

Optimising anaerobic digestion

Charles Banks

University of Southampton

Evaluating the Potential for Anaerobic Digestion to provide
Energy and Soil amendment
University of Reading
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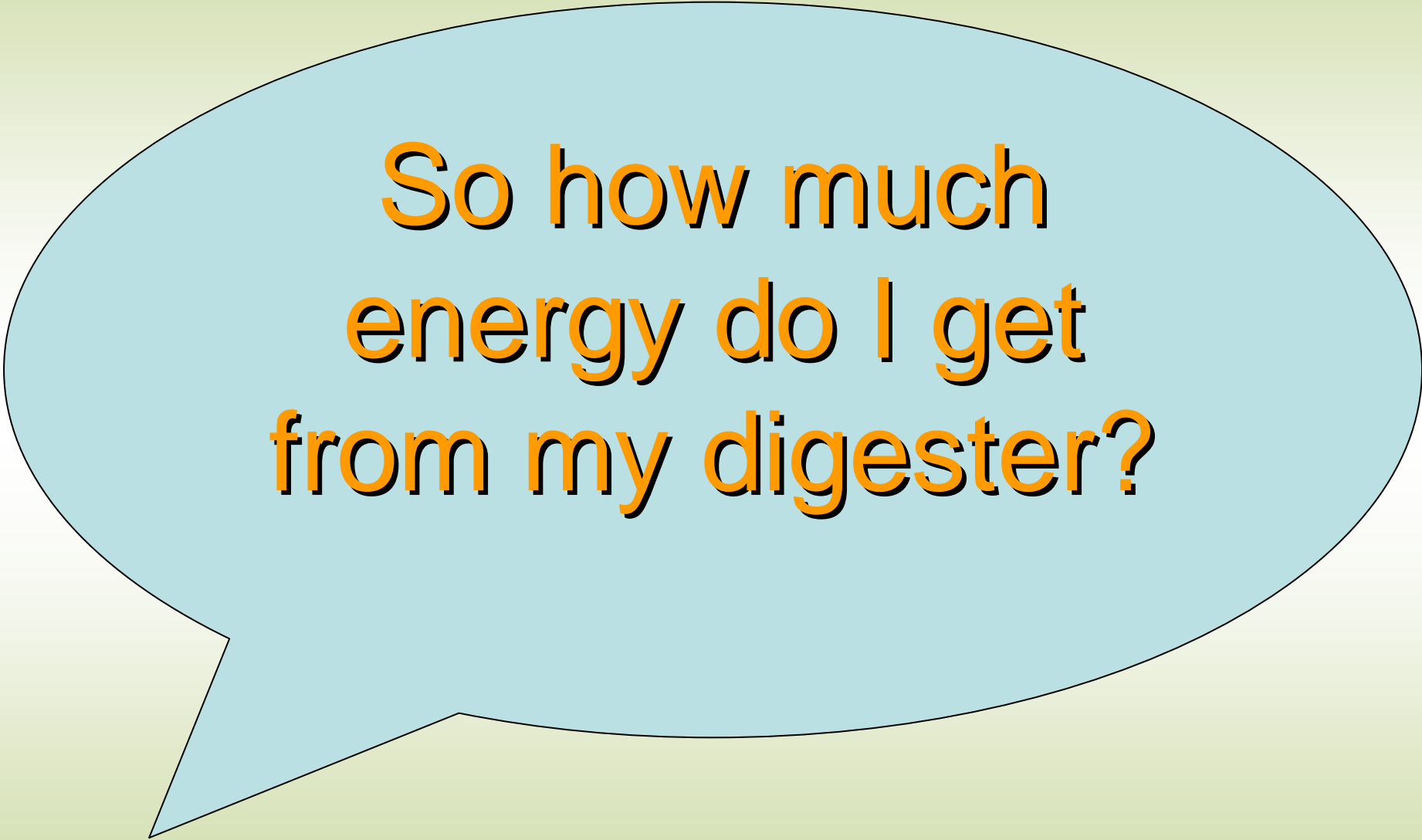
Digestion is an energy producing process

- Up to 75% conversion of substrate into biogas
- Biogas has a methane content of 50-60% (but depends on substrate)
- Biogas typically has a thermal value of about 22 MJ m⁻³



Energy equivalents

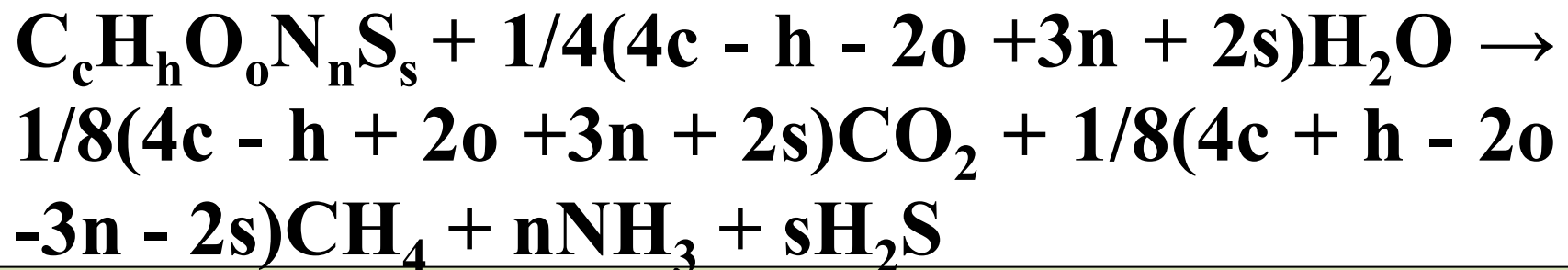
- 1 Watt = 1 joule second⁻¹
 - 1 Wh = 1 x 3600 joules (J)
 - 1 kWh = 3600000 J
 - 1 kWh = 3.6 MJ
 - 22 MJ (1m³ biogas) = 22/3.6 kWh
 - = 6.1 kWh
 - Electrical conversion efficiency = 35%
- Therefore 1m³ biogas = 2.14 kWh (elec)



So how much
energy do I get
from my digester?

