Technology Selection of Biogas Digesters for OFMSW via Multi-criteria Decision Analysis

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***Abstract*—Multi-criteria decision analysis (MCDA) techniques are becoming increasingly popular in decision making for technology selection because of their ability to capture the multi-dimensionality of technologies. Biogas typically refers to an odourless gas produced by anaerobic digestion of biomass using microorganisms. Its production can occur naturally in marshes and landfills or more commonly, in specifically designed plants called biogas digesters under controlled conditions. For techno-economic efficiency of a biodigester, several factors such as cost of plant are taken into consideration. This paper examines various available technologies for biogas digesters using defined selection criteria via MCDA and chooses the best alternatives at various scales of biogas production for a case study in South Africa with municipal biowaste as the target feedstock. 14 biogas plants were analysed in this study and the Puxin and Bio4gas digesters were the best alternatives for small and large scale biogas production respectively.**

***Index Terms*—Biogas, Digesters, Multi-criteria Decision Analysis, Municipal Biowaste, South Africa**

I. Introduction

BIOGAS typically refers to an odourless gas produced by anaerobic digestion (AD) of biomass using microorganisms. It has an approximate composition of 50-70% methane, 30-50% carbon dioxide and other trace gases depending on the nature of the biomass. The first anaerobic digester was built in Bombay India in 1859 and the first notable use of biogas in England was in the same year [1]. Biogas is now used in many developing countries as an alternative and renewable source of energy for wide spread range of end uses The scalability of biogas technology makes it suitable for both rural and urban applications. In contemporary times, biogas has been used most extensively in India and China. Currently in Germany, biogas technology is in advanced stages, producing electricity in medium to large scales [2].

Environmental concerns and rising energy costs in South Africa have sparked sustained interests in biogas as a potential clean alternative to energy production from unsustainable sources like coal and petroleum. However, the penetration of the technology is still low and some of the factors leading to this slow growth are, among others, generally limited experience and lack of biogas specific standards in the country [3].

Based on funding by the South African National Energy Development Institute (SANEDI) the University of Johannesburg (UJ) in South Africa is undertaking a research project to study the potential of biogas produced from the organic fraction of municipal solid waste (OFMSW) or simply municipal biowaste as a vehicular fuel. Part of the project involves the implementation of biogas plants at demonstration and pilot scales utilising OFMSW as the targeted feedstock. Apart from being a good solid waste management strategy, the choice of OFMSW for biogas production presents a substrate with its own set of unique properties that set it aside from other available substrates such as its high efficiency due to its ability to give higher biogas yields of good quality per unit weight than most available substrates and its abundance as well as availability at low costs. However, there are some draw-backs on the use of OFMSW as a substrate for production of biogas such as its heterogeneous nature that calls for extra sorting of the substrate as well as big particle sizes that are harder to work with in AD. Hence special care must be taken in the selection of a biogas technology that addresses all these challenges that are specific to OFMSW [4].

An efficient design of a biogas plant should be able to address quite a number of factors such as cost effectiveness, simplicity, availability of materials and labour, reliability, climate adaptability and suitability for the intended stream of feedstock. Ideally the best choice of biogas plant design should be the type that is obtainable at the least possible initial and maintenance costs while at the same time achieving optimum biogas production rates at set conditions of feedstock quantity and quality [2], [6] - [9].

Unbiased decision making in modern times is guided by the development of models by decision makers commonly referred to as Decision Support (DS) tools. DS tools are usually presented in the form of computer programs into which data variables are fed to yield results that aid the decision making process. Organisations apply DS tools in acquisition of assets, recruitment, and risk analysis among others. Technology designs are most often probabilistic in nature and the evaluation criterion is multi-dimensional therefore the decision making on technology selection calls for complex decision support tools that can capture all the dimensions of a decision problem hence the employment of

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Manuscript received March 05, 2014; revised March 30, 2014. This work is funded by the South African National Energy Development Institute (SANEDI).

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project specific techniques[5]. There have been several applications technology selection as a DS tool such as; Ondrus et al, 2006 applied a multi-stakeholder multi-criteria assessment framework to make a decision on the best form of mobile payments with the Swiss Public Transportation Industry [10] and Wei et al, 2003 adopting the scenario method with the use of grey statistics for technology selection of advanced public transport systems in Taiwan [11].

