PLANNING FOR CLEAN ENERGY COMMUNITY

By

QIANCHENG ZHAO

A thesis submitted to the

Graduate School-New Brunswick

Rutgers, The State University of New Jersey

In partial fulfillment of the requirements

For the degree of

Master of Science

Graduate Program in Industrial Systems Engineering

Written under the direction of

Dr. Mohsen Jafari

And approved by

New Brunswick, New Jersey

October, 2017

ABSTRACT OF THE THESIS

Planning for Clean Energy Community

By Qiancheng Zhao

Thesis Director:

Dr. Mohsen A. Jafari

An optimization model is proposed to find out the best waste to energy (WtE) technology combination and municipal solid waste (MSW) disposal scenario for a disadvantaged community. Three major types of waste streams and three mainstream WtE technologies are of interest there; waste streams are paper waste, plastic waste, and organic waste; WtE techniques are incineration, pyrolysis/gasification, and anaerobic digestion (AD). Whilst other possible renewable energies such as solar resource are considered as an option to make profit and operate the community cleanly. In this study, firstly, forecasts of waste generation and population of this region are performed on a ten-year scale using method called a fuzzy grey model GM (1, 1). The prediction of waste generated in studied region is the feedstock of WtE technologies to produce energy. In addition, the compositions of different waste streams are calculated, assuming waste materials are collected and classified and then could be applied to optimization model directly. The problem arises that for disadvantaged communities to fully utilize the waste land there and recover energy from waste to transfer it into clean one, a multi-objective optimization model is formulated to maximize the profit and minimize the carbon emission of the WtE industries while satisfying the energy consumption. A case study of community in Los Angeles. is performed after methodology was modeled; results show that the installation of WtE plants and solar panels will make this community self-sustaining and accomplish a positive net profit after ten-year run.

This research is a starting point of one new part of a whole simulation platform called Smart City. Aiming at planning for a clean and efficient community, this research mainly finds the possibility of transferring a disadvantaged community and recovering waste energy as much as possible in an optimal setting. Some details of the problem are not addressed, but this study still gives out some possible future work directions.

Acknowledgements

This thesis could not have been completed without the help from faculty of Department of Industrial System Engineering, Rutgers, as well as several PhD students. I could not have completed this thesis without their guidance, suggestion and support.

Surely I would like to especially thank my advisor Dr. Mohsen Jafari first, who gave me a lot of guidance and ideas on this thesis based on his invaluable expertise and experience in the field of energy. Dr. Jafari led me to an absolutely new and promising field of energy resource although my background is electrical engineering. His inspiration and attitude made me learn a lot and get to know how to be a professional industrial engineer in my future study and work.

I would like to thank the members of this research group, Dr. Ali Ghofrani, Dr. Khashayar Mahani, and Dr. Danial Nazemi. Dr. Ghofrani helped me a lot on the preparation of my research and guided me on lots of details that I was not familiar with. Dr. Mahani gave me the hint and inspiration on the electrical vehicle part of my thesis. While Dr. Nazemi provided me with useful suggestion on my thesis defense. Their altruistic suggestion and behavior will truly not be forgotten and it was a good experience to work with those intelligence people.

I would like to thank the members of my thesis committee, Dr. David Coit and Dr. Kang Li. They provided me with valuable feedback, inspiration, and motivation for my work. Their advice and suggestions would not be forgotten and it is been an good experience for me to learn from.

Dedication

To my parents Youming and Daixiu, far away in my homeland.

Table of Contents

List of Figures

List of Tables

Table 1: Table of Acronyms

WtE	Waste to Energy
MSW	Municipal Solid Waste
AD	Anaerobic Digestion
GM	Grey Model
TPA	Ton Per Annum
O&M	Operation and Maintenance
CalEPA	California Environmental Protection Agency
LP	Linear Optimization
EV	Electrical Vehicle
PV	Photovoltaic
AHP	Analytic Hierarchy Process
BOCR	Benefits, Opportunities, Costs and Risks
LCA	Life Cycle Assessment
I-O	Input-Output
3E	Energy, Economy and Environment

Table 2: Table of Nomenclatures

Subscript	
i	Year
j	Types of WtE technologies, 1=incineration, 2=pyrolysis/gasification, 3=anaerobic digestion
k	Types of power plant, 1=incineration, 2=pyrolysis/gasification, 3=anaerobic, 4=solar energy, 5=wind power
Variables	
χ	Set of decision variables
P	Feasible region of optimization model
p	Price of electricity
O_j^x	Output rate for paper waste in technology j $(j = 1,2,3)$
O_j^y	Output rate for plastic waste in technology j $(j = 1,2,3)$
O_j^z	Output rate for organic waste in technology j $(j = 1,2,3)$
x_{ij}	Total paper waste send to technology j in year i $(j = 1,2,3;\ i = 1,2,\ldots,10)$
y_{ij}	Total plastic waste send to technology j in year i $(j = 1,2,3;\ i = 1,2,\ldots,10)$
z_{ij}	Total organic waste send to technology j in year i $(j = 1,2,3;\ i = 1,2,\ldots,10)$
V	Energy output from PV panels
W	Energy output from wind power
C_j	Estimated capital cost for technology j $(j = 1,2,3)$
M_{ij}	Maintenance and operation cost for technology j in year i $(j = 1,2,3;\ i = 1,2,\ldots,10)$
G_j	Gate fee for technology j $(j = 1,2,3)$
E_j	Carbon emission rate in technology j $(j = 1,2,3)$
Com_i	Electricity consumption in year i $(i = 1,2,\ldots,10)$
l_k	Land requirement for power plant k $(k = 1,2,3,4,5)$
L	Total waste land in community
X_i	Total paper waste generated in year i $(i = 1,2,\ldots,10)$
Y_i	Total plastic waste generated in year i $(i = 1,2,\ldots,10)$

Z_i	Total organic waste generated in year i ($i = 1,2,\ldots,10$)
S_j	Capacity of plant j ($j = 1,2,3$)

1. Introduction

Disadvantaged community has multiple definitions related to environment, demography, architecture, or energy. They mainly exist in developing world today; however, a great proportion of communities and neighborhoods is still operating inefficiently and unclean in developed countries such as in the United State where the solid waste is not recovered or vacant land is not utilized properly, causing a great waste of energy and land. They are classified as disadvantaged community as well. It is reported by USEPA that MSW generated in 2014 is 258.5 million tons in US, with a mild increasing trend in past 20 years, and the MSW is projected to reach 9.5 billion by 2050 worldwide because of rapid urbanization and population growth. Absolutely, there is a huge biomass and energy wasted through the process of generating solid waste or wastewater in daily life. Recovering energy in waste will definitely save a lot of energy and resources and at the same time, reduce the carbon emission and pollution. Therefore, recovering energy from MSW becomes imminent and draws a significant attention in recent years as a new way to save energy and environment.

Some materials in waste like metal can already been fully recycled, while others remain untreated in disposal process. Traditional methods treating waste like landfilling can, as well, recover biomass or energy; however, the negative environmental impact of these immature techniques made them less preferable especially in developed countries since they are harmful to land and atmosphere. Therefore, researchers and scientists started to seek new or improved technologies to treat waste and recover energy more efficiently. A hierarchy of waste management is shown in Figure 1; it demonstrates an exhaustive hierarchy and classification of waste management today. The next section provides a brief introduction about major WtE technologies widely studied and applied today which are considered in our problem.

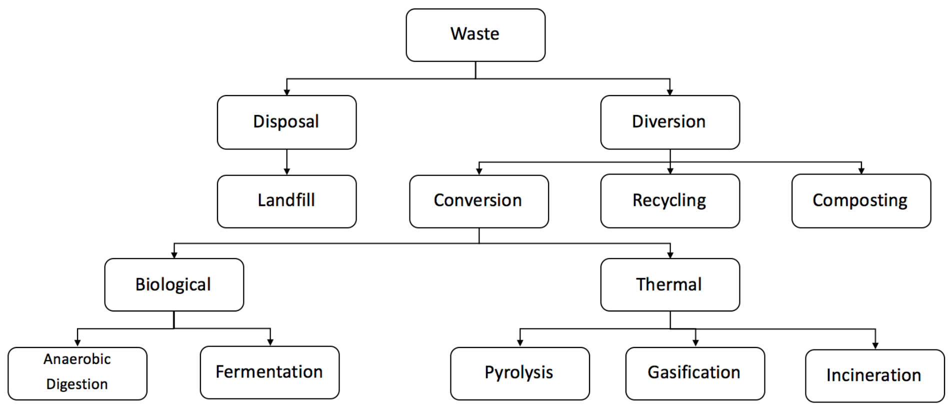

Figure 1: Hierarchy of Waste Management

1.1.WtE Technology Overview

1.1.1. Incineration

Incineration is a mature and well-developed technology, also referred to as mass burning. It involves the combustion of almost all types of solid waste and converts biomass in waste materials to electricity and heat. Figure 2 shows a simplified process in incineration plant. Incinerators have the capability of reduction on the municipal solid waste (MSW) up to 90%, with an overall conversion efficiency of 18-26%. An incineration normally requires a temperature in the region of 850 to 1100℃. The end product derived from this process is primarily hot combusted gas consisting of nitrogen, CO2, and some non-combustible residues or ashes. The heat generated from combustion process can be used to operate steam turbines for electricity production or for heat exchangers used to heat up process steams in industry. Nevertheless, due to the high moisture concentration of MSW, direct energy recovery from waste through incineration will lead to unnecessary energy losses. A pre-treatment of drying is usually required to remove the high moisture content in waste before it feeds combustion chamber.

