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Feasibility Study on Solid Waste to Energy

Technological Aspects

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Abstract: Technologies, such as incineration, conventional gasification, pyrolysis and plasma gasification, have been developed to reduce the amount of waste that goes into landfills [4,17]. However, these technologies have not been widely implemented throughout the world due to various reasons such as environmental and financial concerns. This paper seeks to compare and evaluate each technology by reviewing waste to energy reports and seeking information from technology providers, to determine which technology is the best. The technologies are evaluated based on net conversion efficiency, environmental impact and commercial availability. However in our analysis, there is no clear winner in any of the technologies based on the aforementioned criteria. Plasma arc gasification is better in net conversion efficiency and environmental impact but poor in commercial availability, while conventional gasification is more commercially available. Therefore, in order to choose the right technology, we need to consider the technology user's preferences and risk profile. This means we have to rank each criterion's importance to the technology user and see which technology has the best total rank.

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LIST OF NOMENCLATURE/NOTATIONS

MSW	Municipal solid waste
NRP	Non-recyclable plastics
tpy	tons per year
PM	Particulate Matter
HCl	Hydrochloric Acid
NOx	Nitrous Oxides
SOx	Sulphur Oxides
Hg	Mercury
$r_{i,j}$	Rank of technology i for criterion j
a_j	Value of criterion j awarded by stakeholder
w_j	Weight of importance of each criterion j
$r_{T,i}$	Total rank of technology i
EV_P	Energy value of plastics
EV_{MSW}	Energy value of MSW
$ER_{i,P}$	Energy recovered using technology i and plastics
$ER_{i,MSW}$	Energy recovered using technology i and MSW
$EC_{i,P}$	Energy consumed using technology i and plastics
$EC_{i,MSW}$	Energy consumed using technology i and MSW
$e_{i,P}$	Net conversion efficiency using technology i and plastics
$e_{i,MSW}$	Net conversion efficiency using technology i and MSW
y	Ratio of $EC_{i,P}$ and $EC_{i,MSW}$
z	Ratio of $\frac{ER_{i,P}}{EV_P}$ and $\frac{ER_{i,MSW}}{EV_{MSW}}$

ABSTRACT

Technologies, such as incineration, conventional gasification, pyrolysis and plasma gasification, have been developed to reduce the amount of waste that goes into landfills [4,17]. However, these technologies have not been widely implemented throughout the world due to various reasons such as environmental and financial concerns. This paper seeks to compare and evaluate each technology by reviewing waste to energy reports and seeking information from technology providers, to determine which technology is the best. The technologies are evaluated based on net conversion efficiency, environmental impact and commercial availability. However in our analysis, there is no clear winner in any of the technologies based on the aforementioned criteria. Plasma arc gasification is better in net conversion efficiency and environmental impact but poor in commercial availability, while conventional gasification is more commercially available. Therefore, in order to choose the right technology, we need to consider the technology user's preferences and risk profile. This means we have to rank each criterion's importance to the technology user and see which technology has the best total rank.

1.0 INTRODUCTION

In 1988, the solid waste management hierarchy was adopted into US national policy to reinforce the movement away from landfilling and towards waste prevention, recycling, composting and Energy-from-Waste in that order of priority [7]. This means the Municipal Solid Waste (MSW) used for conversion into energy should only be those that would otherwise be sent to landfills. Since the amount of available land for landfill is finite, it is not a sustainable option to simply dump MSW into landfills. In fact, New York City is already exporting its waste to neighbouring States such as Pennsylvania, Ohio and Virginia [11]. Therefore there is a need to further reduce the amount of waste going into landfills.

The technology to process such MSW has existed for decades, beginning with the use of incinerators, which simply combust the waste into gases and leave ashes as residue. As technology advanced, simple incinerators instead became waste to energy (WTE) facilities, with non-recyclable MSW as the fuel source. The heat generated from combustion of MSW is used to turn water into steam in a boiler. This steam can be used for either heating homes or for generating electricity via a steam turbine [6,20]. However, simple incineration or combustion of waste has the public perception of being environmentally unfriendly despite the emissions from incineration being within EPA limits [23]. Therefore new technologies have been developed in recent years to process non-recyclable MSW, namely pyrolysis, conventional gasification and plasma arc gasification. These technologies operate at various temperatures and amounts of oxygen, which lead to them being more environmentally friendly.

This paper is part of an overall project that studies the feasibility of implementing a WTE facility for The Dow Chemical Company (Dow), which considers different aspects such as the technologies, logistics and economics involved. Thus, the focus of this paper is to evaluate the aforementioned WTE technologies with non-recyclable plastics (NRP) as the feedstock and to recommend the best technology. Each technology will be evaluated based on the following criteria: net conversion efficiency, environmental impact and commercial availability. However, each technology has its own advantages and disadvantages. Therefore this paper also discusses a decision tool for Dow to use to match the technology best suited. In the coming sections I will discuss and evaluate each technology before making some recommendations for Dow and discuss possible future work.

2.0 LITERATURE REVIEW

This section provides background information on the technologies used to process waste, namely incineration, conventional gasification, pyrolysis and plasma arc gasification.

2.1 Incineration

Incineration is the oldest technology used to process waste, consisting of several types of incinerators such as single stage, two stage, grate and fluidized bed incinerators [2,3,17]. They all involve directly combusting the MSW in an oxygen-rich environment, typically at temperatures between 700°C and 1,350°C [24,25]. An exhaust gas composed primarily of CO_2 and water is produced, which flows through a boiler to produce steam to drive a steam turbine generator, producing electricity [4,24]. Inorganic materials in the MSW are converted to bottom ash and fly ash [4]. These byproducts must be disposed in controlled and well-operated landfills to prevent ground and surface water pollution [17]. Although incineration does not eliminate the need for landfills, it does significantly reduce the amount being sent to landfills by about 90% by volume [20]. Over 90% of WTE facilities in Europe utilize mass burn incineration technology, with the largest facility treating approximately 750,000 tpy [17]. Typical systems in North America treat up to 3,000 tons/day of MSW, generating about 605 net kWh/ton of MSW [4]. Figure 1 shows an example of a single stage incinerator.

