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Integrated Waste-to-Energy Approach: An Overview

Tsietsi J. Pilusa, Tumisang G. Seodigeng

***Abstract*—**This study evaluates the benefits of advanced waste management practices in unlocking waste-to-energy opportunities within the solid waste industry. The key drivers of sustainable waste management practices, specifically with respect to packaging waste-to-energy technology options are discussed. The success of a waste-to-energy system depends significantly on the appropriateness of available technologies, including those that are well established as well as those that are less so. There are hard and soft interventions to be considered when packaging an integrated waste treatment solution. Technology compatibility with variation in feedstock (waste) quality and quantities remains a key factor. These factors influence the technology reliability in terms of production efficiencies and product consistency, which in turn, drives the supply and demand network. Waste treatment technologies rely on the waste material as feedstock; the feedstock varies in quality and quantities depending on several factors; hence, the technology fails, as a result. It is critical to design an advanced waste treatment technology in an integrated approach to minimize the possibility of technology failure due to unpredictable feedstock quality, quantities, conversion efficiencies, and inconsistent product yield or quality. An integrated waste-to-energy approach offers a secure system design that considers sustainable waste management practices.

***Keywords*—**Emerging markets, evaluation tool, interventions, waste treatment technologies.

I. Introduction

THE use of combustible biomass residues as a substitute of conventional fossil fuels for energy generation has many advantages, including lesser greenhouse gas (GHG) emissions, cost savings, enhanced feedstock supply, waste minimization opportunities as well as growing the local economy. The extent to realise such benefits depends mainly on the source and nature of the biomass feedstock [1]. Hence, it is critical to identify and quantify feedstock availability within a reasonable vicinity to the proposed treatment facility. The feedstock can include waste material such as municipal solid waste, forest residues and wood waste (e.g. saw mill waste, saw dust, bark and wood off-cuts), agricultural residues (harvesting waste) and food processing residues (e.g. nut shells, fruit sludge from juice processing, spoilt fruits and abattoir waste, poultry litter, etc.) The other important aspect to consider is the economic and technical evaluation of biomass resources, pre-treatment, transportation and bulk-storage, as well as life cycle assessment of side stream generated during processing.

The use of waste derived feedstock for energy generation can be analysed using the following critical components:

- Feedstocks variability in quantities and quality impact for their use for energy generation;
- The source and sustainability of the feedstock is key to an energy generation;
- The conversion process by which feedstocks are transformed into the energy form that will be used to generate heating, cooling and electricity;
- Critical parameters for the feedstock are its energy content (calorific value), ash and moisture content, and uniformity. These parameters will influence the cost per unit energy, transportation, processing and bulk-storage costs, as well as the appropriateness of various advanced treatment technologies.
- Bioenergy can be converted into energy through thermal-chemical processes such as combustion, gasification and pyrolysis, or through bio-chemical processes such as anaerobic digestion, composting and nutrient upcycling. Possible alternative technologies for biomass conversion are presented in Fig. 1;
- There is a range of proven advanced waste treatment technologies suitable for dry combustible or biodegradable waste feedstock as a fuel input; a project's economic and success rely on how the design is packaged.

A. Thermochemical Conversion

1) Gasification

Gasification is partial combustion process of solid biomass fuel in an oxygen deficient environment, resulting with formation of a gaseous product (synthesis gas). The gasification reactor can either be of a "fixed bed", "fluidised bed" or "entrained flow" arrangement. Synthesis gas produced from the chemical reaction of multiples chemical reactions between the biomass and oxygen is a mixture of carbon monoxide (CO), hydrogen (H_2), water (H_2O), carbon dioxide (CO_2), char and tar, and it is suitable for use in internal combustion engines, fuel cells and gas turbines.

Typically, higher electrical efficiencies are achieved when synthesis gas is used in gas turbines and fuel cells as opposed to when it is used in steam turbines, however higher gas quality is required for these processes. In most cases co-firing of gasification plants is possible, for example coal and biomass can be gasified in isolation for application in gas turbines for electricity generation.

2) Pyrolysis

Pyrolysis is a sub-division of gasification process which involves thermal cracking of feedstock in absence of oxygen. The partial decomposition of biomass is terminated at a lower temperature (450 °C to 600 °C), resulting in the formation of a liquid fuel oil fraction, solid char and other uncondensed

T. J Pilusa, is with the Vaal University of Technology, Andries Potgieter boulevard, Vanderbijlpark, South Africa (corresponding author, phone: +27 16 950 9655; e-mail: pilusat@ webmail.co.za).

T. G Seodigeng is with the Vaal University of Technology, Andries Potgieter boulevard, Vanderbijlpark, South Africa, (phone: +27 16 950 9655; e-mail: tumisangs@vut.ac.za).

gaseous product. The condensable fraction is transformed into pyrolysis fuel oil which can be applied directly into combustion equipment to generate heat and electricity.

