EXECUTIVE SUMMARY

Waste-to-Energy is an essential part of a sustainable waste management scheme. And thus the drive for a Circular Economy, having the goal of keeping materials in the economic loop as long as technically and economically feasible. Preserving our resources which are becoming more and more scarce to fill the needs of an evergrowing population, in numbers but also in their standard of living. Eventually, materials will reach their 'end of life' and then the energy and the materials (minerals, metals) still contained therein should be recovered in Waste-to-Energy plants. Landfilling is the least desirable option for this waste, as the resources are not recovered and a long-term liability will be created.

Grate-based incineration is a well proven technology for WtE plants, with high reliability and availability. The focus used to be on reduction of volume and hygienisation. But this has changed to the recovery of energy and materials from waste that can not be utilized in any other form anymore. Due to very stringent regulations, emissions from WtE plants are very small compared to other sources.

INTRODUCTION

Waste-to-Energy (WtE) is often only applied when regulations either demand it and/or favour it over other options, like landfilling. Markets for WtE typically only start to come into play when the regulatory and political framework is firmly set and being administered. In the European Union (EU), the Waste Framework Directive (WFD - 2008/98/EU) gives this regulatory framework, which has to be put into national legislation in all member states of EU-28.

Among other regulations, the WFD sets a 5-step hierarchy (Fig. 1) for waste treatment. According to this hierarchy, WtE can be a recovery operation when the energy recovered is used ‘efficiently’, evaluated by the so-called R1 formula. WtE plants itself are highly regulated, e.g. through the Industrial Emissions Directive (IED - 2010/75/EU), setting operating conditions as well as emission limit values.

That is why today, waste incineration - or WtE as is used more commonly - is accepted in many countries as an important part in an overall sustainable waste management scheme. Not putting the priority for waste reduction and recycling into question. But clearly recognizing the drawback of landfilling, mainly in terms of greenhouse gas emissions, but also the long-term liability and risk to soil and groundwater pollution. Also recognizing that there is a trade-off between the cost involved for additional reduction/recycling of waste and the environmental benefit associated. Thus the recovery of a larger amount of the energy contained in the waste is coming more into focus. Residual municipal solid waste (MSW) is more and more recognized as a resource - of both energy and material - and many discussions/efforts are under way to improve recovery efficiency.
GRATE INCINERATION

A schematic of a modern grate-based incineration system is shown in Fig. 2. The MSW is fed into the feed hopper by a crane. From there it slides through the feed chute, providing a seal against intake of air, to the feeder. The feeder is controlled by the combustion control system, feeding waste onto the grate. The grate itself typically consists of rows of grate bars, fixed and moveable ones. Primary combustion air is usually taken from the waste bunker area and fed into different air zones underneath the grate. Depending on the waste composition (especially the water content), primary air can be preheated. The primary air enters the waste bed at fairly high pressure through holes or slots in the grate bars, first drying the waste, then incinerating it and in the rear part of the grate guaranteeing a good burnout of what is remaining after incineration, bottom ash. The bottom ash falls into a discharger, filled with water which is both cooling the bottom ash but also providing a seal against air intake.
Figure 2: Grate-based incineration system

The flue gases coming from incineration on the grate are entering the furnace, which forms part of the steam boiler. Secondary air is injected from the sides, guaranteeing an excellent burnout of the flue gases, especially destroying organic compounds.

In order to compensate for the thermal expansion when in operation, grate runs are limited in width to typically 2.5 - 3 m. Grate runs are put side by side in order to handle the waste throughput required. As an example, a furnace with a 5-run grate is shown in Fig. 3.
Waste quality and composition is changing over the typically > 30 year lifetime of a WtE plant. Pretreatment and sorting of waste is leading to an increase in heating values. Special waste fractions are to be treated in WtE plants. In order to better adapt to these - and potentially changing conditions in the future - MARTIN has developed the reverse-acting grate Vario, Fig. 4. The well proven reverse-acting principle remains, but the grate has three independently controlled drives, giving more flexibility to the operator. This has also made it possible to improve the separation of the individual primary air zones. After extensive testing and a first commercial installation in the WtE plant in Pozzilli, IT, going into operation in 2007, MARTIN introduced the reverse-acting grate Vario as its main combustion system for the future in 2010, on the occasion of the IFAT exhibition in Munich.
The energy released during incineration of MSW is recovered in a steam boiler, a typical design shown in Fig. 5. This is a so-called ‘horizontal-type’ boiler, where 3 empty passes with heat transfer dominated by radiation are followed by a horizontal pass containing tube bundles where heat transfer is dominated by convection. The steam can either be converted into electricity in a steam turbine, used as process steam in industrial applications or in a district heating/cooling network. Steam parameters (temperature/pressure) are rather limited, compared to power plants fired with fossil fuels like coal, oil, gas. MSW contains pollutants (e.g. Cl, Na, K) that are released during incineration and have a high corrosion potential at high temperatures.
Pollutants contained in the MSW, like Cl, F, S, heavy metals etc. are released into the flue gas during incineration. Other pollutants, e.g. NO\textsubscript{x}, are formed during combustion, particulate matter is released. In order to protect the environment, very stringent emission limits have been adopted in most countries, e.g. in the EU according to IED - 2010/75/EU. Technologies like electrostatic precipitator or fabric filter, wet scrubber or dry/semi-dry absorption systems as well as catalytic or non-catalytic reduction in various combinations are well proven. They guarantee emissions that stay very safely below the above mentioned legal requirements.

