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Waste-to-energy: Coupling Waste Treatment to Highly Efficient CHP

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Abstract:
Municipal Solid Waste Incineration (MSWI) has become the most widespread Best Available Technology (BAT) to treat residual waste streams in a reliable and safe way. As such, MSWI has contributed to achieve the landfill diversion targets in many EU member states. Modern waste incinerators, also referred to as Waste-to-Energy (WtE) plants, have furthermore evolved to producers of electricity, heat and steam for energy-consuming industries, agriculture and residences. However, due to the specific composition and properties of MSW and similar waste, and due to the historical development of MSWI, the exploitation of WtE plants as combined heat and power (CHP) plants is not straightforward. The aims of this paper are to develop a better understanding of these limitations, to point out possibilities for increasing the level of energy recovery and utilization in WtE plants, and to document this approach with data and experiences from selected WtE plants currently integrated in CHP schemes. Finally, some design and operational challenges for waste-fired CHP plants are further elaborated from a WtE plant supplier's perspective.

Keywords: combined heat and power, waste-to-energy, MSW, combustion

DOI: 10.1515/ijcre-2017-0248

Received: December 18, 2017; **Accepted:** January 28, 2018

1 Introduction

Incineration of municipal solid waste (MSW) emerged about 40 years ago, mainly in densely populated and industrialized areas in Western Europe. Meanwhile, the technique has become the most important alternative for direct landfilling, offering advantages such as the reduction of the waste's mass and volume, the abatement of odor nuisance, the avoidance of methane (landfill gas) emissions, and the saving of valuable land (Jeswansi and Azapagic 2016). As some of the first MSW incinerators were confronted with difficult control of dioxin and acid gas emissions, the initial focus in MSW incineration (MSWI) was on reducing the environmental impact of the process. Whilst plant designers and operators gradually expanded their knowledge on pollutant control, emission limit values (ELVs) for MSWI in the EU legislation became increasingly more stringent. Table 1 provides an historical overview of EU ELVs for MSW incinerators and compares the ELVs currently in force with those for power plants (with similar thermal input) combusting coal or other solid fuels. It shows that the current limit values are most stringent for waste incinerators that have the lowest ELVs for total dust, SO_2 and NOx. Furthermore, ELVs for CO, TOC, HCl, HF and heavy metals only apply to MSWI and not to combustion plants using coal or other solid fuels. Partly due to these stringent ELVs, the contribution of waste incineration to the total anthropogenic environmental impact is very limited. Based on emission data from the Center on Emission Inventories and Projections for the year 2010 (Center on Emission Inventories and Projections 2012), it can be estimated that in the EU 27 dedicated MSWI accounted for 0.02, 0.003, 0.002, 0.1 and 0.02 % of the total anthropogenic emissions of NOx, SO_2, CO, heavy metals and dioxins, respectively.

Table 1: Overview of trend in emission limit values for waste incinerators, compared to current typical pollutant concentrations in stack emissions (Van Caneghem et al. 2012), expressed in mg.$(Nm^3)^{-1}$. Normalized conditions (N) refer to: temperature 273K, pressure 101,3 kPa, 11 % O_2 or 9 % CO_2, dry gas.

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Pollutant	Directive 89/369/EEC[a]	Directive 2000/76/EC[b]	Directive 2010/75/EC[c] Waste incineration plants	Directive 2010/75/EC Combustion plants using coal and other solid fuels[d]	Typical pollutant concentration range in flue gas emitted at stack[e]
Total dust	30	10	10	20	0.0–0.8
CO	100	50	50	–	6.0–14
TOC	20	10	10	–	0.1–1.8
SO_2	300	50	50	400	1.6–10.3
NO_x	–	200	200	300	65–145
HCl	50	10	10	–	0.9–6.1
HF	2	1	1	–	–
Heavy metals					
Cd and Hg Pb+Cr+Cu+Mn	0.2	–	–	–	
Ni+As	5	–	–	–	
	1	–	–	–	
Heavy metals[f]					
Cd + Tl		0.05	0.05	–	0.0001
Hg		0.05	0.05	–	<0.0005–0.013
Sum other[g]		0.5	0.5	–	0.09
PCDD/Fs[h]		0.1	0.1	–	0.001–0.01

[a] ELVs applicable for new installations with a capacity > 3 tonnes.h^{-1}, hourly average values.
[b] ELVs applicable for installations with a capacity > 6 tonnes.h^{-1}, daily average values.
[c] ELVs applicable for installations with a capacity > 50 tonnes.year^{-1}, daily average values.
[d] Plants with total rated thermal input of 50–100 MW, which is comparable to average size MSW incinerators, granted a permit after January 7, 2013.
[e] Typical values for MSW grate furnace incinerators.
[f] Average value over the sample period of a minimum of 30 minutes and a maximum of 8 hours.
[g] Sum Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V.
[h] Expressed in ngTEQ.(Nm^3)$^{-1}$

Table 1 also shows that MSWI plants comply very well with Directive 2010/75/EC: the concentration of pollutants in the stack is up to a factor 100 below the ELV. MSWI plants also perform well with regard to waste throughput, the purpose they were built for in the first place; yearly plant availabilities higher than 90 % can be achieved under the condition of appropriate plant maintenance and overhaul (Indaver 2015; ISVAG 2015). In this way, MSWI has become the most applied, best available technology (BAT) to achieve the landfill diversion targets as set by the EU Landfill Directive 1999–31-EC. This directive aims at moving MSW away from landfills in accordance with the “waste hierarchy” principle, which prioritizes waste prevention, followed by re-use, recycling and thermal recovery (European Environment Agency 2009). Indeed, as MSW incinerators are equipped with steam boilers, they are suitable for thermal recovery and are therefore nowadays called waste-to-energy (WtE) plants, which is the term that will be used further in this paper. Comparing MSW treatment in the different EU member states shows that high levels of MSW recycling and low levels of landfilling typically go together with high levels of incineration (Van Caneghem et al. 2012), which supports the role of WtE as a necessary component of sustainable waste management.

