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Techno-Economic Analysis of Electricity Generation from Polyethylene Plastics Using Fast Pyrolysis: A Case Study of Some Selected Cities of Nigeria

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Abstract

This project seeks to determine the most viable states for Energy production using plastic MSW (Municipal Solid Waste) using fast pyrolysis process. This is determined by performing a techno-economic analysis on these states. Two states were chosen in each of Nigeria's six Geopolitical zones. This would provide valuable insight into the energy realizable from this technique, the environmental impact and also the cost implications.

BACKGROUND

Energy since the dawn of the Industrial age has been of insatiable demand by the world, whether to power a simple light bulb or to drive a motor carriage or propel ships across mighty oceans. It has been of perpetual discussion on where to source energy from. Humankind has continued to push the boundaries on energy derivation starting from harnessing the energy of steam to power steam engines by using coke which was prominent in the 1800's, then the use of coal to generate

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steam to turn generators to power homes in the early 1900's then the use of fossil fuels in the later 1900's subsequently. In this present age, new methods of energy production have been devised such as Nuclear energy. Also, renewable energy sources have also been developed which includes Solar energy, Wind Energy, Tidal Energy, Biomass, Fuel cells.

The world is currently looking for very efficient and effective ways to solve the problem of waste and even more so plastic wastes. The world production of plastics reached 269 million tons in 2015 [1] and the greater part of this is PET plastics (Polyethylene terephthalate) which is mainly used for packaging various food products such as mineral water, soft drinks and fruit juices.

In Nigeria, there is also the same problem with MSW (Municipal Solid Waste). The cost of disposal is very high and usual methods of disposal such as landfills and incineration lead to environmental dearth and destruction. A simple way to do this would be to perform fast pyrolysis on the plastic waste (that would have been separated from the MSW) which could be used to generate Electrical power and this would lead to less pollution.

Some of the causes of unprecedented increase in the rate of municipal solid waste (MSW) generation and energy demand in recent years have been attributed to population increase, changing consumption pattern, increased level of urbanization, fast improving industrialization and economic growth [2]. Energy and clean environment are crucial to the development and living standards of any nation. Therefore, effective management, utilization and conversion of MSW to useful energy (Waste-to-Energy) could be a potential means of providing a sustainable and environmental friendly solution to bridging the gap between energy and the environment. Waste - to -energy involves thermal and biological processes that extract the usable energy stored in the organic portion of solid waste to produce heat (steam) or electricity or both (combine heat and power) [3]. This involves recovery of landfill gas, incineration, gasification, production of H2,

pyrolysis and anaerobic digestion of the organic fraction of the waste [4]. Therefore, utilization of MSW as a renewable energy source could overcome waste disposal issues, generate electric power and mitigate GHG emissions. In Nigeria, inadequate waste management and poor electricity generation are some of the main challenges facing the country. There is an increase in the rate at which solid wastes are being generated in recent time as a result of population growth and increasing urbanization. This rate outweighs the current waste management infrastructure and is taking a negative turn on the environmental health related problems. Also, there is a high gap between the electricity generation and demand resulting into energy poverty.

This generated Electrical power can be used to power local provinces or areas where the waste was generated which would be a cheap source of power. Furthermore, the by-product of the pyrolysis process can be further processed and be used to produce bio-fuels such as bio-diesel which would reduce dependence on foreign fuels. Most plastics are not bio-degradable and their deposition in landfills is not a desirable solution from an environmental standpoint.

PROBLEM STATEMENT

In order to discover the beneficial potential of the fast pyrolysis process, there would be a need to discover the amount of electrical energy realizable from pyrolysis of waste polyethylene terephthalate (PET) using the rate of generation in some selected cities in Nigeria which will in-turn reduce and ultimately deplete its presence in landfills and the natural environment.

OBJECTIVES

The following objectives have been set in order to achieve the scheme the project. They are as follows;

i. To model a fast-pyrolysis combustor which can efficiently process the feedstock into fuel for a turbine which would then generate electric power.

ii. To simulate the fast-pyrolysis process on the ASPEN® Plus software.

iii. To derive the amount of energy obtainable per specific amount of feedstock.

iv. To perform a techno-economic analysis on the biomass energy obtainable when compared with that from the local electric company.

v. The amount of waste gases that would be generated per amount of feedstock.

JUSTIFICATION OF STUDY

Nigeria's power generation problem can only be solved if there is diversification of the sources of energy. Recyclable energy is widely being adopted and as it is very advantageous to use wastes to provide clean energy. It would also save the cost of sourcing for feedstock since PETs are plentiful and are cheap to obtain as waste. This study is justified because it will do the following:

- Generate a working model that will yield a feasible solution.
- Generate a model that will reduce cost and also reduce waste plastics in landfills and the natural environment.
- Provide an easy solution to power deficiencies in Nigeria.

SCOPE OF STUDY

This study concentrates on the amount of electrical energy that would be generated from a modelled fast pyrolysis plant and how it can solve Nigeria's power issues and also alleviate environmental destruction. The study will be focusing on the amount of electrical energy realizable from the fast pyrolysis of waste PET plastics from selected states.

OUTLINE OF SUCCEEDING CHAPTERS

This chapter presents description of the background study. Thereafter, the aim and specific objectives, scope of work and the justification of study.

Chapter 2 discusses the past studies in the area of pyrolysis.

Chapter 3 demonstrates how the main aim and objectives highlighted in the first chapter can be achieved.

Chapter 4 focuses on data analysis and results. It presents a detailed discussion on results

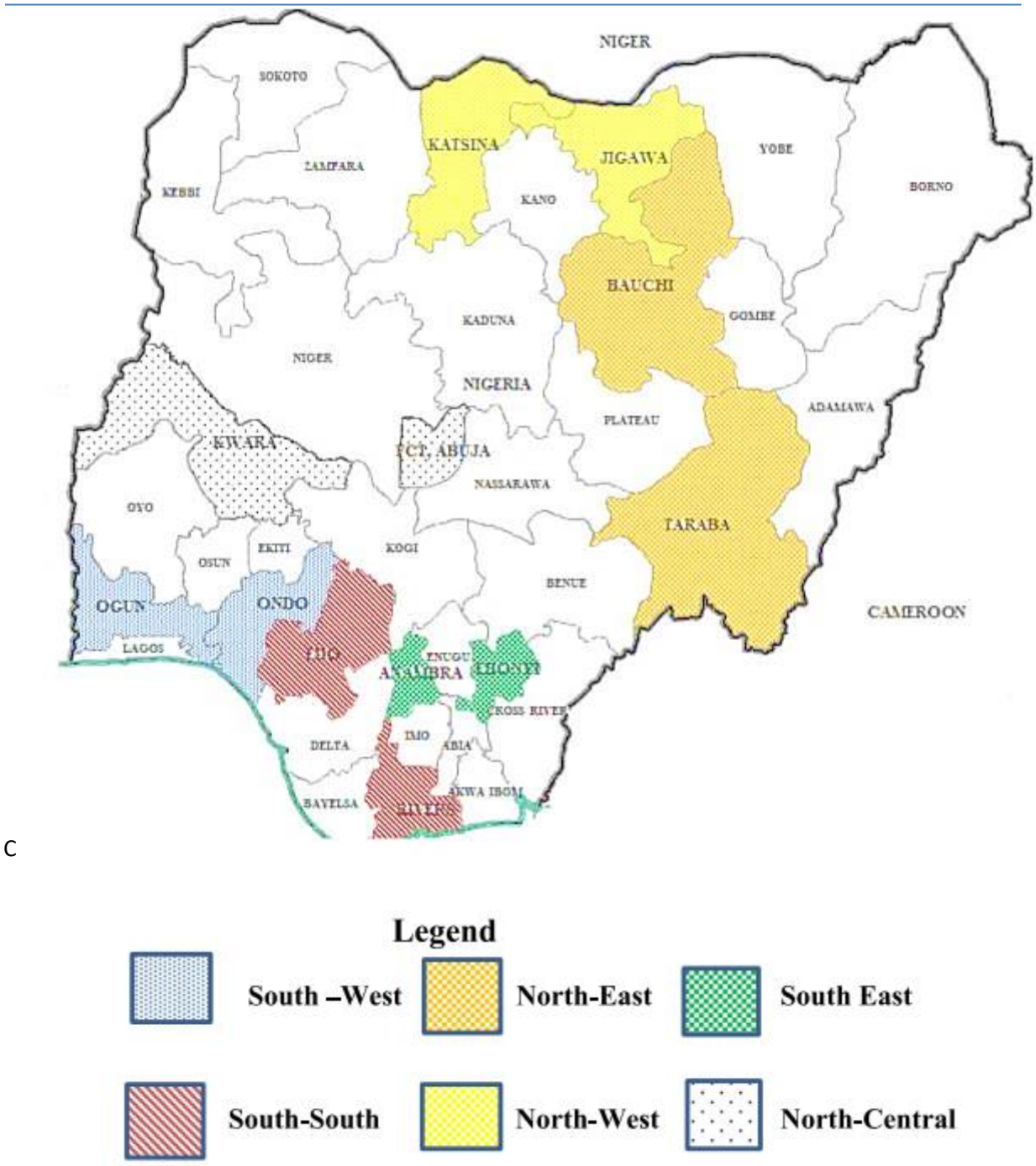
Chapter 5 Draw conclusions based on the specific objectives mentioned in the first chapter.