First we need to predict or measure the methane content

- First attempt to estimate this theoretically by Buswell (1952), who devised a formula based on chemical composition to predict theoretical yields of component products from digestion



Calculations with Buswell formula

Calculation of gas composition based on percentage of elements by weight				
(residual household waste)				
element	empirical formula		% composition	atomic weight
C	4.17		50	12
H	7.90		7.9	1
O	2.44		39	16
N	0.44		6.18	14
S	0.04		1.12	32
			104.2	
H ₂ O	1.32			
		% in biogas		% in biogas (without N and S)
CO ₂	1.88	40.5%	1.88	45.1%
CH ₄	2.29	49.3%	2.29	54.9%
NH ₃	0.44	9.5%		
H ₂ S	0.04	0.8%		
	4.64	100.0%	4.17	
Buswell equation				

Gas composition from residual waste

- From the Buswell equation
- 55% CH₄
- 45% CO₂

Then we have to estimate
the biogas and energy yield

We can calculate this based on
the carbon content of the waste

1000 kg of residual household waste

Water content = 480 kg

Solids content = 520 kg dry matter
(52%TS)

Organic dry matter = 322 kg dry matter
(32%ODM)

50% carbon content in the ODM

Carbon in 1000kg of wet waste
= $322 \times 50 / 100$ kg C
= 161 kg C

If % of carbon biodegraded is 60%
Then $161 \times 60 / 100 = 96.6$ kg C converted to biogas

From Buswell, 55% CH₄ and 45% CO₂
Weight of methane carbon (CH₄-C)
 $96.6 \times 0.55 = 53.13$ kg C

Weight of methane (CH₄)
 $53.13 \times 16/12$
= 70.88 kg CH₄

1 mol gas at STP = 22.4 litres

16g CH₄ = 22.4 litres

70880g CH₄ = 70880/16 mols
= 4430 mols CH₄

4430 x 22.4 = 99232 litres CH₄
= 99.2 m³ CH₄

1000 kg residual waste

= 99.2 m³ CH₄ + 81.4 m³ CO₂ = 180.6 m³ biogas

Energy value of methane and waste

1 m³ methane = 36 MJ

1 kWh = 3.6 MJ

1 m³ CH₄ = 10 kWh

1 tonne (1000kg) wet waste

99.2 m³CH₄ x 10 kWh m⁻³CH₄
= 992 kWh

Residual solids

Solids content = 520 kg dry matter
(52% TS or DM)

Organic dry matter = 322 kg dry matter
(32% ODM)