2 Energy from waste

2.1 Electricity

WtE plants are equipped with steam boilers and are connected to Rankine power cycles, supplying electricity to the public grid. Hence, WtE displaces electricity generated from fossil fuels. The (net) electrical efficiency achieved in WtE plants, i. e. about 22–28 %, is however modestcompared to coal power plants. In view of the main purpose of WtE plants, i. e. to reduce the mass and volume of waste, energy is considered a valuable by-product rather than a production target. This can be easily understood, as the financial model of most WtE plants – in particular when operated within the public sector – is based on gate fees from delivered waste, rather than on revenues from electricity sale. Typically, in countries of northern and western Europe with a long history in WtE (e. g. Belgium, the Netherlands, Germany, etc.), drivers for an energetically optimized design were missing in the time when most of the currently operated plants were built; the payback of plant investments could be largely secured by taxes or contributions on the waste, ultimately paid by the public.

Perhaps, the AEB plant (Amsterdam, the Netherlands) (AEB 2015) is one of few exceptions effectively demonstrating a high electrical efficiency (> 30 %) as stand-alone WtE plant. It should be noted however, that this efficiency level is established through (i) import of high-calorific waste from abroad, and (ii) a local policy, intentionally providing financial compensation for the investment and operational cost related to the implementation of high steam parameters. Indeed, market sales prices for electricity are relatively low in European countries, with nuclear power still having a significant share in the energy mix, and with competition of a growing proportion of subsidized renewable energy sources (i. e. solar, wind and hydropower).

In developing countries, electricity is mostly generated from fossil fuel (coal) and is often priced lower than in Europe. Also, with limited waste policy or legal framework in place, WtE remains an unaffordable waste management option. However, in rapidly growing economies – facing also growing amounts of generated waste – WtE plants have already been established successfully, by exploiting the advantage of scale. In terms of treatment capacity, the world's largest WtE plants are currently being built in China. For example, after construction completion of the phase III extension, the BaoAn WtE plant (Shenzen, China) will incinerate about 9000 tonnes of MSW per day or equivalently, 3 million tonnes of MSW per year on a single site, with a technical capacity of up to 935 tonnes of MSW per day for a single incineration line (Messenger 2016). Whereas the total capacity of the BaoAn WtE plant is clearly driven by the need to cope with an increasing amount of MSW, the sizing/-configuration of the incineration lines is heavily determined by energetic optimization. Here, the challenge is to maximize the electricity output from the available amount of waste, with a limited number of incineration lines, or equivalently, to maximize financial return from electricity sale, for limited investment and operational cost.

2.2 Heat

In WtE plants, heat is always available from the Rankine cycle, more specifically from the condenser unit behind the steam turbine. Recovery of condensing heat allows for a significant and immediate increase of plant efficiency without sacrificing the existing output of electricity. In many cases, this heat is dissipated to the environment (by means of air-cooled condensers), due to a lack of heat demand in the vicinity of the WtE plant. This is explained by the fact that WtE plants initially, when loss of energy was not yet an issue, were often built at considerable distance from residential and business areas. Throughout time, due to population growth, more people have come to live closer to the existing WtE plants, perhaps creating new opportunities for heat offtake. However, projects for construction of new heat distribution networks around existing plants are often not feasible for reasons of planning or turn out not financially viable because of a too low market sales price for heat.

In northern regions, WtE plants can take advantage from cool climatic conditions. In countries such as Denmark, Sweden and Finland, with district heating infrastructure in place for a long time already, it has become common practice to use heat from WtE plants for public heating purpose. District heating systems in these countries typically require a base load of heat throughout all seasons, with peak demands in winter times. WtE plants, also operated almost continuously throughout the year, prove well-matching and reliable as heat sources. The sale of heat, at an interesting market price, then generates a substantial and secure income for WtE plants, in such a way that the energy-optimizing investments are well affordable and gate fees for MSW can be kept reasonably low. Moreover, public opposition against new-generation, heat-supplying WtE plants seems relatively limited, even when these plants are built close to or even inside cities, as people can experience the energetic advantage of WtE in their homes.

In this respect, it is worth noticing that district heating systems also already exist in eastern and central Europe since the era of communism. These systems, today mostly supplied with heat from fossil-fuelled power plants, offer an opportunity for yet-to-be-built WtE plants. (Due to historical and economic reasons, WtE is not yet widespread practice in Eastern Europe). However, to integrate additional/new plants, it is likely that the existing, often outdated network infrastructure needs major refurbishment and that network extensions have to be constructed. The lack of financial means could then become an important hurdle for heat recovery and ultimately for WtE.