CHAPTER 2: LITERATURE REVIEW

INTRODUCTION

Nigeria is in a quandary of how to solve its Energy problems. The energy being distributed to its populace is far below par and this cannot support a developing economy. There is a high gap between the electricity generation and demand resulting into energy poverty [5]. The average electrical energy and power per capita in Nigeria are in the range of 107 kW h per annum and 12 W, respectively. This is considered inadequate when compared to some other developing countries such as South Africa (4347 kW h and 496 W) and Malaysia (3310 kW h and 377 W) [5].

In order not to lag behind this trend, Nigeria should as well follow up and develop its renewable energy capacity as this would not only abate its carbon footprint but at the same time will expand the economy and save scarce resources.



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Map of Nigeria showing the selected Cities

Other methods of Energy generation have been studied extensively by other researchers. Coal for instance, which supplies 40% of the world's energy, [6] explicitly detailed the how Nigeria could take advantage of its 2.734 billion tons coal reserves and also highlights new methods of coal

combustion using clean techniques. Nigeria presently derives 93% of its electric power generation from gas (thermal) and 7% from hydro sources [7]. Nigeria also has the potential to harness the energy of the sun (solar energy). Assuming an arithmetic average of 18.9 MJ/m2-day (5.3 kWh/m2-day), Nigeria therefore has an estimated 17,459,215.2 million MJ/day (17.439 TJ/day) of solar energy falling on its 923,768 km2 land area [8]. [9] estimated the technical potential of solar energy in Nigeria with a 5% device conversion efficiency put at 15.0 $x10^{14}$ kJ of useful energy annually. This will also amount to about 4.2 x 10^5 GW/h of electricity production annually.

Hydropower accounts for 32% of Nigeria's installed commercial installed capacity. [10] and [11]reported that the total hydropower resources potentially exploitable in Nigeria was estimated to be about 11,250 MW with an annual electricity generation potential in excess of 36,000 GWh.

Type			**Average % of total**				
	2002	2003	2004	2005	2006	2007	Average
Coal	0.03	0.03	0.03	0.03	0.05	0.05	0.037(insignificant)
Hydro	11.93	14.2	17.39	12.04	17.03	23.9	16.08
Natural Gas	2.84	1.9	4.54	5.5	7.52	8.73	5.17
Petroleum Products	85.2	83.87	78.04	82.45	75.44	67.32	78.72

Table 1: Commercial energy consumption by type [12]

Wind power is also available to Nigeria in substantial and explorable quantity. It is also observed that the wind speeds in the country are generally weak in the South except for the coastal regions and offshore, which are windy. In the coastal areas and in the large areas offshore from Lagos State through Ondo, Delta, Rivers and Bayelsa States to Akwa Ibom State, potentials exist for harvesting strong wind energy throughout the year [8].

Nigeria is endowed with large reserves of vegetation, shrubs, woods and agriculture. This can be harnessed as dry biomass which can then be used to generate energy using different techniques. Biomass has not been properly adopted in Nigeria and is only used in minute quantities for research which means it is in its infancy stage. This has piqued my interest and I would want to present valuable insight into biomass energy in Nigeria using the modern technique of fast pyrolysis.

The type of renewable energy source sufficiently available for power generation would be Biomass due to the vast availability of feedstock which includes; Agricultural wastes, Commercial wastes, Household wastes, Organic wastes such as wood shavings, sawdust, paper

Municipal solid waste

Municipal solid waste (MSW) consists of refuse from household, market waste, yard waste, and street sweepings which may be in solid, liquid or gaseous form [13]. This garbage is generated mainly from residential and commercial complexes. A typical MSW consists of organic (biodegradable and non-biodegradable) and inorganic (recyclable) components. The organic (biomass) portion of the waste stream includes materials such as food waste, yard waste, paper, cardboard, textiles, leather and wood. Inorganic waste components include glass, ceramics, plastics, rubber and metals. These inorganic waste components can be recycled. The rate of waste generation is highly influenced by the population and income [14] as well as level of industrialization, socio-economic status of the citizens and the kinds of commercial activities predominant in the area [15].

S/N	Geographical location within Nigeria		Designate	Name of selected cities	Population (Po) based on 2006 census	Waste Generated per capital (kg/capita/day)	Lat(°N)	Long(°E)
1	South	South-West	M1	Abeokuta	449,088	0.6	7.14	3.33
2			M2	Akure	491,033	0.54	7.25	5.2
3		South-East	M3	Onitsha	263,109	0.53	6.17	6.78
4			M4	Abakaliki	149,683	0.18	6.32	8.11
5		South-South	M5	Benin	1,086,882	0.5	6.32	5.6
6			M6	Port Harcourt	1,201,965	0.86	4.82	7.05
7	North	North-Central	M7	Abuja	1,406,239	0.66	9	7.27
8			M8	Ilorin	781,934	0.43	8.48	4.54
9		North-East	M9	Bauchi	493,730	0.22	10.64	10.08
10			M10	Jalingo	140,318	0.34	8.89	11.38
11		North-West	M11	Dutse	251,135	1	11.7	9.33
12			M12	Katsina	318,132	1.12	12.51	7.61

Table 2: Location of study across all the 6 Geopolitical zones in Nigeria [16]

From the table above, the different states being considered are shown with their population and waste generated per capita from literature. The states with the largest waste generated per capita are the North-Western states while those with the least waste generated per capita are the North-Eastern states.

Overview of municipal solid waste and legal framework in Nigeria

In Nigeria about 25 million tons of municipal solid waste are generated annually at a rate of 0.44-0.66 kg/person/day [14]. Like most developing countries, wastes are commonly dumped and burned in the open dumps, uncontrolled landfills [14] or buried in the ground, with all their attendant health and environmental hazards [17].

Cities under study

Composition (f) in %	Designate	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
Food Waste	H1	26.3	59.5	40.5	49.5	44.96	62.97	42.6	27.7	-	30	6	4
Yard Waste	H2	-	-	6.5	-	-	-	-	10.7	22.4	-	26	22
Plastics	H3	24.95	1.7	17.9	17.48	25.43	3.53	3.4	26.03	27	15	23	20
Paper	H4	25.5	14.5	8.1	12.96	14.27	9.87	25.3	-	16	-	11	11
Nylon	H5	-	-	-	-	-	14.2	14.5	-	-	-	-	-
Leather/Rubber	H6	-	-	10.11	-	-	-	-	-	-	35	-	-
Textiles	H7	9.48	-	-	3.6	-	-	3.03	-	23.4	2.8	-	-
Metal	H8	5.26	7.2	8.7	7.96	3.21	3.42	3.14			10	6	10
Glass	H9	5.75	6.3	4.5	4.52	3.89	1.87	3	18.03	5.4	0.3	7	8
Wood	H10	-	-	-	-	-	-	-	-	-	5	19	25
Ceramics	H11	-	-	-	-	3.95	-	-	-	-	-	-	-
E-waste	H12	2.69	-	-	-	-	-	2.8	-	-	-	-	-
Other Organic	H13	-	-	-	-	-	-	2.15	-	2	-	-	-
Others/inert	H14	-	11	-	3.98	0.9	3.7	-	17.54	2	1.9	-	-
Another Inorganic	H15	-	-	3.7	-	-	-	-	-	1.8	-	-	-
Combustible	H16	-	-	-	-	3.39	-	-	-	-	-	-	-
Total		100	100	100	100	100	100	100	100	100	100	100	100

Table 3: Percentage waste composition in the selected metropolises according to literature.

From the table above food waste, plastics and paper occupy the largest percentage of the MSW of the selected cities. Hence, plastic waste would be enough to be used as a waste to energy fuel source.

Challenges of utilizing MSW for energy generation in Nigeria

Challenges facing the use of MSW for energy generation in Nigeria includes the followings: lack of comprehensive legal framework and enforcement of the existing regulations [18], lack of comprehensive roadmap on waste to energy project, low investment in infrastructure that can aid the development of waste-to-energy technology, inadequate human capacity for administrative and technical issues relating to management of MSW for energy generation, wrong attitude of the public towards solid waste disposal that can enhance effective waste sorting, fear of cost recovery, Poor Planning towards effective adoption and utilization of waste-to-energy technology, lack of

adequate data on MSW that could support decision process in the utilization of waste to energy technology, uncontrolled dumpsite, uncoordinated institutional functions, low academic research and industry linkages and lack of the needed political will from the government [18].

Estimation of percentage composition of MSW for waste–to energy project

It is assumed that not all the waste generated is disposed-off in the dumpsites. According to [19], only 74% of the waste generated in Nigeria is collected and disposed-off in dumpsites. Therefore, the quantity of waste taken to dumpsite is obtained as:

$$\mathbf{M_F = 0.74 \times M_T\ (kg/yr.)} \quad (1)$$

Location	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
Waste Generated (Tons)	72,339	75,379	38,342	7,134	146,013	191,761	342,296	191,761	90,116	15,476	68,744	91,929

Functional units (i.e. waste generated in tons) for each of the selected locations

M_T is the total mass of waste generated per year and it can be calculated as:

$$\boldsymbol{MT = P \times wc \times 365} \quad (2)$$

where P is the extrapolated population of each of the location based on the population rate (r) of 3.2% and *wc* is the waste generated per capital per day (kg/capita/day). The extrapolated population can be determined as:

$$\mathbf{P = P_o\ (1 + r)^t} \quad (3)$$

where P_o is the base population of each of the location using 2006 census and t is the time of extrapolation interest. The percentage compositions of waste generated in each of the selected metropolis as obtained from literature are depicted in Table 3.

