System Dynamics of the Competition of Municipal Solid Waste to Landfill, Electricity, and Liquid Fuel in California

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Abstract

Increasing concern regarding the cost, security, and environmental impact of fossil fuel energy use is driving research and investment towards developing the most strategic methods of converting biomass resources into energy. Analyses to date have examined theoretical limitations of biomass-to-energy through resource availability assessments, but have not thoroughly challenged competing tradeoffs of biomass conversion into liquid fuel versus electricity. Existing studies have focused on energy crops and cellulosic residues for biomass-to-energy inputs, however the conversion of these biomass resources is often less energetically efficient compared to fossil energy sources. Waste streams are beginning to be recognized as valuable biomass to energy resources. Municipal solid waste (MSW) is a low-cost waste biomass resource with a well-defined supply infrastructure and does not compete for land area or food supply, making it a potentially attractive renewable feedstock for energy conversion. The Waste Biomass to Energy Pathway model (WBEM) described here demonstrates a system dynamics approach to analyze the impact of converting MSW biomass to either bioelectricity or liquid fuel. The WBEM incorporates macro-scale feedback from supply chain costs, energy

sector impacts, and greenhouse gas (GHG) production within the competing pathways of MSW to 1) landfill, 2) electricity, and 3) liquid fuel within California.

Introduction

Many biomass-to-energy studies and assessments focus on liquid fuel and electricity energy conversion pathways separately, rather than their direct competition (Farrell *et al*., 2006; Kaplan, *et al*., 2009; Lin & Tanaka, 2006; Morris, 2010). Regional diversities in energy supplies, costs, and biomass resources suggest considering these pathways in competition. MSW-to-energy is quickly becoming a topic of interest for local and national groups (Kaplan *et al*., 2009; Morris, 2010; CCST, 2011), however detailed MSW-to-energy modeling and planning efforts remains in infancy. For example, the conversion of plastic waste to energy is quickly becoming a topic of research interest due to the lower heating value (LHV) of some plastic wastes (Table 1), however most published work on this topic describes pilot-scale plastic to energy conversion (Arena *et al*. 2011; UC Riverside, 2009).

Table 1. Biomass fuel sources and their lower heating values.

Biomass Fuel	LHV (MJ/kg)	Reference
Polyethylene	42.80	Arena et al. 2011
Household mixed plastic waste	27.00	Arena et al. 2011
Selected mixed plastic waste	30.50	Arena et al. 2011
Paper/Cardboard	13.00	Arena et al. 2011
Petroleum	42.30	Arena et al. 2011
Corn stover	16.37	Wang, 2011
Forest residue	15.41	Wang, 2011
Sugar cane bagasse	15.06	Wang, 2011

Preliminary work in the area of biomass-to-energy analysis has begun to explore the economic and environmental tradeoffs of bioelectricity versus biofuel production. For example, in 2010, Campbell and Block evaluated the competing pathways of waste sugarcane cellulose (bagasse) to bioelectricity and bagasse to cellulosic ethanol on a Brazilian nationwide basis using a linear approach. The study concluded that converting biomass to electric power could provide a substantial portion of the nation's imported electricity as opposed to the bagasse-to-ethanol pathway, which would only meet a small fraction of the typical amount of Brazil's exported ethanol, suggesting that conversion of waste sugarcane biomass to electricity would be more strategic. In 2009, Campbell et al. conducted a life-cycle assessment comparing GHG emissions and the land use efficiency of energy crop biomass as an ultimate energy source for electric vehicles versus ethanol-fueled vehicles. They observed greater net transportation energy output per hectare and greater life cycle GHG emissions reductions for the 100% bioelectricity-fueled vehicle than for the 100% ethanol-fueled vehicle. These initial studies begin to examine some of the important economic and environmental tradeoffs between biomass to electricity versus liquid fuels, generally employing sophisticated linear system modeling in tandem with spreadsheet model calculations. However, unlike the WBEM, they are not able to capture energy system dynamics such as supply chain biomass availability and required feedstock transportation infrastructure together with the costs and efficiencies of the appropriate conversion technologies.