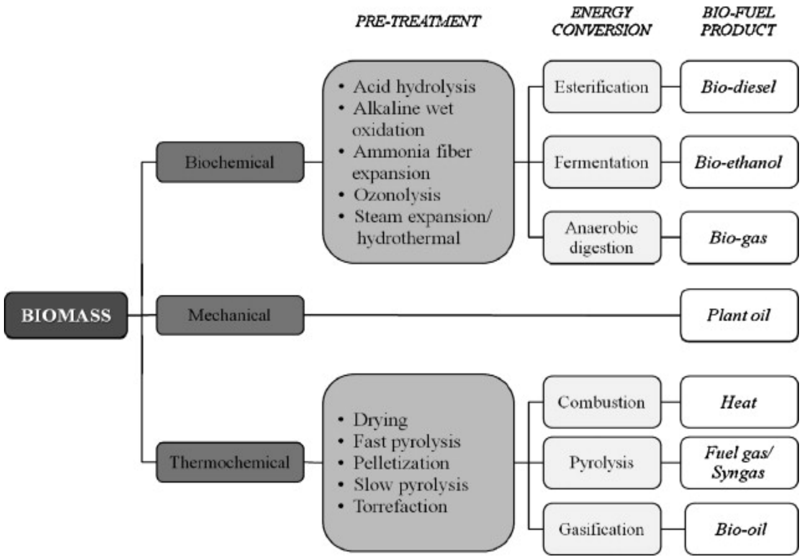

Fig. 1 Alternative waste treatment technologies

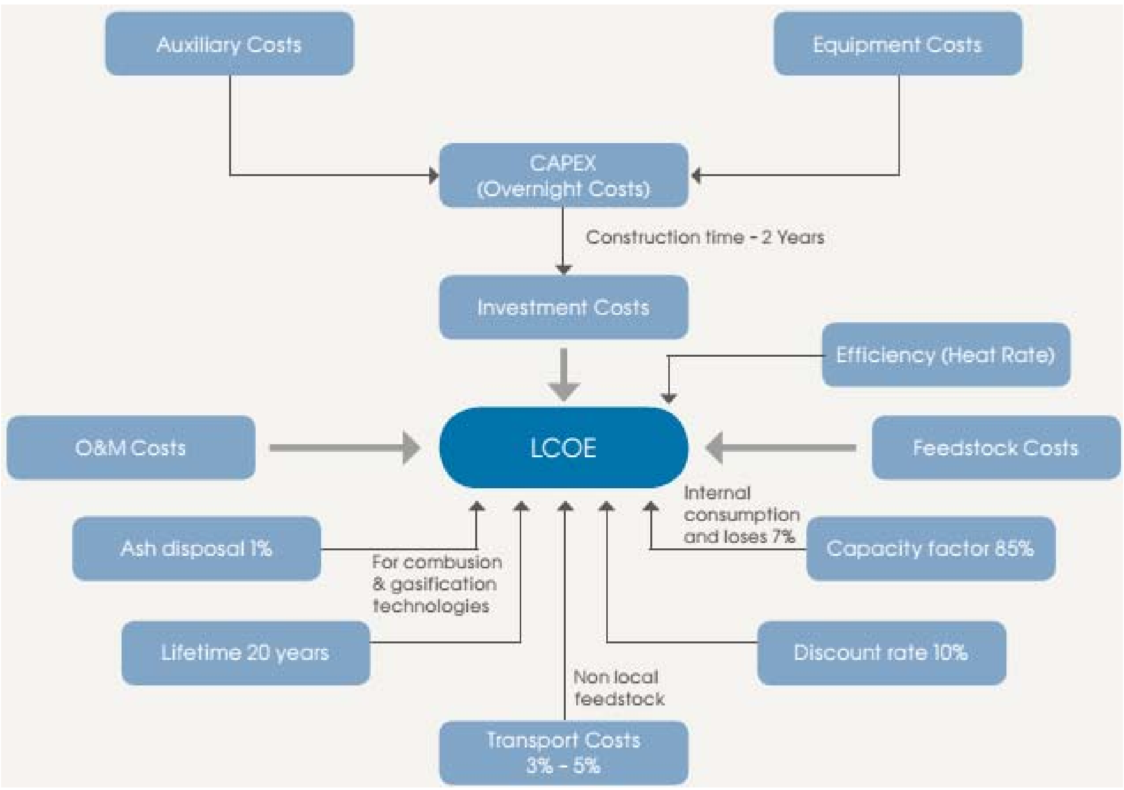

Fig. 2 Input elements of LCOE for biomass powered plant

3) Combustion

Biomass combustion follows the conventional Rankine cycle with biomass being fully oxidised into heat, carbon dioxide and moisture and the heat is directly transferred in a high-pressure boiler to generate steam. This technology offers low electrical efficiencies of about 23% to 25% due to mechanical losses in a steam turbine. The system can also be configured such that the exhaust of the steam turbine can be condensed to produce energy, or used for another useful heating activity such as district heating. Biomass fuel can be used in a direct co-firing system by blending biomass and coal at various mass compositions. It can be co-fired up to 10% of biomass and 80% with extensive pre-treatment of the feedstock such as torrefacation for improved feedstock uniformity.

The levelised cost of electricity (LCOE) of waste-to-energy technologies is another important factor to be considered when assessing waste-to-energy projects. It differs by treatment technology options considered, country and project. It is also based on the biomass resource, operating and capital costs as well as the overall performance efficiency of the alternative treatment technology/combination considered. Fig. 2 shows some important factors influencing the LCOE for a biomass power generation facility.

TABLE I presents the basis for cost estimation of biomass convection systems. This basis provides a high-level cost estimation for some technology options.

TABLE I
TYPICAL COST OF WASTE-TO-ENERGY SYSTEMS [2]

Conversion Technology	Fixed Opex (% of Capex)	Variable Opex (ZAR/MWh) *	**Capex (ZAR/kW)	LCOE (ZAR/kWh)
BFB, CFB	3-4	50-63	43,400	2.75
Gasifiers	3-6	47	63,700	3.50
AD	2-3	53	58,820	1.90

Capex: Capital Investment; **Opex**: Operating cost and Maintenance; **AD**: Anaerobic Digestion System; **BFB**: Bubble Fluidised Bed Technology; **CFB**: Circulating Fluidised Technology; **kW**: kilowatt (Electrical Power); **ZAR**: South African Rand (Currency); **USD**: United States of America Dollar (Currency); **kWh**: kilowatt-hour (Electrical Energy); **MW**: Megawatts (Electrical Power); **LCOE**: Levelised cost of electricity; *(1USD= 12.5 ZAR); ** (Based on feedstock cost of ZAR320-1000/ton forest residue and wood chips).

B. Bio-Chemical Conversion

1) Anaerobic Digestion

Anaerobic digestion is a bio-chemical reaction or process which takes place in almost any biological material that is decomposing and is favoured by temperature, moisture and oxygen deficient environment. In anaerobic digestion, the presence of organic biodegradable compounds promotes biogas production. The biogas is primarily methane (CH_4) and carbon dioxide (CO_2).

The methane formation is primarily influenced by factors such as organic matter and nutrient ratio of the substrate (C: N), other factors playing a role include moisture content, pH and temperature. The anaerobic digestion process is a biological chemical process which is very sensitive to such parameters.

