Waste-valorisation by municipal solid waste carbon use in a Chinese township

S. Petters[1], K. Mauthner[2] & K. Tse[3]
[1]*guo – Business Development Consult, Austria*
[2]*KatyushaTec, Austria*
[3]*Bestrong International Ltd., Hong Kong*

Abstract

A small heavy industry town, severely affected by recent coal-use limitations by central government decided to re-invent itself into a "model-town", following China's new parole of "carbon efficiency". Currently, 250t of municipal solid waste [MSW] are landfill disposed, evenly spread and covered with soil every day. Moisture content of the MSW is 45% and the calorific value is 9.5GJ/t.
o addWe proposed gross separation into bio-chemical and thermo-chemical processing fractions through coarse and drum sorting into fermentable sludge and combustible solid fuel. Anaerobic digestion [AD] residue of ~30% of input mass is mechanically dewatered for co-processing with the solid fuel fractions in a fast internal circulating dual fluidized bed reactor [FICDFB].

The FICDFB decomposes feedstock into energy-rich gases under anoxic atmosphere of a bubbling, steam fluidized bed and can fuel itself from unconverted char, mixing with the bed-material, looping between the two reactor chambers as heat transfer medium, as long as the compounded average calorific value of total feedstock is ≥ 10GJ/t. Due to the AD step, solid fuel fractions and digestate compound to ~17GJ/t feedstock, thus allowing one to further add stabilized sewage sludge at ~27% of per capita waste aggregation, bringing the calorific value down to ~11GJ/t again.

The combined treatments' output from the total chemical energy content of MSW and sewage sludge, representing 37MW_{chem} per hour is 70% "burner-gas" and 22% "heat", whereof ⅕ qualifies as exergy. So total exergy-yield is ~75%.

Since 60% of the gas' energy is represented by typical chemical synthesis gas moieties (hydrogen [H_2] + carbon monoxide [CO]) we further designed thermo catalytic dissociation [TCD] of the methane [CH_4] yields in, representing 40%

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energy, co-producing hydrogen and carbon-12 powder, which can directly be used for CO_2 splitting into further 2CO per molecule, delivering 100% synthesis gas of 1.8 H_2: 1 CO for any gas to liquid synthesis. Consequently the MSW plant can produce RMB 700–1,500 revenue from each ton's MSW ambient carbon reuse-ratio of ~60% and create new employment.

Keywords: 2°C carbon budget, ambient carbon re-uses, atmospheric carbon stock, carbon capture for use, carbon efficiency, CO_2-neutral, CO_2-recycling, chemical synthesis chemicals, fossil substitutes, hydrocarbon transformation.

1 Introduction

Today's promoted best available technologies [BAT] are to incinerate and/or combust decomposition gas of ambient "Hydro Carbonic Matter" contemplated to be *CO_2-neutral*. In order to comply with the United Nations [UN] Intergovernmental Panel on Climate Control [IPCC]'s concept of the world's *2°C carbon budget* [1], we would need to look at carbon as our least abundant resource. Therefore disposing it into *ambient carbon stock* by recovering its energy content at quite poor *carbon efficiencies* per unit of secondary energy obtained will have to become considered out of *2°C carbon budget*'s covenant.

Decarbonisation has become a buzz word in climate change mitigation efforts. Tremendous efforts can be observed in the transportation sector where new technologies and new fuels are being developed. On the other hand, organic waste, globally representing 20% energy-equivalent of the world's primary energy consumption, comprises of 1/6 MSW today [2], projected to increase to 1/4 in the next 20 years, becoming a CO_2 equivalent emitter like transportation at today's technologies, in an order of > 8Gt/year each [3].

Electricity from coal is often criticised for its carbon emissions compared to natural gas (2:1) [4]. However, the real *carbon efficiency* [5] show stopper of solid carbonaceous fuel driven thermo-chemical plants is intermittency in off-take. Due to the lack of possibilities in modulating thermo-chemical conversion of solid fuels, the carbon ratio per secondary output energy may get as bad as 5:1 compared to natural gas. These mechanisms also apply to MSW-to-Energy, even 15% lower in *carbon efficiency* than coal.