A typical incineration plant can generate 550-750 kWh of electricity or equivalent to 2 MWh of heating per ton of mixed waste. Considering an average price of four cents per kWh of electricity in US, revenues from combusting per ton of waste vary from 20 to 30 dollars.

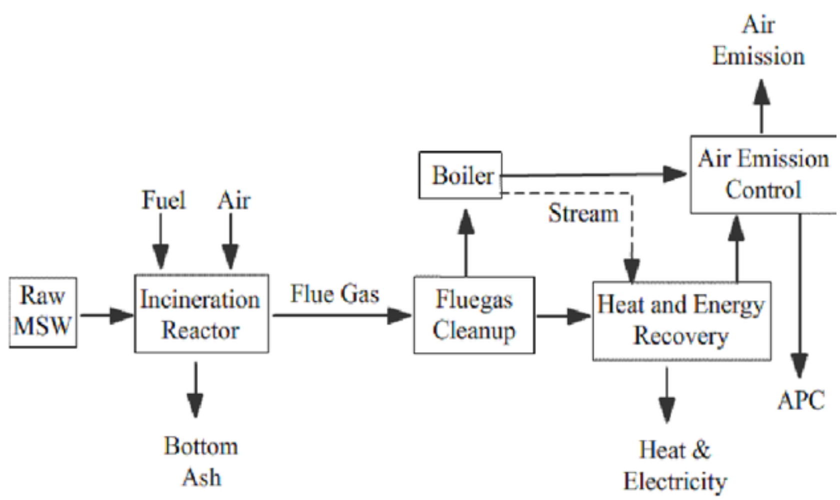

Figure 2: Simplified Schematic of Incineration Process

1.1.2. Pyrolysis and Gasification

Pyrolysis and gasification are both thermal processes similar to incineration, but operated under different conditions. Figure 3 and 4 provide simple processes of pyrolysis and gasification WtE plants. Pyrolysis is a thermochemical decomposition of carbon-based material in waste in an oxygen-free environment and a lower temperature at 250-750℃ comparing to incineration. Gasification is a well-established technology that involves the partial oxidation of organic waste under a temperature range of 800-900℃. Pyrolysis degrades waste into syngas, bio-oil, or tar and char. The fast pyrolysis process primarily produces 75% liquid bio-oil from waste with a heating value of 17MJ/kg which could be burned for electricity or heat generation; whilst, a slow pyrolysis produces bio-char can be used as a fertilizer for agriculture or soil amendment. The gasification mainly produces syngas composed 85% of CO and H2 and a small proportion of CO2 and CH4, with a lower heating value of 4.5MJ/m3. It can be sent to power generation plant for energy production such as steam and electricity. Nevertheless, the gasification-based process for energy recovery is significantly sensitive to the properties of solid waste being processed. Therefore, pretreatment on the waste is preferable to improve the efficiency, but it will inevitably introduce more cost. Gasification process can reach around 18-22% of overall waste to electricity conversion efficiency with conventional steam cycle. It is revealed that the efficiency can be increased to 26-28% through the installation of a gas engine or even up to 30% with a gas turbine. Although all the main types of gasifiers are adaptable to various waste types, plasma arc gasification drew a lot of interest in the research field dealing with MSW. Pyrolysis and Gasification processes can reach around 18-22% overall conversion efficiency. An estimation of 450-530 kWh of energy can be recovered from one ton of waste through pyrolysis, similarly 400-650 kWh from gasification. A gasification or pyrolysis WtE plant has a capital cost ranging from 620-850$/tpa, with O&M cost nearly equal to 10-12% of capital cost.

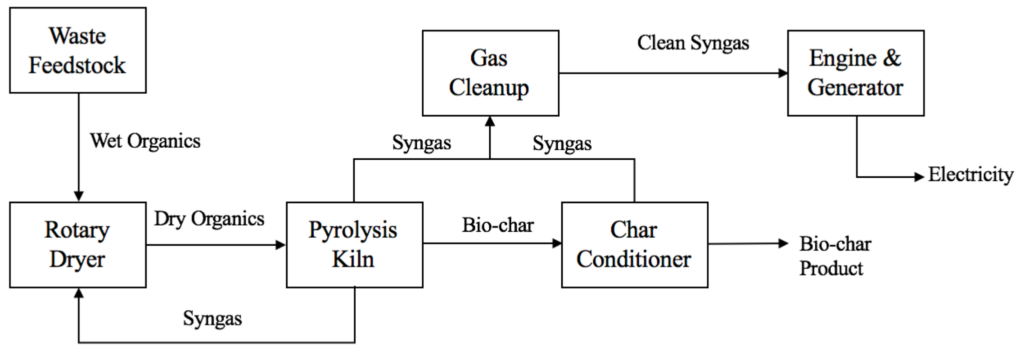

Figure 3: Simplified Schematic of Pyrolysis Process

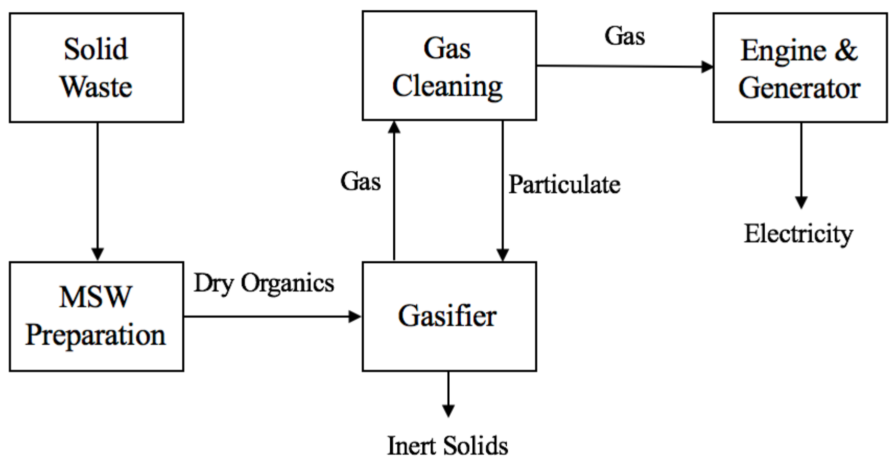

Figure 4: Simplified Schematic of Gasification Process

1.1.3. Anaerobic Digestion

Anaerobic Digestion (AD) is a biodegradation process of organic compounds involving microorganisms in the absence of air to produce biogas consisting of mainly CH4 and CO2. AD of organic waste has many environmental benefits including the production of a renewable energy platform, the possibility of nutrient recycling, and the reduction of 70% of waste volume. A schematic presentation of

AD process is displayed in Figure 5. To address the issue of high salt concentration, a co-digestion of organic waste with sewage sludge or wastewater is preferably used to decrease the concentration of nitrogen. It is observed that anaerobic co-digestion of wastewater and highly rich organic elements such as food waste could increase the CH4 yield in biogas. The overall electrical energy conversion efficiencies are reported to vary from 10% to 12% based on a gas engine. A 367m^3 of biogas could be produced from one ton of dry waste, containing 65% of methane with an energy content of 6.25 kWh/m3, and 1m^3 of biogas could generate 2.04 kWh of electricity regarding 35% of generation efficiency. Investment costs for AD system are considerably lower than those from thermochemical system. The capital cost for AD varies $310-460/tpd and O&M cost approximately 1%-6% of capital cost.

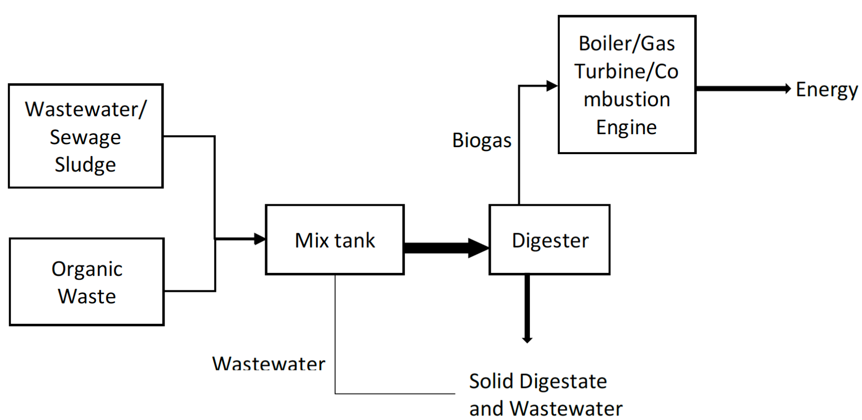

Figure 5: Simplified Schematic of AD Process

1.2.Literature Review

WtE is a developing and promising field, given that contradiction on developing and protecting environment at the same time becomes remarkable. A lot of work has been done related finding out the possibility of WtE in different context, so more and more researchers and organizations start to study the application of WtE.

1.2.1. 3E Analysis of WtE Strategies

A great deal of published existing work has already tried to explore and evaluate the WtE technologies, their efficiency, feasibility and carbon mitigation. Few of them consider the incorporating of WtE in a combination scenario. The combination of WtE possibly involves some kind of optimization when evaluated.