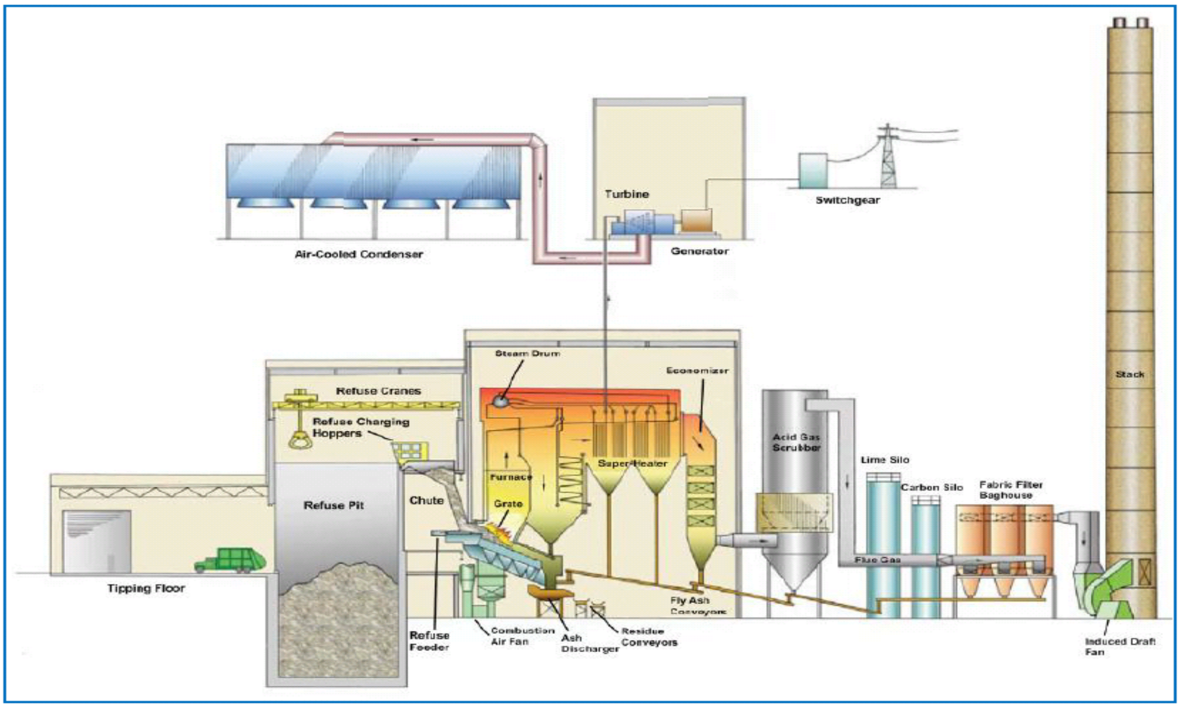

Figure 1. Single Stage Incinerator [17]

It is evident that incineration is currently the most commercialized technology used to process MSW. However, public perception of incineration being environmentally unfriendly means that future projects using incineration will not be supported. Furthermore, there is no flexibility in the products from using incineration because only steam and electricity can be produced. Finally, there is no improvement in the technology continuum if incineration is used because this technology has been stagnant for many years. Therefore further analysis on incineration will not be done in this report.

2.2 Conventional Gasification

Gasification has also been around for decades but was originally only used for coal gasification. It is only in recent years that the technology has been developed for MSW gasification [17]. This process involves the heating of MSW with a controlled amount of air or oxygen to produce a synthetic gas (syngas). This typically occurs in the range of 760 to 1,500°C [4,24,25]. The syngas is processed to remove water vapour and other trace contaminants before it can be used for power generation, heating or as a chemical feedstock [2,4,17]. The amount of byproducts of char/ash produced will be approximately 15 to 20 percent by weight of the feedstock throughput [4]. The oxygen deficient atmosphere also prevents the formation of harmful dioxins and furans [10]. The largest MSW gasification plant is in Kawaguchi, Japan, processing 400 tons/day of MSW using three gasifier trains. An analysis of conventional gasification technologies shows that they can produce up to 750 net kWh/ton of processed feedstock [4]. However, there are operational issues that arise due to the heterogeneous nature of MSW as the gasification process generally requires a fairly homogenous feedstock [17]. Figure 2 shows an example of a gasifier.