Although incineration is promoted as BAT by various interest groups, it can only be refinanced through multiple subsidy measures. Whether via feed-in tariffs [FiT] for generated electricity, extended producer responsibility [EPR] on day-to-day supplies, waste dipping and gate fees, or municipal participation in necessary investments and/or operating cost etc. all end up as charges to citizens.

China often criticised for its extensive use of coal has recently restricted coal use in major cities' greater regions, thrusting towns with energy intensive industries into severe recession. In lack of clear standards for *carbon efficiency* several initiatives were taken by such affected industries. Amongst others, a shift from coal to char from biomass or MSW pyrolysis are being pursued, trusting in currently widespread misconceptions of *CO_2-neutral* combustion of such bio-char [8]. Although this approach can bring cost of investment for MSW treatment down and increase added value from it in comparison with incineration, in terms of *carbon efficiency* and total financial returns, any investments in such concepts may get impaired over their expected life time through new *Ambient Carbon Reuse* Business models [9].

Therefore we have performed an indicative projection of a MSW-treatment concept for a ~750,000 capita population municipality in the greater outer conurbation area of Beijing starting from the local administration's waste specification:

2 Methodologies

2.1 Waste input

Due to the high ratio of wet content with ~⅔ organic dry substance, separate bio- and thermo-chemical processing makes sense [10]. Dry substance of fermentable biomass can be grossly characterized as $C_6H_{10}O_4$, consuming ~25%$_{wt}$ H_2O for decomposition into CH_4 and CO_2. Since moisture content in specified fermentable waste is 150%$_{wt}$ of dry substance, these fractions should at first be undertaken AD to prevent feeding a thermo-chemical waste reduction step with excessive water. For hygiene reasons we would further suggest a thermophile process, removing additional water by evaporation at the same time. By doing so, the average calorific value of the solid organic fractions does not get derogated, so that mechanically dewatered digestion residue and capita equivalent stabilized sewage sludge can be compounded with the remaining waste fractions to achieve optimum final sink reduction for fully inert residues without any auxiliary energy needs.

Table 1: Waste specified by the Municipality.

Basic properties for garbage (based on Reference Data provided)			GJ/t			GJ/t
	Tons per day	Tons per annum	Estimated gross calorific value	Moisture %	Dry matter %	Effective calorific value
Household kitchen waste	150-165	55.000-60.000	12,00	60,00	40,00	4,80
Wooden material	5-8	2.400	18,00	40,00	60,00	10,80
Paper	22-32	10.000	28,80	50,00	50,00	14,40
Ramie cotton fabric	7-9	3.000	29,90	15,00	85,00	25,42
Plastic and rubber	30-50	15.000	31,85	10,00	90,00	28,67
Metal		500-1.000	25,30			
Inorganics		6.000				
Total moisture		42.410,00	2,50	100,00		1,12
Total waste for treatment		94.650,00		44,81	55,19	9,56

2.2 Waste separation

Usually emerging countries have not developed good MSW source separation practices yet. On the other hand, manual labour is more affordable to allow for coarse and drum gravimetric sorting combined with manual metal picking and higher value plastic sorting prior to shredding.

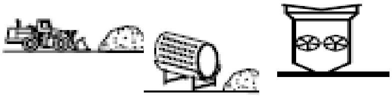

Figure 1: Mechanical preparation.

Inorganic matter (metal, glass, ceramics, etc.) yielded during gravimetric sorting can usually be sold for recycling, achieving higher revenues than the cost of its separation. Such separation prior to shredding mitigates also over-proportional energy need as well as wear and tear of tools.

Shredding should differentiate between bio-chemical treatment → 2–5mm
and fractions to undergo fluidization in thermo-chemical process→ 8–15mm.

2.3 Economic aspects of separated treatment

Food and kitchen waste digesters require investment per hourly capacity in an order of ca. US$ 1mio/t feedstock. Incinerating it without prior drying, the same volume would cause 7–8 times the investment cost and auxiliary fuel needs in the order of the feedstock's compounded mean calorific value's shortfall below 12.5GJ/t.