The biogas can be used in combustion equipment as a fuel. It can be upgraded into bio-methane by isolating methane from carbon dioxide fractions in the biogas stream, whereby the methane-rich fraction (biomethane) can be used directly in internal combustion engines, micro-turbines, gas turbines, fuel cells, or it can be upgraded to bio-methane for distribution either through gas network injection or for storage in compressed specialised gas cylinders [3].

Nutrient Up-Cycling

Food waste bio-conversion into nutrient rich products and quality soil enhancers is recently been practiced in South Africa, Italy and other parts of the world. This process utilises the Black Soldier Fly Larvae (BSFL) or *H. illucens* to break down organic substrates of food waste and return nutrients to the soil. BSFL are an excellent source of sustainable protein for animal feed. Based on a study carried out in a plant located in Southern Italy, from 10 tonnes of food waste, the plant produces 300 kg of dried larvae and 3,346 kg of larvae manure. Dried larvae can be used as a source of protein for fishmeal formulation, and larvae manure as a compost equivalent to a commercial fertilizer in quality [4].

This technology is already commercialised on an industrial scale at AgriProtein facility in Cape Town, South Africa and other parts of the world. BSFL feeds on organic waste until it is ready to be harvested to make natural, high protein animal feed products. The fly farms being rolled out will up-cycle up to 91,000 tonnes of organic waste a year, to produce up to 7,000 tonnes of MagMeal™ and MagOil™ [5]. Waste-to-nutrient technology is beginning to get attention, and product price is the key driver to replace fishmeal [6]. Although this technology is not indicated in Fig. 3, it has a great potential for being incorporated in advanced waste treatment technologies.

2) Composting

Composting has been considered as a viable alternative treatment method for organic biodegradable waste material. Composting can be undertaken in various methods such as In-Vessel Composting (IVC), Aerated Windrow Static Piles (AWSP) and Open Windrow Composting (OWC). These procedures can be considered for small to large scale processing and they vary in terms of reaction kinetics, cost and product quality [7], [8].

3) Other Treatment Technologies

There are other treatment technologies which involve conversion of organic waste into refuse derived fuel, in various forms, such as pellets, granules, briquettes, etc., to be used for heat and power generation thorough incineration or gasification, as well as producing high secondary products such as liquid fuels and char via gasification, pyrolysis and Fischer–Tropsch processes [9]–[11]. Biomass conversion technology maturity status is presented in Fig. 3.

II. METHODOLOGY

A. Intervention Matrix

A multi-step method was used as a decision-making tool to formulate waste management scenarios for suitable integrated waste-to-energy solution. This method involved development of 40 generic interventions (shown in Fig. 5) which were ranked according to the waste management hierarchy (Reduce, Reuse, Recycling and Recovery, as shown in Fig. 4).

The interventions were ranked such that, organic biodegradable waste such as garden greens, paper and food waste can be processed. Packaging material such as plastics, glass and metal can be recycled and in some instances the energy value can be recovered from material that has little or no recycling economic value. An integrated approach to advanced waste treatment was developed using a combination of various technologies available to recover or treat waste material as opposed to landfill disposal.

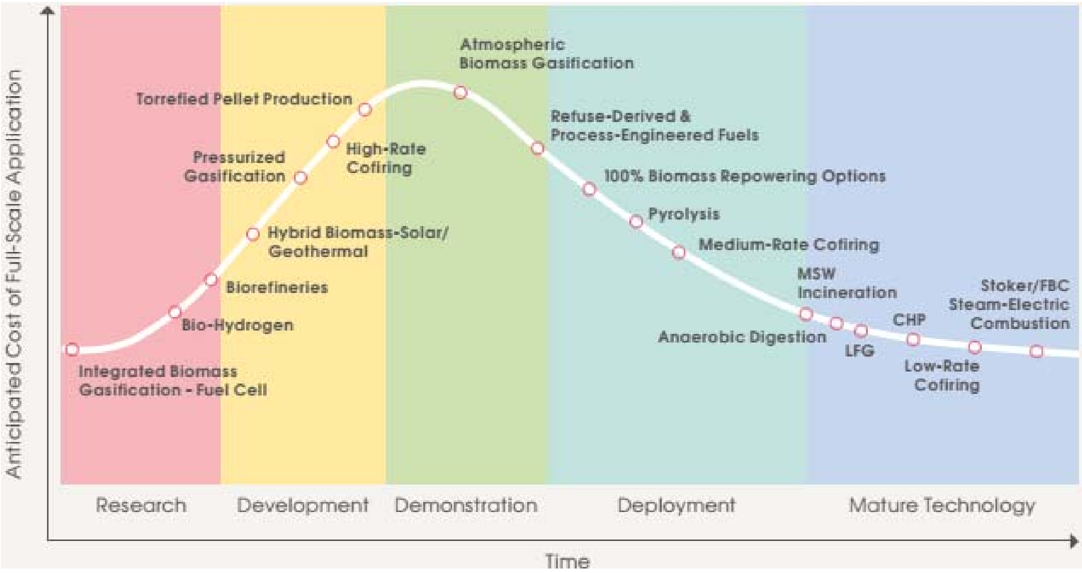

Fig. 3 Biomass treatment technologies maturity status [12]

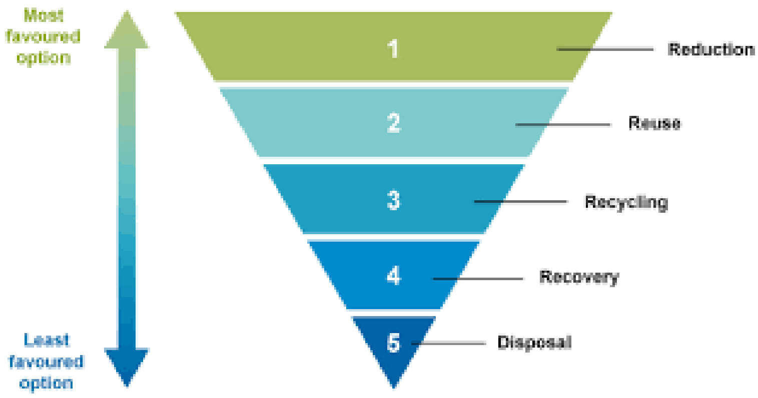

Fig. 4 Waste management hierarchy

B. Integrated Waste Treatment Approach

A high-level process flow diagram of an integrated waste to-energy scenario is presented in Fig. 6. Each processing module can be treated individually; considering that they are more efficient when combined as presented in Fig. 6.

