International Journal of Performability Engineering Vol. 12, No. 01, January, 2016, pp. 63-78.

Evaluation of Advanced Thermal Solid Waste Management Technologies for Sustainability in Florida

DUYGU YASAR, NURCIN CELIK* and JOSEPH SHARIT

Department of Industrial Engineering, University of Miami, Coral Gables, FL, USA

(Received on June 30, 2015, revised on August 12, 2015)

Abstract: The necessity of establishing sustainable solid waste management (SWM) systems has become apparent in the light of detrimental effects of existing SWM systems on the environment. As a result of the growing pressure for environmental protection and sustainability, the State of Florida has established an ambitious 75% recycling goal, to be achieved by the year 2020. Advanced thermal solid waste management (ATSWM) technologies can push Florida closer to this goal by drastically reducing the amount of waste sent to landfills. However, a comprehensive top-to-bottom assessment of technologies as well as their comparison against one another is crucial prior to the consideration of their implementation. The goal of this study was to evaluate emerging ATSWM technologies for Florida using the Analytic Hierarchy Process (AHP). The results indicated that gasification was ranked the highest while pyrolysis ranked the lowest among the three alternatives examined. However, the weights of criteria used for evaluating the technologies varied among the groups of counties. The implications of the findings for sustainability are also discussed.

Keywords: *Sustainable waste management, advanced thermal solid waste management technologies, municipal solid waste, Floridian counties, AHP*

1. Introduction

Municipal solid waste (MSW) is defined as everyday items such as product packaging, food scraps, bottles, newspapers, furniture, and clothing that are discarded by households and industries [1]. Thus, agricultural wastes, medical waste, or radioactive waste are not involved in the definition of MSW. In recent years, a significant increase has been observed in the variety and quantity of MSW worldwide, with the greatest rate of growth, both overall and per-capita, exhibited by the United States.

Due to this burgeoning growth as well as the accompanying increase in strict regulations of disposal operations and the dwindling availability of disposal sites, management of solid waste systems has become increasingly more challenging [2]. Furthermore, despite having improved over time, available waste-disposal methods have failed to meet the requirements of sustainable treatments, namely safety, effectiveness and environmental friendliness [3]. Increasing pressure for environmental protection and sustainability has led to an ambitious 75% recycling goal to be reached by the State of Florida by the year 2020 [2]. Based on 2013 Florida MSW management data, 62% of the annually generated solid waste is either combusted or landfilled [4].

Disposal of waste to conventional landfills leads to serious environmental problems as well as occupation of large amount of lands [5]. In 2013, CH_4 accounted for approximately 10% of all U.S. greenhouse gas emissions from human activities [6], with landfills representing the third largest source of CH_4 emissions with an 18% contribution.

*Corresponding author's email: celik@miami.edu

Another conventional waste management method that releases high volumes of emissions is the incineration technology. This technology provides a reduction in the total volume of waste and generates energy using MSW, yet, releases emissions of pollutant organic compounds such as NO_x, SO_x, and HCl [7, 8], in addition to high volumes of heavy metals [8, 9]. Another problem with MSW incineration is the serious corrosion of the incineration system by alkali metals, which incurs a high maintenance cost [8]. Furthermore, incineration of MSW has a relatively unfavorable energy efficiency due to a low process temperature caused by the low energy density of MSW [10]. Clearly, the need for establishing advanced and sustainable SWM technologies is evident.

Use of advanced thermal solid waste management (ATSWM) technologies to convert waste streams into valuable resources brings about a solution that simultaneously addresses the issues of human security, pollution, and energy recovery need [11]. These technologies have the potential to reduce waste while increasing the recycling rate, thus providing for sustainable waste management. Currently, implementation of these technologies is limited due to a number of factors including but not limited to regional divergence, political factors, market forces, and technical supports. Because these technologies are emerging or being researched in varying geographical locations, a unified and consistent top to bottom assessment needs to be conducted before these technologies can be considered for implementation in the State of Florida counties. Consistent with this objective, the focus of this paper is on the evaluation of ATSWM technologies and their potential for enabling Florida to reach its recycling goal by 2020. This study should also generalize to other geographical locations that are experiencing problems in, and seeking ways to achieve sustainable SWM.

2. Literature Review of Advanced Solid Waste Management Technologies

The importance as well as social and economic complexity of problems related to SWM in industrialized countries have shown a significant increase during the last three decades [12, 13]. The idea of completely eliminating waste is highly unrealistic; therefore, the best approach is to handle solid waste in a sustainable way which protects the environment and conserves natural resources. Accordingly, significant modifications to existing waste management technologies and programs have become necessary. In our considered case of Florida, such modifications are necessary in order to achieve the 75% recycling goal established by the Florida state government.

Compared to traditional disposal landfills which create an open loop in the MSW life cycle, the advanced disposal technologies usually combine recycling and recovery methods, leading to a closed loop in the MSW life cycle and thereby improving the recycling rate. Several researchers have performed evaluations of advanced SWM technologies and analysis for MSW processing and disposal, in order to decrease landfill utilization and increase waste recycling and recovery [12]. These technologies are known to be environmentally sound, cost-effective, and acceptable for implementation [9].

A study that was conducted in New York by the New York City Economic Development Corporation and Department of Sanitation (2004) provided information for future planning of SWM systems. The evaluation considered 43 technologies in total and was conducted based on a set of criteria that included readiness and reliability, size and flexibility, beneficial use of waste, marketability, public acceptability, and cost. The City of Los Angeles and URS Corporation collaborated to carry out an assessment project for identifying alternative MSW processing technologies that could improve landfill diversion in an environmentally sound manner. They concluded that the technologies best suited for processing unrecyclable MSW on a commercial level were the thermal technologies.

Chirico [14] conducted a study with the purpose of evaluation, analysis, and comparison of SWM technologies. This study investigated the capability of SWM technologies to decrease landfill utilization and emissions, promote sustainable economic development, and generate renewable energy in Georgia. It was concluded that plasma arc gasification is the most sustainable option, but with reservations toward its economic profitability.

