

Identification of an Appropriate Alternative Waste Technology for Energy Recovery from Waste through Multi-Criteria Analysis

Sharmina Begum, M. G. Rasul, and Delwar Akbar

Abstract—Waste management is now a global concern due to its high environmental impact on climate change. Because of generating huge amount of waste through our daily activities, managing waste in an efficient way has become more important than ever. Alternative Waste Technology (AWT), a new category of waste treatment technology has been developed for energy recovery in recent years to address this issue. AWT describes a technology that redirects waste away from landfill, recovers more useable resources from the waste flow and reduces the impact on the surroundings. Australia is one of the largest producers of waste per-capita. A number of AWTs are using in Australia to produce energy from waste. Presently, it is vital to identify an appropriate AWT to establish a sustainable waste management system in Australia. Identification of an appropriate AWT through Multi-criteria analysis (MCA) of four AWTs by using five key decision making criteria is presented and discussed in this paper.

Keywords—Alternative waste technology (AWT), Energy from waste, Gasification, Multi-criteria Analysis (MCA)

I. INTRODUCTION

WASTE is a by-product of our everyday activities that creates a serious hazard to civilization all over the world. Changing way of life, the growing use of not reusable materials and extreme packaging are all contributing to increase the amount of waste being created. The problems related with waste management are complex due to quantity and diversity of the nature of waste and economic limitations. The problem is not only limited to land, it includes air and water as well. At present, this is a major concern about environmental impact and greenhouse gas emission, rising global temperatures, and impact on human health, animals, and ecosystems due to increasing amount of waste. The total volume of waste generated in Australia each year has been growing faster than annual GDP growth. Between 1996-97 and 2006-07, the volume of waste produced per person in Australia grew at an average annual rate of 5.4%. In 1996-97, Australians generated approximately 1,200kg of waste per person. In 2006-07, this had increased to 2,100kg per person [1].

Sharmina Begum is with the School of Engineering and the Built Environment, Faculty of Sciences, Engineering and Health, Central Queensland University, Rockhampton, QLD 4702, Australia (Phone: 61749309283; Fax: 61749309382; Email: s.begum@cqu.edu.au).

M. G. Rasul is with the School of Engineering and the Built Environment, Faculty of Sciences, Engineering and Health, Central Queensland University, Rockhampton, QLD 4702, Australia (Phone: 61749309676; Fax: 61749309382; Email: m.rasul@cqu.edu.au).

Delwar Akbar is with the Centre of Environmental Management, Faculty of Sciences, Engineering and Health, Central Queensland University, Rockhampton, QLD 4702, Australia (Phone: 61749302316; Email: d.akbar@cqu.edu.au).

Due to increasing amount of waste generation, presently, managing waste in a responsible and efficient way has become more important than ever. Alternative Waste Technology (AWT), a new category of waste treatment technology, has been developed in recent years to deal with this concern.

AWT is a technology that:

- redirect waste away from landfill;
- pick up more resources from the waste stream; and
- reduce the impact on the environment.

There are two significant benefits can be attained from AWTs; environmentally safe waste management and generation of energy in diverse form. Clean and renewable energy can be generated by AWTs through biochemical, thermal and physicochemical techniques. Environmental impacts and emissions of greenhouse gases are deeply reduced by using AWT as a technique to dispose off solid and liquid wastes and generate power. Through AWT conversion, electricity is generated which reduces the dependence on electrical production from power plants. In Australia, currently energy is recovered from waste through different AWT's, such as pyrolysis, gasification, incineration and anaerobic-digestion.

It is important to identify an appropriate AWT among the AWTs used in Australia for sustainable waste management for Australian condition. This paper illustrates the technology and process to identify an appropriate AWT. Multi-criteria analysis (MCA) is one of the important tools that have been considered in this study to identify an appropriate AWT for Australia. To perform MCA, four AWTs and five criteria have been considered which are mostly used in Australia.

