ON THE ALTERNATIVE SUPPLY OF HEAT AND POWER TO ENERGY-INTENSIVE INDUSTRIES WITH WASTE & RDF – TWO EXEMPLARY CASES FROM SWEDEN AND THE UK

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SUMMARY: The feasibility of waste-fired Combined Heat & Power (CHP) plants is illustrated by two cases in which industrial companies took the opportunity to replace fossil fuels by household originating (or similar) waste as energy source for their industrial production. The Thermal Power Station (TPS) in Runcorn (UK) is being developed as part of the Greater Manchester Waste contract. After completion in 2012 the TPS (2 x 87 MW_{th}) will be processing up to 425000 tons of high-calorific RDF. Herewith, the TPS is an example of how an economy of *scale* allows for a high efficient supply of process steam and electricity to INEOS on one of the largest industrial sites in the UK. The Nordic Paper Waste-to-Energy (WtE) in Åmotfors (Sweden) combusts about 74000 tons of medium-calorific MSW per year and is an example of how CHP can also be realised on the smaller scale (1 x 28 MW_{th}). With a dedicated design, exploiting plant *flexibility*, the neighbouring energy consumers (paper mills, district heating and electrical grid) can be adequately served.

1. INTRODUCTION

Waste-to-Energy (WtE) plants of the 'first-generation' have been conceived as 'stand-alone' facilities with an obvious purpose to get rid of waste. Plants of later construction date were already better equipped to limit energy loss and to actively improve heat recovery. Nevertheless, modest plant efficiencies of about 24% were/are still to be understood. Up to now the income of WtE-plants – certainly when functioning in a public context – is by far more dependent on gate fees from waste supply than on revenues from electricity (Zwahr, 2003). As gate fees are being induced politically through various taxation mechanisms, the viability of WtE-plants is often secured without a strong need for energetic optimization. In spite of limited energetic performance, these plants indeed perform well in terms of waste processing. Yearly availability figures as high as 95% (ISVAG, 2009) are achievable.

Nowadays, a developing EU waste policy framework – based a.o. on waste hierarchy and landfill diversion principles – is steering the member states towards the implementation of recycling and energy recovery schemes. Throughout time, public and political awareness has unarguably risen concerning limitations in natural resources and climate issues. Therefore high-

Proceedings Venice 2010, Third International Symposium on Energy from Biomass and Waste
Venice, Italy; 8-11 November 2010

level focus is set on reducing non-biogenic carbon emissions a.o. by means of R1-targets and subsidies for energetic valorisation of biodegradable waste.

In opposite to landfills, *electricity-from-waste* plants do allow mitigation of carbon footprint by displacement of fossil electricity generation and avoidance of methane emissions (Bahor et al., 2009). Mechanical and thermal pre-processing of waste on the other hand creates a significant energetic debet and hence reasonable debate exists on the sense/nonsense of (advanced) waste pre-treatment. It has been demonstrated that an optimum exists beyond which pre-treatment efforts turn again less beneficial than if the original waste would be combusted in bulk in a WtE-plant (Consonni et al., 2008). Another study (Gentil et al., 2009) illustrates that waste pre-treatment creates an equivalent CO_2-benefit only when it fits into a coherent *integrated waste management* (IWM) approach. Herein, a WtE-plant for thermal valorisation of the final RDF is *indispensible* to restore the overall energetic balance. In case of far advanced IWM, only waste-fired Combined Heat & Power (CHP) schemes with high energy utilization levels can bridge the gap and establish a positive absolute equivalent CO_2-benefit (Ragoßnig et al., 2009). Clearly, the level of WtE-plant efficiency is the key parameter for climate impact control of waste management.

2. RESTRICTIONS TO ENERGY-FROM-WASTE

The configurations of a conventional WtE-plant (i.e. *electricity-from-waste*) and a fossil-fuelled power plant are basically similar but there is still a way to go if the thermodynamic efficiency of the former is to be brought up to the level of the latter. Anyhow, without extra sources of income or financial incentives to compensate for increased plant maintenance it is very unlikely that superheated steam parameters of WtE-boilers are boosted up to high values in a sustainable and profitable way. The bottleneck is the waste itself in terms of its physico-chemical properties, prohibiting a maximal exploitation of the energetic potential of the waste.