This paper represents the use of DS in the technology selection of the most suitable biogas technologies to be used in the waste-to-energy UJ-SANEDI project based on their measurable attributes.

II. Technology Selection Methods

Several DS tools have been developed to give unbiased results when it comes to making decisions on technology selection. These include MCDA techniques, the use of grey statistics and Technology Identification, Evaluation, and Selection (TIES) methods among others [5]. In principle, all technology selection methods are based on the steps as summarised below [10];

- Identification of the problem,
- Identification of stakeholders,
- Seeking the unbiased opinions of the stakeholders in the form of solutions to the identified problem. The identified solutions are treated as alternatives and the measures of importance towards solving the identified problem become the selection criteria,
- Modelling the obtained solutions so as to obtain impartial results through detailed analyses. At the modelling stage is when the decision maker decides on which particular selection method to employ basing on the nature of the problem at hand.

Some of the existing technology selection methods are as explained below;

A. Multi-criteria Decision Making

Multiple-criteria Decision Analysis (MCDA) or Multiple-criteria Decision Making (MCDM) is an approach employed by decision makers to make recommendations from a set of finite seemingly similar alternatives based on how well those alternatives rate against a pre-defined set of criteria [11, 12]. In MCDM, six steps are followed during the selection procedure. They are as follows:

- Definition of the problem and its alternative solutions,
- Identification of the stakeholders,
- Definition of selection criteria,
- Selection of the technique of preferences aggregation,
- Evaluation of solutions in respect to each selection criterion and
- Search for a consensual solution.

There are several variations in MCDM techniques used currently employing mathematics and psychology. These include;

1. The Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) aims at organising and analysing complex decisions basing on their relative importance independent of each other. What sets AHP aside from the other techniques is the inclusion of pair-wise comparisons of the alternatives as well as the criteria to emphasize relative importance and independence. Its major drawback is the alteration of ranks also referred to as "rank reversal" in cases where new alternatives are introduced into an already analysed problem [13], [14].

2. Analytic Network Process (ANP)

Analytic Network Process (ANP) is the more general form of AHP. It's different from AHP in that it incorporates interdependence of alternatives as well as criteria across the board. This makes it more applicable for use in real-life situations where selection criteria actually depend on each other for example the idea of acquiring a car can be governed by its cost, safety and comfort among other factors. AHP will look at each of these three factors independently and yet indeed the cost of the car might only be high because of improved safety features making the two criteria interdependent. AHP organises goals, alternatives and criteria as hierarchies well as ANP represents them as networks. However, both approaches use the pair-wise comparison technique for scoring and ranking of alternatives and criteria [13], [15].

3. Simple Multi-Attribute Rating Technique (SMART)

In the Simple Multi-Attribute Rating Technique (SMART), ranking of alternatives is based on ratings that are assigned directly from the natural scales of the alternatives. For example the prices of the different automobiles will be given in a common currency which will be evidently easy for comparison since it is directly numeric [16]. In situations where the units of measurement for the weights of the criteria for given alternatives are not of a common scale, the decision maker has to create a unifying function referred to as a "value function". In AHP and ANP this is taken care of by the relative nature of the rating technique. The advantage of the SMART technique over AHP and ANP is the fact that the decision model is built independent of the alternatives. Therefore the ratings of the alternatives are not relative and therefore introduction of new alternatives doesn't affect the ratings of the original ones making it a more flexible and simpler technique [17].

B. Technology Identification, Evaluation, and Selection (TIES) method

This is a method for Technology Selection based on benefit, time and budget. The method was developed by the Aerospace Systems Design Laboratory (ASDL) in Georgia U.S.A to address the decision making process for situations whenever there was required intellectual interventions for a failing norm in existing technologies as a result of a dynamic environment. The method is thus rapid and efficient and may be easy to adapt for different applications. It also helps reduce time and costs needed to develop new technologies while simultaneously providing quantitative justification for design decisions [5].

It is broken down into 7 steps as below;

- Problem definition,
- Baseline and alternative concepts identification,
- Modelling and simulation,
- Design space exploration,
- Determination of system feasibility: probability of success,
- Population of the Pugh evaluation matrix,

- Best alternative concept determination.