Tan et al. (2015) performed a comparative study of traditional landfilling and WtE technologies. They tried to assess the energy, economy, and environment of different scenarios applied to Malaysia. It considered landfill gas recovery system (LFGRS), incineration, anaerobic digestion, and gasification individually and in integrated scenarios LFGRS + incineration, LFGRS + AD, and LFGRS + gasification. This research made a simple 3E analysis of different scenario, but the idea to combine and evaluate different WtE technology is of importance. Although the evaluation of this study is correct and efficient, a life cycle assessment (LCA) of the scenarios would provide extra and stronger criterion to assess them in this case.

In many other situation, one would hardly deal with single waste stream and single technologies; the combination of those requires more techniques to simulate and evaluate the results.

1.2.2. Multi-criteria Analysis to Evaluate WtE

Developing and developed countries have different regulations, concerns, and requirements regarding the construction of a power plant, although WtE technologies are clean and efficient comparing to traditional ones. Yap and Nixon (2015) proposed a multi-criteria analysis method to evaluate benefits, opportunities, costs, and risks (BOCR) of five WtE technologies in India and in the UK.

They used an analytic hierarchy process (AHP) to construct the evaluation from major criteria to sub-criteria. A group of experts completed a survey to rate the weightings for all criteria. The final hierarchy structure is shown in Figure 6. The authors obtained general, standard BOCR information of WtE technologies in India and in the UK. Then the evaluation process follow the steps: firstly, evaluate the four major criteria preference rankings respectively with their own sub-criteria and generate the overall preference rankings based on BOCR rankings. The results demonstrated that generally, it is more preferable to choose gasification in the UK, whereas, AD in India.

This research developed a new way to assess WtE technologies in multiple abundant aspects. However, human factor plays an important role in obtaining weightings, and the results are just a general choice for a different country, the objective of Yap and Nixon is to propose this novel approach.

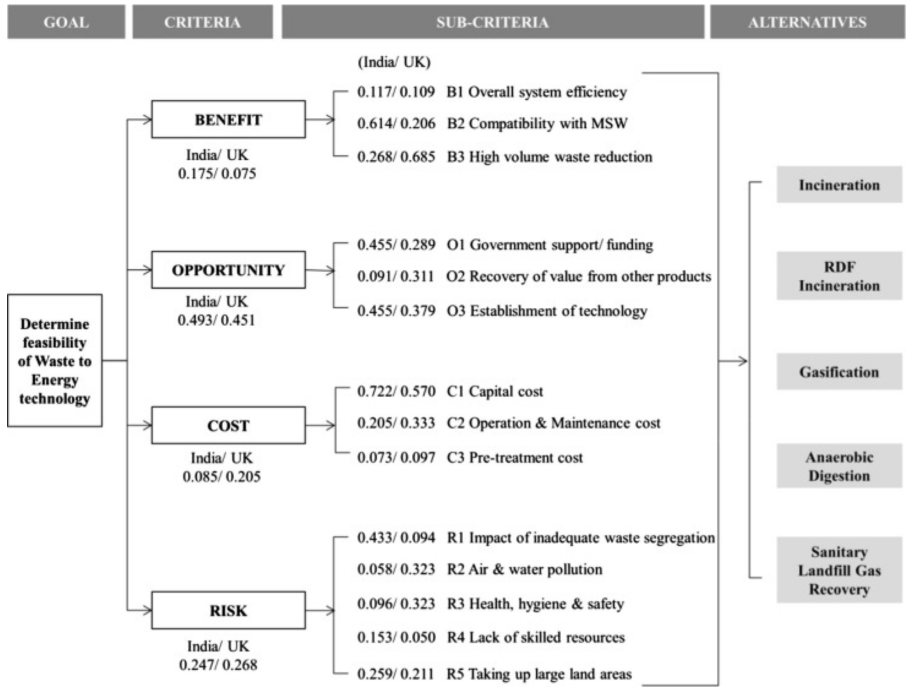

Figure 6: AHP-BOCR Hierarchy Structure with Weightings Obtained from Experts' Opinions

1.2.3. LCA of Segregate Waste to Separate WtE

Arafat et al. (2015) established a novel methodology to assess six waste streams to five WtE technologies. This decision making method considers not only choosing waste to its proper technology, but also decides whether it is more preferable to recycle waste or recover it.

An approach in this work is that authors modeled the energy and emission inventory for each stream based on chemistry, thermodynamics, and engineering principles of materials in waste. The ingredient of compound in waste is location specified. The profit, energy efficiency, and carbon emission are calculated with these thermodynamic principles if the information of waste is obtained. This methodology performed LCA to six waste streams and gave out the preferable disposal choice for these waste streams. Like Yap and Nixon (2015), this assessment involves a scoring system to rank the performance of different technologies.

This methodology has its own limitation, like the calculation of output is different from other existing work. Instead, it is based on chemical principles. Nevertheless, this methodology can be applied to any cases without a specified location.

1.2.4. An Input-Output Model to Discover 3E Potential

China is the largest developing country in the world; it has over one fifth of world's population. Definitely the waste generated in this state is enormous. Under the rapid urbanization and modernization, it would require more energy and at the same time environmental protection from pollution.

Song et al. (2016) developed a novel input-output model incorporating waste-to-energy system in current socioeconomic system in a metropolis. The purposed method of this work is to simulate the results after WtE introduced to a specified case. Therefore, this model simulated the whole system in a generalized way, including many outside factors and assigning waste to appointed technologies. The new socioeconomic system is depicted in Figure 7.

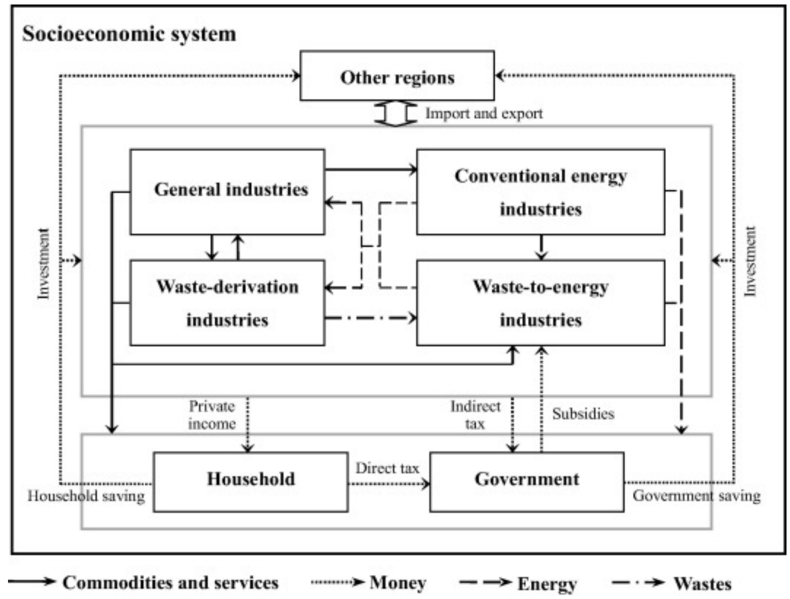

Figure 7: I-O Framework with WtE Industries Introduced

The flows between these blocks reveal the mechanism to deliver parameters and formulate the simulation. This work explains the discovery of inner relationship between components of thee community. But this study only considers more products like diesel oil from both general industries and energy industries in the process since the methodology simulates in a specific city context, all possible products that are useful and can be consumed for other needs. Nevertheless, this is a good reference to motivate and start a simulation on a smaller scale.

Lots of work has proved that the introduction of WtE today is really an important method to save energy for many cases, and it is indeed environmentally friendly with a highly potential application.

1.3.Study objective

The purpose of this study is to formulate a methodology to transfer an energy-inefficient and disadvantaged community into a clean and efficient one considering the possible application of WtE technologies and at the same time, optimizing the process of WtE in both economical and environmental aspects. In other word, a disadvantaged community has waste and a waste land, a reuse of these waste and land is investigated in this research. This study first forecasts the waste amount generated in upcoming years as an input for optimization based on the historical data. With the cost-benefit coefficients associated with different waste materials and technologies, optimization model can be formed. Here, the researcher doesn't just consider WtE since clean energy like solar and wind is included as well. Besides, utilizing the waste land through constructing parking lot to provide EV charging is of interest as well. Therefore, an analysis of renewable resource and forecasting of EV charging loads are also performed before optimization process. The optimization problem is solved using weighted sum multi-objective optimization method. The results give out the combination of WtE plants and the distribution plan for waste management every year, followed by a brief energy, economic and environmental analysis.

The paper is structured as follows: Section 2 describes the modeling methodology with the case study region description, results of case study are discussed in section 3, section 4 reaches to conclusion and few ideas on future research.

2. Modeling Methodology

2.1.Region Description

The region studied in this research is a community chosen from one neighborhood called El Sereno located in east of the City of Los Angeles. California Environmental Protection Agency (CalEPA) proposed a community screening tool as an index map for disadvantaged communities; it makes an overall evaluation of each community considering its environment, demographics, and waste generation. This community mainly consists of residential area with approximately 4311 residents, a small section of light manufacturing industrial area, and commercial shops. The residents here mostly are low-middle income or even low income families, who produced nearly 4000 tons of solid waste in 2012 as estimated. The city land use reports that there are 50 acres of vacant land in this region. This offers a possibility to install WtE plants in this region to provide energy here or even sell electricity to other neighborhoods.