Wilson et al. [15] conducted a study to compare the waste to energy conversion technologies, including gasification, plasma arc gasification, and pyrolysis from the standpoint of economic, design, operation, capacity, and efficiency aspects. In their study, air fed gasification was found to provide the most reliable, cost effective, and environmentally friendly conversion of MSW. Finally, an assessment of advanced thermal treatment of MSW was overviewed in a brief prepared by the Department for Environment and Rural Affairs Waste Implementation Program [16]. Here, benefits of ATSWM technologies, their markets, contribution to national targets, related necessary permits, and social and financial aspects were among the aspects considered.

This study brings a new perspective to the SWM literature by selecting the most suitable ATSWM technology for all the counties by categorizing them based on their annual waste generation and recycling characteristics. SWM divisions of each county were contacted to obtain their criteria preferences. These preferences were then used to determinate the most suitable ATSWM technology through use of the Analytic Hierarchy Process (AHP)—a method used for solving multi-criteria decision making problems by establishing a hierarchical model in the form of goal, criteria, and alternatives.

3. Thermal Treatment Technologies

The increasing environmental, technical, and public dissatisfaction with low performance of conventional incineration processes has rendered thermal processes as attractive choices for the treatment of MSW [17]. Thermal technologies operate at high temperatures that usually range from 700^{o}F to 10,000^{o}F. Papers, plastics, and food scraps are among the waste types used by thermal processes. The main output (byproduct) of thermal technologies is syngas (synthetic gas), a fuel gas mixture which is used for electricity generation. Thermal conversion is known as the most efficient conversion technology [18].

Thermal conversion technologies have several advantages over other treatment technologies such as incineration and composting. First, due to their closed system design, direct air emissions from the system is negligible. Hence, they can meet the air emission limitations established by government regulations. Second, the modular design of these plant technologies make them more flexible as compared to other technologies, thus enabling them to more effectively adapt to changes in waste volumes as well as meet the demands of local municipalities. Another advantage of thermal conversion processes over other options is that the syngas, which is the output of the process, can be converted into electricity.

Gasification, plasma arc gasification, pyrolysis, and steam classification are the four main types of thermal technologies utilized for MSW processing. In this study, only gasification, plasma arc gasification, and pyrolysis were considered in the evaluation as the necessary data could be found in publicly available sources only for these technologies.

3.1 Gasification

Gasification technology is primarily composed of the reaction of carbonaceous feedstock at temperatures above 1400^{o}F. Gasification has several advantages when compared to combustion for treatment of MSW. It operates in a low oxygen environment that bounds the release of emissions, and the hydrocarbon pollutants are removed in an additional gas cleanup process. The process also requires a lower volume of oxygen that further helps reduce the amount of gas produced (thus necessitating a cheaper gas cleaning process) [19], and 90% of incoming energy is available for end use [20]. Generated fuel gas during the gasification process can be used, in combination with reciprocating engines, cycle turbines, and fuel cells to efficiently convert fuel energy into electricity [17].

3.2 Plasma Arc Gasification

Plasma arc gasification is a multi-stage process that is initiated by feeding input materials that can range from hazardous wastes to plant matter [21]. The nature of the output ranges from electricity to a variety of fuels and chemicals. No emissions are released since the entire conversion process constitutes a closed system. According to the Westinghouse Plasma Corporation Report, only about 2-4% of the material introduced into a WPC plasma gasification plant needs to be sent to landfill.

3.3 Pyrolysis

Pyrolysis systems thermally break down solid waste in the absence of oxygen at temperatures of approximately 600°C and 800°C. It is a relatively simple and flexible process that can receive a wide variety of feedstock, and produces several usable outputs from typical waste streams [22]. Pyrolysis produces gases and a solid char product such as activated carbon, international grade diesel, and synthetic gas as a byproduct. A wide variety of waste including hazardous waste can be handled by the pyrolysis process as it can generate excess heat to reduce moisture content of waste below 10%.

4. Methodology

This study aims to assess the use of ATSWM technologies for the management of municipal solid waste. An AHP model was developed for the comparison of different ATSWM technologies and selection of the most appropriate one for a given county. Details of the considered AHP methodology are provided in Section 4.1, and the efficacy of our proposed model is demonstrated in the case study of Floridian counties.

4.1 Analytical Hierarchical Process

The analytical hierarchical process (AHP), first introduced by Saaty in 1980 [23], is a well-known method of addressing complex decision making problems by deriving weights to represent the relative importance of different criteria. In AHP, qualitative human judgments are quantified in the form of paired comparisons using ratio scales, where a subject matter expert (SME) ranks a set of criteria according to their relative importance [24]. The method has several associated advantages including its ease in implementation and adaptability to various applications such as vendor selection, project management, resource allocation, and selecting the best alternative. AHP is a hierarchically structured decision model that consists of objectives, criteria, sub-criteria, and alternatives, respectively. The method essentially relies on making pairwise comparisons between elements at a particular level and its counterparts at the upper levels.[25]. Alternatives (placed at the lowest level) are compared under each criterion; each criterion, in turn, is compared with respect to the goal of the problem, with the aim of computing the global priorities of alternatives in order to select the best one.

Once the model is constructed in this hierarchical manner, SME rankings are obtained on the set of criteria. Here, the selection of appropriate experts from the related fields is critical for the evaluation accuracy. The collected SME opinions (rankings) are converted into a square pairwise matrix A. Matrix A is also a positive reciprocal matrix that meets the reciprocal condition of a_{ji} being equal to $1/a_{ij}$ where, a_{ij} indicates a cell in the pairwise comparison matrix A, located in the i^{th} row and j^{th} column [26]. While there are several scales proposed in the literature to quantify the SME judgments, the original 1-9 scale introduced by Saaty [27] is still the one most widely used due to its application-free nature. Hence, it is utilized in this work to create the A matrix from qualitative SME opinions as demonstrated in Figure 1.

Figure 1: Explanation of 1-9 Saaty Scale

Individual pairwise comparison matrices derived from SME opinions are then combined together to calculate the weight of each criterion. The most common group preference aggregation method in AHP literature is the geometric mean [28]. As such, the aggregation of individual judgments (AIJ) in this work was completed using the geometric mean of corresponding elements from each individual matrix. This aggregated matrix developed to determine the criteria weights is called the consolidated decision matrix. Alternatives are also compared under each criterion in the form of pairwise comparison matrices and their local priorities under each criterion are computed using these matrices.