C. Scenario Method Using Grey Statistics

This approach is used for problems with large future variability and inadequate historical data for reference especially if public sector is involved requiring results within stringent resources. The method suggests strategic proposals and not decisions by involving the stakeholders whose opinions are sought to give grey statistics that are later fed into modelled scenarios to simulate solutions. Precisely, the method follows the steps as listed below [18];

- Analyse the problem,
- Indicate the critical factors of the selection process,
- Highlight the strategic scenarios,
- Assess decisive scenario,
- Select the preferred developed technology.

D. Marginal Analysis Guided Technology Evaluation and Selection

This is an Early Stage Technology (EST) evaluation method used specifically for selection of technology whose future is uncertain and not yet well studied. The decision makers rely on the information and knowledge from previous experiences to support future project evaluation and selection. The technology evaluation model is built in a way that it can easily adapt to any likely changes of the business environment [19],

The method aims to;

- Retain and reuse knowledge as well as experience from previous projects whether successful or unsuccessful as inputs to the evaluation of future projects,
- Adapt to new knowledge and respond to significant events in the business environment, and
- Extract information from the knowledge database to explain and justify the analyses.

III. METHODOLOGY

The straight forward MCDM technique of technology selection was chosen as the simplest and easiest method for the study because the technologies in question had obtainable and measurable qualitative and quantitate attributes such as cost, simplicity, performance and availability among others.

As a first step, to make an informed decision on the best choice, a list of potential technology suppliers was built through extensive research by the decision maker. This yielded a total of fourteen (14) technologies with full specifications of the products as well as associated costs. These would in turn serve as the alternatives from which an analysis would be conducted and decisions made on the best product.

The SMART MCDM technique was used to analyse the products owing to the fact that all their attributes were directly measurable and non-subjective. In addition, the list of suppliers is an ever growing one; hence the choice of the SMART technique because it supports the evaluation of an elastic set of alternatives unlike other MCDM techniques such as AHP and ANP.

The analysis was broken into two (2) parts to accommodate the variation in biogas production scales. That is small and industrial scales. This was necessary because the selection criteria weigh differently at different scales for example temperature regulation is more important for an industrial scale plant than a small scale plant. In addition, particular technology suppliers only produce plants at certain scales for example most German suppliers only set up plants of 2,000m^3 capacity and over whereas most locally available suppliers are only capable of making 10m^3 as a maximum. The division of scales was guided by the ongoing SANEDI research project and case studies at the University of Johannesburg to design biogas plants utilising the organic fraction of municipal solid waste as discussed in the introduction section of this paper. The project intends to design and implement biogas plants at both pilot and industrial scales. From the current preliminary data obtained, the pilot scale plant is of capacity ranges 10-30m^3 and the industrial scale plants are 400-2000m^3.

A. SMART Analysis Procedure by Additive Valuation

To achieve the set objectives, the steps below were followed;

- Listing of all alternatives; a list was made of the 14 biogas technologies from which choices would be made. These are as shown in table I,
- Identification of the goal/objective; the objective of the analysis was to make a decision on what the best biogas plants were for both pilot and industrial scales,
- Listing of selection criteria; a list of factors herein referred to as the criteria was made against which the digesters would be scored for analysis. These included among others price of the plants, suitability of the plant to digest municipal biowaste and ability to regulate temperature. Details of these are listed in table II,
- Creation of a unified weighting scale for the set criteria basing on their level of importance. The criteria were then assigned weights ranging between 0 to1. Unifying the weights implies that the sum of all weights equal 1. That is;

$$\sum_{i=1}^{n} W_i = 1 \tag{1}$$

Where;

W_i is the unified weight of criteria i.

Weights of corresponding criteria are also listed in table II alongside justifications for their corresponding values.

- Assignment of scores to individual alternatives depending on how they score on the set criteria ranging from 0 to 1.
- Computation of the weighted ranks (R) of individual products/alternatives as a sum of the product of scores and attribute weights. That is;

$$\sum_{i=1}^{n} W_i S_1 = R_1 \tag{2}$$

Where;

R_1 is the rank of alternative 1,

And S_1 is the score of alternative 1 with regards to criteria i.

- Then finally, make the decision on the best digester basing on one with the highest rank. Details of the ranking according to corresponding aggregate scores of alternatives as shown in tables III and IV.

