Considerations for Waste Gasification as an Alternative to Landfilling in Washington State Using Decision Analysis and Optimization

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Abstract

The United States is among the highest waste-producing nations in the world, but unlike many other developed nations, it processes only a fraction of its waste for recycling or energy production. The feasibility of alternatives to landfilling was explored using a multi-criteria decision-making model and a linear optimization model. Specifically, further development of waste gasification in Washington State was considered. In Washington, landfilling is still the primary form of waste management, resulting in significant environmental and social costs. The first stage of the analysis entailed the identification of the most effective gasification method for a plant located in Seattle with the objective of significant waste diversion from the largest waste processing site in Washington, the Roosevelt Regional Landfill. The Analytic Hierarchy Process (AHP) was employed to perform an objective comparison. This process ranked the gasification alternatives using various criteria and determined that steam gasification was superior to the other options, due to capacity and clean byproduct gases. Subsequently, a network optimization model was constructed to compare the cost of steam gasification and landfilling over a ten-year period, determining whether gasification plants would be viable in Seattle and Alaska. Results indicate that the Seattle gasification plant would be a superior option to current landfilling practices while an Alaska plant would be infeasible, in part due to the limited quantity of waste transported from Alaska to Roosevelt. Gasification methods will become more cost-effective as technology evolves, suggesting that currently infeasible methods have future potential.

1. Introduction

Methods for effective disposal of waste have been a dilemma since the beginning of urbanization. Until the 20th century, citizens primarily disposed of waste in the streets, destabilizing the surface and creating an environment conducive to the spread of disease. As a result of the Industrial Revolution in the late 19th century, populations in cities increased rapidly and greater quantities of municipal solid waste (MSW) were produced. During this period, some manufacturers recognized the value of industrially repurposing waste to meet production demands. For example, bones from slaughterhouses were processed to extract phosphorus, which was then used to make matches (Barles 2002).

As MSW became a greater public health concern at the beginning of the 20^{th} century, rudimentary waste management techniques were created. Initial waste management consisted of collecting urban waste and dumping it away from the city. In conjunction with landfilling, scrap metal recycling gained popularity during World War II due to the scarcity of resources. After the war, recycling declined until legislation in the 1970s renewed the incentive to recover used materials (Kollikkathara et al. 2009).

Waste incineration gained popularity until the 1960s because it was cheap and rapidly reduced the mass of waste. However, public outcry against the toxic gases emitted by incineration plants prompted the Clean Air Act, which terminated unregulated incineration (Louis 2004). This legislation, along with the discovery that garbage incineration produces cancer-causing dioxins, diverted investment away from combustion of refuse.

In contrast to the United States, many European countries invested in cleaner incineration technology rather than abandoning it. Due to investment in clean waste-to-energy technology, many European countries landfill a minimal proportion of their waste. Germany, an international leader in waste management, recycles 70%, incinerates close to 30%, and landfills less than 1% of its refuse. In Denmark, waste-to-energy plants provide 18% of the country's district heating production while reducing the volume of combusted MSW by over 80% (Shibamoto et al. 2007, Christensen et al. 2013). Much of Europe has recognized MSW as a resource, and they are reaping the economic benefits.

In addition to sustainable waste management, much of Europe has reduced consumption of non-renewable energy sources. For example, Spain generated nearly half of its electricity from zero-emission technologies such as wind and nuclear power in 2014. In fact, Spain is the first country to generate the majority of its energy from wind power. A review of recent literature, however, presented unfortunate results regarding the true cost of wind energy. Wind energy has the potential to destabilize the power grid due to its unpredictability (Simmons et al. 2015). Many wind farms also have transmission problems, as was observed at a promising wind farm in McCamey, Texas. The study concluded that, without heavy government subsidies, wind power is not a viable energy source and that government funds should be more productively allocated.

Photovoltaic solar energy (PV) is another technology that has received significant investment in recent years. Multiple initiatives in the European Union have incentivized the use of PV, and in 2010, Germany installed more PV than the entire rest of the world during the previous year (Timilsina et al. 2017). In spite of the investment, PV only accounts for about 7% of Germany's electrical power generation, in part due to the inefficiency of PV solar cells. At peak performance, thin-film silicon solar cells reach 12%-13% efficiency (Wirth 2017). By comparison, gas turbines routinely operate at over 50% efficiency (Noroozian 2016). Wind and solar energy are two popular alternative energy options, but the disadvantages are clearly documented. Consequently, analysis of other energy generation methods is valuable.