In case far-reaching heat networks are not realizable, heat supply to direct, energy-consuming neighbours is an alternative possibility. An example in this regard is the WtE plant of IVAGO (Ghent, Belgium). Originally built in 1979, this plant of a rather limited size i.e. about 34 MWth installed capacity was upgraded a few times. In 2007, the construction of an underground steam/condensate loop was completed and a connection was made with the central heating of the university hospital (UZG) located at about 1500 m from the plant. Nowadays, about half of the thermal energy from the IVAGO plant is used for the heating of the hospital and for the production of hot water used in sterilization units (IVAGO 2016). In this heat delivery system, the condensing heat is not exchanged against hot water in a condenser unit, probably because an air-cooled condenser was already in place. Instead, steam at 200 °C is deviated upstream from the turbine and sent directly to UZG, after which it is returned in a closed loop to the WtE plant as condensate at 130 °C. In fact, in this specific case, energy from the waste is more directly applied, i. e. as heat rather than being converted to electricity. From an energetic point of view, this is a more valuable solution, as (i) conversion heat losses in the turbine are avoided in the first place, and (ii) heat can be transported by steam in a much more compact way than by hot water.

2.3 Steam

Where energy is required for industrial purposes, WtE plants can supply steam at suitable pressure and temperature. Examples include, amongst others,

- the Greater Manchester Waste TPS (Runcorn), UK: steam at a pressure of 17 bar is supplied via open-loop to the INOVYN (formerly named INEOS Chlor) plant next-door, where it is used in an electrolysis process for chlorine production. Besides steam, electricity is generated in turbines (capacity about 35 MW_{el}) equipped with water-cooled condenser systems, maximizing the electrical efficiency up to 20 % (with the 17 bar steam tapped from the turbine). Taking into account the energy contained by the steam, a total plant energy efficiency of about 48 % is obtained (Keppel Seghers 2016; The Greater Manchester Waste Disposal Authority 2016).
- the INDAVER plant in Beveren, Belgium: boiler steam at a pressure of 40 bar and 400 °C is supplied from one of the 3 grate furnace incineration lines to a steam network, connected to several large steam consumers in the port of Antwerp. The other two incineration lines in this WtE plant produce electricity only. The total combined efficiency of the plant can be estimated at about 50 % from data in literature, if steam is delivered at the full capacity of the network (Vandecasteele et al. 2007). In 2017 the steam network is expanded to supply steam from all three grate furnace incineration lines and from the three neighbouring fluidized bed combustors incinerating non-hazardous industrial waste. The new steam network called "Ecluse" will deliver heat to a broader network of industrial companies in the Waasland Port around the WtE plants and fits in the "Green heat action plan" of the Flemish government that aims at increasing the proportion of green heat in the renewable energy supply in Flanders, Belgium.
- the Attero plant in Moerdijk, the Netherlands: boiler steam at a pressure of 100 bar and 400 °C is exported from the WtE plant to the neighbouring RWE/Essent plant, where further superheating to 500 °C takes place by means of natural gas. Then, via a turbine/condenser system, the steam is expanded to about 25 bar at 320 °C, for final consumption by Shell Nederland Chemie (SNC). In this way, by creating interfaces between different energy producing/consuming parties, all of the thermal energy from the WtE plant can be used (at a rate of 85 % efficiency), and electricity can be generated from waste and natural gas at a combined electrical efficiency of 32 %.

These examples demonstrate the suitability of WtE plants as sources of steam, heat and electricity in industrial areas. When all the energy from the waste is applied as boiler steam directly, energy efficiency levels as high as 85 % can be achieved, i. e. more than 3 times the efficiency of a stand-alone WtE plant producing electricity only. Hence, as an integrated part of combined heat and power (CHP) schemes, MSWI can provide substantial amounts of energy otherwise generated from fossil fuels.

Furthermore, road transport of waste can be reduced significantly, as (i) industrial and commercial waste can be treated locally, and (ii) industrial areas are typically well accessible via waterways. Finally, with higher energy sales returns than from stand-alone plants, the profitability of WtE in CHP schemes is increased strongly, and herewith also the chance to attract private investors.

3 The "R1" criterion (EU)

With climate issues currently gaining strong importance in policy worldwide, increasing the energy efficiency of industries and maximizing energy recovery from renewable sources have become more and more important. Since MSW is also partially regarded as a renewable energy source, the EU waste policy imposes energy recovery objectives on WtE plants. A so-called R1 value is to be calculated for each WtE plant, based on actual operational data, and according to the formula defined by the Waste Framework Directive (Directive 2008/98/EC).

$$R_1 value = \frac{\left(E_p - \left(E_f + E_i\right)\right)}{0.97 \times \left(E_w + E_f\right)}$$

In this formula, E_p is the energy annually exported as heat or electricity; energy in the form of electricity is multiplied by 2.6 and energy in the form of heat is multiplied by 1.1 (GJ.year^{-1}). E_f is the annual energy input to the WtE system from (support) fuels contributing to the production of the exported energy (GJ.year^{-1}). E_w is the annual energy (GJ.year^{-1}) contained in the incoming waste calculated using the net calorific value and the annual throughput of the waste, and E_i is the annual energy imported excluding E_w and E_f (GJ.year^{-1}). 0.97 is a factor accounting for energy losses due to bottom ash extraction and radiation.