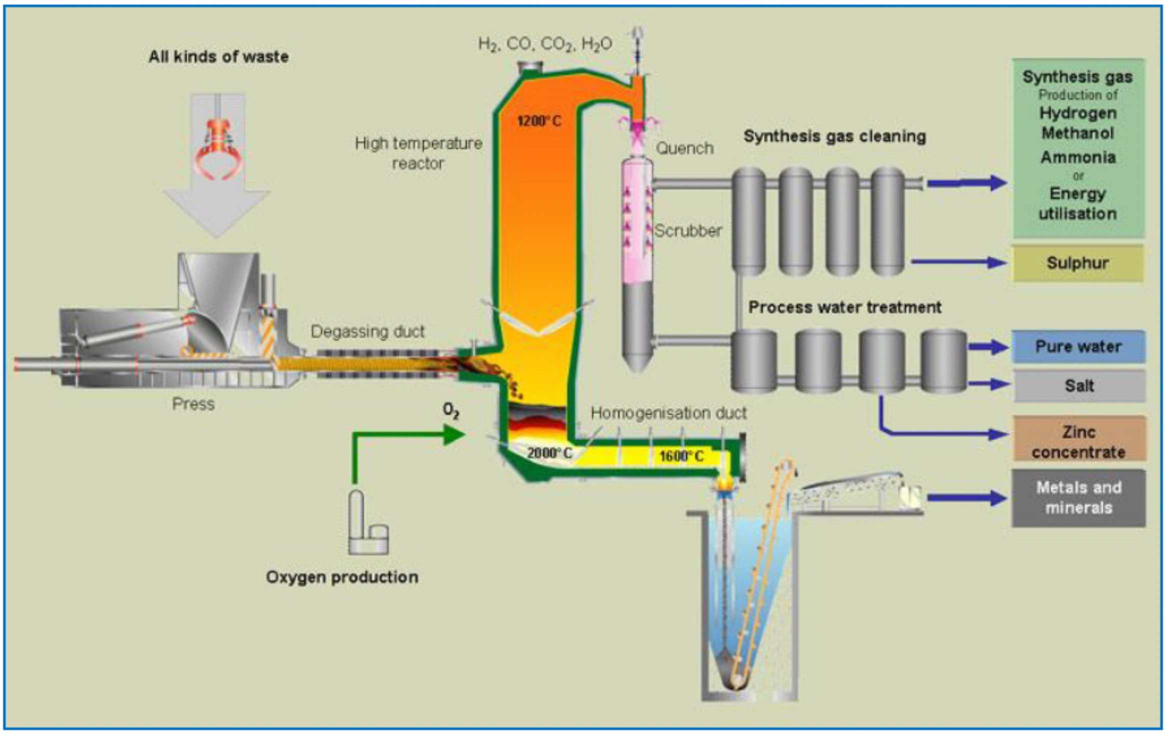

Figure 2: Gasifier [18]

The largest capacity gasification plant is nowhere near the commercial capacity of incineration. This means there is not enough commercial experience for operation of large scale gasification plants. As such, technical and economical problems from scaling up are uncertain. However, production of syngas provides much more flexibility in choice of products, whether it is steam, electricity, fuel or chemical feedstock. Therefore, gasification is an improvement over incineration in MSW processing technology, but commercial experience is lacking. Commercial experience can only be gained by operating a commercial scale plant.

2.3 Pyrolysis

Pyrolysis is the thermal decomposition of feedstock at a range of temperatures from 650 to 1,200°C in the absence of oxygen [2,17,24,25]. The products can vary from solids (char), liquids (oxygenated oils), to syngas depending on the temperature of the system. The pyrolytic oils and syngas can be used directly as boiler fuel or refined for higher quality uses such as engine fuels, chemicals, adhesives, and other products. The solid residue is a combination of non-combustible inorganic materials and carbon [1,17]. However, the pyrolysis process is highly sensitive to the presence of air. Accidental incursions of air can result in process upsets and increase the risk of explosive reactions. Analysis of a wide range of pyrolysis technologies shows that they can produce as much as 770 net kWh/ton of MSW [4]. The largest MSW pyrolysis plant in operation is the Toyohashi City facility in Japan, processing a total of 400 tons/day of MSW [4]. Currently, there is no facility worldwide that produces above 9MW. Figure 3 shows an overview of the pyrolysis process.

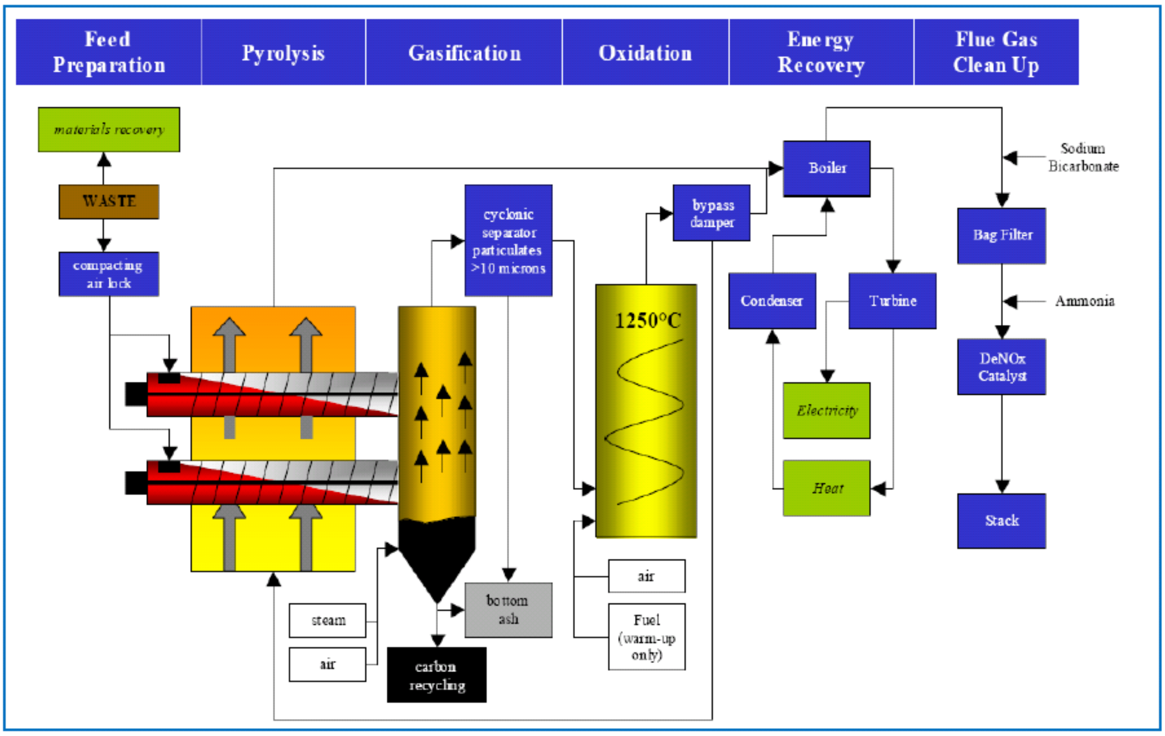

Figure 3: Overview of Pyrolysis [13]

Similar to conventional gasification, the largest pyrolysis facility is nowhere near the commercial capacity of incineration. Therefore technical and economic problems from scale up are uncertain. However, pyrolysis also has the advantage of producing a flexible product in syngas and no formation of dioxins and furans since no oxygen is present in the process. In terms of energy recovery, pyrolysis is similar to conventional gasification and higher performing than incineration.