The proposed location of the facility is critical in identifying any major limitations with regards to quantification of available feedstock for waste-to-energy conversion activities. This will influence the material and energy balances required to establish the possible sizes of waste conversion technologies. It is also crucial to obtain representative samples of feedstock for fuel quality assessment. Using the laboratory test results of the representative samples, a material balances can be conducted and design parameters can be obtained to provide details of feedstock quantification and availability for the envisaged term of the project.

It is recommended that an integrated waste-to-energy facility should have an alternative feedstock source, to provide for feedstock supply uncertainties and possible uninterrupted supply form a single source. In cases whereby, municipal solid waste is used as alternative feedstock for waste-to-energy facility, a detailed waste characterisation study is required. The focus waste streams should be considered and should include, (1) Organics – greens, (2) Organics – food waste, and (3) Packaging waste.

Geographic and climate aspects should also be taken into consideration. This can be done by taking a critical look at the waste stream composition derived from a waste characterisation study, the output/product requirements and the key driving factors such as affordability, institutional capacity and feasibility amongst others.

C. System Interventions

System interventions can then be formulated by combining individual interventions to address a specific identified waste stream, such as organic food waste, organic greens and packaging. These system interventions also highlight the inter dependencies between each individual intervention, as shown in Fig. 7.

No.	Hierarchy	Generic intervention	Circular economy	Lead Time	Point in Value Chain	Interventio Size
1	1. Reduction	Separation-at-Source: Organic Waste Focus	Yes	None	Source	Household
2	1. Reduction	Separation-at-Source: Packaging Waste Focus	Yes	None	Source	Household
3	1. Reduction	Alternative Collection Methods (non-mechanised)	Yes	Short	Collection	Large
4	1. Reduction	Collection and Transfer Optimisation	No	Short	Collection	Large
5	2. Reuse	Buy-Back Centre (BBC)	Yes	Short	Local Treatment	Medium
6	2. Reuse	Resource Management Business Park and Incubator	Yes	Med	Final Treatment	Medium
7	3. Composting	Home Composting	Yes	Short	Source	Household
8	3. Composting	Commercial Containerised Composting	Yes	Short	Local Treatment	Small
9	3. Composting	Decentralised Open Windrow Composting	Yes	Short	Local Treatment	Medium
10	3. Composting	Centralised Commercial Nutrient Up-cycling	Yes	Med	Final Treatment	Large
11	3. Composting	Centralised Open-Windrow Composting	No	Short	Final Treatment	Large
12	3. Composting	Centralised In-Vessel Composting	No	Med	Final Treatment	Medium
13	3. Recycling	On-Site Separation of Commercial / Industrial Waste	Yes	Short	Source	Small
14	3. Recycling	Decentralised Segregated Material Public Drop-Off	Yes	Short	Source	Medium
15	3. Recycling	Decentralised (Peri-Urban) Material Recovery Facility (MRF)	Yes	Short	Local Treatment	Medium
16	3. Recycling	Decentralised Greens Drop-Offs	Maybe	Short	Collection	Medium
17	3. Recycling	Decentralised Greens Chipping	Maybe	Short	Local Treatment	Medium
18	3. Recycling	Decentralised Material Management Park	Yes	Short	Local Treatment	Medium
19	3. Recycling	Decentralised Pre-treatment	Maybe	Med	Local Treatment	Medium
20	3. Recycling	Centralised Greens Drop-Off and Chipping	Maybe	Short	Pre-Treatment	Medium
21	3. Recycling	Centralised Clean Material Recovery Facility (MRF)	Yes	Med	Treatment	Large
22	3. Recycling	Centralised Biomass (Organics) Pre-Treatment	Maybe	Med	Pre-Treatment	Large
23	3. Recycling	Centralised Dirty Material Recovery Facility (MRF)	No	Med	Final Treatment	Large
24	3. Recycling	Commercial Used Oil to Bio-Diesel	Yes	Short	Local Treatment	Small
25	4. Recovery	Landfill Gas Extraction and Energy Generation	No	Med	Final Treatment	Medium
26	4. Recovery	Builders' Rubble Crushing and Reuse	Yes	Short	Final Treatment	Large
27	4. Recovery	Localised Rural Anaerobic Digestion (AD)	Yes	Short	Local Treatment	Small
28	4. Recovery	On-Site Commercial Anaerobic Digestion (AD)	Yes	Med	Source	Small
29	4. Recovery	Decentralised Anaerobic Digestion (AD)	Yes	Med	Local Treatment	Medium
30	4. Recovery	Centralised Anaerobic Digestion (AD)	No	Long	Final Treatment	Large
31	4. Recovery	Centralised Mechanical Biological Treatment (MBT)	No	Long	Pre-Treatment	Large
32	4. Recovery	Decentralised Commercial Pyrolysis	No	Long	Local Treatment	Medium
33	4. Recovery	Centralised Pyrolysis	No	Long	Final Treatment	Large
34	4. Recovery	Centralised Gasification	No	Long	Final Treatment	Large
35	4. Recovery	Biochar Production	No	Long	Final Treatment	Large
36	4. Recovery	Refuse Derived Fuel (RDF)	No	Long	Final Treatment	Large
37	4. Recovery	Incineration (Direct Combustion)	No	Long	Final Treatment	Large
38	5. Disposal	Refuse Transfer Station (RTS)	No	Med	Collection	Medium
39	5. Disposal	Landfill Upgrading	No	Long	Disposal	Large
40	5. Disposal	Regional Landfill	No	Long	Disposal	Large