In Austria, gasification of poor carbonaceous solid fuels has been developed over the last 30 years, originally stemming from auto-thermal fluidized bed sewage sludge incineration [11]. Today, the investment cost for pure biomass is US$ 4.0mio/t hourly input capacity at scales between 10 and $30MWh^{-1}{}_{LHV}$. Due to subsidy and regulatory regime schemes in place in Europe industrial size applications have been focussing on woody biomass energy recovery applications for CHP and bio-substitute natural gas [12]. Since there is higher waste incineration capacities installed in Europe, than available waste, Europe's waste management sector is trying to protect its existing interests by staving off any economically more efficient alternative.

In the USA, the Department of Defense has been supporting waste to bio-fuel concepts by financing small demonstration plants. Due to the strategic motives as well as the lack of any refuse derived fuel [RDF] market due to the low prices for natural gas, impairing any investments needed for flue gas cleaning for industrial RDF use, these initiatives have developed bio-refineries for plastic waste, that could be extracted even from old landfills, wherever the Navy might need to refuel a flat top and its combat planes [13].

In Europe, RDF is an economic basis for high process energy demand industries like cement or pulp, etc. Together with increasing recycling ratios of plastic wastes their procurement market is tensioning up and putting them into competition with waste incineration operators. However, flue gas cleaning and waste water treatment of an incineration plant is contemplated to comprise ~50% of the investment cost of an incinerator.

Therefore, a reduction of what goes into the thermo-chemical treatment helps overall economics. The most fuel-flexible, long term larger scale proven gasification technology at the moment is steam driven indirect fast internal circulating dual fluidized bed [SDI-FICDFB] gasification, developed in Austria. It decomposes feedstock under anoxic operating conditions alike a pyrolysis, can fuel itself from unconverted carbon (char) and totally produces only ~50% off-gas volume of an incinerator. Therefore this process produces less gas volume needing cleaning than incineration [14].

2.4 FICDFB gasification

Steam-driven FICDFB gasification yields two separate gas output streams: (a) Flue gas stream (12% CO_2, 6% O_2, 83% N_2) from the combustion chamber, where char residue of the anoxic, fast pyrolized feedstock gets combusted, and (b) product gas stream, which includes the typical fuel poisons in the form of hydrates, e.g. H_2S, NH_3 or HCl, allowing cleaning by ways of enabling reuse of the same.

The solid fuel transformation into usable energy is here induced by heat from the fast circulating (~50 times/h) bed material (i.e. mineral sand) as a heat transfer medium between the combustion (oxygenic) and gasification (anoxic) chamber. The gasification chamber is a bubbling bed, fluidized by water steam, effecting fast high temperature pyrolysis followed by a steam reforming water shift equilibrium reaction in the free board zone above the bed’s splash zone.

Originally developed as enhancement in sewage sludge incineration, FICDFB can process up to 40% moisture in the feedstock. Within that range the water content actually can be considered part of the water-gas reactions’ “steam: carbon ratio” and reduce fresh water needs [15].

Different material fractions, such as RDF, biomass, coal, sludge of fermentation residues in the feedstock can be fed at the same time from parallel feeders at varying positions of the reactor (shown in Figure 2), as long as the compounded average Lower Heating Value of the solid fuel mix results in $\geq$ 10GJ/ton.

Fuel Input 1 would handle small particle size high ash content fractions to react within the steam reforming and hottest zone of the reactor. Lumpy or pelletized, usually higher fixed carbon containing feedstock fractions are fed via Fuel Input 2 to react within the bubbling zone of the bed. In case of low melting feedstock fractions, such as plastic foils, etc, a Fuel Input 3 at the top of the gasification reactor’s free board zone, between an additional constriction above the upper loop bed return and below the last constriction before the cyclone entry may be advisable to prevent undesirable sand agglomerations with molten mass.