For a WtE plant, to obtain or maintain the status of “recovery” operation (as defined by the waste hierarchy principle, see Section 1) and to be considered a real WtE plant, a threshold value for R1 has to be met: 0.60 for already existing plants and 0.65 for new plants, i. e. plants permitted in accordance to applicable EU legislation after December 31, 2008. Failure in meeting these threshold values results in a status of “disposal” operation (D10) and a subsequent loss of right to claim e. g. renewable energy certificates or subsidies.

Recently, a so-called climate correction factor was added to the R1 formula. Indeed, a WtE plant in southern Europe is in many cases limited in energy output compared to a similar plant in northern Europe, simply because of the climatic conditions and not necessarily because of a less qualitative incineration or energy recovery process. Conversely, MSWI plants in northern Europe often have more opportunities to export heat in a CHP setting, and could easily increase the R1 value without optimization of the incineration and heat recovery process as such. The climate correction factor avoids that similar WtE plants on different locations in the EU are evaluated differently, despite equally performing equipment/technology installed. Without this correction, unrestrained transports of waste throughout the EU would be supported unintendedly.

Clearly, the existence of the R1 criterion supports the actual evolution towards WtE with an advanced/improved design in terms of energy efficiency. However, it is important to notice that the purpose of the R1 criterion is mainly to discriminate between performant and less performant WtE plants in a legal way, despite its technical definition in terms of energy. As such, the R1 criterion is primarily a tool to allow an objective implementation of the waste hierarchy principle. Herewith, the R1 criterion acknowledges the primary and remaining function of WtE plants, i. e. waste treatment, and does not imply that WtE plants are to be considered as power plants in terms of law or policy. Hence, an R1 value, to be expressed as a dimensionless decimal number, is not to be confused with a thermodynamic efficiency percentage. Whereas the latter is simply the result of the technical, as-built situation as a whole, the former is influenced also by legal constraints e. g. ownership of the different parts/zones in a WtE plant.

4 Waste as a fuel

The energy efficiency of stand-alone WtE plants is modest compared to conventional power plants, due to a number of limitations inherent to the treated waste:

- *The calorific value (Lower Heating Value, LHV) of the waste*. The LHV of mixed MSW is modest, in comparison to fossil fuels. This implies that a significantly higher throughput has to be achieved for a WtE plant, compared to e. g. a coal-fired power plant, when aiming for an equal electricity output. It was estimated that the investment per ton of installed incineration capacity is at least 3 times higher for a WtE plant than for a coal-fired power plant (Themelis and Reshadi 2009). Besides, mechanical/construction restrictions rapidly start to prevail for high-throughput WtE process lines.
- *The chemical complexity of the combustion gases*, as a result of the chemical and physical heterogeneity of the waste. Waste combustion gases contain high concentrations of acids, metal species and dust, leading to phenomena of fouling and corrosion, and ultimately limiting the heat exchange in the boiler (Lee, Themelis, and Castaldi 2007). For this reason, the design limit for steam temperature in a WtE boiler is typically 400 or 420 °C (whereas power plants can achieve steam temperatures up to 550 °C), resulting in limited electricity from the turbine. Likewise, at the low-temperature side of a WtE boiler, the surface contact temperature has to be kept sufficiently high, to prevent the tubes from dewpoint corrosion (Villani and De Greef 2010), resulting in heat stack loss (due to non-recovered evaporation enthalpy).
- *The heterogeneous composition of the waste* causes flow and temperature fluctuations in the combustion gas. Hence, the heat recovery in the boiler, and the boiler steam flow are also fluctuating. As a result, in older

WtE plants, the average steam output often stays below the allowable design output, due to suboptimal combustion control settings (De Greef et al. 2013a).

- The *legal requirement* to maintain the combustion gas in the boiler at 850 °C during at least 2 seconds and stringent emission limits (Table 1) significantly restrict the freedom of plant operation. Although not affecting the absolute energy output as such, this requirement limits the operational flexibility of a WtE boiler throughout time, in particular when attempting to integrate a WtE plant in a CHP scheme, as further discussed in Section 6.

To reduce the impact of these limitations, waste pretreatment, by mechanical, biological and/or thermal (MBT) operations upstream of the incineration process e. g. drying, shredding, sieving, mixing, anaerobic digestion, etc. is a possibility. In this way, specific waste fractions can be separated e. g. plastics, inert materials, low-calorific wastes, etc., to obtain different streams of refuse-derived fuel (RDF). RDF is significantly more homogeneous in composition and energetic content, and therefore enables a more stable incineration than heterogeneous MSW. Also, by pretreatment, inert materials and water are removed and typically, an energetically condensed waste stream is obtained, which can then be incinerated in a more compact and less costly WtE plant.

However, the investments for supplementary equipment needed for MSW pretreatment rapidly offset the investment savings in the WtE process and also occupy extra land. Furthermore, electromechanical equipment with moving parts is more prone to failures than hydraulically driven combustion grates, possibly affecting the yearly availability of the WtE plant as a whole. In addition, reject streams typically emerge upstream of the WtE process, which then have to be treated alternatively. These are typical bottlenecks also associated with thermal gasification plants or fluidized bed incinerators, for which pretreatment of the waste is mandatory.

