Integration of anaerobic digestion with grate incineration results in optimized energy and material recovery of MSW

HERMAN SIOEN, PROF. SERGIO GUERREIRO RIBEIRO

CONTACT

Contact name: Herman SIOEN
Organisation: WATERLEAU Group N.V.
Postal address: Nieuwstraat 26, 3150 Wespelaar (Haacht), BELGIUM
Telephone: +32 16 650 657
Facsimile: +32 16 650 663
E-mail: herman.sioen@waterleau.com

EXECUTIVE SUMMARY

The principles defining optimal treatment of municipal solid waste (MSW) ask for maximum recovery of materials and energy. This paper focuses on the recovery of energy. Indeed, the payback of the investment in a waste treatment facility is determined by the possibility to generate income from the plant's outputs such as material, but above all energy. Usually, the energy sales do not suffice to make the plant profitable and the operator is forced to ask for a 'gate fee' or 'tipping fee', which the waste producers are only reluctantly willing to pay. Any means to increase the power output per ton of waste (kWh/ton of waste) is therefore very welcome (as long as it does not entail too much extra costs, of course).

To convert waste into energy two main options exist: thermal conversion or incineration (waste-to-energy or WTE), releasing the energy content of the waste immediately and resulting in hot flue gases. In a traditional closed steam cycle this energy is recovered and converted into heat and power. The thermal efficiency of this cycle is (relatively) limited.

The second way is anaerobic digestion (AD) whereby the organic matter of the waste is first converted to biogas. This biogas is then used in gas engines (or gas turbines) to generate power (and heat). Dedicated AD plants exist, evidently mainly for the organic fraction of MSW (OFMSW). But anaerobic processes also naturally occur in landfills. The landfill gas is recovered and also converted to energy.

This paper will compare the two different waste treatment systems, WTE and AD. Then it will describe a combination of the two (WTE+AD) and will then explore the further optimization using the concept of Optimized Combined Cycle®. It will show that this combination results in a higher power output per ton of waste than the individual plants. It is thus yet another example of 1 + 1 = 3.

INTRODUCTION

The energy value (lower heating value or LHV) of waste is mainly determined by its composition. Waste is a mixture of water, inert matter and combustible matter. The combustible matter is mainly organic, but also includes non-organic substances such as plastics. When looking at the chemical composition, most (>99%) of the energy of waste is coming from its C(arbon) and H(ydrogen) content. Any treatment method that recovers energy from waste will have to convert the carbon and hydrogen to carbon dioxide (CO_2) and water (H_2O).

Incineration or combustion releases the energy of the combustible matter (CM) by (direct) oxidation with oxygen from outside air. The general formula is for the stoichiometric case is:

$$\text{(CM) } C_cH_hO_oN_nS_s + x * O_2 = c * CO_2 + h/2 * H_2O + n/2 * N_2 + s * SO_2 + LHV_{CM} \text{ (kJ/kg)} \qquad (1)$$

with $x = c + h/4 + s$. In reality, a substantial amount of excess air is used to make sure combustion is as complete as possible, as well as keeping the flue gas temperature within engineering limits.

We neglect the presence of S(ulfur) and N(nitrogen) (i.e. $s = n = 0$). The energy content of the combustible matter is completely released. The water in the waste evaporates (this costs some of the energy released by the combustion) and the inert matter remains unchanged.

Anaerobic digestion works differently. It is a two step process: first it converts (only) the organic matter (OM) (not the non-organic combustible matter) to biogas (a mixture of methane (CH_4) and carbon dioxide (CO_2) in anaerobic (i.e. without oxygen) conditions. And in a second step the biogas is used as a fuel in (typically) a gas engine and is thereby completely oxidized.
The anaerobic digestion converts organic matter according to the following general formula [12]:

$$\text{(OM) } C_cH_hO_oN_nS_s + y * H_2O = c * CH_4 + n * NH_3 + (c - x) * CO_2 \qquad (2)$$

with $x = (4c + h - 20 - 3n - 2s) / 8$ and $y = (4c - h - 20 + 3n + 3s) / 4$.

Again we neglect the presence of S and N (i.e. $s = n = 0$). Very little heat is released with the anaerobic bioreaction (2) (e.g. 85% of the energy content of glucose is retained in the methane produced from that glucose [12]). The conversion of organic matter to biogas is not complete. The volume of biogas which can practically be produced depends many factors (a.o. the content of organic matter in the dry matter (DM), the nature of the OM (fats, sugars, proteins,…), the DM content,… [12]). The resulting biogas yield per ton of fresh substrate is thus mostly a matter of experience.
The biogas is converted into power in gas engines or gas turbines, i.e. in an open cycle. The methane (CH_4) is fully converted to CO_2 and H_2O, as follows:

$$CH_4 + 2 * O_2 = CO_2 + 2 * H_2O + 36 \text{ MJ/Nm}^3 \qquad (3)$$

WASTE TO ENERGY PLANT

In this paper we will use as reference a standard waste-to-energy plant with grate incineration technology and a standard steam cycle (4 MPa – 400°C) with only power production (figure 1).