Local priority of each alternative is multiplied by its corresponding criterion weight and added to compile the global priorities of alternatives. The best alternative is chosen based on these global priorities. As an example from our considered case study, the local priority of gasification for the criterion "revenue" is multiplied by its weight; this same process is then repeated for every other criterion prior to their summation into the global priority of gasification (as a weighted sum).

When using the AHP methodology, consistencies of pairwise comparison matrices need to be checked in order to achieve a convincing result [29]. A comparison matrix is consistent if its consistency ratio is less than 0.1 [30]. Since there may be a bias in human judgments and the evaluation of SMEs is subjective, and also due to possible shortcomings inherent to the use of a 1-9 scale, a pairwise comparison matrix may not have a satisfactory consistency ratio. In this case, SMEs are required to reconsider their rankings. For this study, Expert Choice Decision Support Software was used to facilitate ease in computations of results from an established AHP model. The software allows the researcher to build a hierarchy and compute the results using relative or absolute measurements [31].

5. Data Collection

The collection of reliable data from various sources comprises a major task in this work, as these technologies are not currently in widespread commercial use. The data collection process was comprised of four stages. In the first stage, the set of criteria was defined for AHP. In the second stage of data collection, SMEs from Floridian counties were contacted to compute the criteria weights. In the third stage, Florida Department of Environmental Protection (FDEP) SWM 2013 annual reports were explored to obtain the annual waste generation for each waste disposal type of Floridian counties. These data were used to categorize the counties. In the last stage of data collection, advanced thermal SWM technology data were collected from publicly available sources and defined facilities.

5.1 Defining the Set of Criteria

The criteria for evaluation of ATSWM technologies were defined after inspection of a wide range of journal and white papers during the first phase of data collection. Several issues such as environmental policies, regulations, public health, and characteristics of ATSWM technologies were also taken into consideration. The set of criteria and corresponding explanations are given below:

- ***Revenue*** is the profit that the facility earns by selling the outputs of the process. The sales of the energy and products should provide a satisfactory profit.
- ***Tipping fee*** is a charge for a given quantity of waste received at a waste processing facility. For financial feasibility of a project, tipping fees should be cost competitive and should provide a significant contribution to the revenue of the facility.
- ***Capital cost*** of the project is the amount of money which is invested in the SWM project.
- ***Operation cost*** is the ongoing expenses for maintenance of the facility.
- ***Development period*** should not be too long as competitors could enter into the market given the competitiveness of the solid waste industry, even in the public sector.
- ***Flexibility of process*** should be considered since the municipal solid waste has a highly variable nature. The process should be flexible enough to keep up with the changes of the content of the waste. Flexibility of process may affect operation costs and tipping fees. The ability to convert to different waste types through a single process lowers the costs.
- ***Land requirement*** of the facility might be an important issue for some counties that do not own a readily available landsite to establish the facility.
- ***Net conversion efficiency*** shows how much of the received waste is diverted into energy or marketable products. Less efficient processes lead to higher operating costs, which are generally paid by higher tipping fees.
- ***Ease of permitting*** is the criterion to measure how capable the process is at obtaining the necessary local and state permits.
- ***Marketability*** of recovered products shows how much demand exists in the current market for the outputs of the process. It is not possible to generate the necessary revenue to support the process if the markets for the outputs being produced do not have market demand or current markets are too distant or unstable.
- ***Environmental impact*** of the process indicates the level of damage that the process or its byproducts have on the environment. The process itself should not contradict one of its main purposes, which is to reduce the damage on the environment.
- ***Public acceptability*** measures the level of public support to alternative technology. It is not possible for a SWM facility to function properly without public support.
- ***Number of facilities*** affects the availability of data and the size of vendors for ATSWM technologies.

The hierarchical structure of the AHP model developed for assessing alternative ATSWM technologies based on a defined set of criteria is given in Figure 2. The AHP structure was designed in a way that environmental, social, economic, technical, and regulatory issues could be taken into account appropriately. The model consists of three levels: 1) objective level, 2) criterion level, and 3) alternative level. At the alternative level (Level 3), three alternatives were placed under the set that contains 13 criteria. A 3×3 pairwise comparison matrix was created to compute local priorities of alternatives with respect to each criterion. Hence, thirteen 3×3 matrices were created in this work at the alternative level (Level 3). At the criterion level (Level 2), a single 13×13 pairwise comparison matrix was created for the comparison of the set of criteria with respect to the objective (Level 1). The criteria weights were computed from the 13×13 pairwise comparison matrix at the criterion level (Level 2),