**ENERGY EFFICIENCY**

Residual waste contains a substantial amount of energy. In Europe the heating value of residual waste is typically that of brown coal. Thus to recover as much of that energy and make it available for further usage, can substitute other fuel resources. These resources are either becoming scarce, are more expensive or are delivered from countries which are not stable and/or might utilize the supply of these resources for other purposes.

Steam boilers in modern WtE plants can typically recover more than 80% of the energy contained in the waste. When applying flue gas condensation, also the latent heat can be recovered, raising that figure to well over 90%. Some of this energy is needed within the plant itself, e.g. to power drives and supply steam needed for e.g. combustion air preheating or boiler tube cleaning. But by far the largest portion can be exported to external users, either as steam for process applications, to supply energy to a district heating/cooling network or to convert the energy to electricity in a steam turbine. All kind of combinations of these different usages are possible as well.

The efficiency of electricity production from WtE plants is limited due to the corrosive nature of the flue gases. Residual waste contains sizeable quantities of chlorine and sulphur, as well as alkaline (Na, K) and heavy metals (e.g. Pb, Zn). Most of these are released into the flue gas during the combustion process. If deposited on the boiler tubes, they can form quite corrosive mixtures. The actual corrosion process is quite well understood. But why in some plants corrosion rates are acceptable at even ‘elevated’ steam temperature, whereas in other plants, massive corrosion occurs at ‘moderate’ steam temperatures, is still unclear, even though extensive studies have been undertaken. As a general accepted limit for an adequate lifetime of boiler tubes, steam parameters of 40 bar/400 °C are widely used.

Some countries in Europe are subsidizing electricity generated from WtE plants. Thus higher steam parameters are desirable. In the plant in Brescia, IT, (Fig. 6) steam parameters of 60 bar/450 °C resp. 73 bar/480 °C are used, combined with cooling of the flue gases down to around 130 °C. In addition several measures have been taken to lower the internal energy consumption. This gives rise to a net electrical output of more than 27% (compared to around 20% for ‘normal’ plants).
Two additional lines - to the four existing, making it the largest WtE plant in the world - have been added to the plant in Amsterdam, NL, in commercial operation since 2007 (Fig. 7). These are designed with a high electrical efficiency, by using steam parameters of 130 bar/440 °C through internal reheating as shown in Fig. 8.
This together with other improvements gives a net electrical output of more than 30%. Through very generous sizing of the boiler and protection of large parts with Inconel, corrosion so far has been close to negligible.

Another possibility to increase the electricity output is the combination of a WtE plant with a natural gas fired combined cycle plant. In the WtE plant in Mainz, DE, the steam from the WtE plant is fed at 40 bar/400 °C to the intermediate superheating stage of a combined cycle power plant. In Bilbao, ES, the steam from the WtE plant is fed at 100 bar/330 °C to the waste heat recovery boiler after the gas turbine. In both cases, the electrical output is > 40%, comparing the energy fed into the combined process by the residual waste to the electricity exported to the grid.

Even more effective though is the use of the energy recovered from the waste as thermal energy, e.g. in a district heating network, as is practiced quite often in Scandinavia. There, many WtE plants are operated by the demand from the heating network, the plants actually running at full load only in the colder season; during the warmer season, waste is packed in bales and stored to be then incinerated when heat demand is greater. The SYSAV plant in Malmö, SE, has a total of 4 incineration lines (Fig. 9). The older 2 lines are only used during the cold season. In the 2 newer lines, going into operation in 2003 resp. 2008, flue gas condensation is used. With this, the plant reaches a thermal efficiency of well over 90%, making very good use of the energy in the waste.
In order to run at higher steam parameters, especially temperatures, without excessive risk of corrosion and thus plant downtime, MARTIN has developed and successfully tested two new concepts for superheater protection. Both are based on the concept of so-called ‘rear-ventilated’ SiC tiles, which are operating successfully over many years in numerous installations. The surface temperature of these tiles is higher than in usual applications, thus lowering the potential for corrosive compounds to condense. The purge air introduced effectively keeps corrosive gases out, thus protecting superheater and membrane wall.