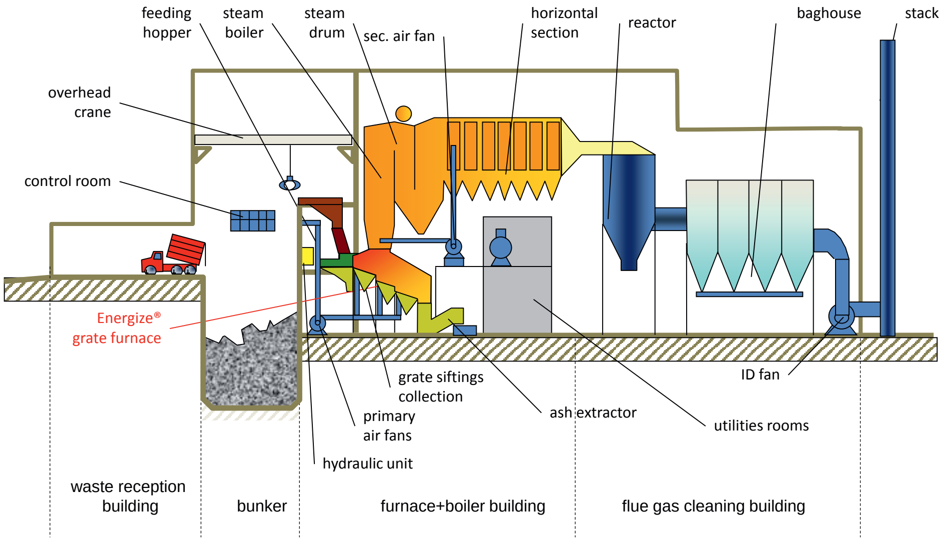


Figure 1: Waste-to-Energy plant, schematic diagram

In the furnace the solid waste is converted according to (1) into hot flue gases, by reaction with oxygen from outside air. The furnace is a high-temperature reaction chamber with as 'floor' a moving grate system. Air is supplied through the grate and the waste (primary air) and above the waste (secondary air). In a properly operated furnace virtually all energy in the waste is converted into the heat of the flue gases. These are cooled in a steam boiler typically recovering 80-85% of the waste LHV in the form of steam. For technical reasons (the explanation of which is beyond the scope of this paper) the steam pressure and temperature remain limited to ‘medium’ values. As a result the gross electrical efficiency (generator output / thermal input of the waste) of the plant is 25% in the best of circumstances. This is relatively modest (large natural gas fired combined cycle power plants can easily reach >50%).

As an example figure 2 shows the WtE plant of the city of Hai’an, Nantong, Jiangsu province, China, built with WATERLEAU Energize® grate incineration technology.

Figure 2: CNTY Hai’an WTE plant (3x250TPD), 15 MWe with WATERLEAU Energize® grate

ANAEROBIC DIGESTION (AD) PLANT

A distinction is made between Wet AD and Dry AD depending on the moisture content of the substrate in the AD reactor. As the organic fraction of MSW (OFMSW) is usually relatively dry, it is best processed in a Dry AD plant. For Kitchen and Restaurant waste (K&R) a Wet AD plant is more suitable. Figure 3 is a schematic diagram of a Dry AD plant.

The OFMSW is first processed by blending and removal of foreign objects, stones and sand. It is then fed to a hydrolysis step after mixing with substrate from the AD reactor. This reactor is a very large vertical vessel in which take place the biological processes (see (2) above) that convert the organic matter to biogas. This takes much longer (weeks instead of hours) than in a WTE furnace. The reactor temperature is by contrast very low (just 35°C) compared to that inside a furnace. The biogas is cleaned and used as fuel for gas engines (as per (3) above). The digestate (solid residue) is further processed (different options exist). This digestate still contains some carbon.

