PILOT SCALE PYROLYSIS - DETERMINATION OF CRITICAL MOISTURE CONTENT FOR SUSTAINABLE ORGANIC WASTE PYROLYSIS

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ABSTRACT

Economic feasibility of large scale organic waste pyrolysis was investigated for Inghams Enterprise (Waitoa) chicken dissolved air flotation sludge (DAF) and activated sludge (biosolids) from the Hamilton municipal waste water treatment plant. Processing data was obtained from pilot plant trials using the Lakeland Steel (Rotorua) continuous auger pyrolysis plant using feedstock at 15, 30, 45 and ~80% moisture contents. Economics were calculated based on estimated capital and operating costs of a large scale facility, revenue from selling char, savings from landfill diversion (including transportation and gate costs), energy savings by recycling syngas product and using waste heat for drying feedstock.

For DAF, 15% moisture content gave yields of 21% syngas, 27% char, and 52% oil (dry weight basis). 15% moisture content gave the best processing conditions based on handling properties and degree of autogenesis. The DAF case does not give a payback period due to low scale of operations.

For biosolids, 15% moisture content feedstock gave yields of 46% syngas, 31% char, and 21% oil (wet weight). Difficulties were found with plant blockages at 45% and 80% moisture contents. 15% moisture content gave the best processing conditions and the best economic performance with a payback time of 4.6 years for a facility that could process 11,000 tonnes per year.

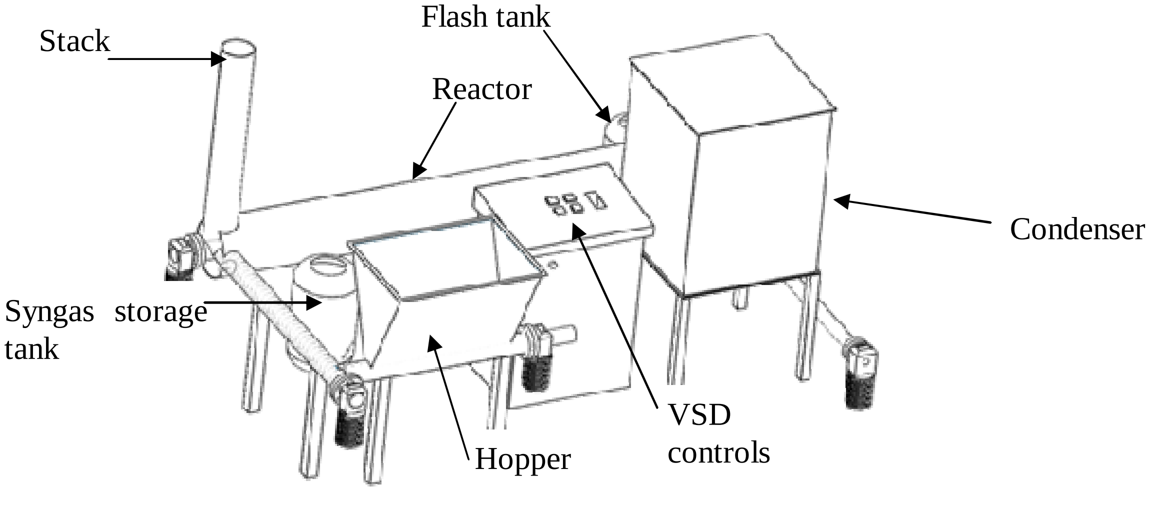
INTRODUCTION

The problem of waste disposal has challenged mankind ever since the dawn of civilisation. For many years landfills have been seen as the most appropriate solution available. However, due to increase in land costs and the awareness of landfill emission, various studies have been conducted to investigate different methods of waste minimisation. The amount of waste in the Waikato region is increasing every year, with the current yearly production totalling at around 1.2 million tpa (Purchas. et al., 2009). Ideally some of this waste is being recycled to be reused while another fraction is being processed (e.g. composting or digested) with approximately 135,000 tonnes/yr. going out to landfill. However, landfilling comes at a cost; both economically (gate charges) and environmentally (landfill leachate). With these costs increasing, more specifically landfills becoming more expensive, Environment Waikato and Partners are looking at alternative waste minimisation options such as pyrolysis that will be economically viable. Thus the main objective of the paper is to provide an economic feasibility assessment of a large scale pyrolysis plant that will be able to process the organic waste.