IV. RESULTS AND DISCUSSIONS

A. *Potential Biogas Digesters/Alternatives*

The developed list of biogas digesters is as in the table 1 below;

TABLE I

A LIST OF POTENTIAL SUPPLIERS OF BIOGAS DIGESTERS

Model	Supplier	Capacity (m^3)	Suitability for OFMSW	Cost of Plant (ZAR)	Cost per m3 (ZAR)	Temperature Regulation	Materials	Origin	Agitation
Agama Pro 6	BiogasPro S.A	6 max	Yes	45,000	7,500	Buried Underground	Prefabricated Polyfibre	South Africa	Manual
Puxin	BiogasSA	10 max	Yes	60,000	6,000	Buried Underground	In-situ Concrete	China/South Africa	Hydraulic
Bio4gas	IBERT	From 200	Yes	600,000	3,000	Incorporated CHP generator	In-situ Concrete	Germany/ South Africa	Incorporated
GREENBOX	AEPS	From 100	Yes	1,200,000	12,000	Insulated	On-site steel	Germany/ South Africa	Incorporated
Geo membrane	Biotech	35	Yes	180,000	5,140	None	Prefabricated Polyfibre	India	Manual
WELTEC	Weltec	2,500	Yes	25,000,000	10,000	Incorporated	Stainless Steel	Germany	Incorporated
PVC Portable digester	Chongqing Biogas New Energy Co.	10	NO	10,000	1,000	Buried underground	Concrete	Chongqing, China	None
ÖKOBIT	ÖKOBIT	2,500	Yes	20,000,000	8,000	Incorporated	Stainless Steel	Germany	Incorporated
BioConstruct	BioConstruct	2,400	Yes	21,000,000	8,750	Incorporated	In-situ concrete	Germany	Incorporated
BITECO	BITECO	600	Yes	4,980,000	8,300	Incorporated	In-situ concrete	Italy	Incorporated
STANDARD	BIODIGESTER	30	NO	210,000	7,000	Insulated	Prefabricated Polyfibre	England	External Hydraulic System
Food Waste Biodigester SR100	Sunrise-econergyCo. Shenzhen	100	Yes	1,000,000	10,000	Incorporated	enamel sheeting	Guangdong, China	Incorporated
Floating Digester	Sunrise-econergyCo. Shenzhen	60	NO	35,000	5,800	Buried underground	Concrete structure	Schenzen, China	None
Helios® system	UTS Biogastechnik GmbH	From 2000	Yes	15,000,000	7,500	Incorporated	Cast In-situ concrete	Germany	Incorporated

At small scale, the Geo Membrane digester from India's Biotech comes at the lowest cost compared to the rest in the top three technologies hence the high score. It also turns out to be the most flexible to size especially at small scale and the best suited plant for treatment of OFMSW as well. However, its downside was the fact the technology is not available locally and hence scoring 0.00 in that particular selection criterion dropping its overall total score considerably as showed in tables III and IV.

The Agama Pro digester is readily available locally for small scale applications in the form of prefabricated Polyfibre tanks making it the easiest to set up since it is already finished from the supplier. The Agama digester however comes in standard non-flexible sizes with the largest capacity of $6m^3$ making it not as easy to size as the Geo membrane digesters and no effort whatsoever was made by the technology designer to incorporate automated substrate agitation as well as system temperature regulation reducing its overall score below the Puxin digester.

The Puxin digester on the other hand has balanced attributes scoring well across all criteria despite not being the best at any hence obtaining the overall highest score and therefore the best option for small scale applications. Its attributes' scores are almost similar to the Agama digester owing to the fact it's a locally available technology and an easy one to construct too. However, the technology design has incorporated a hydraulic agitation modification as well as system temperature regulation through its mode of construction since it is a below-ground construction. The Puxin digesters are available in customisable $10m^3$ and $6m^3$ capacities therefore easily scalable for small scale applications. All these factors combined give the Puxin digester a much higher aggregate score compared to the rest of the small scale favourites.

Generally foreign manufactures mostly venture into large scale projects especially the ones from Europe. However, China and India have potential suppliers that could fit into the needs of small scale criteria but the costs of mobilisation including import duty make imported technology uneconomical to source thereby favouring the locally available technologies.

For large scale applications, the smaller scale favourites evidently appear to be the ones costing the least hence having the better scores in terms of ranking basing of technology cost price. However, their inability to be scaled up to the desired industrial capacity ranges of over $400m^3$ reduces their overall scores and increases the ones that satisfy the criteria better such as WELTEC technology from Germany as showed by tables III and IV.