2.1 Corrosion

The first major restriction is the high concentration of Cl, S and defined metal species in household (and similar) waste. Volatising into combustion gas with a chemically complex composition, these elements have multiple opportunities to form eutectic compounds. The cool-down of the combustion gas along the convective path through the boiler initiates desublimation of those compounds on the pressure parts, where passing through appropriate temperature windows (Born, 2006). Under persisting negative conditions (i.e. low-oxygen and advanced fouling) salt melts are formed on the boiler tubes. On tubes with a surface temperature above 400°C, corrosion is then strongly triggered with Cl-attack on the Fe-ions in the boiler steel as the keystone reaction.

The temperature gradient (ΔT) between combustion gas and boiler tubes is recognised as co-determining the transport rate of HCl/Cl_2-molecules towards and through the corrosive deposits. Given the steamside temperature, the combustion gas temperature therefore needs to be limited to an utmost maximum of 650°C in the superheating section of modern WtE-boilers. The convective heat transfer is furthermore kept under control by restricting the gas velocity. Based on thermodynamic calculations and plant-scale experiences, a Cl-induced corrosion model was gradually built which has become widely accepted in the meantime. Details can be found in reference literature on both the corrosion chemistry (Lee et al., 2006) as well as the rate-determining mass transfer (Horn et al., 2008).

Gradual progress is being made in the development of boiler materials that must allow sustainable increase of steam parameters in a cost-effective way. In this regard the composition of boiler steels as such (Schmitt & Spiegel, 2010; Krejcik et al., 2010) as well as inconel-like materials (i.e. cladding & protective layers) are studied (Schmidl, 2009; Schulein & Höhne, 2009; Epelbaum et al., 2010). The Fe-content and Ni/Cr-ratio seem to determine the effectiveness of the latter in withstanding corrosion attacks. However, together with applying the right materials in the right zone of the boiler, the accuracy of application is essential. As high-temperature corrosion in waste fired boilers starts off as a gas-solid reaction (i.e. so-called oxidative corrosion) a protection layer needs to be solid and continuous with adequate internal overlap between sub-layers. A single crack or pore is sufficient for the corrosive gas to find its way to voids behind the (expensive) protection layer, making it entirely useless. This explains why a single material applied in different boilers can exhibit different protection behaviour (Herzog & Metschke, 2009).

Inner boiler wall and tube protection must be complemented at all times with pro-active corrosion abatement. In this regard it is worth highlighting the importance of reduced flue gas speed (i.e. appropriate boiler sizing), combustion control (El Asri & Baxter, 2004), adequate on-line boiler cleaning, flue gas recirculation and improved post-combustion (Lee et al., 2006). With regard to the latter, the Keppel Seghers Prism (Figure 1) is acknowledged as valuable equipment. Whilst integrated on the *inner* as evaporator unit, the Prism on the *outer* allows for a highly distributed secondary air injection. Moreover, homogenised oxygen levels are attained through (static) mixing of the combustion gas, resulting in an improved gas burn-out at the furnace exit. A rapid and equalised gas cool-down in the radiation part of the boiler furthermore favours chemical reactions that remove alkaline metal species from the gas by capture in sulphate salt deposits (i.e. *sulphatisation*) already in early stage (i.e. the refractory protected zone). The S/Cl-ratio in the gas is thereby decreased and the alkaline chloride load onto the superheaters downstream is reduced (Adams et al., 2004).