Pyrolysis is the thermal degradation of carbonaceous matter in the absence of oxygen. The products of pyrolysis are bio char, bio-oil and syngas (Slesser. and Lewis., 1979).

The organic waste of interest is landfill destined sludge such as waste water treatment plant bio-solids and poultry dissolved air flotation sludge. These sludges have higher moisture content compared to wood based feedstock and requires higher energy input to process. They also are known to have high levels of trace metals. However, the advantages of using these sludges are that they have no current use and pyrolysis reduces landfill loading. The pyrolysis reaction will occur at temperatures over 200°C, at this instance, the feedstock is bone-dry. Presence of moisture in pyrolysis reactions tends to increase the heating duty; however, it also facilitates secondary reactions such as methanation and steam reformation which promote the production of methane and hydrogen respectively. Water can also be used as a heat carrier, especially in operations where feedstock thermal properties do not allow sufficient heat transfer rates once in a bone dry state.

Lakeland Steel has developed a continuous auger pyrolysis pilot plant (Fig. 1). It consists of a kiln, which is a 2.5 m long auger that is heated up to 600oC counter-currently by an external heating jacket with hot air supplied by an LPG gas heater and fan. Exhaust is vented through a stack at the front end of the kiln. The kiln is fed by two augers in series, one underneath the hopper. Solids flowing through these two augers form an air plug, restricting air entering the kiln. Char exits at the end of the kiln via another auger and is collected in a bottle that is coupled to the end of the auger and sealed. The volatiles are vented from the auger. The heavy fraction of the volatiles, typically the tars and heavy oils, are collected in a 20-L sealed vessel, where they drop out of the gas stream by condensing on the sides of the vessel. The lighter fraction of the volatiles, typically the light oils and water, is condensed in a coiled copper tube inside a tank holding water. The condensate is collected in a second sealed vessel and the syngas flared through a narrow tube exiting the vessel. The pilot plant has shown promising results with the organic waste sludge of interest.



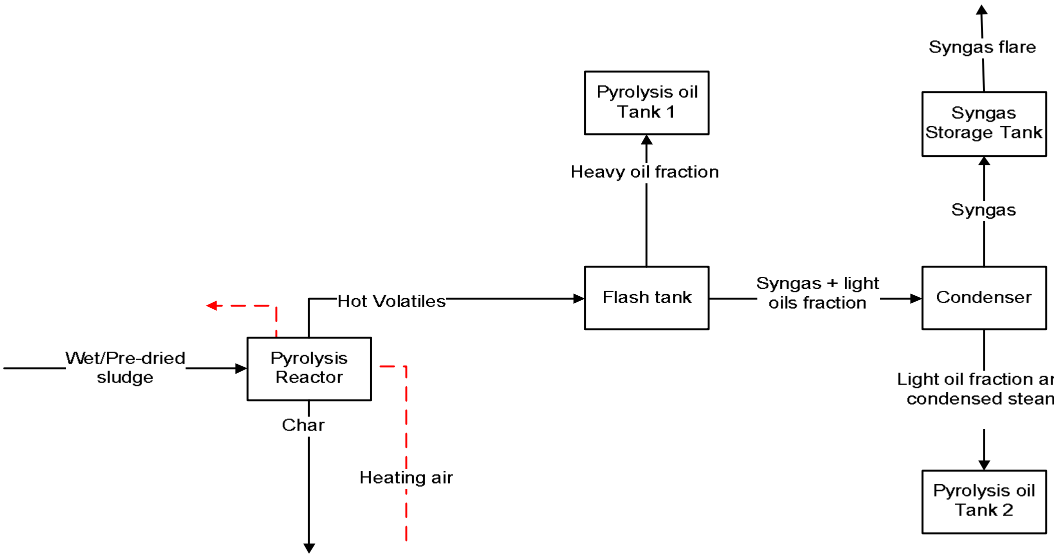


Fig. 1. Process flow diagram of Lakeland Steel's pilot plant.

The biggest barrier faced by waste minimisation is the high moisture content of the feedstock (typically greater than 70% for waste treatment sludges) (Elliott, 2010, Mcbirdle, 2011). Thus, the aim of this research was to pyrolyse feedstock with and without pre-drying to explore the effect of moisture content on product yields, product composition and energy consumption. Mass and energy balances were obtained where possible; the process modelled and scaled up using pilot plant data. Economic feasibility was assessed and feedstock moisture content required for sustainable processing was determined.