Residual non degradable solids = 198 kg

Residual organic solids = $322 \times 40/100$

= 129 kg

+ 198 kg

= 327 kg

The digester solids will be 32.7%

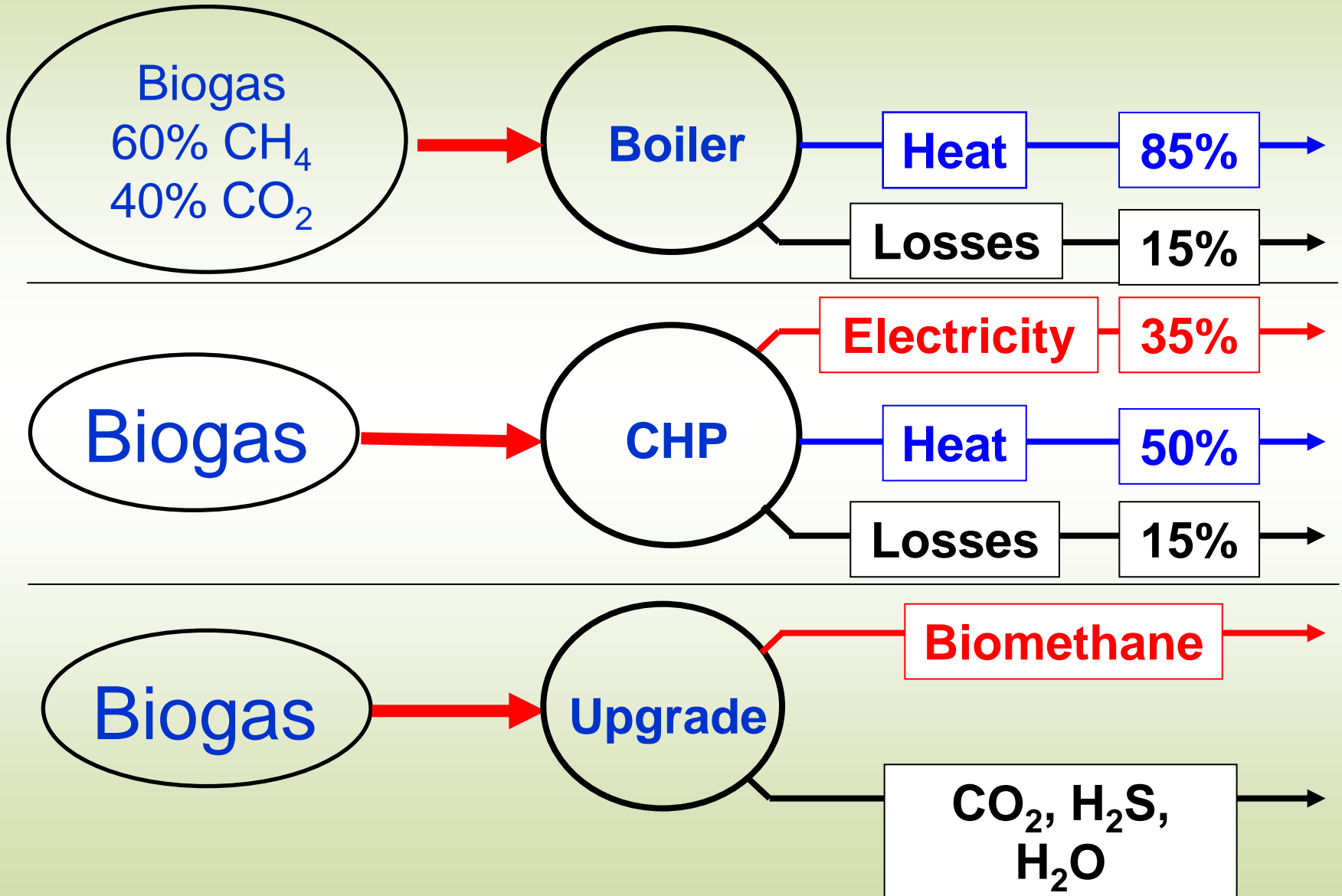
	Digestion													
	1	2				3	4	5		6	7	8	9	10
	Waste input (tonnes)	Proportion dry solids (%)	Proportion of ODM (%)	Proportion of TS available (%)	Proportion fixed carbon (%)	Fixed C (kg)	Proportion converted (%)	Residual dry solids (%)	Proportion to CH4	CH4 carbon (kg)	CH4 (kg)	CH4 (Nm3)	Energy value (MJ)	
Food waste	1.00	28.00	92.00	25.76	52.90	136.27	70.00	9.97	56.00	53.42	71.22	99.71	3571.74	
BMW	1.00	52.00	62.00	32.24	50.00	161.20	60.00	32.66	55.00	53.20	70.93	99.30	3556.90	
Maize	1.00	27.00	92.00	24.84	46.00	114.26	77.00	7.87	60.00	52.79	70.39	98.54	3529.75	
Digestion														
1 Tonnes of wet waste (can be per unit of time e.g. per hour, day, year)														
2 Dry weight of the waste (105 oC to constant weight)														
3 This is the total carbon content derived from elemental or proximate analysis. A value of 0.5 is fairly typical for MSW.														
4 Calculates the available carbon (kg) that could theoretically find its way to methane or carbon dioxide.														
5 This is the factor reflecting the conversion of fixed carbon in the digester (equivalent to the volatile solids destruction). Typical figures 0.3 for a cellulosic waste with high lignin content, 0.7 for a														
6 Depends on the biochemical pathway. 50:50 split if all goes via acetic acid. 60:40 split would reflect 80% via acetoclastic methanogens and 20% via autotrophic methanogens.														
7 Calculates the weight of carbon going to methane														
8 Calculates the weight of methane produced														
9 Calculates the volume of methane at STP														
10 Calculates the energy value of the methane @ 35.82 MJ per Nm3														
11-13 calculates the volume of carbon dioxide														
14 Calculates the total biogas volume at STP														
15 Electrical conversion efficiency														
16 Energy output calculated from the energy available (MJ), the conversion efficiency and the conversion factor of 1kWh = 3.6MJ														
17 Electrical output per Nm3 biogas (typically between 1.75 - 2 kWh depending on the efficiency of conversion)														
18 Residual energy is the heat energy released on combustion of the biogas that has not been converted to electricity														
19 Efficiency of recovery of the residual heat energy (guess a figure!)														
20 Available heat output														

Repeat the calculation for food waste and an energy crop

	Waste input (tonnes)	dry solids (%)	ODM (%)	% conversion	Residual dry solids (%)	CH4 (m3)	Energy value (MJ)	CO2 (m3)	Biogas volume (Nm3)
Food	1	28	92	70	9.97	99.7	3572	78	178
Maize	1	27	92	75	8.37	93	3323	67	160
BMW	1	52	62	60	32.66	99.3	3557	81	180

Conclusion

Uses of biogas



Equivalent fuel values for biomethane

- $1172 \text{ m}^3 \text{ CH}_4 = 1 \text{ TOE}$
- $1 \text{ m}^3 \text{ CH}_4 = 1 \text{ litre diesel fuel}$

Which type of digester?



Instant recognition!