2.4 Plasma Arc Gasification

Plasma arcs have been used for years to treat waste products and incinerator ash, converting them to a non-hazardous, glassy slag [4,5,8]. It is only in recent years that plasma arcs have been used to process MSW. It uses an electric current that passes through a gas (air) to create plasma which gasifies waste into syngas. This typically occurs in the range of 4000 to 6000°C [2,8,24]. As with conventional gasification, the syngas produced can be for power generation, heating or as a chemical feedstock. Due to the high temperatures and throughput capability, these systems have the potential to produce up to 1100 net kWh/ton of processed feedstock [4]. It has great potential to convert MSW to electricity more efficiently than conventional pyrolysis and gasification systems due to its high heat density, high temperature, almost complete conversion of carbon-based materials to syngas, and conversion of inorganic materials to a glassy, non-hazardous slag [4]. However, plasma arc gasification is not commercially proven to treat MSW. The primary reason appears to be the high capital and operational costs for such facilities. Furthermore, the wear on the plasma chamber is very high and redundant plasma chambers are needed to keep the process operating [17]. Figure 4 shows an example of AlterNRG's plasma gasification unit.

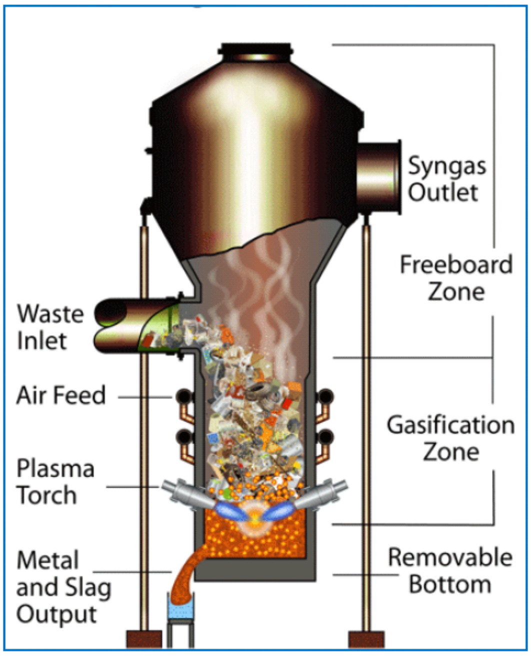

Figure 4: AlterNRG's Plasma Gasification Unit [22]

Plasma arc gasification clearly is the most advantageous in terms of energy recovery and byproducts produced. Like conventional gasification and pyrolysis, it has flexibility in the syngas it produces. However, plasma arc gasification also lacks the commercial availability, with the largest facility in Japan only processing approximately 300 tons/day [7]. Furthermore, this technology has the highest capital cost in addition to the high operating cost due to the high temperatures needed. Therefore technical and economic problems for scale up are uncertain as well.

3.0 METHODOLOGY

3.1 Criteria

In order to evaluate the different types of technology, a set of criteria is needed. As mentioned in the Literature Review section, the criteria are net conversion efficiency, environmental impact and commercial availability. An additional criterion, cost, will instead be evaluated in the financial report of this project. The technologies can then be compared in a table using this set of criteria.

3.1.1 Net Conversion Efficiency

Net conversion efficiency represents the ratio of the net energy recovered per ton of waste to the energy value per ton of waste. Net energy recovered per ton of waste represents the amount of energy recovered in the products less the parasitic load. This energy could be in the form of synthetic oil or electrical power. The amount of energy recoverable from processing the waste directly translates to the amount of revenue receivable. Therefore, the higher the energy recovered per ton of waste, the higher the conversion efficiency and the better the technology. This data is collected through interviews with technology vendors and literature.

3.1.2 Environmental Impact

Environmental impact represents the reduction in landfill use as well as air emissions as a result of processing the waste. The air emissions considered are particular matter (PM), hydrochloric acid (HCl), nitrous oxides (NOx), sulphur oxides (SOx), mercury (Hg), dioxins and furans. Waste would be processed at the waste-to-energy facilities and thus reduce the need for landfills and free up usable land. That said, different technologies would also produce different byproducts which may or may not require landfilling, albeit only about 10% by mass will be byproducts. These byproducts are ash and char. In addition, the air emissions produced by each technology need to be regulated to be within EPA standards. Therefore the technology that produces useful byproducts that do not require landfilling and has the lowest air emissions would be the better technology. This data is collected through interviews with technology vendors and literature. It should be noted that the environmental impact of transporting the waste is not considered in this paper because all three technologies would have equal environmental impact in this aspect.

3.1.3 Commercial Availability

Commercial availability represents the technology's market availability at a capacity that is considered of commercial scale. Interviews with Dow Chemical indicate this to be at least a 25 MW plant [12]. This translates to approximately a capacity of 300 tons of (NRP) waste per day, based on an energy value of 28 MMBtu/ton for NRP and a net conversion efficiency of 22%. Different technologies are at different stages of development, therefore, the technology that is most commercially available would be the better technology. The data is collected through literature and measured by the number of existing facilities for each technology.

3.2 Decision Tool

It is difficult to compare the technologies across 3 criteria and choose the best technology because some technologies could be good in one criterion but bad in another. Therefore each stakeholder's risk profile must be assessed to choose a technology which best fits the organization. This decision tool is developed so that Dow can assess the preferences of different stakeholders, such as municipalities. A questionnaire should be sent to the different stakeholders to ask them to rank the importance of each criterion to them on a scale of 1 to 5. A sample of the questionnaire can be found in Appendix A. The evaluation method procedure is described in the following section. This decision tool is to be used in tandem with the location model and financial model.

3.2.1 Procedure

First, each technology is ranked within each criterion. Let the rank of each technology in each criterion be $r_{i,j}, for\ i = 1 \dots 3, j = 1 \dots 3$, where i represents the technology and j represents the criterion.