As the United States slowly makes the transition to more effective energy generation and waste management, evolving technology presents multiple possibilities. Although Europe has had success with incineration, more efficient processes are being developed, including steam gasification. The gasification process reforms MSW into primarily elemental constituents and syngas. Syngas, comprising of CO and H_2, is used to produce clean biofuels. Gasification is more environmentally friendly than incineration but it is a costly technology that requires an organized waste management infrastructure (EPA 2005). Therefore, a careful analysis is needed to compare the advantages of gasification as the United States advances beyond inefficient landfilling.

An examination of existing research on optimization models for waste management was conducted, which refined the scope of the research question. A recent literature review studied the use of multi-criteria decision-making methods for waste management and found that many researchers prefer to use the Analytic Hierarchy Process due to its simplicity and structured approach (Achillas et al. 2013).

The Analytic Hierarchy Process (AHP) is a systematic optimization technique that was developed in the 1960's to satisfy the need for quantitative decision-making (Forman et al. 1996). The model allows for a synthesis of many complex variables in real-world situations and is applicable in a variety of contexts. Using the AHP, criteria and sub-criteria are given weights by the user (typically on a scale of 1-9) to reflect their importance. Matrices of the weights are created, and the eigenvector corresponding to the dominant eigenvalue of the matrices represents the relative importance of each criteria (at each level). The model may be used to select a single best option from many alternatives.

Review of the literature also found that optimization models for waste management could be categorized based on two topics: optimal strategy and optimal location. The objective of optimal location is to minimize transportation costs among feasible potential locations for a facility. Optimal strategy is concerned with comparing technologies to determine the most effective option based on a variety of criteria, such as environmental impact, cost, or societal perception (Achillas et al. 2013).

Several techniques from operations research are commonly used to model various waste management tasks. Since waste originates from many different areas and must be transported for processing, a network optimization model is a natural modeling choice. Network optimization models are a class of optimization models which define a network of nodes and arcs that may simulate waste generation, transportation and processing (Ahuja et al. 1993). A majority of the studies considered by the literature review employed integer programming, which uses binary decision variables to decide whether or not to construct a waste processing facility. The major optimization objectives included minimization of transportation cost, processing cost, or fixed costs associated with facility construction and operations. Most studies evaluated the potential effect of landfills and recycling facilities, but did not consider waste gasification, presenting an opportunity to extend existing research (Ghiani et al. 2014).

2. Methodology

2.1 Justification for Optimization Model

In order to gain a more fundamental understanding of the costs and benefits of recycling, transportation and process cost data are used to parameterize an optimization model. As part of the environmental analysis, data have been obtained from the EPA, which states the estimated Metric Tons of Carbon Equivalent (MTCE) of various processes. In landfilling, this measure accounts for both carbon emissions and sequestration that occur due to the containment of waste.

Gasification is a complicated process, since there are various methods for reforming waste. All gasifiers share common characteristics, such as the significant thermal energy requirements for the gasification reaction to occur. However, part of the thermal energy produced by the exothermic reaction may be recirculated through the system in a process known as cogeneration, reducing heating costs. In addition, the syngas produced by the thermal decomposition of MSW must be treated before being converted to biofuels (Bosmans et al. 2012). Different gasification techniques vary in syngas quality. For example, downdraft fixed gasifiers produce little tar, while updraft gasifiers suffer from high tar production. However, updraft gasifiers generally have greater capacity and excellent carbon conversion efficiency (Roos 2010).