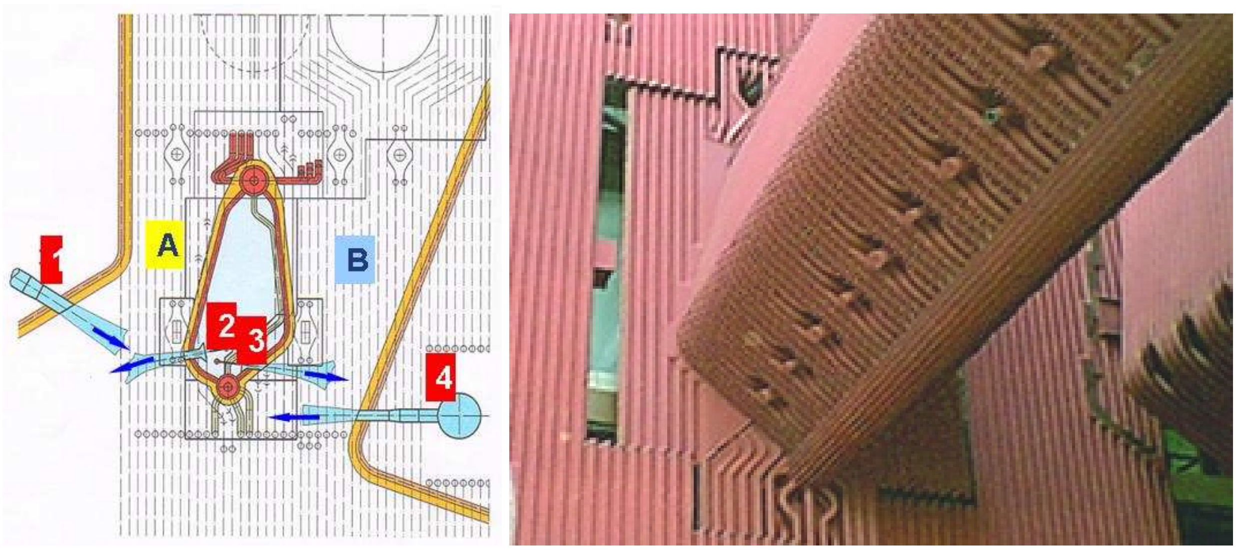

Figure 1. Keppel Seghers Prism. (left) Scheme of principle showing tie-ins to boiler membrane walls, gas flow sections [A&B] and nozzle rows for secondary air injection [1,2,3&4] (right) View from below as installed (Mannheim, Germany).

A similar sulphatisation effect has been aimed for previously also by means of solid additives to the waste or liquid injections into the combustion gas. The common *keystone* in these trials is to reduce the alkaline chloride load on the superheaters either by directly capturing Na and K while being released from the burning waste or by establishing an SO3-enriched atmosphere. The latter in turn also reacts with the aforementioned metal species. Whereas rather successful for combustion of biomass in fluidised bed boilers, this approach seems less effective for waste-fired grate boilers. This is due to significant differences in heterogeneity and chemical composition of the fuel (in terms of metals, chlorine and sulphur), mechanical mode of firing and applicable temperatures. The additive/injection approach is mentioned here just for sake of completeness. More details can be found in dedicated reviews (for e.g. Fossum, 2009).

Particularly interesting is also the development of on-line monitoring tools for early assessment of fouling and high-temperature corrosion, s.a. the heat flux sensor (Beckmann et al., 2007), the Corrmorran probe (Waldmann et al., 2010) and KEMCOP (Zhan et al., 2010). Actual conditions inside WtE-boilers are often unpredictable, troubling the calibration and the accuracy of such advanced monitoring tools. Nevertheless, first plant-scale experiences do give a useful up-front indication of boiler behaviour.

On the low-temperature end of the boiler, reduced flue gas temperatures are regularly established with tail-end economizers behind the flue gas cleaning (FGC) system (i.e. after SO_2-removal) in order not to induce corrosion when reducing both the flue gas and boiler feedwater temperatures. However, plant scale experiences and *ECO*-probe monitoring experiments at the ISVAG WtE-plant (Antwerp) illustrate that low-temperature corrosion of economizers *upstream* of the FGC is initiated only (far) below 100°C of feedwater temperature (Villani & De Greef, 2010).