II. MULTI-CRITERIA ANALYSIS (MCA)

Multi Criteria Analysis (MCA) is a tool that has been developed for complex multi criteria problem(s) within decision making. The method(s) include qualitative as well as quantitative aspects of the problem(s) in the decision making process.

A. MCA can be defined as assessment models which include [2]

- A set of decision options which need to be ranked or scored by the decision maker;
- A set of criteria, typically measured in different units; and
- A set of performance measures, which are the raw scores for each decision option against each criterion.

MCA consists of identifying a list of alternative courses of actions and a set of evaluative criteria as well as the weights reflecting the significance of these criteria. The score of each

action option against the evaluative criteria is then determined. The scores may then be normalised and weighted. Comparison between alternative courses of action is then made by dominance pair wise comparison or other genuine methodologies. Several attempts to use weighted summation MCA in waste management were found in recent literature [3, 4, 5, 6].

To solve MCA problem, many techniques have been emerged since 1960. As discussed by Figueira [7], the following methods of performing MCA operation:

- Outranking approach
- Distance to ideal point methods
- Fuzzy set analysis
- Tailored methods
- Multi-criteria value functions
- Pair-wise comparisons method (PCM)

Among a number of approaches of MCA, a combination of Multi-criteria value functions and Pair-wise comparisons method (PCM) have been used in this study due to its flexibility, capturing capability of quantitative and qualitative data and familiarity.

B. Multi-criteria value functions

In this technique, there are two commonly applied value functions are weighted summation and weighted multiplication. The weighted summation model is often expressed as:

$$u_i = \sum_{j=1}^m v_{i,j} w_j$$

The weights (w_j) are non-negative and sum to 1, and $v_{i,j}$ is a transformed performance score for $x_{i,j}$ on a scale of 0 to 1 where 1 represents best performance. The overall performance score for each option is given by u_i . Simple additive weight (SAW), which is one of the techniques of multi-criteria value function have been used in this study.

C. Pair-wise comparisons method (PCM)

The most widely applied and well-known pair-wise comparison techniques are the Analytic Hierarchy Process. These approaches provided comparing criteria and alternatives in every unique pair giving $n(n-1)/2$ comparisons. The comparisons can be made to attain criteria weights and decision option performance scores. Various scaling systems (specially Likert's scale) are used.

Analytical hierarchy process (AHP), which is a technique of PCM, is one of the most popular processes to execute a MCA that was developed by Saaty [8, 9]. AHP allow users to judge the relative weight of multiple options adjacent to given criteria in an instinctive manner. In case of unavailability of quantitative ratings, judges can still recognise whether one criterion is more essential than another. Saaty established AHP in a consistent way of converting such pair-wise comparisons (X is more important than Y) into a set of numbers demonstrating the relative priority of each criteria. This method is used to derive ratio scales from paired comparisons. In this study, combinations of SAW and AHP have been used in this study.

III. MCA ON AWT

This study used MCA method supported by analytical hierarchy process for weight calculation and simple additive weighting for estimated weighted value of each alternative. Resource Assessment Commission [10], Howard [11] and Saaty [13] suggested the following steps in using MCA and this study also follow these established steps in applying MCA on identifying best suitable AWT for Australia's municipal waste management.

A. Choose decision options.

The first step of MCA is to choose decision alternatives. Generally there is a finite set of decision alternatives that are to be ranked or scored. There are a number of AWTs used in Australia. Table I presents' available AWTs and criteria with qualitative and quantitative data collected from Australian regional councils and waste management organisations. In this study, there are four decision options/AWTs have been considered which are widely used in Australia, they are: Anaerobic Digestion, Pyrolysis, Gasification and Incineration.