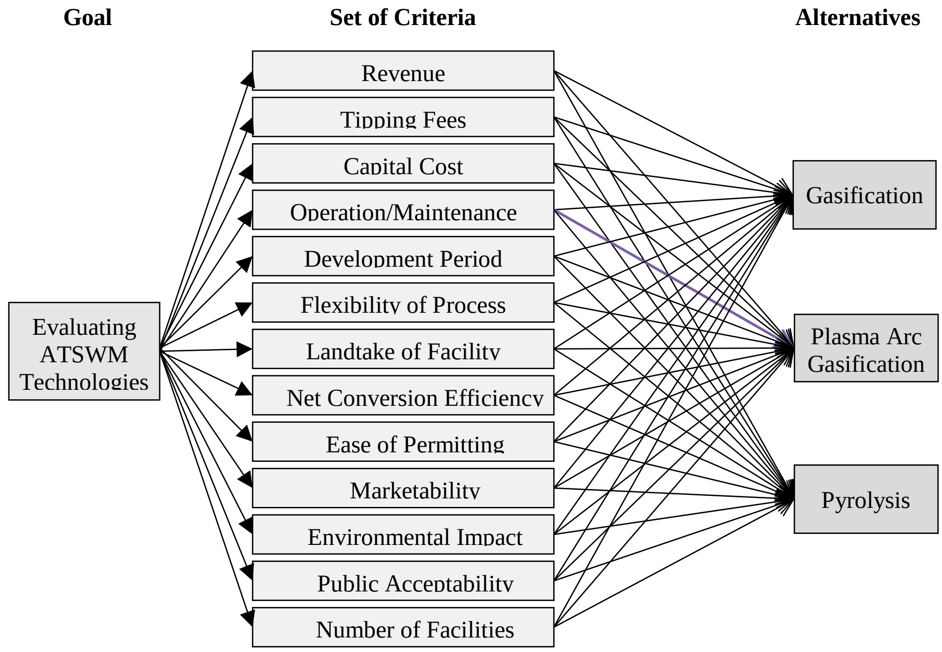

Figure 2: Hierarchical AHP Structure for Selection of ATSWM Technologies

5.2 Contacting SMEs

In the second stage of data collection, criteria weights were determined after SMEs from SWM divisions of Floridian counties and the FDEP were asked to rank the set of criteria via surveys. Here, a total of 173 requests were placed to waste management experts in 67 different counties within the state of Florida. Since the counties were categorized into groups (see Section 5.3), each SME ranking contributed to the computation of criterion weight of its corresponding county group. The ranking obtained from the FDEP was also added to each group of counties in order to reflect the impact of overall state considerations within these rankings. To this end, FDEP works with all counties to protect Florida's environment. For instance, there are 10 counties in Group 1. In order to calculate the weights of the set of criteria, 10 rankings of the set of criteria obtained from 10 counties and 1 ranking obtained from FDEP were incorporated into AHP. Thus, 11 different rankings were used in computation of the weights of the criteria set for Group 1. Similarly, as there are 7 different counties in Group 4, a total of 8 rankings (7 rankings obtained from 7 counties and 1 ranking obtained from FDEP) were incorporated into AHP to compute the weights of the set of criteria for this group. The sets of criteria for the remaining counties were performed in a corresponding manner.

Experts contacted from these counties came from various backgrounds related to solid waste. Their backgrounds and job titles included solid waste specialists, solid waste managers, environmental service directors, public works directors, solid waste recycling coordinators, hazardous waste professional engineers, recycling coordinators, utility operations directors, solid waste facility directors, sanitation directors, and environmental managers. Their opinions represent the preferences of SWM divisions of Floridian counties on the evaluation of technologies.

5.3 Categorization of Counties

In the third stage of data collection, similar counties were categorized based on their ability to manage waste using similar advanced SWM technology. This categorization of counties into different groups was conducted based on the waste disposal types and annual waste generation. FDEP SWM 2013 annual reports were used to obtain solid waste disposal types and waste generation data of each county [4]. The first step was to classify counties based on least recycled disposal types. The formed groups were then divided into subgroups based on their annual waste generation amounts.

5.3.1 Municipal Solid Waste Types in Floridian Counties

According to United States Environmental Protection Agency (EPA), MSW heavily consists of daily items that are discarded by the residents and businesses such as newspapers, office papers, paper napkins, plastic films, clothing, food packaging, cans, bottles, food scraps, yard trimmings, product packaging, grass clippings, furniture, wood pallets, appliances, paint, and batteries [1]. In this study, the definition provided by the EPA for MSW is used to categorize the counties based on the waste types. Waste types that are not considered in the categorization of counties and reasons for not using them are discussed below.

For some waste types that are 100% recyclable, recycling technologies are already well established with their associated markets. For instance, non-ferrous metals such as brass, stainless steel, copper, and aluminum are 100% recyclable materials that do not require other conversion processes. Moreover, 48% of Floridian counties have a recycling rate greater than 50% for non-ferrous metals. As such, these wastes do not need to be converted by ATSWM technologies and therefore are not considered as part of the categorization.

Construction and demolition (C&D) debris waste is formed during new construction, renovation, and demolition of buildings, roads, and bridges. C&D debris often contains massive materials such as concrete, asphalt, doors, windows, gypsum, and bricks. C&D waste is primarily sent to landfills that have permission to receive only C&D waste or that receive primarily MSW. As C&D debris has a separate disposal stream than MSW, C&D debris is also not considered as one of the waste types for categorization of the counties.

5.3.2 Floridian County Categories for AHP

The main purpose of using ATSWM technologies is to reduce the amount of landfilled waste. For this reason, categorization was performed based on the least recycled waste type in each county. The counties with the lowest recycling rates of yard trashes were categorized into the same group while the counties with the lowest recycling rates of various paper waste, including newspaper, office paper, and cardboard, were categorized into another group. The most widely generated waste type was chosen when more than one type has the lowest recycling rate.

Three groups, food-yard trash, paper, and plastic trash, were obtained in the first categorization as these were the three waste types that had the lowest recycling rate in each county. Subgroups were obtained in the second step based on the waste generation amount of each county.

The grouping procedure is illustrated in Figure 3. 2013 Solid Waste Annual Report County MSW and Recycling Data were used for grouping these counties. The grouping process shown in Figure 3 can be implemented to rearrange the groups as more annual waste generation data become available.

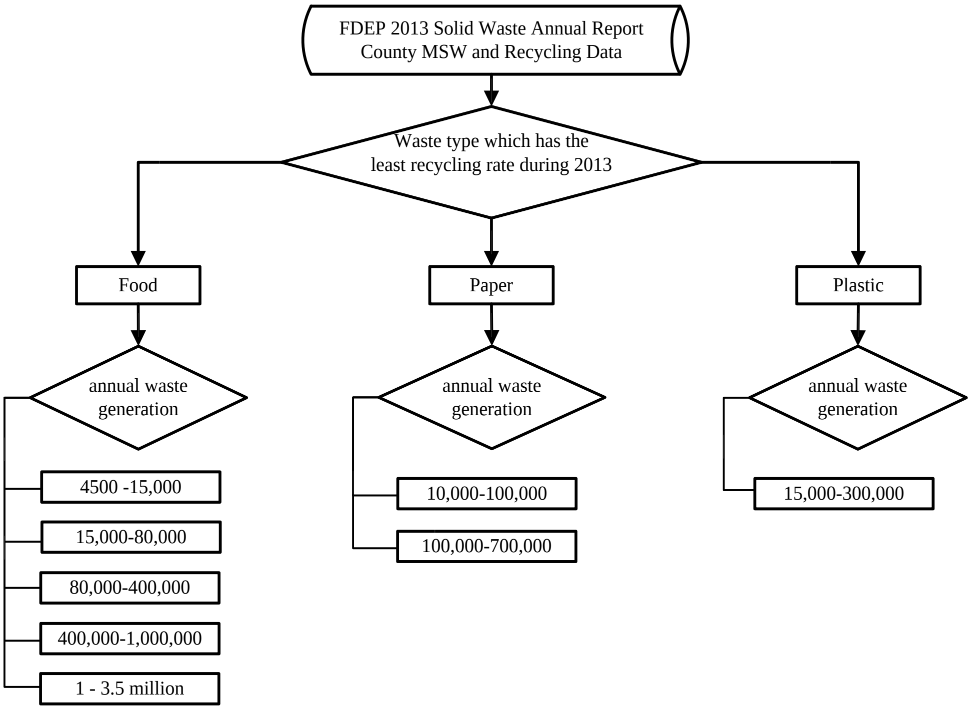

Figure 3: Grouping Procedure of Floridian Counties

Formed county groups were as follows:

- ***Group 1*** consists of 10 counties. The counties had the least recycling rates for food where their annual waste generation ranged from 4500 to 15,000 tons.
- ***Group 2*** consists of 10 counties. The counties had the least recycling rates for food where their annual waste generation ranged from 15,000 to 80,000 tons.
- ***Group 3*** consists of 10 counties. The counties had the least recycling rates for food and yard trash where their annual waste generation ranged from 100,000 to 400,000 tons.
- ***Group 4*** consists of 7 counties. The counties had the least recycling rates for food where their annual waste generation ranged from 450,000 to 950,000 tons.
- ***Group 5*** consists of 8 counties. The counties had the least recycling rates for food where their annual waste generation ranged from 1 million to 3.5 million tons.
- ***Group 6*** consists of 6 counties. The counties had the least recycling rates for paper product where their annual waste generation ranged from 10,000 to 100,000 tons.
- ***Group 7*** consists of 10 counties. The counties had the least recycling rates for plastic products where their annual waste generation ranged from 15,000 to 300,000 tons.
- ***Group 8*** consists of 6 counties. The counties had the least recycling rates for paper products where their annual waste generation ranged from 100,000 to 700,000 tons.

5.4. Technology Data

In the last stage, data for advanced SWM technologies were collected from publicly available sources and from facilities in the U.S. Non-financial data are presented in Table 1. Some of the criteria were based on verbal assessments prior to their conversion into numerical values (e.g., environmental impacts of technologies were assessed in the available sources as low, medium, or high, and converted into numerical values using a scale of 1 to 9, with 9 indicating the highest performing alternative).

Table 1: AHP Input: Non-Financial Data for Alternative Technologies

Non-financial Data	Plasma Arc Gasification	Gasification	Pyrolysis
Development Period	7	9	4
Flexibility of Process	5	9	7
Landtake of Facility	1	6	9
Net Conversion Efficiency	9	7	4
Ease of Permitting	5	9	9
Environmental Impact	7	9	2
Public Acceptability	2	9	5
Number of Facilities	2	9	4

As indicated in Table 2, financial data included the capital cost and operation cost of technologies, the revenue that the facility obtains, and the tipping fee of the facility. These data were converted into values on the 1-9 scale prior to being used as input in AHP.

Table 2: AHP Input: Financial Data for Alternative Technologies

Financial Data	Plasma Arc Gasification	Gasification	Pyrolysis
Revenue *$/year*	3,200,000	250,000	300,000
Tipping Fee *$/ton*	30-50	120-140	130-160
Capital Cost *$ million*	450	230 - 415	250-500
Operation Cost *$ million/year*	9	13 - 23	11-25

Technology data were used for pairwise comparison of alternatives under each criterion. For each group of counties, 13 pairwise comparison matrices were formed using the technology data obtained during the study. Local priorities of alternatives under each criterion were then calculated. Finally, the local priorities were used to calculate global priorities of alternatives.

6. Criteria Weights and AHP Results

The next task was to compute the weights of the set of criteria for each group of counties. The AHP procedure, as discussed in the previous sections, was repeated eight times for the eight groups of counties. SME rankings obtained from counties were distributed to the related groups of counties based on their categorization. Rankings were then converted into pairwise comparison matrices using the 1-9 scale. After pairwise comparison matrices were incorporated into the AHP model, results for criteria weights were obtained for each group of counties. Eight 13×13 square pairwise comparison matrices were created in total. The computed criteria weights for each group of counties are shown in Figure 4, where the sum of criteria weights inside each group is equal to 1.

In the AHP model, pairwise comparisons of alternatives were also performed under each criterion for each group of counties. $8 \times 13 = 104$ (number of groups × number of criteria) 3×3 square matrices (for alternatives) were created using the technology data.

Local priorities of alternatives were then calculated in this intermediate step, with the results from this step used for calculating the global priorities (which are presented in Section 7).

Consistency ratios were computed for each group of counties, with ratios below 0.1 indicating consistency in the judgments of the SMEs. The results indicated (Figure 5) that the overall consistency ratios for all of the considered groups were below 0.1.