2.2. Calorific Value (LHV)

Secondly, the modest energetic content of household waste (MSW or similar) is restricting the thermal output of WtE-boilers. Whereas the lower heating value (LHV) of fossil fuels is in the order of 40 MJ/kg, for unsorted waste this value is commonly situated below 10 MJ/kg. It helps in understanding that for combustion grate design mass load (kg/h/m²) becomes the limiting factor more rapidly than thermal load (MW_{th}/m²). Together with thermal corrosion restrictions as elaborated above it explains why only few WtE-boilers exceed a size of 100 MW_{th}. Furthermore, WtE-boilers at all achieving such a high thermal output need to be fired with Refuse Derived Fuel (RDF) or Commercial & Industrial (C&I) waste with a higher LHV of about 15 MJ/kg.

It was noticed before that the capital cost for an electricity-only WtE-plant (in the US) is about 3 times higher than the cost of installing a coal-fired capacity (Themelis & Reshadi, 2009) on the basis of equal electrical output (i.e. compared per MW_{el}). Notwithstanding the need for a detailed cost setting to obtain a full comparison between both plant types, one can indeed reconstruct this figure roughly by: 1) taking into account a factor 4 of difference in fuel LHV, 2) correcting for the difference in overall plant efficiency with a factor of about 0.7 (= ± 0.25/0.35) and 3) adding a limited cost percentage for extra protection materials in a WtE-boiler. It is anyhow clear that most WtE-plants would not exist if the fuel (i.e. the waste) had to be paid for – as in the case of coal – instead of being a source of revenue in the form of gate fees.

Although MSW can be deployed effectively as a fuel for power applications (Vandecasteele et al., 2007) RDF is clearly more interesting from an industrial perspective. Its higher energetic yield per ton indeed allows combustion grates to be run at their full intrinsic thermal load capacity. This increase in turn allows for plant footprint (and hence capital cost) reduction, given the same thermal output. Conversely, for equal waste throughputs, extra investment and maintenance costs need to be encalculated.

Unfortunately, the increased LHV of RDF often involves upconcentrated levels of corrosive chemical elements. However, even for *electricity-from-waste* plants the extra costs for protective measures are rapidly (over-)compensated by the increased revenues from electricity only (Adams et al., 2006). This is not only the result of a higher thermal output. The attractive features of RDF – s.a. low water content, small particle size, homogeneity, compactness and storability – result in an improved combustion stability. Typical waste-originating fluctuations at the turbine's steam inlet are mitigated, allowing for a slight average increase of the boiler steam production setpoint.

3. FROM WTE TO CHP

For existing WtE-plants possible measures towards a higher energetic efficiency are situated at first in the *process* environment itself, s.a. an optimization of combustion control settings and an intelligent use of air and condensate preheaters. In this way WtE-process stability can be improved and average steam production setpoints slightly increased. More costly but creating larger benefits (in the order of several percents) are remediations of critical process spots throughout the whole steam cycle (i.e. an energy *loss minimization*) and an increase of yearly plant availability by improved on-line maintenance of the boiler (i.e. an *operational* approach).

For new WtE-plants one can aim *upfront* for a high steam/electricity yield from the turbine/condenser (i.e. energy *output maximisation*). This would be feasible with boiler steam at high temperature and pressure, but technical and economical boundary conditions as described under Chapter 2 have pinned the European WtE-boiler steam standard at 40 barg & ± 400°C. However, to the current state-of-development some variation on this theme is feasible. For e.g. a superheated steam temperature up to 430°C is in some cases considerable, notwithstanding a reduction of superheater lifetime down to two years (Wiesendorf & Benz, 2009). Such finding is obviously not to be generalized as tariffs and grants for waste, disposals, chemicals, electricity, heat etc. are everywhere different.

Yet the efficiency gain that can potentially be achieved for WtE by increasing the superheated steam parameters is limited to a praiseworthy 10%. It remains furthermore a relatively expensive objective that depends on specialised long-term research & development of boiler/protection materials. *Electricity-from-waste* plants with efficiencies up to 33% remain rare (for e.g. AEB in Amsterdam) and it must be acknowledged that the development of such projects (in a public context) equally depend on strong political drivers.