Fig. 5 List of waste management interventions

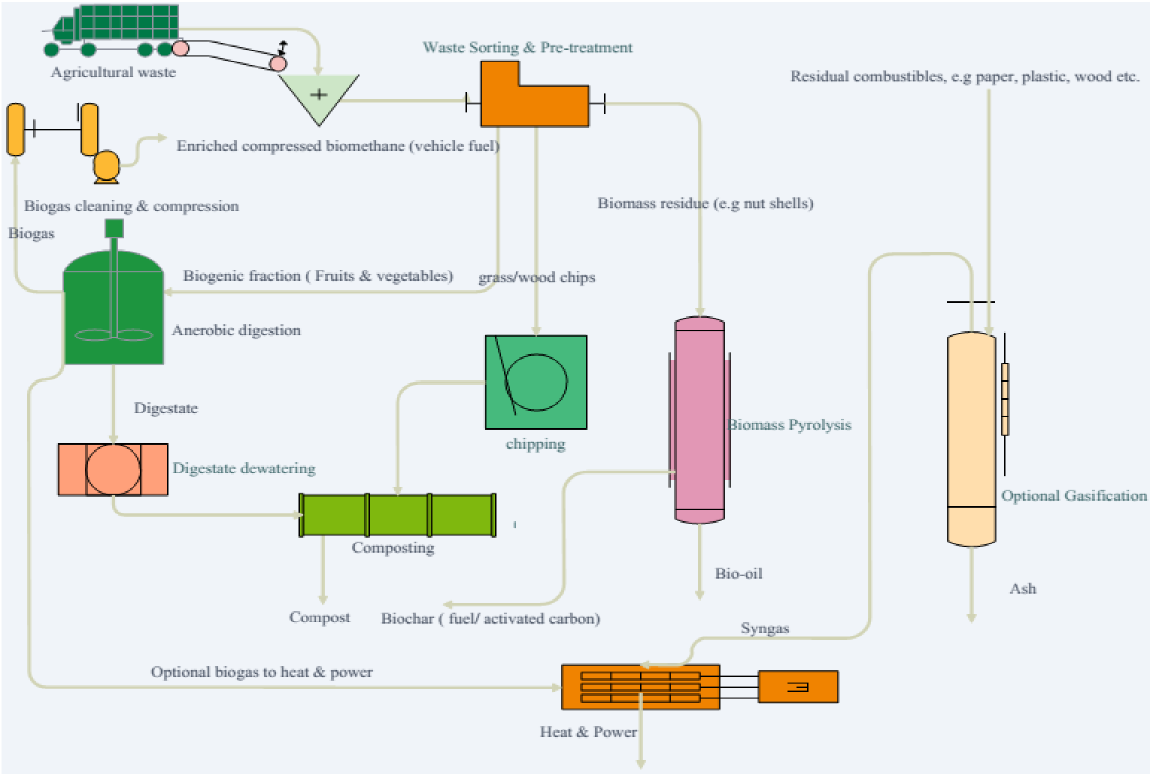

Fig. 6 Process flow of the integrated waste-to-energy scenario

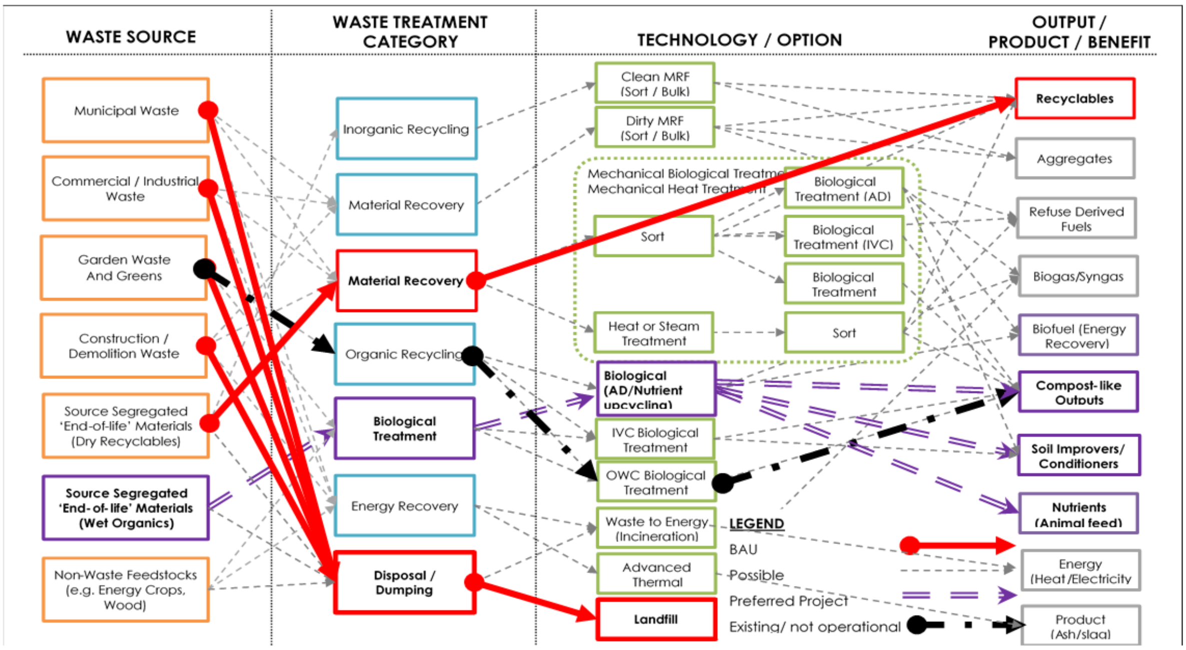

Fig. 7 Inter-dependencies between individual interventions

System interventions for all three waste streams can be linked together in order to formulate a set of scenarios suitable for each source. Each of the solid red lines represents the conventional waste management practices, whereas the dotted lines represent the sustainable waste management approach and opportunities.

D.Scenario Formulation

System interventions for all three waste streams can be linked together in order to formulate a set of scenarios for each waste source. The formulated scenario takes in to consideration the location, stage, scale and affordability. An example of the formulated scenario is illustrated in the process flow diagram shown in Fig. 8.