Wet digester



mesophilic

Dry digester



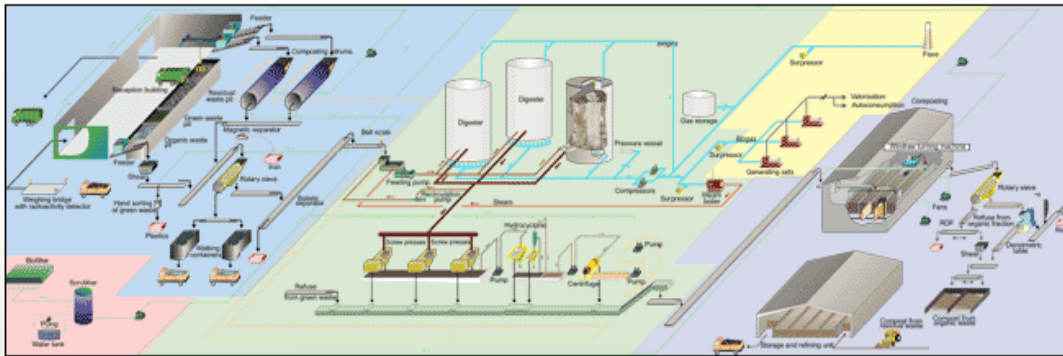
thermophilic



Dry digester

Residual waste treatment

The digester must be part of an integrated package



Grey waste
pre-treatment

Digester

Digester residue
treatment

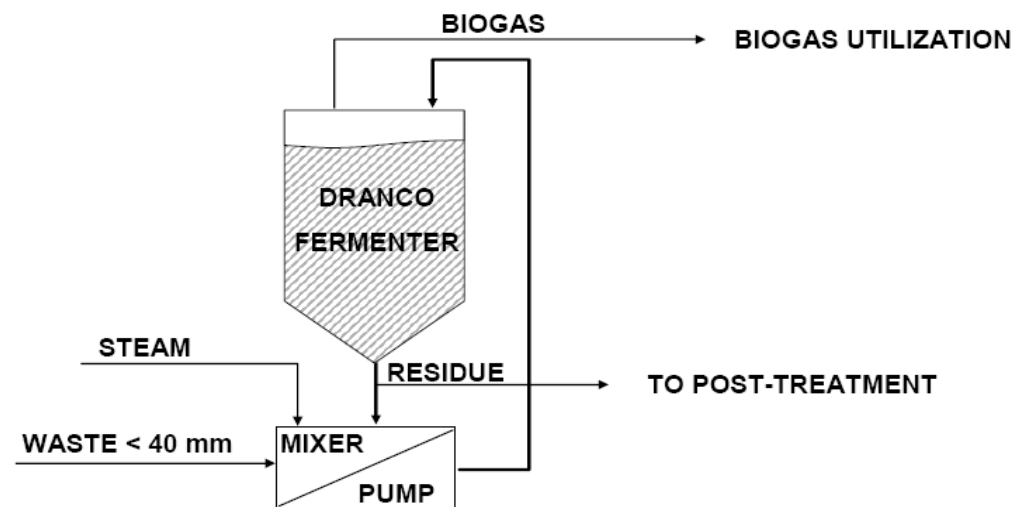
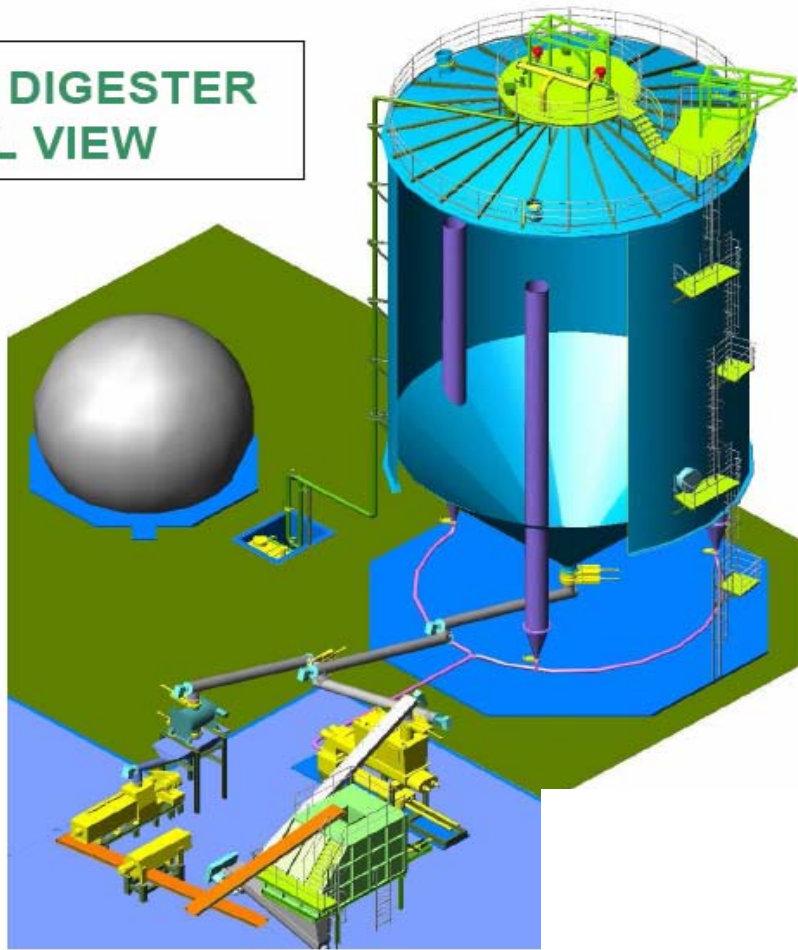
Dry anaerobic digestion for residual waste