METHODOLOGY

Two feedstocks were used: Biosolids (dewatered activated sludge) from the Hamilton Pukete waste water treatment plant, and poultry DAF and dewatered pond sludge from Inghams Enterprise, Waitoa.

Feedstock Characterisation

Moisture content was determined by oven drying samples at 65°C for a minimum of 48 hours or until no mass change was observed. The temperature was kept low because the feedstock appeared to be heat sensitive. This also reduced the amount of volatile matter being evaporated.

Ash and volatile content were determined by ashing dry samples of feedstock at 600°C for two hours. The mass loss was taken as a fraction of the initial mass and recorded as the volatile matter; the balance was recorded as ash.

Fat content was determined by soxhlet extraction with dichloromethane. The extraction was carried out overnight for 17 hours.

Ultimate analysis of feedstock and product were performed by Campbell micro-analysis lab, Otago. This also included calorific value analysis.

Thermo-gravimetric analysis was performed on feedstock samples by heating in argon to 600 °C using a heating rate of 20 °C /min to emulate the heating rate and expected residence time of approximately 30 minutes as used in the pilot trials. The TGA was repeated three times to account for variability in feedstock properties.

Pyrolysis

The first set of trials used non-dried feedstock with the reactor operating at 600°C. The second set of trials involved pyrolysing feedstock that had been pre-dried in a timber drying kiln to 15, 30 and 45% moisture content and undried feedstock at 400°C.

The pyrolysis plant was first heated to temperature by turning on the fan and gas burner for the reactor and allowing the system to warm-up. While the system was warming up, the feedstock mass was weighed and placed into the hopper. Once the system was at temperature, the augers were turned on, directing feed into the reactor.

The feedstock in the hopper was continuously compacted to make sure no air pockets entered the system. Mass flows of the products were taken every 15 minutes once the system achieved steady state.

A 1-L tedlar bag was used to measure the flow rate of the hot volatiles.

The syngas flow rate was measured by allowing the hot volatiles in the tedlar bag to condense leaving only syngas in vapour form. The vapour volume was measured by piping it into an inverted measuring cylinder filled with water.

Temperature logging was used to monitor the pilot plant thermal conditions and perform energy balances.

GC Analysis

Gas chromatography analysis results for the syngas were provided by CRL Energy Ltd (Lower Hutt).

Determination of Critical Moisture Content for self-sufficient pyrolysis

Using a calculated heating efficiency of 80% for the pilot plant, and the data from the wet feedstock trials at 600°C, the system energy balance was analysed to test for pyrolysis autogenesis. This would help predict the moisture content level which would allow the syngas product to provide the energy needed for the pyrolytic reactions. The system energy balance was assessed using the following formula:

$Q_{balance} = k_r Q_{syngas} - Q_{pyrolysis}$

Where Q_{syngas} is the heat produced from combustion of the syngas product; $Q_{pyrolysis}$ is the heat needed for pyrolysis. k_r is reactor efficiency. The system energy balance was predicted for the whole moisture content spectrum under the assumption that the syngas yields and calorific value remained constant. The analysis shows that pryolysis can achieve autogenesis for biosolids at moisture contents lower than 35% and 50% for DAF (Fig.2a). A plant with combined feeds needed feedstocks with less than 40% moisture.

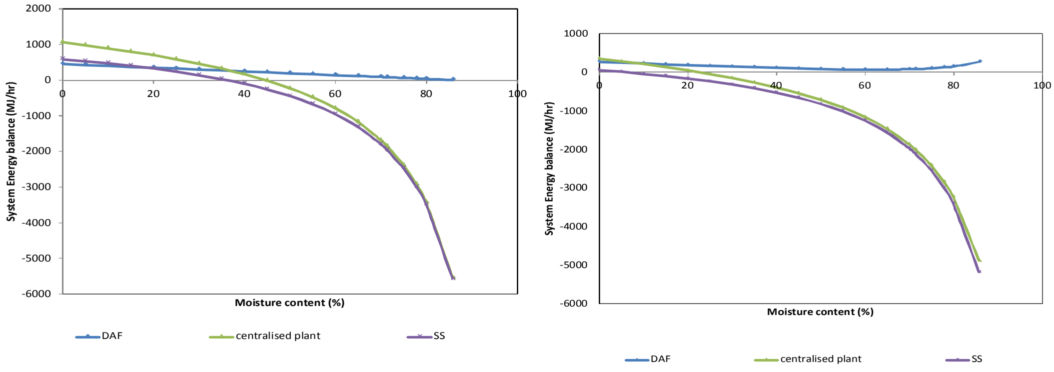


Fig. 2.a) Post pyrolysis system energy balance vs moisture content
b) “Post drying+pyrolysis” system energy balance vs moisture content