2.2.Methodology

2.2.1. System Framework

A new framework of socioeconomic system is designed to imply the mechanism of new system with WtE and renewable resources introduced for a better understanding of how it works. As shown in Figure 8, waste flow from a waste generation block is sent to WtE industries for energy generation, and in turn, the energy generated satisfies the energy demand of the whole region. The profit of selling energy to grid can be an investment to energy generation, all of these establish a close loop of flows inside the new system to realize self-sufficiency on energy level.

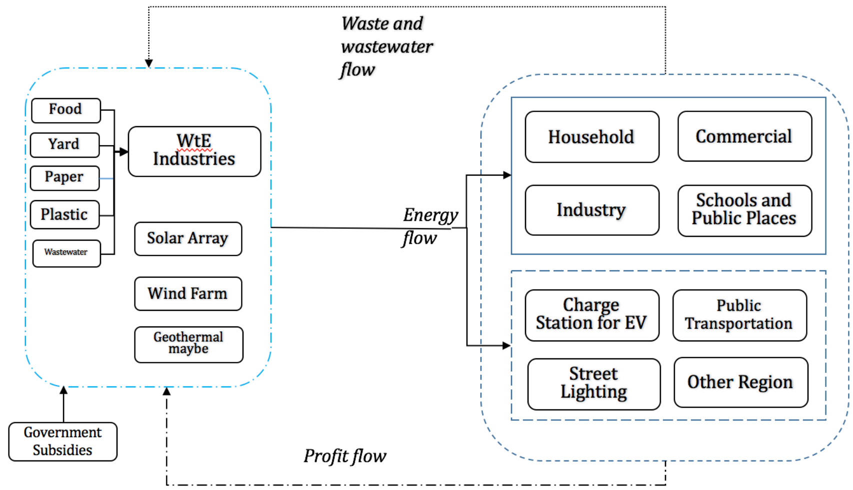

Figure 8 System Framework with WtE and Renewable Resources Introduced

2.2.2. Estimation of Waste Generation

This study focuses on finding the best portfolio of WtE technologies and waste allocation plan for the concerned community. The primary tasks, of course, are to forecast the waste generation in a period of time as feedstock for power plant. However, this community is a grey box in the sense of performing a real-time simulation because of the lack of information and behavior of components within it. Wang et al. (2000) proposed an improved step-by-step fuzzy grey modeling method (GM (1, 1) SSODMM) to forecast the upcoming data given historical data. Based on the old GM (1, 1) directing modeling method, the author expressed the idea that "the new method has the monotone consistency, convex consistency, linear transformation consistency and gradual approaching white exponential law inosculation property" (p. 1). This method could handle a small volume of data and give out a much precise forecasting model in an exponential manner.

The preparation of this method is to perform a first-order accumulation of original data to create a non-decreasing series of data. Then let the initial iteration step $S = 0$, and initial value $a_s = 0$, then the expression of ξ_s is given by Equation 1:

$$\xi_s = \lim_{a \to a_s} \xi(a) = \lim_{a \to a_s} \left(\frac{e^a}{e^a - 1} - \frac{1}{a}\right) \tag{1}$$

Then through linear regression, the representation of a's white value is as in Equation 2:

$$a_{s+1} = -\frac{S_{xys}}{S_{xxs}} \tag{2}$$

where

$$S_{xys} = \sum_{k=1}^{n-1} (x_{sk} - \overline{x_s})(y_k - \bar{y}) \tag{3}$$

$$S_{xxs} = \sum_{k=1}^{n-1} (x_{sk} - \overline{x_s})^2 \tag{4}$$

$$x_{sk} = (1 - \xi_s)x(k) + \xi_s x(k+1) \tag{5}$$

$$y_k = x(k+1) - x(k) \tag{6}$$

$$\overline{x_s} = \frac{1}{n-1} \sum_{k=1}^{n-1} x_{sk} \tag{7}$$

$$\bar{y} = \frac{1}{n-1} \sum_{k=1}^{n-1} y_k = \frac{x(n) - x(1)}{n-1} \tag{8}$$

Through Equation 3 to Equation 8, $x(k)$ is the k^{th} data in a new series. For $\left(e^{-a_{s+1}k}, x(k)\right), k \in K$, do linear regression analysis and get the exponential forecasting model M_{s+1} in Equation 9

$$\hat{x}_{s+1}(t) = c_{s+1}e^{-a_{s+1}t} + b_{s+1} \tag{9}$$

where

$$c_{s+1} = \frac{\sum_{k=1}^{n}[e^{-a_{s+1}k}-\frac{1}{n}\sum_{k=1}^{n} e^{-a_{s+1}k}][x(k)-\frac{1}{n}\sum_{k=1}^{n} x(k)]}{\sum_{k=1}^{n}[e^{-a_{s+1}k}-\frac{1}{n}\sum_{k=1}^{n} e^{-a_{s+1}k}]^2} \tag{10}$$

$$b_{s+1} = a_{s+1}[\frac{1}{n}\sum_{k=1}^{n} x(k) - c_{s+1}\frac{1}{n}\sum_{k=1}^{n} e^{-a_{s+1}k}] \tag{11}$$

Repeating the iteration for $s = s + 1$ until the precision of model is satisfied. The accuracy of this model is tested by small error probability *p* and posterior error ratio *c*, a classification of level is given in Table 3. When *c*<0.35 and *p*>0.95, the process would stop the iteration and accepted the model since accuracy of the model reaches level I. The future data could be estimated based on the model. This method requires the pre-treatment of first-order cumulative sum of raw data to create a none-decreasing series for modeling.

Table 3: Accuracy Level of Grey Model

Index / Accuracy Level	Posterior error ratio *c*	Small error probability *p*
Level I	0.35	0.95
Level II	0.5	0.8
Level III	0.65	0.7
Level IV	0.8	0.6

2.2.3. Modeling of EV Charging Load

Reusing of the waste land in community is not merely a construction of power plants; maybe a parking lot is of interest to satisfy the demand of car parking in this region. Besides, it can provide charging of EVs to make profit. The EV stations are also one part of the smart city project as mentioned before; here the EV load is an energy consumption constraint in optimization. A simple modeling of EV charging load is inspired by a method proposed by Ahourai et al. (2013). In this method, the EVs are arranged into two major classifications based on several key characteristics, as shown in Table.4:

Table 4: Classification of EVs

Types	EV Battery Size	Miles Classification	State of Charge	Charging Amp.	Charging Volt.
Type 1	25kWh	75 miles	20%	30A	240V
Type 2	40kWh	140 miles	25%	30A	240V

Furthermore, Ahourai et al. (2013) state that given the community is mainly residential area, the arrival and departure of EVs is simply modeled as normal distribution centered in the morning and early evening as shown in Figure 9. Surely, the effect of EVs from workers working in this area is also considered as well. To simplify this problem, there isn’t any charging strategies considered; in other words, the vehicles would get full volts and amps as soon as EVs get connected.

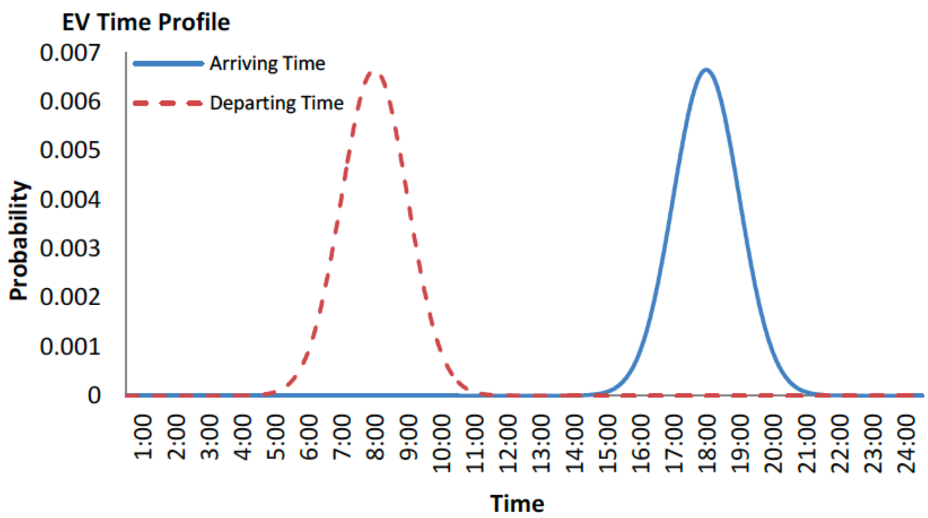

Figure 9: Departure and Arrival Time Profile for EVs

2.2.4. Optimization Formulation

A multi-objective optimization programming is formed in this section. In the new framework, the goal is to produce as much energy as possible to satisfy the energy consumption of this region and whilst produce less environmental pollutants. We try to solve this problem in an economic way, that's to say, make profit from this system. Other renewable resources (solar in this case) are also considered as extra energy generations. Obviously, each waste stream has its cost-benefit facts associated with the difference of WtE technologies, numbers are calculated and presented in Table. 5.