Finally, waste pretreatment consumes a considerable amount of energy, depending on the MBT techniques applied. Hence, a balance calculation is required case-by-case, to assess the energetic advantage of MSW pretreatment. It was concluded from simulations before, that a combination of pretreatment with WtE becomes less advantageous than a stand-alone WtE plant incinerating the non-separated waste stream, if this waste stream has a LHV of 10 MJ/kg or higher (Consonni, Gugliano and Grosso 2015). As a consequence, in countries with an advanced sorting and recycling policy, already generating MSW with LHVs of 9–10 MJ/kg, waste pretreatment in addition to WtE has little or even a negative impact from an energetic point of view. On the other hand, countries without sorting and recycling policy, typically generating MSW of low quality for WtE, can benefit strongly from waste pretreatment.

5 Energetic optimization of a WtE process

By thermodynamic rule, when electricity is the only energy form produced in a Rankine steam cycle, losses due to energy conversion (from thermal to electrical) are considerable. Furthermore, for turbine-generator systems of a rather small scale – as is the case for typical-sized WtE plants compared to coal power plants – optimization possibilities in the steam cycle are also limited. So, in WtE systems, focus rapidly shifts to the incineration and heat recovery as such when aiming for higher plant efficiencies. By combining several measures as discussed in Sections 5.1–5.5 – and of which a detailed energy assessment was done before using heat and mass models proven on the industrial scale (De Greef et al. 2013b) – a total relative improvement of the electrical efficiency up to 10 % is possible in a stand-alone WtE plant. For existing plants, this difference can be already sufficient to increase its R1 value to the limit value of 0.60.

5.1 Optimization of process control

Unstable operation of an incinerator grate causes a variable heat release from the combusting waste, a fluctuating heat recovery in the boiler, and finally, an unstable supply of steam to the turbine. The plant operator is then forced to lower the average operational setpoint of the steam turbine, as steam overshoots can heavily damage the generator equipment of the turbine. Hence, on average, less electricity is produced and less yearly income from energy sale is generated than aimed for by design.

Therefore, grate systems in WtE plants are nowadays equipped with a combustion control system. Through automated waste feeding, automated air management and automated movement of the grate bars, the control system assists in (i) maintaining the target waste throughput (mass per time) and (ii) releasing the energetic content of the waste in the most possible stable way. The advantage of combustion control optimization in a WtE was illustrated by De Greef et al. (2013a) who showed that a reduction in variation of the boiler steam flow with only 1.4 % (around a steady setpoint value), allowed for a relative increase of at least 3 % of the gross electricity output. This result indicates that significant improvement of energy efficiency can be made in many older WtE plants, typically showing large steam flow fluctuations, just by improved tuning of the combustion control.

Because of the variable composition of incoming MSW, the automated combustion control can cause for the waste layer thickness on the grate to vary over time. A particular challenge for large-size WtE furnaces is then to keep the distribution of the waste equal over the entire grate width, e. g. with a so-called matrix control (Villani et al. 2016). Furthermore, different arrangements of the waste on the grate can affect the concentration of gaseous species such as SO_2 and HCl in the combustion gas in the boiler, which in their turn possibly cause boiler corrosion (De Greef, Verbinnen, and Van Caneghem 2016; Verbinnen, De Greef, and Van Caneghem 2017). Hence, when optimizing a combustion process for waste throughput and steam production, care has also to be taken to avoid chemical conditions in the flue gas favoring fouling and corrosion of the boiler.

5.2 Lowering of excess oxygen

Oxygen has to be supplied to the furnace for the waste to combust. Therefore, an adequate flow of ambient air is distributed over primary and secondary air injection levels. The distribution ratio is dependent on the LHV of the waste; a low LHV typically requires more primary than secondary air and vice versa. Part of the air/oxygen is not consumed in thermal reactions in the incinerator but is excess air that cools down the flue gas. Hence, the heat transfer in the boiler can be increased by reducing the amount of excess air, e. g. through replacing part of the secondary air by flue gas from behind the boiler or behind the flue gas cleaning units, which has a reduced O_2 content. By doing so, the total flue gas volume is reduced (possibly allowing for a more compact boiler), and the NO_x concentration is typically reduced. As shown by De Greef et al (De Greef et al. 2013b), the relative increase in electricity production in a WtE plant is in the order of 2 % for a reduction of O_2 concentration in the secondary combustion air from 6 to 2 %v.

However, a minimum amount of excess air is required to assure complete combustion at all times and to avoid peak emissions of CO. Excess air also suppresses slagging and corrosion of heat exchange surfaces in the boiler. Indeed, corrosion in MSWI boilers is typically due to excessive deposition of chloride salts (NaCl, KCl, ZnCl and $PbCl_2$) on tubes and surfaces (Ma and Rotter 2008; Nielsen et al. 2000). In the deposit layers, cyclic corrosion reactions are then triggered by the chlorides present. This corrosion can be avoided or reduced by converting the chloride salts to their sulphate equivalents (Andersson et al. 2014). However, a sufficient O_2 level in the flue gas is essential for this chemical conversion to take place (Verbinnen, De Greef, and Van Caneghem 2017). Therefore, based on empirical experience, it is advisable after all not to drop below 5%v O_2 on average in the flue gas at the boiler outlet.