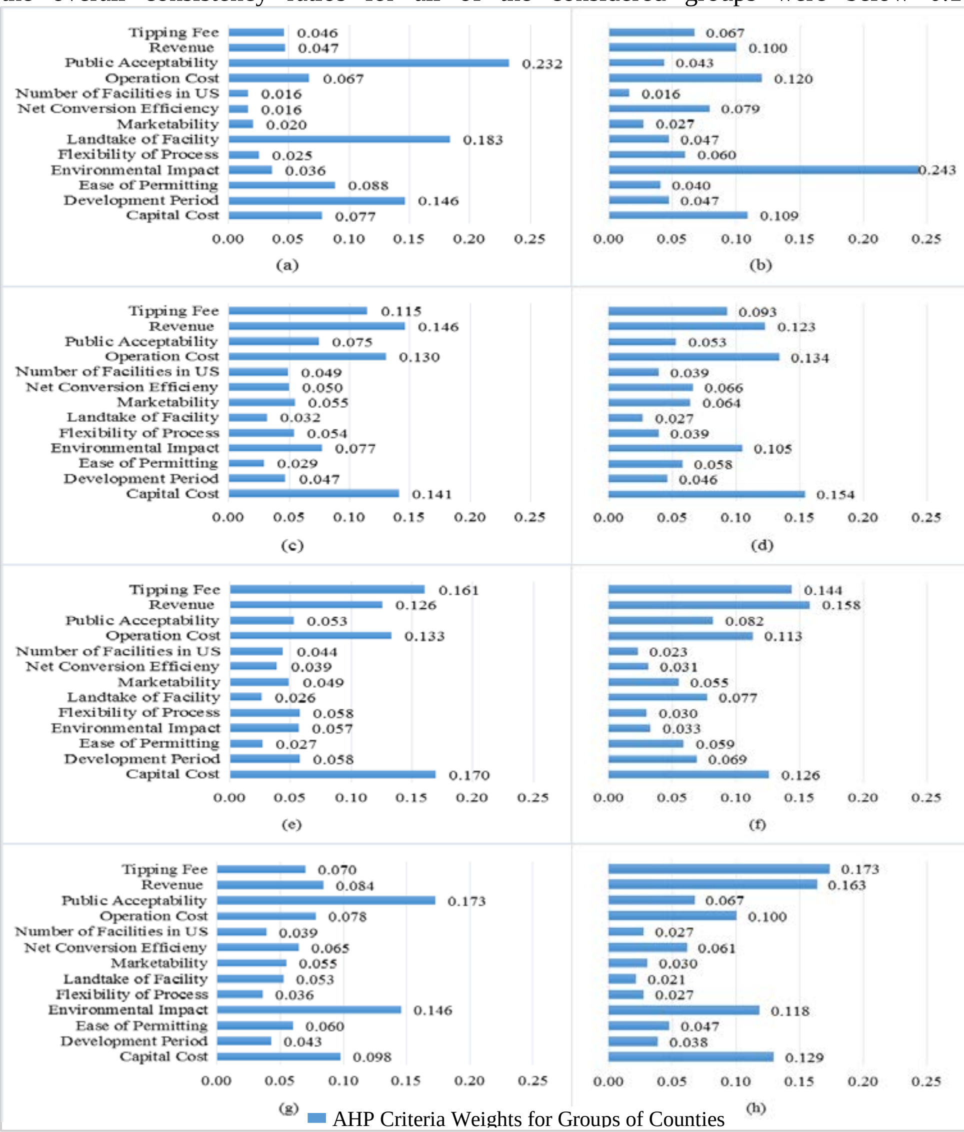

Figure 4: Criteria Weights Obtained from Our Model (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4, (e) Group 5, (f) Group 6, (g) Group 7, (h) Group 8

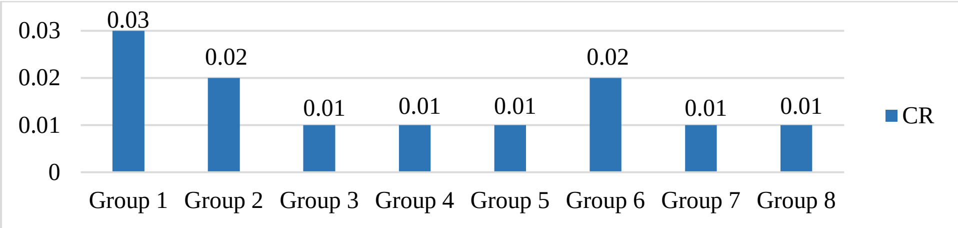

Figure 5: Overall Consistency Ratios (CR) Obtained from Our Model (<<0.1)

7. Recommendations

Global priorities of alternatives were obtained for each group of counties as shown in Figure 6. The data in Figure 6 were computed by combining the criteria weights and the local priorities of alternatives under each criterion. In order to compute local priorities, 13 (number of criteria) 3×3 square pairwise comparison matrices were formed for each group of counties, which resulted in 104 matrices in total.

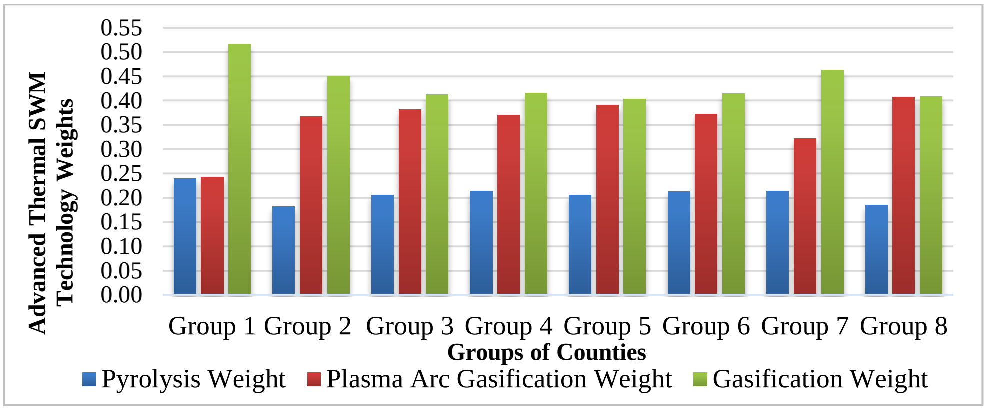

Figure 6: Global Priorities for All Groups of Counties

The results obtained from our AHP model indicated that the gasification had the highest ranked global priority for all groups as shown in Figure 6. However, it can be seen that weights of the plasma arc gasification and gasification technologies for Groups 5 and 8 are very close as well. Because the capital cost criterion has been quite highly ranked for Groups 5 and 8, and plasma arc gasification technology comes at the expense of high capital cost, this technology cannot be recommended for these groups.

For Groups 1, and 7, where the most important criterion is public acceptability, plasma arc gasification does not present a valid option unless significant public outreach is performed due to existing public concerns about this technology. As the most important criterion for the Group 2 is environmental impact, and the gasification and plasma arc gasification technologies both perform well on reducing the greenhouse gas emissions, either of these two technologies may be recommended. Because revenue is the most important criterion for Groups 3 and 6, plasma arc gasification is recommended as it may be best at serving to increase revenue in the long term. Capital cost is the most important criterion for Group 4; thus, gasification is the most viable option for these counties considering they have a limited budget for investment.

For the counties interested in the syngas output of thermal technologies, all of the considered alternatives may serve as a good option since they all generate syngas that can be converted into energy. When the availability of the technology is considered, gasification technology has been commercially used worldwide and in the U.S., with a large supply of available vendors. For counties that may collaborate with the facilities in other countries, plasma arc gasification is also a viable option.

These evaluations and recommendations provide a robust basis and structural framework for the counties that are presently considering implementing advanced SWM technologies. Further evaluations can be built based on this study for those municipalities that are conceiving SWM projects.