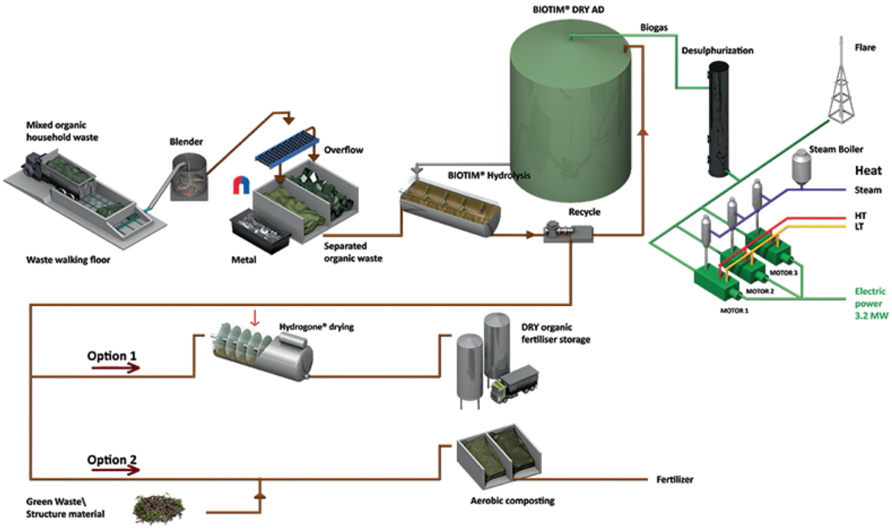


Figure 3: Dry AD plant; schematic diagram

WATERLEAU develops and markets both wet and dry systems, called Biotim® Wet AD and Biotim® Dry AD. An example is the Biotim® Wet AD plant in Ieper, also operated by WATERLEAU. This plant has three gas engines with an electrical efficiency of >40% (generator output / thermal energy in the biogas).

Figure 4: WATERLEAU New Energy Ieper, Biotiom® Wet AD plant, 3.2 MWe

MSW TREATMENT: WTE OR AD OR BOTH?

We will now compare the performance of WTE vs AD with respect to power production (thus without heat recovery except for the plant's own use, e.g. air preheating, biomass preheating). WTE has the advantage that all waste (or rather: all C and H) is converted, but the disadvantage that the conversion of heat to power uses a relatively inefficient steam cycle. AD on the other hand produces a biogas that can be converted to power at better efficiency but has the disadvantage that only part of the C and H is effectively converted. How does this balance out? We consider three cases (figure 5):

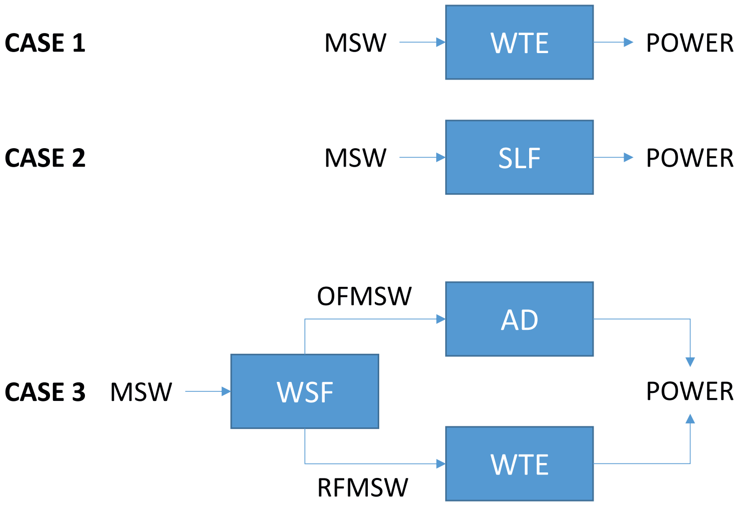


Figure 5: Three cases for comparison

1. Case 1: all WTE i.e. all MSW is incinerated in a WTE plant.
2. Case 2: all AD. For this case we assume a new sanitary landfill (SLF) with optimal landfill gas production and collection ('bioreactor landfill'). We assume ([14]) 65% of the C remains sequestered and 85% of the landfill is captured and used in gas engines. The Case 2 is theoretical and is likely overly optimistic, as the actual biogas production in a landfill is stretched over a long period of time (complete digestion may take one year or more), so the power available is smaller and variable in time.
3. Case 3: combination of WTE and AD. For this case we assume the MSW is first treated in a simple waste segregation facility (WSF), splitting it in an organic-rich fraction (OFMSW)

going to AD and a residual fraction (RFMSW) going to WTE. Alternatively, we can assume the waste is source-separated and collected in the same two fractions.

As input material we assume a standard MSW with a LHV of 8.4 MJ/kg (2,000 kcal/kg).

Table 1 summarizes the calculation results.

Case 1 (WTE) results in a (gross) power output of 582 kWh/ton and Case 2 (Landfill 100% AD) 393 kWh/ton (= 32% less than in Case 1. This is an upper limit, actual landfills are far below this value [15]), whereas the combination WTE+AD (Case 3) results in 605 kWh/ton (= 4% more than in Case 1). We can thus conclude that the combined solution (Case 3) has the highest power output, even though not all (96%) carbon is converted. The advantage of the higher efficiency of the gas engine more than compensates the disadvantage of partial C-conversion. The AD part of Case 3 produces 16% of the power, the WTE part the remaining 84%.