5.3 Internal recycling of process heat

By preheating the primary combustion air, typically in heat exchangers supplied with low pressure steam from the turbine, heat can be recycled and in fact sent twice through the boiler. This results in a relative increase of the electricity output of about 0.5–1 % (De Greef et al. 2013b). This finding is valid for waste with sufficiently high LHV (>9 MJ/kg). In case of waste with a lower LHV, the heat input via the primary air is partially lost as enthalpy to evaporate the water in the waste, in order to enable ignition of the waste on the grate.

In case of high-calorific (RDF) waste (LHV = 16 MJ/kg), a relative increase of up to 2.1 % can be established by secondary air preheating. When cumulated with primary air pre-heating, a relative electricity production increase of 3 % is achievable (De Greef et al. 2013b). However, for the typical cost of additional heat exchangers, the gain in electricity output remains limited after all. Therefore, the number and size of heat exchangers around a typical WtE furnace system is dedicated to the heat needed to maintain the incineration process only, or as required to protect the incineration grate system.

5.4 Recovery of low-temperature heat

Low-temperature heat can be recovered by including extra heat exchange surface, either at the outlet of the boiler, in the flue gas cleaning section or just before the stack. Energetically, all options are equivalent, and allow to increase the electricity output with about 1 % of relative increase per 10 °C of the flue gas temperature reduction (De Greef et al. 2013b). However, as flue gas from waste contains a significant amount of condensable acid compounds (such as SO_x, HCl and HF) in presence of water vapour, corrosion can occur when the temperature of the flue gas drops below the dewpoint of any of these compounds.

For this reason, heat recovery from the flue gas after dechlorination and desulfurization is the option with the lowest risk for corrosion. Heat recovery in an extended economizer section of the boiler is the option with the highest corrosion risk, but is perhaps most compact and economic. Tests were done with probes in a full-scale WtE plant, proving the feasibility of this option, where flue gas was cooled to 140 °C at the exit of the boiler, against 105 °C boiler feed water (Villani and De Greef 2010). The possibility to recover heat in the flue gas section finally depends on the precise configuration of the boiler and also on the type of flue gas cleaning process.

5.5 Increase of boiler steam parameters

Finally, for WtE boilers in stage of design, steam parameters i. e. superheated steam temperature and pressure can be chosen above the usual standard of 400 °C/40bar. Nowadays, boilers are designed occasionally for steam at e. g. 420 °C or 440 °C, and for pressures adapted accordingly. De Greef et al. (2013b) calculated that an increase of steam temperature from 400 °C to 440 °C, at a pressure of 60 bar, results in a significant relative efficiency increase of about 6 %. However, given the corrosive properties of combustion gas from MSW/RDF, costly protective measures e. g. overlay welding, spray coatings, boiler cleaning systems, etc. are required. Then, the extra income of increased energy sale must be sufficient to offset the increased investment and maintenance costs. Often this is not the case, so that extra financial support e. g. through subsidies is required.

6 Combined heat & power (CHP) production in a WtE plant: Design and operational challenges

As the efficiency of a modern WtE boiler is typically about 85 %, an equal level of overall plant efficiency can be established by exporting all steam as produced (i. e. without any conversion of energy and omitting minor energy losses due to heat transport). However, in case of steam and/or heat export, the overall energy efficiency of a WtE plant becomes relatively more dependent on the *external demand* of energy, rather than on *internal* optimizations of the incineration and heat recovery process. (From this point of view, the term ‘energy utilization degree’ would perhaps be more appropriate). Typically, a number of challenges are to be dealt with in the design and operation of a WtE plant for CHP purpose, as discussed in Sections 6.1–6.4 below

6.1 Annual waste throughput

Unlike *fossil*-fuelled CHP plants, wherein the amount of fuel can be adapted to the external demand of energy at any time, *waste*-fuelled CHP plants must ensure an annual throughput of waste, to meet contractual obligations towards waste suppliers. This implies that waste incineration has to be continued at a certain rate at all times, also when the energy demand is low. So, when there is a steam layoff e. g. by an industrial consumer, it has to be possible to send additional steam to a turbine or to deliver the excess heat e. g. to a buffering heat network. Hence, the design of a waste-fuelled CHP plant has to include for several interfaces, allowing the WtE plant to continue its operation under all conditions, whilst supplying variable rates of steam, heat and electricity throughout the year.

6.2 Plant availability

Customers for steam include chemical processing industries, paper mills, large greenhouses, district heating networks, etc. Typically, they are in operation, year-round, 7 days out of 7, and 24 hours a day. Hence, they require a base load of steam 100 % of the time, in fact exceeding the state-of-the-art availability of WtE technology, which is typically between 90 and 95 % on yearly basis (De Greef et al. 2010). In view of CHP to increase the overall energy efficiency, in many WtE plants attempts are undertaken to extend the operation period between two consecutive shutdowns, e. g. by installation of redundant equipment, additional on-line boiler cleaning systems and more frequent technical inspection and repair of smaller plant items. Nevertheless, a WtE line has to be taken out of duty on regular basis, e. g. to enable internal cleaning and repair of the boiler system.