Since pyrolysis autogenesis was conditionally feasible for all three case studies, the potential for autogenesis of the pre-dried pyrolysis feedstock was examined using the data from the trials of wet feed at 600°C. The energy balance was expanded to account for drying:

$Q_{balance}=k_r\ k_d\ Q_{syngas}-(Q_{drying} +Q_{pyrolysis})$

By decreasing the moisture content the drying duty is increased but the pyrolysis duty is reduced because of the reduction in the excess water. However, if the feedstock is not pre-dried the pyrolysis load has to include evaporating the water and raising it to pyrolysis temperature. The system balance intersects the zero at 8%, 23% and infinite moisture fraction for the biosolids, centralised plant and the DAF respectively. (Fig. 2b). Thus supplementary fuel is needed to handle any feedstock with moisture content greater than the specified amount for the biosolids and centralised cases. The critical moisture content had been calculated using an assumed dryer efficiency(k_d) of 65% (Perry and Green, 1999). In reality, the efficiency of the rotary dryer will decrease as you lower the outlet moisture content by (Downie, 2012) the law of diminishing return. To account for this trend and ensure that this 65% dryer efficiency assumption did not limit trials, the moisture levels chosen for testing were 15%, 30% and 45%. The feedstock was not processed at bone dry conditions because some moisture is needed for steam reformation to occur (Serdar, 2004).

RESULTS AND DISCUSSION

Feedstock Characterisation

The undried feedstock has a high moisture content with the bio-solids containing 78% and the DAF containing 72% water (Tab. 1). DAF has higher carbon content, more volatile matter, more fat and lower ash than biosolids (Tab. 1 and 2).

Tab 1. Characteristics of Organic Feedstock

	Proximate analysis (wt. %)				
Feedstock	M	A	V	F	HHV[a]
Biosolids	77.88	6.95	15.17	2.18	20.0
DAF	71.39	1.5	27.11	18.3	32.2

M= moisture, A = ash, V = volatile matter, F = fat, HHV = higher heating value (MJ/kg), a = dry sample

Tab 2. Feedstock ultimate analysis.

	Ultimate analysis of dry feedstock (wt. %)					
Feedstock	C	H	N	S	O (*)	Ash
Biosolids	35	9.0	5.3	0.4	19.9	31.4
DAF	55	6.0	5.4	0.8	27.6	5.2

Analysed by Campbell Micro-analytical Laboratory, Dunedin, NZ

Thermo-gravimetric analysis of both feedstock shows their expected thermal behaviour (Fig. 3). DAF loses 75% of its mass by 400°C whereas biosolids has only lost 55%, therefore biosolids can be expected to produce more char, has a lower amount of volatile matter and is less volatile than DAF.

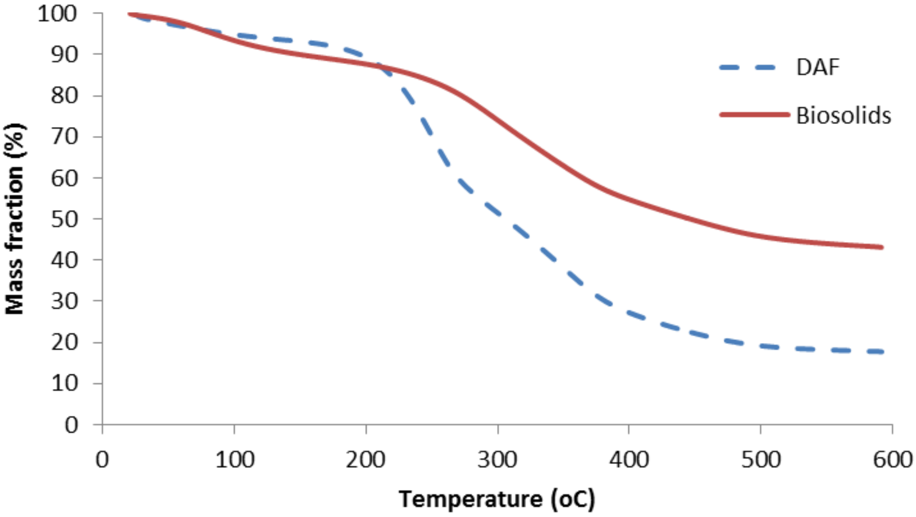


Fig.3. TGA curves for DAF and biosolids.