2.2 Gasification Comparison: AHP Model

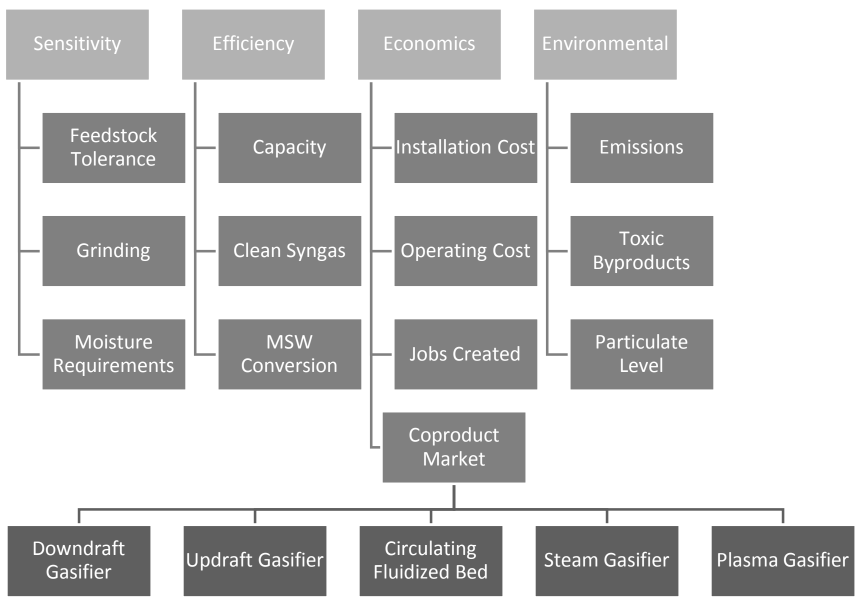
Many variables contribute to the overall effectiveness of a gasification system. Consequently, the AHP is a valuable tool that allows for the assimilation of both quantitative and qualitative aspects of different gasification methods in order to determine the most appropriate technology for a specific situation. Fixed bed downdraft and updraft gasification are compared, in addition to circulating fluidized bed, steam and plasma gasification. Data from prior studies and the EPA was used to make the pairwise comparisons necessary for a reliable model. The four most important criteria are explained in Table 1.

TABLE 1. AHP Primary Criteria

Criteria	**Explanation**
Sensitivity	Flexibility of the option, which depends largely on the amount of pre-processing needed.
Efficiency	Considers plant capacity and thermal efficiency, in addition to the amount of tar produced. Tar reduces overall efficiency since additional treatment is required if tar levels are significant. Treatments of resultant compounds, such as ammonia and hydrochloric acid, also affects system efficiency.
Economics	Accounts for capital and operating cost, in addition to job creation and the coproduct market. Since biochars are valuable byproducts, they help offset high process costs.
Environmental	Gasification eliminates organic compounds, leaving heavy metals which must be processed. However, the residual metals are often trapped in bio-char, which mitigates their hazardous potential. Particulate matter and emissions are also important environmental considerations, since no filtration system is infallible.

The focus of our analysis was Washington State's regional landfill: the Republic Services Landfill in Roosevelt, Washington. This landfill currently recycles and incinerates some waste, but gasification has not yet been implemented. The Roosevelt Landfill collects waste for the entire state, incurring a significant carbon footprint. Due to low processing fees, over 20,000 tons of waste are transported from Alaska to Roosevelt Regional Landfill each year, adding the environmental and economic burden of over a thousand miles of transportation (Judd 2012). Additionally, the Roosevelt Landfill is located in the Columbia Basin; any leakage would flow directly into the Columbia River and cause serious environmental damage (Cole et al. 2011). The AHP model provides a multi-criteria optimal solution which identifies the most critical factors for the Roosevelt Landfill (see the AHP schematic shown in Figure 1).

Figure 1. AHP Schematic



After identifying the most effective gasification technology for Roosevelt, the economic and environmental consequences of two gasification plants (in Seattle and Anchorage) are considered, with the objective of waste diversion from Roosevelt Regional Landfill using a network optimization model. The network optimization model systematically parses the problem into a linear program that may be clearly analyzed. The objective of the model was to minimize the total cost of the operation, including operating, environmental and capital costs. The accuracy of this model would critically depend on estimation of the various costs considered. An extensive and careful review of literature and resources was conducted to estimate each of the costs as accurately as possible. The waste is transported by truck from each county to a centralized railway in Seattle to be taken to the Roosevelt landfill. The five counties with the highest waste generation, in addition to the waste transported from Alaska to Roosevelt landfill, were considered to be a representative sample for the model. The costs are shown in Table 2.

TABLE 2. Transportation Cost and Waste Generation

Transportation Cost		**Source**
Trucking	$0.1225 / mi	Gonzales 2016
Barge	$0.0716 / mi	
Rail	$0.015 / mi	
Site	**MSW to Roosevelt (annual)**	ECY 2013
Lewis County	61,708	
Skagit County	92,814	
Snohomish County	436,115	
Thurston County	152,162	
Whatcom County	50,384	
Alaska	21,475	
Gasification ($/ton)	$86	EPA 2012
Landfill Tipping Fee	$24	ECY 2013
Plant Construction	$15,832,000	EIA 2013

3. Results and Discussion

Efficiency and economics were determined to be the most important primary factors for the Roosevelt scenario after individual weights were assigned. Efficiency was estimated to be six times more important (on a scale of 1-9) than sensitivity since required feedstock preparation adds to total process time, but inefficient gasification is a more serious issue. Since the operating cost of gasification is nearly twice the cost of landfilling, the process efficiency is paramount to be a viable option (Gonzalez et al. 2017).