B. Choose evaluation criteria.

The criteria are used to measure the performance of decision alternatives. As per Keeney and Raiffa [12, 13], all criteria should be non-redundant and related to the decision maker's objectives. There are five criteria (shown in Table I) have been considered in this study based on environmental, social, economical and technological aspect. They are: Public acceptability, Diversion from landfill, Capital cost, Complexity and Energy produced.

Public acceptability has been chosen considering social aspect of AWT. Capital cost represents the establishment cost of each AWT which has been considered for economic feature. Diversion from landfill which represents the quantity of waste diverted by each AWT away from landfill considered environmental aspect. Complexity represents for technological risk and difficulty of each AWT. Energy produced has been considered on aspect of economic and system efficiency. Data for MCA have been collected from a Report of Asset and infrastructure department, Sunshine Coast Regional council, Australia, 2008 as a secondary source.

C. Obtain performance measures ($x_{i,j}$) for the evaluation matrix.

Performance measures for the evaluation matrix are source from expert judgments or other environmental and economic models.

D. Transform into commensurate units.

To perform MCA, it is important to transform all criteria into commensurate scale, often 0 to 1, so they can be meaningfully combined in the overall utility function. In this study, Likert's scale-5 has been used to transform qualitative data to quantitative data using commensurate units. Linguistics data transformations by using Likert scale-5 have been shown in Table II.

TABLE I
 DATA FOR MCA

<i>AWTs /Decision Options</i>	<i>Capital Cost</i>	<i>Complexity</i>	<i>Public acceptability</i>	<i>Diversion from landfill</i>	<i>Energy produced (kWh per ton MSW)</i>
Anaerobic Digestion	Medium	Medium	Very high	65%	250
Pyrolysis	Very high	Very high	Medium	100%	660
Gasification	High	Very high	Very High	100%	660
Incineration	Very high	High	low	70%	585

TABLE II
 LINGUISTIC DATA TRANSFORMATION BY USING LIKERT SCALE

<i>Decision Options</i>	<i>Capital Cost</i>	<i>Complexity</i>	<i>Public acceptability</i>	<i>Diversion from landfill</i>	<i>Energy produced (kWh per ton MSW)</i>
Anaerobic Digestion	3	3	5	0.65	250
Pyrolysis	5	5	3	1.00	660
Gasification	4	5	5	1.00	660
Incineration	5	4	2	0.70	585
MAX	5	5	5	1.00	660
MIN	3	3	2	0.65	250
WEIGHT	0.25987	0.10296	0.38230	0.07234	0.18253
Relationship	-ve	-ve	+ve	+ve	+ve

E. Weight the criteria.

A variety of methods are available to assign weights at either cardinal or ordinal levels of measurement. In this study AHP has been used for weighting the criteria. To perform weight analyses, the steps have been followed according to the AHP as follows:

1. Structuring a decision problem and selection of criteria

In this first step, all components of decision problem and selection of criteria are structured in a hierarchy to provide an overall view of the relationships and help the decision maker to judge whether the elements in each level are in the identical scale so that they can be compared precisely.

2. Priority setting of the criteria by pair-wise comparison (weighting)

At this step of AHP, rating the relative 'priority' of the criteria has been done by assigning a weight between 1 (equivalent importance) and 4 (most importance) to the more important criterion. In order to obtain an average weighting for each criterion, the weightings are then normalised and averaged. Using PCM, weight analysis has been performed and square pair-wise comparison matrix of the criteria has been shown in Table III.

To set the importance of each criteria in relation to other criteria, rating of the relative 'priority' of the criteria have been done by assigning a weight between 1 (equal importance) and 4 (extreme importance) to the more important criterion, whereas the reciprocal of this value is assigned to the other criterion in the pair. Weighting factors have been set in Table III after discussion with a waste to energy conversion expert and have been reviewed by expert reviewers.