Second, the answers given by the stakeholders will give the relative weights of importance for each criterion. Let the values awarded by the stakeholder for each criterion be $a_j, for\ j = 1 \dots 3$ and the weights of importance for each criterion be $w_j, for\ j = 1 \dots 3$. Then,

$$w_j = \frac{a_j}{\sum_{k=1}^{3} a_k}, for\ j = 1 \dots 3$$

Third, the total rank can be calculated by the following equation:

$$r_{T,i} = \sum_{j=1}^{3} r_{i,j} w_j\ , for\ all\ i$$

Finally, the technology best suited to the stakeholder's preference will be technology i based on $\max(r_{T,1}, r_{T,2}, r_{T,3})$. A sample of how the data would be organized is shown in Tables 1 and 2.

Table 1: Results from questionnaire

	Net Conversion Efficiency	**Environmental Impact**	**Commercial Availability**
Value of Importance Awarded	5	4	3
Weight of Criterion	0.42	0.33	0.25

Table 2: Best suited technology based on results from questionnaire

	Individual Rank by Criteria			
Technology	**Net Conversion Efficiency**	**Environmental Impact**	**Commercial Availability**	**Total Rank**
Pyrolysis	2	1	2	1.67
Conventional Gasification	1	1	3	1.50
Plasma Arc Gasification	3	3	1	2.50

4.0 DISCUSSION

4.1 Criteria

Data were collected and organized into the criteria described in the Methodology section.

4.1.1 Net Conversion Efficiency

Data for net conversion efficiency were collected for pyrolysis of plastics and gasification of MSW [15,16]. This data is presented in Table 3 below.

Table 3: Net conversion efficiency

Company	Technology	Net Conversion Efficiency
Agilyx	Pyrolysis	72.97%
Envion	Pyrolysis	53.55%
Climax	Pyrolysis	58.58%
JBI	Pyrolysis	85.72%
Enerkem	Conventional Gasification	22.65%
Plasco	Plasma Arc Gasification	26.98%

From Table 3, the net conversion efficiency for Enerkem and Plasco is significantly lower because they produce electrical power as their product. Some energy is lost when syngas is passed through the gas engine while most of the energy is recovered when syngas is condensed into synthetic crude oil.

Since the focus of this paper is on plastics, data is needed for conventional and plasma arc gasification. However, data for conventional gasification and plasma arc gasification of plastics is not available. Therefore, assumptions have been made in order to determine the net conversion efficiency for plastics. In general, the formula for net conversion efficiency using technology i and material j is as follows:

$$e_{ij} = \frac{ER_{ij} - EC_{ij}}{EV_j} \tag{1}$$

where e = net conversion efficiency
ER = Energy Recovered
EC = Energy Consumed
EV = Energy Value

From equation 1, ER and EC data for plastics are unavailable, thus making e an unknown. With one equation and three unknowns, two additional relationships will need to be assumed in order to solve for the unknowns. The first assumption is that $EC_{i,MSW} \approx EC_{i,P}$. It is reasonable to expect the energy consumption for MSW to be more than or equal to that of NRP given the homogeneity of NRP. For simplicity, they are assumed to be approximately equal. This relationship will be evaluated by a sensitivity analysis later in the section. For the second assumption, there are 2 possible scenarios.

4.1.1.1 Scenario 1

Scenario 1 assumes that $e_{i,P} = e_{i,MSW}$. This relationship means that the net conversion efficiency is constant regardless of the material used. This results in the following:

$$ER_{i,P} = \left(\frac{ER_{i,MSW} - EC_{i,MSW}}{EV_{MSW}}\right) * EV_{i,P} + EC_{i,P} \tag{2}$$

Since data is available for the energy value of MSW and plastics, let $\frac{EV_P}{EV_{MSW}} = x$. Along with the first assumption, equation 2 becomes:

$$ER_{i,P} = x * ER_{i,MSW} - (x - 1) * EC_{i,MSW} \tag{3}$$

4.1.1.2 Scenario 2

Scenario 2 assumes that $\frac{ER_{i,P}}{EV_P} = \frac{ER_{i,MSW}}{EV_{MSW}}$. This relationship means that the amount of energy recovered is proportional to the energy value of the material regardless of the technology used. This results in the following:

$$e_{i,P} = e_{i,MSW} + \frac{(x-1)*EC_{i,MSW}}{EV_P} \tag{4}$$

Comparing the 2 scenarios, scenario 2 makes a more reasonable assumption that scenario 1 because the homogeneity of plastics compared to MSW means that it is likely $e_{i,P} > e_{i,MSW}$.

Using scenario 2's assumption, it is projected that the net energy recovered per ton of waste and net conversion efficiency for conventional and plasma arc gasification will increase, as shown in Table 4 below.

Table 4: Projected net conversion efficiency

Company	Technology	Net Conversion Efficiency
Enerkem	Conventional Gasification	29.70%
Plasco	Plasma Arc Gasification	32.18%

4.1.1.3 Ranking

In order to make a fair comparison between the technologies, it is assumed that if the crude oil from pyrolysis is converted to electrical power, the net conversion efficiency will have to be multiplied by the efficiency of a gas engine, which is 37.5% on average [9]. Table 5 shows the result.

Table 5: Net conversion efficiency compared on basis of production of electrical power

Company	Technology	Net Conversion Efficiency
Agilyx	Pyrolysis	21.89%
Envion	Pyrolysis	16.06%
Climax	Pyrolysis	17.57%
JBI	Pyrolysis	25.72%
Enerkem	Conventional Gasification	29.70%
Plasco	Plasma Arc Gasification	32.18%

Based on Table 5, the ranking of technologies by net conversion efficiency is as follows:

Table 6: Ranking by net conversion efficiency

Technology	Ranking
Pyrolysis	1
Conventional Gasification	2
Plasma Arc Gasification	3

As described in the methodology section, a rank of 3 means that that technology is the best. Therefore plasma arc gasification has the best performance in the net conversion efficiency criterion.

4.1.2 Environmental Impact

In order to evaluate the technologies by their environmental impact, their byproducts as well as emissions are compared in the tables below. However, because emissions data for plastics as feedstock are not readily available, emissions data for MSW as feedstock are presented instead.