Many alternative energy options, such as wind power, are significantly better for the environment than fossil fuels, but a lack of energy density prevents them from becoming reasonable possibilities with current technologies (Pirrong 2013). Consequently, efficiency was chosen to have a weight of three times greater than environmental concerns. Table 3 demonstrates the results of the first AHP comparison, with higher values indicating higher importance in the decision-making model while summing to one.

TABLE 3. AHP Results: Primary Criteria

Sensitivity	0.08
Efficiency	0.48
Economics	0.31
Environmental	0.13

3.1 Justification of Weights for Analytic Hierarchy Process

3.1.1 Sensitivity- One primary criterion, sensitivity, was further divided into three subcategories: feedstock tolerance, moisture requirements, and particle size requirements. Feedstock tolerance refers to the composition of the input system. Some gasification methods, specifically downdraft gasification, require uniform particle size and dry feedstock to function correctly, contributing to higher operating costs.

Thermal energy is a valuable byproduct of the exothermic gasification reaction, and most gasification facilities use the excess energy for combined heat and power (CHP) to increase efficiency. Heat from the reaction may be recycled through the system to dry input MSW during the pre-processing stage. However, gasification techniques that do not require low moisture content, such as steam and plasma arc gasification, are much more efficient, as the heat may be instead used to power a steam generator. Due to significant increases in gasifier efficiency when feedstock moisture is reduced, moisture requirements were chosen to be the most important variable, weighted at three and five times more important than feedstock tolerance and particle size requirements, respectively (Pavel et al. 2016). Table 4 shows the results of the Sensitivity AHP comparison.

TABLE 4. AHP Sub Criteria of Sensitivity

Feedstock Tolerance	0.23
Moisture Requirements	0.65
Grinding Pre-processing	0.12

3.1.2 Efficiency- The three subcategories for efficiency included the following: plant capacity, syngas purity and MSW conversion percentage. Plant capacity varies widely between the different gasification options. For example, downdraft gasifiers have a capacity of less than 2 MegaWatt-Thermal (MW_{th}), while steam gasification plants have the potential to be larger than 100 MW_{th} (Proll et al. 2005). The Roosevelt regional landfill processes over 800,000 tons of waste per year from the five highest-volume counties in Washington; a large scale gasification facility would be necessary to divert the waste flow to the landfill (ECY 2013).

Tar is a byproduct that contaminates syngas, making it unusable without further treatment. Tar is especially problematic for updraft gasification, which produces syngas that contains up to 20% tar (Balas et al. 2014). Research and practical application have demonstrated success with tar removal using compounds such as rapeseed oil methyl ester (RME) for coal gasification. Since RME is renewably sourced, it provides a reliable method for tar removal. In the AHP model, capacity is considered to be of higher importance than tar removal by a factor of six because RME is a proven solution that lessens the importance of tar-free syngas.

Since gasification produces both heat and product gas that may be converted to fuel, it is a more efficient process than combustion. Gasification methods have varying degrees of conversion efficiency. For example, circulating fluidized bed reactors have the advantage of extremely good mixing and high heat transfer, resulting in uniform bed conditions and efficient reactions (Roos 2010). The MSW conversion proportion is important, but was considered less significant than capacity by a factor of three because capacity will be an immediate concern if waste is to be diverted from Roosevelt. Table 5 shows the AHP results for efficiency.

TABLE 5. AHP Sub Criteria of Efficiency

Capacity	0.64
Clean Syngas / Tar	0.09
MSW Conversion %	0.27

3.1.3 Economics- Financing and economics are primary drivers of long-term sustainability. Capital and operating costs, along with coproducts and job creation, were used to define Economics in the AHP model. The capital cost of gasification is high—a 160 MW_{th} entrained flow reactor in Freiburg, Germany cost over 120 million USD (Schlissel et al. 2008). However, a 600 MW_{th} coal power plant can cost over 600 million USD, which is comparable per unit energy. Therefore, capital cost is of less importance than operating cost, since perpetual high costs impair a facility's profitability. The weight of operating cost was chosen to be five times greater than the coefficient for capital cost since the capital expenditures for landfill site construction were estimated to be over $350,000 per acre, which mitigates the necessity of low capital cost for the purpose of this study (Duffy 2016).