Table 5: Cost and Benefit Summary of Waste to Energy

	Incineration	Pyrolysis/Gasification	Anaerobic Digestion
Estimate output-paper waste	1018kWh/t	1157kWh/t	694kWh/t

Estimate output-plastic waste	1990kWh/t	2261kWh/t	
Estimate output-Organic waste	477kWh/t	543kWh/t	325kWh/t
Capital cost	660$/tpa	730$/tpa	380$/tpa
O&M cost	66$/tpa/year	80$/tpa/year	14$$/tpa/year
Gate fee	100$/t	100$/t	60$/t
CO2e emission	0.22g/kWh	0.11g/kWh	0

The decision variables of this problem are then the amount of waste for different streams to different technologies in each year, the size of the power plant, and the scale of the solar PV panels. Therefore, the multi-objective problem is to simultaneously maximize the net profit(f_1) and minimize the carbon emission(f_2); in other words,

$$\text{Maximize } \{f_1, -f_2\} \tag{12}$$

$$\text{s.t. } \chi \in P$$

where χ is the set of decision variables, and *P* is the feasible region of this problem. The f_1 and f_2 are defined as below:

$$f_1 \sim \sum_i \sum_j p(O_j^x x_{ij} + O_j^y y_{ij} + O_j^z z_{ij} + V + W) - \sum_j C_j - \sum_i \sum_j M_{ij} - \sum_j G_j \sum_i (x_{ij} + y_{ij} + z_{ij}) \tag{13}$$

$$f_2 \sim \sum_j E_j \sum_i (O_j^x x_{ij} + O_j^y y_{ij} + O_j^z z_{ij}) \tag{14}$$

Equation 13 consists of the electricity selling, capital cost, O&M cost, and gate fee through year one to ten. Equation 14 calculates the carbon dioxide equivalent emitted in the simulation years as the second objective. It is clear that this problem is constrained by the following:

(1)Energy requirement: $\sum_i \sum_j (O_j^x x_{ij} + O_j^y y_{ij} + O_j^z z_{ij} + V + W) \geq Com_i$

(15)

(2)Land use constraint: $\sum_{k=1}^{5} l_k \leq L$ (16)

(3)System input constraint: $\sum_j x_{ij} = X_i$ (17)

$$\sum_j y_{ij} = Y \quad (18)$$

$$\sum_j z_{ij} = Z_i \quad (19)$$

(4)Plant capacity constraint: $x_{ij} + y_{ij} + z_{ij} \leq S_j$

(20)

Solving this problem using the weighted sum method will transfer it into a single-objective LP,

$$\text{maximize } \omega_1 f_1 + \omega_2(-f_2) \quad \text{where } \omega_1 + \omega_2 = 1 \quad (21)$$

$$\text{s.t. } \chi \in P$$

here the weights of each objective can be considered as interests on each target. However, since the units of f_1 and f_2 are not synchronized, it is not proper to directly combine them into a single objective function. Thus, before the operation and planning, it is reasonable to normalize the two objectives into unit scale. That's to say, finding out the maximum and minimum values of the two objectives and scale them into interval $[0, 1]$, then the preparation for programming is set up. If to care more about the profit, a larger weight for f_1 is preferable, and vise versa. Therefore, an optimization problem is formed and solved in a linear programming manner.

3. Results and Discussion

In this section, the methodology is applied to the interested community described in former section to perform a case study. The weights for profit and carbon emission are set to be $\omega_1 = 0.7$ and $\omega_2 = 0.3$.

3.1.Solar Energy

The city of Los Angeles receives adequate solar radiation according to the solar map; therefore, solar energy is feasible there while wind power is not since insufficient wind speed. The average solar radiation data in each month in east Los Angeles is given in Table 6, and the estimated unit electricity generation each month is calculated and shown in Figure 10. Definitely, the solar energy output would reach a peak during summer, while it remains at a high level during the rest time of a year.

Table 6: Average Solar Radiation Data in L.A.

		Jan	Feb	Mar	Apr	May	Jun
EAST	Global	570	690	850	1000	940	930
	Diffuse	300	380	480	570	610	620
Clear Day	Global	740	910	1130	1290	1370	1390

Table 6: continue

		Jul	Aug	Sep	Oct	Nov	Dec	Year
EAST	Global	1050	980	840	720	610	530	810
	Diffuse	620	570	500	420	320	280	470
Clear Day	Global	1370	1300	1160	960	770	680	1090

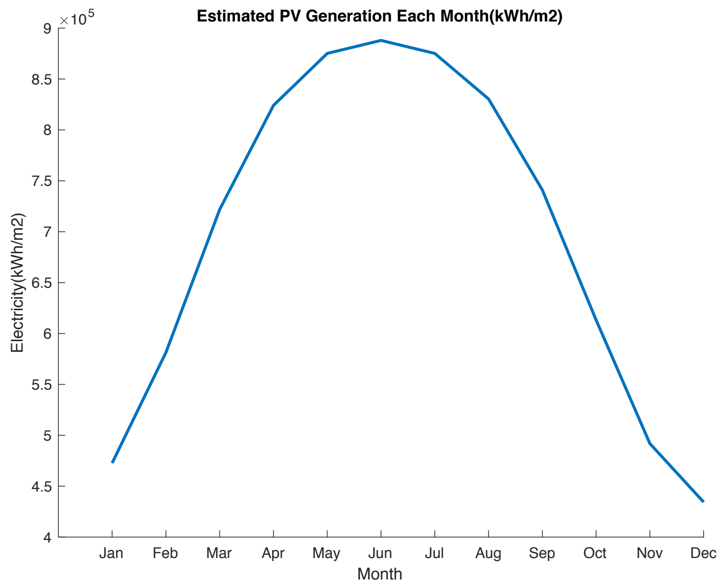

Figure 10: Estimated Unit Electricity Generation from PV (kWh/m2)

3.2.EV Charging Load

Energy consumed in EV charging is also a part of energy constraint in optimization at this point as discussed in previous section. Due to the of lack of detailed information, the estimation of EV quantity in this region is based on the proportion of EV throughout L.A. Therefore, charging profiles in one day and in ten years are given in Figure 11 and 12. It can be obtained from Figure 11 that there are two peak loads during one day. The implication of this is that the first peak appears around 9am because of the arrival of workers in this region, and the second peak is the result when people who live here return home at the end of day. In a ten-year run, energy consumption to this part doesn't fluctuate significantly since evolution of EV is not addressed as well as other related issues.

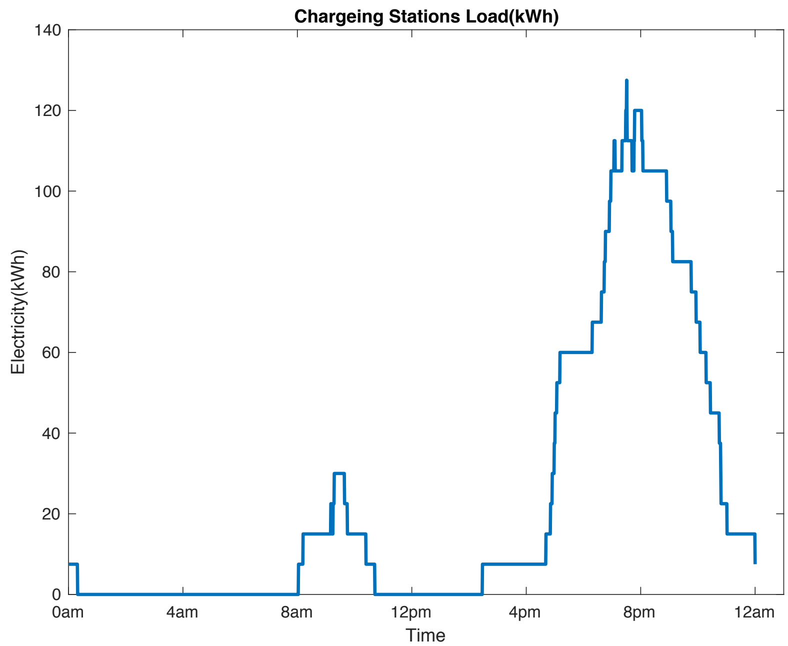

Figure 11: EV Charging Profile in One Day

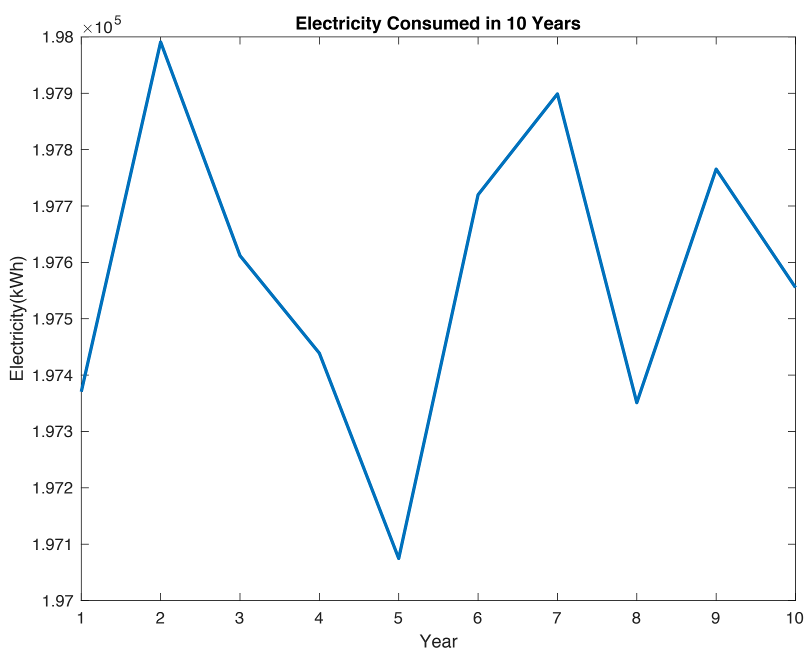

Figure 12: EV Charging Energy Consumption in Ten Years

3.3.Forecasting of Waste Generation

Right before the optimization process, a forecasting of waste generated in the upcoming ten years is shown in Figure 13. It can be foreseen that a slight decreasing trend is presented in total solid waste generated here based on the historical records. This may result from the fact that people utilize resources more efficiently, and hence less waste is generated in daily life. Figure 14 plots classified waste streams generated, displaying a decreasing tendency. Obviously, organic waste occupies the largest proportion of municipal solid waste since food waste is one of the primary sources of organic waste, and it remains a critical issue for both poor and prosperous area as reported. Therefore, with this prediction of waste, the optimization model can be applied.