Different waste compositions require different technology for energy production. The amount of waste composition that could be utilized for different technologies (i.e. LFGTE, incineration, pyrolysis, anaerobic digestion) for electricity production in a waste-to-energy project was estimated from Table 2 using:

$$\mathbf{M_{F(i)} = 0.74 \times M_T \times f_{(i)}\ (kg/yr.)} \quad (4)$$

Where f is the organic fraction of the waste composition that goes into the specific technology option. Organic fraction of the possible waste composition (f) that could be used for waste-to-energy project using any of the three technologies was extracted in Table 3.

Methods of Energy production from MSW Feedstock

There are several methods of energy production from Biomass. These includes:

i. ***Thermal Conversion*:** This is when the biomass is heated to a suitable temperature. This can be subsumed as **combustion** and **pyrolysis**.

ii. ***Thermochemical Conversion*:** A thermochemical process uses heat and chemicals to break down a variety of biomass feedstocks into a syngas or gas mixture that contains varying amounts of carbon monoxide and hydrogen [20]. **Gasification** technology along with **Fischer-Tropsch** synthesis can produce renewable diesel from many different carbon-containing feedstocks [20].

iii. ***Biochemical Conversion*:** The bio-chemical conversion method involves biological decomposition of organic components of the waste under microbial action in the presence of oxygen (aerobic digestion) or absence of oxygen (anaerobic digestion) to produce compost or biogas (landfill gas) respectively [16].

PYROLYSIS

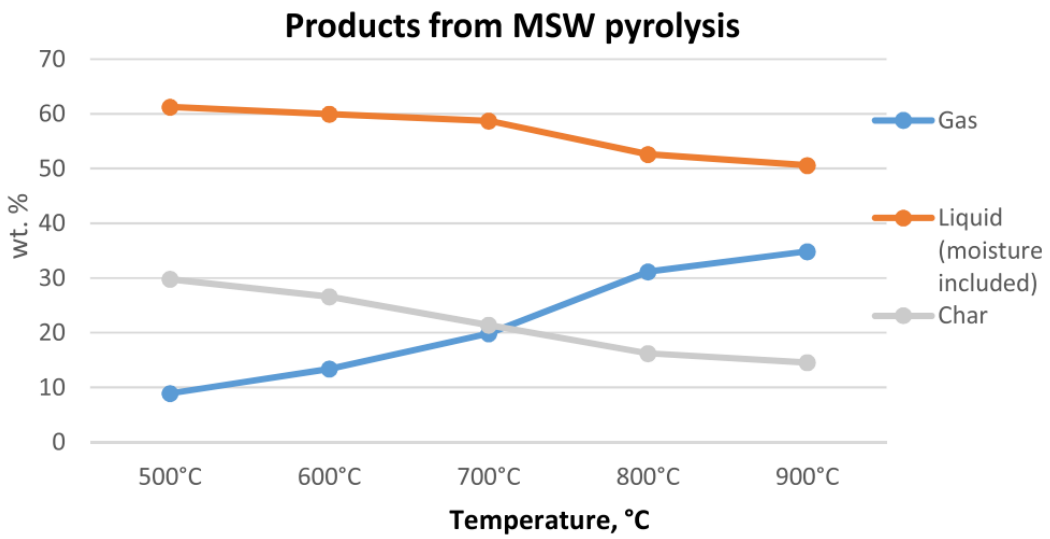
Pyrolysis is thermal decomposition occurring in the absence of oxygen. It is always also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the primary products. Lower process temperature and longer vapor residence times favor the production of charcoal. High temperature and longer residence time increase the biomass conversion to gas and moderate temperature and short vapor residence time are optimum for producing liquids There are two major forms; Fast pyrolysis and Slow pyrolysis. Fast pyrolysis would be considered here because of its higher efficiency.

Mode	Conditions	Liquid(%)	Char(%)	Gas(%)
Fast	Moderate temperature, around 500oc, Short hot vapor residence time ~1s	75	12	13
Intermediate	Moderate temperature, around 500oc, Moderate hot vapor residence time ~10-20s	50	20	30
Slow(carbonization)	Low temperature, around 400oc very long residence time	30	35	35
Gasification	High temperature, around 800oc long residence time	5	10	85

Typical Product Yields obtained from different modes of pyrolysis of wood [21]

Principles of Fast Pyrolysis Process

Fast pyrolysis is a high temperature process in which the feedstock is rapidly heated in the absence of air, vaporizes and condenses to dark brown mobile liquid which has a heating value of about half that of conventional fuel oil. While it is related to the traditional pyrolysis processes used for making charcoal, fast pyrolysis is a more advanced process that can be carefully controlled to give high yields of liquid. It has been observed that maximum liquid yields are obtained with high heating rates, at reaction temperatures around 5000C and with short vapor residence times to minimize secondary reactions.



Yields of products from MSW sample [22]

Fast pyrolysis processes have been developed for production of food flavors (to replace traditional slow pyrolysis processes which had much lower yields), specialty chemicals and fuels. Liquid yield depends on biomass type, temperature, hot vapor residence time, char separation, and biomass ash content. The process includes drying the feed typically less than 10% water in order to minimize the water in the product liquid oil, grinding the feed to give sufficiently small particles to ensure rapid reaction, rapid and efficient separation of solid (char), and rapid quenching and collection of the liquid product.

Plastics

Plastics are much less likely to biodegrade than other organic materials in MSW. They form a heterogeneous mixture of various components with unstable internal structure and changeable external characteristics. Moreover, the contents of plastic waste vary with the region and the season [23]. As most plastics are not biodegradable, their deposition in landfills is not a desirable solution from an environmental standpoint. There is also a lot of controversy about the incineration of these wastes, due to the release of toxic and greenhouse gases [24]. For example, only very high

incineration temperatures can prevent the release of dioxins and furans from plastics, but this requires huge quantities of energy. Another disadvantage of traditional incineration is that it completely destroys all organic matter, which could be valuable for different purposes. The effective treatment of plastic waste is a challenge for the protection of the environment and natural resources. The pyrolysis of plastics has been reviewed previously by Sharuddin et al. [25]. They concluded that pyrolysis has great potential to convert plastic waste to valuable, energy-bearing liquid oil, gas and char. Therefore, it is one of the best solutions for plastic waste conversion and it is also economical in terms of operation. The flexibility that it provides in terms of desired products can be achieved by changing operating parameters accordingly.

Type of plastics	Plastics type marks	Moisture (wt%)	Fixed carbon (wt%)	Volatile (wt%)	Ash (wt%)
Polyethylene terephthalate (PET)	1 PET	0.46 0.61	7.77 13.17	91.75 86.83	0.02 0.00
High-density polyethylene	2 HDPE	0.00 0.00	0.01 0.03	99.81 98.57	0.18 1.40
Polyvinyl chloride (PVC)	3 V	0.80 0.74	6.30 5.19	93.70 94.82	0.00 0.00
Low-density polyethylene	4 LDPE	0.30 –	0.00 –	99.70 99.60	0.00 0.40
Polypropylene	5 PP	0.15 0.18	1.22 0.16	95.08 97.85	3.55 1.99
Polystyrene	6 PS	0.25 0.30	0.12 0.20	99.63 99.50	0.00 0.00
Polyethylene (PE) Acrylonitrile butadiene styrene (ABS) Polyamide (PA) or Nylons Polybutylene terephthalate (PBT)	7 OTHER	0.10 0.00 0.00 0.16	0.04 1.12 0.69 2.88	98.87 97.88 99.78 97.12	0.99 1.01 0.00 0.00

Table 4: Proximate Analysis of Plastics [26]

Based on Table 4, it was observed that the volatile matter for all plastics is very high while the ash content is considered low. These characteristics indicate that plastics have high potential to produce large amount of liquid oil through pyrolysis process. Since the results of plastics

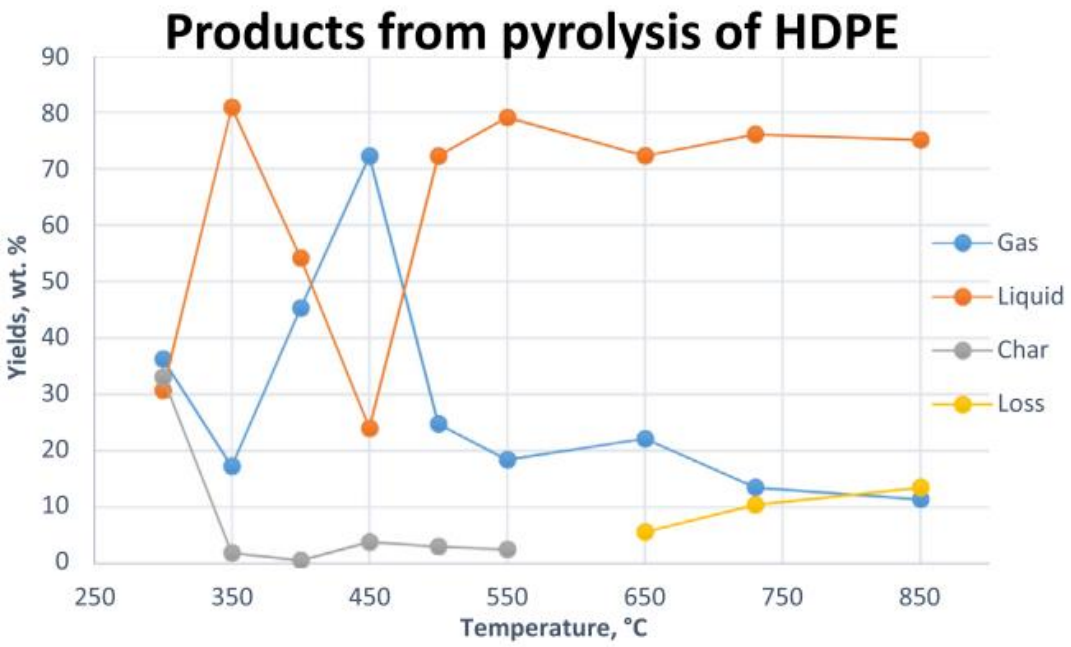
proximate analysis are very convincing, the following discussion would focus more on the process parameters involved during the pyrolysis process that would have major influence in the liquid production