The market for gasification coproducts (besides syngas) allows for greater profitability. Fly ash, an inert powder created by gasification, may be used to improve the workability and long-term strength of concrete (Klinghoffer et al. 2011). Another coproduct, biochar, is used for soil remediation. The structure of biochar particles is similar to a micro sponge, absorbing contaminants in the soil. As its usage in agriculture expands, biochar has become increasingly valuable. However, the relative yield of chars and fly ash per kilogram of MSW is often less than 20%, suggesting that the sale of coproducts could not offset a high operating cost (Roos 2010). As a result, operating cost was chosen to be seven times more important than the coproduct market in the AHP model. Table 6 summarizes the AHP model results for economics.

TABLE 6. AHP Sub Criteria of Economics

Capital Cost	0.21
Coproduct Market	0.09
Jobs Created	0.07
Operating Cost	0.64

3.1.4 Environmental Considerations- Since little oxygen is present during the gasification reaction, few toxic compounds form. Although the formation of dioxins and harmful nitrogen oxide compounds are a concern for incineration, they are avoided with gasification. However, CO_2 is still a major byproduct of gasification, resulting in greenhouse gas emissions. Consequently, emissions were chosen to be three times more important than toxic byproducts in the model.

The byproduct slag from gasification may contain heavy metals, depending on the original composition of the waste, leading to some risk of toxic residue even though toxic gaseous compounds are avoided. Heavy metals are a more serious environmental concern than particulate, which only contributes to the level of syngas cleaning needed before combustion in a gas turbine. Toxic byproducts were chosen to be twice as critical as the particulate level. Table 7 shows the model results for environmental considerations.

TABLE 7. AHP Sub Criteria of Environmental Considerations

Emissions	0.67
Toxic Byproducts	0.22
Particulate Level	0.11

3.1.5 Comparison of Alternative Gasification Methods- The next stage of the AHP model compares the gasification alternatives (downdraft, updraft, circulating fluidized bed, indirect steam and plasma arc gasification) for each variable. The Table 8 summarizes the weighted priorities of each variable from the first stage, demonstrating that plant capacity and operating cost are the most important variables.

TABLE 8. Cumulative Priorities

Factor	Priority
Capacity	0.307
Operating Cost	0.201
MSW Conversion %	0.129
Emissions	0.085
Installation Cost	0.066
Moisture Requirements	0.052
Clean Syngas / Tar	0.041
Toxic Byproducts	0.028
Coproduct Market	0.027
Jobs Created	0.021
Feedstock Tolerance	0.018
Particulate Level	0.014
Particle size	0.010

Many of the variables in Table 8 have only a slight impact on the decision-making process for a gasification plant to divert waste from Roosevelt. They will gain importance for continued operation of the facility, but in the short-term, financing considerations and conversion efficiency are more serious concerns.

The comparisons of each variable for the gasification alternatives are included in Table 9. Data from the United States Department of Ecology, bioeconomy consultants NNFCC and research by Dr. Carolyn Roos were used to parameterize this stage of the AHP model (Roos 2010, E4 Tech 2009, EPA 2005).

TABLE 9. Final AHP Results

Alternative	Priority
Steam	0.286
Circulating	0.254
Plasma	0.193
Downdraft	0.134
Updraft	0.133

Based on the AHP decision-making process, steam gasification is the most promising method for the Roosevelt regional landfill. This conclusion is supported by prior research. Elementa Group presented their findings regarding steam gasification at the Solid Waste World Congress, stating that steam gasification resolves many obstacles that other gasification methods face (Dueck et al. 2013). Syngas from steam reforming contains few contaminants and comprises elements in near-optimal proportions. Hydrogen accounts for nearly half of the volume, and carbon-based gases are the remaining constituents, resulting in a high-energy syngas that is readily usable. Due to the large proportion of hydrogen, the syngas is well-suited for gas conversion technologies that produce biofuels.

Fischer-Tropsch synthesis is a promising technology for the production of biofuels (Anderson et al. 1984). Catalysts promote the formation of hydrocarbons from syngas in this process, and research has shown that cobalt and platinum catalysts result in greater conversion efficiency while increasing catalytic stability (Wang et al. 2013). Even considering the cost of platinum, the catalyst-supported synthesis could make Fischer-Tropsch more viable in the future, further improving the potential value of steam gasification.