DRANCO

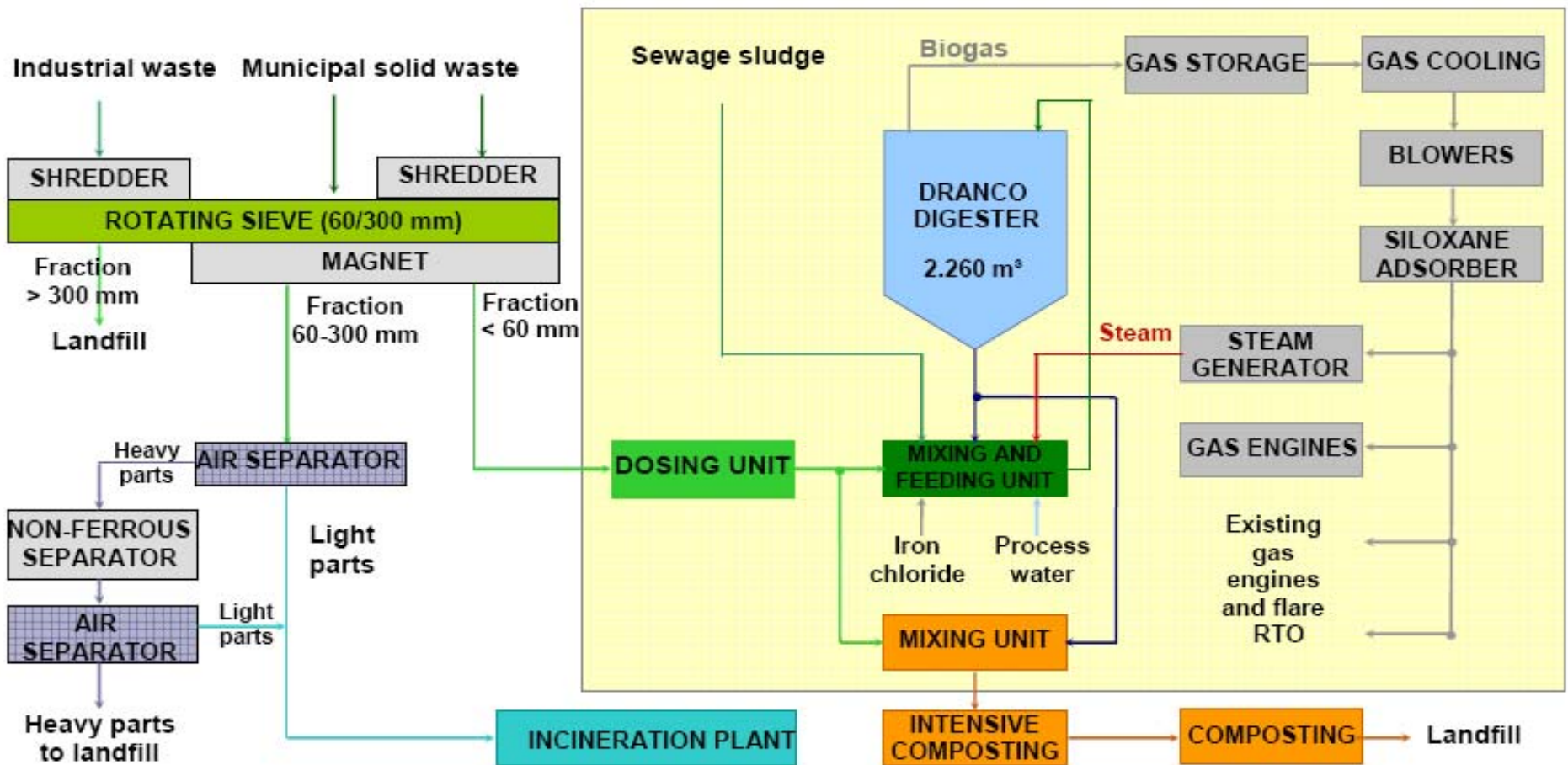
- DRy ANaerobic COMposting
 - Vertical plug flow design
 - Waste at 35-40% TS shredded and sieved (22 mm)
 - Waste fed in at top of reactor with recycled digestate at a ratio 1:6
 - Steam injected to 55 °C (thermophilic)
 - No internal mixing, unloaded at base by helical screw
 - Retention time 2-3 weeks, little or no liquid effluent
 - Biogas yield 5-8 m³ day⁻¹ per m³ reactor