Polyethylene terephthalate (PET)

PET has become the great choice for plastic packaging for various food products, mainly beverages such as mineral water, soft drink bottle and fruit juice containers. This is due to its intrinsic properties that are very suitable for large-capacity, lightweight and pressure-resistant containers. Other applications of PET include electrical insulation, printing sheets, magnetic tapes, X-ray and other photographic film [27]. The extensive applications of PET would cause an accumulation of PET waste in the landfill. Recycling PET waste was the current practice of handling accumulated plastic waste. However, the bulkiness of the containers causes high frequency of collections and therefore, increases the transport costs. To ease the recycling process, the PET waste needs to be sorted into different grades and colors that make its recovery inefficient and uneconomical. Hence, other alternative for PET recovery such as pyrolysis process has been explored and the product yield was analyzed by several researchers.

High-density polyethylene (HDPE)

HDPE is characterized as a long linear polymer chain with high degree of crystallinity and low branching which leads to high strength properties. Due to its high strength properties, HDPE is widely used in manufacturing of milk bottles, detergent bottles, oil containers, toys and more. The various applications contribute about 17.6% in plastic waste category which is the third largest plastic type found in municipal solid waste (MSW) [28].



Products from Pyrolysis of HDPE [29]

HDPE wastes have a great potential to be used in pyrolysis process since it can produce high liquid yield depends on the set-up parameters. Many studies have been conducted on HDPE pyrolysis at different operating parameters to investigate the product yield obtained.

Low-density polyethylene (LDPE)

In contrast to HDPE, LDPE has more branching that results in weaker intermolecular force, thus lower tensile strength and hardness. However, LDPE has better ductility than HDPE since the side branching causes the structure to be less crystalline and easy to be molded. It has an excellent resistance to water, thus widely applied as plastic bags, wrapping foils for packaging, trash bags and much more. All these items are commonly used in our daily lives and therefore, LDPE waste has been accumulated day by day that it is known as the second largest plastic waste in MSW after PP [28]. As one way to recover energy and reduce waste, pyrolysis of LDPE to oil product has received much attention by researchers nowadays.

By-products of the plastic pyrolysis

Pyrolysis of plastics also produces char and gas as by-products. The proportion of by-product in pyrolysis strongly depends on several parameters such as temperature, heating rate, pressure and residence time. They are generally discussed below:

Char

Generally, slow heating rate at very low temperature and long residence time maximizes the char formation in pyrolysis process. Even though the char formation in fast pyrolysis process is commonly low, it is worth noting the properties and usage of the char to fully maximize the potential of plastic pyrolysis. Jamradloedluk and Lertsatitthanakorn [30] analyzed the char properties obtained from the pyrolysis of HDPE plastic waste. From the proximate analysis, volatile matter and fixed carbon were found to be the main components of the char (>97 wt.%) while moisture and ash were the minorities. These components were closely related to the proximate analysis of the raw plastic as tabulated in Table 4, showing that most plastics were composed from almost 99 wt.% of volatile matter. The calorific value of the char was about 18.84 MJ/ kg. Furthermore, the low sulfur content made it suitable to be used as fuel, for instance in combustion with coal or other wastes. Besides that, the char formation was found to be increased with the temperature and this trend was observed by Jung et al. [31] in pyrolysis of PE and PP wastes.

Gas

According to Prabir [32], high temperature and long residence time were the best condition to maximize gas production in pyrolysis process. However, these conditions are opposite with the parameters to maximize oil production. Generally, gas production in pyrolysis process of polyolefins and PS plastics were quite low in the range of 5–20 wt% and it is strongly dependent

on the temperature and type of plastics used in pyrolysis. The effect of temperature and plastic types were further studied by Onwudili et al. [34] in a pyrolysis of LDPE, PS and their mixture. At 350 C, it was discovered that the gas product from the mixture was more than the pyrolysis of individual plastic.

The pyrolysis of PET and PVC plastics produced large amount of gases in comparison to other polyolefin plastics. The gas produced in pyrolysis process also has significant calorific value. Jung et al. [33] reported that the gas produced from the pyrolysis of PE and PP alone had high calorific value between 42 and 50 MJ/kg. Thus, the pyrolysis gas had high potential to be used as heating source in pyrolysis industrial plant.

Fluidized bed reactors

Typically, fluidized-bed reactors are used to study the behavior of fast pyrolysis and to investigate the secondary cracking of oil at longer residence times. Fluidized-bed reactors are characterized by a high heating rate and a good blending of the feedstock.

This type of reactor seems to be a good solution for waste polymer pyrolysis. For example, polymer pyrolysis in a fluidized-bed reactor can provide remarkable advantages over the processes in other reactors in which heat is not transferred as efficiently for the cracking of polymers because polymers have a very low thermal conductivity and high viscosity.

On the other hand, there are important difficulties in using fluidized-bed reactors to utilize MSW. First, the raw material provided to the reactor must be tiny, so it could float in the fluid. Second, there is a big problem with separating the char from the bed material.

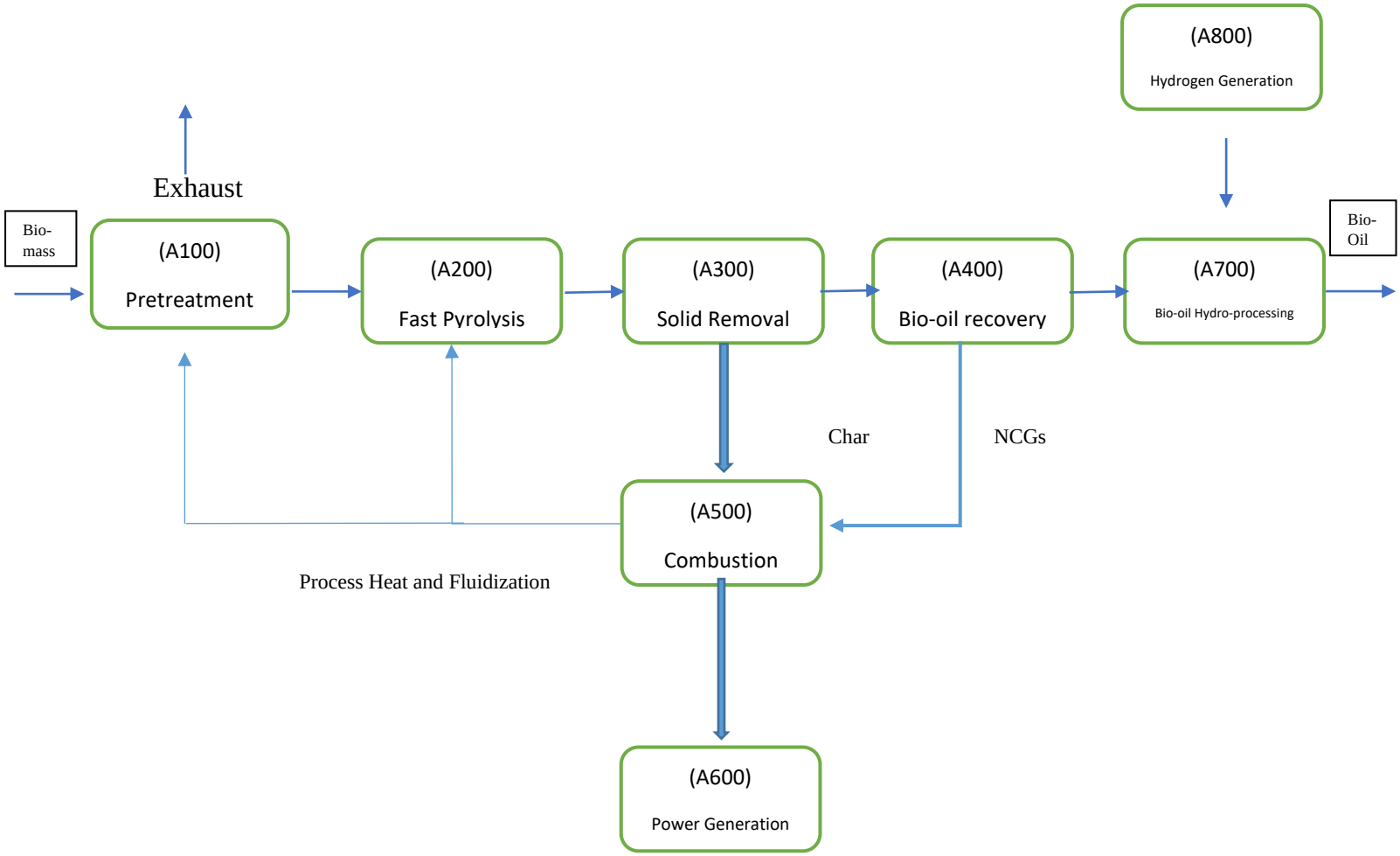
CHAPTER 3: MODEL DESIGN AND ANALYSIS

BACKGROUND

This project restricts the study area to the 12 selected states of study using each of their waste generated per capita. The model is a pyrolysis plant designed on ASPEN® and the waste PET plastics estimated from each cited state's total waste and fed as input for the model. The energy generated and pollution would also be calculated.