Pyrolysis results

Results from the pyrolysis trials are shown in Tab. 3. A general observation was that increasing moisture content reduced feedstock feed rate into the kiln, presumably due to the material slipping more easily on the auger compared to drier feedstock. Wet biosolids and DAF had poor flow-ability due to its rubbery behaviour with feed rates 0.2 and 0.6 kg/hour respectively. The feedstock was easier to process with decreasing moisture content with feed rates going up to 2.2-2.4 kg/hour. The exception was dry biosolids which had a low feedrate of 0.7 kg/hour, due to the feedstock being more a coarse powder rather than large clumps or granules. DAF with higher moisture contents produced more tar-like oil which formed in the kiln. This tar drained down the char auger to cause blockages by forming a cake with the char, but also in some cases blocked the kiln resulting in pyrolysis gases exiting through the feed hopper. The kiln blocked completely for DAF at 72% moisture content and biosolids at 45% and 78% moisture content at 400°C operating temperature, therefore yields for these conditions were not able to be obtained.

There was an increase in syngas production for DAF for moisture contents between 15% and 30% from 21% to 45% yield (Tab. 3). This could be due to a gas-water shift reaction resulting in increased syngas production. However the syngas yield then decreases to 18% for the 45% moisture DAF. This is likely caused by the higher heating demands associated with high moisture feedstock. The high moisture reduces the extent of the pyrolysis reaction, reducing syngas production. The 72% moisture feedstock has a yield of 25% which is high compared to the 15% and 45% moisture content DAF, but this is due to a higher kiln operating temperature of 600°C.

X yield = (dry product flowrate)/ (dry feed throughput)

Tab. 3. Pyrolysis yields (dry weight) and operating conditions. Results for DAF at 72% moisture content and biosolids at 45% and 78% moisture content and 400°C were not reported as the pyrolysis plant repeatedly blocked at these conditions.

Feedstock	Moisture content (%)	Mean Reactor temperature (°C)	Stack temperature (°C)	Feedrate (dry solids kg/hr)	% yields (dry weight)			
					Char	Oil		Gas
						Heavy	Light	
DAF	15	438	141	2.4	27	30	22	21
DAF	30	420	147	2.3	34	12	3	45
DAF	45	428	127	0.7	59	12	10	18
DAF	72	600	115	0.6	26	19	13	42
Biosolids	15	445	120	0.7	31	21	0	46
Biosolids	30	413	107	2.2	37	15	7	36
Biosolids	78	600	115	0.2	37	22	14	27

The char yield increases with moisture content for the trials performed at 400°C, and this was due to reduced volatilisation of organic material (Tab. 3) because more heat was consumed by evaporating the water than volatilising the organic matter. Char produced using 30% moisture feedstock at 400°C did not have a uniform colour. The oil yields did not show an apparent trend, other than higher operating temperatures resulting in greater oil production, while increasing moisture content for DAF reduced oil production. For biosolids, oil production was similar for both 15 and 30% moisture feedstocks. The 15% moisture DAF feedstock produced the highest oil yield total of 52%. The oil yield then dropped to 15% for 30% moisture feedstock and climbed to

23% and 54% for the 30% moisture content and 72% moisture content feeds respectively.

Results from Tab. 3 are comparable to other research where commonly reported char yields are around 10-40% and 5-75% oil and the remainder syngas, depending on feedstock, operating conditions and desired product(Mohan et al., 2006).

Product Composition

Bio Char

The composition of bio-char produced is shown in Tab. 4. High operating temperatures for wet feedstock resulted in high carbon content in the char of around 77-78%, whereas low operating temperatures resulted in carbon contents that were similar or slightly less than the feedstock, lower hydrogen content, presumably due to the oils and fats volatilising, and similar or slightly lower nitrogen contents. Other research has reported carbon content of chars around 50-60% (Ozcimen and Karaosmanoglu, 2003) . Higher pyrolysis temperatures resulted in higher carbon content (Antal, 2003)

Tab.4. Ultimate analysis of char products.