8. Sensitivity Analysis

Following the derivation of the AHP results, we performed a sensitivity analysis to evaluate how input uncertainty might impact the outputs. We confined this exploratory analysis to groups 5 and 8, in which the capital cost criterion was found to be highly ranked. Our aim was to show how the reduction in the weight of capital cost affects the technology evaluation results. Here, two criteria weights, marketability and capital cost, were switched. In AHP, the total weight of the 13 criteria should be equal to 1. Therefore, a sensitivity analysis for a given criteria can only be conducted by changing the weight of at least one other criterion weight (while keeping the other criteria weights constant). In our case, we selected to switch the weights of capital cost and marketability for both groups, as the impact of changing the weight of marketability is rather insignificant compared to changing the weight of any of the other criteria in all three of the technologies. This enables us to better observe the impact of changing the weight of capital cost on different technologies.

For Group 5, the weight of capital cost was decreased to 0.049 whereas the weight of marketability was increased to 0.170. As shown in Figure 7, these changes resulted in plasma arc gasification being ranked the highest. Specifically, the global weight of plasma arc gasification increased from 0.391 to 0.407, the weight of gasification decreased from 0.403 to 0.373, and the weight of pyrolysis increased from 0.206 to 0.220. Thus the effects of high capital cost on the global weights of plasma arc gasification and pyrolysis were decreased following a decrease in the weight of the capital cost criterion.

The same process was followed for Group 8. The weight of capital cost was decreased from 0.129 to 0.030. The global weight of plasma arc gasification increased from 0.407 to 0.420, the weight of gasification decreased from 0.408 to 0.381, and the weight of pyrolysis increased from 0.185 to 0.199. However the relative rankings of the technologies based on their global weights did not change for Group 8.

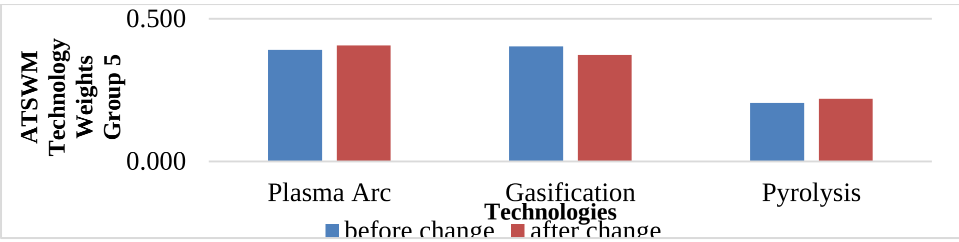

Figure 7: Sensitivity Analysis Results for Group 5

9. Contributions to Sustainability

Sustainability is defined as satisfying the needs of the present without precluding future generations from meeting their own needs [32]. One of the most important strategies for implementing sustainability involves preventing waste generation [33]. Sustainable waste management comprises a variety of practices whose implementation depends on the involvement of various stakeholders, including households, industries, and government institutions.

For a waste management system to be sustainable it must be environmentally effective, economically affordable, and socially acceptable [3]. ATSWM technologies contribute to sustainable waste management by reducing waste sent to landfills and by developing sources of renewable energy. Recovered products meet some market demands and contribute to sustainable resource consumption, which helps to close the material consumption loop. Unless we replace what we consume, by converting our waste into usable products, our resources will become depleted. For instance, the gasification process generates syngas as an output, which can then be used for generating electricity. Thus, utilization of ATSWM technologies to generate energy from MSW, which is otherwise landfilled, has the potential to make a significant contribution to sustainable development.

10. Conclusions

This research dealt with establishing a structural framework for assessment of ATSWM technologies for the counties comprising the state of Florida. In order to have an adequate number of SME opinions, counties were grouped based on waste disposal types and annual waste generation. The findings indicated that the most and least important criteria weights varied from one group to another; still, gasification was found to have the highest global priority while pyrolysis had the lowest global priority for all groups. This supports the information obtained from the literature for the comparison of ATSWM technologies. A number of studies on the issue of thermal waste to energy processes, including those done by the US Department of Energy [34], the US Environmental Protection Agency (USEPA), and Alameda Power & Telecom [35], have concluded that conventional gasification systems provide the most cost-effective and clean form of waste to energy systems. These results, however, were obtained from currently available data and may change as the commercial status of these technologies change. This study provides a practical analysis of ATSWM technologies for Floridian counties as well as a structural framework for future works for evaluating advanced SWM technologies that is believed to be generalizable to other locations as well.

References

[1] United States Environmental Protection Agency. Wastes-Municipal Solid Waste. U.S. Department of State, Washington, D.C. [updated 2/28/2014]. Available from: http://www.epa.gov/epawaste/nonhaz/municipal/.

[2] Antmann, E. D., X. E. Shi, and B. Hayton. *Simulation-Based Optimization for Planning of Effective Waste Reduction, Diversion, and Recycling Programs*. Coral Gables, 2012.

[3] Morrissey, A. J. and J. Browne. *Waste Management Models and their Application to Sustainable Waste Management.* Waste management, 2004; 24(3): 297-308.

[4] Solid Waste Management in Florida 2013 Annual Report. Florida Department of Environmental Protection. Tallahassee, 2013.

[5] Belevi, H. and P. Baccini. *Long-Term Behavior of Municipal Solid Waste Landfills*. Waste Management & Research, 1989; 7(1): 43-56.

[6] United States Environmental Protection Agency. Overview of Greenhouse Gases. U.S. Department of State, Washington, DC. [updated 5/7/2015]. Available from: http://epa.gov/climatechange/ghgemissions/gases/ch4.html.

[7] de Holanda, M.R. and J.A.P. Balestieri. *Cogeneration in a Solid-Wastes Power-Station: A Case-study*. Applied Energy, 1999; 63(2):125-139.

[8] McKay, G. *Dioxin Characterisation, Formation and Minimisation During Municipal Solid Waste (MSW) Incineration: Review*. Chemical Engineering Journal, 2002; 86(3): 343-368.

[9] Suksankraisorn, K., S. Patumsawad and B. Fungtammasan. *Combustion Studies of High Moisture Content Waste in a Fluidised Bed*. Waste Management, 2003; 23(5):433-439.

[10] Wiles, C. C. *Municipal Solid Waste Combustion Ash: State-of-the-knowledge*. Journal of Hazardous Materials, 1996; 47(1): 325-344.