Table 7: Technologies and their byproducts

Technology	Byproducts	Leachate?	Landfill Required?
Pyrolysis	Char	Possible	Yes
Conventional Gasification	Ash/Char	Possible	Yes
Plasma Arc Gasification	Vitrified Slag	No	No

Table 8: Technologies and their emissions with MSW as feedstock [19,21]

		Emissions(µg/N-M3 @ 7% O_2)					
Company	**Technology**	**PM**	**HCl**	**NOx**	**SOx**	**Hg**	**Dioxins/furans ($ng/N\text{-}M^3$)**
EPA Standards	-	20	40.6	308	85.7	50	13
International Environmental Solutions	Pyrolysis	5.75	-	129	0.44	-	0.000581
JFE Environmental Services/Thermoselect	Pyrolysis	<4.7	11.6	-	-	-	0.0250
Mitsui Recycling 21	Pyrolysis	<1.0	55.8	82.8	25.9	-	0.00450
Ebara TwinRec	Gasification	<1.4	<2.8	41	<4	<0.007	0.0000720
Nippon Steel DMS	Gasification	14.1	<12.5	31.2	<21.9	-	0.0450
OE Gasification	Gasification	7.5	25.3	59	18.7	<0.007	0.0983
Plasco Energy Group	Plasma Arc	12.8	3.1	150	26	0.0002	0.00925

Based on Table 7, plasma arc gasification has the best environmental impact because its byproduct, vitrified slag, does not leachate and can be used to produce other products such as rock wool, floor tiles, roof tiles, insulation, and landscaping blocks. On the other hand, the byproducts of pyrolysis and conventional gasification, ash and char, need to be cleaned up before proper disposal at a landfill.

Based on Table 8, it is difficult to determine which technology has an advantage over another because these companies could have varying compositions of MSW which affect the type of emissions they have. However, it is important to note that all the technologies are able to operate within EPA emission standards, thus making them equally competitive on that front. Also note that

Mitsui Recycling 21's HCl emissions exceed EPA's standards but they operate in Japan and are within Japan's standards. This does not mean pyrolysis is unable to operate within EPA standards because Thermoselect's HCl emissions are within EPA standards.

4.1.2.1 Ranking

After comparing the each technology's environmental impact, their ranking is shown in Table 9.

Table 9: Ranking by environmental impact

Technology	Ranking
Pyrolysis	2
Conventional Gasification	1
Plasma Arc Gasification	3

Plasma arc gasification is given the highest rank because its byproduct, vitrified slag, does not impact the environment compared to ash and char. Pyrolysis is given a rank of 2 because it has better emissions that conventional gasification.

4.1.2 Commercial Availability

This paper defines commercial availability as the number of facilities using the technology of interest, which also directly correlates to the technology's commercial maturity. In order to evaluate the technology's commercial availability, the number of facilities available in North America is considered. From Figure 5 below, there are a total of 10 pyrolysis facilities and 22 gasification facilities.

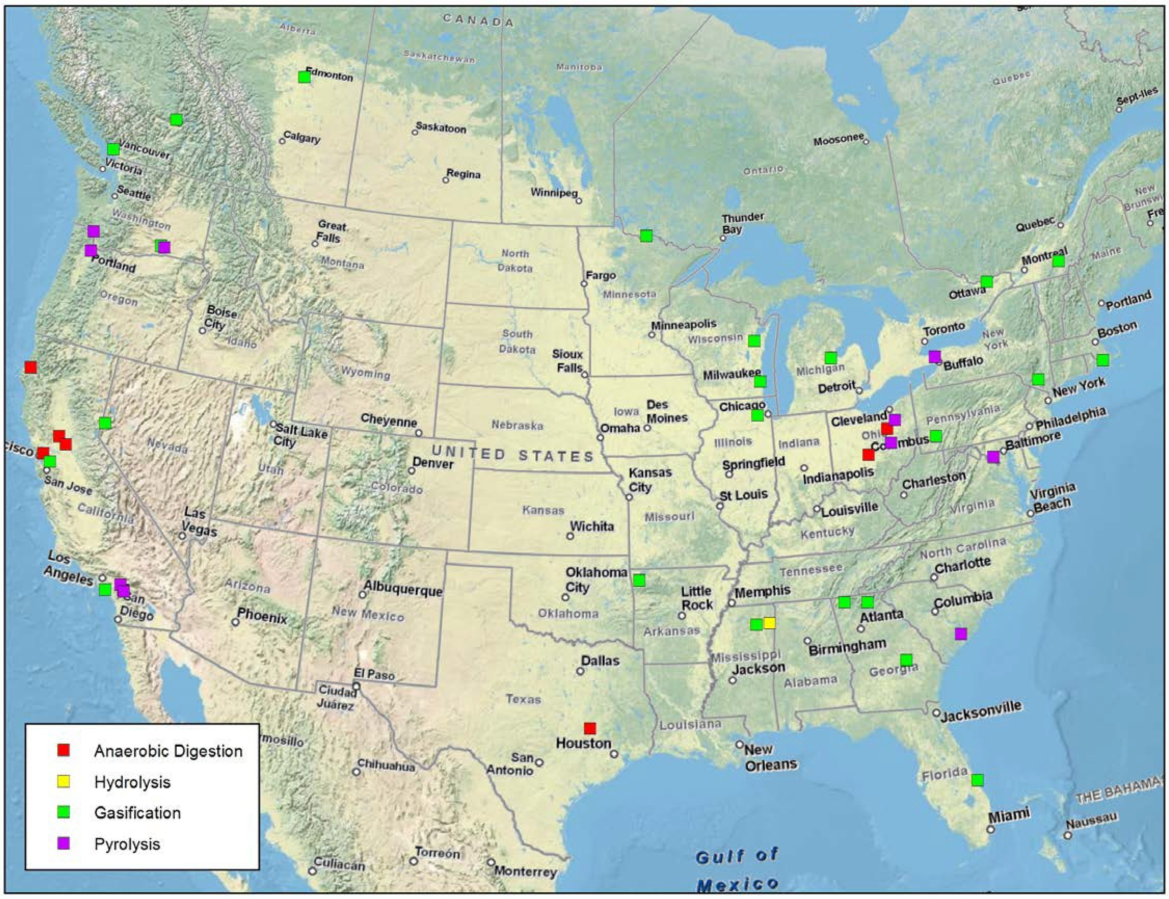

Figure 5: Location of WTE facilities [16]

Of the 22 gasification facilities, only 4 use plasma arc technology [16]. This indicates that conventional gasification is more commercially available, followed by pyrolysis and plasma arc gasification. Figure 6 shows the relative commercial maturity of each technology in this industry. Anticipated cost in Figure 6 refers to the investment required to yield commercially mature systems. Therefore, Figure 6 is in agreement with this order of commercial readiness.