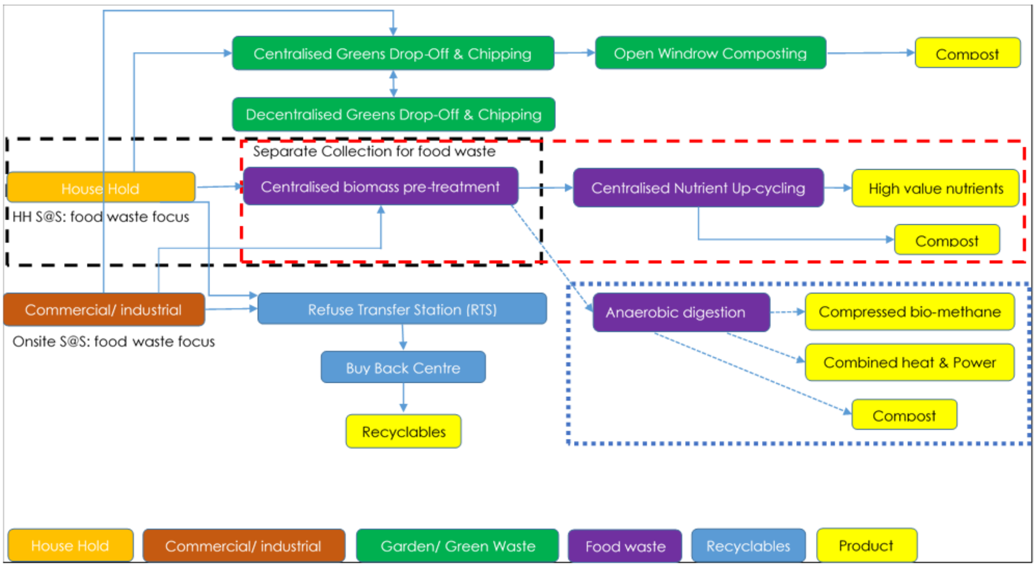

Fig. 8 An Example of formulated waste management scenario

E. Consolidated Evaluation Approach

In order to highlight a "preferred" scenario from the selected comparative scenario evaluations, the unique Triple 'A' Consolidated Evaluation Method can be used. This method focuses on three key criteria of an Advanced Integrated Solid Waste Management (AISWM) scenario or project, which addresses, (1) how appropriate the selected technology option is, (2) whether the selected technology option applicable, and (3) if it is affordable. In the context of alternative waste management, each of these three terms was defined as follows:

The "**Appropriate**" consolidated evaluation criterion answers the key question, "Is the scenario technically (stage and scale, technical complexity, utilities and land usage, etc.) and environmentally (carbon emissions mitigation, contamination, etc.) viable for the local context and conditions? Appropriateness relies on the professional judgement, and empirical assessments of the specialists, by utilising all the information pertinent to the individual intervention(s), system intervention(s) and scenario(s). The "Appropriate" criterion is informed solely by the Technical and Environmental specialist evaluations.

The "**Applicable**" consolidated criterion answers the key question, "Is the scenario legitimate and institutionally compatible with the current local, district and national policy and regulatory frameworks, or can these frameworks be readily adjusted to improve legitimacy and compatibility Applicability is a jurisdictional determination, and assesses the local institutional capacity and structural requirements necessary to facilitate AISWM. The "Applicable" criterion is informed solely by the Institutional and Legal specialist evaluations.

The "**Affordable**" consolidated criterion answers the key question, "Are the full scenario savings (benefits) greater than the full scenario costs?" Affordability assesses the savings less costs to government, on a scenario-wide net present value (NPV) basis. The financial assessments can be structured to determine, inter alia, the subsidy required for the private sector to deliver the selected AISWM intervention(s). The Affordable criterion is informed solely by the financial specialist evaluation.

III. Discussions

A. Scoring and Weighting Mechanisms

A simplified scoring approach can be applied throughout the preceding specialist evaluations, which ultimately score each scenario as Preferred (3 points), Less Preferred (2), and Least Preferred (1 point).

B. Technical and Environmental Evaluation

The method for technical evaluation includes the detailing of the formulated scenarios for each source. In order to accurately evaluate the landfill diversion potential as well as environmental and financial components of each scenario, the formulated system interventions were detailed with credible information which is of a representative scale, and at a particular stage in the source waste management process. Furthermore, having determined the technical complexity and maturity of the interventions, it was envisaged that the private sector will deliver the interventions as part of the selected scenarios.

The intergovernmental panel for climate change (IPCC) Waste Model was used to compare previous evaluations with current evaluations as well as to align with international best practice. The IPCC Waste Model has been shown to provide 'fair results compared to field measurements' in other studies Wangyao et al. [13], [14], considering the climatic conditions associated with the area as well as the variation of degradation rates between seasons. The same methodology has been applied (First Order Decay method), is widely used and internationally recognised. This method takes into consideration long-term methane generated at the landfill.

C. Institutional and Legal Evaluation

Certain waste activities will, or may require, lengthy additional, and often costly, steps prior to implementation (e.g. waste license, atmospheric emission license, environmental impact assessment) and these should be borne in mind when deciding on a scenario. In addition, possible larger ongoing or periodic costs (e.g. monitoring) imposed by legal requirements must be considered.

Deciding which scenario is preferred, from a legal perspective, is inherently difficult, unless there are clearly identified legal challenges (e.g. where the law currently does not allow a proposed option, is unclear, or where a possible conflict may arise with other legislation). As such the ranking is, to a degree, subjective. Choosing the preferred option, in terms of legal requirements, may therefore be one involving the least formalities (e.g. one not needing an environmental authorisation, license or permit).

D. Financial Evaluation

The selected scenarios were allocated a score of 1, 2 or 3, respectively, for each of the four financial categories. A weighting was assigned to each of the categories based on the category's perceived importance and a weighted score was calculated per category and totalled to calculate the total score per scenario.

E. AAA Evaluation

Each of the scores for the specialist evaluations are assigned a weighting in their respective sub-groups, i.e. the technical evaluation has a weighting of 50% of the total "Appropriate" sub-group. Moreover, each of the sub-groups are assigned a weighting for the total consolidated evaluation, i.e. the "Appropriate" sub-group is assigned a weighting of 25%. An example of the evaluation is presented in Fig. 9.