SYSTEM DESIGN

The model will consist of the pretreatment side after which comes the fast pyrolysis then the solid residue (char) would be removed and be combusted. The combustion process can be used to further drive the pretreatment and fast pyrolysis parts by process heat and fluidization. After the solid char has been removed, Bio-oil can be recovered and the NCGs (Non-Combustible Gases) can be burned alongside the char which would then further improve the efficiency of the combustion process and this can used to drive a turbine which would get generate electrical power.



Generalized process flow diagram.

i. **Pretreatment(A100):** In this section, the feedstock (plastic), supplied is fed into a multiple roll crusher (CHR) in which the particle size is reduced and followed by a screen (SCRN) for particle separation. The exiting wet feedstock stream (CHR-2) with initial moisture content of 25% is then fed into a rotary dryer (DRYER) at an operating temperature to reduce its moisture content. A rotary dryer was adopted in the model due to its flexibility in operation, low maintenance costs and high operating temperature range. The energy required for drying is supplied by a fraction of flue gas from the combustor

which exits the dryer as a mixture of hot air and water vapor, while the dried feedstock exits the dryer with a 10% moisture content. The dried feedstock then goes into the fluidized bed reactor.

ii. **Fast Pyrolysis(A200):** This is where the actual fast pyrolysis takes place. The plastic would be heated to about 500^{o}c in the absence of oxygen. The reactor products comprising a mixture of hot vapors, gas and solids are sent into a cyclone (SP-CYC) to separate the solids particles (PYR-SD) from the mixture.

iii. **Solid Removal(A300):** Char and unreacted biomass (PYR-SD) are separated from the hot vapor and gas stream (PYR-VAP) in a cyclone (PYR-CYC) Char and unreacted biomass (PYR-SD) are separated from the hot vapor and gas stream (PYR-VAP) in a cyclone (PYR-CYC). NCG and the remaining condensable vapors (QC-GAS) then go into a high-pressure vapor–liquid separator (DEMISTER) operated at 10 bars to collect the bio-oil vapors entrained as aerosol particles. The resultant dry NCG goes to a combustor along with char while the quenched bio-oil is sent for further upgrading in the bio-oil hydro-processing section (A700-A800).

iv. **Combustion section (A500):** The combustion section is modelled by a yield reactor (CB-DEC)

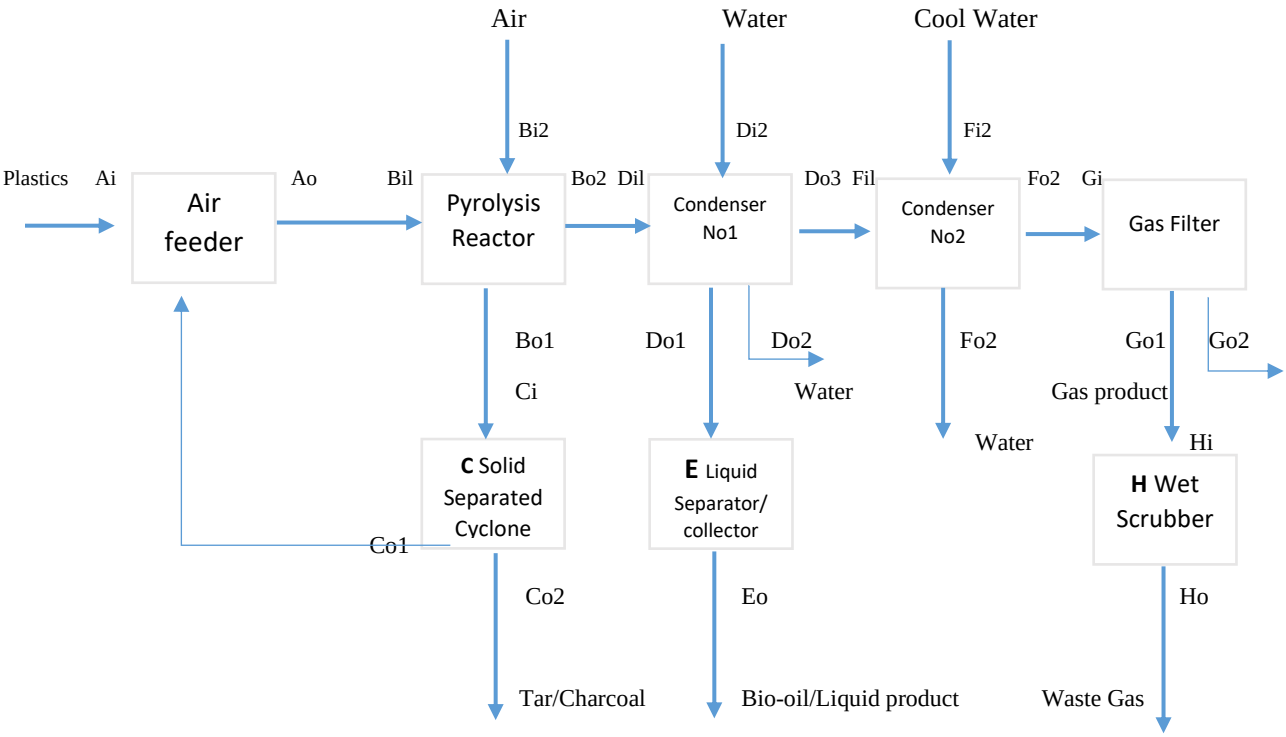
and a Gibbs reactor (CB-BUR). Unreacted biomass separated from the cyclone goes into the yield reactor (CB-DEC) where it is decomposed into its constituent elements before it is fed into the Gibbs reactor (CB-BUR) along with char (assumed to be 100% carbon in elemental constitution) and NCG. Although a maximum temperature of 1700^{o}C can be achieved at complete combustion, the fuel mixture of solids and NCG are combusted in 60% theoretical air at a combustion temperature of 1269^{o}C in order to mitigate ash melting

and prevent material failure at severe temperatures. Ash is separated from the resultant combustion gases by a hot cyclone (ASH-SEP). The resultant flue gas (FL-GAS) is sent into a splitter (GAS-SPLIT), where it is divided into two streams (PYR-FLGS) and (DRY-FLGS). These are supplying heat for the feed nitrogen gas, which goes to the fluidized bed pyrolysis reactor and for the feed air, which goes to the dryer via two-stream heat exchangers. The residual flue gas heat at 800 C is used for superheated steam generation for subsequent electric power generation.

v. **Power generation (A600):** The residual heat from combustion is exchanged with water in a two-stream heat exchanger to generate superheated steam at 450^{o}C and 50bar with an outlet flue gas temperature of 90 C. The superheated steam is supplied to a steam turbine (TURB), modelled at 80% isentropic efficiency and mechanical efficiency of 95% to generate electric power (POWER).

vi. **Bio-oil Hydro-processing (A700):** A yield reactor is introduced afore the hydrotreaters to lump bio-oil into five pseudo-components, namely, light non-volatile; heavy non-volatile; phenolics; aromatics + alkanes; Coke + H2O + outlet gases. Since all chemical compounds in the bio-oil are primarily composed of carbon, hydrogen and oxygen, the pseudo components are grouped solely based on their molecular weights and functional groups.

vii. **Hydrogen production (A800):** The target hydrogen product flow rate is determined by varying the flow rate of superheated steam required in the reformer using a design specification block. The product from the aqueous reformer goes into a flash drum where the gas mixture is separated from the water vapor and then the gas mixture is sent to a pressure swing adsorption (PSA) unit, which separates the hydrogen from the gas mixture, which is then recycled for hydro-processing.



Mass flow Diagram

The mass balance calculation method was performed as the derivation of simple expressions for the total syngas mass and the total pyrolysis liquid mass are

$$X = (G_s + L_s) / (D - C + M) \quad (5)$$

$$G = G_s / X = G_s (D - C + M) / (G_s + L_s) \quad (6)$$

$$L = L_s / X = L_s (D - C + M) / (G_s + L_s) \quad (7)$$

where nomenclature is dry mass of feed **(D)**, mass of moisture in feed **(M)**, char mass yield **(C)**, syngas mass yield **(G)**, liquid mass yield **(L)**, syngas sample mass **(G_s)**, liquid sample mass **(L_s)**, and unknown fraction sampled of total gas phase mixture **(X).**

This can be seen to be logical, as splitting the total volatile mass released through pyrolysis in the proportion of gas to liquid in the sample taken, with an adjustment to the liquid yield for the moisture present in the feed.

