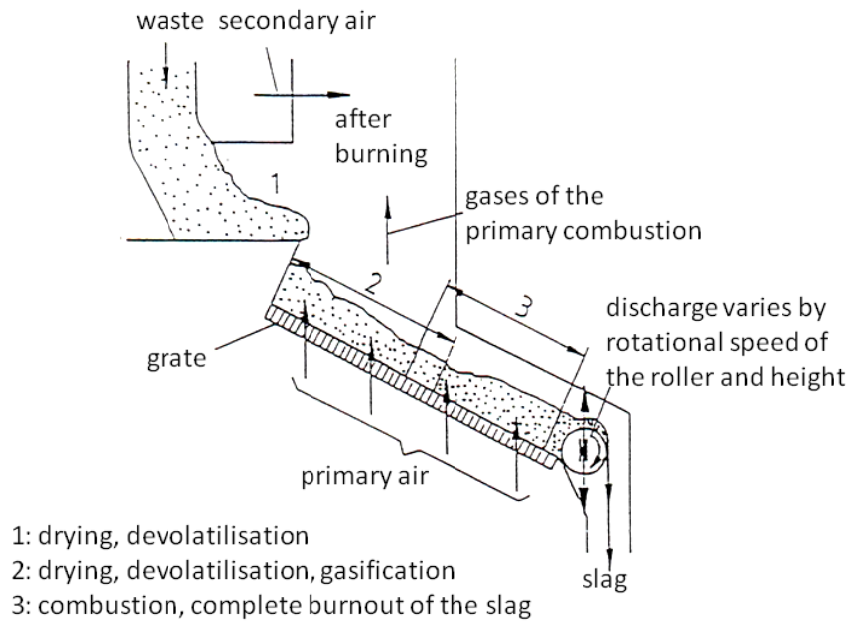
Figure 3.1: Combustion zones on a grate, adapted [10]

As firing system and boiler form a procedural unit, the grate is integrated in the combustion chamber and forms its bottom. [56]

The width of the grate depends on the thermal grate load (MW/m²) and on the mechanical grate load (t/(m²h)). The length of the grate is decisive to obtain a good slag quality. 65-70% of the length have to be applied as a drying and combustion zone. On the remaining part the complete burnout of the slag takes place; it ensures complete combustion. [57]

Primary air is supplied sub-stoichiometrically, which corresponds to an excess air ratio λ less than 1. Because of the variation of waste composition and calorific value, a flexible primary air system allows to change the location and quantity of the air injection. Usually, primary air is drawn from the pit, which causes low pressure in the pit and avoid smell nuisance. Ambient air is sucked from the outside into the pit. [66]

The unburned gases of the primary combustion are burned with excess of oxygen in the afterburner chamber. It consists of the first part of the first radiation pass of the boiler and starts after the last injection of secondary air. Secondary air is injected through several rows of nozzles and ensures effective mixing of the flue gases in a turbulent flow. The excess air ratio λ is in the range of 1.5-2.0. [66]

Complete combustion requires a long retention and reaction time of the flue gases at high temperatures. The temperature in the afterburner chamber should be increased to a minimum of 850°C for at least two seconds according to the EU Waste incineration directive of 2000 [11] and the Austrian law [3]. Auxiliary burners are used in case that the temperature drops lower than 850°C.

Slag and ash are discharged at the end of the grate. In order to avoid sintering the end of the grate is cooled. [66]

3.2.3 Rotary kiln

The main part of a rotary kiln firing is an inclined cylinder, which is lined on the inside with refractory material or a cooled steel shell. The cylinder is filled with waste up to 20%. Waste is transported due to the rotation of the cylinder and forms a moving bed.

It is not necessary to pretreat the waste for the rotary kiln firing. In contrast to grate firings, a rotary kiln is a closed system, where all kinds of waste, whether they are solid, paste like or liquid can be incinerated. The rotary kiln is not sensitive to a varying composition of the waste. Thus, the rotary kiln is especially suited for hazardous wastes with unknown composition. [66]

It is also possible to use a rotary kiln for "normal" municipal waste incineration. It is less common than the grate firing, because the maximum capacity is lower and the capital costs are relatively high. [57]

A rotary kiln firing, which is presented in Figure 3.2, consists of the following parts:

- feed devices
- air supply
- auxiliary firing
- rotary shell and lining
- drive
- afterburner
- ash and slag discharge devices
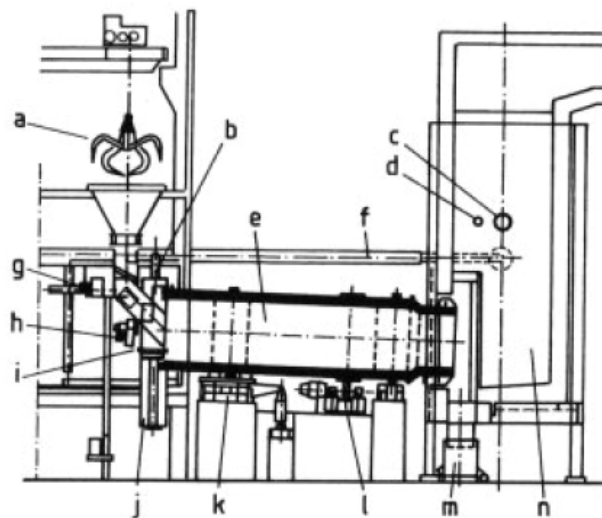
a) Charging by crane; b) Primary air system; c) Oil burner; d) Wastewater injection; e) Rotary kiln; f) Secondary air system; g) Drum charging; h) Oil burner; i) Injection of solvent sludge, pastelike wastes; j) Head wall of rotary furnace; k) Thrust rolls and longitudinal positioning; l) Drive; m) Slag discharge system; n) Post-combustion chamber

Figure 3.2: Rotary kiln, [66]

The charging system has to ensure that the mixture of waste of different consistency forms a viscous melt. Thus, there is a coat of slag on the cylinder, which protects the refractory bricks against erosion and corrosion.

The charging system is located at the head of the furnace. A crane conveys solid waste into the charging hopper. There is a drum elevator for drums, thick-matter pumps and fuel nozzles for paste like wastes and lances for liquid wastes. Hospital refuses are stored in drums. The drum size has to be limited in order to ensure uniform combustion. When a drum drops into the furnace, heat is released very quickly and with increasing size of the drum the combustion will not be complete anymore. In newer plants drums are not allowed anymore; they have to be discharged beforehand. [66]

Auxiliary burners are used to ignite the charge and to ensure that the ignition boundary does not move too far to the end of the furnace.

The shell of the furnace is made of cylindrical welded rings with refractory lining on the inside. Typical dimensions of a cylinder are 8-12 m in length and diameters in the range of 1-5 m. The average residence time of waste in the furnace is about 60 min and depends on the rotational speed of the cylinder. [66]

The excess air ratio λ is above the ratio of the grate firing and the fluidised bed incinerator and reaches a value of 2.0-2.5; in extreme cases up to 3. [66]

There are several combustion zones in a rotary kiln and the refractory lining has to be adapted to the special conditions in every zone. It is necessary to renew the lining periodically because of the permanent contact of charge and lining. Wear is caused by thermal, mechanical and chemical stress. In the furnace feed zone mechanical damage is decisive for the choice of lining. In the pyrolysis zone bricks with higher thermal fatigue resistance are used. Desorption of moisture and formation of pyrolysis gases lead to thermal stress. The highest thermal stress occurs in the main combustion zone with temperatures up to 1500°C. In the burnout zone the slag is in a thin liquid state, therefore very dense bricks are employed there. The terminal segments of the rotary kiln are made of heat-resistant cast steel with air cooling due to high thermal stress. [66]

An afterburner chamber is integrated in the first part of the boiler because the residence time of the flue gases is usually too short for complete reaction in the rotary kiln itself. There are three main tasks for the afterburning:

- complete combustion of the flue gas
- incineration of liquid wastes that are injected directly into the afterburner chamber
- mixing of flue gases and secondary air

The residence time has to be about 5 s at 950°C to make sure that the combustion is complete and there are no temperature differences between the gas streams. Ceramic mixing screens may be used to mix the gas streams and to remove the dust. [66]

The lining of the lower part of the afterburner chamber suffers from chemical attack by liquid slag coming from the furnace, so a chemical resistant material is needed. In the upper part the lining is made of corundum.

High-quality masonry does not support frequent changes in thermal load. That is why fuel oil burners are provided to keep the temperature at the level of 500°C, when there are repair works in the second pass or waste incineration is interrupted for a short time.

Slag and ash are discharged at the end of the rotary kiln via an ash chute. [66]

3.2.4   Fluidised bed

An initially fixed bed of sand is fluidised by an upward streaming gas flow. In the fluidised bed the reaction takes places. The fluidisation principle has been applied first in industry in 1922 to gasify fine-grained coal. Now there are various applications ranging from physical processes such as drying, cooling, sublimation or coating to chemical reactions such as heterogeneous gas-solid catalytic reactions. [71]

Due to fluidisation there are several important advantages:

- high heat transfer coefficient in the bed because of turbulence in the bed
- large exchange surface due to the particles used as bed material
- no moving parts in the reactor
- possibility to remove pollutants by reaction with additives in the bed

In comparison to the grate firing and the rotary kiln the requirements that the waste has to meet to be used in a fluidised bed incinerator are stricter. The maximum grain size is limited to enable evenly feeding of the waste to the incinerator. As municipal solid waste is heterogeneous, it cannot be burned as-delivered and requires pretreatment, such as crushing, shredding, metal separation and screening to meet the fuel requirements. [56]

Fluidised bed reactors are usually used for combustion of sewage sludge, the light fraction of household waste and for contaminated wood and soil. [66]

A fluidised bed incinerator consists of a refractory lined reactor with a distribution grate at the bottom, where the bed material, usually silica sand or other ceramics, forms an initially fixed bed. The bed is fluidised by preheated air; waste is fed continuously. [66]

First the waste is dried in the hot bed. If primary air is supplied sub-stoichiometrically, the waste devolatilises in the lower part of the bed; the gases are burned afterwards with secondary air in the upper zone of the reactor. The excess air ratio is lower than in grate firings ranging from 1.3 to 1.5, which leads to smaller quantities of flue gases. [66]

Non-combustible compounds sink to the ground of the bed, where they can be discharged. During combustion the size of the waste decreases continuously. At a certain size the ash particles are small enough to be entrained by the air flow and are carried out of the bed. In a fluidised bed incinerator the dust content of the raw gas is usually higher than in a grate firing, in the order of 20-80 g/m³. This has to be considered for the design of the flue gas cleaning equipment. [66]

There are two major types of fluidised beds: stationary and fast or turbulent fluidised beds.

If a fixed bed is fluidised with air, the pressure drop increases with increase in gas velocity. At the minimum fluidisation velocity the fixed bed turns into a stationary fluidised bed. The pressure drop stays constant then. Particles are floating in the gas flow and the bed behaves

similar to a liquid. There is a well defined surface of the bed. It can be stirred like a liquid. Objects of greater specific gravity sink in the bed and those of lower specific gravity float. If two fluidised beds with different heights are connected, they will form one single bed with an equal height. In the stationary bed gas bubbles are rising and cause turbulence, mixing and convective transport of particles. [71]

If the surface velocity of the gas is increased, the well defined surface disappears. When the bubbles burst at the top of the bed, particles that are entrained are carried out and the solid concentration in the bed decreases. To return the particles to the bed, an integrated cyclone can be used. With further increase in gas velocity the solid concentration in bed decreases. As a large amount of particles is carried out of the bed, a solids recycle system is necessary. A fast fluidised bed with a hot cyclone is called a circulating fluidised bed. [71] In Figure 3.3 the different types of fluidised beds are illustrated.
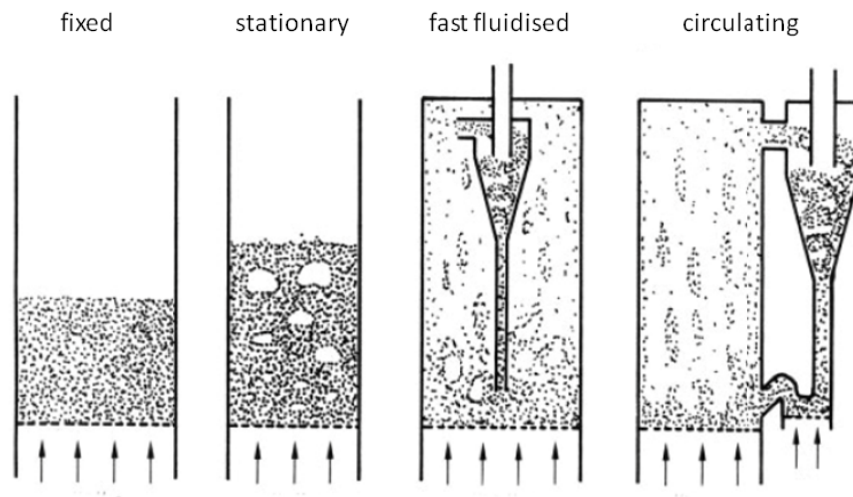
Figure 3.3: Different types of fluidised beds, [71]

As there are different types of fluidised beds, there are also different types of incinerators (Figure 3.4).
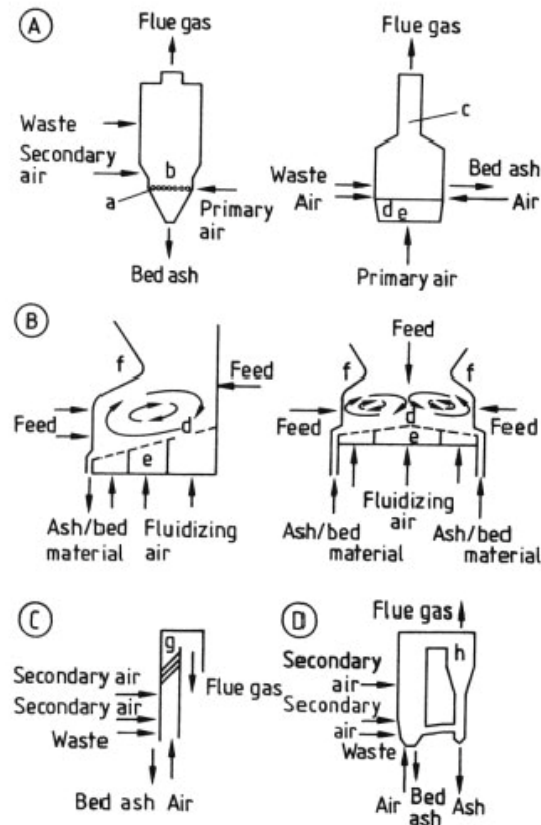
A) Stationary fluidized bed; B) Rotating fluidized bed (special case of stationary fluidized bed); C) Expanding fluidized bed; D) Circulating solids fluidized bed
a) Distributor pipes; b) Ash hopper; c) First boiler pass; d) Distributor plate; e) Air chambers; f) Deflector plate; g) U-beam particle collector; h) Hot cyclone

Figure 3.4: Fluidised bed incinerators, [66]

A stationary fluidised bed is usually used for the incineration of sewage sludge. The moist, centrifuged sludge contains about 25% dry substance by volume. It is fed to the bed by piston pumps and it is dried, devolatilised and burned in the reactor. [71] A stationary fluidised bed is less sensitive to changes in particle size. [66]

A circulating fluidised bed reactor consists of a bed vessel, a cyclone and a special valve to connect the standpipe of the cyclone with the bed vessel. In the valve the precipitated particles are fluidised again to be able to move back into the bed vessel. The mass flow of returning particles can be controlled by the fluidisation gas velocity. An additional external fluidised-bed cooler cools the particles and allows more accurate control of the temperature in the bed vessel. It permits load variations over a wide range. [71]

Stationary fluidised beds are chosen, when the furnace capacity is lower than 100 MW because at higher furnace capacities the heat exchange to the water-steam cycle is not sufficient anymore. The lower limit for the use of circulating fluidised beds is 50 MW; the heat exchange does not degrade, when the capacity is increased. [6]

The rotating fluidised bed incinerator has been developed especially for the incineration of municipal solid waste. It is a special case of the stationary fluidised bed with a forced rotation

of the bed. The grate is inclined and the gas velocity in the lower part of the grate is increased. Due to gravity waste moves towards the lower end of the grate, where it is blown up to the deflector plate and then to the upper part of the grate. A roller is established. In reactors with two beds the rollers are counter rotating. The additional horizontal movement distributes the waste more evenly and only one feed location is necessary. The temperature distribution is more uniform. [66]

3.2.5 Overview on technologies used in Austria

The table provides an overview on all plants in Austria, where only waste is incinerated.

There are seven grate incineration plants, which are operating now and two planned plants. The oldest plant is located in Vienna, Flötzersteig, and was commissioned in 1963. In all these grate incineration plants untreated municipal solid and commercial waste and bulky waste, which is shredded beforehand, is incinerated. All plants are equipped with bar grates. Three different ways of grate moving are applied: combined forward and backward, reverse-acting and reciprocating. The type of grate changes with time; in newer plants reciprocating grates are used. In Dürnrohr the grate is water cooled to provide a higher furnace capacity.

In two rotary kilns in Vienna and in the fluidised bed incinerator in Arnoldstein, hazardous wastes are treated.

There are six fluidised bed incinerators and it is planned to build three new ones. There are five stationary and one existing circulating fluidised bed incinerators. All the planned plants are also circulating fluidised bed incinerators. In Simmering the fourth stationary fluidised bed incinerator WSO4 has a rotating bed. As a fluidised bed system is not suitable for untreated waste, the plants are either equipped with internal mechanical waste processing or only pretreated waste is delivered. Municipal solid waste, commercial waste with similar properties and sewage sludge are incinerated there.

Table 3.2 gives an overview on Austrian waste incineration plants.

Table 3.2: Waste incineration plants in Austria

	operator	references	commissioning	number of lines	nominal capacity (t/h)	furnace capacity (MW)	forward+backward	reverse-acting	reciprocating
grate firing									
Flötzersteig	Fernwärme Wien	[56][6][19]	1963	3	25	57	x		
Spittelau	Fernwärme Wien	[56][6][19]	1971	2	32	82		x	
Wels 1	AVE	[56][6][35][1]	1995	1	9	29		x	
Wels 2	AVE	[56][6][35][1]	2006	1	30	80		x	
Arnoldstein KRV	KRV	[56][6][40]	2004	1	11	30			x
Dürnrohr	AVN	[56][6]	2004	2	48	120			x
Pfaffenau	Fernwärme Wien	[6][19]	2008	2	32	80			x
Zistersdorf	ASA	[56][6][2]	2009	1	17	46			
Dürnrohr 3	AVN	[6][4]	2010	1	38	90			x
rotary kiln									
Simmering 1,2	Fernwärme Wien	[56][6][19]	1980	2	20	62			
Arnoldstein ABRG	ABRG	[6]	2005	1	3	10			
stationary fluidised bed									
Simmering 1-2	Fernwärme Wien	[56][6][19]	1980	2	7,0-60	60			
Simmering 3	Fernwärme Wien	[56][6][19]	1992	1					
Arnoldstein ABRG	ABRG	[56][6]	2001	1	4	5			
Simmering WSO4	Fernwärme Wien	[56][6][19]	2003	1	36	45			
Niklasdorf	ENAGES	[56][6][14]	2004	1	12				
circulating fluidised bed									
Lenzing	RVL	[56][6][45]	1998	1	38	110			
Heiligenkreuz	RVH	[6][36][46]	2010	1	31	99			
Frohnleiten	Mayr-Melnhof	[6][52]	2010	2	50	160			
Linz	Linz AG	[6][55]	2011	1	21	66			

3.3   Energy recovery

During combustion waste is converted into hot flue gases carrying the energy of the waste. The average temperature of the gases is 1000-1200°C. In a boiler the gases are cooled to recover the energy. Depending on the use of energy there are three different types of boilers:

- Hot water boilers
- Low pressure steam boilers
- High pressure steam boilers

3.3.1   Hot water boiler

In a hot water boiler the hot flue gases pass through a heat exchanger. The energy of the gases is transferred to an internal circuit of hot water with temperatures in the range of 110-160°C. Figure 3.5 shows a typical arrangement of a hot water boiler circuit.

As hot water has very low energy content, its use is limited. District heating systems are a common application. In summer, when there is lower demand for heat, the hot water is cooled away in a cooling facility. This is for example a heat exchanger or cooling towers with river or sea water as coolant. If there is no river or sea nearby, fan mounted air coolers are implemented. They are less efficient.

If there is no use for the energy content of the waste at all, a hot water boiler with a cooling facility allows cooling away the heat in the most efficient way to reach the temperature necessary for the flue gas cleaning system. [57]
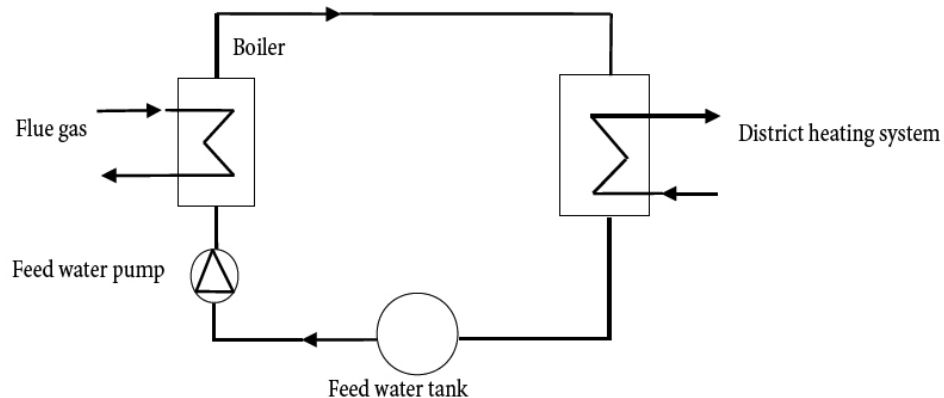
Figure 3.5: Hot water boiler circuit, [57]

3.3.2   Low pressure steam boiler

Low pressure steam has a temperature of approximately 120°C-250°C and a pressure up to 20 bar, it is used as process steam for industrial applications. The exact steam parameters depend on the end user; in Table 3.3 there are some examples. Complexity and cost of the low pressure steam boiler are in the same order as the hot water boiler. [57]

Table 3.3: Steam parameters for process steam in various industries, [57]

industry	steam temp. (°C)
breweries	150 - 250
chemical industries	200 - 500
sugar production	100 - 200
paper industries	100 - 300
wood industries	100 - 200
cement production	120 - 150
absorption cooling	150 - 200
food industries	150 - 200
drying purposes (e.g. sludge)	150 - 200

3.3.3   High pressure steam boiler

A high pressure steam boiler is more complex than the other boilers. There are three types: natural circulation, forced circulation and once-through. For waste incineration natural circulation is used because of the typical thermal load and the steam parameters.

In a modern grate firing incinerator the boiler is placed above the grate. The walls are either membrane walls or finned tubes. In the past the walls of the furnace were not cooled. But due to the increasing calorific value of waste in the last twenty years it is necessary now to cool the walls of the furnace with the tubes of the evaporator. The flue gas temperature is too high for the heat exchanger bundles. So there are one to three idle passes that may be equipped with heating surfaces lined by refractory material.

In the passes the gas velocity has to be low enough so that fly ash can sink due to gravity. There are cleaning equipments to reduce the contamination of the walls, for example air is injected perpendicularly to the walls. After the radiation pass the flue gas has to be cooled below 750°C, otherwise entrained particles remain doughy and cause contamination that cannot be removed by the cleaning equipment. [66]

In the following convection passes the flue gases having an average temperature of 650°C pass first the tube bundle of the superheaters and then those of the economiser, where the feed water is preheated. Then the temperature of the flue gas is about 200°C, which is low enough for the flue gas cleaning system. [6]

A high pressure steam boiler for rotary kilns and fluidised bed incinerators is different from the one used for grate firing. In contrast to grate incinerators, where the firing system and the boiler form a procedural unit, the waste heat boiler of a rotary kiln or a fluidised bed incinerator is separated from the firing system. As the residence time in the rotary kiln is not long enough to ensure complete burnout, an afterburner chamber is necessary. The heat of the flue gases is then recovered in a waste-heat boiler. In a fluidised bed incinerator the hot flue gases leave the cyclone and flow through a boiler with heating surfaces in the walls and

heat exchanger bundles to recover the sensible heat of the flue gas. An afterburner chamber may be inserted after the cyclone for complete burnout. [66]

There are three different applications for high pressure steam:

- electrical power generation
- combined heat and power generation
- combined process steam and power generation

3.3.4   Corrosion

The steam parameters of high pressure steam are usually less than 60 bar and 420°C. They are rather moderate because serious corrosion problems occur with increasing temperature. The chloride content of waste leads in combination with sodium and potassium to high-temperature corrosion at lower temperatures. As it is indicated in Figure 3.6, the temperature of the flue gas, which is in contact with the heat exchanger, should not exceed 500°C. The limit value for the temperature of the surface of the heat exchanger is 420°C to avoid corrosion. [6]
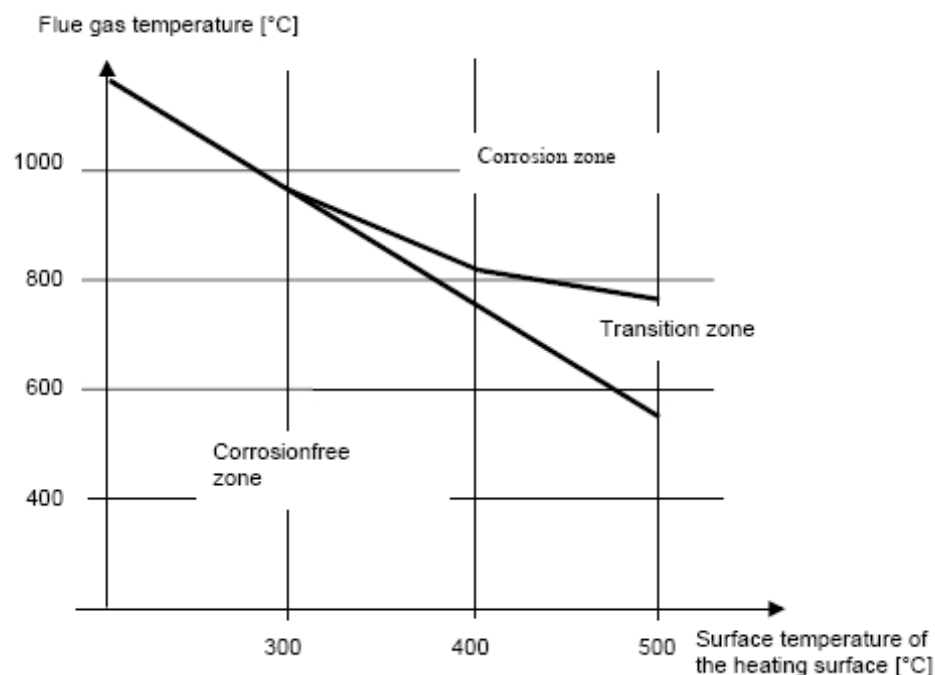
Figure 3.6: Corrosion as a function of temperature, [56]

3.3.5   Efficiency

In general, the efficiency is defined as the ratio of a useful output and a necessary input.

$$\eta = \frac{\text{useful output}}{\text{necessary input}} \qquad (3.1)$$

Concerning waste incineration, the ratio describes the conversion of the energy content of the waste into other forms of energy. The efficiency depends on the boundary of the system, which is observed. Thus, there are several different definitions. Mass and energy balances of

the system indicate the in- and outgoing streams. All the outgoing streams, which are used beneficially, are considered as useful output. All the ingoing streams, which are necessary to produce the benefit, are considered as necessary input.

$$\text{Useful output} = \text{input} - \text{losses} \tag{3.2}$$

$$\eta = 1 - \frac{\text{losses}}{\text{necessary input}} \tag{3.3}$$

[48]

Overall efficiency:

The overall efficiency is defined as the ratio of useful energy output to the necessary input. In a waste incineration plant the useful output can be electricity, heat and process steam depending on the type of energy recovery. The energy input comprises the energy content of waste, auxiliary fuel and preheated air. Values during nominal operation are placed to calculate the overall efficiency.

$$\eta = \frac{\text{electricity, heat and/or process steam}}{\text{waste, air, auxiliary fuels}} \tag{3.4}$$

In the overall gross efficiency the power demand of auxiliary units is neglected.

Fuel utilisation rate:

Similar to the overall efficiency, the fuel utilisation rate is defined as the ratio of useful output to the energy input. The fuel utilisation rate is calculated from average values during a period of time. In a cogeneration plant the amount of electrical power generation can be varied as a function of heat demand. Due to the lower heat demand in summer, more electricity is produced. In annual average values those changes are included. Thus, the fuel efficiency is always lower than the overall efficiency.