	DAF			**BIOSOLIDS**		
	Wet DAF @ 600°C	**DAF $_{15\%}$ @ 400°C**	**DAF $_{30\%}$ @ 400°C**	**Wet BS @ 600°C**	**BS $_{15\%}$ @ 400°C**	**BS $_{30\%}$ @ 400°C**
C	78.67	45.15	43.42	77.98	35.12	30.24
H	2.33	4.9	4.18	2.1	2.7	2.76
N	0.3	4.97	5.26	0.48	3.72	3.74
S	<0.3	0.71	0.62	<0.3	0.68	0.63
O	<10			<10		

Analysed by Campbell Micro-Analytical Laboratory, Dunedin

Carbon captured in the char (Tab. 5) was calculated based on the carbon contents of the chars produced (Tab. 4) and feedstock (Tab. 2) and char yields (Tab. 3). For DAF, carbon capture was between 22-37%, mainly because DAF has a high fat and volatile content (Tab. 1 and Fig. 3) which end up as syngas and oil. For biosolids, carbon capture was around 31-32% at low operating temperatures, but was around 82% for biosolids at high operating temperatures and high moisture content. The high capture seemed unusual given the relatively high yields of oil and syngas (Tab. 3) and would need to be confirmed.

Tab.5. Carbon captured for the different operating conditions.

Feedstock	**Moisture content (%)**	**Mean Reactor temperature (°C)**	**Stack temperature (°C)**	**Feedrate (dry solids kg/hr)**	**Char yield (% dry basis)**	**Carbon in char (%)**	**Carbon captured (%)**
DAF	15	438	141	2.4	27	45	22
DAF	30	420	147	2.3	34	43	27
DAF	72	600	115	0.6	26	79	37
Biosolids	15	445	120	0.7	31	35	31

Biosolids	30	413	107	2.2	37	30	32
Biosolids	78	600	115	0.2	37	78	82

Syngas

During the pilot plant trials, it was observed that the syngas produced from DAF pyrolysis burned more vigorously than that of the bio-solids. However, the analysis of the syngas produced at 600°C by the different feedstock showed that the syngas produced by DAF had the similar calorific values to biosolids (11.17MJ/dscm and 11.88MJ/dscm). The calorific value of syngas for the pre-dried feedstock decreased with increasing moisture content. Increasing moisture content increases the probability of water-gas shift reactions potentially increasing CO_2 content in the syngas. Syngas for DAF at 30% moisture showed abnormally high O_2 and N_2 suggesting the sample had been contaminated by air or the analysis was incorrect.

Tab. 6. Syngas analysis for pilot trials.

	DAF			**BIOSOLIDS**		
	Wet DAF @ 600°C	**DAF $_{15\%}$ @ 400°C**	**DAF $_{30\%}$ @ 400°C**	**Wet BS @ 600°C**	**BS $_{15\%}$ @ 400°C**	**BS $_{30\%}$ @ 400°C**
CH_4	14.5	15.2	7.3	15.2	12.5	11.3
CO_2	28.6	16.1	17.4	25.9	15.7	36.3
C_2H_4	3.1	2.5	0.9	3.1	0.9	0.5
C_2H_6	1	4.8	1.6	1.18	2.3	2.1
C_3H_6	0.9	N/a	N/a	0.99	N/a	N/a
C_3H_8	0.1	N/a	N/a	0.2	N/a	N/a
C_{4+}	N/a	N/a	N/a	N/a	N/a	N/a
H_2	18.5	15.7	6.9	22.3	18.2	10.3
O_2	3.3	5	52.3	0.79	8.5	4.9
CO	18.8	12.7	5.1	28.1	7.8	12.1
N_2	11.2	20.9	52.3	1.97	34.3	23
HCV MJ/dscm	11.1	13.82	5.79	11.8	9.91	8.64
LCV MJ/dscm	10.1	12.58	5.26	10.6	8.93	7.89
Density (kg/dsm)	1.11	0.97	1.19	1.06	1.05	1.28

Analysed by CRL Energy, Lower-Hutt

Using the data from the analysis, each scenario was up-scaled according to the amount of feedstock available in the Waikato region as highlighted by Sinclair Knight Merz' (SKM) Regional Waste Options Study (Purchas. et al., 2009).

The syngas produced from wet DAF at 600°C achieved the highest autogenesis rating of both pyrolysis and pre-drying for all starting feedstock moisture levels (Tab.7.). The autogenesis assessment showed that the critical moisture content for pyrolysis of the feedstock at 400°C is 15%. The bio-solids product could be optimised by increasing the reaction temperature because reducing the moisture content any lower might have negative effects such as inhibition of water-gas shift reactions.