This pyrolysis plant is regarded as a closed system, with total heat equation as

$$\Delta Q = Q_{out} - Q_{in} \quad (8)$$

Evaluation of electrical energy potential from the char collected from Pyrolysis technology

The electrical energy (kW hr./year) that could be obtained from the char collected from the pyrolysis process can be obtained using:

$$E_{P(pyro)} = \frac{\varepsilon \times Q_c \times \varphi_1}{\varphi_2} \quad (9)$$

Where ε is the lower heating value of char which is 15.3MJ/Kg. φ_1 is the electrical conversion efficiency for internal combustion engine given as 0.33, φ_2 is the conversion factor from MJ to KWh based on heat content, Q_c is the average char generated per annum(Kg/yr.) and can be obtained as:

$$Q_c = \lambda \times Q_g \quad (10)$$

$$Q_g = \frac{\sum_{i=1}^{n} Q_{C_jH_k(i)}}{n} \quad (11)$$

where λ is collection efficiency (75%), n is the number of years the char is collected.

Evaluation of the Economic viability of Pyrolysis Technology

For optimal investment in any waste-to-energy project, the knowledge of economic viability of such project is important. Net Present Value (NPV) and Levelized Cost of Energy (LCOE) and are used to determine the economic viability of the technologies for each of the sites:

Net Present Value (NPV)

This is the present value of all the costs that the system incurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. It is one of the ways of examining costs cash outflows and revenues cash inflows. Its value must be positive for the system to be economically viable. NPV can be calculated as follows:

$$\text{NPV} = \sum_{n=0}^{N} \frac{F_n}{(1+d_r)^n} = F_o + \frac{F_1}{(1+d_r)^1} + \frac{F_2}{(1+d_r)^2} + \ldots\ldots\ldots + \frac{F_N}{(1+d_r)^N} \quad (12)$$

where, F_n is the net cash flow rate, d_r is annual real discount rate and N is the total number of years under study. Both F_n and d_r can be determined using

$$F_n = \mathrm{R}_{ev(i)} - C_{inv(i)} - C_{o\,\&\,M(i)} - C_{Tax} \quad (13)$$

$$d_r = \left(\frac{1+d_n}{1+e}\right) - 1 \quad (14)$$

$$d_r = \left(\frac{1+d_n}{1+e}\right) - 1$$

$$= \left(\frac{1+0.1}{1+0.094}\right) - 1 \quad = 0.005484$$

where, R_{ev} is revenue earned from the project, C_{inv} is the total investment cost of the project $C_{O\,\&\,M}$ is operation and maintenance cost, C_{Tax} is tax paid on the project, d_n is the nominal discount

rate and *e* is the inflation rate as furnished by Central Bank of Nigeria. Their values as used in this paper can be found in the Table

Indices	**Inflation rate (e)**	**Nominal discount rate (d_n)**	**Marginal tax rate (t)**	**(F_d) $/kWh**	**Project life time (N) years**
Value	9.40%	10%	30%	0.1868	20

Determination of investment cost (Ci_{nv}), operation and maintenance cost ($C_{O\ \&\ M}$):

To determine the net cash flow rate F_n, the investment cost (C_{inv}) as well as operation and maintenance cost ($C_{O\ \&\ M}$) must be evaluated. The revenue (Rev) earned from the project can be estimated as:

$$R_{ev(i)} = E_{p(i)} \times F_d \tag{15}$$

Where E_p is the total energy obtainable, F_d is the cost sale of electricity in $/kWh ($1 = N200) as determined by the Nigerian Electricity Regulation Commission (NERC).

The Levelized cost of energy

Levelized Cost of Energy (LCOE) is another metric by which the economic viability of a project can be measured. It is the minimum cost in ($/kWh) of energy generated by renewable energy system at which the system breaks even. It can serve as a basis by which different technologies can be compared in terms of economic viability. It can be determined using:

$$LCOE_{(i)} = \left(\frac{LCC_{(i)}}{E_{P(i)}} \right) CRF_{(i)} \tag{16}$$

where LCC is the life cycle cost of the project, CRF is the capital recovery factor. The LCC and CFR can be calculated using:

$$LCC = C_{inv(i)} + \sum_{n=1}^{N} \frac{C_{o\ \&\ M(i)}}{(1+d_n)^n} \infty \quad (17)$$

$$CRF = \frac{d_n(1+d_n)^N}{(1+d_n)^N - 1} \quad (18)$$

where N is the number of years.

The investment cost includes the following: energy, labor and personnel, land, equipment, construction. The cost function factoring all these costs has been estimated using experimental data in form of a cost function by Tsilemou and Panagiotakopoulos [34]. However, the cost function could be adapted from one region or to another using appropriate conversion coefficient. The investment cost and the operating & maintenance costs function was adjusted using Purchasing Power Parity (PPP), Consumer Price index (CPI) and exchange rate as follows:

$$C_{inv(INC)} = 4900 \times (M_{F(INC)})^{0.8} \times Q \times R \times S \quad (19)$$

$$C_{O\ \&\ M(INC)} = 700 \times (M_{F(INC)})^{-0.29} \times Q \times R \times S \quad (20)$$

where, Q, R, S are cost adjustment factors. Q is conversion rate from Euro to US dollar taken as 1.0815 {multiplied by 200 ($1 = N200)}, R is the inflation rate (CPI) from 2003 to 2015 taken as 1.4315 and S is the Purchasing Power Parity adjustment from Euro to US dollar taken as 1.0400 {multiplied by 200 ($1 = N200)}.

Payback Period

Payback Period (PBP) is one of the metrics to be considered in taking decision to embark on a project. It is the number of years at which the project cost breaks even (i.e. the time at which the cost of investment equals operating cost) and it can be calculated using:

$$PBP = \frac{C_{inv}(\$) - \mathrm{Re}\,bates(\$)}{AnnualEnergySaving(\$/year)} \tag{21}$$

$$AnnualEnergysavings = \mathrm{R}_{e\,v} - C_{O\,\&\,M} \tag{22}$$

Flue Gas

Flue gas is the combustion product gas from a fireplace, oven, furnace, boiler or steam generator that exits to the atmosphere via a "flue" which may be a pipe, channel or chimney. The flue is most commonly referred to as a "flue gas stack" by engineers. Flue gas is usually composed of carbon dioxide (CO_2) and water vapor as well as nitrogen and excess oxygen remaining from the intake combustion air. It may also contain a small percentage of air pollutants such as particulate matter, carbon monoxide, nitrogen oxides, sulfur oxides and mercury.

From Table A, the composition of flue gas can be estimated. Co_2 can be calculated as the percentage.

According to the conservation of energy (energy balance), the heat energy liberated in the furnace is equal to the heat energy used in raising steam in the boiler plus heat energy loss due to unburned fuel and through stack to the atmosphere. The amount of useful heat (Btu) needed to raise steam in the feed water boiler [35] is given as:

$$Q_{inc} = \frac{b \times HHV(100 - e)}{100} \quad (23)$$

where e is the sum of all the efficiency losses, b is the dry mass of fuel (waste) in (lb.) and this can be obtained by converting kg to lb. (1kg = 2.205lb) and HHV is the high heating value which is 11,150Btu/lb. Assuming efficiency losses of 40%,

From table A,

To convert from scf (standard cubic feet) to m^3 multiply by 0.0283168.

From Table A, the amount of CO_2 produced would be

Conclusion

The energy potential, Net Present Value, Levelized cost of Energy, Dry flue gas generated can be evaluated and this can be analyzed to find plausibility of establishment.

CHAPTER 4: RESULTS

Evaluation of Total Plastic Waste and Energy Potential

The total plastic waste was compared with the Energy potential and the results are shown in figure 4.1. It was shown that the greater the plastic waste for the state, the greater the Energy potential. M5(Benin) has the largest energy potential while M2(Akure) has the least energy potential.