A more economically viable strategy is based on the concept of waste-fuelled Combined Heat & Power (CHP). By constructing new WtE-plants in industrial areas, where they can maximally be exploited as sources of steam, heat and power for surrounding buyers, the profitability is boosted up and interesting opportunities are created for private investors. An 'upgrade' to WtE-plant efficiency levels as high as 90% can be theoretically achieved, i.e. about 3.5 time the efficiency of average 'stand alone' WtE-facilities. Political and public acceptance is likely to increase as WtEs are being moved further away from residential areas and the treatment of industrial & commercial waste can eventually be addressed *in situ*.

As full EPC-contractor, Keppel Seghers has built up valuable experience with CHP-projects in different industrial sectors. For the purpose of present article two recent project references are compared in Table 1. The first project is located in Åmotfors (Sweden), where a rather small-scale WtE was built to generate process steam for a leading Scandinavian paper industry. An early technical and financial assessment made it clear that a WtE-plant could replace the existing (and maintenance intensive) oil-fired boilers on the condition of building a highly-flexible power cycle (De Greef et al., 2009). The second CHP-project is situated in Runcorn in the area of Liverpool (UK). It is being developed under the Greater Manchester Waste (GMW) contract, the largest private funding initiative (PFI) in the waste sector ever. RDF and residues from waste pre-treatment and anaerobic digestion operations in Manchester are to be transported by train to the INEOS-site in Runcorn for thermal valorisation. A constant quantity of steam and electricity is to be produced in a large-scale WtE and supplied to one of the largest chemical industries in the UK. For an in-depth description of the different technologies applied in both plants (i.e. grates, boiler, flue gas cleaning and steam/condensate) the reader is kindly referred to De Greef & Kipp (2010).

4. DISCUSSION

4.1 Steam & Condensate

The plant in Åmotfors conciliates steam production from a waste boiler with a rapidly changing steam demand from two paper mills. Therefore, the steam/condensate system (Figure 2a) is provided with equipment for steam accumulation and back-up steam production. The accumulator was designed based on statistical evaluation of historical data on paper mill steam consumption. Secondly, the seasonal variation in heat demand from the local district heating (DH) is addressed by different modes of turbine operation. Whereas the process steam for the paper mills is always taken from the 7 bara header, the DH is supplied by this steam header only in winter times. In summer when the DH demand is low, the equivalent amount of steam is expanded further down to 1.2 bara (backpressure). Surplus electricity is hence generated and condensation heat is delivered to the DH at lower temperature. Back-up steam production (with auxiliary fuel) occurs at low steam level in the accumulator in case of insufficient time for accumulator replenishment. Different plant operation modes are discussed by De Greef et al. (2009).

The Runcorn TPS on the other hand must deliver a constant large amount of steam throughout the whole year (Figure 2b). In order to keep up INEOS's chemical production continuously, downtime for both lines together is to be reduced to the absolute minimum. This requirement is addressed by redundancy of critical equipment in the steam cycle, s.a. feedwater tanks and pumps. In order to achieve a high (yearly) average electrical output at the turbine, the installed size of the low-pressure (LP) stage is adapted to the reference situation. I.e. from the ±200 tons per hour of incoming boiler steam, 65 tons per hour are exported from a 17 bara controlled turbine tap behind the high-pressure (HP) stage. The LP-stage could thus be reduced to 2/3rd the size of the HP-stage.

Given the large steam export that must be maintained under all circumstances, situations can occur whereby the LP-stage receives a critically low steam load. Therefore, the use of steam bleeds from the low-pressure (LP)-stage had to be mimimised to secure partial load operation. Since the use of primary air preheating is not mandatory for an RDF-mixture of 13 MJ/kg, any occasional requirement is fulfilled with 7 bara steam which is expanded from the 17 bara steam header. In this way, the 7 bara bleed on the turbine is relieved from instantaneous peak demand and needs to be coupled only to smaller consumers for which steam pressure variation is not critical (s.a. deaerators). Finally, in the unlikely case that steam export to INEOS is ceased, the power island can go into (partial) bypass mode with an increased pressure in the watercooled condensor (up to max. 300 mbara).