			CASE 3			CASE 2			CASE 1		
			MSW	OFMSW	RFMSW	MSW	OFMSW	RFMSW	MSW	OFMSW	RFMSW
Segregation	[%]	:	100%	**40%**	60%	100%	**100%**	0%	100%	**0%**	100%
Input	[kg]		**1000.0**	400.0	600.0	1000.0	1000.0	0.0	1000.0	0.0	1000.0
Moisture	[%]	:	**39.0%**	**55.0%**	28.33%	**39.0%**	**39.0%**	0.00%	**39.0%**	**55.0%**	39.00%
Inert	[%]	:	**20.0%**	**25.0%**	16.7%	**20.0%**	**20.0%**	0.0%	**20.0%**	**25.0%**	20.0%
CM (on total)	[%]	:	41.0%	20.0%	55.0%	41.0%	41.0%	100.0%	41.0%	20.0%	41.0%
OM/CM	[%]	:	**75.0%**	**95.0%**	70.2%	**75.0%**	**75.0%**	0.0%	**75.0%**	**95.0%**	75.0%
OM (on total)	[%]	:	30.8%	19.0%	38.6%	30.8%	30.8%	0.0%	30.8%	19.0%	30.8%
Non-OM	[%]	:	10.3%	1.0%	16.4%	10.3%	10.3%	100.0%	10.3%	1.0%	10.3%
DM	[%]	:	61.0%	45.0%	71.7%	61.0%	61.0%	100.0%	61.0%	45.0%	61.0%
C	[%]	:	55.7%	50.7%	56.9%	55.7%	55.7%	0.0%	55.7%	50.7%	55.7%
H	[%]	:	**7.5%**	**7.0%**	7.6%	7.5%	7.5%	0.0%	7.5%	7.0%	7.5%
O	[%]	:	**35.0%**	**40.0%**	33.8%	35.0%	35.0%	0.0%	35.0%	40.0%	35.0%
N	[%]	:	**1.5%**	**2.0%**	1.4%	1.5%	1.5%	0.0%	1.5%	2.0%	1.5%
S	[%]	:	**0.3%**	**0.3%**	0.3%	0.3%	0.3%	0.0%	0.3%	0.3%	0.3%
LHV	[MJ/kg]	:	**8.4**	**2.7**	**12.2**	**8.4**	**8.4**	**0.0**	**8.4**	**2.7**	**8.4**
Energy	[MJ]	:	8,376.9	1,065.7	7,311.2	8,376.9	8,376.9	0.0	8,376.9	0.0	8,376.9
Energy	[kWh]	:	2,326.9	296.0	2,030.9	2,326.9	2,326.9	0.0	2,326.9	0.0	2,326.9
			100%	13%	87%	100%	100%	0%	100%	0%	100%
biogas											
Volume per kg input	[Nm³/kg]	:		**0.110**			**0.210**			**0.000**	
Volume	[Nm³]	:		44.000			210.000			0.000	
Mass	[kg]			56.198			268.218			0.000	
Molar mass	[kmol]	:		1.963			9.369			0.000	
CH4	[vol%]	:		**55%**			**55%**			**0%**	
CO2	[vol%]	:		45%			45%			100%	
CH4	[kmol]	:		1.080	0.000		5.153	0.000		0.000	0.000
CO2	[kmol]	:		0.883	15.636		4.216	0.000		0.000	19.013
H2O	[kmol]	:			12.476			0.000			15.254
Conversion factor											
C	[-]	:		0.581	0.990		0.493	**0.990**		0.000	**0.990**
LHV	[MJ/Nm³ or /kg]	:		19.8	12.2		19.8	0.0		0	8.4
LF gas recovery							85%				
Available Energy	[MJ]	:	8,182.4	871.2	7,311.2	3,534.3	3,534.3	0.0	8,376.9	0.0	8,376.9
Conversion	[-]	:	95.9%	81.7%	99.0%	42.2%	42.2%	99.0%	99.0%	0.0%	99.0%
Electrical efficiency	[-]	:		**40.0%**	**25.0%**		**40.0%**	**0.0%**		**0.0%**	**25.0%**
Gross Power Output	[kWh]	:	**604.5**	96.8	507.7	**392.7**	392.7	0.0	**581.7**	0.0	581.7
			100.0%	16.0%	84.0%	67.5%	67.5%	0.0%	100.0%	0.0%	100.0%
Overall efficiency	[-]	:	**26.0%**			**16.9%**			**25.0%**		

Table 1: Calculation results for Case 1, Case 2 and Case 3.

An increase of 4% (Case 3 vs Case 1) is not very much and it is likely that the combination will be more expensive than a WTE alone, so that the extra power will not compensate the additional investment. That is why will now further optimize Case 3 by combining the two cycles, the open biogas cycle with the closed steam cycle.