This implies that variations *throughout time* of the amounts of energy (MW_{th} and MW_{el}) to be supplied strongly influence the configuration i. e. size and number of WtE lines in a waste-fueled CHP plant. The design also has to anticipate alternate downtimes of the WtE process lines. Furthermore, the Rankine steam cycle might have to be installed with high level of equipment redundancy, including e. g. a multi-staged turbine and, if necessary, a water-cooled condenser with sufficient oversize capacity, allowing to bypass the steam turbine for at least part of the time. So, to ensure 100 % availability, the investment for a Rankine cycle in a waste-fueled CHP plant is typically much higher than for a more basic cycle in a typical stand-alone WtE plant.

6.3 Plant operation: flexibility versus continuity

Different energy customers can have very different demands for steam, heat and/or electricity. Whereas a chemical factory typically demands a large and continuous steam supply for processing purposes, smaller industrial production units e. g. paper mills rather require a flexible, discontinuous supply of steam. Alternatively, when coupled to a district heating network or large green-houses, a WtE plant has to be able to cope with seasonal variations. In this way, the design of Rankine cycles for WtE plants in a CHP scheme can become very complex, especially when multiple energy customers with divergent needs are to be supplied with different types of energy. The impact on the design and operation mode of Rankine steam cycles in WtE CHP plants is illustrated by comparing two very different cases (Figure 1).

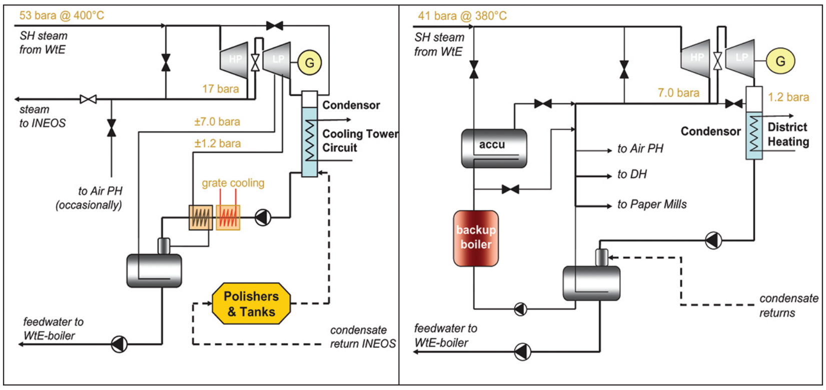

Figure 1: Principle schemes of two steam cycles (redundant equipment not shown). The TPS in Runcorn (left) combines a large steam export with a high electricity production. The WtE plant in Åmotfors (right) supplies steam to paper mills, heat to a district heating network and electricity to the grid. The design includes for steam back-up and accumulation equipment to ensure flexibility.

The first case concerns the Thermal Power Station (TPS) in Runcorn, UK, developed under the Greater Manchester Waste Disposal Authority contract in 2009. With a thermal design capacity of 2 × 87 MW_{th}, the TPS is in operation since early 2015, and currently treats up to 425.10^3 $tonnes.year^{-1}$ of high-calorific RDF. It is an example of how the advantage of scale enables a WtE plant to supply a large amount of process steam and electricity to a large chemical site. 65 to 110 $tonnes.h^{-1}$ of process steam at 17 bar is continuously supplied to INOVYN (formerly named INEOS Chlor). To maximise the electrical efficiency, a double-staged turbine was installed. The second stage i. e. behind the main steam export bleed was designed smaller than the first stage, and equipped with an adequate bypass, to avoid suboptimal use of the turbine i. e. at reduced isentropic efficiency during the majority of time. Other measures, e. g. to cope with partial/peak load conditions and so-called island mode operation, were described in (Verbinnen, De Greef, and Van Caneghem 2017).

The second case concerns the WtE CHP plant of AB Energi in Åmotfors, Sweden, with a thermal design of 1 × 28 MW_{th} and treating about 74,000 $tonnes.year^{-1}$ of medium-calorific MSW. This plant supplies energy to several customers i. e. paper mills, district heating and electrical grid and is an example of how a CHP scheme can be realised on the small scale (1 x 28 MW_{th}) by a dedicated design (De Greef et al. 2010). The main operational challenge in this plant is to match the continuous steam production from the WtE boiler with the rapidly changing steam demand (+/−50 % in flow) of two paper production lines. For this reason, a back-up boiler and a steam accumulator were integrated in the steam cycle. Secondly, the variating heat demand of the local district heating system has to be met, without disturbance of the fluctuating demand of the paper mill. In winter times, the district heating system is supplied with heat by a 7 bar steam header. In summer times, with low district heating demand, low-temperature heat is taken by heat exchange from the condenser behind the turbine, and hence, steam consumption is minimized. In this way, extra electricity is produced.

6.4 Stability of energy supply

Finally, for industrial consumers of energy, it is of utmost importance to receive flows/currents with the least disturbance possible. Hence, for a CHP-coupled WtE plant, the stability of the steam produced by the boiler(s) is typically subject to more stringent requirements than for a stand-alone WtE plant. Typically, boiler steam stability is evaluated based on a continuous measurement of the steam flow, as minutely averaged process value, during a defined period of e. g. 12 or 24-hours in which the steam temperature and pressure have to remain constant to obtain a reliable result. This measurement is then repeated several times during e. g. one week or one month.