F. Analysis of the Integrated Waste-to-Energy Scenario

An example of integrated waste-to-energy scenario is presented in Fig. 6 based on a case-study. The mass balance summary of the proposed integrated waste-to-energy scenario is presented in Fig. 10. This specific case study assumes that 70,748 and 8,500 tonnes per annum of biomass and organic (food and abattoir) waste is available for power and gas fuel generation, respectively. The process shows other side streams that could be produced from the combined processes.

TRIPLE 'A' CRITERIA	TECHNICAL	ENVIRONMENTAL	INSTITUTIONAL	LEGAL	FINANCIAL	TOTAL WEIGHTING
APPROPRIATE	50%	50%	-	-	-	25%
APPLICABLE	-	-	50%	50%	-	25%
AFFORDABLE	-	-	-	-	100%	50%

TRIPLE 'A' CRITERIA	TECHNICAL			ENVIRONMENTAL			INSTITUTIONAL			LEGAL			FINANCIAL			WEIGHTING TABLE		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
APPROPRIATE	3	2	1	3	1	2										3	1.5	1.5
APPLICABLE							3	2	1	3	2	1				3	2	1
AFFORDABLE													3	2	1	3	2	1
													TOTAL SCORE			9.0	5.5	3.5

Fig. 9 Weighting assigned to triple 'A' sub-groups and total consolidated evaluation.

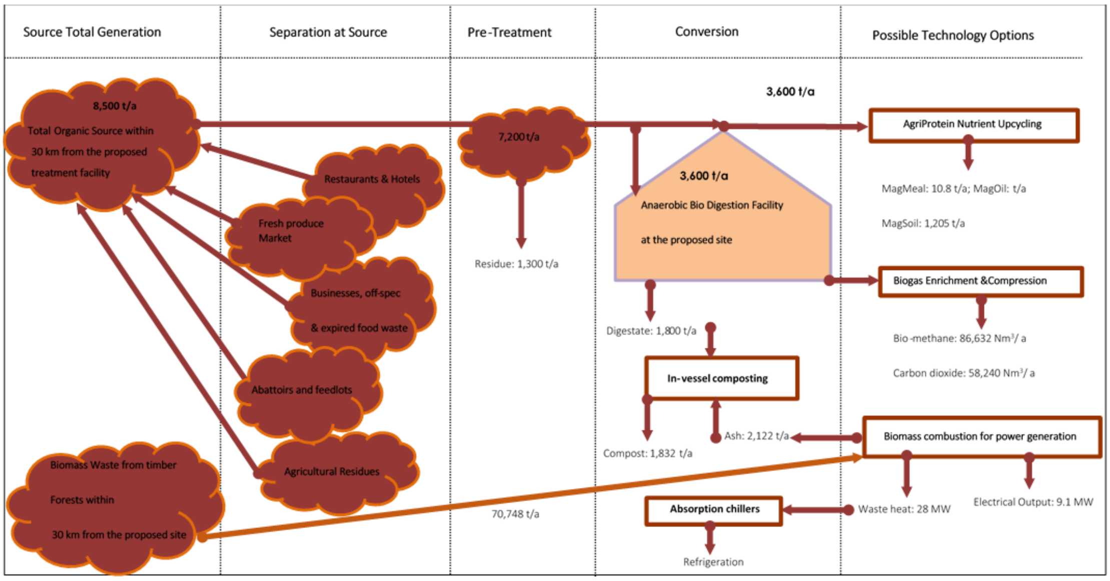

Fig. 10 Simplified diagram of integrated waste-to-energy scenario

G.Biomass to Electricity

The case study considered assumed a total biomass feedstock potential of 70,748 tonnes per annum, which can supply a 9.1 MW electrical output biomass power plant facility. Due to low electrical efficiency (~25%) of the technology proposed, Jenkins et al. [15], it is recommended that the excess waste heat (~28 MW) generated during combustion of biomass fuel is recovered for other possible uses, e.g. district cooling/ heating. Technologies such as fluidised bed and gasification could be considered. This technology would require a capital investment of approximately ZAR 395mil (~US$31.6 mil) with fixed operating cost, variable operating cost and levelised cost of electricity of ZAR15.8 mil/annum (~US$1.2mil/annum), R4.6mil/annum (~US$368,000) and R2.75/kWh (~US$0.22/kWh), respectively, based on cost assumptions presented in

TABLE I.

Approximately 3 wt.% of the biomass combusted will end-up as ash which could be used as a bulking agent for the liquid digestate from an anaerobic digester which could be used as a soil enhancer or processed via an in-vessel composting process to generate compost.

H.Nutrient-Upcycling

It is assumed that a minimum of 10 tonnes per day is available for a commercial scale waste to nutrient plant. This material includes pre-processed food waste and agricultural residues such as fruit processing waste (pulp) that can be used for the nutrient upcycling process. It is common practice in South Africa to feed animals with food processing by-product, due to its nutritional composition.

In livestock farming, feed accounts for 70-80% of the operational cost of feedlotting. The high feed cost in the feedlot system, predominantly protein supplements, are suggestions of the need to consider alternate low-cost feed which can provide nutrient needs of livestock [16]. The nutrient upcycling process can be used to produce high quality MagSoil™ (1,205 tonnes per annum), Magmeal™ (10.8 tonnes per annum) and MagOil™.

I. Anaerobic Digestion

Based on the assumed theoretical feedstock quality and assumption that 10 tonnes per day of fruit, vegetable and harvesting waste is available. The biomethane potential (BMP) analysis is typically undertaken to assess the degree of bio-degradability of sampled organic waste as confirmation. However, for the purposes of this article, it is theoretically assumed that the feedstock of this nature can generate 18.2 m^3/h of biogas with 59.5% methane content for 10 tonnes of feedstock [17]. This is equivalent to 86,632 Nm^3 per annum biomethane (72,193 diesel litre equivalent per annum) and 58,240 Nm^3/year beverage grade carbon dioxide. Biomethane with no less than 32.3 MJ/m^3 heating value can be used in many natural gas combined heat and power (CHP) engines with slight or no alteration. However, most original equipment manufacturers of compressed natural gas (CNG) vehicles require a at least 34 MJ/Nm^3.