3. Pair-wise comparison of options on each criterion (scoring)

In this step, better option have been awarded a score on a scale between 1 (equally good) and 4 (absolutely better) for each pairing within each criterion. Later, the ratings have been normalised and averaged. Comparisons of elements in pairs require that they are consistent with respect to the common feature. The weightings are then normalised in Table IV using Equation 1 (the weighting have to sum up to 1) and averaged in order to obtain an average weighting for each criterion. Normalise matrix = Selected criteria / Sum of all criteria

$$w_j = \frac{w_j}{\sum_{i=1}^n w_j} \quad (1)$$

TABLE III
WEIGHT ANALYSIS – SQUARE PAIR-WISE COMPARISON MATRIX OF THE CRITERIA

Criteria	Capital Cost	Complexity	Public acceptability	Diversion from landfill	Energy produced (kWh per ton MSW)
Capital Cost	1	3	1/2	3	2
Complexity	1/3	1	1/4	2	1/2
Public acceptability	2	4	1	4	2
Diversion from landfill	1/3	1/2	1/4	1	1/3
Energy produced (kWh per ton MSW)	1/2	2	1/2	3	1

TABLE IV
NORMALIZED MATRIX

Criteria	Capital Cost	Complexity	Public acceptability	Diversion from landfill	Energy produced (kWh per ton MSW)
Capital Cost	0.24000	0.28571	0.20000	0.23077	0.34286
Complexity	0.08000	0.09524	0.10000	0.15385	0.08571
Public acceptability	0.48000	0.38095	0.40000	0.30769	0.34286
Diversion from landfill	0.08000	0.04762	0.10000	0.07692	0.05714
Energy produced (kWh per ton MSW)	0.12000	0.19048	0.20000	0.23077	0.17143
Sum	1.00000	1.00000	1.00000	1.00000	1.00000

4. Obtaining an overall relative score for each option

To produce an overall score for each option, the scores have been combined with the criterion weights. The criteria are weighed according to the relative importance with each another. This has been done by simple weighted summation. Finally, after judgments have been made on the impact of all the elements and priorities have been computed for the hierarchy as a whole. Average weighting have been calculated from Table IV and shown in Table V. The MMULT function has been used to calculate Ratio values using Equation 2 and these values are stated in Table V.

$$\text{Ratio} = \text{MMULT}(\text{Array1}, \text{Array2}) \quad (2)$$

Consistency Index has been calculated using Equation 3:

$$\text{Consistency Index, CI} = (\gamma_{\max} - n) / (n - 1) \quad (3)$$

where, γ_{\max} is the Eigen value obtained by

$$\gamma_{\max} = \text{Avg weight} / \text{Ratio} \quad (4)$$

TABLE V
AVERAGE WEIGHT AND RATIO OF AWTs

	Average Weight	Ratio	Ratio/Weight
Capital Cost	0.25987	1.34198	5.16407
Complexity	0.10296	0.52110	5.06119
Public acceptability	0.38230	1.96829	5.14855
Diversion from landfill	0.07234	0.36686	5.07153
Energy produced (kWh per ton MSW)	0.18253	0.92655	5.07602
Sum	1.00000		

Then, the consistence ratio (CR) has been calculated as the ratio of consistency index (CI) and random consistency index (RI) using equation 5. The RI is the random index representing the consistency of a randomly generated pair-wise comparison matrix.

$$CR = CI/RI \quad (5)$$

$CR \leq 0.1$, the pair-wise comparison matrix is considered to be consistent enough. In this study, the value of $CR=0.02327$ falls much below the threshold value of 0.1 and it indicates a high level of consistency. Hence the weighting has been accepted.

F. Rank or score the options

Weights are combined with the performance measures to attain an overall performance rank or score for each decision option. Using ordinal and/or cardinal properties of the performance measures, a wide range of ranking algorithms is

use. In this study, qualitative data have been converted to quantitative data in Table II using Likert's scale including maximum and minimum value of each criterion. Weighting analysis and Relationship of each criterion have been specified and stated in Table II. Standardised values of each criterion are shown in Table VI having been derived using Equations 6 and Equation 7. Scoring of each option has been done by using the SUMPRODUCT function and stated in Table VII.