Boiler efficiency:

It is the ratio of the energy absorbed in the water-steam cycle to the energy input to the combustion chamber. The energy input comprises the energy content of waste, auxiliary fuel and preheated air.

$$\eta_B = \frac{\text{energy content of the water} - \text{steam cycle}}{\Sigma \text{ energy input}} \tag{3.5}$$

Gross electrical efficiency:

It is defined as the ratio of produced electrical energy to the total energy input.

$$\eta_{el,g} = \frac{\text{produced electrical energy}}{\Sigma \text{ energy input}} \tag{3.6}$$

Net electrical efficiency:

It is electrical energy exported to the power grid in relation to total energy input. The difference between gross and net electrical efficiency is the power demand of auxiliary units.

$$\eta_{el,n} = \frac{\text{exported electrical energy}}{\Sigma \text{ energy input}}$$

(3.7)

[6]

Thermal efficiency:

When steam is condensed in a turbine, thermal energy is converted into mechanical energy. By reason of the second law of Thermodynamics, the Carnot efficiency is the upper bond of efficiency of the process. It is the ratio of the temperatures between which the turbine works. [49]

$$\eta_{th} = 1 - \frac{T_{condensation}}{T_{steam}}$$

(3.8)
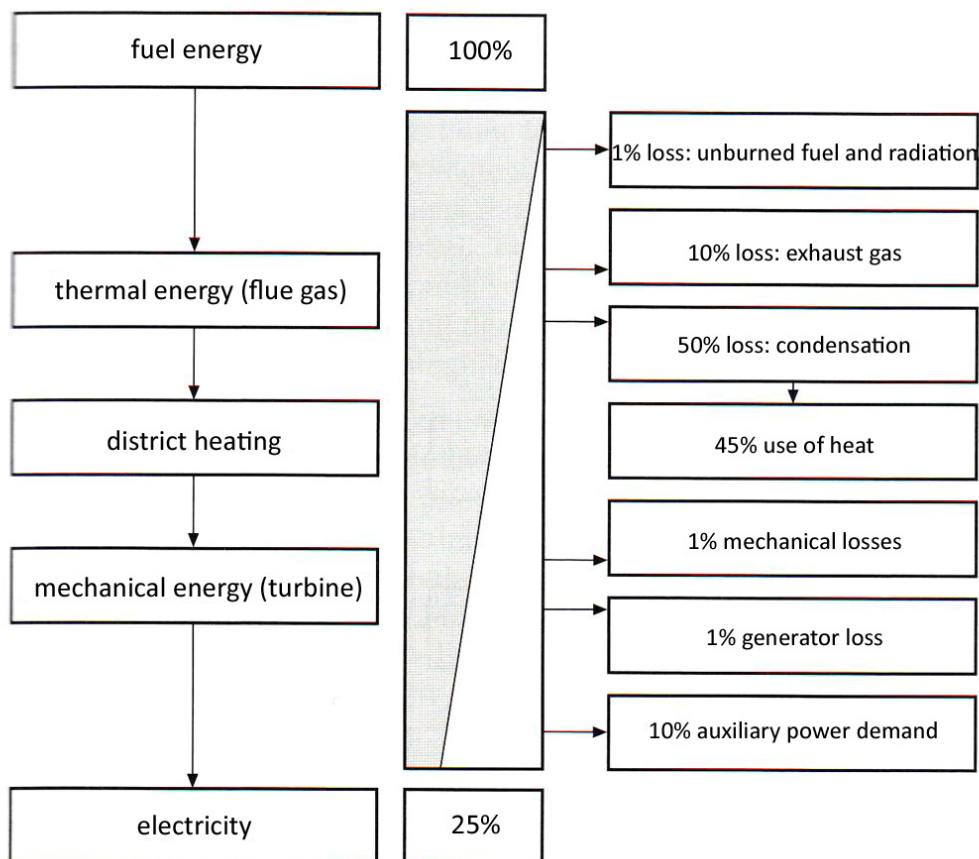
Figure 3.7: Energy conversion and its efficiency, adapted [49]

The losses of energy conversion are demonstrated in Figure 3.7. If the energy content of waste is converted to thermal energy in a hot water boiler, the thermal efficiency is very high and values of 80% are achieved. [57]

With a back pressure turbine, electricity and heat are produced. The back pressure of the turbine is determined by the district heating system. In a heat-lead cogeneration plant 85% of the energy of the steam are used for heat production and 15% for electrical power generation. The plant reaches an overall (gross) efficiency of about 80%. [6]

If process steam is produced instead of heat, an extraction turbine is used. It is possible to operate as a fully condensing turbine for power generation. In case of demand steam can be extracted from a bleed at desired parameters. The efficiency is a function of the amount of steam extracted; it is between the electrical power generation and the cogeneration.

For electrical power generation a fully condensing turbine is used. A cooling facility is necessary to dissipate the excess heat because the temperature is too low for any further use. Electrical power generation is the least efficient process, but it leads to a high valuable energy form because it can be converted into all other forms. Power generation is independent of the location of the consumer due to the power grid.

The net electrical efficiency of a waste incineration plant amounts to approximately 20% because of the rather moderate steam parameters of 60 bar and 420°C. A net electrical efficiency of 30% is attainable with increased steam parameters of 80 bar and 500°C. A further increase of efficiency is only possible, if the steam produced in the waste incineration plant is superheated and converted into electricity in a conventional plant nearby. [56]

The power demand of auxiliary units in grate firings and rotary kiln furnaces is in the range of 3-6% of the energy input of the waste, which is equivalent to 20-30% of the electrical power generation. Due to the higher number of auxiliary units in fluidised bed incinerators, the auxiliary service power consumption is 50% higher. [6]

Efficiency

Overall Recovery	Recovery
80%	80%
80%	80%
0%	0%
35%	35%
	0-35%
	75%
35-75%	20-25%
85%	65-60%

Energy Production

End Use: Heat Only · Steam Only · No Recovery · Power Only · Combined Steam and Power · Combined Heat and Power

Heat Production: Heat Exchangers · Cooling Tower · Condensing Heat Exchanger

Power Generation: Condensing Steam Turbine · Extraction Turbine · Back Pressure Turbine

Energy Recovery

Boiler: Hot Water Boiler · LP Steam Boiler · Steam Boiler

Incineration

Furnace: Moving Grate · Rotary Kiln · Fluidized Bed

Pretreatment

Homogenization: Mixing · Shredding

Sorting: No Sorting · Coarse Mechanical Sorting · Automatic Sorting · Fine Manual Sorting
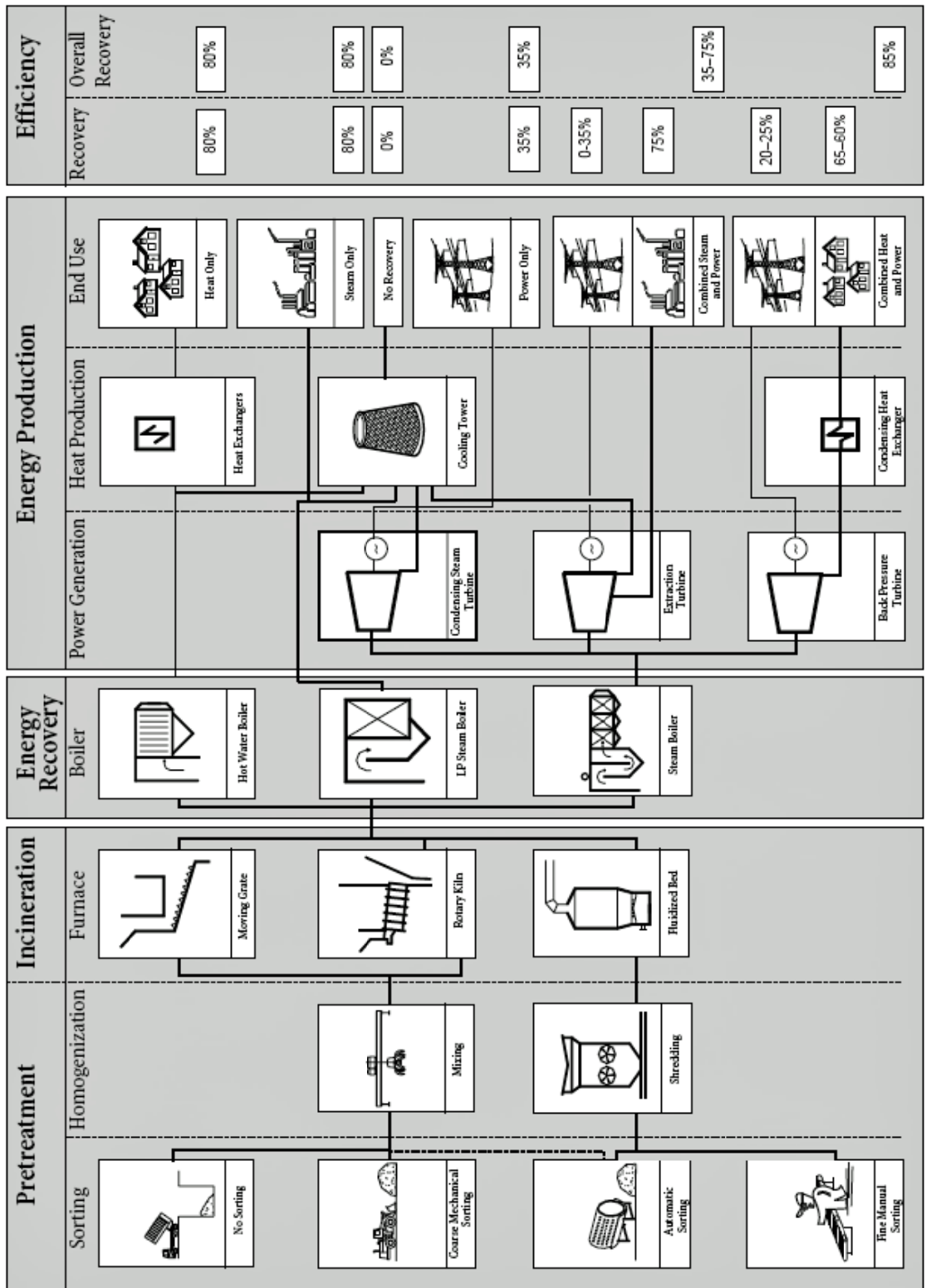
Figure 3.8: Comparison of efficiencies, [57]

In Figure 3.8 there is an overview on the whole waste incineration process and the different pathways compiled by the International Bank for Reconstruction and Development. For power generation only an overall efficiency of 35% is indicated. A standard waste incineration plants in Europe achieves an average electrical efficiency of 20%. In Amsterdam there is a waste incineration plant with improved performance reaching an overall efficiency of 31%. A further description of measures of improvement in this plant can be found in Chapter 3.3.7.

3.3.6   Overview on technologies used in Austria

In Austria the energy recovery systems of all waste incineration plants are equipped with natural circulation water systems. In Flötzersteig and Arnoldstein the boilers can be considered as low pressure boilers due to the pressure of 16 bar. All the others are high pressure boilers.

Because of the corrosive nature of the flue gases the steam temperature does not exceed 400°C except for the circulating fluidised bed incinerator in Lenzing. There the steam is superheated to 485°C and a pressure of 78 bar in an additional superheater in the fluidised bed cooler. The fluidised bed cooler is placed between the cyclone and the standpipe of the vessel. Ash and bed material are fluidised by air; heat exchanger bundles are situated in the stationary fluidised bed. Heat is transferred from ash and bed material to steam in the bundles. In the ash there are a lot of corrosive salts; that is why the superheaters of the fluidised bed cooler are very likely to be damaged and there are high requirements for the material of the superheaters. In Heiligenkreuz and Frohnleiten it is also planned to integrate fluidised bed coolers with superheaters to reach the indicated high steam parameters.

The lower calorific value of waste incinerated in grate furnaces is precisely defined and is in the range of 9-16 MJ/kg. In fluidised bed incinerators higher calorific values ranging from 7-29 MJ/kg are accepted.

The furnace capacity of grate furnaces is lower than in fluidised bed incinerators. The furnace capacity of circulating fluidised bed incinerators exceeds the values of stationary ones. For high furnace capacities such as 60 MW per line in Dürnrohr water-cooled grates are used.

In Table 3.4 data on energy recovery in Austrian waste incineration plants is compiled.

Table 3.4: Energy recovery in Austrian waste incineration plants

grate firing	number of lines	furnace capacity (MW)	nominal capacity (t/h)	av.lower calorific value (MJ/kg)	steam parameters (bar)	steam parameters (°C)
Flötzersteig	3	57	25	9	16	270
Spittelau	2	82	32	10	33	240
Wels 1	1	29	9	9.0 – 12.0	40	400
Wels 2	1	80	30	9.0 – 12.0	40	400
Arnoldstein KRV	1	30	11	10	40	400
Dürnrohr	2	120	48	10	50	380
Pfaffenau	2	80	32	9	40	400
Zistersdorf	1	46	17			
Dürnrohr 3	1	90	38		50	400

rotary kiln						
Simmering 1,2	2	62	20		52	350
Arnoldstein ABRG	1	10	3	13-16	16	200

stationary fluidised bed						
Simmering 1-2	2	60	7.0-60	16	52	350
Simmering 3	1				52	350
Arnoldstein ABRG	1	5	4	7	16	200
Simmering WSO4	1	45	36	8.0 - 15	52	350
Niklasdorf	1		12	<10	40	400

circulating fluidised bed						
Lenzing	1	110	38	6.5 - 29	74	485
Heiligenkreuz	1	99	31	7.0 - 30	75	470
Frohnleiten	2	160	50	8.0 - 20	70	470
Linz	1	66	21	n.a	40	400

In Austria the energy of waste is used for the production of process steam, steam for power plants, district heat and electrical power. In Dürnrohr and in Lenzing the produced steam is converted into electricity in an adjacent conventional power plant to increase the efficiency. The waste incineration plants in Lenzing, Niklasdorf and Arnoldstein and the planned ones in Frohnleiten and Heiligenkreuz produce process steam for industrial applications.

The plants in Lenzing, Niklasdorf, Spittelau, Wels and the planned ones in Linz and Heiligenkreuz can be considered as cogeneration plants. In Flötzersteig and Simmering only district heat and electricity for auxiliary units is produced. The values in the table for the rotary kiln 1 and 2 in Simmering indicate the total amount of energy produced at the site including energy production of four fluidised bed incinerators.

A comparison of efficiencies is difficult as there is only few data available. The average boiler efficiency of newer plants exceeds 80%. It is a function of the quantity and the temperature of the flue gases leaving the furnace and the excess air ratio. Thus, the boiler efficiency of fluidised bed incinerators is supposed to be higher than in grate firings. In planned plant in Frohnleiten the boiler efficiency amounts to 89%, which exceeds the boiler efficiency of 85-86% in the planned plant Zistersdorf.

The fuel utilisation rate is the highest in cogeneration plants because there the maximum of the produced energy is considered as a useful output. When only electrical power is generated, the efficiency decreases to about 18%.

In the column "efficiency" all values without special indication are compiled. It is likely that they are overall efficiencies.

Since 2008 the waste incineration plant in Wels is connected to the district heating system. Thus, the efficiency has increased from 26% to 72%.

In Niklasdorf the efficiency varies as a function of the amount of process steam, which is delivered. When there is high demand of process steam, only a small amount of electricity is produced and the efficiency reaches values up to 85%. In times of lower demand the energy of the waste is converted into electricity and the fuel efficiency decreases.

The same is true for Heiligenkreuz, where an EU compliant efficiency value is calculated. In the European Framework Directive [12] a formula for the calculation of efficiency is included. There the energy output is rated with factors depending on the type of energy; annual average values are used for the calculation. The calculation and the EU Framework Directive are further explained in Chapter 3.8. As this efficiency value is not comparable to the others, it is marked with an asterisk. The Framework Directive imposes that the efficiency is higher than 65% for new built or planned plants, which is fulfilled in Heiligenkreuz with 75-85%.

In Arnoldstein a special type of grate incinerator is installed. In the so-called Martin Syncom process waste is burned in an oxygen-enriched atmosphere. Thus, the temperature of the furnace is higher and better burnout is achieved. The auxiliary service power consumption increases because of the required air separation facility. From all that a fuel efficiency of 57% results.

Table 3.5 shows all efficiency values.

Table 3.5: Efficiency of Austrian waste incineration plants

grate firing	steam output (t/h)	electricity (MW)	heat (MW)	boiler efficiency (%)	electrical efficiency (%)	fuel utilisation rate (%)	efficiency (%)
Flötzersteig	-	-	53	75.0			
Spittelau	-	5	60			74.5	
Wels 1	-	7	15		18.6		
Wels 2	-	20	45				72.0
Arnoldstein KRV	-	0.9 - 5	9		17.0	57.0	
Dürnrohr	160	-	-				
Pfaffenau	-	8	53				
Zistersdorf	-	13	-	85-86			
Dürnrohr 3	106	-	-				

rotary kiln							
Simmering 1,2	-	7	59				
Arnoldstein ABRG	max.10	-	-	80.0			

stationary fluidised bed							
Simmering 1-2	-	7	59	73.3			
Simmering 3	-			80.0			
Arnoldstein ABRG	max. 5	-	-	76.0			
Simmering WSO4	48	7	59	82.5			
Niklasdorf	27	3	-				75 - 85

circulating fluidised bed							
Lenzing	130	-	-				
Heiligenkreuz	x	14	40				74 - 83*
Frohnleiten	40 - 140	32	x	89.0		80.4	
Linz	-	18	40				

3.3.7 How to increase the efficiency

Concerning the operation of a power plant, increasing efficiency is equivalent to reducing the amount of fuel input. As a major aim of an incineration plant is waste disposal and the operator earns money due to the tipping fee, a decrease of fuel input is not desired.

Waste incineration plant in Amsterdam [70]

In Amsterdam there is the world's largest waste incineration plant with an extraordinary electrical efficiency of 31%. It is an electrical power generation plant only and it is a good example how to increase the efficiency in a new-built plant.

Reduction of air excess

Usually, the excess air ratio in waste incineration plants is rather high because excess air stabilises the combustion process of inhomogeneous waste. If the excess air is reduced, there is less flue gas and the following devices can be smaller. The induced draught fan consumes less energy. In lieu of excess air, combustion is stabilised by good mixing of the waste prior to incineration and the width of the grate of 12 m. A negative consequence is the increase in corrosion risk because of the lower oxygen content of the flue gas, which leads to wear.

Steam temperature

The steam temperature has a direct impact on the thermal efficiency. Because of chloride and sulphur in the flue gas, corrosion already occurs at moderate steam temperatures. Thus, the steam temperature is limited to 420°C in standard waste incineration plants. In Amsterdam, however, the steam temperature is increased to 440°C. The membrane walls of the first pass are protected with cladding and due to the big volumes of the passes the flue gas velocity is low. Because of the lower life expectancy of the tube bundles, they are designed in such way to allow quick changes within 72 h.

Condensation pressure

Similar to the steam temperature the condensation temperature and pressure influences directly the turbine efficiency. A water cooled condenser is more efficient than an air cooled one due to the lower temperatures. As the incineration plant in Amsterdam is close to the harbour, sea water serves as cooling agent. The temperature of 15°C is considerably lower than in air cooled condensers. With decreasing condensation temperature the water content of the gas increases, which stresses the blade rows of the turbine.

Reheat cycle

The corrosive nature of the flue gas attacks most notably the superheaters. The heating surfaces of a reheat cycle are endangered the same way and the failure probability would be doubled. That is the reason why there is no reheat cycle in standard waste incineration plants. In Amsterdam the reheat cycle is not heated by the flue gas but by saturated steam coming from the steam drum. This measure increases the efficiency by 5%. As this special equipment is not commercially available, it is very expensive.

Other examples

Internal superheaters

In Lenzing (Austria) the steam parameters are 78 bar and 500°C. To reach these values the last superheaters are arranged in the fluidised bed cooler. There the ash and bed material of the circulating fluidised bed incinerator are fluidised by air and cooled by the heat exchanger bundles of the superheater. Because of corrosive nature of the ash in the cooler, the heat exchanger bundles are very likely to damage. [6]

External superheaters

A reheat cycle with saturated steam is limited in temperature. If the steam is superheated in external devices to avoid contact with the flue gas, even higher efficiencies are attainable. In Mainz (Germany) the steam is fed into the steam system of another combined cycle power plant, where it is superheated. [21]

In Bilbao (Spain) natural gas is used to superheat the steam. The pressure is similar to a normal power plant, the electrical efficiency with 42% too. [21]

Decrease of the auxiliary server power demand

In addition to a reduction of the air excess, frequency-controlled engines for blowers and pumps allow saving energy. [5]

3.4 Air pollution control (APC)

Waste incineration generates large volumes of flue gas charged with residues and harmful pollutants. The dust in the flue gas consists of fly ash and heavy metals in the form of particles. There are also pollutants in the form of harmful gases such as HCl, HF, SO_2, Hg, dioxins and NOx. As there are severe emission standards for waste incineration plants, all those pollutants have to be removed from the gas stream.

3.4.1 Dust collectors

Mechanical collectors (cyclones and multi-cyclones)

In a cyclone dust particles settle at the walls of the cyclone due to centrifugal forces. As it is demonstrated in Figure 3.9, the design of a cyclone is very simple; there are no moving parts in it. The cyclone is not sensitive to high temperatures or pressures. Cyclones are typical first-stage collectors that separate larger particles in an efficient way. The remaining dust content is too high to use a cyclone as the only dust collector. [73]
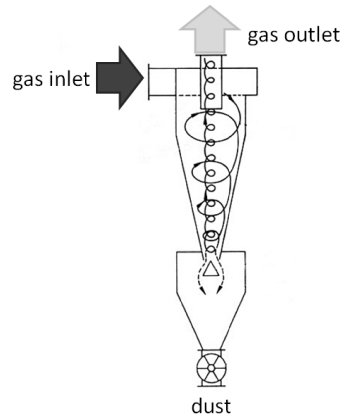
Figure 3.9: Cyclone, adapted [73]

Wet scrubbers

In a wet scrubber particulate and gaseous components are collected by water droplets. The droplets are settled afterwards in a cyclone. In a Venturi scrubber there is a throat, where the gas stream is accelerated (Figure 3.10). Water is injected at the narrowest point of the throat and it is dispersed into droplets. The waste water is acidic because water also removes HCl in the flue gas. The operation costs are high because of the high pressure drop in the Venturi scrubber. [57]
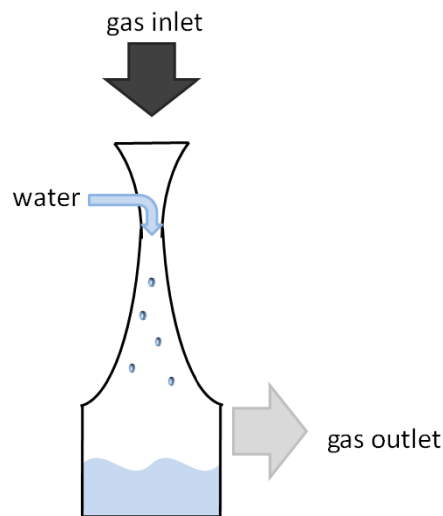
Figure 3.10: Venturi scrubber

Electrostatic precipitators (ESP)

The principle of an ESP is based on the forces exerted on charged particles in an electric field. In a simplified version an ESP comprises two parallel plates with an electrical field in between (Figure 3.11). Dust particles are charged by electrodes with corona discharge in the middle of the plates. Due to electrical forces they move towards the plates, where they are discharged and precipitated. [56]
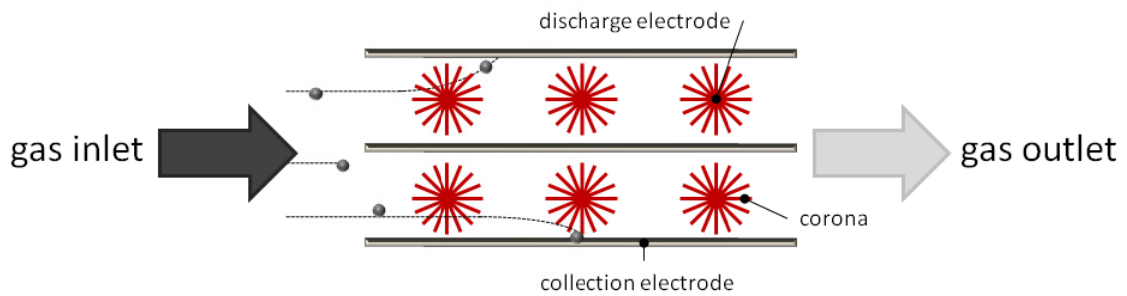
Figure 3.11: Principle of an electrostatic precipitator

ESP are usually used for large dust contents because of the high initial costs. The pressure drop is slight, thus the operation costs are low. The design is simple and robust; it is also possible to precipitate heavy metals except for Hg. [57]

The efficiency depends on the dust resistivity. Particles of too low resistivity are discharged very quickly, so that they are repelled from the electrode and get back into the gas stream. If the resistivity is too high, a continuous layer of charge is generated on the plates that weakens the electric field and causes discharge effects. Another inconvenience of the ESP is that there is no mechanical barrier trapping the particles. In case of a blackout the flue gas leaves the stack without being cleaned. [73]

Fabric filters

Fabric filters allow highly efficient collection of the finest particles and a reduction of the dust content to reach the mandatory limits. The raw gas enters a box with filter bags. They consist of nonwoven or needled felts of glass, plastic or ceramic fibres or of woven metal wires. It is possible to remove high dust loads ranging from several grams to hundreds of grams per cubic meter. At the beginning of the filtration particles are trapped in the interior of the filter layer. With increasing dust deposition on the layer a filter cake is formed, which collects the particles then (Figure 3.12). Acid gases may be removed too. [73]
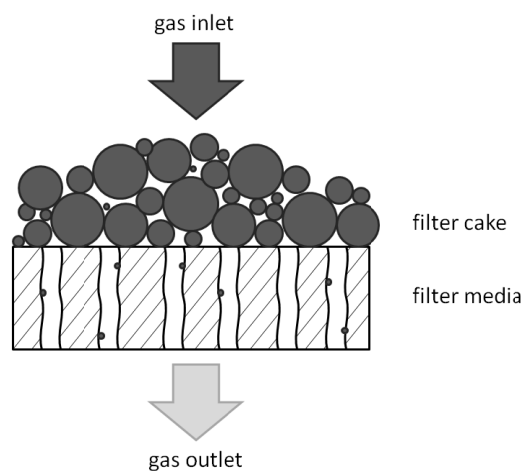
Figure 3.12: Fabric filter with filter cake

After a certain time the pressure drop caused by the filter cake increases too much and the filter bag has to be cleaned. A multi-chamber bag house is cleaned with shaker cleaning. The

gas feed is cut off in one chamber and the bags are shaken. There are dust hoppers to collect the dust. If pulse-jet filters are used, there are no chambers in the bag house. The filters are cleaned online with jets of compressed air. [73]

There are some restrictions for the use of fabric filters. They are not suitable for flue gas temperatures above 200°C. Fine dust may clog the filter and hygroscopic dust forms a dense coating on the filter cloth. [73]

Fabric filters are moderate in cost. [57]

3.4.2　　HCl, HF, SO$_2$ and Hg removal

Dry and semidry scrubber

Activated coke or Ca(OH)$_2$ is used as adsorption media as a function of the pollutants. Activated coke adsorbs gaseous heavy metals and their compounds such as Hg and also organic compounds such as dioxins. Ca(OH)$_2$ is used to precipitate SO$_2$.

In dry scrubbers solid Ca(OH)$_2$ is injected into the gas stream; in semidry ones lime slurry is dispersed. The reaction starts with the injection and ends at the dust separation. The acid gases are converted into solid substances. The products are CaCl$_2$, CaSO$_3$, CaSO$_4$ and CaF$_2$ and they are precipitated in the bag house filter. Unused adsorption material can be recycled to reduce the amount of reactant. The advantage of these concepts is the lack of waste water. The residues have to be disposed as hazardous waste. [56]

It is also possible to use a CaO suspension in semidry scrubbers. It contains more Ca per ton, which is the active compound, but it is more expensive. If activated carbon is added to lime, Hg and dioxins are precipitated too. [57]

Wet flue gas cleaning

The typical arrangement for a waste incineration plant is two-stage scrubbing.