The steam export to INEOS is compensated by condensate return towards the CHP-plant on a variable/discontinuous basis. This condensate is of high quality but not originating from the exported steam. It is returning from other sources where chlorine and salts are processed. Adequate boiler feedwater buffering, polishing and storing capacities are thus foreseen in order to secure continuous steam export for several hours.

Table 1 - Comparative overview of two waste-fired CHP-designs.

Data per line	*unit*	Nordic Paper (Åmotfors, S)	GMW - INEOS (Runcorn, UK)
N° lines	-	1	2
Waste type		MSW	RDF (floc+digestate)
LHV	*MJ/kg*	8 – 14	9,5 – 16
moisture	*m% (on total)*	20 – 35	< 15
Thermal design	MW_{th}	28	87
Throughput design	*Mg/h*	10,5	27,2
Grate			
type		Keppel Seghers air-cooled	Keppel Seghers water-cooled
surface	*m²*	42	100
inclination	°	21	21
configuration	-	5 elements	5 elements
tile rows per element	-	2 fixed + 2 sliding + 2 tumbling	3 fixed + 3 sliding
Grate cooling system			
pressure	*PN*	n/a	16
temperature (in-out)	*°C*	n/a	90 – 130
recovery	-	n/a	boiler feedwater preheating
Steam boiler			
type	-	4-pass vertical	3-pass vertical + 1-pass horizontal
steam pressure	*bara*	41	53
superheated temperature	*°C*	380	400
Flue Gas Cleaning			
type		semi-wet: CaO (Keppel Seghers Atomizer)	all-dry: $Ca(OH)_2$ (Keppel Seghers Double-Dry)
inlet flow	*Nm³/h*	57.000*	170.000*
inlet temperature	*°C*	260	135 – 145
max. inlet HCl / SO_x	*mg/Nm³*	1300 / 400*	3600 / 1500*
stack NO_x / NH_3	*mg/Nm³*	135 / 10*	200 / 10*
Heat & Power			
steam	*Mg/h @ bara*	23 @ 7	≥ 65 @ 17
(district) heat	MW_{th}	0,6 – 2,5	n/a
gross electricity	MW_{el}	≤ 2,4	≤ 34,7
net plant efficiency	*%*	64**	48
Main CHP purpose		deliver steam for two rapidly switching paper mills: small-scale flexibility	deliver steam and electricity for industrial electrolysis process: large-scale continuity
Specific plant features		steam accumulator & back-up boiler two-stage steam turbine DH at low & high temperature low-footprint plant layout	water-cooled condensing & cooling towers two-stage steam turbine redundancy in the steam cycle waste delivery by train
Project Status (2010)		plant started up & fully operational	engineering stage concluded construction started 07/2010