For (+ve) relationship,

$$1 - \frac{x_i - Min}{Max - Min} \quad (6)$$

$$\frac{x_i - Min}{Max - Min} \quad (7)$$

TABLE VI
 STANDARDISED VALUE

<i>Decision Options</i>	<i>Capital Cost</i>	<i>Complexity</i>	<i>Public acceptability</i>	<i>Diversion from landfill</i>	<i>Energy produced (kWh per ton MSW)</i>
Anaerobic Digestion	1.00	1	1	0	0
Pyrolysis	0	0	0.33	1	1
Gasification	0.5	0	1	1	1
Incineration	0	0.5	0	0.14	0.82

G. Perform sensitivity analysis.

Sensitivity analysis is required to perform a MCA for its perfection measurement. Performance measures, systematic variation of the weights and ranking algorithms can expose where the MCA model needs strengthening and the robustness of results given input assumptions.

H. Make a decision.

The MCA model intends to inform, but not create the final decision. There is typically a requirement for some level of human judgment to account for relevant issues that could not be adequately modeled in the MCA. In this study, ranks are defined for each options based on scoring values (shown in Table VII). At the end the of total MCA process, it is identified that Gasification is an appropriate AWT in Australia based on current conditions.

TABLE VII
 AGGREGATION

<i>Decision Options</i>	<i>Score</i>	<i>RANK</i>	
Anaerobic Digestion	0.74513	2	
Pyrolysis	0.38231	3	
Gasification	0.76711	1	Most preferred AWT
Incineration	0.21096	4	

IV. DISCUSSIONS

Selection of a suitable AWT in Australia is a difficult decision-making problem, which has to take into account different, often inconsistent goals and tasks, and social-economic and environmental aspect. In this study, most favourable scenario has been selected for AWT on the basis of

defined indicators to perform MCA. The methodology guarantees possibility to carry out quantitative, multidimensional, and at the same time objectivised evaluation of system solutions, which would replace intuitive or requiring expert's opinions assessments used so far.

The criterion maps were combined by logical operations. To generate criterion values using a Ranking Method for each evaluation unit, the values between 1 and 4 were given, where 4 indicates high importance and 1 indicates low importance depending on the criteria's class values. $CR \leq 0.1$, the pairwise comparison matrix is considered to be consistent enough. In this study, the value of $CR=0.02327$ falls much below the threshold value of 0.1 and it indicates a high level of consistency. Hence the weighting has been accepted.

Using PCM the criterion weights were calculated for Capital cost, Complexity, Public acceptability, Diversion from landfill and Energy produced as 0.25987, 0.10296, 0.38230, 0.07234 and 0.18253 respectively (shown in Table II). Scoring values for different AWTs have been determined as 0.74513, 0.38231, 0.76711 and 0.21096 for Anaerobic Digestion, Pyrolysis, Gasification and Incineration correspondingly (shown in Table VII). Ranking have been done according to scored value. It was observed that scored value of Anaerobic Digestion (Score: 0.74513) and Gasification (Score: 0.76711) are very close to each other that varies only decimal value. But as scoring limit maintains 0.1 to 1 and the score of Gasification is higher than Anaerobic Digestion, it is clear that Gasification has been ranked 1 and identified as an appropriate AWT in Australian conditions (shown in Table VII).

V. CONCLUSION

In this study, PCM has been applied under AHP to calculate the weight of the key indicators of AWTs. There were four AWTs / decision options considered (Anaerobic Digestion, Gasification, Pyrolysis and Incineration) with respect to five criteria (Capital cost, Complexity, Public acceptability, Diversion from landfill and Energy produced).

Finally, based on the currently available information and data, the outcome of this MCA of waste management options in Australia indicates that Gasification of waste is an appropriate waste to energy technique.

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