First stage

This scrubber consists of two parts. In the first zone the hot flue gases are quenched with water in order to cool them and to reach the saturation temperature. There a part of the water evaporates. In the second zone gaseous pollutants are absorbed in water.

$$HF(g) + H_2O(l) \rightarrow HF(l) + H_2O(l) \tag{3.9}$$

$$HCl(g) + H_2O(l) \rightarrow HCl(l) + H_2O(l) \tag{3.10}$$

Nozzles are arranged in the scrubber so that small droplets of water are distributed evenly. Hydrated lime is added to the water of the scrubber and causes the absorbed pollutants to form their corresponding salts. Because of the remaining ions the pH value of the first stage is 1.

$$2HF(l) + Ca(OH)_2 (s,l) \rightarrow CaF_2(l) + 2H_2O(l) \tag{3.11}$$

$$2HCl(l) + Ca(OH)_2 (s,l) \rightarrow CaCl_2(l) + 2H_2O(l) \tag{3.12}$$
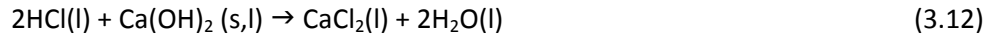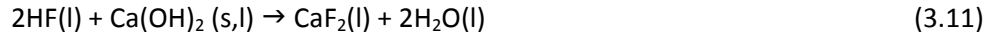
More than 95% of Hg is present as $HgCl_2$ due to the presence of chlorine and temperatures above 850°C in the furnace. $HgCl_2$ is also absorbed by water. [56]

In the first stage also a limited amount of SO_2 is removed. [73]

Second stage

The main task of this scrubber is the precipitation of SO_2. SO_2 has negative environmental and health effects. It is a major reason for acid rain, which causes forest dieback and erosion of structural and ornamental stonework. [50] Two different reactants can be used: NaOH or lime.

NaOH scrubber

NaOH solution is injected in a counter-current or cross flow scrubber. Due to NaOH the pH value is neutral or slightly acid. SO_2 is reduced with NaOH as the following:

$$SO_2 (g) + H_2O \rightarrow H^+ + HSO_3^- (l) \tag{3.13}$$

$$H^+ (l) + HSO_3^- (l) + \tfrac{1}{2} O_2 \rightarrow SO_4^- (l) + 2H^+ (l) \tag{3.14}$$

$$HSO_3^- (l) + Na^+ \rightarrow NaHSO_3 (l) \tag{3.15}$$

$$SO_4^- + Na^+ \rightarrow Na_2SO_4 (l) \tag{3.16}$$
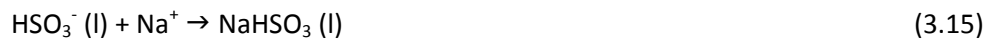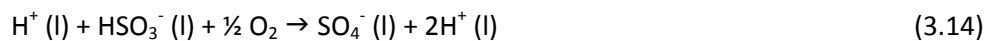
There are only soluble products; this is why a NaOH scrubber is easy to operate. Waste water of the second stage is added to the waste water of the first stage. The disadvantage of NaOH is that there is no use for the reaction products.

With an external precipitation step the Na_2SO_4 solution can be turned into gypsum. Therefore, $Ca(OH)_2$ is added to react with the sulphate ions. Afterwards gypsum is separated and dewatered. [56]

Gypsum scrubber

When limestone or hydrated lime reacts with the flue gases, gypsum is produced. At the bottom of the scrubber air is blown into the solution for the oxidation reaction. Thus water can be removed more easily. Gypsum is dewatered by means of centrifuges or bandfilters. The clear fraction is returned to the scrubber, a small part of it goes to the waste water treatment. [73] [56]

$$\text{Absorption:} \quad SO_2 (g) + H_2O (l) \rightleftarrows SO_2 (l) + H_2O (l) \tag{3.17}$$

$$\text{Neutralisation:} \quad SO_2 + CaCO_3 + x\,H_2O \rightarrow CaSO_3 \cdot xH_2O + CO_2 \tag{3.18}$$

$$\text{Oxidation:} \quad CaSO_3 \cdot \tfrac{1}{2} H_2O + \tfrac{1}{2} O_2 + 2\,H_2O \rightarrow \tag{3.19}$$
$$CaSO_4 \cdot 2\,H_2O + \tfrac{1}{2} H_2O$$
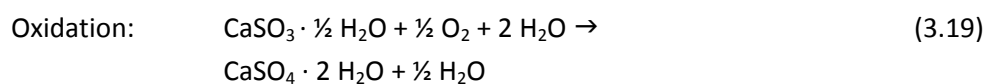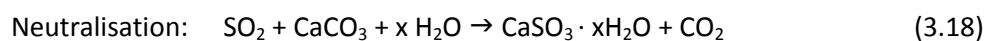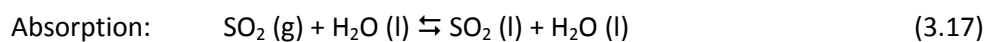
3.4.3 Sorbent injection system for SO_2 control

In a fluidised bed reactor pollutants can be precipitated during combustion in the bed. Limestone or hydrated lime is added as dry sorbent to react with sulphur oxides. The maximum reaction rate occurs at 800-950°C, in the fluidised bed the temperature is kept within 750-900°C.

$$\text{Limestone:} \qquad CaCO_3 \rightarrow CaO + CO_2 \text{ (endothermic)} \qquad\qquad (3.20)$$

$$\text{Hydrated lime:} \quad Ca(OH)_2 \rightarrow CaO + H_2O \text{ (endothermic)} \qquad\qquad (3.21)$$

$$\text{Sulphation:} \qquad CaO + SO_2 + 0.5O_2 \rightarrow CaSO_4 \text{ (exothermic)} \qquad\qquad (3.22)$$
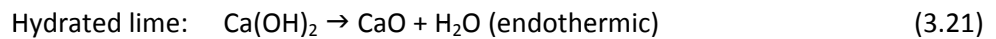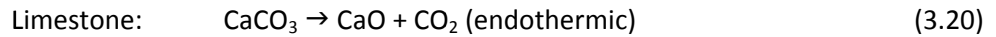
The efficiency depends on the Ca/S ratio, which is defined as the ratio of the amount of Ca in the limestone or hydrated lime and the amount of S in the fuel. If hydrated lime is used and the Ca/S ratio is 2, an efficiency of 50% is reached. It is considerably lower if limestone is used with the same Ca/S ratio because hydrated lime is more reactive but also more expensive. The efficiency also depends on the particle size of the sorbent. The reaction occurs on the particle surface and as the $CaSO_4$ layer is very tight, the reaction stops when the surface is completely covered. With a particle size smaller than 5 μm and an even distribution in the bed the excess of sorbent can be decreased and the conversion maximised. The average particle size of hydrated lime is about 5 μm, limestone particles are in the range of 20 μm. [30]

In addition to the reaction with SO_2 chlorine and fluorine are also removed. The optimum temperature range for these reactions is 300°C. As the temperature in the bed is higher, only 50-80% of the chlorine and 90-99% of the fluorine are captured. [30]

3.4.4 NOx removal

The emission of nitrogen oxides such as NO, NO_2, N_2O is collectively referred as NOx. There are several sources for the formation of NOx.
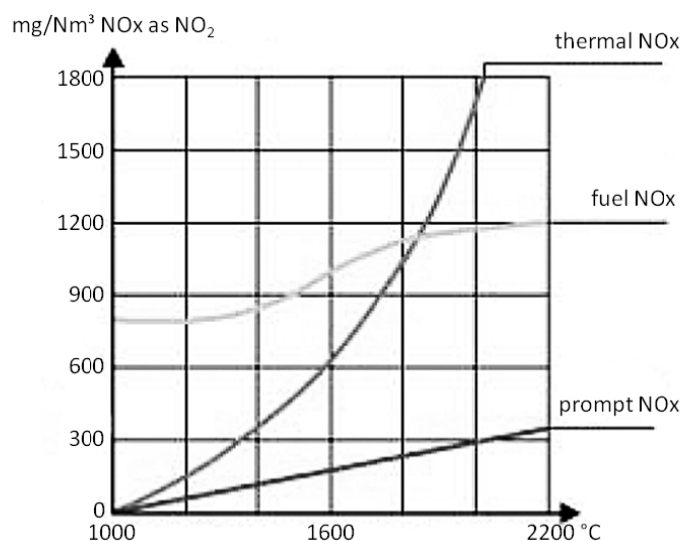
Figure 3.13: Sources for the formation of NOx, adapted [56]

Thermal NOx is atmospheric nitrogen, which turns into NO with increasing temperature. Oxygen radicals react with atmospheric nitrogen as the following (Zeldovich mechanism): [50]

$$O* + N_2 \rightarrow NO* + N* \tag{3.23}$$

$$N* + O_2 \rightarrow NO* + O* \tag{3.24}$$

The major part of thermal NOx is formed above 1300°C; the reaction rate is a function of temperature and is proportional to the concentration of oxygen. [56]

Prompt NOx is generated, when CH radicals attack atmospheric nitrogen.

Fuel NOx is released from chemically bound nitrogen in the fuel in the form of HCN and HNCO. Similar to the prompt NO mechanism, these species are converted to NHx and then to NO.

In Figure 3.13 the temperature dependence of the NOx formation is illustrated.

More than 90% of the NOx is NO. The NO_2 formation increases with decreasing temperature. That is why NO_2 is formed by further oxidation of NO in colder parts of the furnace. [50]

$$NO + HO_2* \rightarrow NO_2 + OH* \tag{3.25}$$

Primary measures

To hinder the formation of thermal NOx, the temperature in the furnace is held below 1500°C. If the nitrogen content in the fuel cannot be reduced as it is true for waste, staged combustion can be applied to reduce the formation of fuel NOx. In the first stage waste is burned with sub-stoichiometric air supply (λ<1). In an atmosphere of oxygen deficiency NOx formation stops and part of NOx that is already present can be reduced. Fuel nitrogen is released as N_2. In a second step the gases are burned completely with oxygen excess.

Flue gas recirculation is also a primary measure against NOx. Flue gas is injected as a part of the primary air. Thus, the oxygen concentration in the primary air is reduced. In addition to that, the total calorific value of all substances in the combustion chamber is reduced because the flue gas has no calorific value. A decreased calorific value reduces the temperature in the furnace. [50]

Secondary measures

Secondary measures remove a pollutant that is already present. NO is reduced with NH_3, which is injected in the form of an aqueous solution. This reaction occurs at high temperatures or with the aid of a catalyst.

$$4NH_3 + 4\,NO + O_2 \rightarrow 6H_2O + 4\,N_2 \tag{3.26}$$
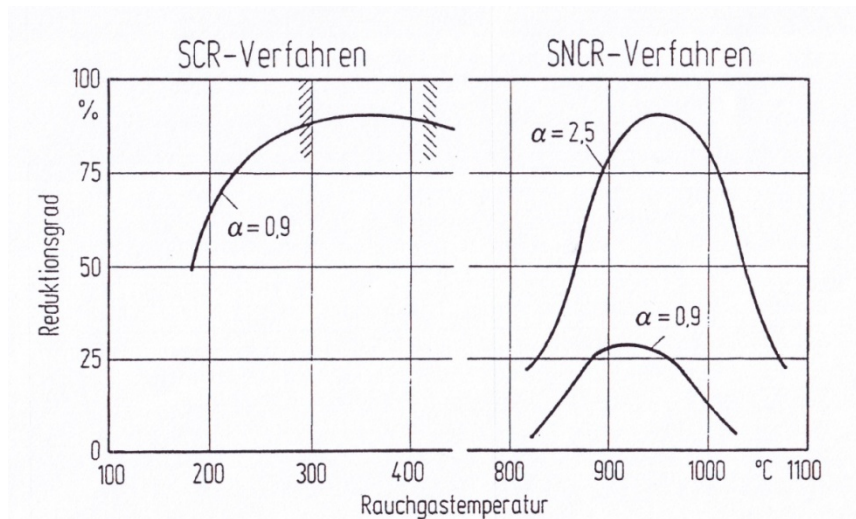
Figure 3.14: Temperature range for SCR und SNCR, [34]

In Figure 3.14 the necessary temperature range for the application of an SCR or SNCR system is indicated. The rate of conversion is plotted versus the flue gas temperature. The parameter α is defined as the ratio of moles of NH_3 and moles of NOx. When α increases, the rate of conversion is increasing, but the surplus of NH_3 remaining in the flue gas is rising too.

SNCR = Selective non-catalytic reduction

As the reaction occurs as a homogenous gas-phase reduction in a temperature range of 800-1000°C, NH_3 is injected into the furnace or into the afterburner chamber. [56] The surplus of NH_3 remains in the flue gas and can be converted to NH_4Cl in an acid scrubber. [73]

50-60% of NO is converted by SNCR. There are no solid or liquid residues. In addition to that, the de-novo-synthesis of dioxins and furans is hindered because of the presence of ammonia. [56]

SCR = Selective catalytic reduction

There are two possibilities for the arrangement of the SCR device in the air pollution control system.

Crude gas circuit (Figure 3.15): Ammonia is added to the hot flue gases from the steam generator as reducing agent. The gases pass over the catalyst without any precleaning. There are fixed bed catalysts with bulk honeycombs made of titanium or vanadium oxides and moving bed catalysts using activated carbon as adsorbent. [73]
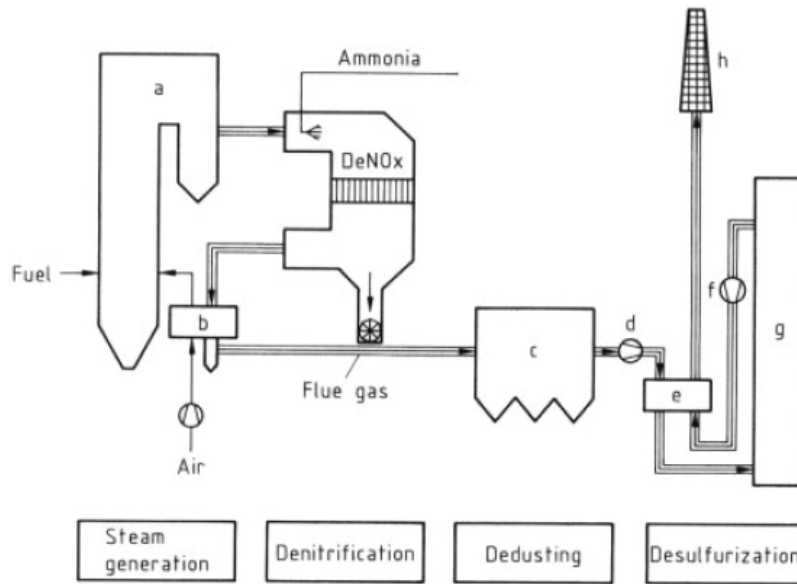
a) Steam generator; b) Air preheater; c) Filter; d) Induced-draught blower; e) Gas heater; f) Blower; g) Washer; h) Stack

Figure 3.15: SCR in the crude gas circuit, [73]

Clean gas circuit (Figure 3.16): Dust and sulphur oxides have already been removed from the flue gas. The gas has to be preheated to reach the necessary reaction temperature of 300°C. Fixed bed catalysts for the clean gas circuit are similar to those for the crude-gas circuit. Due to the clean gas, the activity of the catalyst is higher and the life cycle of the equipment is longer. [73] The lifetime of catalysts in the clean-gas circuit is at least 10 years. [56]
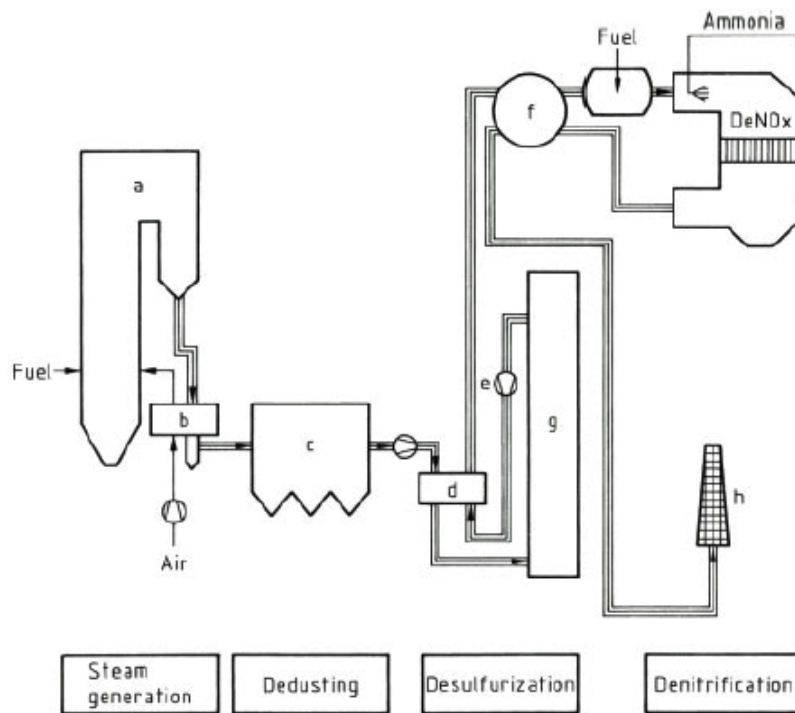
a) Steam generator; b) Air preheater; c) Filter; d) Gas heater; e) Blower; f) Gas heater; g) Washer; i) Stack

Figure 3.16: SCR in the clean gas circuit, [73]

3.4.5 Dioxins and furans (PCDD, PCDF)

Dioxins and furans are formed out of carbon compounds and organic and inorganic chloride compounds as side reactions of incomplete combustion. The reaction is conducted the fastest at 300°C, the reaction rate decreases severely at 600°C. At higher temperatures dioxins are dissociated. At 850°C dissociation is quantifiable. Oxygen deficiency and excess accelerate the reaction, the presence of copper and other metals in the fly ash too. The formation of dioxins and furans occurs on hot surfaces. That is why they are mainly bonded to fly ash particles.

75 types of dioxins and 135 furans are collectively referred as PCDD and PCDF. They are very stable and toxic. TCDD, also known as Seveso dioxin, is the most toxic substance in the world. The toxicity of a mixture of dioxins and furans is classified in toxicity equivalent quantities TEQ in reference to TCDD. The emission limit for a waste incineration plant in Austria is 0.1 ng TEQ/m³. [60]

It is imposed by law that the flue gas of a waste incineration plant has to reach 850°C for more than 2 s. If there is more than 1% by mass of halogenated compounds, the temperature has to be raised to 1100°C [3]. At 850°C dioxins and furans are destroyed.

De-novo-synthesis of dioxins and furans occurs in a temperature range of 200-500°C, when the flue gas is cooled in the boiler. For the reaction chloride, oxygen and carbon or metal as catalyst are necessary. Primary measures against the formation of dioxins require a high cooling rate at the critical temperature of 300°C and complete combustion, above all complete oxidation of carbon compounds. If dust is precipitated at high temperatures and dust depositions in the boiler are avoided, the risk of de-novo-synthesis is reduced. [56]

By secondary measures the dioxin and furan concentration can be further diminished in the air pollution control system. As the major part of the dioxins is bonded to fly ash particles, they are precipitated in the dust collector.

Activated carbon filters can be used to remove residual dioxin. They are multifunctional separators for heavy metals, organic trace substances and HCl and SO_2 that have passed the scrubber. There are different arrangements: fixed or moving bed reactors, but also injection of adsorbents in the gas flow with precipitation. [73]

In the fixed bed reactor (Figure 3.17) the precleaned gas reacts with activated coke at 100-130°C. The gas inlet is located at the bottom of the reactor. Dust, aerosols and gaseous organic pollutants are removed. Loaded coke is incinerated afterwards, thus organic pollutants are destroyed and inorganic compounds are trapped in the slag. [56]
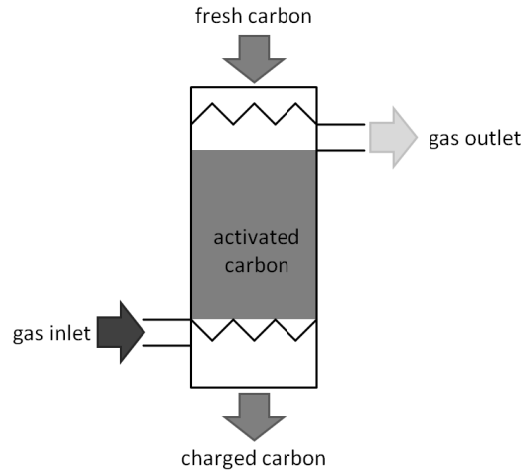
Figure 3.17: Activated carbon fixed bed filter

The flow injection process comprises adsorption and filtration. The precleaned gas is thoroughly mixed with the powdery adsorbent, which is a mixture of activated coke and hydrated lime to adsorb organic pollutants and heavy metals. Activated carbon only traps dioxins but does not destroy them. Spent adsorbent is precipitated in a downstream dust collector, as it is shown in Figure 3.18. [56]
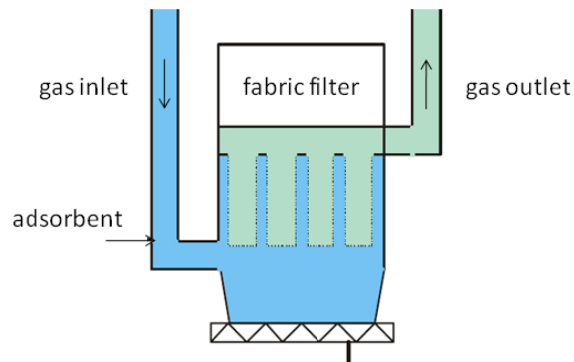
Figure 3.18: Flow injection process with fabric filter, [6]

Reactors with activated carbon and hydrated lime are also used to remove simultaneously SO_2, NOx and dioxins in a dry flue gas cleaning equipment. In a circulating fluidised bed reactor the adsorbents and gas are mixed intensively. Particles are precipitated in dust collectors afterwards (Figure 3.19).
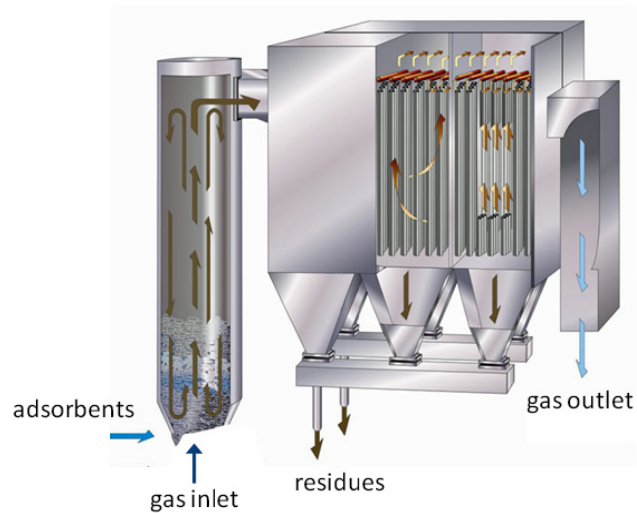
Figure 3.19: Fluidised bed adsorption reactor, [2]

In a SCR reactor 90-95% of PCDD and PCDF are catalytically oxidised as a side reaction. There is no additional residue. [56]

Waste incineration plants are the best analysed dioxin emitters. A modern plant is a dioxin sink because dioxin in the waste is destroyed and the emission of dioxin in the flue gas is far below the emission limit value. Figure 3.20 shows the development of waste incineration plants in terms of dioxin emissions. [10]
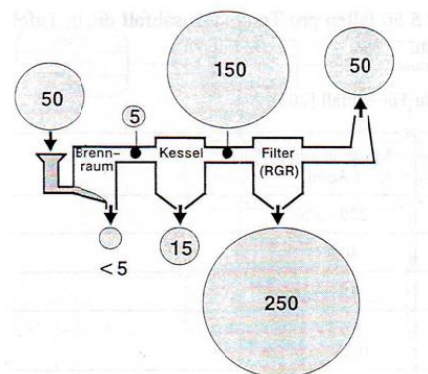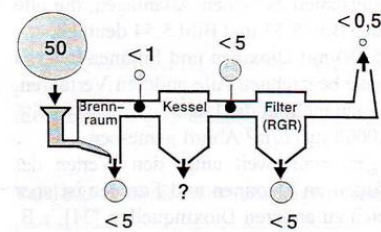
Figure 3.20: Balance of dioxins in old and modern waste incineration plants, [10]

3.4.6   Overview on technologies used in Austria

Grate firing

In Table 3.6 the air pollution control system for Austrian grate incinerators is contrasted. The numbers in the table indicate the order of the flue gas cleaning equipment. If there are two numbers for one device, it is used twice. Devices with the same number belong together.

Three different types of air pollution control systems can be distinguished.

- ESP + multi-stage scrubbing + SCR
- Dry SO_2 absorption + fabric filter + multi-stage scrubbing + SCR
- Dry flue gas cleaning

A completely dry flue gas cleaning system is installed in Arnoldstein and a similar system is planned in Zistersdorf, both plants with a rather small furnace capacity.

Dust is precipitated by ESP or fabric filters. Fabric filters precipitate fine dust more efficiently. That is the main reason why in many industrial applications ESP are now replaced by fabric filters. Flue gas containing condensable salts, as it is true for waste incineration, can clog fabric filters permanently. In general, ESP are implemented in older waste incineration plants. In more modern ones fabric filters are used. All plants in Vienna and Wels were equipped with ESP. In Spittelau an additional Venturi scrubber lowers the amount of fine dust considerably. The APC system of Flötzersteig, which is the oldest plant in Austria, had to be adapted to new emission limits. In 2006 the ESP was changed into fabric filters. In line 2 in Wels, which was commissioned in 2006, dust is precipitated by an ESP and a fabric filter.

In older plants NaOH scrubbers with external precipitation of gypsum are implemented, in contrast to newer ones, where gypsum scrubbers can be found. In line 1 in Wels a NaOH scrubber is used. Line 2 in Wels is also equipped with a NaOH scrubber because the waste water of both lines is cleaned in a joint treatment stage.

NOx emissions are controlled by SCR systems in all plants. Only the low dust system is applied in Austria.

To reduce the amount of organic trace compounds different systems such as flow injection or fixed bed reactors with activated carbon or furnace coke are implemented in addition to the SCR system.

grate firing	commissioning	nominal capacity (t/h)	ESP	fabric filter	Venturi	dry SO$_2$	acid scrubber	NaOH + gypsum	gypsum	SNCR	SCR clean	AC fixed bed	flow injection	catalytic oxidation
Flötzersteig	1963	25		2		1	3	4			5			5
Spittelau	1971	32	1		4		2	3			5			5
Wels 1	1995	9	1				2	3			5	4		
Wels 2	2006	30	1	5			2	3			6		4	
Arnoldstein KRV	2004	11		2		1					4	3		
Dürnrohr	2004	48		2		1	3		4		5		2	
Pfaffenau	2008	32	1				2		3		5	4		
Zistersdorf	2009	17		2		1					3		1	3
Dürnrohr 3	2010	38		2		1	3		4		5		2	

Rotary kiln

The rotary kiln in Arnoldstein is the only incineration plant, where a SNCR system is used. As hazardous waste is incinerated in Simmering, the APC system is more complex and comprises four stages of wet scrubbers.

Table 3.7: APC systems after rotary kiln firings in Austria

rotary kiln	commissioning	nominal capacity (t/h)	ESP	fabric filter	Venturi	dry SO$_2$	acid scrubber	NaOH + gypsum	gypsum	SNCR	SCR clean	AC fixed bed	flow injection	catalytic oxidation
Simmering 1,2	1980	20	1		4,5		2	3			7	6		
Arnoldstein ABRG	2005	3		1		4	2	3		5			4	

Fluidised bed incinerators

Again three different arrangements of APC systems can be distinguished.

- ESP + multi stage scrubbing + SCR
- Cyclone + dry sorption + fabric filters + multi stage scrubbing + SCR
- Dry flue gas cleaning

Stationary fluidised bed incinerators are equipped with ESP except for the waste incineration plant in Niklasdorf. All circulating fluidised bed incinerators use cyclones as first stage precipitators. In Heiligenkreuz it is planned to implement a dry flue gas cleaning system, where no waste water is produced.