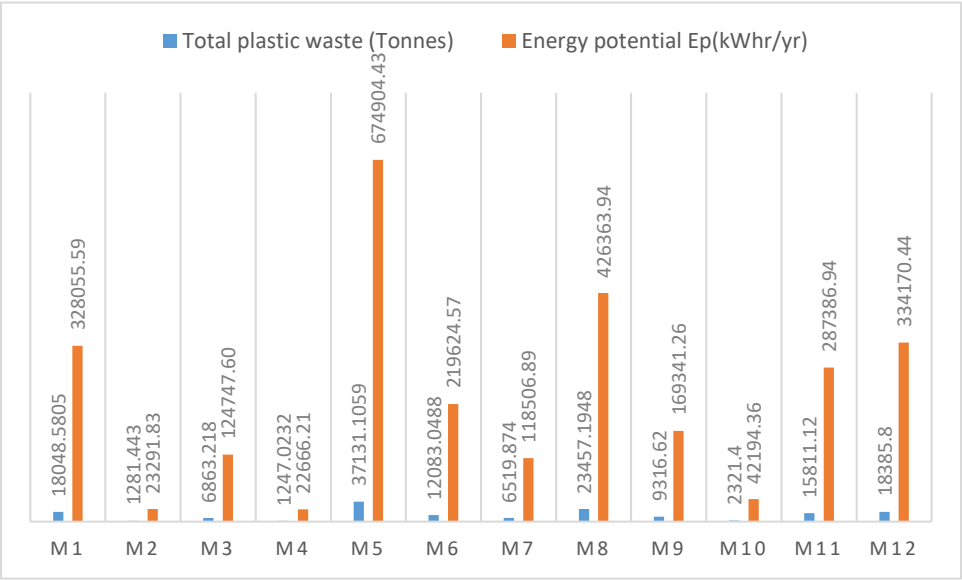
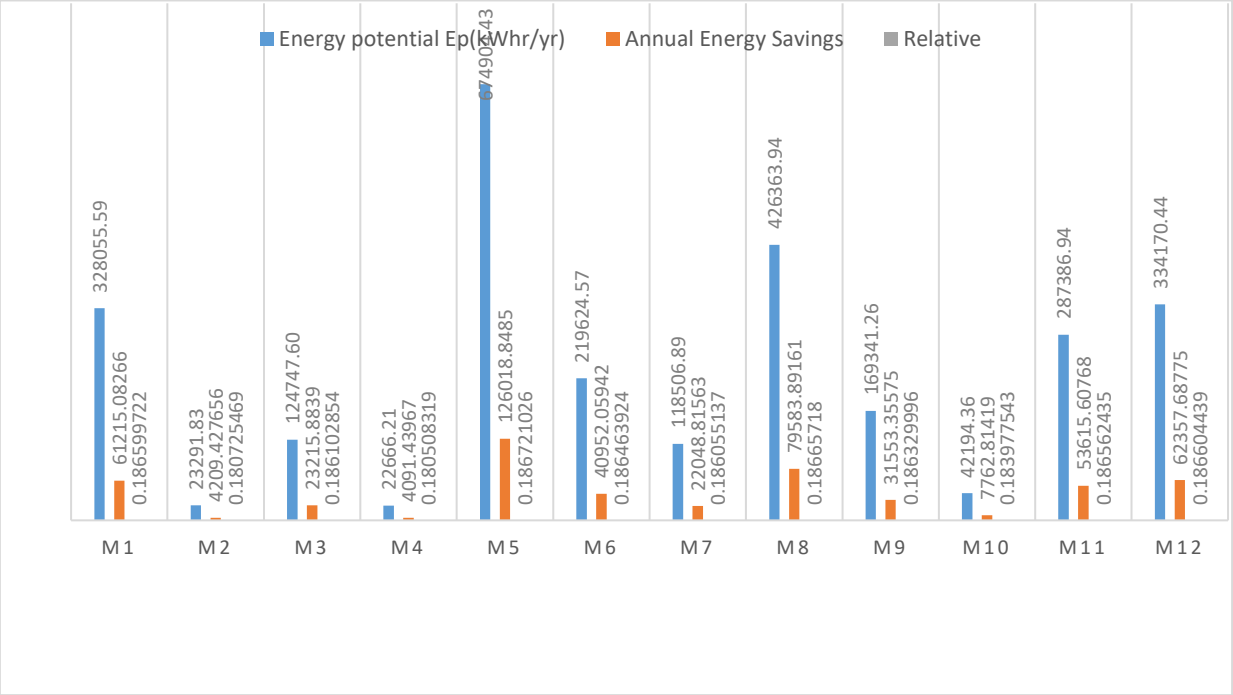


Figure 4.1 Total Plastic Waste in comparison with Energy potential

Evaluation of Energy Potential and Annual Energy Savings

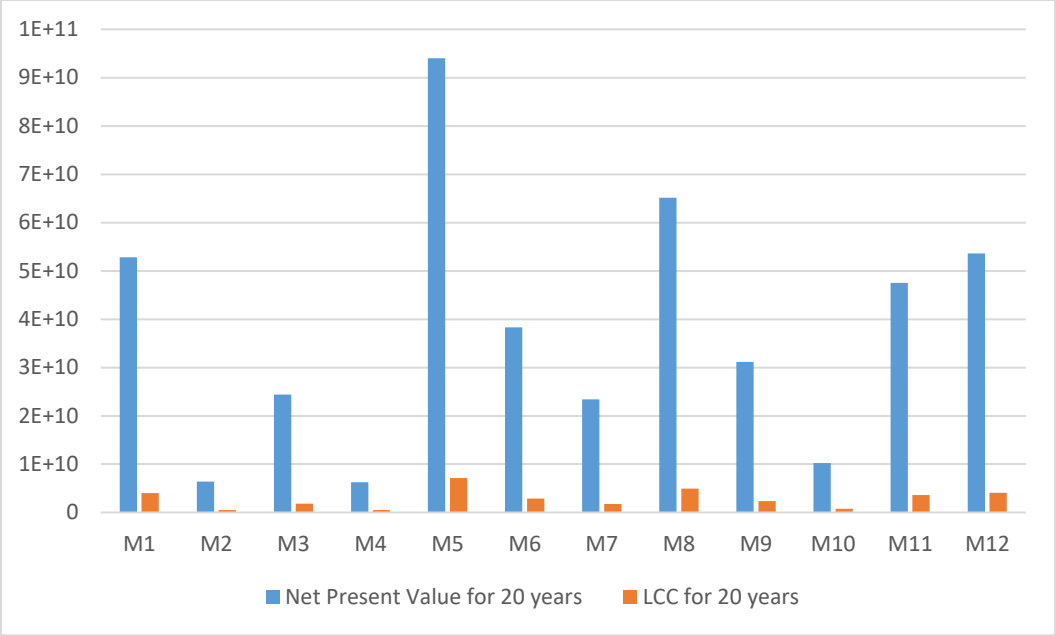
The Energy potential of each state was also compared with the Energy savings and the results are shown in figure 4.2. Relatively, cities M1, M5, M8, M11, M12 (Abeokuta, Benin, Ilorin, Dutse and Katsina) have the largest relative of the Energy potential and Annual Energy Savings. The

least relative potential and Energy savings would be M2 and M4 (Akure and Abakaliki). The range of Energy potential is 670690.07KWhr/yr.



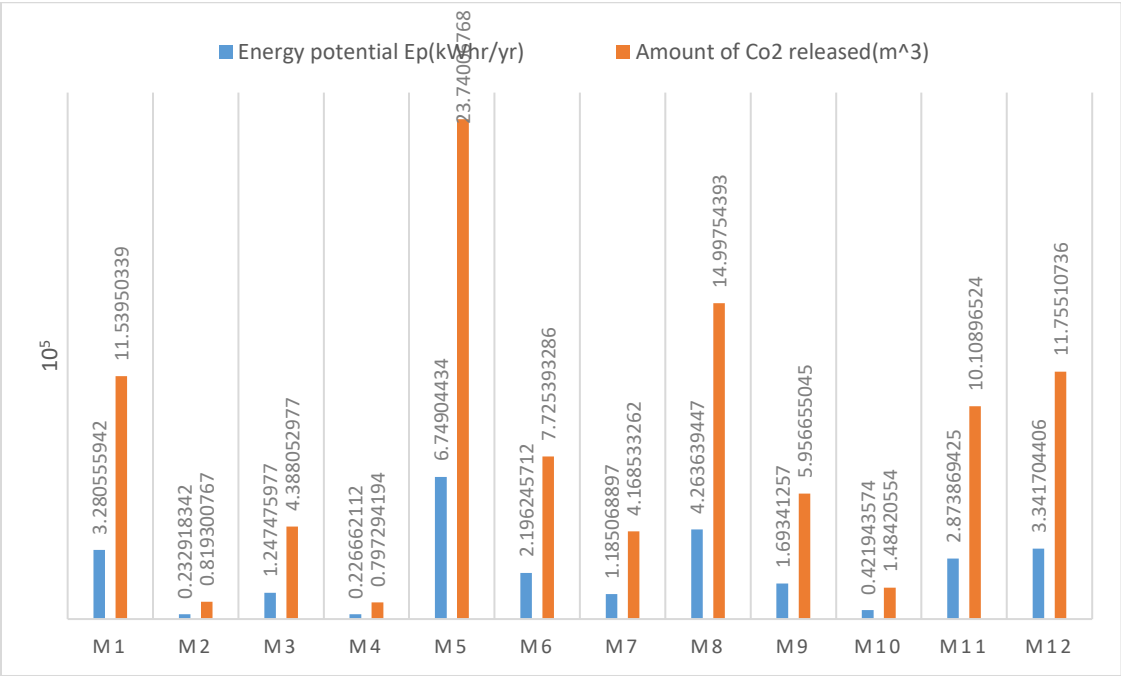
Evaluation of Net Present Value and LCC:

The Net Present Value was compared with the LCC (Lifetime Project Cost). The costs are in billions of Naira cities M2, M4 and M10 have the largest relative NPV to LCC which are Akure, Abakaliki and Jalingo while M5 (Benin) had the least.



Evaluation of Energy potential to Amount of Co_2 released:

The energy potential was also related to the amount of Co_2 that would be released and cities M1, M5, M11, M12 (Abeokuta, Benin, Dutse and Katsina) had the largest greatest amount of Co_2 to be released while M2 and M4 had the least (Akure and Abakaliki).



CHAPTER 5: Conclusion

From the results, it was shown that cities such as M1, M5, M11 and M12 (Abeokuta, Benin, Dutse and Katsina) were the most viable for establishment of a pyrolysis plant from the MSW of plastics they generated and cities such as M2 and M4 (Akure and Abakaliki) were the least viable.