HYBRID COMBINED CYCLES

[13] Several power plants use hybrid cycles where gas turbine or gas engine exhaust heat is used in steam bottoming cycles burning MSW [1, 2, 4, 5]. One of the largest of this kind is the Zabalgarbi plant in Bilbao, Spain, where the clean exhaust gases of a GE LM6000 gas turbine are used to superheat the steam produced in the MSW boiler. This has many advantages such as reducing corrosion in boiler superheaters and increasing thermodynamic efficiency. The drawback however is that the natural gas share, a fossil fuel, is high.

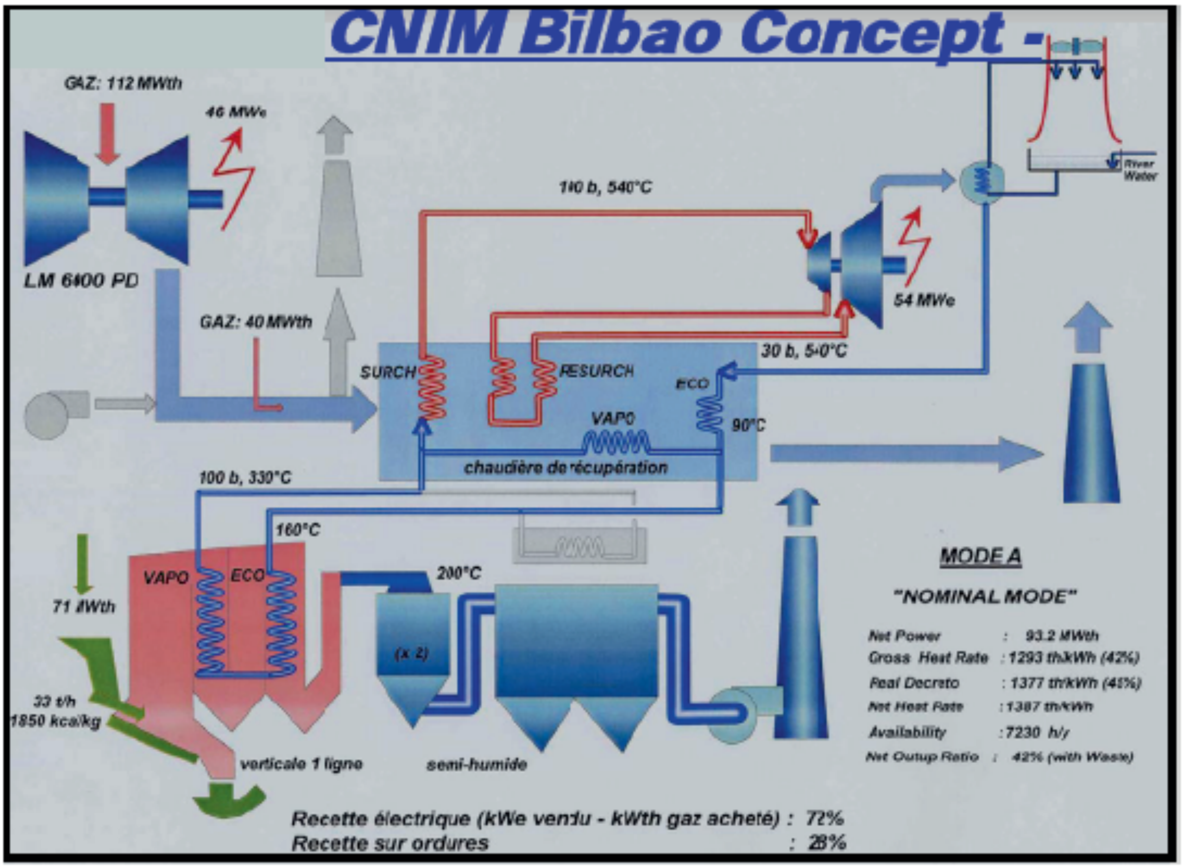


Figure 6: Zabalgarbi Plant concept in Bilbao, Spain [3]

In Bilbao only 22% of the exported power comes from MSW and 78% from natural gas. Several other WTE plants use hybrid cycles, e.g. Sakai, Linköping, Vantaa, Heringen [2, 9, 10], and others, but either the natural gas share is high or its efficiency is low.

OPTIMIZED COMBINED CYCLE®

In [13] the authors present a method, named Optimized Combined Cycle® (OCC®), to reduce the natural gas share to less than 25% by introducing a small gas turbine, or gas engine, capable of providing approximately the plant's own power consumption. The exhaust of such a small gas machine does not have the energy necessary to superheat all the steam produced in the MSW boiler, in general, below 420°C. To solve this problem the gas machine exhaust flow is 'artificially' increased with pre-heated fresh air and using a duct burner (DB) in order to reach the required steam superheating. Gas consumption in the DB is reduced by preheating the air supply to the duct burner using the hot flue gas exiting the external steam superheater (SH), similar to what is done in SCR De-NOx systems [7] for flue gas cleaning.