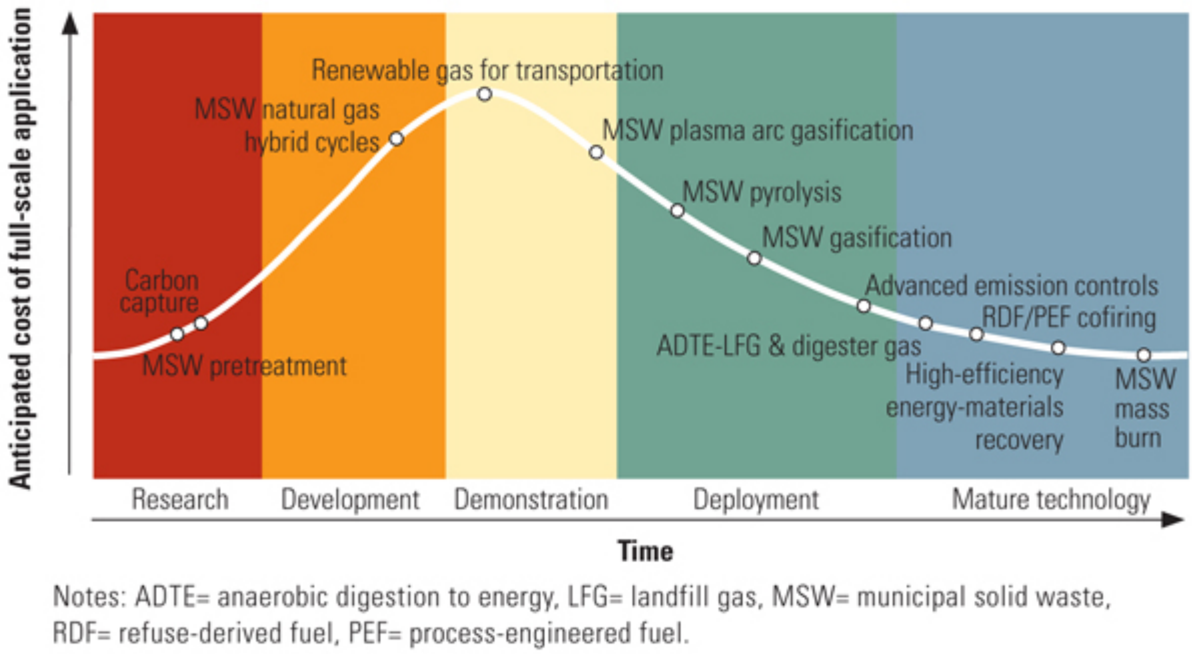

Figure 6: WTE technologies at varying stages of commercial maturity [14]

4.1.3.1 Ranking

After comparing the each technology's commercial availability, their ranking is shown in Table 10.

Table 10: Ranking by commercial availability

Technology	Ranking
Pyrolysis	2
Conventional Gasification	3
Plasma Arc Gasification	1

4.2 Sensitivity Analysis

In section 4.1 it is assumed that $EC_{i,MSW} \approx EC_{i,P}$. However, it is likely that $EC_{i,MSW} = y * EC_{i,P}$, where y represents a multiple or a fraction. Since this directly impacts equation 4, sensitivity analysis is done on equation 4 on the impact of y on $e_{i,P}$. Equation 4 then becomes:

$$e_{i,P} = e_{i,MSW} + \frac{(x-1/y)*EC_{i,MSW}}{EV_P} \tag{5}$$

Given the homogeneity of waste plastics compared to MSW, it is likely that $EC_{i,MSW} \geq EC_{i,P}$ and therefore it should be expected that $y \geq 1$.

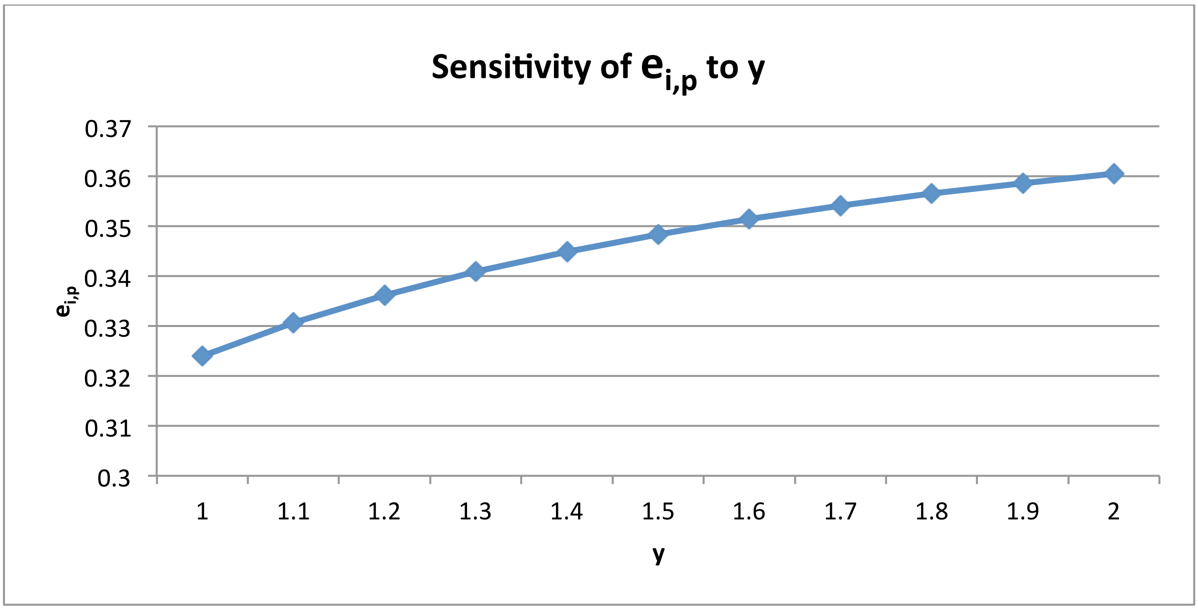

Figure 7: Sensitivity of $e_{i,P}$ to y

Figure 7 shows that as y increases, $e_{i,P}$ increases, albeit a 100% increase in y results in only a 11% increase in $e_{i,P}$. Therefore the net conversion efficiency is not sensitive to a change in y, thus it is relatively safe to assume $EC_{i,MSW} \approx EC_{i,P}$.