Table 3.8: APC systems after fluidised bed incinerators in Austria

stationary FB	commissioning	ESP	fabric filter	Venturi	dry SO_2	acid scrubber	NaOH + gypsum	gypsum	SNCR	SCR clean	AC fixed bed	flow injection	catalytic oxidation	cyclone
Simmering 1-2	1980	1		4,5		2	3			7	6			
Simmering 3	1992	1		4,5		2	3			7	6			
ABRG	2001	1			4	2	3			5		4		
WSO4	2003	1		4,5		2	3			7	6			
Niklasdorf	2004		3		2	4		5		6		2		1
circulating FB														
Lenzing	1998		3		2	4		5		6		2		1
Heiligenkreuz	2010		3		2					4		2		1
Frohnleiten	2010		3		2	4		5		6		2		1
Linz	2011		3		2	4		5		6		2		1

Assembly of an air pollution control system

In Figure 3.21 the air pollution control system of a hazardous waste incineration plant is illustrated. Waste is incinerated in a rotary kiln with afterburner chamber and waste heat boiler. To reach the necessary temperature for the ESP, the hot flue gases are quenched in an evaporative cooler. After the wet ESP, where particles and a part of the heavy metals are precipitated, the flue gases pass a two stage scrubbing system. Prior to the removal of NOx in the SCR reactor the gases are reheated. A mixture of activated carbon and lime is injected to trap dioxins, furans and acid compounds that have passed the scrubber. A fabric filter removes the reactants and the remaining particles before the gases leave the plant via the stack.
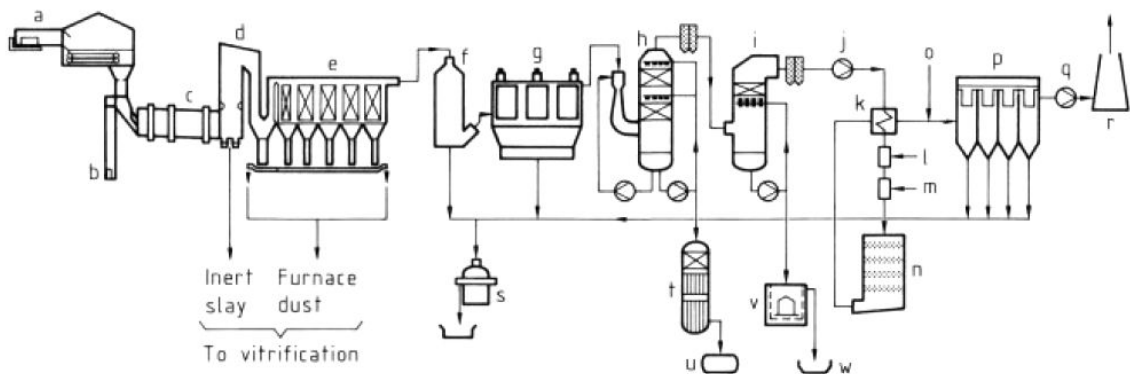
a) Material supplied in containers; b) Charging of drums; c) Rotary furnace; d) Post-combustion equipment; e) Waste-heat boiler; f) Evaporative cooler; g) Electrostatic scrubber; h) HCl scrubber; i) SO_2 scrubber; j) Suction pump 1; k) Heat exchanger; l) Burner; m) Aqueous ammonia addition; n) Combination catalyst; o) Addition of activated coke – lime mixture; p) Filter/adsorber; q) Suction pump; r) Stack; s) Fly ash vitrification; t) Hydrochloric acid recovery; u) Container for hydrochloric acid; v) Gypsum dewatering; w) Gypsum silo

Figure 3.21: Air pollution control system, [73]

3.5   Waste water treatment

Waste water, which is produced in wet scrubbers, wet ESP and in the ash and slag treatment, requires waste water treatment.

Usually, it is a multi stage treatment. In the first stage heavy metals are removed by precipitation, flocculation and sedimentation. The waste water has to be neutralised by adding alkaline or acid species; the sludge containing heavy metals is dewatered.

In the second stage the waste water flows through a gravel filter. An activated coke filter can be used to precipitate organic compounds. An ion exchanger removes heavy metals and organic trace compounds very effectively but it has high operation costs. [56]

It is also possible to produce technical grade HCl from the waste water of the acid scrubber in a three stage scrubbing process. First dust and heavy metals are removed, and then the concentration of the acid is adjusted. In the third scrubber the final purification takes place. Technical grade HCl is removed and distilled. [73]

3.6 Residues from waste incineration

3.6.1 Grate firing

```
         Wastes              Air
         1000 kg           6450 kg

Slag 300kg
Iron metal                Combustion
ca. 30 kg
Boiler ash 7 kg
Filter dust 40 kg        Flue gas cleaning
Mixed salts
10 kg
                          Off-gas
                          7063 kg
```
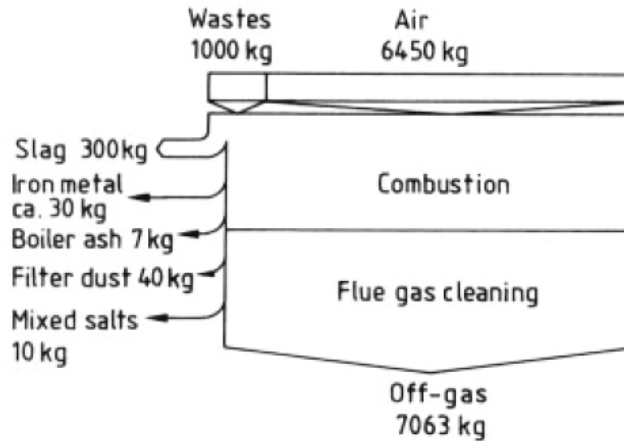
Figure 3.22: Mass balance of a grate incinerator, [66]

A major reason for waste incineration is the reduction of volume and mass to be landfilled. The residues from incineration are slag, which are incombustible parts that are removed from the rear end of the grate, ash and residues from the air pollution control system. Figure 3.22 presents a mass balance of a waste incineration plant with grate firing.

Slag is the major waste product; 30% by weight of the initial amount of waste remain as slag and are discharged at the end of the grate. It consists of 85-90% by weight of mineral compounds such as silicon, sulphates, calcium, etc., 7-10% of scrap metals and 1-5% of unburned material. Slag is less polluted by dioxins and furans. [38]

The content of total organic carbon in the slag is limited by the law to a maximum of 3%. [3]

There are several further treatment steps for the slag in order to reuse it or to dump it safely. Ferrous metals are recovered with magnetic separators and sold to a scrap dealer. They can be reused in the steel industry. Slag may be washed with water to extract soluble pollutants, mainly chloride, sulphates and heavy metals. Thus the leakage behaviour is improved. Slag can be solidified with binding systems to immobilise pollutants. It is also possible to treat slag thermally to reduce the content of heavy metals and dioxins. [56]

Very fine particles, molten plastics and metals with a low melting point such as lead, are able to penetrate the primary air openings of the grate. The fraction represents 0.1-2% of the waste. It may be either reintroduced to the furnace or mixed into the slag. [57]

Boiler ash is settled in the boiler due to gravity and is discharged via the bottom hoppers. Particles precipitated in the dust collectors are called filter dust. It is a mixture of fly ash and reaction products from the flue gas cleaning system. The ash represents approximately 4% by weight and it consists of inert, mineral particles, soluble salts and condensed heavy metal compounds; it is very fine and dusty. As there is no industrial use for it because of the salts and the heavy metals, it is landfilled. [66]

The filter cake of the waste water treatment is heavily charged with Hg. The concentration of Zn and Cd are also very high. Thus, it has to be disposed in an underground depot.

Loaded activated carbon from the flue gas cleaning system can be combusted in the waste incineration plant. [56]

Residues from a dry flue gas cleaning system are mainly the reaction products $CaCl_2$, CaF_2 and $CaSO_3$ and the $Ca(OH)_2$ excess. The total amount of the residues is approximately 30-50 kg/t waste. There is no use for these residues either, so they are landfilled. $CaCl_2$ is soluble by rain water. Due to $Ca(OH)_2$ the pH value of the solution is 12, where lead is soluble too. Thus, water pollution by the leakage has to be prevented and a watertight cavity, for example an old salt mine, is considered to be a good landfill site for filter dust. [57]

3.6.2   Fluidised bed reactors
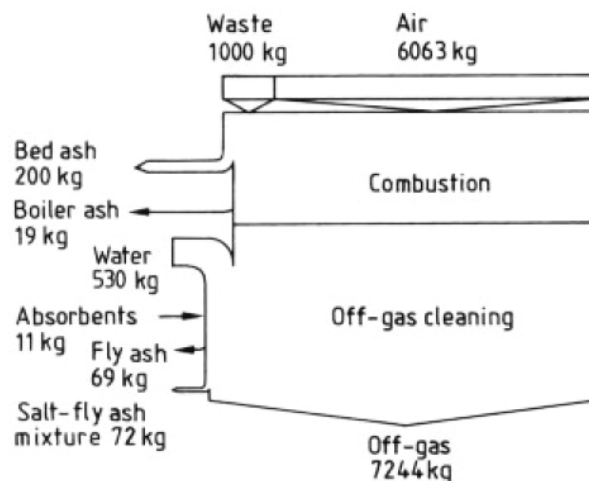
Figure 3.23: Mass balance of a fluidised bed reactor, [66]

In comparison to grate incinerators, the air excess in fluidised bed reactors is lower. Figure 3.23 shows that the difference is 400 kg of air, when 1000 kg of waste are incinerated.

Particles of higher specific gravity sink in the fluidised bed; they are discharged through the grate. The bed ash consists of silicon, aluminium, cadmium and other incombustible compounds and oversize material. A part of the bed ash may be reintroduced to the bed. Fly ash is finer and contains heavy metals. [66]

3.6.3 Rotary kiln
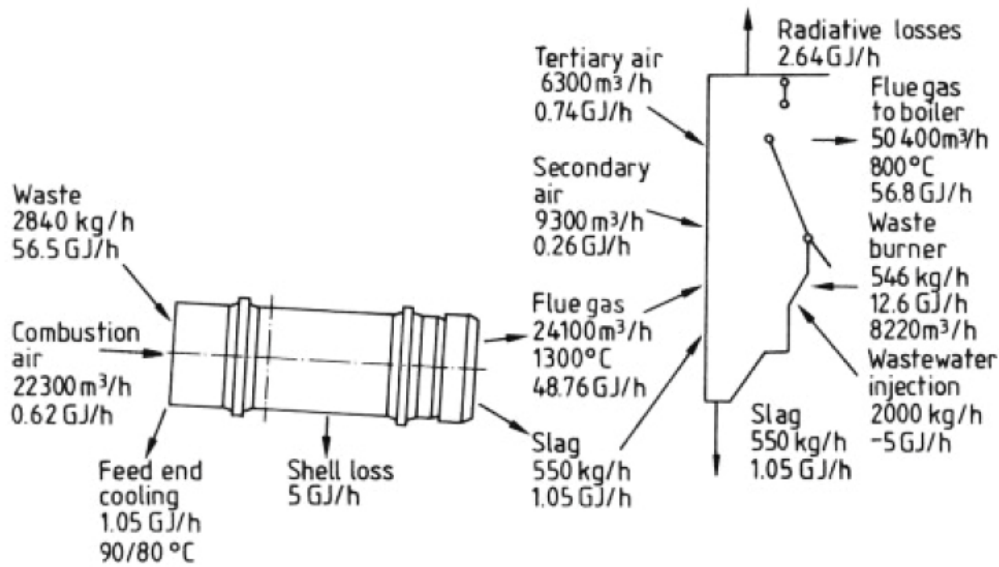
Figure 3.24: Mass and energy balance of rotary kiln, [66]

In Figure 3.24 there is a mass and energy balance of a rotary kiln. The solid residues from a rotary kiln incinerator are ash and slag. Ash is discharged wet or dry. If the temperature in the kiln is very high, liquid slag is formed, where metal oxides are trapped in inert material. Liquid slag has to be discharged into a water quench. [66]

3.7 Legal regulations for waste incineration in Austria

In Austria the "Abfallverbrennungsverordnung" (BGBl. II Nr. 296/2007) [3] regulates waste incineration plants and relates to standards and methodologies required by the European Union (Waste Incineration Directive). The aim of the regulation is to minimise negative effects on the environment and human health because of emissions from waste incineration.

It is imposed by law that the generated heat has to be recovered as far as practicable. Concerning the operation conditions (article 1, section 2) it is said that the temperature of the combustion gas after the last injection of combustion air has to reach 850°C for at least 2 s even under most unfavourable conditions. Each line of the incineration plant has to be equipped with an auxiliary burner to control the temperature of the gas. Hazardous waste of a content of more than 1% halogenated organic compounds has to be burned at 1100°C for at least 2 s.

According to Article 1 §9 several process operation parameters have to be measured continuously:

- the temperature near the inner wall of the combustion chamber
- volume flow rate and temperature of the exhaust gas
- pressure
- concentration of oxygen

Table 3.9 gives an overview on air emission limit values for waste incineration plants in Austria.

Table 3.9: Air emission limit values in Austria

air pollutant		half-hourly average value	daily average value
dust	mg/m³	10	10
total organic carbon	mg/m³	10	10
HCl	mg/m³	10	10
HF	mg/m³	0.7	0.5
SO_2	mg/m³	50	50
NOx nominal capacity < 2 t/h	mg/m³	300	200
NOx nominal capacity: 2-6 t/h	mg/m³	200	150
NOx nominal capacity > 6 t/h	mg/m³	100	100
CO	mg/m³	100	50
Hg	mg/m³	0.05	0.05

air pollutant		average value	sample period
Cd, Tl	mg/m³	0.05	0.5-8 h
total of Sb, As, Pb, C, Co, Cu, Mn, Ni, V, Sn	mg/m³	0.5	0.5-8 h
NH_3	mg/m³	5	0.5-8 h
dioxins and furans	ng/m³	0.1	6-8 h

There are water emission limit values too.

Incineration plants shall be operated in such way that complete combustion is achieved. Thus, the content of total organic carbon TOC in the ash and slag is limited to less than 3%. The amount and harmfulness of residues shall be minimised. [3]

3.8   European Waste Framework Directive [12]

The European Parliament passed the new Waste Framework Directive in June 2008. It is the new waste legislation, which emphases on reuse and recycling of waste. The target for 2020 is to recycle 50% of paper, metal and glass from households and similar waste streams.

A five-stage waste hierarchy has been established, which shall be treated as an order of preference for waste operations:

1. prevention
2. preparing for reuse
3. recycling
4. other recovery, e.g. energy recovery
5. disposal

Waste incineration may be classified as a recovery operation R1, where waste is principally used as fuel or other means to generate energy, or as disposal D10. The classification depends on the energy efficiency of the incineration facility. An energy efficiency formula is included in annex II to the directive:

$$R1 = \frac{E_P - (E_F + E_i)}{0.97\,(E_W + E_F)} \tag{3.27}$$

In this formula E_P is the annual energy produced as heat or electricity in GJ. To evaluate and summarise different kinds of energy, there are equivalence factors. It is 2.6 for electricity, assuming an overall European average of 38% conversion efficiency for electrical power generation. The factor for heat is 1.1 with an efficiency of 91% for heat generation. It is not specified, whether E_P is the net or gross production.

$$E_{P,net} = E_{P,gross} - \Sigma\,\text{auxiliary power demand} \tag{3.28}$$

E_F means the annual energy input to the system from fuels contributing to the production of steam, E_W is the energy content of the waste, using the lower net calorific value. E_i comprises additional imported energy. Energy losses due to bottom ash and radiation are accounted with the factor 0.97.

If the energy efficiency R1 is equal or above 0.60 for installations in operation before 2009, and equal or above 0.65 for installations permitted after the end of 2008, the incineration facility is classified as a recovery facility.

Energy efficiency R1 equal to 1 signifies that the conversion process in the waste incineration plant is close to standard processes.

The regulation of shipment of wastes (No 1013/2006) [44] provides that waste, which is recycled energetically in a R1 facility, is subject to the principle of free movement of goods in the EU. By contrast, waste disposal in a D10 facility has to meet the principles of proximity, priority for recovery and self-sufficiency at community and national levels. Waste should be disposed close to where it is produced.

3.8.1 Comparison of electrical efficiency and R1 value [21]

It is assumed that the waste incineration plant only generates electricity.

$$\eta_{el,net} = \frac{\text{output} - \text{auxiliary power demand}}{\text{thermal output of the waste}} \tag{3.29}$$

A simplified formula is applied without considering the use of auxiliary fuels. E_P is the gross production including the auxiliary service power consumption.

$$R1 = \frac{2.6\,E_P}{0.97\,E_W} \tag{3.30}$$

Key data of a standard waste incineration process:

- steam parameters: 40 bar, 380°C
- incineration of 21.6 t/h
- calorific value of the waste: 10 MJ/kg
- temperature of the flue gas at the end of the boiler: 209°C
- air excess = 1.75
- air cooled condenser with 150 mbar
- auxiliary service power consumption: 2.1 MWel = 0.1 MWh/t waste

The standard process reaches a net electrical efficiency of 20.6%, which corresponds to a R1 value of 0.63. The limits for R1 incineration facilities are 0.6 and 0.65 corresponding to an efficiency of 19% and 21%. The exact values change as a function of the auxiliary service power consumption. If auxiliary fuel is added, the R1 value decreases. The R1 value rises if heat is recovered additionally.

4 Waste gasification

4.1 Physical principle of gasification

Gasification is the conversion of solid carbonaceous materials into combustible gases by gasification agents. The first industrial application of gasification was coal gasification in order to produce town gas. The range of potential feeds is large; it is possible to gasify any carbonaceous material, including oil, biomass and waste. The principle is virtually always the same, thus the reactions can be described by the gasification of pure carbon. [24]

Similar to combustion, gasification consists of three sub-processes. When feedstock is heated, it is dried first and then devolatilisation occurs. During devolatilisation macromolecules are thermally destroyed and volatile matter is released. Gaseous carbon compounds, pyrolysis oils and char, which consists mainly of carbon and ash, remain. The gasification agent does not get close enough to the particles to react because of the escaping gases. If the conversion is stopped at this point, the process is called pyrolysis. It is schematically shown in Figure 4.1. [32]

When devolatilisation is finished, the remaining char reacts with the gasification agent and is converted into combustible carbonaceous gases (Figure 4.2). In contrast to drying and devolatilisation that consist only of endothermic reactions, gasification reactions are partly exothermic and partly endothermic. [32]
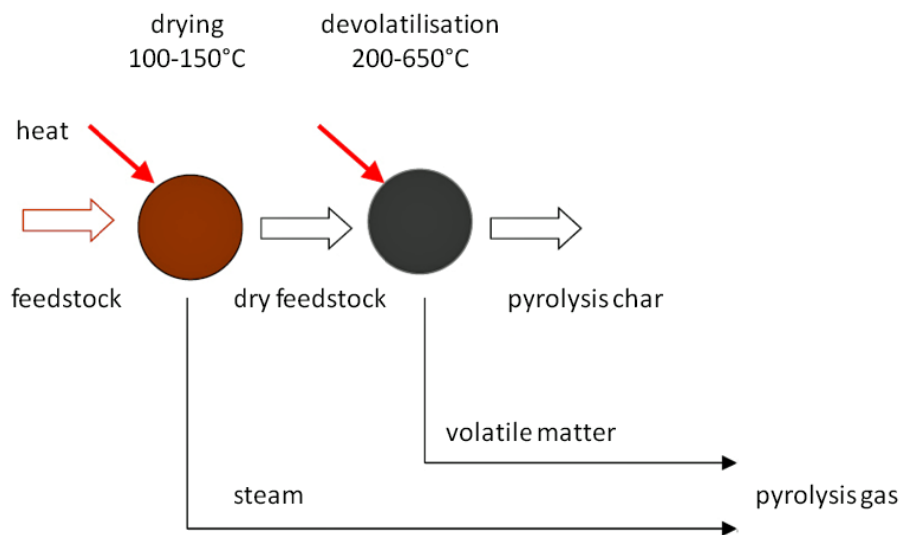
Figure 4.1: Sub-processes of pyrolysis, adapted [32]
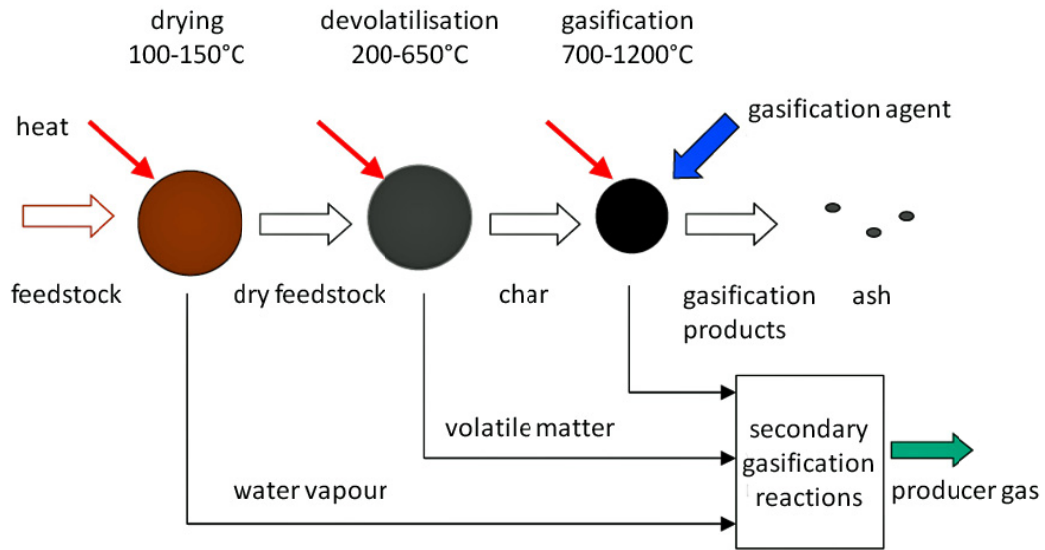
Figure 4.2: Sub-processes of gasification, adapted [32]

4.2 Reactions

Oxygen, steam, carbon dioxide and hydrogen can be used as gasification agents, which react with carbon to form gaseous compounds. In general, air, steam or steam-oxygen mixtures are used. As gases react with solids, the reactions are classified as heterogeneous reactions. Carbon is completely or partially oxidised to CO and CO_2 in exothermic oxidation reactions, which provide the heat necessary for drying, devolatilisation and reduction. Gasification requires temperatures above approximately 700°C.

$$C + O_2 \rightarrow CO_2 \qquad \Delta H = -394 \text{ kJ/mol} \qquad \text{complete oxidation} \qquad (4.1)$$

$$C + \tfrac{1}{2} O_2 \leftrightarrows CO \qquad \Delta H = -111 \text{ kJ/mol} \qquad \text{partial oxidation of carbon} \qquad (4.2)$$
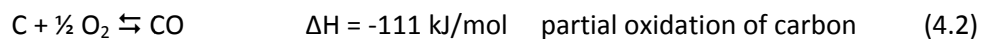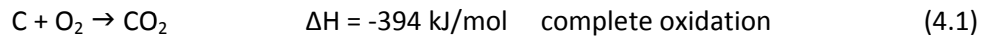
The water gas reaction and the Boudouard reaction are endothermic reductions, where the major part of combustible gases is formed. CO_2 and H_2O are generated during combustion and are reduced by carbon to yield CO and H_2. Due to gas formation the volume increases.

$$C + H_2O \leftrightarrows CO + H_2 \qquad \Delta H = +119 \text{ kJ/mol} \qquad \text{water gas reaction} \qquad (4.3)$$

$$C + CO_2 \leftrightarrows 2CO \qquad \Delta H = +160 \text{ kJ/mol} \qquad \text{Boudouard reaction} \qquad (4.4)$$
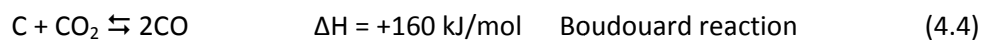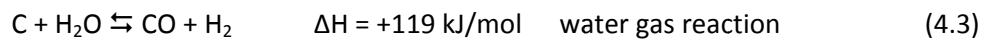
The gases yielded in the reactions above, CO and H_2, are converted further in homogeneous reactions such as the water gas shift reaction and the steam methane reforming reaction. Carbon can be gasified by H_2 in the heterogeneous methanation reaction.

$$C + 2H_2 \leftrightarrows CH_4 \qquad \Delta H = -88 \text{ kJ/mol} \qquad \text{methanation} \qquad (4.5)$$

$$CO + H_2O \leftrightarrows CO_2 + H_2 \qquad \Delta H = -41 \text{ kJ/mol} \qquad \text{water gas shift reaction} \qquad (4.6)$$

$$CO + 3H_2 \leftrightarrows CH_4 + H_2O \qquad \Delta H = -203 \text{ kJ/mol} \qquad \text{steam methane reforming} \qquad (4.7)$$
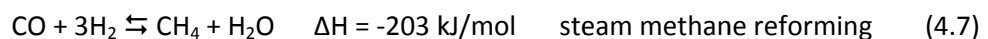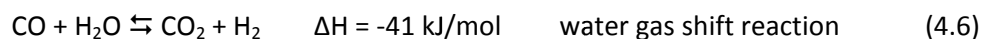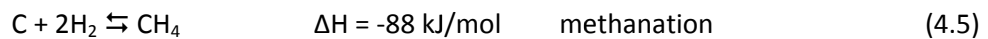
The chemical equation of reforming of hydrocarbons describes more generally, how higher hydrocarbons formed during devolatilisation are gasified.

$$C_mH_n + m\ H_2O \leftrightarrows mCO + (m+ \tfrac{1}{2}n)\ H_2 \qquad \text{reforming of hydrocarbons} \qquad (4.8)$$

The overall energy balance of the gasification reactions is endothermic, thus heat has to be supplied to the process. [32]

Two ways of heat supply are distinguished: In autothermal processes a part of the feed is combusted to obtain heat. In allothermal processes gasification and combustion are spatially divided and heat is transferred by heat exchangers or circulating bed material from combustion to gasification. [33]

4.3   Properties of the producer gas

The main compounds of the producer gas are CO, H_2, CH_4, H_2O, CO_2 and N_2. Undesired by-products are tars, ash and dust. The gas composition depends on the gasification agent, the temperature and the pressure during gasification, the reactor design and the size and properties of the feedstock.

In the heterogeneous water gas reaction and the Boudouard reaction (equation 4.3 and 4.4) the volume is increased because of gas production. Thus, the equilibrium is shifted to CO and H_2 with increasing temperature and decreasing pressure. In Figure 4.3 the equilibrium curves of the two reactions are illustrated. In the heterogeneous water gas reaction (equation 4.3) more CO and H_2 are yielded at temperatures exceeding 800°C. [32]
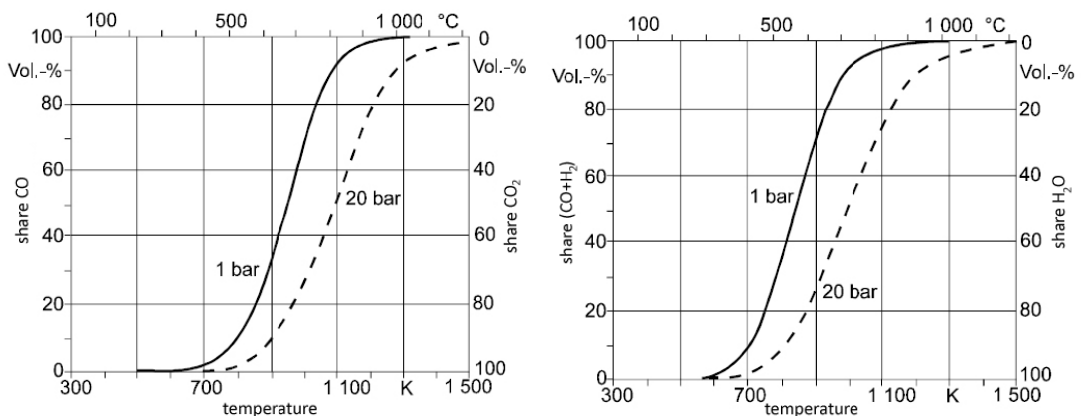
Figure 4.3: Equilibrium curves of Boudouard and heterogeneous water-gas reaction, adapted [32]

The equilibrium of the water gas shift reaction (equation 4.6) does not depend on pressure. It is shifted toward CO and H_2O with increase in temperature, which is illustrated in Figure 4.4 on the left.