Steam stability can be defined in different ways, for example,

1. as the standard deviation (σ_0) of the selected process values (PV) of the steam flow, relative to the average of those values (μ_0), whereby it is required that μ_0 approaches the setpoint (SP) very closely. In this way, *stability* = σ_0/μ_0
2. as the 95 % percentile of all selected PV of steam flow
3. as the average of deviations of the selected PV from the setpoint (i. e. PV – SP) relative to the SP value. In this way, *stability = average [(PV-SP)/SP]*

Moreover, when steam production is important – as is typically the case in a WtE CHP plant – dynamic setpoint control is possibly applied, complicating the evaluation of stability. Dynamic control implies (i) that the setpoint of the steam flow remains constant (at set value) as long as the full throughput capacity of the incineration grate is not exceeded, and (ii) that it is adapted along with changes in the LHV of the incoming waste, when full throughput capacity is reached. Indeed, when full capacity is reached and the LHV of the waste drops, it is no longer possible to aim for 100 % steam production. Then, both the process value and the setpoint become a function of time, which affects the calculation of the steam stability as explained below.

The impact of the definition used for the evaluation of steam stability is illustrated in Figure 2. Graphs (a) and (b) show real data from a WtE CHP plant, as logged by the plant control system. For reasons of confidentiality, the scales are expressed relative to the steam flow as expected by design i. e. a steam flow of 1.00 corresponds to the design steam flow. Graph (a) contains data from a period in which the setpoint remained constant, whereas graph (b) contains data from a period in which the setpoint was dynamically adapted. In order to make a correct assessment of the control system's performance, the impact of a changing setpoint was eliminated by converting graphs (a) and (b) into graphs (c) and (d), respectively, showing the same process values relative to the actual setpoint at each moment in time.

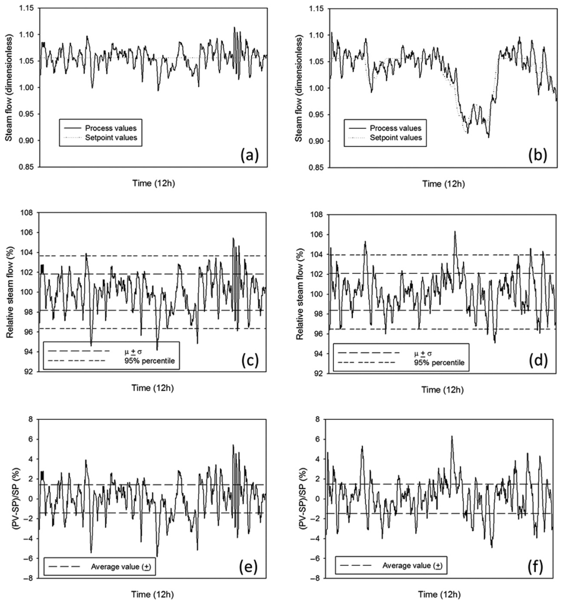

Figure 2: Impact of stability definition on the steam stability figure obtained. Dimensionless steam flow data from a WtE CHP plant are shown (a) for a constant setpoint and (b) for a dynamic setpoint (dimensionless scales for reason of confidentiality). Graphs (c) and (d) contain the same data, however represented relative to the steam setpoint, to allow a correct application of stability definitions 1 and 2. Graphs (e) and (f) show the relative deviation from the setpoint, for application of definition 3.

Applying definition 1 on these data results in a steam stability of ± 1.8 and ±1.9 % respectively, as represented by the inner set of dashed lines in graphs (c) and (d). It can be seen that almost equal stability figures are obtained, despite the change of the setpoint during part of the time in graph (b). However, when definition 2 i. e. 95 %-percentile, is applied, represented by the outer set of dashed lines on graphs (c) and (d), a steam stability of ± 3.6 and ±3.5 % are obtained for the same dataset, respectively. Finally, application of definition 3 on these data results in a steam stability of ± 1.4 and ±1.5 %, as indicated by the dashed lines in graphs (e) and (f), respectively, showing the percentage of deviation from the respective setpoints. This analysis makes clear that the precise definitions behind a given steam stability figure is important to make a correct assessment of the steam production performance of a WtE plant. In any case, the steam production of the considered WtE plant is sufficiently stable to reliably provide industrial customers in a CHP scheme.

7 Conclusions

Due to properties inherent to waste, be it MSW, RDF or equivalent, the energy efficiency of WtE plants is limited. However, with state-of-the-art waste incineration technology, WtE plants can be integrated in combined heat and power (CHP) schemes, to deliver steam, heat and electricity to neighboring energy consumers. This way, plant energy efficiency – or alternatively stated, the level of energy utilization – can be increased up to 3 times the energy efficiency of stand-alone WtE plants. This offers a potential to replace significant amounts of fossil fuel for industrial, agricultural and residential purposes.

As a result of stringent emission limits and minimum waste throughput targets imposed on waste incineration, the operational flexibility of a WtE plant is more restricted than for e. g. fossil-fueled or biomass power plants. Nevertheless, the demand of large and small energy consumers can be satisfied by deliberately configuring WtE CHP plants in terms of numbers and size of incineration lines, and tailored design of the steam cycle. This way, WtE plants that are integrated in a CHP scheme, can meet several criteria by design and operation, such as

- a high yearly availability
- the ability to deliver different types of energy to multiple energy consumers
- the ability to cope with divergent operation modes in time, e. g. continuous versus discontinuous energy supply, variable/seasonal demand, etc.
- a qualitative (stable) steam supply

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