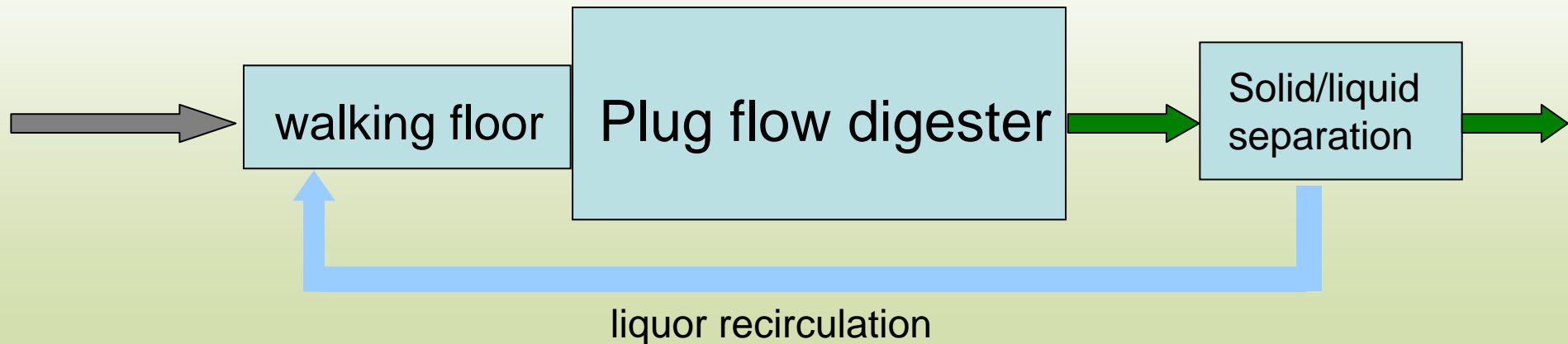
DRANCO DIGESTER GENERAL VIEW



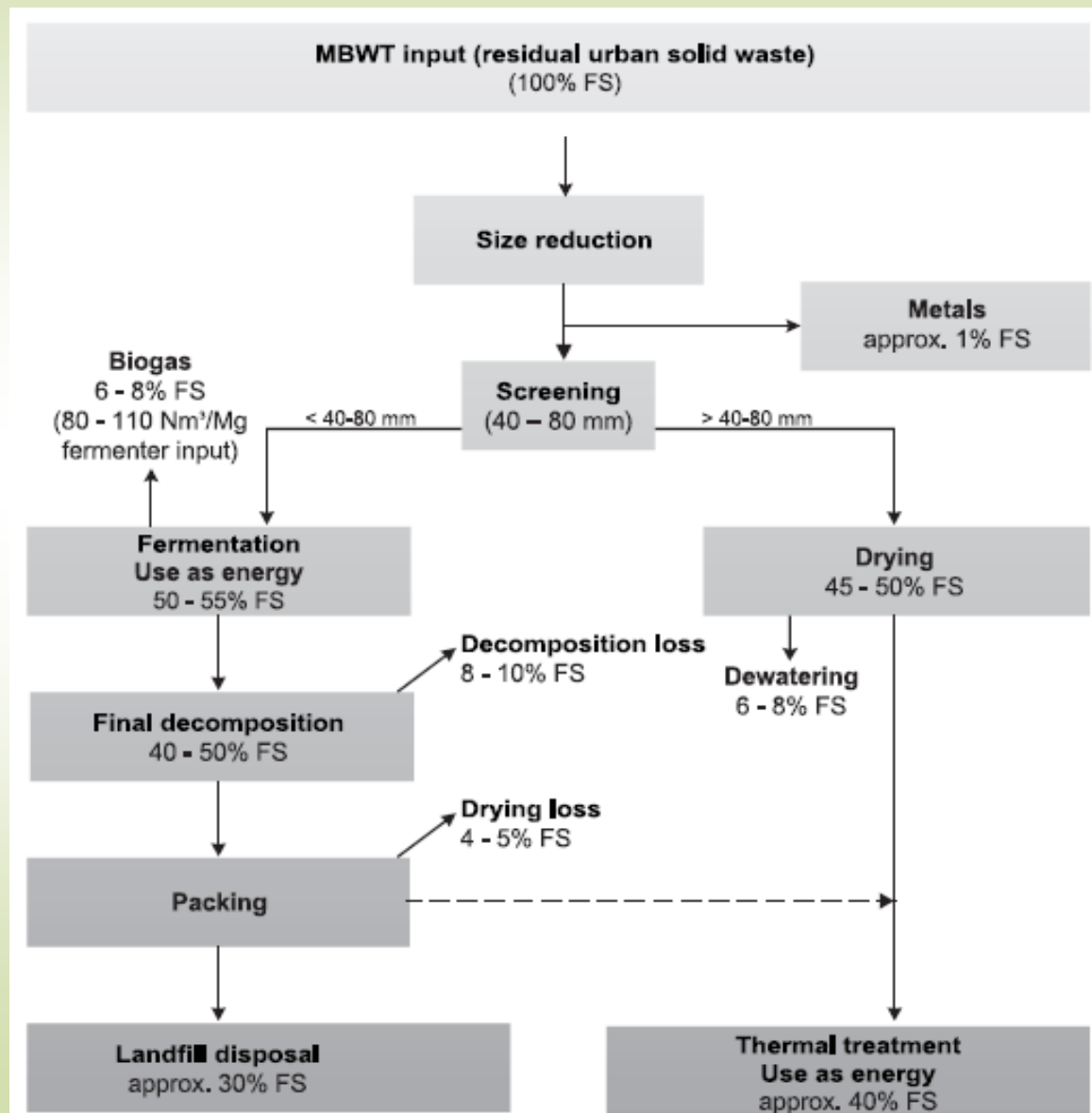
Dranco plant flow diagram on mixed waste