In contrast to steam gasification, other gasification alternatives would not be well-suited for the Roosevelt landfill. Updraft gasification, the lowest-priority option in the AHP model, has capacity restraints and produces impure syngas. Most updraft gasifiers have a maximum capacity of 10 MW_{th} per day, which would be insufficient for significant diversion of waste from the Roosevelt landfill (Roos 2010). Additionally, the updraft gasification produces very high levels of tar—over 100 ppm. Since gas turbines require tar levels of less than 1 ppm to function, syngas from updraft gasification is unusable without serious treatment.

Downdraft gasifiers operate at higher temperatures than other gasification methods, resulting in higher maintenance costs. Precise pre-treatment of MSW is required for correct function, contributing to higher process costs. They also have the smallest capacity at only 2 MW_{th}, making a downdraft gasification facility infeasible for the Roosevelt landfill (Roos 2010).

The advanced technology of plasma arc gasifiers produces pure syngas due to extremely high treatment temperatures, but the process is cost-prohibitive (E4Tech 2009). As the treatment must be tightly controlled, plasma arc gasifiers have limited capacity. The combination of high costs and low throughput makes plasma arc gasification unfeasible with current technology.

Circulating fluidized bed (CFB) gasification was determined to be the second best option by the AHP model. CFB technologies have been successfully used in a number of facilities to reform agricultural waste (Anthony 1995). Low treatment temperatures (850°C) and fuel flexibility reduce process costs as extensive pre-treatment is not necessary. As a result, CFB reactors generally have very high throughput, which is necessary for a facility intended for landfill diversion. However, the CFB process produces very high levels of particulate matter, which erodes equipment and requires syngas cleaning. Steam gasification, which produces cleaner syngas at similar treatment temperatures, is a superior option.

3.2 Network Optimization Model:

After selecting the optimal gasification options, a network optimization model was constructed to analyze the potential economic benefits of gasification plants in Seattle, Washington and Anchorage, Alaska. Steam gasification facilities in these locations would eliminate significant costs associated with waste transport to the Roosevelt regional landfill. The five counties with the highest-volume of MSW transport to Roosevelt were selected: Lewis, Skagit, Snohomish, Thurston, and Whatcom counties currently ship waste to Seattle before it is taken by rail to Roosevelt. The network optimization model addresses the viability of a gasification plant from the perspective of profit potential while considering often-overlooked environmental costs.

Data were gathered from government studies and extrapolated based on prior trends when current values were not available. For example, a simple linear regression model of the years 1997 to 2007 was used to estimate the current cost per ton-mile of MSW shipment by truck.

The transportation costs by barge, truck, and rail were calculated using estimates from the Bureau of Transportation Statistics and are recorded in Table 2 (USDT 2013). The revenues generated from gasification include the sale of energy and fly ash, which is useful for concrete remediation. These values were obtained from studies by the University of Kentucky and the EPA (Robl et al. 2014). Char is the most valuable gasification byproduct, but steam gasification produces little char. As a result, revenues from char were excluded from the current model. Revenues were determined to be $30/ton for syngas and $2.5/ton for fly ash. The National Renewable Energy Laboratory conducted a cost analysis of waste gasification and estimated that the cost is approximately $62/ton of MSW (Dutta et al. 2011).

Environmental impact of a process is often difficult to calculate, but the EPA has defined the “social cost of carbon”, to evaluate climate impacts of emissions. Methane is another important, often overlooked, greenhouse gas since its social cost is more than twenty times that of CO_2, according to the EPA (ICAC 2015). Rotting waste in landfills emits significant amounts of methane, and systems are often implemented to capture and utilize the energy in the CH_4. Roosevelt landfill produces enough energy to power 20,000 homes per year by converting methane to electricity, but the system is not perfectly efficient. According to a study of the CH_4 capture system at the Vancouver landfill, only about 70% of emissions are captured, resulting in significant environmental cost (Ritchie et al. 2009). Using the results of the study, CO_2 and CH_4 emissions, along with savings from carbon sequestration due to the containment of carbon-containing waste, were factored into the net environmental cost of landfilling.