B. Criteria/Attributes

TABLE II
SELECTED CRITERIA/ATTRIBUTES WITH CORRESPONDING WEIGHTS

Attribute	Unified Weights (W_i)		Justification
	Pilot Scale	Industrial Scale	
Price	0.17	0.17	The cost price of any technology to be procured is a very vital factor in the selection process since it dictates the economic viability of the project. An economical choice of technology is the one that will serve the intended objective of the project at the least possible cost. The price of the plant therefore is a *strong* attribute in the selection process having a weight of 0.17 just 0.01 below local availability at 0.18. The strength of price as a selection criterion is the same across all the scales because it affects the project equally no matter the scale. However, cost of project is a not a limiting factor unlike some like the scale of the project that are fixed hence not the strongest criterion [20], [21].
Local Availability	0.18	0.18	Locally available technologies reduce the project costs considerably since there are no extra costs incurred in mobilisation of labour and materials as well as reduced taxes. In addition to lowering project costs, locally available technologies are already understood within the area of application therefore easy to set up and promote the development of local products as well as the economy at large. Therefore local availability is a *strong* factor and hence carries a strong weight at 0.18. This is also not a limiting factor on the project no matter the cost implications. The strength of local availability as selection factor is the same across all the scales because it affects the project the same way no matter the size [8], [22].
Capacity Scalability	0.2	0.2	This is the measure of the ease with which the presented technology can be scaled to the envisaged capacity of the project plant. This is a very important factor in that some plants are only available in particular scales. This is a project limiting factor in that if a plant is out of the required scale is automatically disqualified therefore having a *very strong* weight of 0.2. The weight for scalability is the same across both scales [6], [20].
OFMSW Suitability	0.2	0.2	The nature of substrate is one of the most important factors in the selection of a given biogas plant. In this case the substrate to be treated was fixed as OFMSW and therefore the suitability of the given technology to treat this substrate was a project limiting factor hence carries a *very strong* weight of 0.2 just at the same level of importance as the scalability of the plant. The weight for OFMSW suitability is the same across both scales [2], [23].
Temperature Regulation Ability	0.1	0.1	Anaerobic digestion of biomass by microbes for biogas production occurs optimally at temperature ranges of 30^0-40^0C. Therefore a techno-efficient biogas plant system should have the ability to regulate its working temperatures within the optimal range otherwise the system can underperform or even fail at certain temperatures. However, most systems have labored to a certain degree to incorporate temperature regulation design modifications making the factor a rather *fairly strong* one as a selection criterion with a weight of 0.1. And its importance is of equal strength across all scales [2], [9], [24].
Presence of Agitation Accessory	0.05	0.1	Constant agitation of the substrate in the digester needs to be done to ensure intimate contact between the microorganisms and substrate which ultimately results in improved digestion process. Most systems have however labored to a certain degree to incorporate modifications to facilitate substrate agitation making the factor also rather *fairly strong* as a selection criterion with a weight of 0.1 at industrial scale and 0.05 at pilot scale. It is more important to have incorporated mechanical agitation at industrial scale than pilot scale because at small scale the substrate can be agitated manually unlike on large scales where it has to be mechanical automated agitation [24].
Ease of Construction	0.1	0.05	The plant should be easy to construct to reduce the need for expatriate labour which usually increases the project cost. Most available biogas technology has been simplified for easy project set up making the criterion also a rather *fairly strong* one. However, industrial scale plants are usually complex projects that it would not make so much difference to weigh them against the ease of construction whereas small scale projects on the other hand should be as simple as possible since they operate under low budgets and hardly make any profits hence the difference in weights with pilot scale at 0.1 and industrial scale at 0.05 [20].

Majority of the potential large scale energy suppliers are foreign companies therefore leading to most of them scoring low given that local availability of the technology is one of the most important attributes carrying a weight of 0.18. This therefore implies that any large scale biogas technology supplier that is available locally has a competitive edge over the rest hence favouring IBERT's Bio4gas digester which is supplied locally.

In addition to its availability locally, the application of the cost effective TGL technology for substrate agitation reduces the overall project cost of the Bio4gas digester making it a much more economical option than the rest of the large scale plants that utilise energy consuming and costly mechanical attachments for substrate agitation. In terms of the accessories of the reactor such as agitation extras as well as temperature regulation, all large scale plants are well equipped but the difference in score is mostly attributed to how simple and economical the particular accessory is.