Kompogas



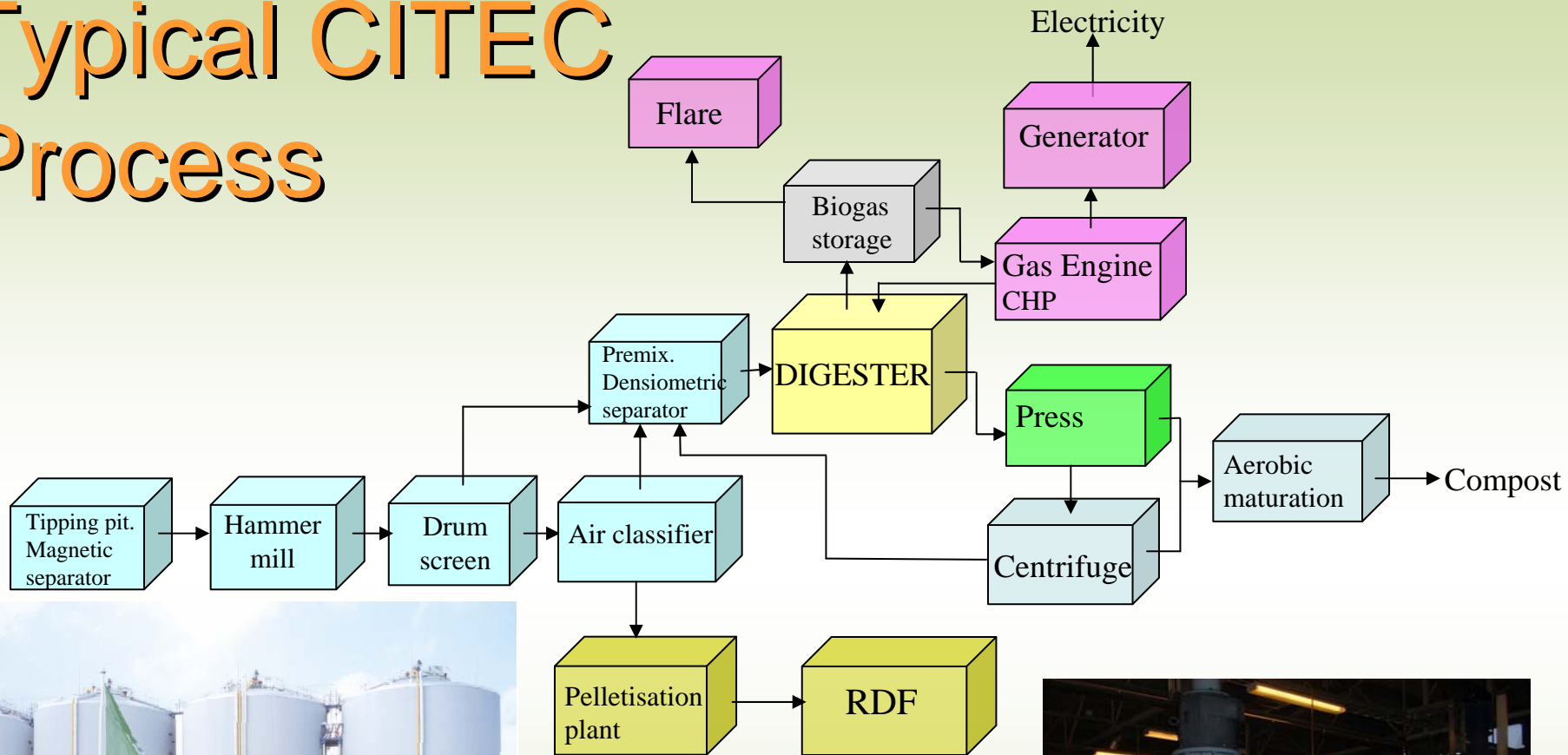
Kompogas MBT process



FS = fresh substance/input

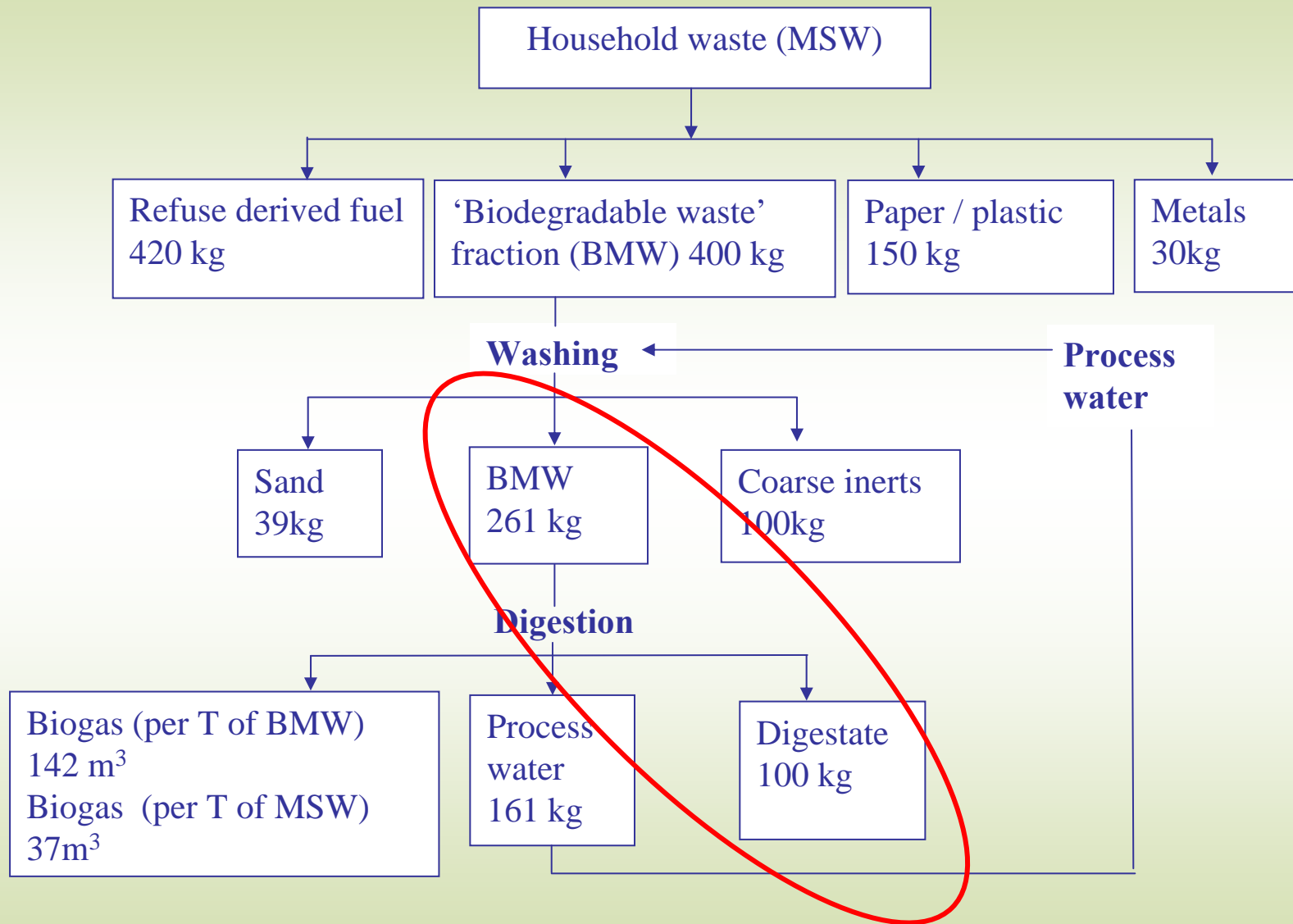
Can we have 'wet'
anaerobic digestion for
residual waste treatment?

Typical CITEC Process



Wet single phase complete mix digester

Mass balance for 1 tonne of waste



Based on a 230,000 tonne/year plant at Vargon, NL

Summary

- The above examples can be described as Mechanical Biological Treatment (MBT) processes in which the biological part is anaerobic
- Designed to operate with residual or only partially kerbside segregated waste
- Operated at high organic loading rates with high volumetric gas production
- In the UK at present the 'compost' from this sort of plant could not be applied to agricultural land
- It could be used for land reclamation, landfill cover, as a means of stabilising waste destined for landfill, or used for further energy recovery through incineration