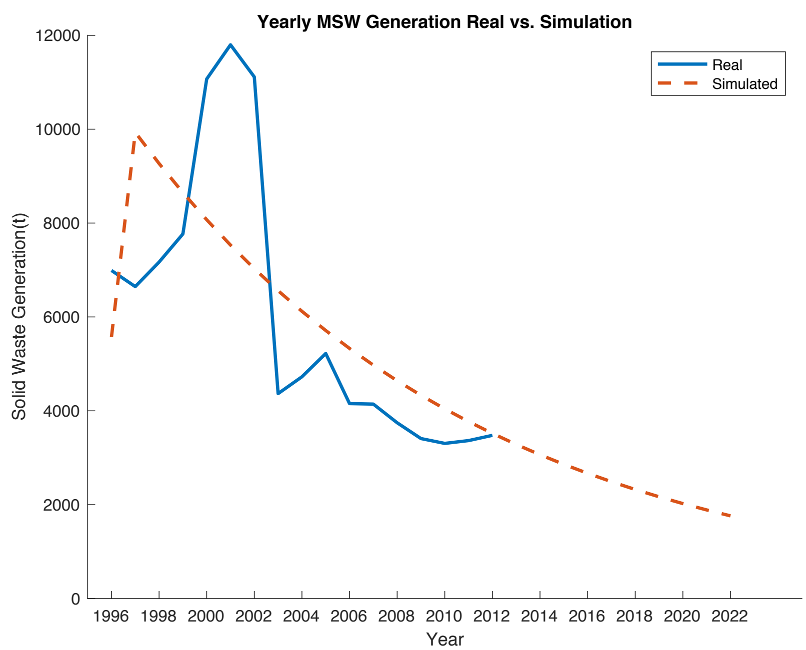

Figure 13: Simulated Waste Generation vs.Real Data

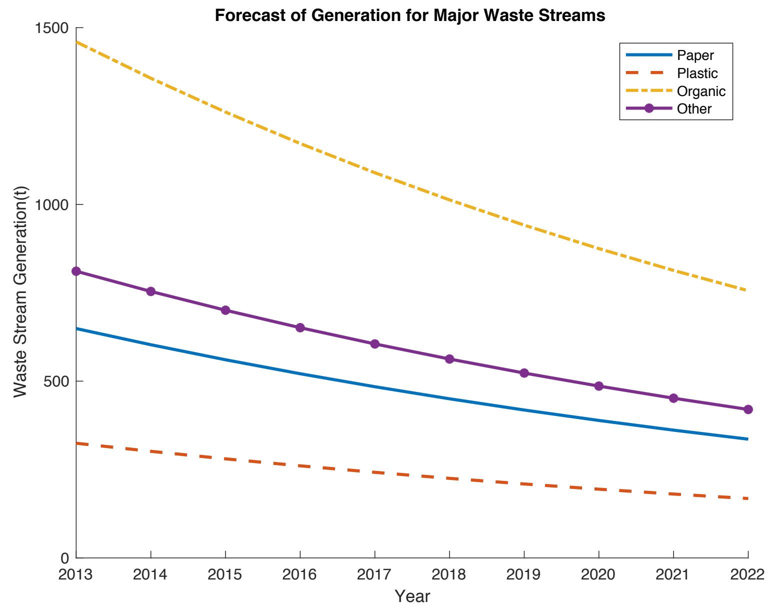

Figure 14: Forecasting Generation of Waste Streams

3.4.Optimization Results

Optimization results reveal that installations of pyrolysis and anaerobic digestion is the best combination of WtE choices for this community, in addition to PV panels. Moreover, the optimization model indicates that the optimal capacity of pyrolysis plant is disposing 325 tons per annum(tpa), 2100 tpa for AD plant. The size of pyrolysis in this case is relatively small because it is only designed to treat solid waste generated in this region. In future work or a real situation, a WtE plant may play a role as a waste disposal center for nearby regions. In addition, the assignment plan for this WtE system is provided in Figure 15 and 16. As shown in Figure 15 and 16, all of paper waste is sent to pyrolysis plant every year, while all organic waste is preferred to be sent to AD plant. However, plastic paper is partially distributed to pyrolysis plant each year with increasing amount; the remaining part is sent to AD plant.

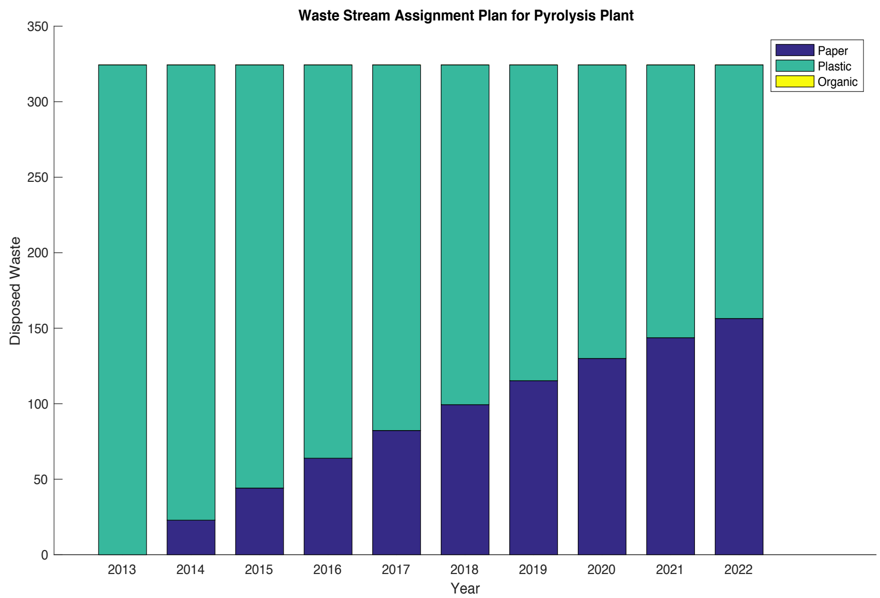

Figure 15: Waste Assignment Plan for Pyrolysis Plant

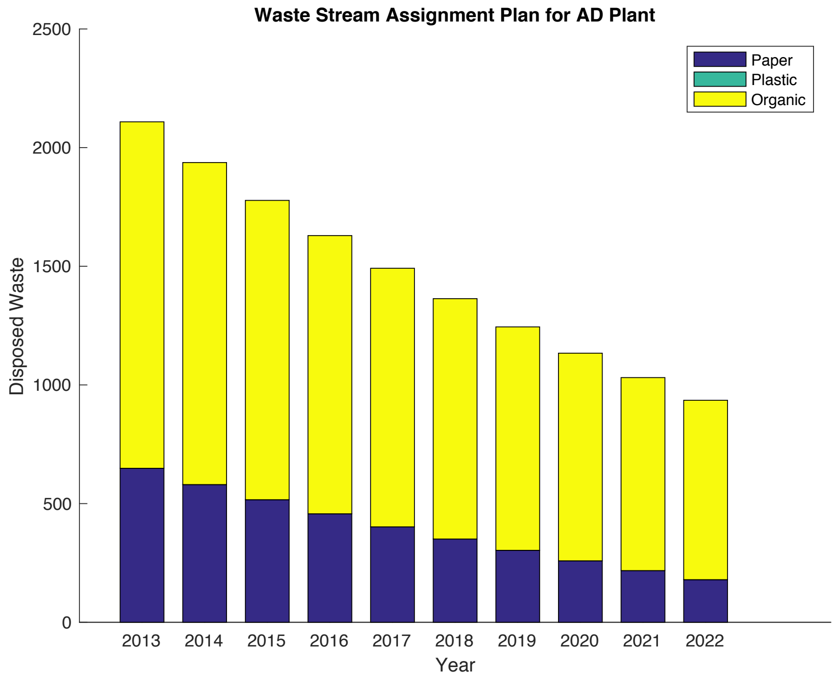

Figure 16: Waste Assignment Plan for AD Plant

According to the optimal distribution scenario, the estimated output electricity can be calculated regarding the information in Table 4. The annual energy generated from separate waste streams in pyrolysis and AD plant is provided in Figure 17 and 18 respectively. Due to the fact that solid waste is in a decreasing trend, the output for both plants are showing different degrees of decline.