The methanation reaction (equation 4.5) yields more CH_4 with increasing pressure and the amount of CH_4 decreases when temperature rises (Figure 4.4, right). During the reaction the gas volume decreases due to CH_4 formation. Thus, the equilibrium is shifted to the right with increasing pressure and more CH_4 is produced. [32]
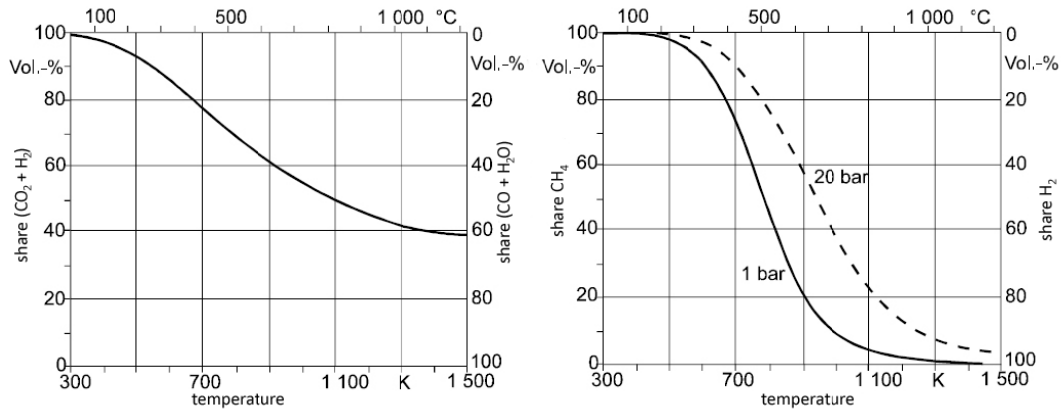
Figure 4.4: Equilibrium curves of homogenous water gas shift and methanation reaction, adapted [32]

If air is used as gasification agent, the producer gas contains a considerable amount of atmospheric nitrogen, which dilutes the producer gas and decreases the calorific value. Steam or mixtures of steam and oxygen lead to a nitrogen free producer gas with higher calorific values [32]. Gasification with pure hydrogen is too expensive for biomass and wastes. [66]

The calorific value of the producer gas is calculated by summarising the shares of the gas composition multiplied by the calorific values of the respective gas compounds. The calorific value of CO is approximately 12.6 MJ/Nm³ and of H_2 10.8 MJ/Nm³. In contrast, the calorific value of methane CH_4 is considerably higher at 35.9 MJ/Nm³. [32]

Gasification with air results in nitrogen-diluted producer gas with low calorific values of approximately 5 MJ/Nm³. It is also called low calorific value (LCV) gas. When steam is used as gasification agent, producer gas with ca. 12.6 MJ/Nm³ is yielded. A mixture of air and oxygen leads to values in the range of 5 to 12 MJ/Nm³ depending on the amount of oxygen in the gasification agent. [66]

In the producer gas there are also contaminants such as particles and tars. Inorganic ash and unreacted char can be entrained by the gas flow in the form of particles. Condensable vapours that escape during devolatilisation with molecular weights higher than benzene (78 g/mol) are collectively referred as tars. The amount of tars formed depends on the residence time of the producer gas at high temperatures. They are thermally destroyed above 1200°C. As they form depositions, when the producer gas is cooled, they have to be removed. In addition to that, the disposal of tars constitutes environmental problems. Thus, the formation of tars should be minimised. [32]

4.4 Reactor design

4.4.1 Fixed bed gasifiers

A fixed bed gasifier consists of a packed bed of feedstock, which is added continuously from the top. Because of gravity and decomposition the fuel is moving downwards slowly through the different reaction zones until it reaches the ash hopper. The ash is drawn off from a rotating grate. In fixed bed gasifiers the sub-processes of gasification are spatially divided but

the transition between the zones is gradual. Depending on the direction of the gas flow in the bed, two types of fixed bed gasifiers are distinguished. They are illustrated in Figure 4.5. [32]
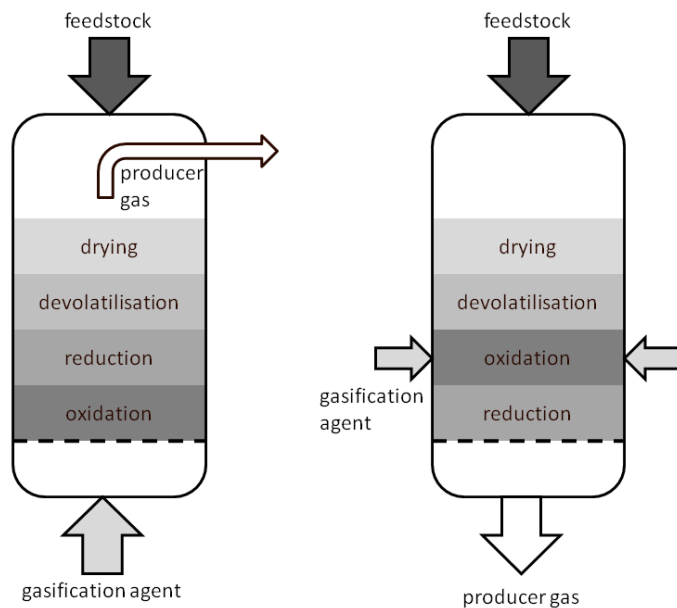
Figure 4.5: Up- and downdraft fixed bed gasifiers

Updraft gasifiers

The gasification agent is injected at the bottom of the reactor and is flowing upwards. First it oxidises the carbon of the feedstock in the oxidation zone at the bottom of the reactor. These reactions supply the heat necessary for gasification. The hot gas, consisting of the gasification agent, CO_2 and H_2O, reacts in the reduction zone with the carbon of the feedstock and CO, CH_4 and H_2 are yielded. In the devolatilisation zone macromolecules are thermally decomposed because of the heat carried in the gas. Before leaving the reactor the producer gas transfers heat to the incoming fuel in the drying zone. [32]

Advantages of the updraft gasifier are the simple design and the relatively good char burnout. Due to the internal heat exchange in the drying and devolatilisation zone the producer gas outlet temperature is low, which increases the efficiency of the gasifier. A negative aspect is the high amount of tar and pyrolysis products in the producer gas, which are entrained and do not pass the hot oxidation zone. Hence, expensive gas cleaning is required. [33]

Downdraft gasifiers

In a downdraft gasifier fuel and gas flow co-currently. At the top of the reactor the feedstock is dried and devolatilised in a virtually oxygen-free atmosphere. Then the gasification agent is injected. In the oxidation zone the fuel is oxidised and the gas is heated to temperatures above 1000°C. Long-chain carbon compounds yielded by devolatilisation are cracked. In the adjacent reduction zone the gas reacts with carbon and more gas is formed. [32]

The tar content of the producer gas is low because tars are cracked in the oxidation zone. A disadvantage is the high outlet temperature of the producer gas. Thus, the efficiency is lower than in updraft gasifiers. The requirements for the fuel properties are stricter. The amount of

fines is limited, as it is important for the gas flow that a porous bed is formed, which may be clogged by small particles. [33]

Another disadvantage is that downdraft gasifiers are limited in size. With increasing cross section the risk of bridging, channel formation and irregular gas distribution in the gasifier augments. As a result, those gasifiers are usually used for small capacities. [32]

Double-fire gasifier

The design of the double-fire gasifier aims at combining the advantages of the updraft and the downdraft gasifier. Feedstock is added at the top of the reactor and gravitates towards the bottom. The gasification agent, usually air, is injected on two stages. In the upper part of the reactor it is injected radially and reaction zones similar to the downdraft gasifier are formed. Thus higher hydrocarbons that are released during devolatilisation are thermally cracked in the hot oxidation zone. There is another air intake at the bottom of the gasifier in order to reduce the high carbon content of the ash, which is typical for downdraft gasifiers.

Due to the special design the tar content of the producer gas is low, which also reduces the risk of clogging in the reactor. Since the major part of the reactor is operated as a downdraft gasifier, the size of the gasifier is limited. [32]
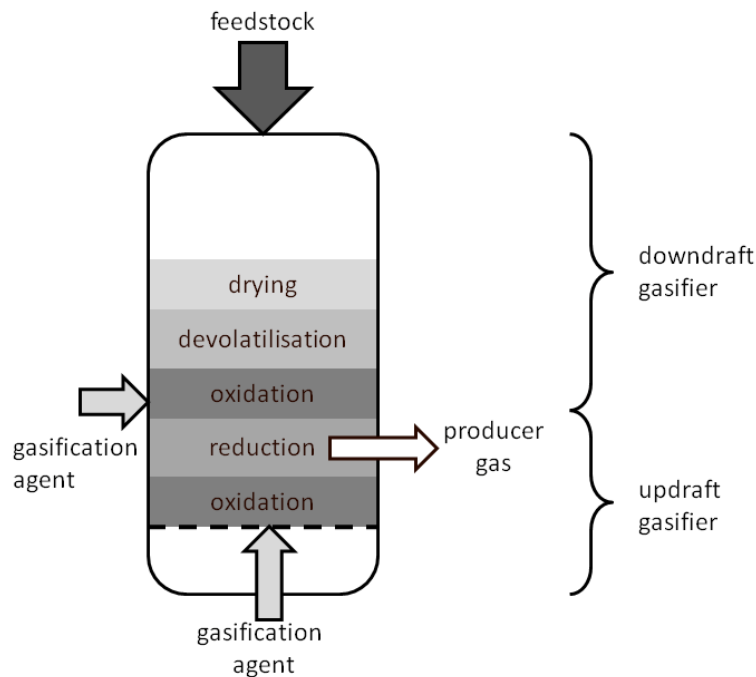
Figure 4.6: Double-fire gasifier

4.4.2 Fluidised bed gasifiers

The fluidised bed principle is described in chapter 3.2.4. Fluidised bed incinerators demand more severe fuel requirements in comparison to grate firings and rotary kilns, which are more robust. By contrast, fluidised bed gasifiers are more robust than other types of gasifiers.

In relation to downdraft gasifiers, fuel requirements are less strict and they are suitable for a larger variety of feedstock. In the gasifier the bed material is fluidised by the gasification agent.

There are no distinct reaction zones because of intensive mixing and uniform temperature distribution in the bed. Devolatilisation is very fast; hence a large amount of pyrolysis gases is generated. As usually in fluidised bed reactors dust, tars and bed material can be entrained by the producer gas and the dust content of the producer gas is higher than in fixed bed gasifiers. When the producer gas leaves the gasifier, it has the temperature of the hot fluidised bed. Thus heat recovery is necessary to increase the efficiency. In addition to that, compressing the fluidisation agent consumes energy. [33]

In general, the operation of fluidised bed gasifiers is restricted to temperatures below the softening temperature of the ash. Otherwise, agglomeration of slag and bed material will disturb the fluidisation of the bed. [24]

Stationary fluidised bed gasifier

A stationary fluidised bed has a distinct surface. Concerning the reaction, it behaves like a continuous stirred thermal reactor. In the space above the surface of the bed, the freeboard, the gas reactions continue. With increasing residence time the amount of tars in the producer gas declines. [33]

Circulating fluidised bed gasifier

In a circulating fluidised bed particles such as the bed material and char are carried out of the bed and are recycled by a cyclone and a return leg. Due to the circulation the residence time in the reactor is prolonged, which leads to better carbon burnout and higher char conversion. [33]

4.4.3 Entrained flow gasifier

Finely ground fuel is entrained by the gasification agent in a co-current flow in a long reactor. Because of the high temperature and the small size of the particles, they can be gasified virtually completely within a few seconds. Thus, high capacities are possible. Entrained flow reactors are operated at temperatures in the range of 1300 to 1600°C, where tars are thermally destroyed. [33]

4.4.4 Rotary kilns

Usually, rotary kilns are used for pyrolysis. Waste is heated in double-walled steel drums, which are inclined and rotating slowly. In contrast to rotary kilns used for waste incineration described in chapter 3.2.3, they are heated indirectly. Thus, heating pipes are integrated in the wall of the drum. A part of the producer gas is burned and the hot combustion gas is flowing counter-currently to the movement of the fuel in the rotary kiln. Heat is transferred mainly by conduction. To maintain reducing conditions for pyrolysis, air leakages have to be avoided, which is especially crucial for the feeding system. Typical dimensions of a rotary kiln are 20-30 m in length and 2-3 m in diameter. [66]

4.5 Waste gasification plants

4.5.1 Clinical waste incineration plant Baden (Austria)

In Baden hospital refuses are incinerated in a discontinuous process. Waste is fed into the shaft furnace, which is heated by natural gas burners. Volatile matter is released; it is combusted with air in the afterburner chamber. The solid devolatilisation residue is combusted completely at the end of each cycle. The heat of the flue gases is transferred to a hot water boiler. A two stage flue gas cleaning is implemented. In a NaOH scrubber HCl, HF, SO_2 and parts of the dust are removed. Then activated coke and hydrated lime are injected and precipitated by fabric filters in order to adsorb pollutants. Figure 4.7 shows the process flow sheet of the waste incineration plant. [56]
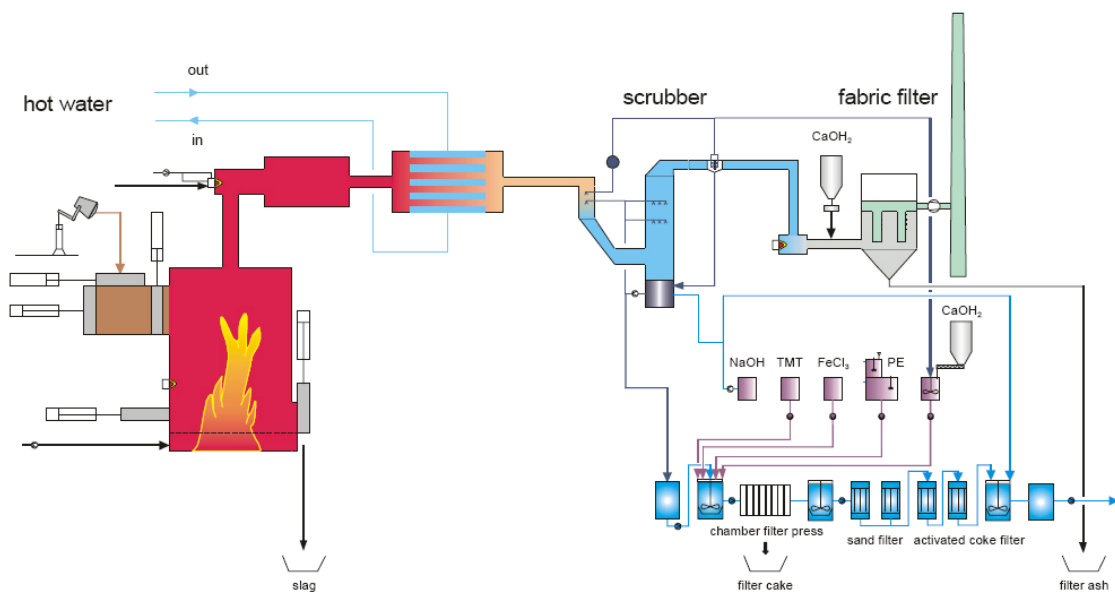
Figure 4.7: Clinical waste incineration plant Baden, [56]

4.5.2 Contherm

In the Contherm process waste is pyrolysed and the pyrolysis products are incinerated in the adjacent coal power plant Westfalen in Hann-Uentrop (Germany). The plant is operated by RWE.

Shredded municipal solid waste, automotive shredder residues and up to 50% of plastic waste are used as feedstock. [39] At full load up to 10% of the thermal input of the power plant can be replaced by pyrolysis products. [17]
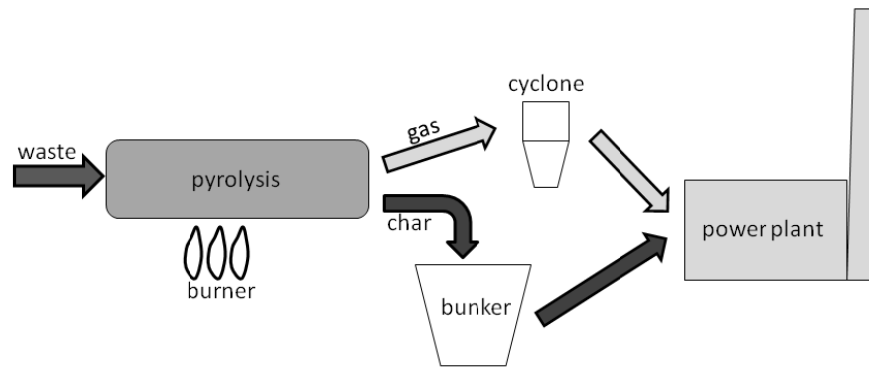
Figure 4.8: Process flow sheet of the Contherm process

There are two rotary kilns with an annual throughput of 50 000 t each, where the waste is heated to 500°C and is pyrolysed for 1 h. Natural gas burners heat the rotary kilns indirectly. Waste is converted into pyrolysis gas and char. The gas contains water vapour, H_2, CO, CH_4 and higher hydrocarbons; it is injected into the boiler after being dedusted by a cyclone. The char is fed to the coal bunkers. It is ground with the regular feedstock and blown in the boiler. The pyrolysis products are incinerated at 1600°C, thus all organic pollutants are destroyed. In Figure 4.8 the main units of the Contherm process are shown. [17]

4.5.3   Siemens (Kiener Pyrolysis)

The process combines pyrolysis in a rotary kiln and closed-coupled high temperature combustion and uses municipal solid waste as feedstock. In Figure 4.9 the process flow sheet of the Siemens process is shown.
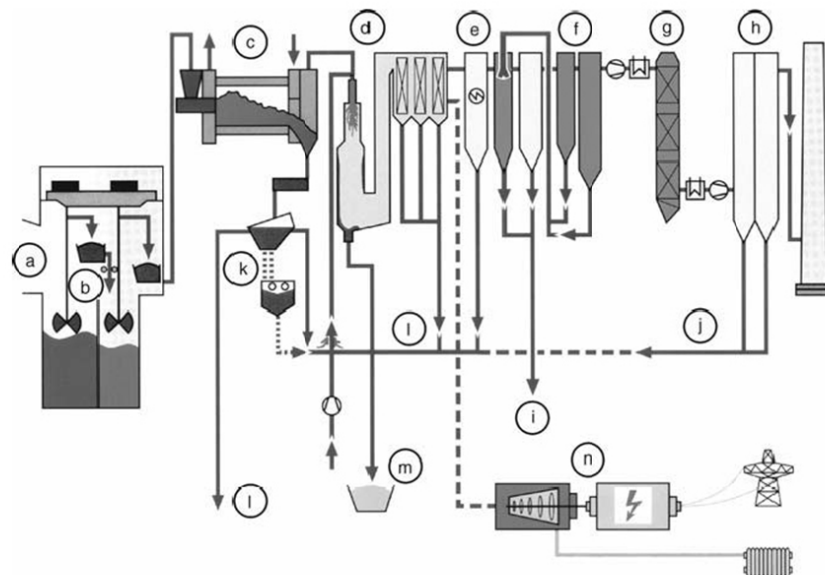
a: pit, b: shredder, c: pyrolysis kiln, d: combustion chamber and waste heat boiler,
e: ESP, f: wet scrubber, g: SCR, h: activated carbon filter, i: salts, j: adsorbent,
k: separation of inert material, l: filter dust, m: granulated slag, n: power generation

Figure 4.9: Siemens pyrolysis and combustion process, [74]

First the waste is shredded to a size of 200 mm and it is fed continuously to the rotary kiln, where pyrolysis takes place. The rotary kiln is heated indirectly by the hot flue gases in a

counter-current flow. The inlet temperature of the gases is 520°C, the outlet temperature amounts to 250°C. The waste stays in the kiln for approximately 1 h and reaches a final temperature of 450°C. Conversion gas and carbonaceous residue are yielded.

Metals are removed from the carbonaceous residue and it is screened to obtain a fine dust. In the combustion chamber conversion gas and fine dust are incinerated at 1300°C. Thus liquid slag is discharged with a carbon content lower than 0.1%. To ensure complete combustion, the residence time has to be at least 2 s.

The energy of the hot flue gases is recovered in a waste heat boiler and then the flue gases are cleaned. The air pollution control system is similar to a conventional waste incineration plant. [66]

The pyrolysis and combustion process is based on the Kiener Pyrolysis and was further developed by Siemens. In Fürth (Germany) a commercial plant with a nominal capacity of 100 000 t/a was built. In 1999 the plant was decommissioned and disassembled after an accident. [65]

4.5.4   Grève-in-Chianti (Italy)

In Grève-in-Chianti refuse derived fuels (RDF) have been gasified in a circulating fluidised bed gasifier, which was close-coupled to a combustion chamber with boiler. [29]

RDF was produced and pelletised in a specialised plant near the gasifier and was composed of 60% paper and 40% plastics. The pellets had a diameter of 10-15 mm and a length of 50-150 mm. The calorific value was 17 MJ/kg.

The air-blown gasifier was operated slightly above atmospheric pressure and at 850°C. It consisted of a cylindrical riser. At the bottom there was a dense bubbling fluidised bed, where the gasification of the RDF pellets took place at 700-800°C. Secondary air was injected with high gas velocities creating a circulating fluidised bed in the upper part of the riser. A part of the producer gas was burned there and the temperature rose to 850°C. Entrained coarse particles were separated by impingement in the U-beam conduit and finer ones in the cyclone. They were recycled to the riser via the return leg, which was fluidised with nitrogen to avoid ignition of the hot char particles.

The producer gas consisted of 9% each, CO and H_2, the rest was nitrogen and CO_2, the average calorific value was 7.5 MJ/Nm³. It was combusted with high excess air at 1050°C in the combustion chamber. In order to destroy dioxins, the flue gas was kept at 850°C for 2 s in the afterburner chamber. There were auxiliary natural gas burners to maintain the temperature. In the boiler steam with 380°C and 42 bar was produced for electrical power generation. In Figure 4.10 the process is schematically illustrated.
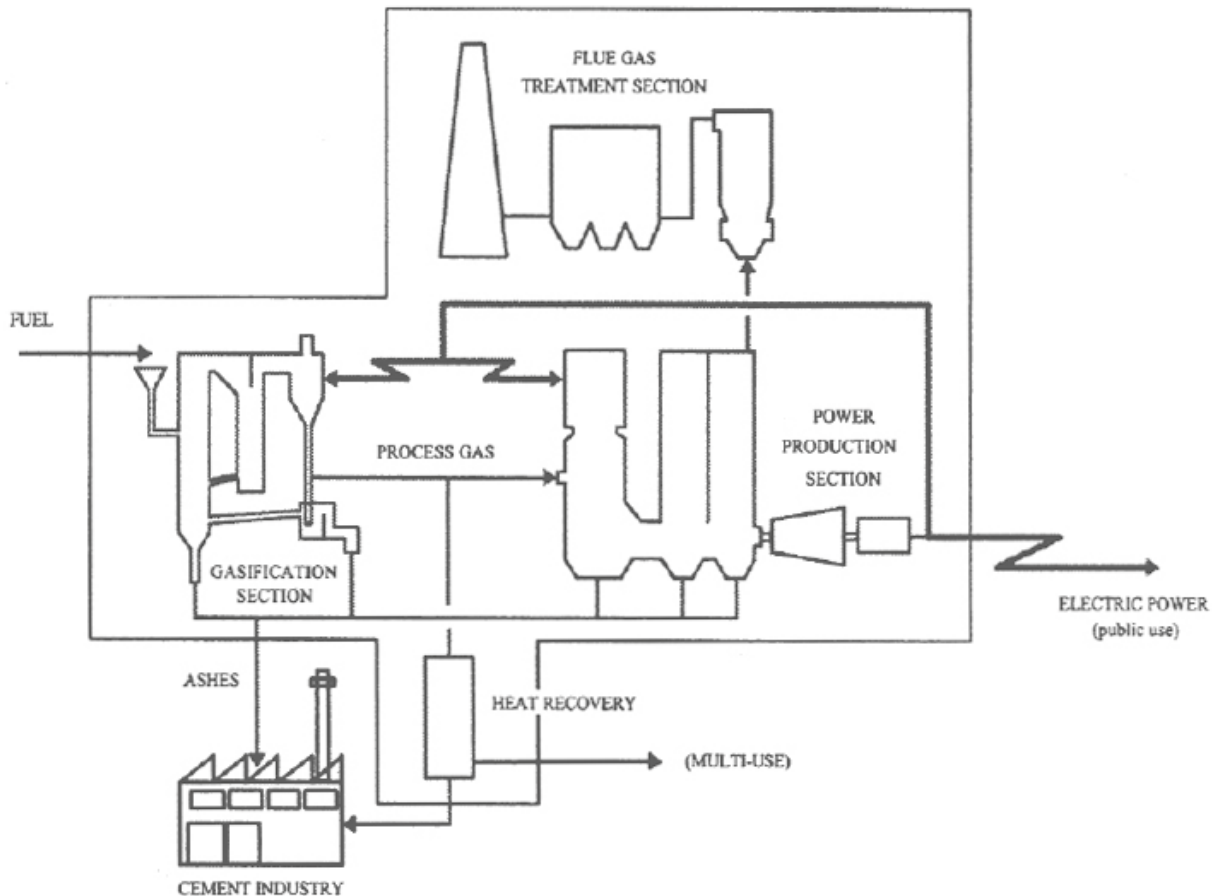
Figure 4.10: Process flow sheet of RDF plant in Grève in Chianti, [22]

The flue gas had to be cleaned. Ammonia was injected into the afterburner chamber to reduce the content of NOx by SNCR. After the boiler a hydrated lime scrubber and a bag house filter were implemented. To improve the flue gas quality dry hydrated lime was injected additionally prior to the bag house.

The plant comprised two gasifiers and a boiler. It was possible to transfer excess producer gas to an adjacent cement plant. Therefore, the producer gas was only cooled to 400°C, but not cleaned. This measure provided additional operational flexibility. The cement plant also used the ash and the spent lime from the flue gas cleaning system.

The producer gas contained about 75 g/Nm³ of tars. As the tars had coated the tube surface of the boiler, the availability of the boiler was reduced. For that reason, an expensive retrofit was necessary. The boiler was overhauled with new surface area and modified gas pathways. A gas cleaning system was inserted between the gasifier and the boiler comprising dedusters, high temperature acid gas removal and ceramic filters. The gas quality was so much improved that the use of a gas turbine would have been possible. A second boiler line was added as well. [22]

The plant was shut down in 2004 because of fuel supply restrictions. [68]

4.5.5 Lahti (Finland)

Since 1998 a circulating fluidised bed gasifier provides low calorific value gas for a pulverised coal boiler in Lahti. It is operated on a recycling fuel mixture consisting of wood, paper, cardboard, RDF and plastics. Up to 15% of the boiler heat input can be replaced by producer gas.

The gasifier consists of a reactor, a cyclone and a return leg and is illustrated in Figure 4.11. The feedstock is pretreated and blended prior to the gasifier; so that the particles are smaller than 5 cm. Air is used as gasification agent leading to a producer gas with a calorific value in the range of 2.0-3.5 MJ/Nm³. The air feed controls the temperature in the reactor, which is typically at 800-1000°C.

The producer gas is fed to the coal boiler below the coal burners. Thus, the most heat and the longest residence time for pollutant destruction are ensured. [29]
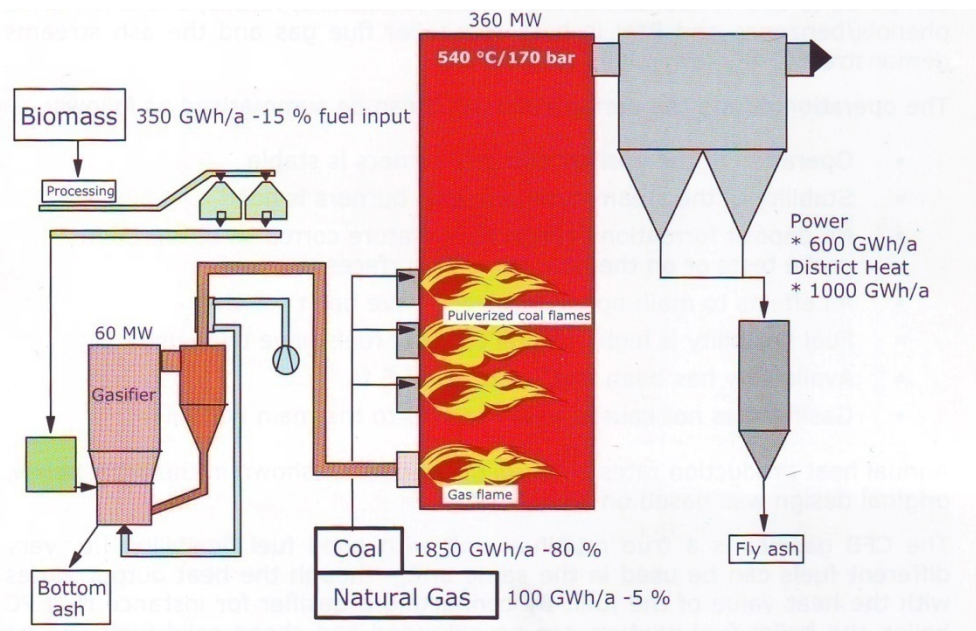
Figure 4.11: Process flow sheet of Lahti, [29]

The overall efficiency of this process is 90.8% and an average gasification efficiency of 92% is reported. The performance of the plant has not been adversely affected by the impurities of the producer gas such as tars and alkalis.