Figure 2 shows several constrictions above the splash zone of the bubbling bed of the steam fluidized gasification chamber, repeated across the lateral cut of the free-board zone where the “solid fuel steam reforming” and “pyrolysis gas equilibrium reactions” take place. Since the circulating bed material is chosen from catalytic kind, these constrictions can maximize surface contact between the reactants and this catalyst, resulting in a high conversion ratio. The cyclone shown, almost representing a second chemical loop configuration can actually

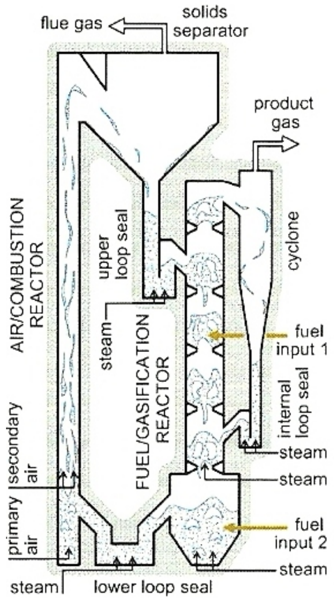

Figure 2: Dual-fluid reactor.

ensure good conversion rates of small particle size fractions in the feedstock, otherwise tending to go into the ash filters too fast, causing thermal challenges there on the expense of overall thermal efficiency [16].

Therefore, another coarse and gravimetric sorting after shredding according to 2.2 might be advisable to ensure a smooth and stable efficient operation.

3 Results

3.1 Anaerobic digestion of organic slurry [ADOS]

The ADOS process achieves 60% mass and > 80% moisture reduction. As food and kitchen waste are of unknown upstream identity we follow EU directives, not allowing bringing fermentation residue out to agricultural fields as certain pharmaceuticals common in meat production might cumulate across future food chains. Therefore, we foresaw undertaking the digestate a thermo-chemical reduction of final sink volume.

3.2 Anoxic thermo-chemical treatment

Should the necessary minimum average compounded calorific value fall below 10GJ/t feedstock, auto-thermal FICDFB operation could be supported by adding some brown coal (lignite) to the feedstock, which is widely available across China. However, in the underlying specification and separated treatments this does not seem necessary [17].

Table 2: Specified by municipality.

A D O S	t/h Input	m³/h output	t output/h
Kitchen waste & Ramie etc.	8,85	444,7	
55% hereof water	4,90		5,90
63% Methane		280,1	0,20
37% CO_2		164,5	0,33
36% digestate			2,42
t Carbon	1,10	- 0,24	0,86
t Nitrogen	0,05		0,05

Table 3: Feedstock composition.

FICDFB MSW + coal + SewageSludge	**t/h Input**	**% moisture**	**% ash**	**% volatiles**	**% fixed C**	**Carbon %**	**Hydrogen %**	**Nitrogen %**
Wooden material	0,32	40,0%	0,17%	52,4%	8,1%	30,1%	4,2%	0,03%
paper	1,33	50,0%	4,3%	74,6%	5,3%	26,8%	4,0%	0,34%
cotton fabric	0,40	15,0%	9,6%	90,7%	7,3%	45,0%	6,0%	0,55%
Plastic and rubber	2,00	10,0%	2,2%	88,0%	2,7%	79,5%	10,6%	0,46%
ADOS digestate	3,17	23,5%	21,6%	45,3%	8,7%	27,1%	3,8%	1,55%
Sewage Sludge ⅓ of MSW	3,40	63,2%	22,8%	33,8%	3,0%	10,0%	1,4%	0,7%
Lignite	-	20,0%	24,8%	21,7%	58,3%	40,9%	2,7%	1,1%
Total Feedstock in t/h	**10,62**	**3,95**	**1,60**	**5,87**	**0,56**	**3,42**	**0,47**	**0,09**

3.3 Total energy output

From the original ~37MWh$^{-1}{}_{chem}$ MSW and sewage sludge input's energy content 27.9MWh$^{-1}{}_{chem}$ decomposition gas can be harvested. In addition usable waste heat in an order of 7.5MWh$^{-1}{}_{therm}$ occurs, whereof 20% may be seen as exergy. Total η_E therefore is 95% (or 79.5% exergy).

Table 4: MSW outputs.