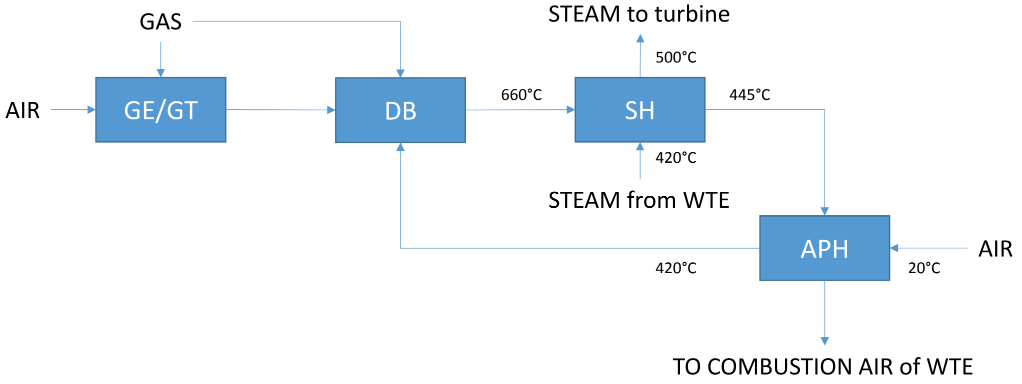


Figure 7: Typical configuration of OCC®.

To further increase the steam bottoming cycle efficiency the boiler flue gas stack temperature is decreased to 70°C, this way reducing the ‘stack loss’. This concept greatly reduces the amount of natural gas needed to increase the efficiency of MSW combustion [5]. With OCC 75% or more of the net energy comes from MSW, allowing the use of biogas from anaerobic digestion (instead of natural gas as used in ‘large’ combined cycles). The efficiency of the MSW can reach values of more than 30%. The gas efficiency is similar to that attained when large gas turbines are used in stand-alone combined cycles without MSW and approaches 50%, even for gas engines smaller than 3 MWe. The OCC concept has other advantages such as the plant being able to start up without external power, the fact that no attemperation is needed for live steam temperature control, reduced amount of startup auxiliary fuel both in design and operational phases.

In OCC® the optimum configuration is not the one with the highest thermodynamic efficiency (in general leading to higher prices), but the one that gives the best economic results for a given amount of MSW to be treated. OCC® is an efficient tool to improve economic feasibility of WTE plants.

OPTIMIZED COMBINATION OF WTE AND AD

As an optimization we will combine the two cycles of Case 3 to develop a Case 4. This OCC® concept is illustrated in Figure 8. First the steam pressure in the MSW boiler is increased to 90 bar which requires additional superheating far beyond 400°C to avoid excessive moisture at the steam turbine exit. The steam is superheated using part of the biogas produced by the AD plant in a duct burner (DB). Gas consumption in the DB is greatly reduced by pre-heating the air supply to the duct burner using the flue gas exiting the external steam superheater (SH).

The remainder of the biogas is used to generate power in one or more gas engines (GE). The medium temperature GE exhaust is used as part of the combustion air in the MSW boiler. The low O_2 content of the GE exhaust, around 9%, does not have an impact on the total O_2 for MSW combustion because the mass flow is less than 10% of the total combustion air.