A gas cleaning device prior to combustion in the boiler is investigated since the NOx emissions have to be lowered to meet regulations such as the Waste Incineration Directive. Various methods are tested with a bleed from the gasifier to achieve an economic solution. [23]

4.5.6 Rüdersdorf (Germany)

In Rüdersdorf a circulating fluidised bed gasifier is incorporated in the process of a cement plant since 1995. Limestone used as raw material in this cement production process consists of 84% of $CaCO_3$, thus it is necessary to add sand and clay to produce cement. Instead of clay wet brown coal ash from a power plant is used, which is not completely burned out. In the

circulating fluidised bed gasifier the mineral and organic content of the wet ash are separated. The ash is burned completely and the chemical energy is transferred to the producer gas, which is added to the calciner to supply energy. The ash is cooled and serves as raw meal component. The gasifier has a thermal capacity of 100 MW. Up to 40% of the heat requirements of the cement kiln can be substituted by producer gas. [72]
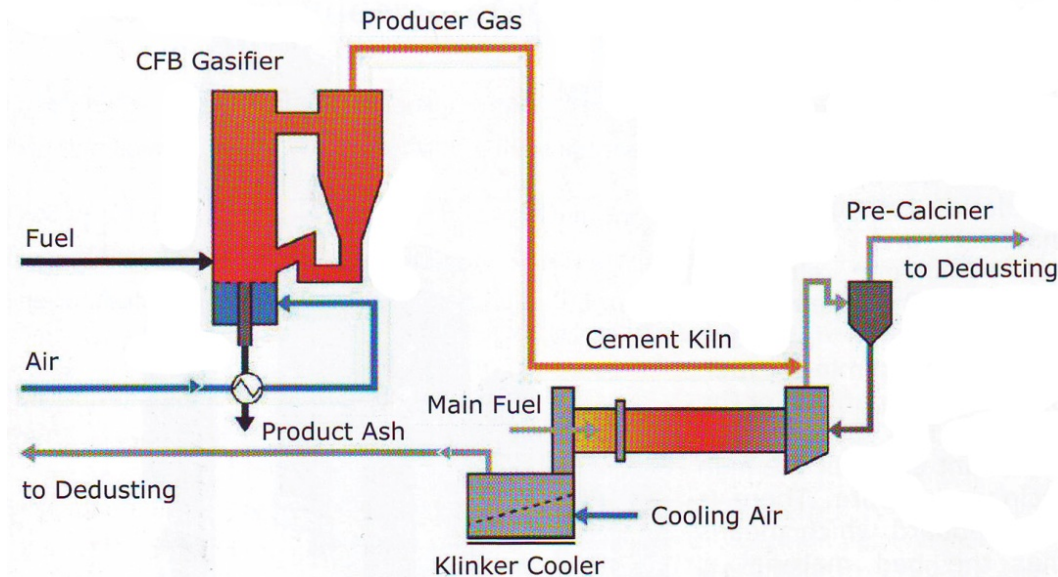
Figure 4.12: Process flow sheet of cement plant in Rüdersdorf, [29]

The gasifier is able to handle flexible feedstock. In order to reduce costs, not only wet brown coal ash is gasified but also a wide variety of wastes. Typical process parameters are 25 t/h secondary fuels, such as meat and bone meal, wood, etc., 1 t/h coal and 6 t/h mineral residues.

The circulating fluidised bed gasifier is air blown and is operated at 1.3 bar and 800-900°C. Due to the high gas velocity in the range of 5-8 m/s, the particles are distributed evenly in the reactor and there is no freeboard. Particles are entrained, carried out and returned by the cyclone and the seal pot. Incoming fuel is heated rapidly and the gasification starts immediately. Air, as gasification agent, leads to a producer gas with a low calorific value, which contains 5% CO and 2.5% CH_4. [29]

About 50000 Nm³/h of producer gas are generated. [24]

4.5.7   Ebara Twinrec

The Ebara Twinrec reactor comprises an air-blown gasifier and a close-coupled cyclonic combustion chamber as it is shown in Figure 4.13. [24]
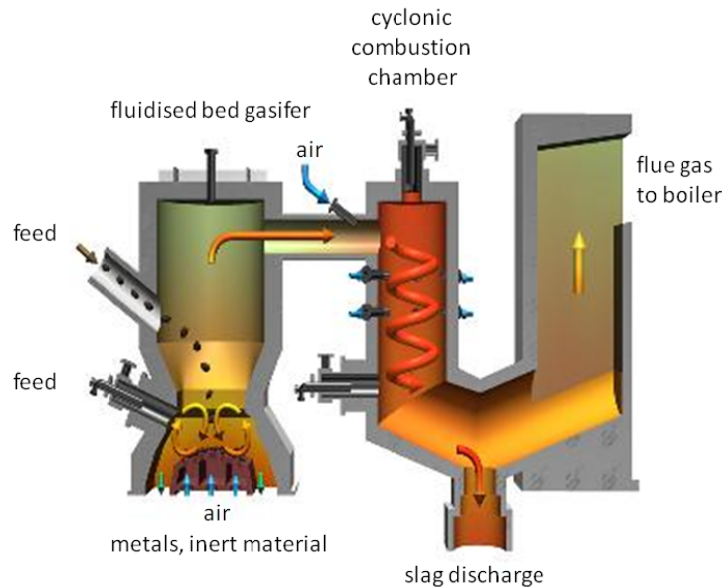
Figure 4.13: EBARA Twinrec reactor, adapted [13]

The reactor is suitable for a variety of feedstock such as MSW, refuse derived fuels, shredder residues, waste plastics, sewage sludge, and medical waste. In the gasifier, which operates at 580°C, waste is separated in the combustible organic fraction and the non-combustible solids. Dust is entrained by the producer gas flow. The non-combustible solids are discharged at the bottom of the reactor and metals are precipitated and recovered. The combustible fraction is incinerated in a cyclonic combustion chamber at 1350-1450°C. Thereby liquid slag is deposed at the walls. [13]

The molten slag is quenched and granulated. Due to the excellent leaching behaviour it can be sold to the construction industry. [53]

It is a full scale proven technology, and there are eleven commercial plants operating in Japan. [13]

4.5.8   Ebara-Ube process (two-stage pressurised gasification)

Two Japanese companies, Ebara and Ube Industries, developed a two stage gasification and slagging combustion system called EUP or PTIFG (Figure 4.14). This chemical recycling system converts plastic waste into syngas for chemical synthesis.

In the first stage pelletised waste is gasified at low temperatures in the range of 600-800°C in a fluidised bed gasifier with internal circulation. A mixture of oxygen and steam is used as gasification agent; the bed material consists of silica sand with a grain diameter of 0.4 mm. The low temperature gasifier is close-coupled to the high-temperature gasification unit, which operates at temperatures above 1300°C. Both reactors are pressurised at 8 bar. Molten slag is precipitated at the walls of the cyclonic high-temperature gasifier due to centrifugal forces in the gas stream and is granulated in a water quench at the bottom of the reactor. The water quench also serves as a seal for the gas, which has to pass through it and is cooled rapidly to 200°C there. Thus, de-novo-synthesis of dioxins and furans is hindered. The producer gas consists of CO, H_2 and CO_2.
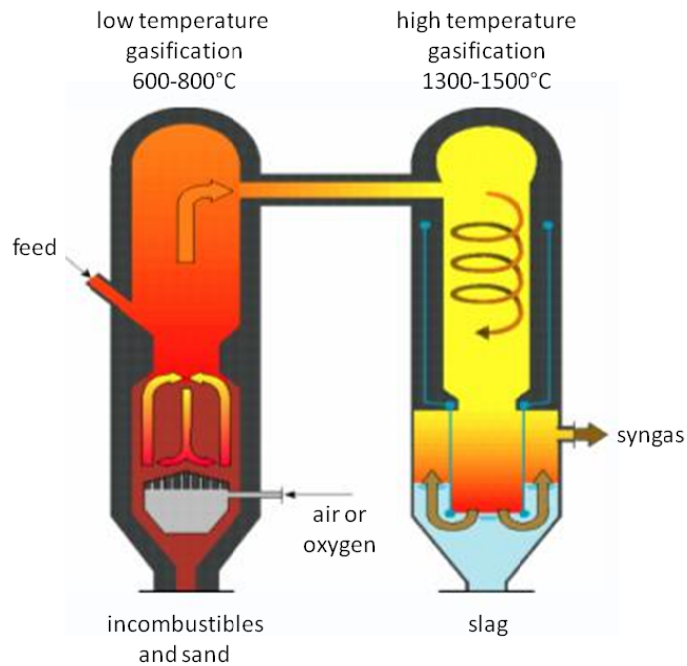
Figure 4.14: EUP gasifier, adapted [13]

In 1999 the first EUP plant was commissioned; commercial operation started in 2001. 30 t/d of plastic waste are treated and the producer gas is used for ammonia synthesis or as a fuel for the boiler. Two other plants with higher capacities (65 and 98 t/d) have been built. [13]

4.5.9   Thermoselect

The Thermoselect process consists of pyrolysis and high-temperature gasification.

The waste is compacted in a hydraulic press to 10% of its initial volume. Thus, the water is distributed more evenly and the air content is lowered. In addition to that, the heat transfer is promoted in more dense packets of waste.

The press is connected to the pyrolysis channel, which is a pusher furnace. It is heated indirectly by combustion of producer gas. Every 5 to 10 minutes a packet of waste is fed into the channel. There the waste is dried and pyrolysed. In order to facilitate the gas discharge, the channel is tapered and there are gas discharge ducts. At the end of the channel heat is also supplied by radiation of the high-temperature gasification section. The final pyrolysis temperature is 600°C; the partly pyrolysed packets drop into the shaft gasifier. Since gases escape, the packets are destroyed and a gas-permeable bed is created. At the lower end of the gasifier oxygen is added as gasification agent. Carbonaceous compounds are oxidised at 2000°C, then CO_2 is reduced to CO in the bed. In the upper part the pyrolysis gas from the tunnel and the gases flowing upwards in the gasification reactor are mixed. Oxygen is supplied there too. The gases remain in the stabilisation zone at 1200°C for 4 s followed by a water quench. The producer gas is further cleaned. Because of the high temperatures molten slag is obtained. [66]
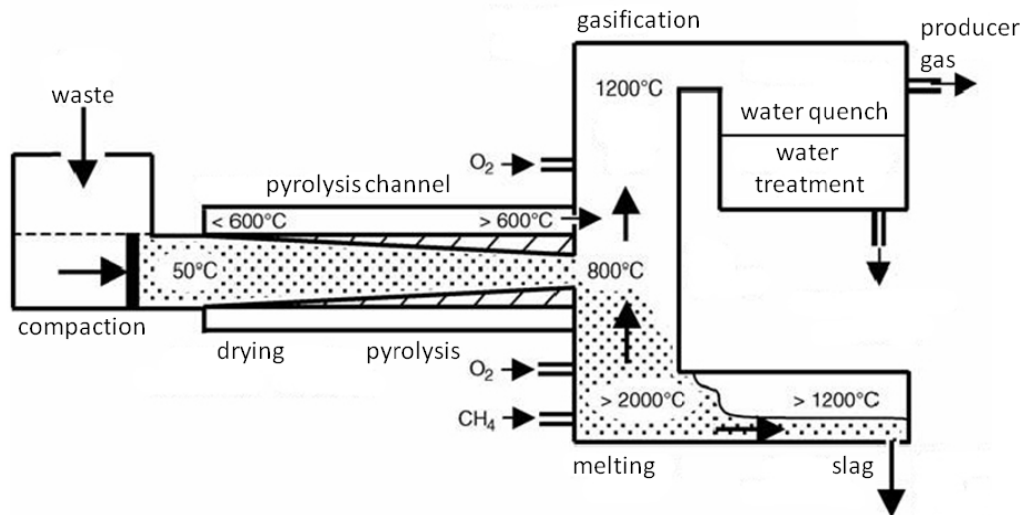
Figure 4.15: Flow sheet of the Thermoselect process, adapted [74]

In 1992 a pilot plant with a nominal capacity of 4.2 t/h was operated in Verbania (Italy). The first commercial plant was built in Karlsruhe (Germany) in 1997. It was designed for a nominal capacity of 225 000 t/a, but in 2003 only a capacity of 117 000 t/a was reached. On that account, the plant was decommissioned in November 2003. [65]

4.5.10   SVZ Schwarze Pumpe

Schwarze Pumpe is an industrial site in the east of Germany. The waste gasification facility was part of a larger complex producing electric power and methanol. Until 1995 lignite was gasified in order to generate town gas. Then the gasifiers were adapted for the use of refuse derived fuels. The producer gas was converted into electric power and was also used for methanol synthesis. In 2004 the operator of the plant became bankrupt and sold the plant to Sustec, a Swiss company. The gasification plant was shut down in 2007 because waste treatment was no longer profitable. It is planned to relaunch the gasification process again using coal as feedstock.

At Schwarze Pumpe several types of gasifiers were operated; they are illustrated in Figure 4.16.
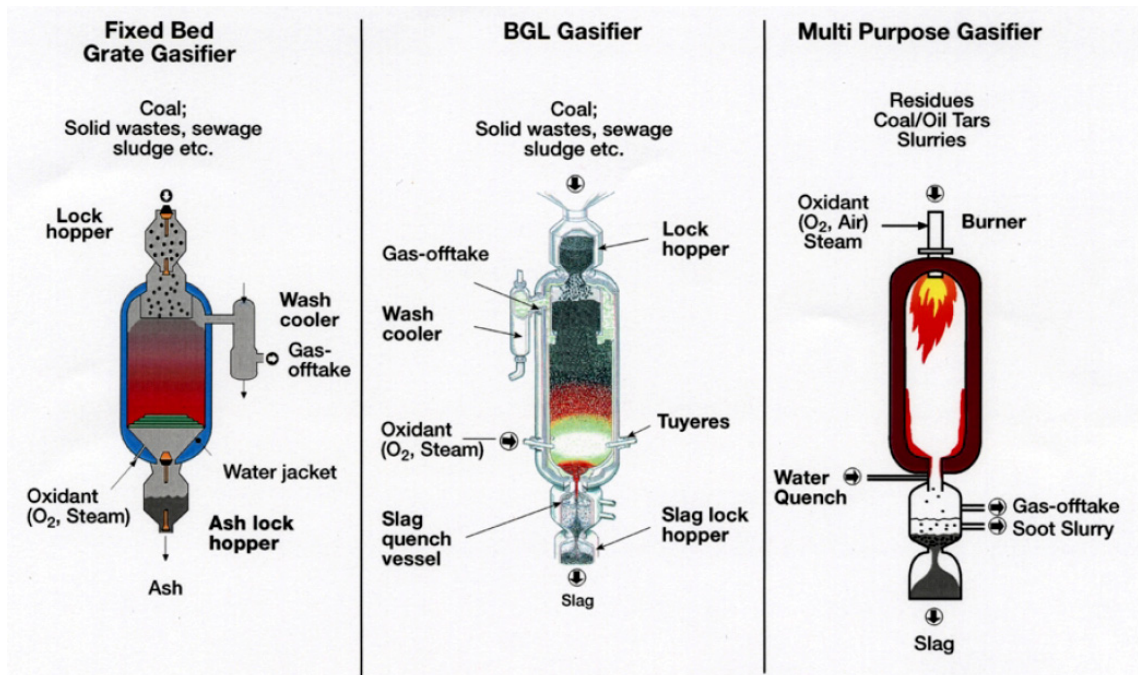
Figure 4.16: Different types of gasifiers at Schwarze Pumpe, [15]

Municipal solid waste, such as plastics, automotive fluff, paper, contaminated wood, residues of paints and sewage sludge were gasified in updraft fixed bed gasifiers. The reactors had an inner diameter of 3.6 m filled with lumpy fuel in the particle size range of 20-80 mm. A mixture of steam and oxygen was injected as gasification agent. The gasifier was operated at 24 bar. [33]

Coal was added up to 15% to compensate different properties and calorific values of the waste. Because of the operation temperature of 800-1300°C solid ash was discharged via a rotating grate. [17] The grate also distributed the oxygen-steam mixture. [24]

A further development of the fixed bed gasifier is the BGL gasifier (British Gas Lurgi). The gasification agent was injected via tuyères (water-cooled tubes) in the lower part of the reactor just above the level of the molten-ash bath. [24] It was operated at very high temperatures ranging from 1600 to 2000°C in the oxidation zone, thus molten ash was discharged through a slag tap and vitrified in a water quench. In the fixed bed gasifiers the excess steam was used for ash cooling. Since this was not necessary in the BGL gasifier, the amount of gasification agent could be reduced, which increased the efficiency. [29]

In the BGL gasifier 30% of coal was added to the waste and the operation pressure was 25 bar. Figure 4.17 shows the schematic construction of the gasifier. [17]
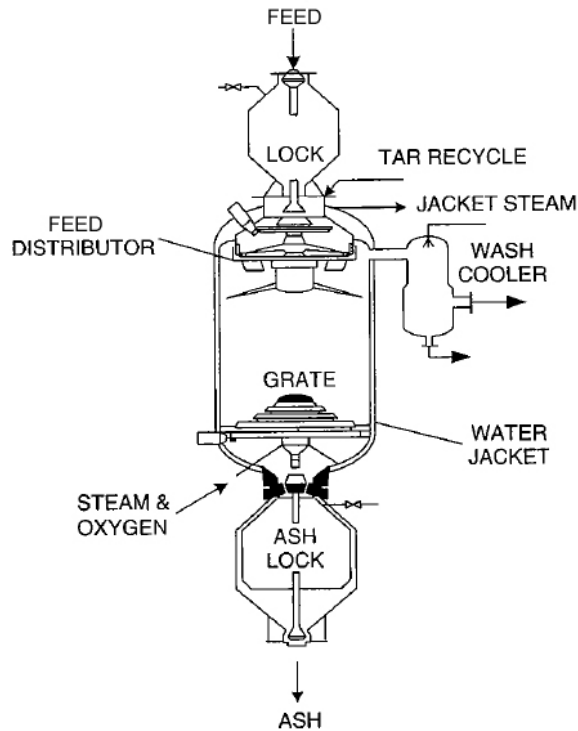
Figure 4.17: BGL gasifier, adapted, [24]

Liquid waste such as oil slurries, pastes, tars and sewage sludge was gasified in an entrained flow gasifier, which was operated at 25 bar and a temperature of 1600-1800°C. At a nominal capacity of 130 MW 310 t/a of waste oil were treated in the entrained flow gasifier. It was operated for ten years. [17] A Noell gasifier was implemented at Schwarze Pumpe too; it will be further described in chapter 4.5.12.

4.5.11   Carbo-V

The Carbo-V process was developed by CHOREN Industries, a German company. It is designed for solid biomass or organic waste substances as feedstock. Tests were performed using also municipal solid waste, bone meal and hard coal.
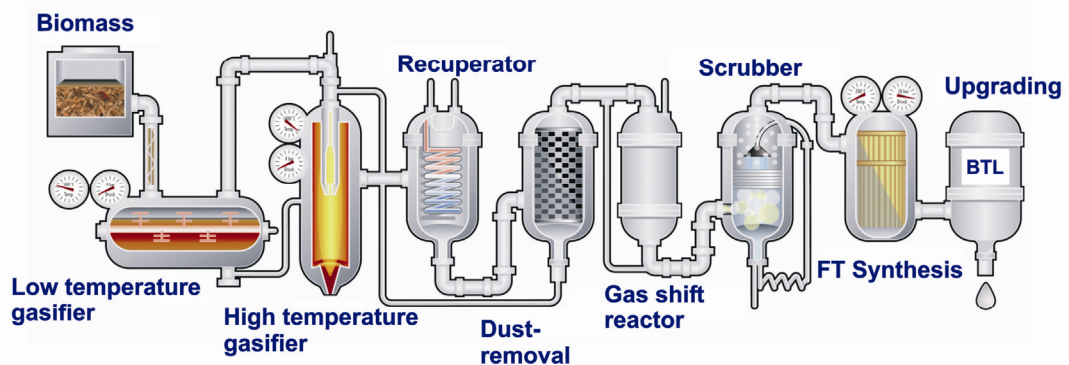
Figure 4.18: Biomasse-to-liquid process, [9]

Figure 4.18 illustrates the three stage gasification process. In the first stage low temperature gasification takes place at 400-600°C. The feedstock, which has a water content of 15-20%, is dried and carbonised by partial oxidation with air or oxygen. Thus, it is converted into char and volatile matter, which are separated then.

The volatile matter is burned sub-stoichiometrically with air or oxygen in the second stage, the high temperature gasification. The device is operated above the ash melting point at 1300-1500°C. The tars and other higher hydrocarbons in the volatile matter are gasified and CO, H_2 and CO_2 are yielded. The gases are used as gasification agent in the next stage.

Solid residue from the first stage, the char, is finely ground and blown into the entrained flow reactor below the second stage. There the char reacts with the gasification agent. Because of the endothermic gasification reactions the temperature in the reactor drops within a few seconds from 1300°C to 800°C. Raw synthesis gas is produced. [29]

The process has been successfully tested on pilot level. The synthesis gas is used for the production of synthetic biodiesel by Fischer-Tropsch-Synthesis. In 2008 the construction of the first commercial Biomass-to-liquid-plant in Freiberg (Germany) was completed, now the commissioning has started. [9]

As the Biomass-to-liquid process uses biomass as feedstock and the use of waste only has been tested but is not part of the design, the Carbo-V process is not really a waste gasification plant and will be neglected in the following chapters.

4.5.12   Noell-Conversion

The Noell-Conversion process was first developed by Deutsches Brennstoffinstitut Freiberg in 1975 in order to use brown coal as feedstock. The Noell Group acquired the technology in 1991 and developed it further to gasify waste and liquid residues. [24]

In the process pyrolysis and entrained flow gasification are realised consecutively in disconnected devices.
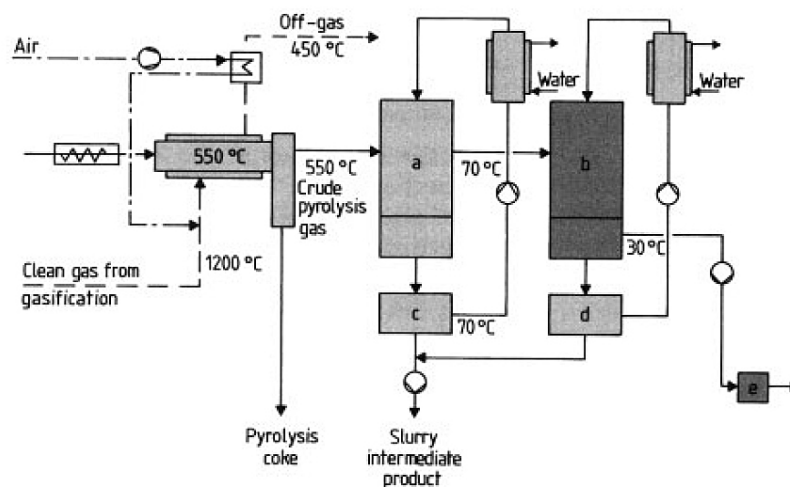
a) Quench cooler; b) Final cooler; c) Decanter 1; d) Decanter 2; e) Gas tank

Figure 4.19: Flow sheet of the pyrolysis section of the Noell-Conversion process, [66]

The shredded waste is heated and pyrolysed in a rotary kiln at 650-750°C. 20-25% of the clean producer gas have to be combusted to supply the heat to the rotary kiln. During pyrolysis the waste is converted into pyrolysis gas and char.

The char is cooled and after the separation of metals it is ground. The pyrolysis gas is quenched to 70°C; thereby liquid hydrocarbons, water and dust are precipitated (Figure 4.19). Gas, dust-oil-water slurry and char are stored as intermediate products. Since pyrolysis and gasification take place in disconnected devices, they can be operated separately if the intermediate products are stored.

Gasification takes place in an entrained flow gasifier with oxygen as gasification agent and operates at a pressure of 25 bar. The intermediate products are injected at the top of the gasifier in a single burner with nitrogen or producer gas as gas carrier. The burner maintains a pilot flame. In the flame organic compounds are combusted and CO_2 is produced, which is reduced to CO according to the Boudouard reaction. 1 kg of waste generates 0.7-1 Nm³ of producer gas depending on the water and ash content of the feedstock. The producer gas consists of 89% of CO and H_2, there is virtually no CH_4 nor higher hydrocarbons. Since the final temperature in the gasifier is 1400-1700°C, liquid slag is discharged at the bottom of the gasifier. [66]
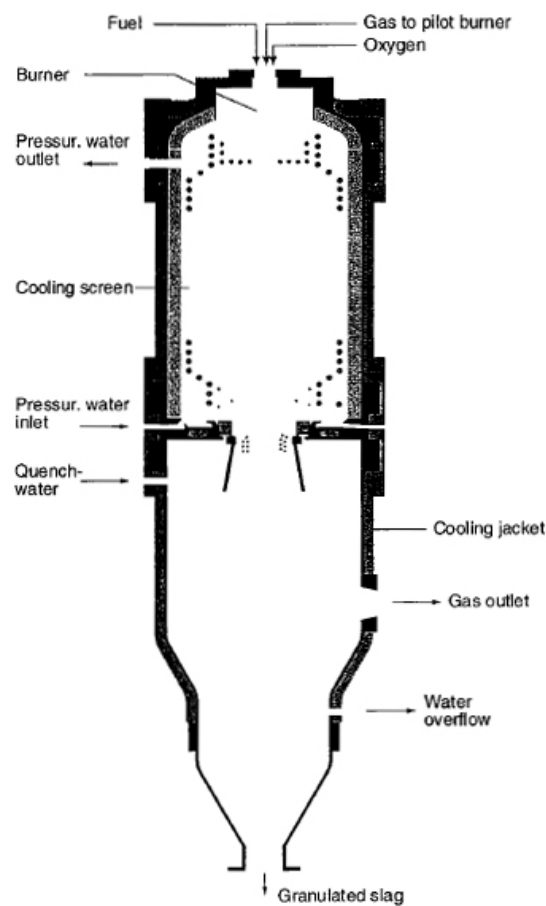
Figure 4.20: Noell gasifier, [24]

There is a 3 MW demonstration plant for the Noell-Conversion process in Freiberg operating since 1979, where different types of feedstock are tested to gain data. The entrained flow gasifier at Schwarze Pumpe was a 130 MW Noell gasifier. [66]

4.5.13   Summary

In Table 4.1 the different reactor designs of waste gasification plants are characterised. If the process consists of more than one device, the numbers in the table indicate their order. Devices with the same number belong together.

Usually pyrolysis takes place in rotary kilns, except for the discontinuous pyrolysis in the shaft furnace in Baden and the pyrolysis channel of the Thermoselect process. The waste is heated to a final temperature in the range of 450-700°C.

Fluidised bed gasifiers are operated at 580-900°C. For high temperature gasification entrained flow reactors or gasification chambers with a special design such as the EBARA reactors are used.

Table 4.1: Overview on reactor design of waste gasification plants and typical reaction temperatures

	fixed bed	entrained flow	stationary fluidised bed	circulating fluidised bed	rotary kiln	high temp. Gasification	pyrolysis	final temp. pyrolysis (°C)	1st stage gasification (°C)	2nd stage gasification (°C)
Baden	1						1			
Contherm					1		1	500		
Siemens					1		1	450		
Grève-in-Chianti				1					850	
Lahti				1					900	
Rüdersdorf				1					850	
EBARA Twinrec			1						580	1400
EBARA Ube			1			2			700	> 1300
Thermoselect	1					2	1	600	2000	1200
SVZ	1	1							> 1400	
Carbo V	1	2				2			500	1400
Noell-Conversion		2			1		1	700	> 1400	

In Table 4.2 the main compounds of the producer gas can be found. There is no data available for the pyrolysis gas in Baden and the gas produced by Siemens, Contherm and EBARA processes. Air gasification leads to a low calorific value of the producer gas, since it is diluted by nitrogen. The calorific value of the producer gas in steam blown gasifiers is considerably higher. If oxygen is added to steam or air, the calorific value of the producer gas rises. A characteristic of high temperature gasification is a very low methane content. In the Thermoselect gasifier and the Noell gasifier pure oxygen is employed as gasification agent. The

use of oxygen requires an air separation unit, which augments markedly the auxiliary power demand of the whole process. It has to be noted that the gas composition at SVZ Schwarze Pumpe was measured after the shift reaction. That is why the hydrogen content is much higher than in other plants.