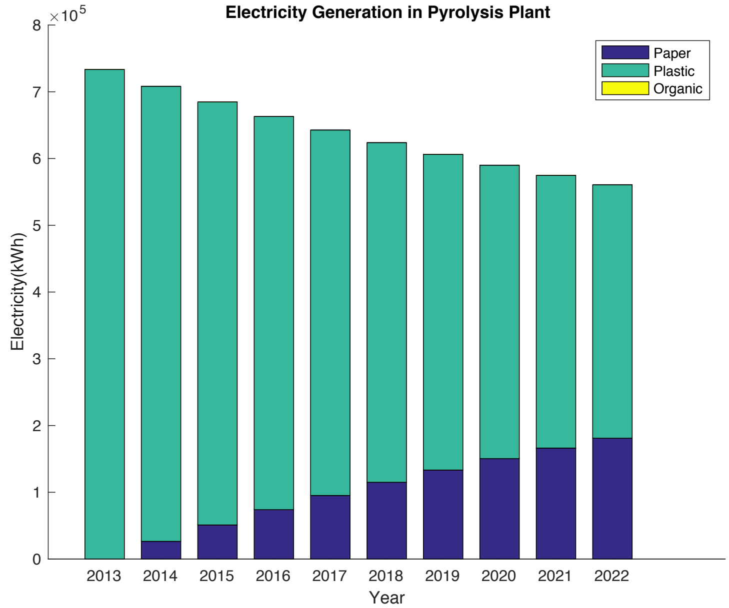

Figure 17: Estimated Energy Generation in Pyrolysis Plant

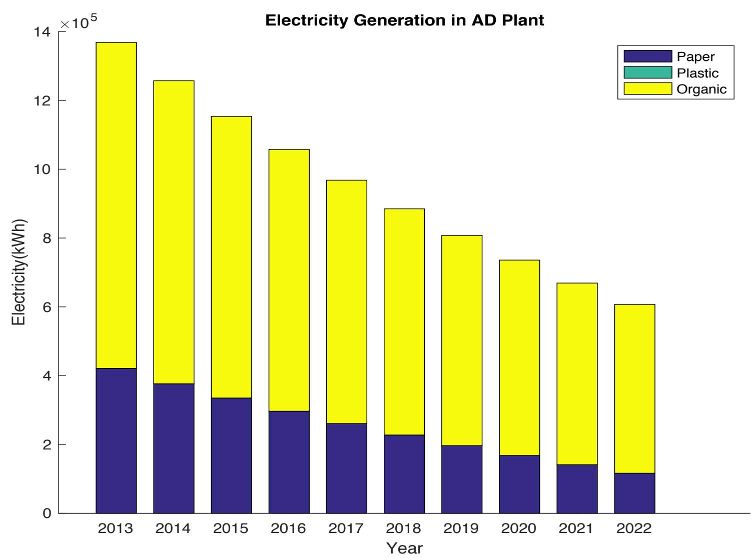

Figure 18: Estimated Energy Generation in AD Plant

An economic and environmental analysis is necessary after the acknowledgement of this problem. A rough estimation of accumulated profit of this system is computed for a better understanding of the economic assessment. We don't address the problem of price fluctuation. Using the average electricity price of $0.21/kWh in USA, and an annual rate of 6% when considering the time value of money, the results are shown in Figure 19. Besides, the carbon emission during ten years is given in Figure 20. As a conclusion, the estimated payback time of this system is at eighth year, and at the end of the whole simulation, approximately $8.3m of profit can be obtained. At the same time, the equivalent carbon emitted from WtE plants will be decreased from 80kg to 60kg a year. It is all contributed from pyrolysis plant since AD has capability of gaining net positive carbon emission which is regarded as zero.

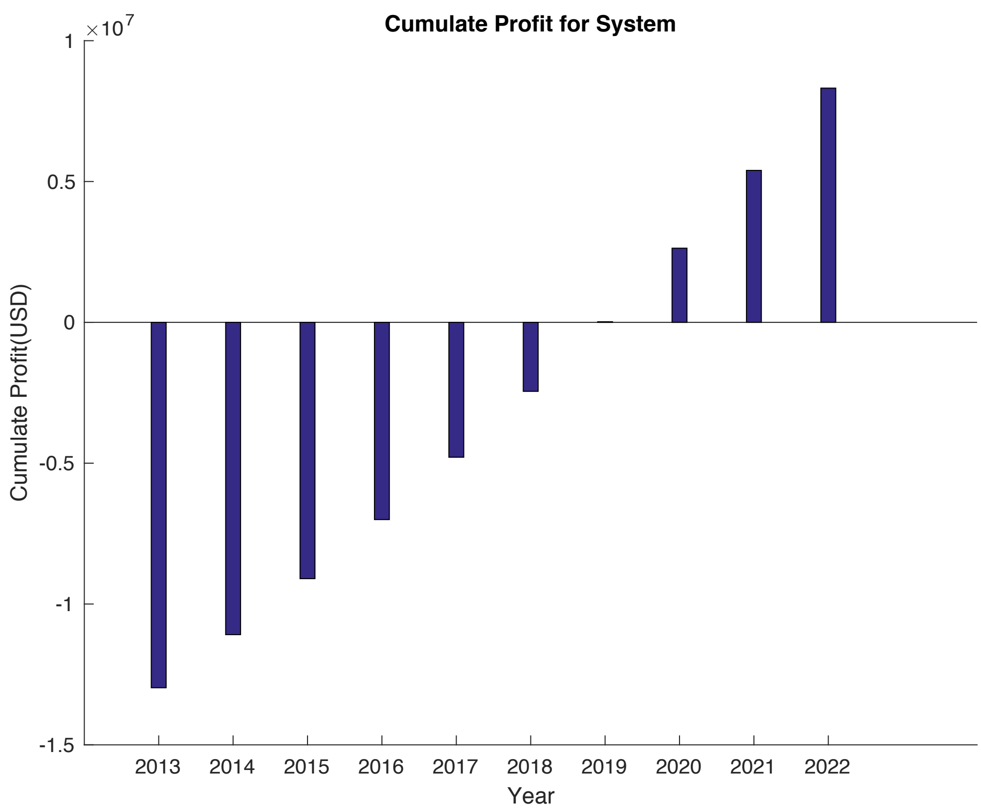

Figure 19: Accumulated Profit during Ten Years

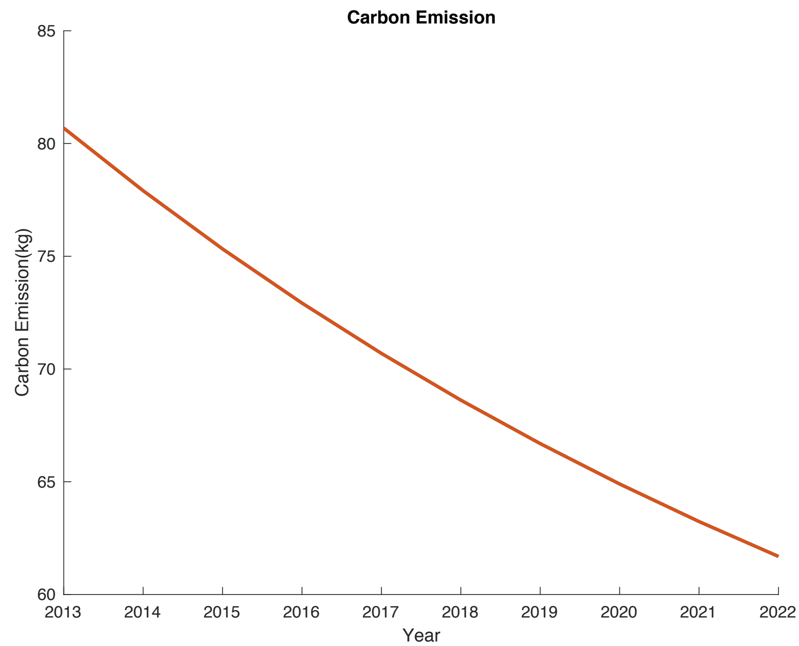

Figure 20: CO2 Equivalent Emission during Ten Years

Further analysis of the optimization model for this case indicates that when $0.68989 \leq \omega_1 \leq 1$, the optimal solution remains the same. While $0 < \omega_1 < 0.68989$, the model yields an alternative distribution plan, but still, pyrolysis and AD are preferred for this community. For instance, $\omega_1 = 0.3$, $\omega_2 = 0.7$, the alternative results are depicted in Figure 21 and 22. Paper and organic waste are only distributed to AD plant, while plastic waste are all sent to pyrolysis plant for power generation. Consequently, the estimated profit gained is still around \$8.3 million. As a comparative comprehension, Table 7 lists the annual cumulative profit of this system under two portfolios, it can be easily obtained that profit curves nearly follow same pattern, and both portfolios would finish with a payback time at 8^{th} year. On the other hand, the carbon emission mitigation is much higher than it was since weights are inclined to carbon emission. During previous years, carbon emission still stays at high level, but would end up with much fewer emission at the tail years comparing to former results, because the power generation is mainly shifted to AD plant which could complete nearly no emission.