Recommendation

From this analysis, the aforementioned most viable cities can use to understand the benefits and implications of the project which would go a long way in creating energy independence and simultaneously reducing plastic pollution.

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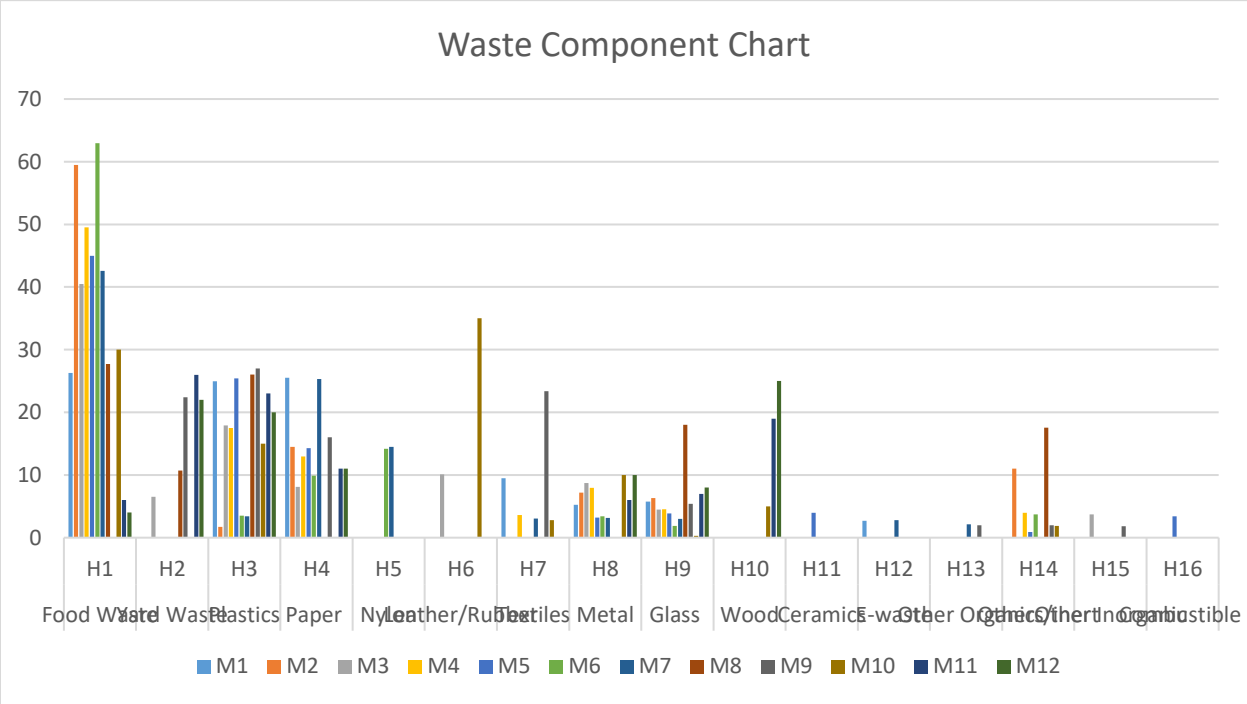
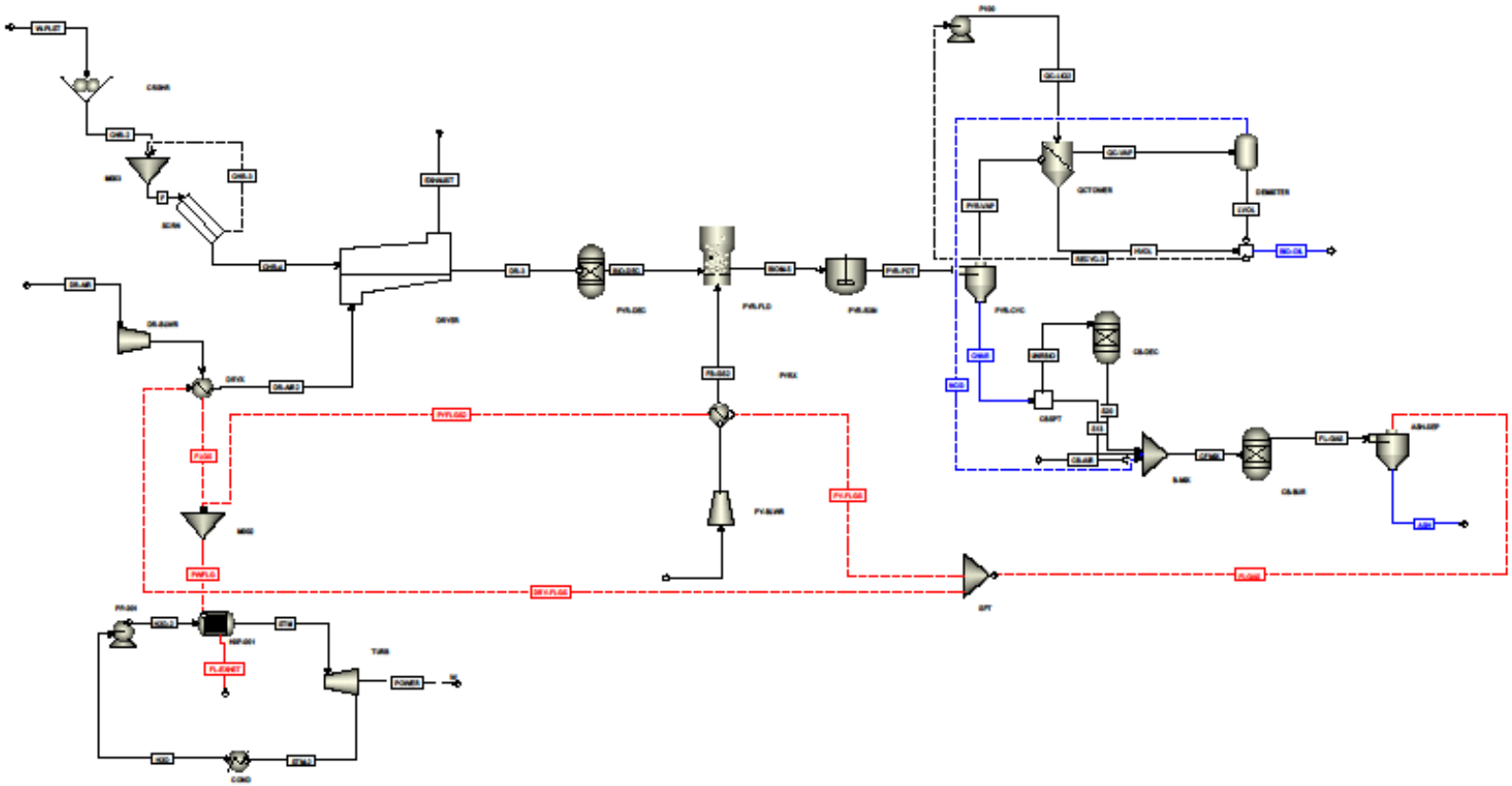
APPENDIX


Waste Component Chart
70
60
50
40
30
20
10
0
H1
H2
H3
H4
H5
H6
H7
H8
H9
H10
H11
H12
H13
H14
H15
H16
Food Waste
Yard Waste
Plastics
Paper
Nylon
Leather/Rubber
Textiles
Metal
Glass
Wood
Ceramics
E-waste
Other Organics
Other Inert
Other Inorganic
Combustible
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
M12



Exhaust flue gas generated by combustion of fossil fuels
(In SI metric units and in US customary units)

Combustion data	Fuel gas	Fuel oil	Coal
Fuel properties:			
Gross caloric value, MJ/m³	43.01		
Gross heating value, Btu/scf	1,093		
Gross caloric value, MJ/kg		43.50	
Gross heating value, Btu/gal		150,000	
Gross caloric value, MJ/kg			25.92
Gross heating value, Btu/lb			11,150
Molecular weight	18		
Specific gravity		0.9626	
Gravity, °API		15.5	
Carbon/hydrogen ratio by weight		8.1	
weight % carbon			61.2
weight % hydrogen			4.3
weight % oxygen			7.4
weight % sulfur			3.9
weight % nitrogen			1.2
weight % ash			12.0
weight % moisture			10.0
Combustion air:			
Excess combustion air, %	12	15	20
Wet exhaust flue gas:			
Amount of wet exhaust gas, m³/GJ of fuel	294.8	303.1	323.1
Amount of wet exhaust gas, scf/10^6 Btu of fuel	11,600	11,930	12,714
CO_2 in wet exhaust gas, volume %	8.8	12.4	13.7
O_2 in wet exhaust gas, volume %	2.0	2.6	3.4
Molecular weight of wet exhaust gas	27.7	29.0	29.5
Dry exhaust flue gas:			
Amount of dry exhaust gas, m³/GJ of fuel	241.6	269.3	293.6
Amount of dry exhaust gas, scf/10^6 Btu of fuel	9,510	10,600	11,554
CO_2 in dry exhaust gas, volume %	10.8	14.0	15.0
O_2 in dry exhaust gas, volume %	2.5	2.9	3.7
Molecular weight of dry exhaust gas	29.9	30.4	30.7

Note: m³ are standard cubic meters at 0 °C and 101.325 kPa, and scf is standard cubic feet at 60 °F and 14.696 psia

Table A