Table 4.2: Overview on producer gas properties (dry gas) as far as available from literature

	CO vol%	H_2 vol%	CO_2 vol%	CH_4 vol%	C_xH_y vol%	N_2 vol%	air gasification	oxygen gasification	steam gasification	LCV gas (MJ/m³)
Grève-in-Chianti	10	10	18	7	5	51	x			7.5
Lahti	15	11	18	5		51	x			2-3.5
Rüdersdorf	5-18	7-18		2-6			x			3-6
EBARA Twinrec							x			
EBARA Ube								x	x	
Thermoselect	33-48	30-38	19-30			2		x		10
SVZ	19-27	56-64	3	4-17	3	2-3		x	x	12-16
Noell-Conversion	H_2+CO=67-89			0	0			x		8-12

4.6   Gas cleaning

As the producer gas contains contaminants, it is necessary to clean the gas prior to its application. Particles, such as inorganic ash, char and bed material in a fluidised bed, are likely to be entrained by the gas flow. The particle content in the producer gas of a fluidised bed reactor is higher than in a fixed bed gasifier.

Tar formation is also an important aspect. The amount of tars depends on the temperature and the residence time of the producer gas in the hot gasification zone. In the updraft fixed bed gasifier the tar content of the producer gas is the highest, because the producer gas does not pass through the hot zone, where the tars are cracked as it is the case in the downdraft gasifier. The amount of tars is lower, but those tars are more stable and thus more difficult to precipitate. The fluidised bed gasifier falls in the category between the updraft and the downdraft gasifier. Due to high temperatures in the entrained flow gasifier, tars are thermally destroyed and a virtually tar free producer gas is generated.

There are several other feedstock-specific pollutants. Alkali compounds evaporate at temperatures above 800°C and form solid depositions on colder surfaces. They also provoke high-temperature corrosion on gas turbine blades. Fuel nitrogen is mainly converted to NH_3 and HCN during gasification and result in NOx emissions, when the producer gas is burned. Sulphur compounds cause SO_2 emissions during combustion and poison catalysts of most

chemical applications. The existence of chlorine compounds represents a catalyst poison too and leads to serious corrosion and fouling problems. [32]

The extent of the gas cleaning depends on the application of the producer gas. Heat generation is a non-demanding application and requires no or minimal gas cleaning. When the gas is used in gas engines or turbines, more stringent requirements have to be met. As particles cause wear, they have to be precipitated prior to combustion. The amount of tars also has to be reduced. Gas turbines are less sensitive to tars but more sensitive to particles and alkalis than gas engines. When the producer gas is used as intermediate for chemical synthesis, the limits for tars, NH_3 and sulphur are considerably lower than in gas engines. Low nitrogen content is also required just as it is achieved by steam gasification. Fuel cells also have severe requirements, but they have not been precisely defined yet. [32]

4.6.1 Removal of particles

Different devices to remove particles from a gas stream already have been described in chapter 3.4.1. Here only the special requirements for producer gas cleaning are highlighted.

Cyclones are applied as first stage precipitators at high temperatures, however finer particles will remain in the gas stream.

Usually fabric filters are not suitable for producer gas containing tar because they tend to be plugged. This can be prevented if the filter is precoated. Tars are bonded to the precoat material and are not doughy anymore. The precoat material can be removed similar to dust by regular cleaning of the bag house.

For small systems also packed bed filters are used. They are not sensitive to corrosive compounds and high temperatures and the pressure drop is low. Tars and particles are accumulated in the filter and as there is no reconditioning of the filter, it has to be disposed.

Barrier filter candles made of ceramics or metal wires are especially useful in combination with gas turbines because they can stand temperatures up to 900°C. Thus, they can be used for hot gas cleaning.

In an ESP particles and liquid aerosols are precipitated from the hot gas stream. When the ESP is operated wetly, tars are removed too but the gas has to be cooled beforehand.

It is also possible to collect particles and tars by collision with droplets in a scrubber. It is necessary to cool the gas prior to the scrubber. [32]

4.6.2 Tar removal [32]

Physical tar removal

When the gas is cooled, tars condense. They are precipitated similar to particles in ESP, filters and packed bed filters.

Scrubbers are most commonly applied to remove tars. Because of the hydrophobic nature of the tars, water as solvent only cools the gas and causes the tars to condense. Thereby, 20-40 mg/Nm³ of tars remain in the cleaned gas. Tars are dissolved in oils. The charged solvent

can be thermally recovered. The final concentration of the tars in the gas is in the range of 10 mg/Nm³ when oils are used as solvent. In the OLGA process an organic solvent is used in a closed circuit. In the first scrubber tars are solved. The spent solvent is stripped with air in another column. The tar-rich gas is injected into the gasifier and the solvent is recycled. Scrubber systems reduce the overall efficiency.

Catalytic tar removal

Tars can be efficiently destroyed by means of catalytic cracking. At 800-950°C more than 99% of the tars are cracked. Metal and non-metal catalysts are distinguished. Non-metal catalysts such as dolomites, zeolites and other minerals are very cheap. Metal catalysts are usually made of nickel or iron; they are also able to destroy 70-80% of ammonia, but they are prone to be poisoned by H_2S. The activity of the catalyst is improved if steam is added. Char depositions can be formed on the surface of the catalysts. Fixed bed catalytic reactors are flushed with air from time to time, so that the char depositions are partially oxidised and heat is supplied. In a fluidised bed reactor the bed material consists of the catalyst, which has to be abrasion-resistant.

Thermal tar removal

Tars are thermally destroyed at temperatures of about 1200°C without help of catalysts. Air or oxygen is injected into the gas stream and partial oxidation occurs. Thus, the calorific value of the producer gas drops and heat losses increase because of the high temperature.

In coal gasification plates with a surface temperature exceeding 1000°C are inserted in the gas flow; they crack 80-90% of the tars colliding. It is also possible to reach the requisite temperature in a plasma arc, but it is very expensive.

Because of economic and operational considerations thermal cracking is a less attractive solution for large-scale gasifiers.

4.6.3   Removal of other impurities

Sulphur

Sulphur compounds can be removed by absorption in an alkaline scrubber similar to those in chapter 3.4.2. The loaded solvent has to be treated in a waste water treatment facility.

For larger gas streams physical and chemical absorption processes with regeneration are applied. In a scrubber the solvent absorbs the pollutant. It is recovered in another reactor and in the process the pollutant is released in its original form. [32]

Rectisol and Purisol are physical absorption processes operating at ambient temperature employing high-boiling organic solvents. Those processes are ideally suited for large gas streams with high contents of pollutants. Absorption is pressurised; the solvent is recovered to a great extend by relieving. Higher purities require inert gas stripping. An H_2S stream is generated, which can be fed into a Claus process to produce elemental sulphur. [61]

Ethanolamines, such as DEA and MDEA, are used as chemical absorption solvents. The spent solvent has to be heated for recovery, which requires more energy than physical absorption. [61]

The Sulferox process is a liquid phase oxidation process. In the absorber H_2S is absorbed from the gas stream and it is oxidised to solid sulphur in the solution. The oxidising agent is reduced at the same time. In the oxidiser air is injected and the oxidising agent is oxidised. In the settling vessel the sulphur particles gravitate and form a slurry, which is dewatered afterwards. A schematic process flow diagram is shown in Figure 4.21. [61]
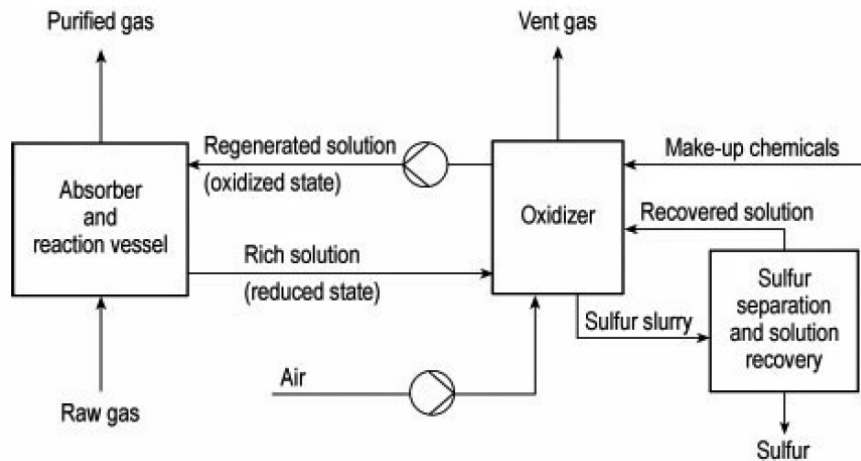
Figure 4.21: Sulferox schematic flow diagram, [25]

In the Sulferox process an iron chelate solution is used. Organic chelating agents (L) are added, so that iron is solved. The basic reactions are the following:

$$\text{Absorption:} \qquad 2\ Fe^{3+}L + H_2S \rightarrow 2\ Fe^{2+}L + S + 2H^+ \qquad\qquad (4.9)$$

$$\text{Regeneration:} \qquad 2\ Fe^{2+}L + \tfrac{1}{2}\ O_2 + 2\ H^+ \rightarrow 2\ Fe^{3+}L + H_2O \qquad\qquad (4.10)$$
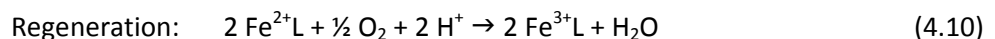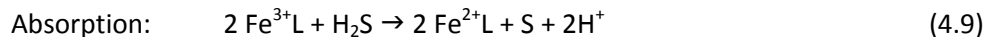
In contrast to physical absorption, where elemental sulphur has to be produced in an additional process, the formation of elemental sulphur occurs in the purification step of the Sulferox process. Economic operation is limited to a low sulphur production rate, as the oxidation capacity of the solvent is relatively low resulting in large solvent circulation rates. [25]

Another possibility to remove H_2S is a fixed bed of zinc oxide. At temperatures of 350-450°C chemisorption of H_2S results in zinc sulphide and water. Purities in the range of ppb are attainable and also small amounts of H_2S can be removed. Zinc sulphide is generated and has to be disposed. [27]

Activated carbon can be employed as adsorbent too. On the surface of the particles H_2S is oxidised in the presence of oxygen to elemental sulphur. Then sulphur can be extracted by means of ammonium sulphide solution; water vapour is used to clean the activated carbon. Finally, sulphur is separated from the ammonium sulphide solution by distillation. [61]

Nitrogen compounds

Nitrogen compounds such as ammonia have to be removed from the gas stream because they are converted to NOx when the gas is combusted. They can be destroyed catalytically or precipitated in a wet scrubber.

Catalysts similar to those employed for tar cracking are also able to destroy nitrogen compounds in the hot gas stream. The reaction of dolomite and nickel-based catalysts requires temperatures above 750°C. If iron-based catalysts are used, the temperature has to be 900°C. The major advantage is the simultaneous removal of tars and nitrogen compounds at high temperatures. [54]

If the gas has to be cooled prior to its application, nitrogen compounds can be precipitated efficiently in wet scrubbers. [31]

Alkalis

Alkalis are present in the form of vapours in the hot producer gas. At temperatures lower than 600°C alkali compounds condense into or on small solid particles. Thus, the most efficient way to remove them is to cool the gas stream and to precipitate condensed alkalis by dust collectors. [54]

In order to retain the sensible heat of the producer gas, hot gas adsorption by activated bauxite has been tested on laboratory scale. At 650-750°C 95% of potassium and 99% of sodium are removed. [32]

Halogens

Chloride and other halogens can be removed in alkaline scrubbers similar to sulphur. They also can be bonded to adsorbents such as limestone. [32]

4.6.4   Gas cleaning in waste gasification plants

Three different measures to clean the producer gas can be distinguished.

- no gas cleaning
- significant gas cleaning
- gas cleaning for synthesis

In Table 4.3 significant gas cleaning and gas cleaning for synthesis in waste gasification plants are compared. The numbers in the table indicate the order of the gas cleaning equipment. If there are two numbers for one device, it is used twice. Devices with the same number belong together.

Table 4.3: Overview on gas cleaning in waste gasification plants

	gas cleaning	quench	scrubber	Sulferox	Rectisol	low.-temp. drying	AC filter	cyclone	dust removal	limestone injection	CO shift converter
Grève-in-Chianti	yes							1,3	4	2	
EBARA Ube	yes	2	3					1			4
Thermoselect	yes	1	2	3		4	5				
SVZ	yes	1			3						2
Noell-Conversion	yes	1	2	5		3	4				

No gas cleaning

In closed-coupled combustion processes like the circulating fluidised bed gasifiers in Rüdersdorf and Lahti, the Siemens pyrolysis process, the Contherm process, the waste gasification plant in Baden and the EBARA Twinrec reactor, the producer gas is not cleaned prior to combustion.

Significant cleaning

Advanced gas cleaning prior to combustion is investigated in Lahti.

In Grève-in-Chianti a gas cleaning unit was added subsequently in order to reduce the fouling of the boiler. After a cyclone serving as first deduster acid gases and chlorine compounds were removed by injection of limestone at 800°C. There was a second cyclone; then the gas was cooled and flew through ceramic filters. Thus, the lifetime of the boiler was prolonged. [22]

In the Thermoselect process the producer gas is shock cooled in a water quench to prevent dioxin formation. In addition to that, dust and heavy metals are precipitated. In a two-stage acid scrubber HCl and HF are eliminated. The first stage consists of a rotary scrubber using water as solvent. Water and additives are injected into a packed tower to remove fine solids in the second stage. Sulphur compounds are converted into sulphur in a Sulferox scrubber. A suspension of water and iron chelate is used as solvent. Then the gas is cooled in a heat exchanger with cold water to 5°C. Thus, remaining heavy metals and water are condensed. Residual gaseous contaminants are trapped in an activated coke filter. The clean gas is burned in a combustion engine or a gas turbine. [66]

Cleaning for synthesis

Noell-Conversion

Two Venturi scrubbers are inserted downstream of the gasifier to remove dust and salts. Metal oxides are precipitated too in the form of metal sulphides.

As the gasifier is operated at a pressure of 25 bar and the saturation temperature is 205°C, 65% of the gas consists in water vapour, which has to be condensed. It can be further used as low pressure steam at 6 bar. Salts and fine solids are also precipitated during condensation.

In the producer gas sulphur is present in the form of 10% H_2S and 90% COS. Several desulphurisation units are necessary. COS is catalytically hydrolysed and H_2S is removed in an activated carbon moving bed adsorber. Oxygen is added and H_2S is oxidised to yield elemental sulphur inside the activated carbon particle. Spent activated carbon has to be disposed. In the Sulferox process H_2S is oxidised by means of iron chelates in a bubble column absorber. Elemental sulphur is generated, which can be further utilised. As waste water is generated, a waste water treatment facility is necessary. [66]

In Figure 4.22 there is an overview on the gas cleaning equipment of the Noell-Conversion process.
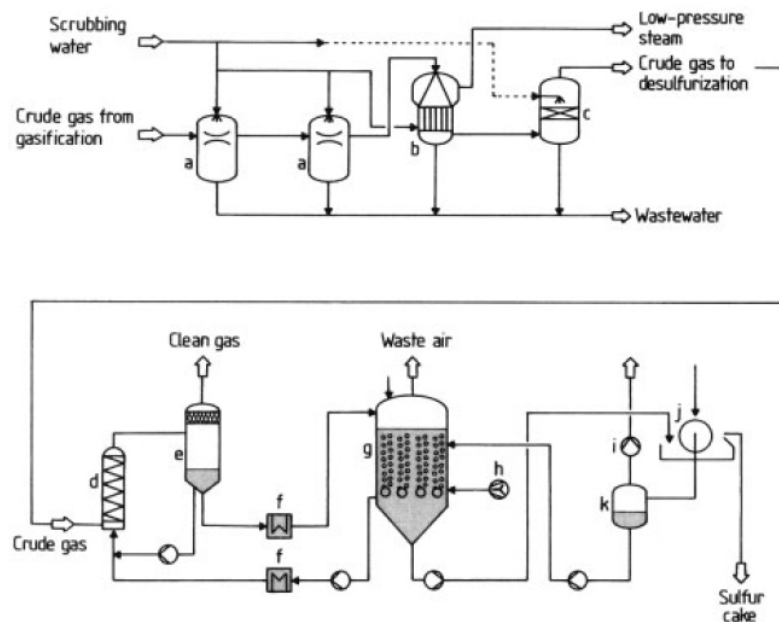
a) Venturi scrubbers; b) Waste-heat boiler (partial condensation); c) Separator (mist eliminator); d) Absorber; e) Separator; f) Startup heaters; g) Regenerator; h) Air blower; i) Vacuum pump; j) Drum filter; k) Filtrate tank

Figure 4.22: Gas cleaning unit of the Noell conversion process, [66]

EBARA-Ube process (two-stage pressurised gasification)

The syngas of the EBARA EUP process is fed into an ammonia synthesis plant. Prior to chemical synthesis, the gas has to be cleaned. In Figure 4.23 the assembly of the gasifier and the gas cleaning equipment is illustrated. A water quench is incorporated in the gasifier; there the slag is granulated and the gas is cooled rapidly to hinder the formation of dioxins. Particles and salts are precipitated. Then a scrubber removes other pollutants, so that only CO and H_2 are present in the gas afterwards. By means of the water gas shift reaction CO is converted into H_2. A pressure swing absorption unit separates H_2, which is the raw material for ammonia synthesis and the residual fuel gas. [20]
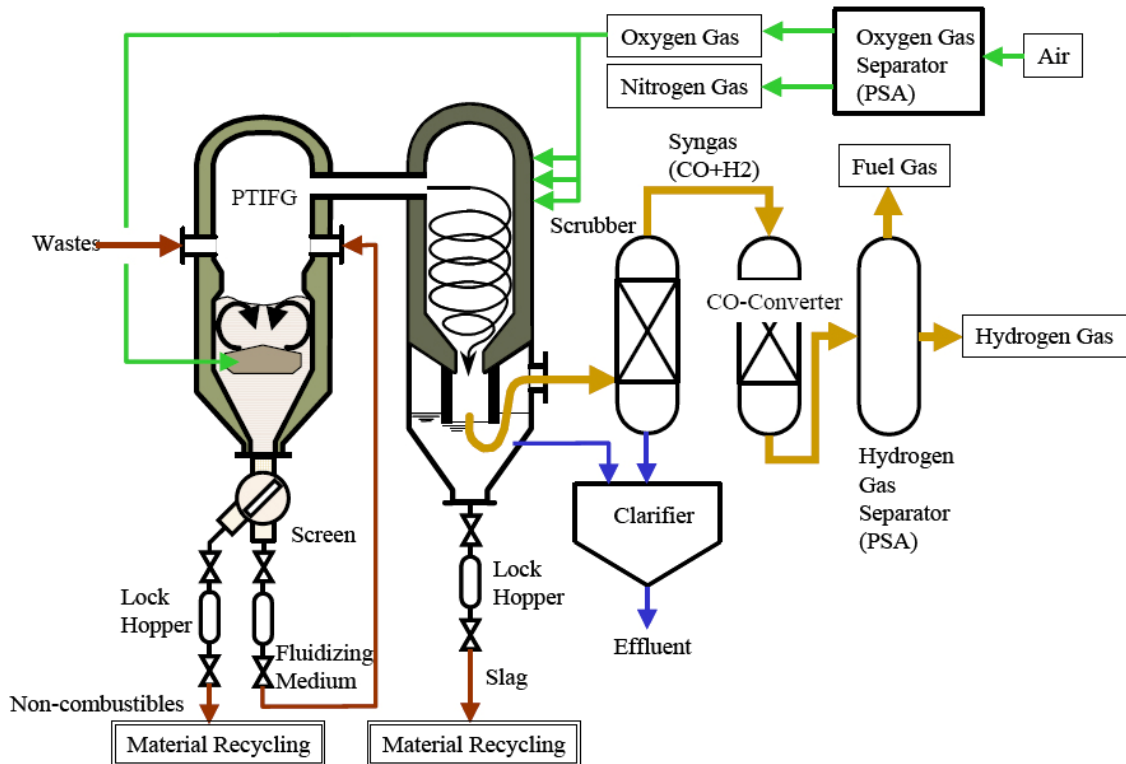
Figure 4.23: Ebara EUP process with gas cleaning for ammonia synthesis, [20]

SVZ Schwarze Pumpe

Several different gasifiers produced syngas for methanol synthesis and power generation in a gas and steam turbine combined cycle plant. As methanol synthesis required an H_2/CO ratio of 2, part of the syngas was fed into a shift plant, where the H_2/CO ratio was adjusted by means of steam and a catalyst. Sulphur, residual light hydrocarbons and other undesired compounds were removed in a Rectisol unit. Cold methanol was employed as solvent. Prior to the methanol plant there was a three stage fine gas cleaning system in order to protect the synthesis catalyst.

Part of the gas leaving the Rectisol cleaning unit was fed into the gas turbine, where heat and power were generated. There were also two additional boilers to produce process steam. [29]

4.7 Applications [32]

4.7.1 External combustion

Heat generation is the simplest application of producer gas with no or only minimal requirements for gas properties. Gas is combusted in a burner, which has to be adapted to the characteristics of the producer gas. In a waste heat boiler heat is transferred to the water-steam cycle and electricity is produced by the steam turbine coupled to an electrical generator. More details on waste heat boilers can be found in chapter 3.3.

A similar application is cofiring, where the producer gas is used as additional fuel in a conventional coal fired power plant. Up to 10-15% of the heat input of the furnace can be replaced by producer gas.

Producer gas also may be used for the operation of a hot air turbine. Therefore, a heat exchanger is necessary to transfer the combustion heat of the producer gas to air, which is compressed to be used in a turbine. Thus problems caused by tars and other pollutants are avoided. The heat exchanger has to be made of highly heat resisting materials, which are expensive. The electrical efficiency of this process is rather modest.

4.7.2 Internal combustion

Gas engine

Diesel and Otto engines are suitable for the combustion of producer gas. The requirements for the gas used in engines are more severe: condensable tars and particles have to be removed from the gas stream as they cause depositions and/or wear. The same is true for alkalis, halogens, H_2S and NH_3 because they can reduce the operation time of engine oil.

If air is used as gasification agent, the producer gas has good antiknock properties and low ignitability. Since the H_2 content in gas produced by steam gasification is higher, the antiknock properties are enhanced.

Prior to the engine the gas has to be cooled by heat exchangers or quenched to increase the amount of gas filled into the engine. Thus, engines are cold gas applications. An electrical efficiency of 35-40% is attainable, which exceeds the efficiency of gas turbines in the range of small and medium capacities. Disadvantages of gas engines are CO emissions, which require catalytic afterburning.

Gas turbine

Gas turbines are hot gas applications. The particle and alkali content of the producer gas has to be lower than for the use in gas engines because they can form depositions on the blades of the turbine. In contrast to gas engines, turbines are not sensible to tars. If tars remain gaseous, they increase the calorific value of the producer gas. Unlike gas engines, turbines are not seriously affected by changes in gas composition and generate markedly less emissions.

Gas turbines are suitable in the range of 2-20 MW of electrical power. Below 2 MW the electrical efficiency is only about 15-25%. In the range of 10-20 MW an efficiency of 30-35% is reached. Waste heat is produced at higher temperatures than in gas engines, which offers more applications. In a combined cycle the sensible heat of the exhaust gas can be recovered in a waste heat steam generator.

There are two ways of the gas turbine process: pressurised gasification or atmospheric gasification and compression of the producer gas. Both ways are not established yet for biomass gasification nor for waste gasification.

4.7.3   Syntheses

Chemical synthesis involves even more extensive gas quality requirements. The content of inert gases such as nitrogen and CO_2 has to be as low as possible, that is why only syngas produced by steam gasification is suitable for synthesis. A multistage fine gas cleaning is necessary to reach minimal particulate and tar content. Sulphur, nitrogen and halogen compounds are removed to attain levels lower than 1 ppm. In a subsequent conditioning step the properties of the syngas are adjusted according to the desired synthesis. Thus, the H_2/CO ratio is corrected, hydrocarbons are reformed and CO_2 is precipitated.

The H_2/CO ratio is adjusted by means of the water gas shift reaction, where CO reacts with water vapour and CO_2 and H_2 are yielded. The reaction takes place at 300-500°C in the presence of iron or chrome-based catalysts. If CO should be removed completely, the reaction is conducted in two steps at different temperatures.

CO_2 dilutes the syngas. It can be removed physically by pressure-swing adsorption or by scrubbers. Rectisol or Selexol processes are very complex but remove a broad range of other pollutants too.

Reforming of higher hydrocarbons is necessary for fluidised bed gasification as the CH_4 content is very high and also a considerable amount of higher hydrocarbons is produced. They are cracked at 800-1000°C in an endothermic reaction on a nickel-based catalyst. Thus, heat has to be supplied. In autothermal reformers part of the producer gas is combusted in order to produce the heat necessary for the reaction.

H_2 and CO are the interesting compounds for chemical synthesis and there are numerous reactions using those reagents. An important application is the production of liquid and gaseous fuels: By means of Fischer-Tropsch synthesis liquid fuels and waxes can be produced. Methanol can be yielded by a catalytic reaction; it is the base material for MTBE, an antiknock compound. In the methanation reaction H_2 and CO are converted into CH_4 and synthetic natural gas (SNG) is yielded. Dimethylether, another product, can be used as fuel gas and base material for the chemical industry. In Table 4.4 some information on those reactions is compiled.

Table 4.4: Characteristics of some synthesis reactions, adapted [32]

	H₂/CO ratio	catalysts based on	pressure (bar)	temp. (°C)
Fischer-Tropsch	0.85 - 3	Fe/Co/ZrO₂/SiO₂	1 – 70	120 – 350
methanol	1 - 2.15	Zn/Cr/Cu	50 - 300	220 – 380
dimethylether	1 - 2.15	Cu/Zn/Al₂O₃	15 - 100	220 – 300
methanation	2 -3	Ni/Mg	1 – 10	200 – 450

4.8 Efficiency

Cold gas efficiency

The cold gas efficiency characterises the quality of conversion in the gasifier. It is defined as the ratio of the chemical energy of the producer gas and the initial energy content of the feed.

$$\eta_{CG} = \frac{\text{chemical energy of producer gas}}{\text{energy content of feed}} \qquad (4.11)$$

Hot gas efficiency

This efficiency value also considers the sensible heat of the producer gas, which is typical for hot gas applications.

$$\eta_{HG} = \frac{\text{chemical energy + sensible heat of producer gas}}{\text{energy content of feed}} \qquad (4.12)$$

Typical average values for cold gas efficiencies are in the range of 50-75% and hot gas efficiencies of 75-90% for biomass gasifiers.

Gross electrical efficiency

The definition of the two types of electrical efficiency is similar to chapter 3.3.5.

$$\eta_{el,g} = \frac{\text{produced electrical energy}}{\Sigma \text{ energy input}} \qquad (4.13)$$

Net electrical efficiency

$$\eta_{el,n} = \frac{\text{produced electrical energy} - \text{auxiliary service power}}{\Sigma \text{ energy input}} \qquad (4.14)$$

Table 4.5 gives an overview on efficiencies of the waste gasification plants described previously. There is only few data available, however some conclusions can be drawn.

Table 4.5: Efficiencies of waste gasification plants

	fixed bed	entrained flow	stationary fluidised bed	circulating fluidised bed	rotary kiln	net electrical efficiency (%)	hot gas efficiency (%)	overall efficiency (%)
Baden	x					no		
Contherm					x			
Siemens					x	13		13
Grève-in-Chianti				x		18-20	85-95	18-20
Lahti				x			92	
Rüdersdorf				x		no		
Ebara Twinrec			x					
Ebara Ube			x			no		
Thermoselect	x					13		13
SVZ	x	x						35-40
Carbo V alpha	x	x					> 80	45
Noell		x			x			13

In Baden only hot water is produced, so there is no electrical efficiency of the process. The same is true for Rüdersdorf, where the producer gas is employed to heat the cement kiln.