The objective of the network optimization model is to test whether gasification facilities in Seattle and Alaska would be superior options to landfilling over a ten-year period. The construction of each facility was modeled by a binary variable as part of the integer programming. A value of one would indicate that the facility would be viable, based on current parameters in the model. It is indeed necessary to use a binary variable to model whether a facility is established or not, since it is not clear how to interpret a fractional value in this context. In particular, rounding a fractional value to the nearest integer might not work well—a value of 0.500 might suggest the facility is viable, but 0.499 suggesting it is not so.

The complete optimization model is shown below, along with descriptions for each part of the model. The decision variables were taken to be the total amount of waste sent from each county to either the landfill or gasification facilities over a ten-year period (x_{iS} and x_{iG} for i=1 to 5 for the five counties Lewis, Skagit, Snohomish, Thurston, and Whatcom in that order, and i=A for Alaska). Figure 2 below provides a view of the waste transport distances. We use also a decision variable x_{SR} to capture the total amount of waste transported from Seattle to Roosevelt for landfilling. The choice to build gasification plants was modeled by binary variables (y_S and y_A for Seattle and Alaska, respectively) capturing the Yes/No decisions.

Figure 2. Map of Sample Waste Nodes

To aid understanding, values for operating costs and revenues were not summed and simplified in the description of the model. For example, the operating margin for gasification consisted of $62 per ton operating cost and revenues of $30 per ton revenue from the sale of syngas, $25 per ton from the sale of fly ash and $30 per ton due to the net environmental benefit.

The model (in Figure 3) was implemented and solved using the modeling language AMPL and solver CPLEX (Fourer et al. 1993), and the results are presented in Table 10. The second column of the results displays the optimal quantity of waste to be sent to Roosevelt, while the third column displays the optimal quantity of MSW to be gasified at the Seattle plant. The maximum annual capacity of the facility was set to be 146,000 tons based on a similar plant constructed by Rentech Inc., and the model output indicates that the optimal solution would utilize the gasification plant at full capacity (E4Tech). Although a single plant cannot fully solve the landfilling issues, a 17.92% waste diversion rate would be achieved if a gasification facility were constructed in Seattle. Diversion of nearly a fifth of the waste stream from the Roosevelt landfill would be an important step towards sustainable waste management.

Figure 3. Network discrete optimization model, with descriptions.

Objective Function and constraints:	*Description:*
Minimize total_cost: z =	
$10.9(x_{1S} + x_{1G}) + 9.1(x_{2S} + x_{2G}) + 5.5(x_{3S} + x_{3G}) + 7.5(x_{4S} + x_{4G}) + 12.1(x_{5S} + x_{5G})$	Transport cost to Seattle from each county by truck
$+ 25.5x_{AS}$	Transport cost AK to Seattle by barge
$+ 16.5x_{SR}$	Transport cost Seattle to Roosevelt by rail
$+ (62\text{-}30\text{-}2.5\text{–}30)(x_{1G}+x_{2G}+x_{3G}+x_{4G}+x_{5G}+ x_{AG})$	Gasification operating cost - revenue
$+ (.02*24)(x_{1G} + x_{2G} + x_{3G} + x_{4G} + x_{5G} + x_{AG})$	Gasification residual waste to landfill
$+ (15\text{-}25)\, x_{SR}$	Landfilling operating cost - revenue
$+ (12.49+5.67\text{-}4.49)(x_{SR})$	Roosevelt landfill social cost
$+ (1.45)(x_{1G} + x_{2G} + x_{3G} + x_{4G} + x_{5G} + x_{AG})$	Social cost of gasification
$+ 15{,}832{,}000y_S + 15{,}832{,}000y_A$	Capital cost of gasification plants
Constraints:	
$x_{1S} + x_{2S} + x_{3S} + x_{4S} + x_{5S} + x_{AS} = x_{SR}$	Waste sent to Seattle for landfilling equals amount shipped to Roosevelt
$x_{1G} + x_{2G} + x_{3G} + x_{4G} + x_{5G} \leq 1{,}460{,}000\ y_S$	Waste sent to Seattle gasification plant does not exceed capacity
$x_{AG} \leq 1{,}460{,}000\ y_A$	Waste sent to AK gasification plant does not exceed capacity
$x_{iG} \geq 0$ for i = 1 to 5, and i=A (for Alaska)	Gasification processing quantities are nonnegative
$x_{iS} \geq 0$ for i = 1 to 5, and i=A (for Alaska)	Landfilling processing quantities are nonnegative