Output MSW & sewage	**Energy**		kg	m³
Heat	**8,7**	MWh_{th}		
parasitic	- 1,2	MWh_{th}		
Hydrogen	**11,9**	MWh_{chem}	**356**	**3.964**
		MWh_{chem}		
Carbon Monoxide	**4,6**	MWh_{chem}	**1.523**	**1.324**
		MWh_{chem}		
Methane	**11,4**	MWh_{chem}	**818**	**1.140**
Bio-chemical	2,8	MWh_{chem}	201	280
Thermo-chemical	8,6	MWh_{chem}	617	860
CxHy	**1,8**	MWh_{chem}	**128**	**52**
CO_2			**3.346**	**1.690**
Bio-gas			326	165
Product-gas			982	496
Flue-gas			2.038	1.029

About 60% of the chemical energy harvest from this waste occurs in chemical synthesis gas moieties. 40% can be called bio-substitute natural gas [Bio-SNG] which however cannot compete against natural gas [NG] in today's markets.

If, however, downstream use of such energy harvest from waste was geared towards gas to liquid chemical synthesis products, only 40% of required feedstock energy would need to be converted from Methane into H_2 and CO => synthesis gas – compared to 100% if all was to be produced from NG.

Therefore waste to chemical synthesis products become competitive with NG feedstock processes at the synthesis gas level, bringing waste management into a completely new paradigm – financially self-sufficient waste treatment!

3.4 Synthesis gas optimization

Although above illustrated product gas could be used as is for CHP gas-engine generator electricity production of ~10MWh$^{-1}{}_{el}$, we recommend to rather refine it towards fossil substitute chemical synthesis commodities. The most common synthesis gas H_2:CO ratio however is 2:1. Therefore the methane reforming has to make up for the 3:1 ratio of the synthesis gas moieties in the raw product gas, in other words a > 50% CO conversion from the methane.

(a) Dry methane reforming [DMR]: $CH_4 + CO_2 \Leftrightarrow 2CO + 2H_2$ has been studied in various literature and reported successful only in
  - either $CH_4 + 2CO_2 \Leftrightarrow 3CO + H_2 + H_2O$ which in our case would cause a Hydrogen deficit, needing to be balanced out by $CO + H_2O \Leftrightarrow H2 + CO_2$
  - or a combination with Partial Methane Oxidation [PMO]: $3CH4 + O_2 + CO_2 \Leftrightarrow 4CO + 6H_2$ requiring a source of pure oxygen

(b) Thermo catalytic methane dissociation [TCD] for CO_2 splitting [19]: $CH4 \Leftrightarrow 2H2 + C \rightarrow C + CO_2 \Leftrightarrow 2CO$ [20]. . .Σ: $2H_2 + 2CO$ having the advantage that carbon from TCD can be stored until synthesis hydrogen is not needed for other purposes, such as:
  - Transportation fuel;
  - Electricity grid back-up (if the bio-refinery was integrated into a local grid, using excess electricity for electrolysing hydrogen.

Due to the flexibility gains of option (b), as well as reported conversion losses due to additional equilibrium reactions ≥ 30% in option (a), we promote TCD as the more robust and overall energy efficient way to go.

In all options, the final product gas composition yield in synthesis gas moieties ends up in an order of 1.8-2 H_2: 1CO, which is an ideal range for gas to liquid chemical synthesis.

3.5 Downstream use of synthesis gas yields

A latest state-of-the-art incineration plant (using biogas from the fermentable fractions as auxiliary fuel in the thermo-chemical treatment,) could produce 30.6kWh$_{el}$ + 193kWh$_{therm}$ per GJ$_{MSW}$, producing 123kg CO_2, such electricity would have to compete against utility procurement spot market prices between 15 and 40US$/MWh [21].

In the case of thermo-chemical decomposition into producer gas (rather than incineration,) the energy yield according to 3.3 could be used in CHP gas-engine electricity generation, delivering 53.5kWh$_{el}$ + 90kWh$_{therm}$ per GJ$_{MSW}$, producing 61kg CO_2 (still > 1.5 x CO_2 from NG electricity).

Apart from any possibility to sell the heat, $1GJ_{MSW}$ could produce either US\$0.85 or US\$1.56 worth of electricity (at a mean spot market price of (15+40)/2). Therefore today's waste to energy concept requires cross-subsidization through several regulatory supports. For example FiT, EPR, public subsidies of capital expenditures [CAPEX] and operating expenditures [OPEX] out of municipal taxes, waste charges and gate fees. However, at the end of the day all are lading the consumers' free available income for a prospering local economy.