There is no efficiency indicated for cofiring plants such as Lahti, Rüdersdorf and Contherm because the producer gas is combusted in a conventional power plant or a cement kiln. Typical electrical efficiency values of coal fired power plants amount to 40%. As the use of producer gas should not affect the initial efficiency of the power plant, 40% of electrical efficiency also can be assumed for cofiring plants.
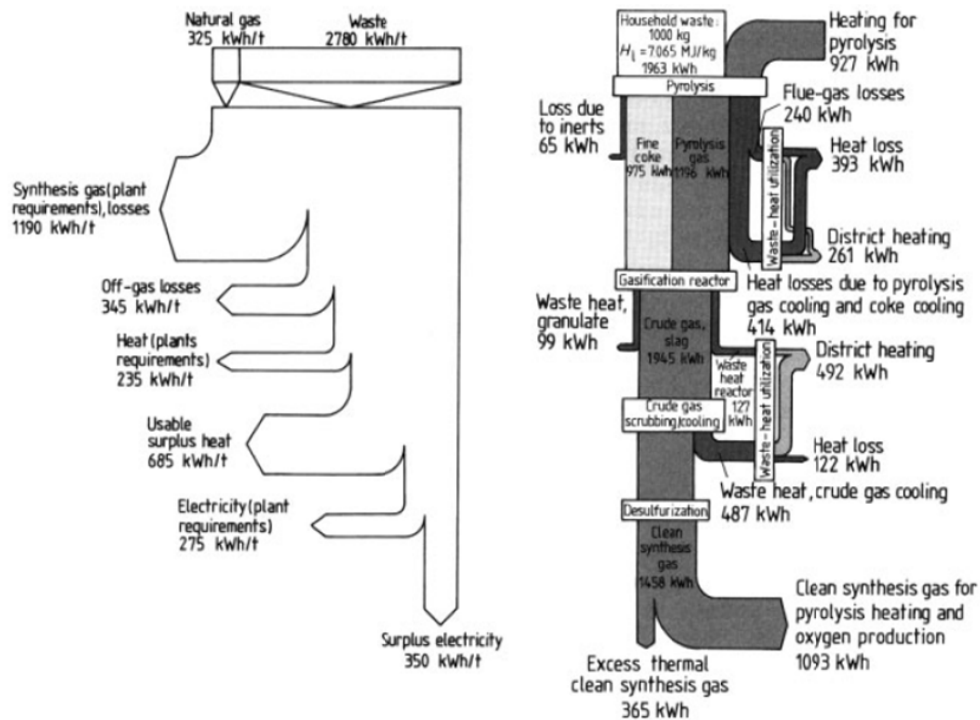
Figure 4.24: Energy balance of Thermoselect and Noell-Conversion, [66]

The net electrical efficiency of Thermoselect and Noell-Conversion is calculated on the basis of the energy balances in Figure 4.24. It is obvious that the energy consumption by the process is very high. The major part of producer gas is used to heat the pyrolysis kiln or tunnel. As a result, the net electrical efficiency is modest and attains about 13%.

In Grève-in-Chianti a net electrical efficiency of 18-20% was reported after the expensive revamp of the boiler and the new hot gas cleaning equipment. [22]

In contrast to Europe, where numerous waste gasification plants have been shut down, waste gasification seems to be quite successful in Japan. Unfortunately, there is no extensive current information available.

As mentioned before, the typical range of hot gas efficiency for biomass gasification is 75-90%, which is also true for the fluidised bed gasifiers in Lahti and Grève-in-Chianti using waste as feedstock.

If not only electricity is produced, the overall efficiency of the process is increased markedly. Heat and power generation by the Noell-Conversion process reaches 67%. Due to polygeneration at SVZ Schwarze Pumpe, the overall efficiency amounts to 35-40% for methanol synthesis, heat and power generation. CHOREN determined an efficiency of 45% for the biomass-to-liquid process for fuel production. As waste only has been tested as feedstock, but the process is designed for biomass, it is not really representative for waste gasification.

Summary of the efficiencies as far as available from the experience of the demonstration plants for waste and biomass:

- Cold gas efficiency: 50-75%
- Hot gas efficiency: 75-90%
- Electrical efficiency: 13-35% (higher values for combined cycles)

5 Comparison of waste incineration and gasification

The following chapter is dedicated to a comparison of waste incineration and gasification. Three model processes are selected in order to evaluate the possibilities of application. Case 1 represents a typical waste incineration plant and case 2 and 3 are waste gasification plants.

5.1 Model processes

Waste incineration (case 1)

Figure 5.1 gives a general overview on waste incineration processes. Waste incineration is the state-of-the-art technology for thermal waste treatment. However, there is still some potential of improvement.
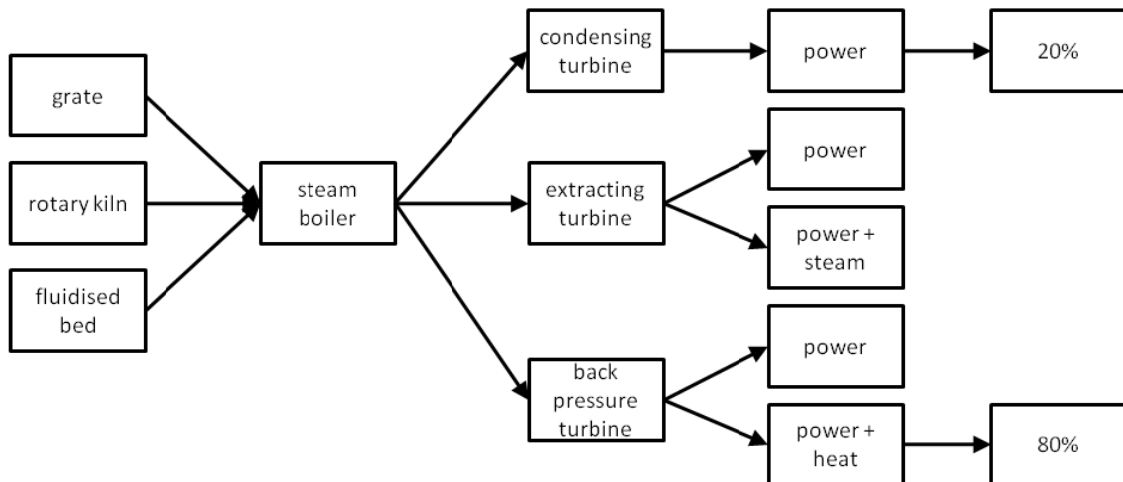
Figure 5.1: Efficiency of waste incineration processes

Case 1 is considered to be a waste incineration plant with grate firing or a fluidised bed incinerator. Usually, rotary kilns are used for the incineration of hazardous wastes and are thus neglected in this comparison, which is focussed more general on municipal solid and organic waste. Figure 5.2 shows a detailed process flow sheet starting from the waste until the flue gas released via the stack. The process flow sheet contains typical gas cleaning steps, which can be considered as state-of-the-art technology.
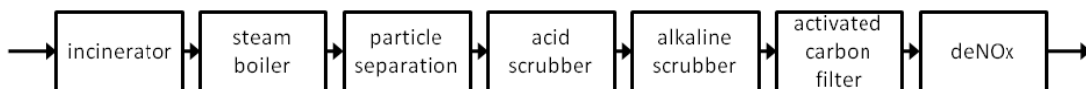
Figure 5.2: Typical process steps for a conventional state-of-the-art waste incineration plant including gas cleaning

Waste gasification (case 2 and case 3)

Case 2

There is hardly any general example for a waste gasification plant that could be used directly for a comparison with waste incineration. A suitable approach to create a new waste gasification process is based on waste incineration. Usually, staged combustion takes places in

many waste incinerators: primary air is added sub-stoichiometrically and volatile matter is released, which is in fact gasification. Oxidation is completed by injection of secondary air in an atmosphere of air excess.

The rotating fluidised bed incinerator, for example the WSO4 at EBS Simmering in Vienna (Austria), has been designed especially for municipal solid waste. In this case gasification or in other words sub-stoichiometric combustion is used explicitly to control the temperature in the stationary fluidised bed. If there was no injection of secondary and tertiary air in the upper part of the reactor (freeboard), it would be operated as an autothermal air blown gasifier.

Following this approach of a bubbling fluidised bed incinerator without combustion of volatiles in the freeboard, the incinerator turns into a gasifier. A possible flow sheet of the process chain is shown in Figure 5.3.
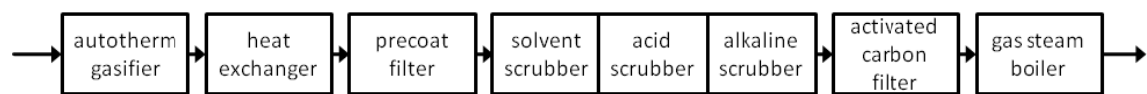

Figure 5.3: Autothermal waste gasification

In this flow sheet some elements are already included, which have been successfully tested in biomass gasification plants. The heat exchanger after the gasifier is mainly used for air preheating and the remaining heat for a district heating system. A precoat filter is operated successfully for many years in the biomass gasification demonstration plant in Güssing (Austria). Furthermore, a solvent scrubber has proven to be an efficient tool to remove tars from the producer gas (see case 3). The cleaned producer gas can be used in a gas boiler, in a gas engine or in a gas turbine. In case of a gas boiler higher steam parameters can be applied compared to a waste incineration boiler as the gas is virtually free of chlorine and sulphur, which can lead to higher electrical efficiencies. In addition to that, a deNOx device can probably be avoided since the gas is nearly free of nitrogen compounds.

Case 3

The development of biomass gasification has been more successful than waste gasification and it has been studied in detail during the last decades. As there is already a lot of experience in biomass gasification and there are numerous successful applications, it is an inspiring example for waste gasification. Based on the biomass gasification process in Güssing a waste gasification process can be developed (case 3).
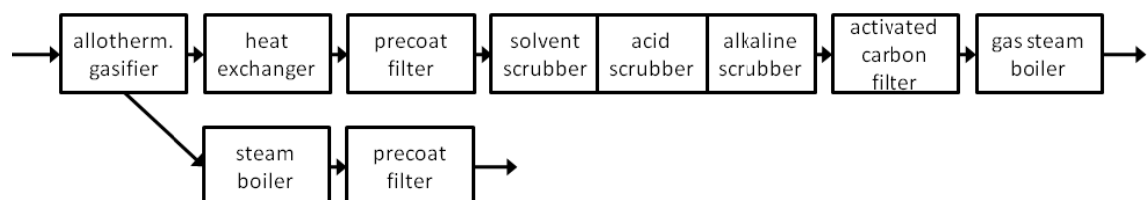
Figure 5.4: Allothermal waste gasification

Figure 5.4 presents a schematic flow sheet of the process. In Güssing a fast internal circulating fluidised bed gasifier is used. Biomass is gasified with steam in a stationary fluidised bed, which is connected to a fast fluidised bed combustion zone. There the unreacted char is completely

oxidised with air. Heat is released and is transported to the gasification zone via the bed material. The principle of heat exchange is illustrated in Figure 5.5.
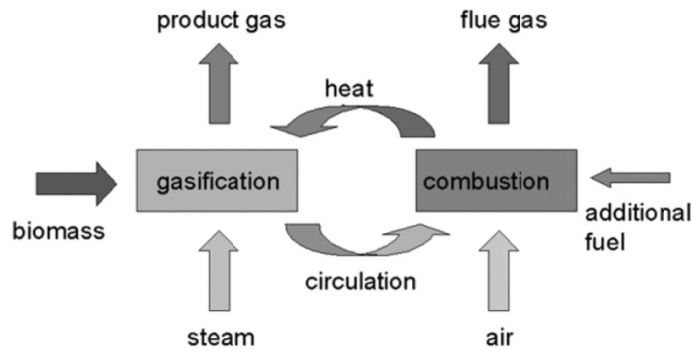
Figure 5.5: Heat exchange in an allothermal gasifier, [28]

Because of the spatial division of gasification and combustion the producer gas and the flue gas streams are also separated. The producer gas, which has a high calorific value and contains virtually no nitrogen due to steam gasification, is cleaned prior to the gas engine. In the original process tars and particles are removed in a precoated bag filter. It has been found that HCl is precipitated to a large extend by reaction with the precoat material in the producer gas filter and is captured in the ash. In Figure 5.6 the distribution of chlorine compounds in the biomass gasifier in Güssing is illustrated.
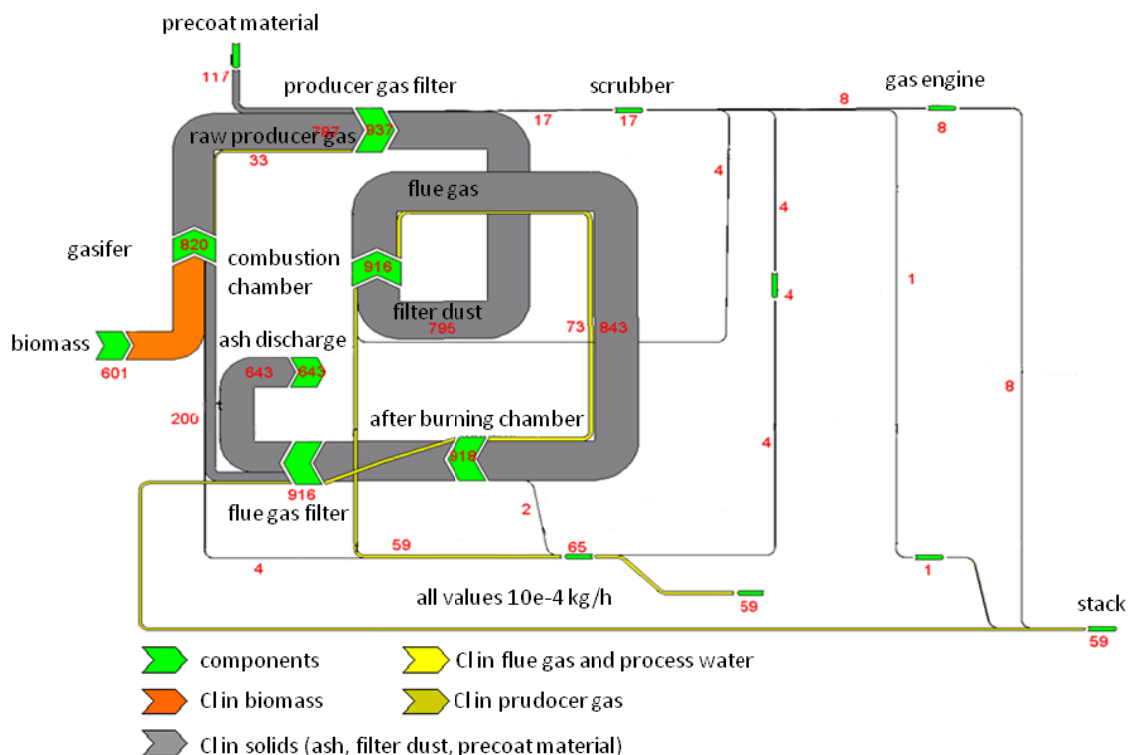
Figure 5.6: Concentration of chlorine compounds in the biomass gasifier Güssing, [51]

Residual tars are captured in a solvent scrubber. The charged solvent is fed to the combustion zone of the gasifier. [29]

On account of the higher content of sulphur, halogens and heavy metals in the waste in comparison to biomass, additional cleaning of the producer gas is necessary. Similar to flue gas cleaning in waste incineration plants, two more scrubbers are implemented.

In the acid scrubber HCl, HF and heavy metals are precipitated in water. The concentration of NH_3 can reduced markedly too if the pH value in the scrubber is lowered. Thus, the acid scrubber also removes ammonia. [42]

In the alkaline scrubber NaOH is used in order to remove H_2S. It is a non-recyclable solvent, which is suitable for gas streams with low sulphur content. [43]

It is likely that all pollutants are present in the producer gas and not in the flue gas, because the fuel is fed into the gasification zone, where the fuel particles are heated up to 850°C. At this temperature all volatile compounds are released in this zone. Therefore, the flue gas stream is expected to be mainly composed of CO_2, water and nitrogen. Thus, no further flue gas cleaning except for a bag house filter to remove particles is necessary. Of course this assumption has to be confirmed by further experimental investigations.

A main advantage of case 3 compared to case 2 is that a producer gas is obtained, which is virtually free of nitrogen. This is a precondition for the use of the producer gas as syngas for synthesis applications. Furthermore, the presence of a combustor in the gasification system offers the possibility to get an almost carbon free residue, which is discharged from the combustion zone.

5.2   Comparison

5.2.1   Waste treatment

Fuel pretreatment mainly depends on the thermal conversion system. Incineration using a grate incinerator is more tolerant than a fluidised bed. The most flexible system is a rotary kiln. As gasification can be carried out principally in the same conversion systems as incineration, no real difference is expected as far as waste treatment is concerned for incineration or gasification. In this work fluidised bed systems are taken into consideration especially for gasification. The main restrictions for fluidised beds relate to fuel particle size (< 100 mm) and ash melting. On account of the restrictions of ash melting and also because of the low melting point of inorganic materials such as lead or aluminium several fluidised bed incinerators are operated at temperatures below 700°C in the bed. That can be reached easily by sub-stoichiometric combustion in the bed and final combustion in the freeboard.

Regardless of the process, whether it is waste gasification or incineration, waste should be treated, so that only a small amount of residues that are not harmful anymore remains. There are national and European laws for waste incineration plants (see chapter 3.7 and 3.8). It will be the scope of future research work to proof that waste gasification processes are able to meet those requirements too.

5.2.2 Thermal conversion

There is a wide difference between incineration and gasification concerning thermal conversion. In case of incineration complete oxidation and the total release of energy takes place in the combustion chamber. There the whole amount of flue gas is generated. It is cooled in the boiler and it is cleaned afterwards.

In case of gasification only partial oxidation occurs in the gasifier and producer gas is obtained. The producer gas – the amount is much smaller than the amount of flue gas in case of incineration – is cooled and cleaned. Finally, the cleaned producer gas is burned in a gas steam boiler, where most of the heat is released (about 70% of the total energy content). These differences have essential impacts on gas cleaning and electrical efficiencies, which are discussed in the following chapters.

5.2.3 Gas cleaning

The power demand of auxiliary units in grate firings and rotary kiln furnaces is in the range of 3-6% of the energy input of the waste, which is equivalent to 20-30% of the electrical power generation. Due to the higher number of auxiliary units in fluidised bed incinerators, the auxiliary service power consumption is 50% higher. [6] Auxiliary service power also includes the power demand of the flue gas cleaning system and the induced draught fan.

The complexity of the gas cleaning system in case of incineration and gasification is comparable. On the one hand, an additional solvent scrubber is necessary to remove tars in gasification systems. On the other hand, a NOx removal is avoided as NH_3 is already washed out of the producer gas.

Waste is combusted with air oxygen and because of the nitrogen content of the air the amount of flue gas is much higher than the amount of producer gas in a gasifier. In an average grate incinerator 7000 kg of flue gas are generated by 1000 kg of waste, which have to be treated. [66] Assuming a gas density of 1.3 kg/Nm³, which is a typical value for the combustion of solid fuels, there are about 5400 Nm³ of flue gas. [26]

Roughly speaking, 1000 Nm³ of gas are yielded from 1000 kg of waste in a steam blown gasifier. Thus, the volume of producer gas that has to be cleaned is more than 5 times less than the flue gas volume in waste incineration plants.

In an air blown gasifier 1000 kg of waste lead to 2500 Nm³ of producer gas, which is diluted by nitrogen. The gas volume is still about 3 times smaller than in waste incineration plants.

The advantage of smaller gas volumes seems to lose validity when producer gas is combusted with air, which is part of each process. The excess air ratio in grate incinerators is 1.5-2.0 because air stabilises the combustion and the excess is required to ensure complete combustion. Gaseous fuels can be mixed thoroughly with air and thus less air is necessary. Typical values for the excess air ratio for the combustion of natural gas in power plants are in the range of 1.05 to 1.1. [26] This leads to lower amounts of flue gas and therefore lower losses and higher efficiencies.

In combination with precipitation of ammonia and other nitrogen compounds in the producer gas cleaning units, no further flue gas cleaning to remove NOx should be necessary. In waste incineration plants NOx emissions are controlled by SCR devices.

In this study it is assumed that producer gas cleaning in gasifiers is performed with similar systems as it is done currently for flue gas in incinerators. Most of the pollutants are not present in the oxidised form as it is the case in the flue gas of waste incinerators. Tests on producer gas cleaning with acid and alkaline scrubbers show encouraging results. Nevertheless, the performance is not proven yet and has to be investigated in further scientific and demonstration work.

5.2.4 Electrical efficiency

The net electrical efficiency seems to be a good basis for a comparison of different processes that produce electrical energy.
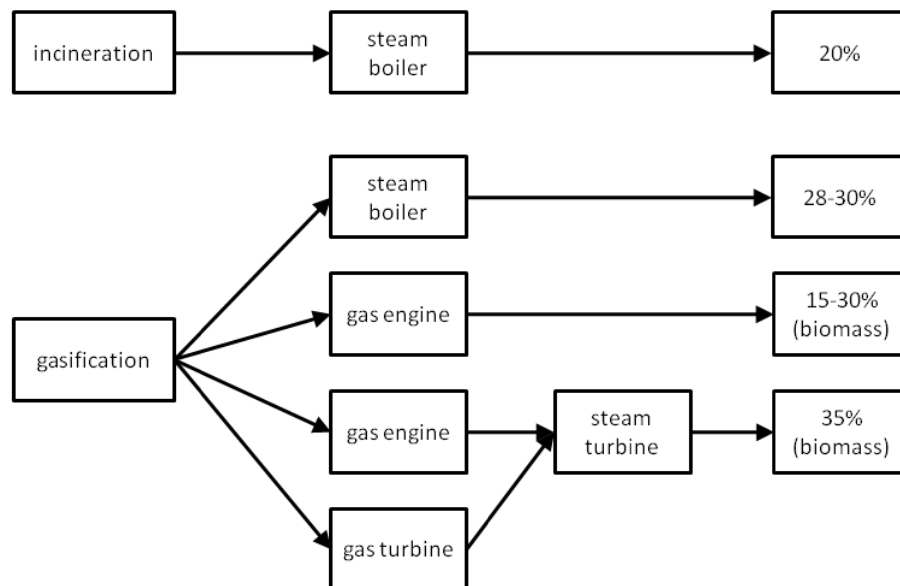
Figure 5.7: Comparison of electrical efficiency

The net electrical efficiency of a waste incineration plant amounts to approximately 20% because of the rather moderate steam parameters of 60 bar and 420°C. The steam temperature is limited by chlorine-induced corrosion. [6]

Waste gasification offers a possibility to avoid chlorine-induced corrosion. If chlorine is removed from the producer gas, for example by means of lime injection and filters, the gas can be combusted in boilers operating at higher steam temperatures. As a result, the electrical efficiency can amount to 28-30%, which corresponds to an increase of 40-50% in comparison to conventional waste incineration. [41]

As there is no reliable data for waste gasification, but a lot of data for biomass gasification, biomass and waste are compared first in order to find similarities and to adapt the values for waste gasification then.

The net electrical efficiency of biomass power plants amounts to approximately 28% [8], which is considerably lower than the efficiency of fossil fuelled plants. The main raison therefore is that biomass power plants are designed for rather small capacities because of the logistics of biomass. The measures of improvement such as preheating of feed water and reheat cycles are usually too expensive for small plants. [32] In Figure 5.8 the dependency of electrical efficiency on the thermal capacity of biomass plants is illustrated.
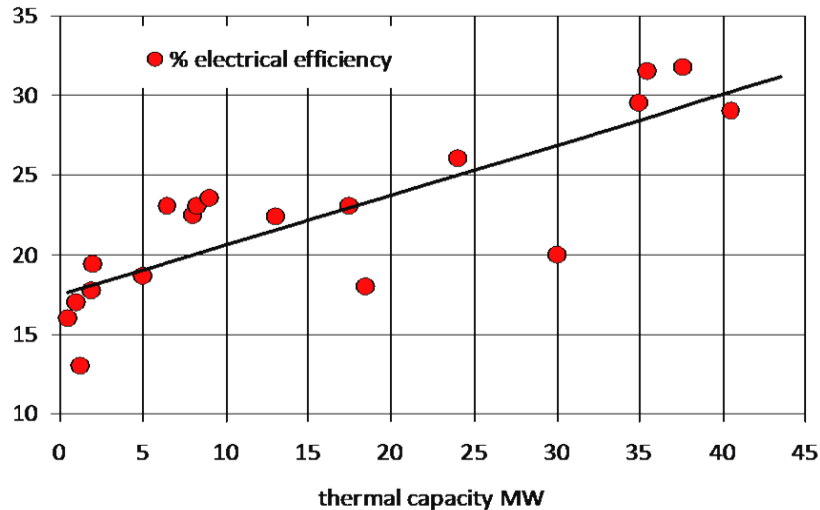

Figure 5.8: Efficiency of biomass power plants as a function of capacity, adapted [69]

However, the efficiency of biomass power plants is higher than the efficiency attained by conventional waste incineration plants regardless of the plant capacity, which highlights that waste is a more complicated feedstock than biomass.

Biomass gasification leads to an electrical efficiency in the range of 15-30%, when the producer gas is combusted in a gas engine. [41]

In a combined cycle producer gas is combusted in a gas turbine and the sensible heat of the exhaust gas is further used in a heat recovery steam generator. Efficiency values up to 35% are predicted for combined cycle biomass gasification according to [8].

It can be expected that the electrical efficiency of waste gasification is lower than the values achieved for biomass gasification. Nevertheless, there is some potential for waste gasification between 20% of net electrical efficiency for conventional waste incineration plants and 35% for combined cycle biomass gasification plants (BIGCC).

5.2.5   Product range and overall efficiency

In waste incineration plants only power and/or heat are generated. About 80% of overall efficiency is attainable in cogeneration waste incineration plants. A precondition for heat use is heat demand. Thus, the plant has to be located close to a district heating system or an industrial site.

Due to gas production in gasification plants the product range can be extended considerably. By means of chemical synthesis syngas can be converted to products such as methanol, ammonia, liquid fuels (Fischer-Tropsch synthesis), synthetic natural gas (SNG),.. For syngas

production case 3 has to be applied since no nitrogen should be present in the producer gas (=syngas). The technical and economic feasibility of polygeneration strongly depends on the gas cleaning system because there are severe requirements for syngas purity. In a polygeneration plant the overall efficiency increases markedly, as not only the energy content of the waste is recovered, but there is also chemical recycling. In addition to that, the possibility to use chemicals, liquid fuels and gas produced in polygeneration plants does not depend on the location of the plant. They can be transported more easily.

5.3   SWOT for waste incineration

Strengths
- established and proven technology
- suitable for almost all kinds of waste
- reduction of the amount of waste to be landfilled
- destruction of hazardous compounds
- concentration and lock out of inorganic compounds
- destruction of organic compounds
- recovery of the energy content of the waste

Weaknesses
- anticipate recycling
- incineration of unsorted material anticipate recovery of compounds such as aluminium
- de-novo-synthesis of harmful pollutants possible
- no chemical recycling (= gas production for chemical synthesis) possible
- no combined cycle possible

Opportunities
- legal obligation to pretreat the waste before it is landfilled
- high efficient waste incineration is considered as a recovery operation
- mankind produces more and more waste
- the heating value of the waste is increasing
- waste serves as fuel in times of fuel shortage

Threats
- bad image of waste incineration plants: not in my back yard (nimby)
- politics: not in my terms of office (nimtoo)

5.4   SWOT for waste gasification

Strengths
- chemical recycling possible
- enlarged product range: liquid and gaseous fuels, chemicals
- significantly smaller amount of gas to be treated
- higher efficiency possible by means of combined cycle plants

Weaknesses
- no mature technology
- need to be proven that pollutants are destroyed and locked out

Opportunities
- no incineration technology → important for Nord America
- legal obligation to pretreat waste before it is landfilled
- mankind produces more and more waste
- the heating value of the waste is increasing
- waste serves as fuel in times of fuel shortage

Threats
- maybe not possible to meet laws for waste treatment
- might be too expensive
- difficult permission procedure as currently not accepted by public in Europe

5.5 Conclusion

As there is a legal obligation to treat waste before it can be landfilled and the amount of waste generated is increasing constantly, thermal waste treatment is a very important issue.

In this work two pathways of thermal waste treatment, incineration and gasification, are compared. For this purpose, literature on both technologies has been reviewed and the state-of-art technologies for waste incineration and gasification are presented. The comparison highlights the strengths and weaknesses of both technologies and identifies future potentials.

Waste incineration is the state-of-the-art technology for thermal waste treatment ensuring destruction of the pollutants and allowing recovery of the energy content of the waste. Waste gasification, however, has several advantages due to gas production. Higher efficiencies can be attainable by means of combined cycles. Not only power and heat might be produced but also liquid and gaseous fuels or other chemicals.

Waste gasification processes have been developed in the past, but the plants were shut down because of economic reasons and/or technical problems. However, important research has been done in the field of biomass gasification and thus gasification technology has been improved markedly. The fluidised bed gasifier in Güssing is one of the most successful examples; this technology is about to be commercialised.

Considering these developments, there is definitely interesting potential for waste gasification now and the design of a new waste gasification process based on the findings in biomass gasification will be the scope of future research work.

Further steps will be gasification tests with representative waste samples in order to determine the producer gas properties. It is also necessary to measure the carbon content of the residues. Producer gas cleaning with acid and alkaline scrubbers has to be investigated to prove whether it is a reliable cleaning method. Another interesting point is the flue gas composition of the allothermal gasifier in case 3 to determine if a bag house filter as the only flue gas cleaning device is sufficient.

According to the principles of process design, laboratory tests have to be conducted first. Then a demonstration plant can be erected.

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