TABLE 10. AMPL Results

	Tons MSW Transported to Roosevelt	Tons MSW Transported to Gasification	Construct Facility (Binary)
Lewis County	0	617,080	-
Skagit County	85,220	842,920	-
Snohomish County	4,361,150	0	-
Thurston County	1,521,620	0	-
Whatcom County	503,840	0	-
Alaska	214,750	0	-
Seattle Facility			1 (Yes)
Alaska Facility			0 (No)
Totals	**6,686,580**	**1,460,000**	
Diversion Rate	**17.92%**		

In spite of the high cost of waste transport from Alaska (over $30 per ton-mile), a gasification facility constructed in Anchorage to divert waste from Roosevelt would not be feasible. Since only 21,500 tons of waste are transported from Alaska to Roosevelt regional landfill each year, an Alaska plant would only operate at 15% capacity, assuming that other waste streams do not change.

4. Conclusion

The two primary objectives of this research project were to identify the best gasification option for waste diversion from the Roosevelt regional landfill and then to construct a linear program to determine the viability of a gasification facility in Seattle over a ten year period in comparison to landfilling. Environmental cost, in addition to capital and operating costs, were considered as part of our holistic analysis.

The AHP decision-making process was used to determine that steam gasification is the most effective technique, due to high-quality syngas generation, minimal contaminants, and high efficiency of the process. The AHP model considered the flexibility of each gasification method, as well as environmental concerns, financial considerations, as well as efficiency to identify the optimal process.

The results from the linear programming model demonstrate that a gasification facility in Seattle would be both economically and environmentally beneficial in comparison to waste disposal at the Roosevelt regional landfill. A large facility in Alaska would not be viable due to the limited amount of waste currently transported to Roosevelt. The proposed gasification plant in Seattle would provide significant cost savings due lower environmental cost and reduced transportation cost, in comparison to landfilling at Roosevelt. Future studies may consider the implementation of an additional facility or an expansion of the capacity of the Seattle plant to determine whether the benefits would extend to a larger scale operation.

The results from this study are limited by the availability of current data on transportation costs and the market price of gasification byproducts, especially syngas and fly ash. Performing further analysis using current values would test the validity of the conclusions produced by this optimization model and more accurately portray the viability of gasification. Additionally, analysis of modular gasification facilities may also prove valuable. Numerous small plants would further reduce waste transportation costs and provide energy directly to the community, improving the efficiency of the process. However, the high construction cost of gasification facilities would be a major impediment to the feasibility of modular plants.

Since gasification is a developing technology in the United States, the conclusions reached from this optimization model have potential value. Future studies may compare gasification with recycling and anaerobic digestion, two other environmentally friendly options. Gasification may complicate solid waste management because it competes with recycling for feedstock. Paper, for example, is both an excellent material to recycle and an energy-rich fuel source for waste-to-energy plants. A 2012 study comparing incineration and recycling found that the residues from the recycling process were generally landfilled (Wang et al. 2012). Furthermore, wood fibers also become slightly weaker when reprocessed, resulting in lower quality for recycled paper products. As the United States transitions to the digital age, paper products will experience diminishing demand. In contrast, the clean biofuels produced by gasification will be increasingly utilized as emissions standards become more rigorous.

Therefore, a careful analysis is needed to determine whether recycling is truly the optimal use for post-consumer paper and other products.

Furthermore, technologies that are not cost-effective today may become viable in the near future. Although plasma gasification is currently cost-prohibitive, technological advances may reduce costs, enabling industrial-scale plasma gasification to produce pure syngas at reasonable prices while avoiding contaminant issues faced by lower-temperature gasification techniques. Studies in the future may also consider multi-staged gasification, which would reform waste in a preliminary stage using a cheap, efficient process before plasma-arc gasifying the residuals to eliminate unprocessed slag.

Analysis of the social cost of carbon for landfilling and gasification allowed for the monetary environmental penalty of each process to be calculated. Future research may explore the social cost of other toxic emissions, such as N_2O and heavy metals. Since these values are difficult to estimate, stochastic models would help address parameter uncertainty. A 2014 literature review discussed the fact that few waste management papers have employed stochastic models, suggesting a future area for research (Ghiani et al. 2014).

Based on the positive data and increased adoption of waste gasification technology in other parts of the world and the model results, steam gasification may be an important waste management option in the future. Landfills spends significant resources on toxic emissions sequestration and waste containment. By choosing alternative options, these funds may be diverted toward investment in superior processing technologies such as gasification, leading to a reliable source of alternative energy while eliminating many negative consequences associated with traditional techniques.

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