In contrast hereto, the valorization of $1GJ_{MSW}$' synthesis gas yield according to 3.4 could be in a range of about 10 times the electrification values for 120% CAPEX of incineration (as shown for several output options in Table 5).

Table 5: Achievable revenues per 1 GJ feedstock.

Product in kg/$GJ_{feedstock}$		CO_2	**kg by-Product & kind**		Σ U\$/$GJ_{feedstoc}$	Uses
Hydrogen	5,6	47,7	-		16,0	as a fuel, building block for fertilizer,
$_{nano}$Carbon	9,5	-	-		19,7	as CO_2 refining intermediar
1 propanol	15,5	0,2	15,5	Hydrogen	21,6	as a solvent, cleaner, sterilizing fluid
acetic anhydride	14,8	-	14,1	Methanol	16,1	as a acetylation compound, wood impregnation
Methanol	27,5	9,5	-		8,9	as a chemical buildinig block or fuel
Ethanol	16,6	2,5	16,6	Hydrogen	18,4	as basis for medical, drinks, fuel, chem. Compound
Ethylene	9,5	1,1	13,6	Hydrogen	14,9	as a basis for Polyethylene
Formic acid	13,6	23,1	23,1	Methanol	11,6	as a building block in protein feed production
Fisher Tropsch Fuel	9,8	11,4	3,1	Bio-Wax	9,2	as synthetic fuel (at RMB 3.50/ltr)
Acetic acid	17,4	14,1	17,4	Methanol	11,5	as a reagent for VA plastics

3.6 Carbon efficiency optimizations

The synthesis gas optimization according to 3.4 represents an ambient carbon re-use ratio of ~60% of the ~23.6kg/GJ_{MSW} carbon content. In case abundant hydrogen from electrolysis off excess grid electricity was available, 1kg/GJ_{MSW} could uplift this ratio to > 80%.

4 Conclusions

A macro-economic study of the above described MSW to bio-chemicals concept has shown significant qualitative economic growth [22]:

- Creating new employment~1 per 1,000 ton per year capacity; (30% onsite/60%indirect/10% induced)
- (Re-) using local resources ~1.6boe [barrel oil equivalent]/t_{MSW} (at 9.5GJ/t specified)
- Valorizing 1boe 2nd-ary resource to US\$53–126 product market value (1boe = 5.86GJ x Table 5)
- Cost per t waste treatment ~US\$ 40/t_{MSW} (specified) at 3.3 CHP (equaling US\$ 55/MWh_{el} base load)
- additional cost for 3.4/t_{MSW} ~US\$ 33.5/t_{MSW} = US\$ 20.9/boe
- additional cost for 3.5/t_{MSW} ~US\$ 26.5/t_{MSW} = US\$ 16.6/boe

Total cost to product value **US\$ 100.0/t_{MSW}** = US\$ 62.5/boe
Total cost of Singapore MSW US\$ 116.5/t_{MSW} [23].

Refining end-of-lifecycle organic, ambient hydrocarbons in lieu of fossil primary energy therefore makes economic sense, particularly in the case of municipal solid waste organic residues. Under the fiscal gross domestic product [GDP] return structure per employment in Austria the total additional GDP effects resulted ~30% of the MSW-refinery's revenues.

Therefore waste to fossil substitute chemical synthesis products open a wide level playing field for political qualitative growth initiatives. Depending on energy import dependencies and local primary energy resources as well as local industrial procurement needs, each configuration might prefer a different output model and may deem specific incentives worthwhile, which as long as bottom line zero cost to the population, would absolutely make sense. An example for a net zero cost subsidy scheme is the Colombian National Ethanol Initiative [24].

By the way, lignin ($C_9H_{10}O_2$, $C_{10}H_{12}O_3$, $C_{11}H_{14}O_4$) waste streams from ethanol production could also be a very rewarding field for combining 2.4 and 3.4 for 3.5 in analogy to the described MSW value chain.

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