Some larger scale plants such as WELTEC and the HELIOS System have agents that are present locally to provide product support information and other logistical support services but the technologies still have to be imported from their origin which is Europe in this case giving them mid-range scores with respect to local availability.

The large scale plants are more complex projects to set up therefore all large scale plants score quite low in terms of ease of construction as compared to the small scale plants that are usually a few days' work of simple or sometimes prefabricated installations.

All large scale plants are designed to accept a wide range of feedstock and hence all are equally good to an acceptable degree with regards their suitability in the treatment of OFMSW which is our target feedstock. All plants scoring 0.7 on average across.

C. Scores

TABLE III
SCORES FOR PILOT/DOMESTIC SCALE (6-30M^3) CONSIDERATION

CRITERIA	Cost		Local Availability		Scalability		OFMSW Suitability		Temperature Regulation Ability		Presence of Agitation Accessory		Ease of Construction		
WEIGHT	0.17		0.18		0.2		0.2		0.1		0.05		0.1		
MODEL	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	TOTAL
Puxin	0.65	0.111	0.85	0.153	0.85	0.170	0.70	0.140	0.50	0.050	0.10	0.005	0.80	0.080	0.709
Agama Pro 6	0.60	0.102	1.00	0.180	0.65	0.130	0.70	0.140	0.10	0.010	0.10	0.005	1.00	0.100	0.667
Geo membrane	0.80	0.136	0.00	0.000	1.00	0.200	0.90	0.180	0.30	0.030	0.30	0.015	0.70	0.070	0.631
Bio4gas	0.75	0.128	0.70	0.126	0.00	0.000	0.80	0.160	1.00	0.100	1.00	0.050	0.50	0.050	0.614
GREENBOX	0.20	0.034	0.35	0.063	0.40	0.080	0.80	0.160	0.70	0.070	0.90	0.045	0.50	0.050	0.502
Helios® system	0.60	0.102	0.40	0.072	0.00	0.000	0.70	0.140	0.85	0.085	0.90	0.045	0.50	0.050	0.494
SR100	0.30	0.051	0.00	0.000	0.20	0.040	1.00	0.200	0.85	0.085	0.80	0.040	0.70	0.070	0.486
PVC Portable	1.00	0.170	0.00	0.000	0.80	0.160	0.00	0.000	0.50	0.050	0.10	0.005	0.80	0.080	0.465
STANDARD	0.65	0.111	0.00	0.000	0.90	0.180	0.00	0.000	0.65	0.065	0.60	0.030	0.75	0.075	0.461
BITECO	0.60	0.102	0.00	0.000	0.10	0.020	0.70	0.140	0.80	0.080	1.00	0.050	0.40	0.040	0.432
BioConstruct	0.60	0.102	0.00	0.000	0.00	0.000	0.70	0.140	0.85	0.085	1.00	0.050	0.40	0.040	0.417
WELTEC	0.30	0.051	0.20	0.036	0.00	0.000	0.70	0.140	0.90	0.090	0.90	0.045	0.40	0.040	0.402
ÖKOBIT	0.55	0.094	0.00	0.000	0.00	0.000	0.65	0.130	0.85	0.085	0.90	0.045	0.40	0.040	0.394
Floating Digester	0.80	0.136	0.00	0.000	0.50	0.100	0.00	0.000	0.50	0.050	0.10	0.005	0.70	0.070	0.361