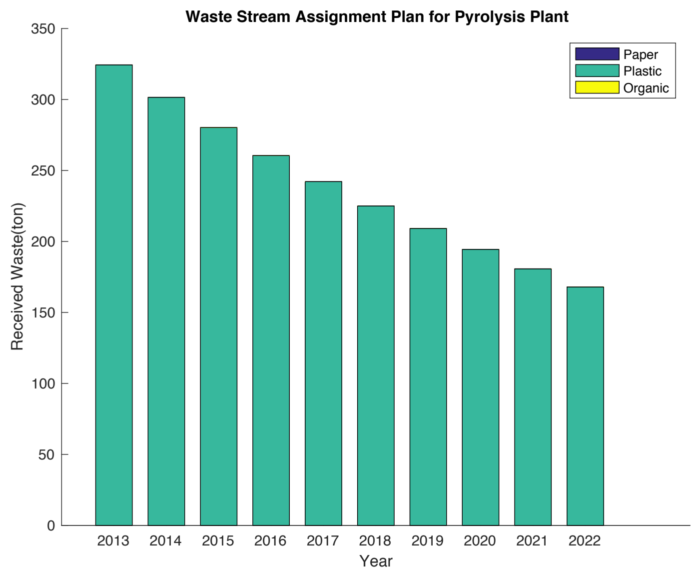

Figure 21: Waste Assignment Plan for Pyrolysis Plant ($\omega_1 = 0.3$)

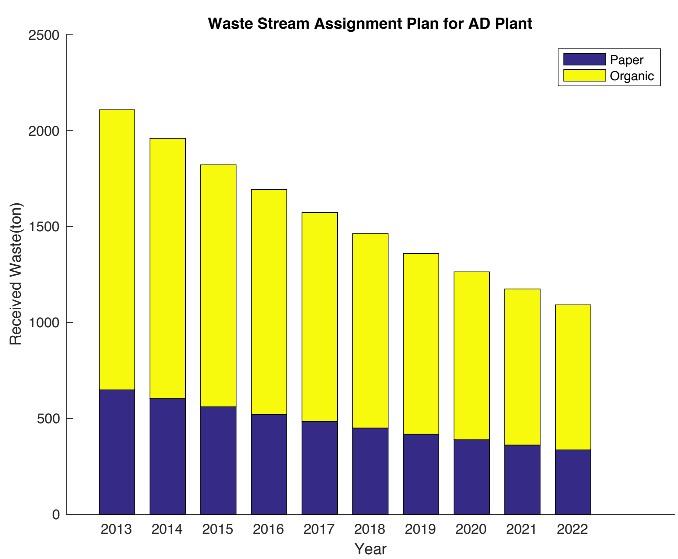

Figure 22: Waste Assignment Plan for AD Plant ($\omega_1 = 0.3$)

Table 7: Cumulative Profit for Two Portfolios in Ten Years(Unit: 10^3 USD)

Year	1	2	3	4	5	6	7	8	9	10
Portfolio1($\omega_1 =$ 0)	-9396.72	-8035.06	-6603.71	-5097.64	-3511.57	-1839.97	-77.04	1783.33	3747.60	5822.52
Portfolio1($\omega_1 =$ 0.3)	-12973.41	-11089.45	-9104.45	-7011.52	-4803.38	-2472.38	-10.49	2590.78	5340.40	8247.79
Portfolio2($\omega_1 =$ 0.7)	-12973.41	-11087.92	-9099.89	-7002.42	-4788.25	-2449.72	21.21	2633.06	5394.79	8315.88

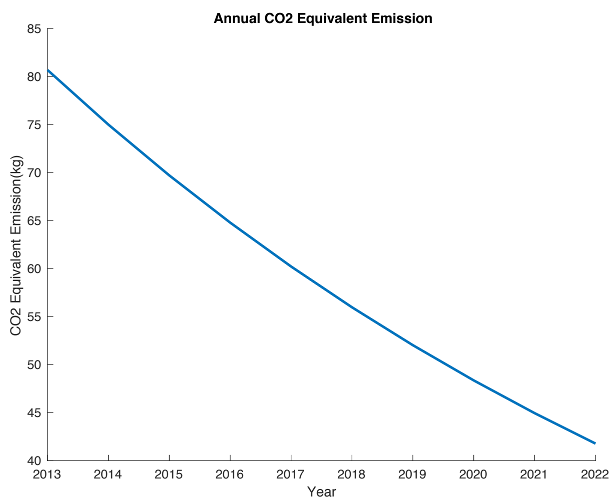

Figure 23: CO2 Equivalent Emission during Ten Years ($\omega_1 = 0.3$)

From these results of this given case study, we could see that the profit wouldn't improved significantly as stakeholders' interests changing during process, while the optimal portfolios are just trade-offs on carbon dioxide emission. Therefore, for this case, a low carbon emission portfolio is ideal while profit would stay at a rational level.

Besides, when ω_1 instantly decrease to 0, which means the profit is not of interest, the programming process yields a third results. But in this solution, all the other decision variables stay the same as the former solution, the only difference occurs at the size of solar energy, which is much smaller than before, this may resulted from that since $\omega_1 = 0$, then the energy generated only have to meet the energy consumption as least as possible. Therefore, the carbon footprint almost stays the same, while profit curve is reduced to $5.8m as shown in Table 7.

4. Summary and Future Work

4.1.Summary

The problem of transferring a disadvantaged community into a clean and efficient one with application of WtE technologies in this region is presented and solved using a multi-objective optimization method. It successfully disposes the recoverable waste which is not treated properly before, and it fully re-utilizes the waste land to valid purposes; therefore, a community becomes more environmentally friendly and energy efficient. This methodology handles the basic information about a given community, and forecasts the solid waste generation in the following years in simulation period. An optimal decision making plan for waste sent to different plants for energy recovery is proposed after simulation. This methodology can be theoretically applied to various cases without a specified location, as long as the required input signals are available to setup simulation. In this research, a case study of a real community is performed to illustrate application of this methodology. It can be obtained that multiple results can be generated with different stakeholders' interests in different situations.

4.2.Future Work

Nevertheless, there are still some limitations in the methodology, and issues that remain unaddressed. This provides some possible insights on future work to perfect this method. The fact is that degree of accuracy for data is at year level time frequency; as a results, the optimization process can only be planned on annual scale, which results in the limited information to forecast the waste generation. The future work may involve an extension of this simulation to a day-ahead or even real-time planning for waste distribution in the process; however, a highly precise simulation of waste generation requires massive inputs. The individuals' behaviors and states in the system all make the effects on final results. This type of planning is much more reasonable as taking into account a real-time energy price and immediate building energy demand, where inflation, fluctuation, change of interests, and some other economic factors can be included for a long time run analysis that would lower the risks of the whole project.

Besides, there are plenty of challenges in practical application of WtE technologies in different context. Right now, there are 77 incineration plants operating in the USA, approximately 20 pyrolysis/gasification facilities in operation, under construction, or in planning. Thirty-nine anaerobic digestion facilities are in operation, 25 of which are in California. WtE is still a newly emerged field that is facing lots of practical issues. Therefore, the application of WtE has not been widely accepted, especially, in developing countries. Stakeholders that are trying to investigate clean energy community need to concern more in real situation.

References

Advancing sustainable materials management: 2014 fact sheet, Nov, 2016, 3

Arafat, H.A., Jijakli, K., Ahsan, A. (2015). Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. *Journal of Cleaner Production, 105, 233-240.*

Ahourai, F., Huang, I., Faruque, M.A.A. (2013). Modeling and simulation of the EV charging in a residential distribution power grid. *Proceedings of Green Energy and Systems Conference*

Environmental Protection Agency: Energy recovery from the combustion of municipal solid waste (MSW)

Environmental and Energy Study Institute, Issue Brief: Reconsidering Municipal Solid Waste as a Renewable Energy Feedstock, July 2009.

Greater London Authority, 2008. Costs of Incineration and None-incineration Energy from-waste

Gómez, X., Cuetos, M.J., Cara, J., Morán, A., García, A.I. (2006). Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes. *Renewable Energy 31, 2017–2024.*

Knoef, H. Practical aspects of biomass gasification. In: Knoef, H. (Ed.), Handbook Biomass Gasification. BTG-Biomass Technology Group. Enschede, The Netherlands. 2015.

Kosseva, M.R. (2011). Management and processing of food wastes. In: Reference Module in Earth Systems and Environmental Sciences Comprehensive Biotechnology, second edition, 557–593.

Lombardi, L., Carnevale, E., Corti, A. (2015). A review of technologies and performances of thermal treatment systems for energy recovery from waste. *Waste Management. 37, 26–44.*

Murphy, J.D., McKeogh, E., Kiely, G. (2004). Technical/economic/environmental analysis of biogas utilization. *Applied Energy 77, 407–42*

Nao, Y., Liu, G., Liu, K. (2000). A step by step optimum direct modeling method of GM (1, 1). *System Engineering Theory and Practice 9*

Nao, Y. (1988). A direct modeling method of GM (1, 1) and its property. *System Engineering Theory and Practice 1*

Pham, T.P.T., Kaushik, R., Parshetti, G.K., Mahmood, R., Balasubramanian R. (2015). Food waste-to-energy conversion technologies: Current status and future directions. *Waste Management, 38, 399-408*.

Retrieved from California OEHHA website: https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-version-20

Song, J., Yang, W., Li, Z., Higano, Y., Wang, X. (2016). Discovering the energy, economic and environmental potentials of urban wastes: An input-output model for a metropolis case. *Energy Conversion and Management, 114, 168-179*

Staley, B. (2013). Summary of waste conversion technologies: Prepared for NEWMOA, 2013.

Tan, S.T., Ho, W.S., Hashim, H., Lee, C.T., Taib, M.R., Ho, C.S. (2015). Energy, economic and environmental (3E) analysis of waste-to-energy strategies for municipal solid waste (MSW) management in Malaysia. *Energy Conversion and Management 102, 111-120*

Yap, H.Y. and Nixon, J.D. (2015). A multi-criteria analysis of options for energy recovery from municipal solid waste in India and the UK. *Waste management. 46, 265-277.*

Zaman, A.U.Technical development of waste sector in Sweden: Survey and life cycle environmental assessment of emerging technologies. *KTH, Department of Urban Planning and Environment Division of Environmental Strategies Research,* 2009.