Furthermore, in section 4.1.1.2, it is assumed $\frac{ER_{i,P}}{EV_P} = \frac{ER_{i,MSW}}{EV_{MSW}}$. However, it is possible that $\frac{ER_{i,P}}{EV_P} = z * \frac{ER_{i,MSW}}{EV_{MSW}}$, where z represents a multiple or a fraction. This directly impacts equation 4, thus sensitivity analysis is done on equation 4 on the impact of z on $e_{i,P}$. Equation 4 then becomes:

$$e_{i,P} = z * e_{i,MSW} + \frac{(z*x-1)*EC_{i,MSW}}{EV_P} \qquad (6)$$

It should be expected that $e_{i,P}$ and z have a linear relationship of the form $e_{i,P} = z * m + c$.

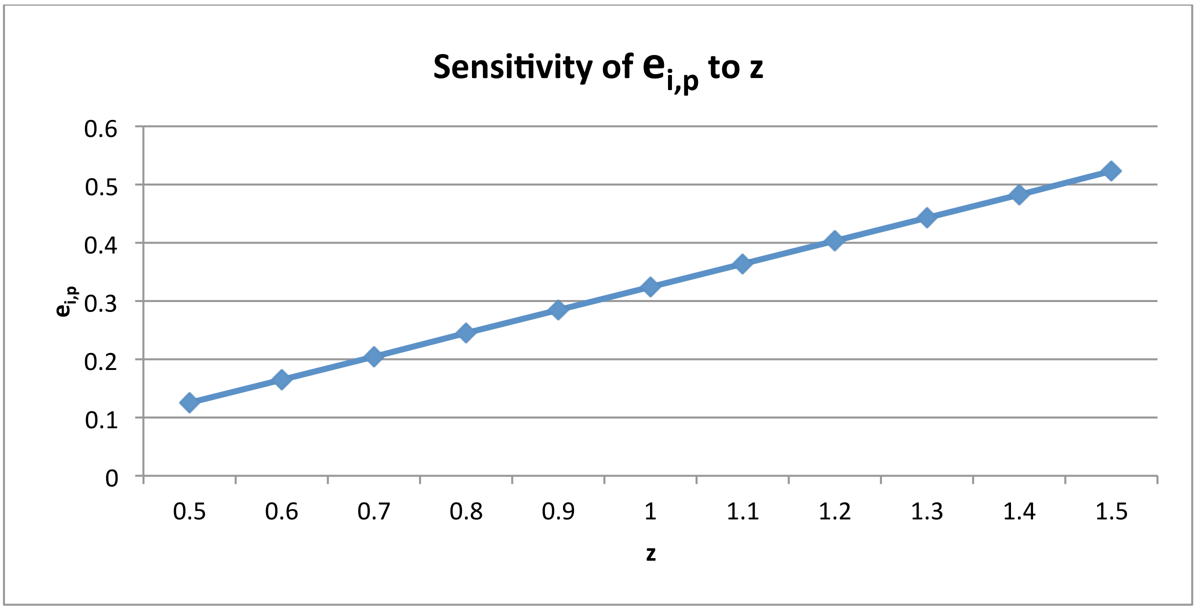

Figure 8: Sensitivity of $e_{i,P}$ to z

As expected, Figure 8 shows a linear relationship between $e_{i,P}$ and z. A 10% increase in z causes a 12% increase in $e_{i,P}$. Thus, a comparison between y and z's impact on $e_{i,P}$ shows that $e_{i,P}$ is much more sensitive to a change in z.

5.0 CONCLUSION

Thus far in the analysis, there is no clear winner in any of the technologies based on the criteria discussed. Table 11 shows a summary of the criteria evaluation.

Table 11: Summary of criteria evaluation

Technology	Net Conversion Efficiency	Environmental Impact	Commercial Availability
Pyrolysis	1	2	2
Conventional Gasification	2	1	3
Plasma Arc Gasification	3	3	1

Therefore, the stakeholders need to consider their preferences and risk averseness and use the decision tool developed and discussed in section 3.2. Although only 3 evaluation criteria are considered in this report, additional evaluation criteria can be added by Dow by modifying the technology decision tool. The technology decision tool has to be used in tandem with the location decision tool and financial model developed by other reports of the same project to determine the best suited technology and location for the most profits.

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APPENDIX A – QUESTIONNAIRE

We are a group of Master of Engineering students at UC Berkeley, working on a project studying the feasibility of implementing a solid waste to energy (WTE) plant. Part of this study includes choosing the right technology to process the waste. However, as each WTE technology has its own advantages and disadvantages, there will be trade-offs in choosing one technology over another. Thus, it is essential that we assess your organization's preferences through this survey to match the technology best suited to your organization. From a scale of 1 to 5, with 1 being low and 5 being high, please rank independently each criterion's importance to your organization.

1. What organization are you from?

2. Net conversion efficiency
   This relates to the net amount of electricity or synthetic oil that can be recovered
   1 2 3 4 5

3. Environmental Impact
   This relates to the emissions as well as the byproducts that may require proper treatment before disposal.
   1 2 3 4 5

4. Commercial Availability
   The technologies are at different stages of development. This criterion will determine how much risk your organization is willing to take on relatively unproven technologies.
   1 2 3 4 5