[11] Ripa, M., C. Buonaurio, S. Mellino, G. Fiorentino and S. Ulgiati. *Recycling Waste Cooking Oil into Biodiesel: A Life Cycle Assessment.* International Journal of Performability Engineering, 2014; 10(4): 347-356.

[12] Antmann, E. D., X. Shi, N. Celik and Y. Dai. *Continuous-Discrete Simulation-based Decision Making Framework for Solid Waste Management and Recycling Programs.* Computers & Industrial Engineering, 2013; 65(3): 438-454.

[13] Hokkanen, J. and P. Salminen. *Choosing a Solid Waste Management System using Multicriteria Decision Analysis*. European Journal of Operational Research, 1997; 98(1): 19-36.

[14] Chen, Y., J. J. Cheng and K.S. Creamer. *Inhibition of Anaerobic Digestion Process: A Review.* Bioresource Technology, 2008; 99(10): 4044-4064.

[15] Wilson, B., N. Williams, B. Liss, and B. A. Wilson. *Comparative Assessment of Commercial Technologies for Conversion of Solid Waste to Energy*. EnviroPower Renewable Inc., Boca Raton, 2013.

[16] Department for Environment Food and Rural Affairs (DEFRA). *Advanced Thermal Treatment of Municipal Solid Waste*. Policy Paper. London, 2013. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221035/pb13888-thermal-treatment-waste.pdf

[17] Zafar, S. *Gasification of Municipal Solid Wastes Bioenergy Consult Webpage 2015* [cited 2015]. Available from: http://www.bioenergyconsult.com/category/waste-to-energy/.

[18] URS Corporation. Evaluation of Alternative Solid Waste Processing Technologies. City of Los Angeles, Department of Public Works, Bureau of Sanitation. Los Angeles, 2005.

[19] Popov, V., Itoh, H., Mander, U., and Brebbia, C.A. *Waste Management and the Environment V*: WIT; Boston; 2010.

[20] Paisley, M. A. *The Taylor Biomass Gasification Process - An Advancement in Biomass Energy Options*. Taylor Biomass Energy, LLC. Montgomery.

[21] Dodge, E. *Plasma Gasification: Clean Renewable Fuel Through Vaporization of Waste.* Waste Management World. 2009; 10(4).

[22] Serio, M. A., E. Kroo, R. Bassilakis, M. A. Wójtowicz, E. M. Suuberg. *A Prototype Pyrolyzer for Solid Waste Resource Recovery in Space.* SAE Technical Paper, 2001.

[23] Saaty, T. L. *The Analytic Hierarchy Process*. McGraw-Hill, New York 1980.

[24] Sharit, J., S. J. Czaja, D. Perdomo and C. C. Lee. *A Cost–benefit Analysis Methodology for Assessing Product Adoption by Older User Populations*. Applied Ergonomics, 2004; 35(2): 81-92.

[25] Schmoldt, D. L., D. L. Peterson, R. L. Smith (editors). *The Analytic Hierarchy Process and Participatory Decision Making*. Proceedings of the Fourth International Symposium on Advanced Technology in Natural Resources Management; 1995: Citeseer.

[26] Saaty, T. L. *Deriving the AHP 1-9 Scale from First Principles*. ISAHP 2001 proceedings, Bern, Switzerland, 2001.

[27] Saaty, T. L. *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*. RWS Publications, Pittsburgh 1994.

[28] Xu, Z. *On Consistency of the Weighted Geometric Mean Complex Judgement Matrix in AHP.* European Journal of Operational Research, 2000; 126(3): 683-687.

[29] Wan, C., X. Yan, J. S. Di Zhang and S. Fu. *Facilitating AHP-TOPSIS Method for Reliability Analysis of a Marine LNG-Diesel Dual Fuel Engine*. International Journal of Performability Engineering, 2014; 10(5): 453-466.

[30] Zeshui, X. and W. Cuiping. *A Consistency Improving Method in the Analytic Hierarchy Process.* European Journal of Operational Research, 1999; 116(2): 443-449.

[31] Saaty, T. L., and L. G. Vargas. *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*. Springer Science & Business Media, New York 2012.
[32] McDougall, F. R., P. R. White, M. Franke, and P. Hindle. *Integrated Solid Waste Management: A Life Cycle Inventory*. John Wiley & Sons, Oxford 2008.
[33] Misra, Krishna B. *Handbook of Performability Engineering*. Springer, London 2008.
[34] Klein, A. *Gasification: An Alternative Process for Energy Recovery and Disposal of Municipal Solid Wastes*. Columbia University. New York, 2002.
[35] Clayton, S., G. Stiegel, and J. Wimer. *Gasification Markets and Technologies—Present and Future: An Industry Perspective*. US Department of Energy, Gasification Technologies Product Team. Washington, 2002.

Duygu Yasar is a Ph.D. student in the Department of Industrial Engineering at the University of Miami. She earned her B.Sc. degree in the field of Industrial Engineering from the Yildiz Technical University, Turkey. She graduated in the top 5 percent of her class. Her research interests evolve around sustainable solid waste treatment, evaluation of solid waste management technologies, multi-criteria decision analysis, advanced thermal treatment of municipal waste, and modeling of integrated large-scale and complex systems.

Nurcin Celik is an Assistant Professor in the Department of Industrial Engineering at the University of Miami. She received her M.S. and Ph.D. degrees in Systems and Industrial Engineering from the University of Arizona. Her research interests lie in the areas of integrated modeling and decision making for large-scale, complex and dynamic systems with applications to electric power grids, semiconductor manufacturing, and solid waste systems. She has received several awards, including the 2014 Eliahu I. Jury Early Career Research Award, 2013 AFOSR Young Investigator Award, 2011 IAMOT Outstanding Research Project Award, and 2009 IIE Outstanding Graduate Research Award.

Joseph Sharit is a Research Professor in the Department of Industrial Engineering at the University of Miami. He received his M.S. and Ph.D. degrees in Systems and Industrial Engineering from Purdue University. He is a principal investigator in the Center on Research and Education for Aging and Technology Enhancement (CREATE) at the University of Miami and a research scientist with the Laboratory of E-Learning and Multimedia Research within the Miami Veterans Health System. His research interests include human-machine interaction, human error and human reliability analysis, and system safety.