TABLE IV
SCORES FOR INDUSTRIAL SCALE (400-2000M^3) CONSIDERATION

CRITERIA	Cost		Local Availability		Scalability		OFMSW Suitability		Temperature Regulation Ability		Presence of Agitation Accessory		Ease of Construction		
WEIGHT	0.17		0.18		0.2		0.2		0.1		0.1		0.05		
MODEL	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	TOTAL
Bio4gas	0.75	0.128	0.70	0.126	0.90	0.180	0.80	0.160	1.00	0.100	1.00	0.100	0.50	0.025	0.819
Helios® system	0.60	0.102	0.40	0.072	0.80	0.160	0.70	0.140	0.85	0.085	0.90	0.090	0.50	0.025	0.674
BioConstruct	0.60	0.102	0.00	0.000	0.80	0.160	0.70	0.140	0.85	0.085	1.00	0.100	0.40	0.020	0.607
BITECO	0.60	0.102	0.00	0.000	0.80	0.160	0.70	0.140	0.80	0.080	1.00	0.100	0.40	0.020	0.602
SR100	0.30	0.051	0.00	0.000	0.75	0.150	1.00	0.200	0.85	0.085	0.80	0.080	0.70	0.035	0.601
WELTEC	0.30	0.051	0.20	0.036	0.80	0.160	0.70	0.140	0.90	0.090	0.90	0.090	0.40	0.020	0.587
Puxin	0.65	0.111	0.85	0.153	0.40	0.080	0.70	0.140	0.50	0.050	0.10	0.010	0.80	0.040	0.584
ÖKOBIT	0.55	0.094	0.00	0.000	0.80	0.160	0.65	0.130	0.85	0.085	0.90	0.090	0.40	0.020	0.579
GREENBOX	0.20	0.034	0.35	0.063	0.65	0.130	0.80	0.160	0.70	0.070	0.90	0.090	0.50	0.025	0.572
Geo membrane	0.80	0.136	0.00	0.000	0.50	0.100	0.90	0.180	0.30	0.030	0.30	0.030	0.70	0.035	0.511
Agama Pro 6	0.60	0.102	1.00	0.180	0.00	0.000	0.70	0.140	0.10	0.010	0.10	0.010	1.00	0.050	0.492
STANDARD	0.65	0.111	0.00	0.000	0.30	0.060	0.00	0.000	0.65	0.065	0.60	0.060	0.75	0.038	0.333
PVC Portable	1.00	0.170	0.00	0.000	0.10	0.020	0.00	0.000	0.50	0.050	0.10	0.010	0.80	0.040	0.290
Floating Digester	0.80	0.136	0.00	0.000	0.10	0.020	0.00	0.000	0.50	0.050	0.10	0.010	0.70	0.035	0.251

The worst option of biogas plant for both industrial and pilot scales is the floating digester produced by China's Sunrise Econergy Company Shenzhen. The digester, although an easy one to construct and quite affordable, it is not an available product on the market locally, it is not suitable for the treatment of OFMSW, only available for small scales and lacks design modifications to cater for substrate agitation and system temperature regulation as well.

V. CONCLUSIONS

From the results obtained, the best biogas digester model for small scale production was the Puxin digester originally from China but locally produced by BiogasSA. The plant is constructed below ground using in-situ reinforced concrete to maintain a warm temperature within the plant for optimum performance. It also runs as a hydraulic system to automatically agitate the substrate. This was closely followed by the Agama Pro digester and the Biotech's Geo membrane digester from India in that order.

At industrial scale the best plant is the Bio4gas model originally from Germany but supplied locally in South Africa through Iskhus Bio4gas Express Reactor Technology (IBERT). It is constructed above ground from in-situ reinforced concrete and has an incorporated combined heat and power (CHP) generator on the system that maintains a constant optimum temperature for anaerobic digestion. To ensure substrate agitation, the system design employs a patented Thermo-Gas-Lift (TGL) Technology in such a way that the substrate is automatically mixed simultaneously as the system is fed. The TGL technology sets the IBERT design apart from the rest of the available industrial scale technologies. TGL makes the system much cheaper than other ordinary industrial scale plants that require mechanical agitation accessories like installed rotor blades. Next in line were the Helios System and the Bio Construct digester.

RECOMMENDATIONS

The choice of suitable techno-economic technology is a very vital step in project design, feasibility study and subsequent implementation. Therefore for the successful development of biogas projects in South Africa more of similar studies should be undertaken so as to develop baseline case studies for the biogas industry whose growth up to date is still undermined by lack of demonstration projects. For example other studies targeting plants to handle different types of substrates like farm manure or industrial wastes instead of the organic fraction of municipal solid waste should be undertaken.

At the time of the study, 14 suppliers were the ones that could give satisfactory required information for the study. This in a way could lead to a bias in decision making. Therefore additional studies are encouraged with larger sample sizes of suppliers from numerous locations worldwide.

ACKNOWLEDGEMENT

The authors are grateful to the South African National Energy Development Institute (SANEDI) and the Technology Innovation Agency (TIA) through the Process Energy and Environmental Technology Station (PEETS) at the University of Johannesburg for supporting this research.

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