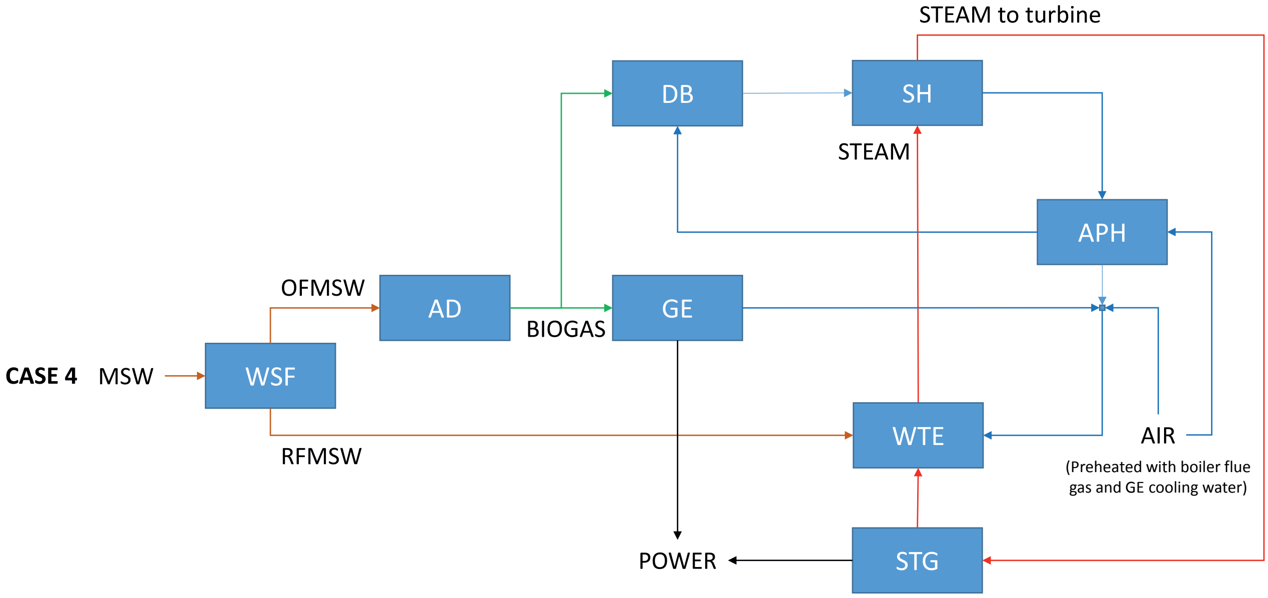
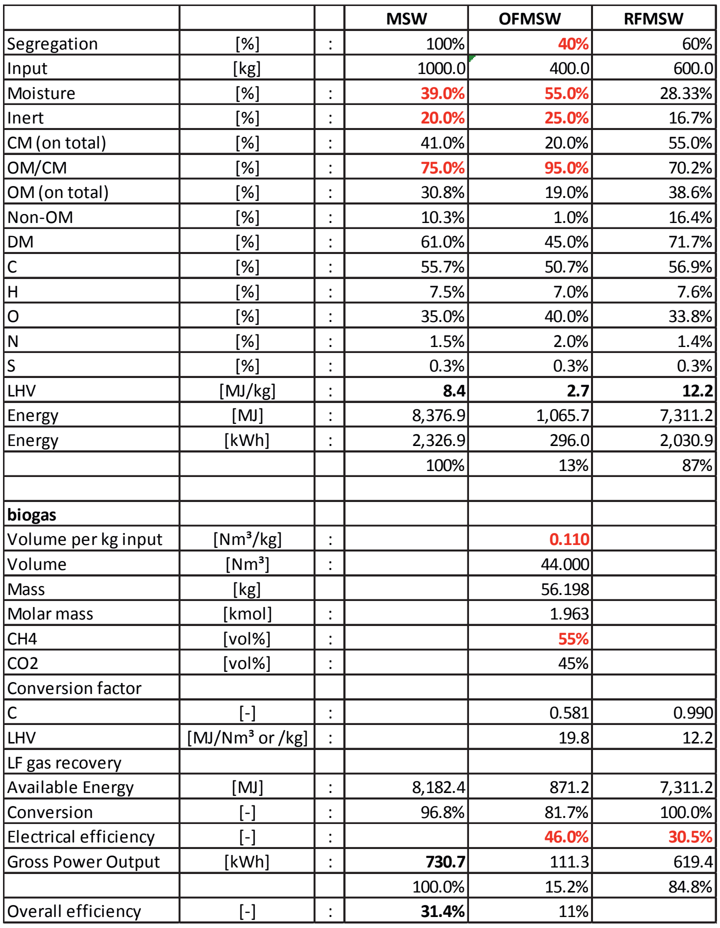


Figure 8:

Let us now compare the Case 4 (WTE+AD with OCC®) to the other cases (see Table 1 above). The GE exhaust heat is entirely reused in the steam cycle and thus is also converted into power (at the efficiency of the steam cycle). In addition some of the engine cooling water heat is recovered in the steam cycle (e.g. for air preheating or condensate preheating).

From [13] we assume a steam cycle efficiency of 30.5% and a biogas gas efficiency of 46.0%. The result is a power output of 730 kWh per ton MSW, an increase of 21% compared to Case 3 (without OCC®) and an increase of 26% with respect to Case 1 (WTE). The share of the biogas in the power production is 15%.