* reference: 11%O_2, dry, normalized conditions

** incl. auxiliary fuel back-up for 12% of the operation time

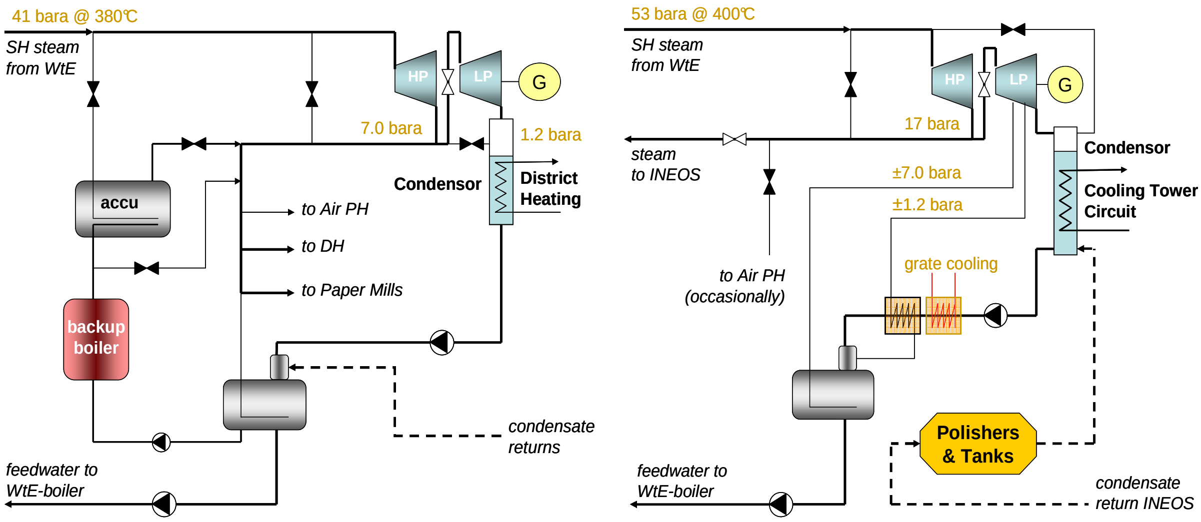

Figure 2. Principle schemes of two steam cycles, redundant equipment not shown. The CHP in Åmotfors (2a: left) includes steam back-up and accumulation equipment to obtain maximal flexibility. The TPS in Runcorn (2b: right) combines a large steam export (up to 2/3rd of the generated load) with a high electricity production, also during partial load operation.

4.2 Combustion & Heat Recovery

For both plants the thermal 100%-line of the combustion diagram (Figure 3) – i.e. the diagram reflecting the operation limits of the plant as built – was defined with a margin of ≥1 MJ/kg around the nominal LHV. In this way, slight changes in calorific value (to the lower end) do not immediately affect steam production.

The Åmotfors-WtE is intended for the combustion of household originating waste. This waste with a (rather high) nominal LHV of 10.5 MJ/kg is being fired on an air-cooled grate with adequate primary air preheating. The Runcorn-TPS on the other hand is designed for combusting high calorific RDF-mixtures and is equipped with appropriate technology including Keppel Seghers water-cooled grates and Prisms. The nominal LHV of 13 MJ/kg results from mixing two fractions with strongly diverging LHV: 88% of floc RDF (high calorific) and 12% of digestate (very low calorific). Therefore, air preheating is included in the plant design to support combustion and to keep up steam quality when peak amounts of digestate are coming. The heat from the grate-cooling is fully recovered in condensate preheating, in turn reducing the consumption of steam (1.2 bara) from the LP-stage (cfr. partial turbine load operation under Paragraph 4.1).

The boilers of both plants were customized differently. The Åmotfors plant, with vertical boiler design and flue gas outlet at 260°C, reflects restraints in plant foot-print, investment cost and energy export capacity. Conversely, for the Runcorn-TPS with horizontal boiler design, a maximization of future financial returns from energy as such prevailed. The boiler-FGC interface of the latter is energetically optimized towards gas exit and BFW-inlet temperatures of 145°C and 105-115°C respectively as discussed in detail by Villani & De Greef (2010).