Tab.7. Process energy autogenesis assessment

	DAF			**Biosolids**		
	Wet DAF	**DAF $_{15\%}$**	**DAF $_{30\%}$**	**Wet BS**	**BS $_{15\%}$**	**BS $_{30\%}$**
	@ 600°C	**@ 400°C**	**@ 400°C**	**@ 600°C**	**@ 400°C**	**@ 400°C**
Amount Processed (tpa)	4,200	4,200	4,200	11,000	11,000	11,000
Pyrolysis charge (kg/hr)	530	178	217	1,389	361	439
Energy requirements*(kJ/hr)	452,156	231,088	287,550	903,389	567,966	682,322
Degree of autogenesis (%)	157	118	84	26	141	80

**Energy requirements refer to the energy demands of pyrolysis and drying*

Economic feasibility assessment

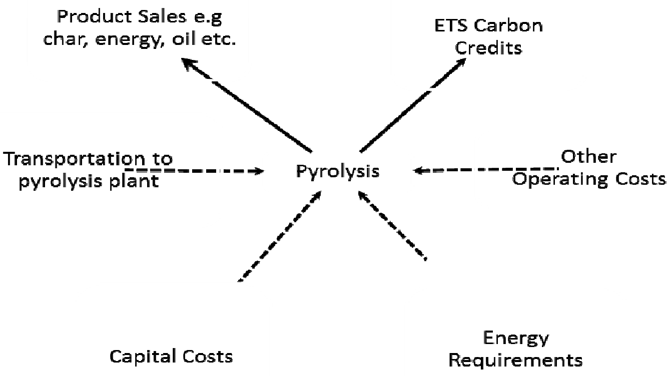


Fig4. Directional schematic of potential revenue streams associated with pyrolysis plant

The economic feasibility of the process was developed with the main plant items costing (MPIC) method using the itemised factorial approach for capital costs. Costing data and Lang factors were obtained from SCENZ (2004), and prices were adjusted for inflation using the capital goods prices index. Where quotes for items were not readily available from the SCENZ pricing handbook, quotes were obtained from industry. Landfilling costs of the feedstock were provided by the respective waste water treatment plants and these included transportation and gate costs. Operating costs were calculated using methods made by (Peters, 1991).

Due to insufficient data on the cost of oil treatment or disposal, the economic model does not consider this as a variable. Carbon credits have not been included either due to the large uncertainty associated with the carbon market.

The economic feasibility of each case was rated using the payback period. The variables that affect the payback period include capital costs, operating costs and profits. This cost comparison compared the economics of scaled-up plant models operating at the same conditions and yields obtained from successful trials.

Tab. 8. Capital costs (in $) for scaled-up pyrolysis plants.

Waste processed	**Biosolids**	**DAF**	**CP**
	11,000tpa	4,200tpa	15,200
Equipment			
Heat pump	1,676	257,954	662,555
Rotary dryer	133,110	86,771	174,369
Rod and ball mill	2,180	176,004	176,004
Feeding auger	2,180	21,308	21,308
Reactor auger	200,627	34,377	60,999
Heating jacket	31,613	31,613	68,286
Flash Drum	10,642	1,319	2,653
Cyclone 1	2,180	1,126	3,202
Cyclone 2	2,180	1,126	3,202
Cyclone 3	200,627	86,406	482,705
Vertical tank	336,071	10,598	11,269
Heat exchanger	10,642	10,974	13,077
Total plant direct cost	1,008,214	719,581	1,679,636
Indirect costs	336,071	239,860	559,878
Fixed capital investment	1,344,286	959,442	2,239,515
Working capital	268,857	191,888	447,903
Total Capital Investment	1,613,143	1,151,331	2,687,418

The capital cost of equipment (Tab. 8) was assumed to be a constant for pre-dried cases due to the negligible change in feedstock volume by with reduced moisture content for the 15-45% range. For simplicity, the feedstock moisture will only affect the operating costs. The annual profits from each case study are negative (total earnings in Tab. 9), proving that the case is economically unfeasible if landfill savings are not included. However, the results suggest that pre-drying the feedstock increases the savings made by diverting the waste from landfill, resulting in an economic process and shortened payback time.

There was not enough revenue generated to offset the operating costs and capital repayments in all cases viewed resulting in negative annual operating cash flows. Thus it was not possible to calculate NPV and IRR for the project. However the landfill disposal savings show how much cheaper the waste management via pyrolysis compared to landfilling.