			MSW	OFMSW	RFMSW
Segregation	[%]	:	100%	40%	60%
Input	[kg]		1000.0	400.0	600.0
Moisture	[%]	:	39.0%	55.0%	28.33%
Inert	[%]	:	20.0%	25.0%	16.7%
CM (on total)	[%]	:	41.0%	20.0%	55.0%
OM/CM	[%]	:	75.0%	95.0%	70.2%
OM (on total)	[%]	:	30.8%	19.0%	38.6%
Non-OM	[%]	:	10.3%	1.0%	16.4%
DM	[%]	:	61.0%	45.0%	71.7%
C	[%]	:	55.7%	50.7%	56.9%
H	[%]	:	7.5%	7.0%	7.6%
O	[%]	:	35.0%	40.0%	33.8%
N	[%]	:	1.5%	2.0%	1.4%
S	[%]	:	0.3%	0.3%	0.3%
LHV	[MJ/kg]	:	**8.4**	**2.7**	**12.2**
Energy	[MJ]	:	8,376.9	1,065.7	7,311.2
Energy	[kWh]	:	2,326.9	296.0	2,030.9
			100%	13%	87%
biogas					
Volume per kg input	[Nm³/kg]	:		0.110	
Volume	[Nm³]	:		44.000	
Mass	[kg]			56.198	
Molar mass	[kmol]	:		1.963	
CH4	[vol%]	:		55%	
CO2	[vol%]	:		45%	
Conversion factor					
C	[-]	:		0.581	0.990
LHV	[MJ/Nm³ or /kg]	:		19.8	12.2
LF gas recovery					
Available Energy	[MJ]	:	8,182.4	871.2	7,311.2
Conversion	[-]	:	96.8%	81.7%	100.0%
Electrical efficiency	[-]	:		46.0%	30.5%
Gross Power Output	[kWh]	:	**730.7**	111.3	619.4
			100.0%	15.2%	84.8%
Overall efficiency	[-]	:	**31.4%**	11%	

Table 2: Calculation results for Case 4.

The Case 4 with OCC® comes at an additional cost compared to the Case 3 without OCC® because of:

- The air preheater (APH) and duct burner (DB).
- The gas engine(s) (GE) or gas turbine (GT).
- The external superheaters.
- The Inconel® cladding of the membrane walls of the empty passes.
- The added complexity.

But on the other hand there are cost savings in:

- The smaller superheaters in the steam boiler.
- No need for Inconel® superheaters.
- The smaller condenser.
- The air preheating.

Any actual case has to be studied individually to evaluate whether or not the benefit of the extra income from power sales outweighs the additional investment.

RESIDUES

Comparing the four cases (WTE, LF, WTE+AD and WTE+AD with OCC®), from the point of view of the solid residues (Table 3) we can draw following conclusions:

- The landfill option (LF) evidently results results in the highest amount of solid residues that remain sequestered in the ground.
- The WTE plant results in bottom ash residues and flue gas cleaning residues. The carbon content of these residues is typically very low, for the evident reason that a WTE strives for maximum burnout. Further processing makes it possible to reuse a large part of the residues.
- The AD+WTE plant without or with OCC® result in less bottom ashes (50% less compared to the WTE case only) and FGC residues but on the other hand there is a substantial

amount of AD residue (digestate). This residue contains more carbon (typically 5%) because the carbon to methane conversion is not (cannot be) perfect. Further processing of this residue is possible. If this requires heat for drying, this can be obtained efficienty from the steam cycle. The dried digestate may be fed also to the WTE plant. The current paper will not further explore this option.

		CASE 3 & 4			CASE 2			CASE 1		
		MSW	OFMSW	RFMSW	MSW	OFMSW	RFMSW	MSW	OFMSW	RFMSW
Residues										
Digestate	[kg]		344			732			0	
Bottom ashes	[kg]			125			0			250
FGC residues	[kg]			16.5			0			20.5

Table 3: Residues.

CARBON CONVERSION

The landfill option converts part (50%) of the carbon to methane of which 85% is assumed to be captured (and converted to CO_2) and thus 15% is lost to the atmosphere. As methane has a global warming potential of 28 this loss should be minimized. In a modern landfill with a comprehensive gas collection system, an average of 85% of the gas will be collected, whilst the remaining methane will migrate through the capping layer where 90% will be oxidised by methanotrophic bacteria en route [14]. Nevertheless, methane gas emission from landfills remains a very large contributor to the greenhouse effect.

The WTE plant converts the C nearly perfectly (>97%) to CO_2. The AD plant converts typically 60% of the carbon in the feed to CH_4 (55%) and CO_2 (45%). Some of the carbon thus remains sequestered in the digestate. The carbon conversion of the WTE+AD solutions however is still more than 90%.

CONCLUSION

Recovering the energy in waste can be done either directly via oxidation or combustion in a WTE-plant or indirectly by first converting the organic matter to biogas in anaerobic digestion (AD) and then using the biogas as fuel in an internal combustion machine. This paper compared different scenarios (WTE only, AD only, the combination of WTE with AD) concluding that the combination WTE+AD results in the highest power output. A further optimization, using an optimized combination of the closed steam cycle of the WTE plant with the open biogas cycle of the AD plant, results in an additional impressive efficiency increase. An integrated plant according to this concept can obtain an electrical efficiency of well over 30%.

ACKNOWLEDGEMENTS

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