Digestion of energy crops



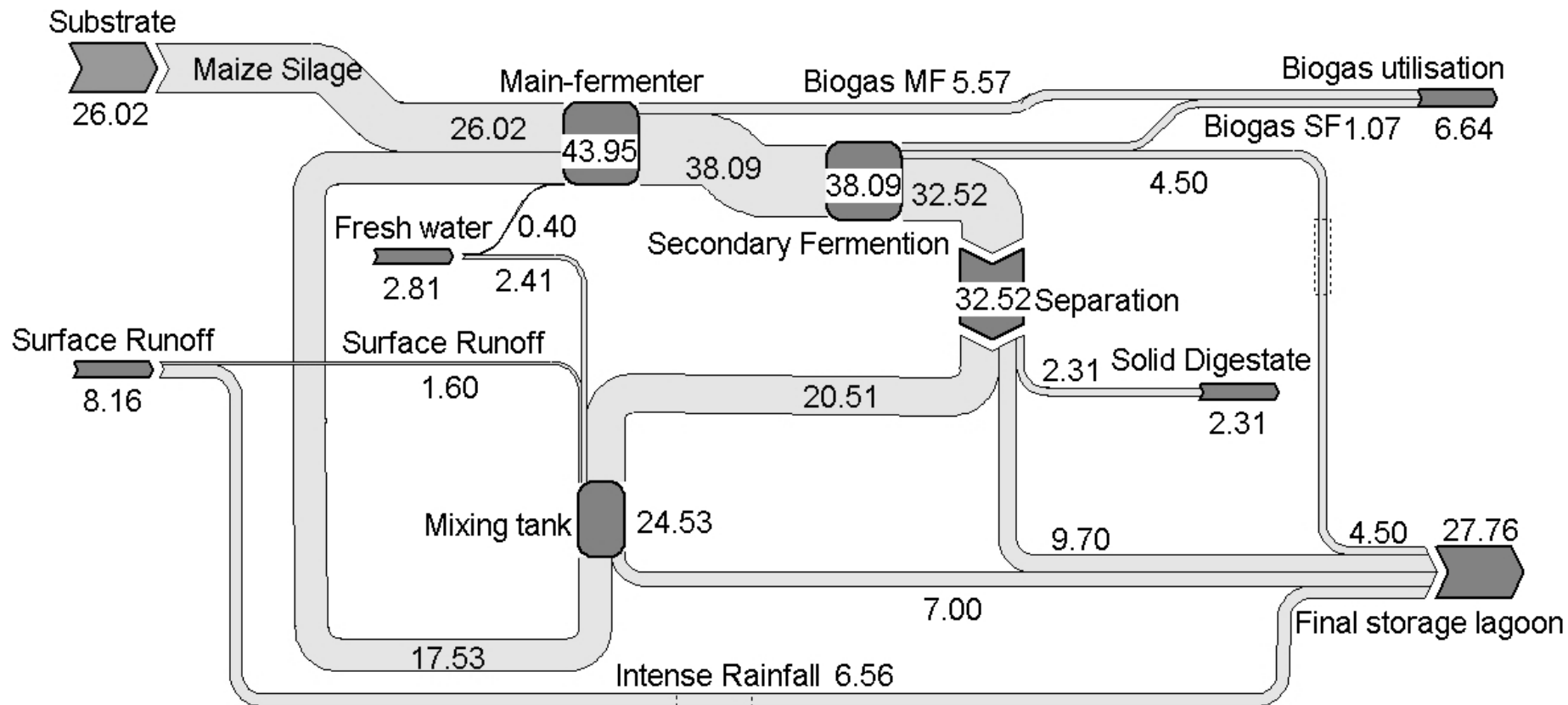
Maize silage and agro wastes



Digestion plant

loading rate (kgVS m ⁻³ d ⁻¹)	HRT * (days)	Volumetric CH ₄ prod. (m ³ CH ₄ m ⁻³)	Specific CH ₄ prod. m ³ CH ₄ (kg ⁻¹ VS _{added})	% VS removal
4.2	82	2.83	0.35	87.4

Average daily mass balance for a full scale digester using maize



Maize digestion (spreadsheet calculation)

	Waste input (tonnes)	dry solids (%)	ODM (%)	% conversion	Residual dry solids (%)	CH4 (m3)	Energy value (MJ)	CO2 (m3)	Biogas volume (Nm3)
Maize	1	27	92	75	8.37	93	3323	67	160

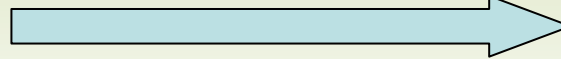
Summary of example digester types and their performance

Process technology supplier/operator	Process Load (Kg TS/m ³ /d)	Process configuration and operating temperature	Biogas m ³ /Tonne waste (wet)	Retention time (Days)
Citec	5.0	Wet complete mix mesophilic	100-150	20
Dranco	11.4	Dry vertical plug flow thermophilic	100-200	25
Kompogas	10.8	Dry horizontal plug flow thermophilic	150 (average)	23
Energy crop	4.2	Wet complete mix mesophilic	210	87
Greenfinch	2.7	Wet complete mix mesophilic	156	100

Optimisation through co-digestion



750 kWh potential energy



375 kWh
surplus heat

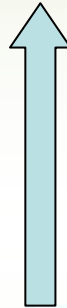
250 kWh
electricity



50 kWh
parasitic
heat



Volumetric gas
production = 0.83 m³ m⁻³



biogas potential 25
m³ / tonne





1710 kWh potential energy



Volumetric gas production = 1.9 m³ m⁻³

50 kWh parasitic heat



biogas potential
160 m³ / tonne



biogas potential
25 m³ / tonne

Type of waste	Source	Amount	Dry matter (volatile solids)		Biogas Potential	Biogas Production
		<i>tons/day</i>	<i>%VS</i>	<i>ton VS</i>	<i>m³CH₄/kgVS</i>	<i>m³CH₄/day</i>
Pig manure	Farms	40	3.48	1.4	0.21	294
MSW	Household	19	25	4.8	0.45	2,160
Total		59		6.2		2,454

Biomass	Amount <i>tons/day</i>	VS%	COD/day	Red %	Methane Production <i>Nm³CH₄/day</i>
Pig manure	30	4	1.2	55	231
Silage	1	25	0.4	65	91
Greased Sludge	5	25	2.8	90	882
Various liquid Industrial wastes	6		1.8	90	567
Total	42		6.2		1,771 to 2,700 <i>Nm³ Biogas</i>

	Pig Manure <i>m³/day</i>	Lipid Waste <i>m³/day</i>	Bentonite Bound oil <i>tons/day</i>	Total Load <i>m³/day</i>	Methane production <i>m³ CH₄/day</i>
Average Daily Production	35	12	3.3	50	1,840

Thanks

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