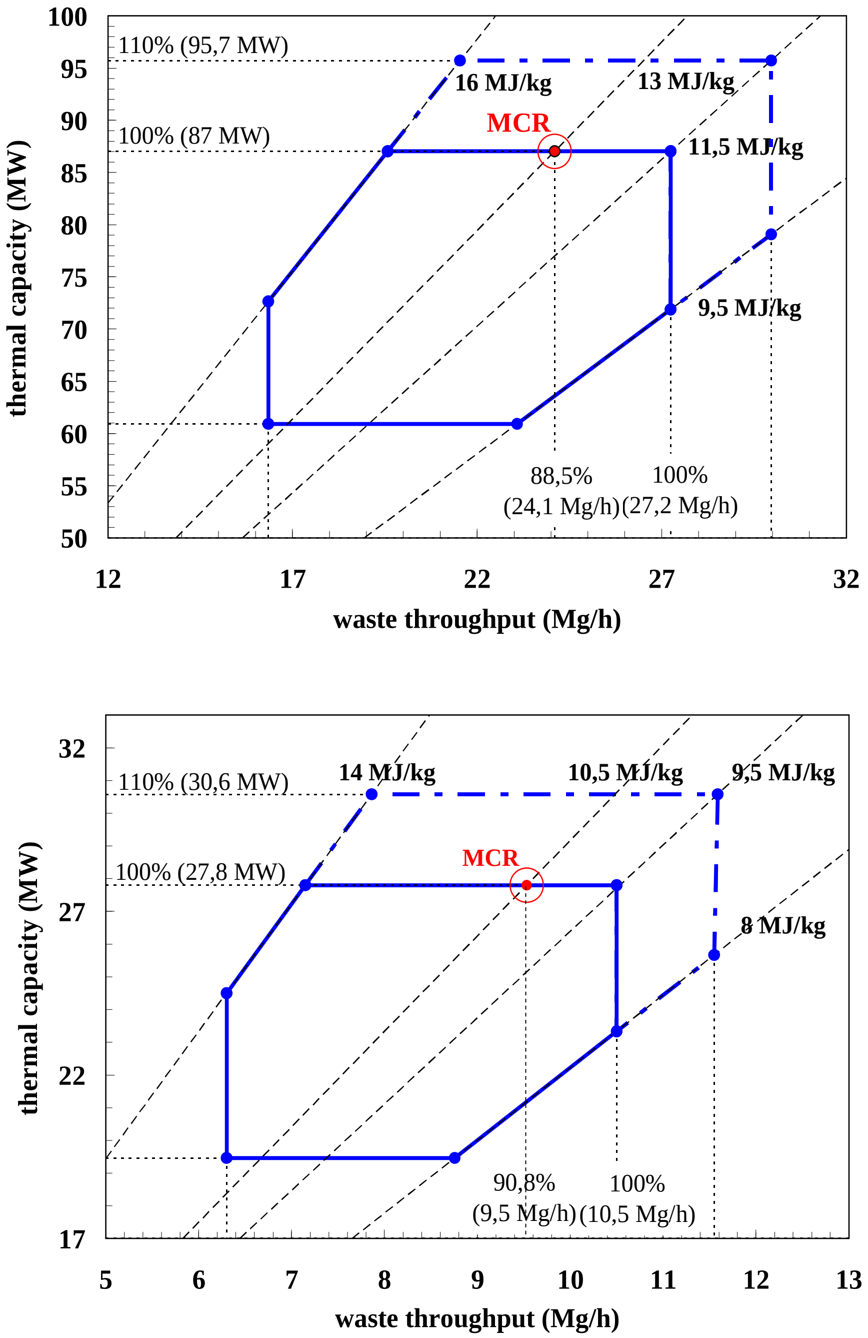

Figure 3. Combustion diagrams for the Runcorn-TPS (up) and the Åmotfors-CHP (down). Allowance is made for variation in waste LHV in the nominal operation point (MCR), without immediately dropping below 100% thermal output of the WtE-boilers.

5. CONCLUSIONS

Efforts to increase the steam parameters of waste/RDF-boilers are valuable but unfortunately limited by nature of the waste. Therefore, establishing WtE-plants as high performant CHPs is a very interesting strategy to boost up significantly the energetic efficiency levels. Furthermore, an advanced integrated waste management scheme is deemed to have negative impact in terms of carbon footprint without valorising the residual waste in a high-efficient CHP. As household originating waste/RDF is a valuable fuel for power applications, opportunities can be created by moving Waste-to-Energy from a public to a private/industrial environment.

Two waste-fired CHPs have been compared. The first reference plant in Runcorn (INEOS), built under the Greater Manchester Waste contract, is an example of how a source of bulk steam & power for the chemical industry can be established by exploiting the economy of *scale*. The Åmotfors reference on the other hand illustrates that also small- and intermediate scale WtE-plants can deliver industrial energy by exploiting plant *flexibility*. In both cases, an early in-depth understanding of the steam/heat/electricity needs and plant design integration by a knowledgeable single party constitute the basis for high plant efficiency and reliability.

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