One concept is the so-called “wall superheater”. This superheater is installed in the first boiler pass. Depending on the specific plant design, the steam temperature can be raised by 40 - 50 °C. The other concept is the “radiation superheater”, with superheater tubes introduced from the roof of the boiler into the first pass, also protected by a specially designed rear-ventilated tile system. Heat transfer is from several sides, many panels can be installed, thus the increase of steam temperature is even higher.

Both concepts have been tested and are ready for commercial application.

**MATERIAL RECOVERY**

Bottom ash is the largest fraction of residues remaining after combustion, with about 20 - 25%. It contains a sizeable amount of ferrous (about 10%) and non-ferrous (about 1 - 3%), mainly copper and aluminium. The largest portion though is composed of glass, stones, ceramics, bricks and a mineral fraction, which contains chlorides, sulphates and heavy metals. But after so-called ‘aging’ of about 3 months, the properties of this mineral fraction are such that it can be used for construction purposes, mainly in road construction. Up to this point in time though, rules in Europe vary widely from country to country, as to the testing method prescribed and the limit values that are acceptable as well as concerning the actual use of this material.

A number of developments have taken place in the last years, with different aims. One development direction was to improve the quality of the mineral fraction, meaning lowering the leaching of heavy metals, by producing a more glassified mineral fraction. But thereby loosing the opportunity to recover many metals, especially the more precious ones. Another direction is to improve the performance of bottom ash separation processes, aiming at a higher yield of metals and different fractions of minerals, based on grain size, which are then more suitable for specific recycling applications. Mainly Switzerland is following another quite different direction. There the aim is to recover more metals, especially non-ferrous, in a superior quality. Dry discharging of the bottom ash is an essential first step for this process, followed then by different ways to separate the bottom ash. Higher metal recovery rates from bottom ash is clearly the focus of today’s developments.

**Wet bottom ash treatment**

Mainly in the Netherlands, Belgium and Denmark, new concepts for wet bottom ash treatment have been developed and implemented. They all aim at a more distinct separation without making any modification to the bottom ash itself or the way it is being discharged from the combustion process. In principle the processes are similar, consisting of sieving/washing steps, metal removal and flotation/density separation. As output all processes have ferrous and non-ferrous metals for recycling; 2 size fractions of granulate that are re-used in the cement or asphalt industry; a ‘sand’ fraction that can either also be used in the cement industry or used for landfill construction. And a sludge/filter cake which needs to be landfilled. More and cleaner metals are thus recovered.

**Dry bottom ash treatment**

Switzerland has in the past decided not to re-use the mineral fraction from bottom ash, but has focused on separating larger amounts of metals, especially non-ferrous, in an improved quality. Essential for this is the development of a dry discharge system, which avoids distributing the fine fraction, containing many heavy metals, over all materials, especially the metals. This has the additional benefit to save cost for the consumption of water, but mainly for its transport and landfilling.
Two processes for the dry discharge of bottom ash are under development. One process is developed by ZAR - Zentrum für nachhaltige Abfall- und Ressourcennutzung - at the WtE plant in Hinwil, CH. They separate large pieces after discharge from the furnace and transport the remainder via a specially designed long conveyor to transport the bottom ash to the plant which then sorts out different metal fractions. Another process is developed by MARTIN, shown in Fig. 8, operating in the WtE plant in Monthey, CH. In this process, a windsifter is used to separate the coarse from the fine fraction. The majority of metals remain in the coarse fraction; the fine fraction is separated in a cyclone, the air needed for the windsifting process still containing some very fine material is utilised as combustion air. Separation of the metals form the coarse fraction will be done in the plant developed by ZAR, of which MARTIN is a founding member.

By utilizing dry bottom ash discharge, potentially also more precious metals, like silver, gold and rare earth could be recovered. Being stored in underground mines these residues can probably serve as a source for future metal recovery if the separation technologies have been further developed.

CONCLUSION

Grate incineration of MSW is a well proven, safe and reliable technology for the treatment of residual waste. Volume and weight of the MSW is greatly reduced. The energy contained in the MSW can be recovered and utilised in form of steam or electricity or any combination thereof. Ferrous metals remaining after incineration are already recycled to a large portion as well as some of the non-ferrous like Cu, Al. But a lot more of these non-ferrous as well as precious and rare earth metals could be recovered and recycled, strong and very promising development efforts are under way. Bottom ash can be utilised in e.g. cement kilns or for road construction. With modern flue gas treatment systems, emissions to air are very low, in many cases negligible compared to other sources.

Grate incineration can be adapted to a wide range of MSW composition. From MSW with fairly high heating value in e.g. European countries to MSW with high water content (and thus low heating value) in many countries in Asia.

Thus Waste-to-Energy plays an important role in sustainable waste management and the Circular Economy, worldwide.