Considering the landfill diversion savings as a relative profit, with landfilling being the datum, the 15% moisture case study has the quickest individual payback period of 4.6 years for the biosolids case. This is due to the high char production rates and its high degree of autogenesis. There is also a decrease in operating costs with decrease in moisture of the feedstock.

The poultry DAF case does not seem economically favourable even when weighed against landfilling due to a low scale of operation.

Tab. 9. Economic assessment for a scaled-up pyrolysis plant.

	Biosolids	DAF	CP
Landfill Costs ($/yr.)	917,000	567,000	1,484,000
	600°C using wet feedstock		
Operating Costs ($/yr.)	955,984	656,760	2,290,580
Char revenue ($/yr.)	117,847	37,120	154,967
Annual cash flow ($/yr.)	-838,137	-619,640	-2,135,613
Landfill Disposal Savings ($/yr.)	78,863	52,640	297,947
Payback period (yrs.)	9.99	N/A	4.53
	400°C using 30% moisture feedstock		
Operating Costs ($/yr.)	802,622	745,045	2,225,503
Char revenue ($/yr.)	134,310	59,976	194,286
Annual cash flow ($/yr.)	- 668,312	- 685,069	- 2,031,217
Landfill Disposal Savings ($/yr.)	248,688	- 118,069	402,343
Payback period (yrs.)	6.49	-9.75	6.68
	400°C using 15% moisture feedstock		
Operating Costs ($/yr.)	694,903	719,850	2,092,589
Char revenue ($/yr.)	129,326	47,210	176,536
Annual cash flow ($/yr.)	-565,576	-672,641	-1,916,053
Landfill Disposal Savings ($/yr.)	351,424	-105,641	- 432,053
Payback period (yrs.)	4.59	-10.90	-6.22

CONCLUSION & RECOMMENDATIONS

The critical moisture content for the self-sufficient pyrolysis of DAF and the centralised plant at 400°C is 15%. This shows that pre-drying the feedstock has a positive impact on the economics of the process because it reduces the amount of energy required for the pyrolysis reactions.

Despite the wet DAF case at 600°C having the highest degree of autogenesis, the 15% moisture biosolids has the shortest payback period due to lower operating costs and higher char production rates which are a result of the larger scale of operation and higher char yields.

The research verified that the pyrolysis of high moisture organic waste is not economically feasible. However, the success of this project is not solely based on the process economic feasibility. Positive results such as the waste minimisation savings attained from landfill diversion and the reduction of capital and operating costs can also be considered beneficial and this makes pyrolysis a cheaper alternative to landfilling for the sludge.

Future research regarding the economic feasibility assessment should aim to include more variables that might influence the economics of the process. The properties of bio-oil may also be of relevance if producing liquid fuels is an avenue being pursued. Other factors such carbon sequestration value (Emission reduction credits) of the process and the true market value of its products can be investigated to assist in expanding the potential viability.

REFERENCES

ANTAL, M. J. 2003. The Art, Science, and Technology of Charcoal Production.

DOWNIE, A. 2012. *RE: EW Pyrolysis Project Milestone 5 Report Feedback call.* Type to K. SICHONE, H. K., M. LAY.

ELLIOTT, D. C. 2010. *RE: EW PYROLYSIS:Market and Technical Assessment.* Type to BERG, L. V. D.

MCBIRDLE, T. 2011. *RE: EW PYROLYSIS:Market and Technical Assessment.* Type to BERG, L. V. D.

MOHAN, D., PITTMAN, C. U. & STEELE, P. H. 2006. Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy & Fuels,* 20**,** 848-889.

OZCIMEN, D. & KARAOSMANOGLU, F. 2003. Production and characterization of bio-oil and biochar from rapeseed cake.

PERRY, R. H. & GREEN, D. W. (eds.) 1999. *Perry's Chemical Engineers' Handbook.*

PETERS, M. S. 1991. *Plant design and economics for chemical engineers,* New York.

PURCHAS., C., TAMMIK., S., HEWITT., T. & HUTCHINSON., A. 2009. Organic Waste Options Study. *In:* CLARKE., B. & MILTON., N. (eds.).

SERDAR, Y. 2004. Pyrolysis of biomass to produce fuels and chemical feedstocks. *Energy Conversion and Management,* 45**,** 651-671.

SLESSER., M. & LEWIS., C. 1979. *Biological Energy Resources.*