Beverage grade carbon dioxide can sell for up to ZAR 0.6/Nm^3 (~24US$/ton). Digestate can be composted and used as soil enhancer, typically 50 wt.% of digester feed [18]. Approximately 46.7 wt.% of the in-vessel composting feed is lost during aerobic biodegradation process [19]. It is assumed that biomethane has calorific value of 10.64 kWh/Nm^3 [20] and that 50 wt. % of feed materials can be composted and sold to the farmers at ZAR 300/ton (~US $ 24/ton). A fraction of the feed can be used for nutrient up-cycling process, to produce high quality MagSoil™, Magmeal™ and MagOil™.

The estimated capital investment for a 10 tonnes/day bio digestion facility with gas cleaning and compression system will be ZAR 8.5 million (~ US$ 680,000).

IV. Conclusion

The “AAA” approach developed and presented in this article is an innovative and simple decision-making tool which uses an advanced platform for holistic evaluating waste management scenarios. The scenarios can be easily formulated based on the selection of short- and medium-term interventions that will inform strategic planning and waste management policies while establishing and improving the IWMS, maximising carbon emission reductions and boosting jobs in the municipality. It will also assist project developers to make technically informed engagements with private technology providers, consulting firms and other relevant stakeholders.

The case study assessed, based on the integrated waste-to-energy approach, and outlined opportunities that can be created by combining appropriate technology options when developing waste treatment options. This integrated facility could be operated as a combined biomass to electricity, nutrient upcycling and organic waste to fuel gas. The technology combination approach, eliminates the risk of possible technology failure, mainly anaerobic digestion due the seasonal variability of feedstock. It also makes it possible to derive other value chain side streams from the facility, these streams include high quality animal feed, commercial grade carbon dioxide and high-quality soil enhancer. Waste heat from the biomass combustion process can also be recovered and used for district cooling/heating which will result in the overall increased facility efficiency. There is also a need to upgrade the existing waste management infrastructure to allow long-term quantification, diversion and bulking of organic biomass material from various sources including agro-processing waste and municipal solid waste which could result in increased capacity of the project or longer life span of the projects.

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REFERENCES

[1] IRENA (2012). Renewable energy technologies: cost analysis series. International Renewable Energy Agency: Biomass for power generation. Vol 1-Power Sector issue 1/5.
[2] Mott MacDonald (2011), Costs of Low-Carbon Generation Technologies. Committee on Climate Change, London.
[3] Eltrop L (2016). Modern Technologies and Pathways for the Energetic Use of Biomass, Workshop 6-9 September 2016, Resolution Circles, Johannesburg, South Africa.
[4] Salomone R Saija, G., Mondello, G., Giannotti., Fasul, S., Savastano, D (2017). Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using Hermetia illucens, *Journal of Cleaner Production* 140,890-905.
[5] Venter, I (2017) Fly farm venture AgriProtein signs deal for 25 fly farms a year. *Engineering News*. Creamer Media.
[6] AgriProtein (2017) http://agriprotein.com/our-products/ date accessed: 15/09/17.
[7] Makan A (2015) Windrow co-composting of natural casings waste with sheep manure and dead leaves. *Waste Management 42*, 17-22.
[8] Moh Y, Manaf LA (2017) Solid waste management transformation and future challenges of source separation and recycling practice in Malaysia. Resource, *Conservation and Recycling* 116, 1-14.
[9] Aspray TJ, Dimambro ME, Wallace P, Howell G, Frederickson J (2016) Static, dynamic and inoculum augmented respiration based test assessment for determining in-vessel compost stability. *Waste Management* 42, 3-9.
[10] Tamuhairwe JB, Tenyewa JS, Otabbong E, Ledin S (2009) Comparison of four low tech composting methods for market crop waste. *Waste management* 29, 2274-2281.
[11] Von Blottnitz H (2012) Three Not Two! How Strong is The Case for Separate Organic Waste Management Systems in the Municipal and Commercial Sector? *Institute of Waste Management of South Africa*. East London Convention Centre, 9-12 October 2012.
[12] EPRI (2011) Power generation technology data for integrated resource plan of South Africa. EPRI, Palo Alto, CA.
[13] Wangyao, K., Yamada, M., Endo, Ishigaki, T., Naruoka, T., Towprayoon, S., Chiemchaisri, C., Sutthasil, N. (2010). Methane Generation Rate Constant in Tropical Landfill, Journal of Sustainable Energy and Environment, 1 (4), 181-184.
[14] Pipatti R, Svardal P, Alves JWS, Gao Q, Cabrera CL, Mareckova K, Oonk H, Scheehle E, Sharma C, Smith A, Yamada M (2006) *Intergovernmental Panel for Climate Change*, Guidelines for National Greenhouse Gas Inventories: Chapter 3, vol. 5: Waste Disposal.
[15] Jenkins BM, Baxter LL, Miles TR (1998) Combustion properties of biomass. *Fuel processing technology*, 54, 17-46.
[16] Henning PH (1999) The Feeding Program. Feedlot Management Handbook, ANPI, ARC, South Africa.
[17] Banks C (2009) Optimising Anaerobic Digestion: Evaluating the Potential for Anaerobic Digestion to Provide Energy and Soil Amendment. Presentation. University of Southampton.
[18] Makádi, M, Tomócsik A, Orosz V (2012) Digestate: a new nutrient source – review. Biogas, Kumar, S (Ed.). InTech Research Institute of Nyíregyháza, RISF, CAAES, University of Debrecen, Hungary.
[19] Breitenbeck GA, Schellinger D (2013) Calculating the Reduction in Material Mass and Volume During Composting. *Journal of Compost Science & Utilization*,12: ,365-37.
[20] Curry N, Pillay P (2012) Biogas Prediction and Design of a Food Waste to Energy System for the Urban Environment. *Renewable Energy*, 41, 200-209.