Model Description

The WBEM accounts for MSW chemical and physical composition variability that is geographically categorized in terms of carbon content, LHV, required pre-processing, and other factors that affect its conversion chemistry according to the available literature. The California

Department of Resources Recycling and Recovery completed Waste Characterization studies that include the rate of waste generation, landfill size and location, where all MSW is transported to and from, and the type of waste generated. As model input, the supply of potentially available MSW is described by mass accumulation rate, composition, and collection network as a function of population. National Renewable Energy Laboratory's (NREL) thermodynamic combustion database, Argonne National Lab's Greenhouse Gases, Regulated Emissions and the Energy Use in Transportation (GREET) model, and other literature sources were referenced to determine detailed chemical compositions for all MSW types (Arena *et al*., 2011; Domalski *et al*., 1987; Wang, 2011). Although transportation and processing of MSW will have associated costs as adapted from Thorneloe et al. 2007, the MSW feedstock itself is assumed to have zero cost.

Figure 1 shows a high-level model representation of the WBEM, which is designed to capture the potential system dynamics of the three competing pathways of waste biomass to 1) landfill, 2) electricity, and 3) liquid fuel from 2011 into 2050.

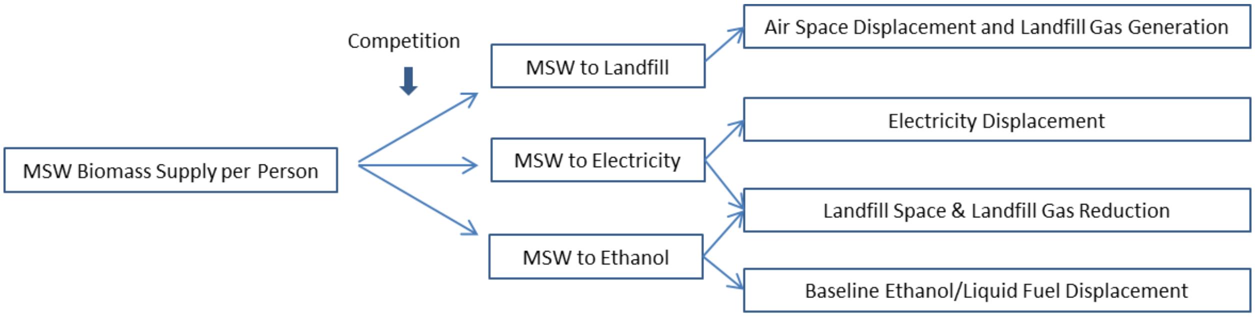

Figure 1. High-level Waste Biomass to Energy Pathway model (WBEM) representation.

These three pathways have economic costs, energy requirements, and environmental impacts, such as GHG emissions, associated with them. The described modeling approach can consider all of these pathway factors simultaneously in order to determine which waste biomass pathway is the most beneficial given a specific objective, e.g. reduce greenhouse gas emissions. As MSW is transported and deposited into landfill, the WBEM describes the complex stock and flow behavior of MSW accumulation in landfill and its generation of landfill gases over time due to decomposition, as well as land and air volume taken up by the waste over time which is described by a displaced air space metric. Some MSW may be converted to electricity or to ethanol, reducing MSW accumulation in landfill space and the resulting landfill GHGs, while providing an alternative electricity or liquid fuel source.

Waste Supply Chain and Landfill Use

Over the past 50 years the state of California has made substantial progress in waste diversion, diverting over 60% of generated MSW from landfills into compost and recycling programs which are organized at the municipality level. Despite these successes, approximately 30 million tons of waste was transported to California landfills in 2009, 60% of which was either paper, organic materials such as food or other plant material, or mixed plastics (CA Waste Characterization Study, 2009). The 2008 California Waste Characterization Study was referenced to determine the supply of MSW biomass available for energy conversion (CA Waste Characterization Study, 2009). MSW types that are considered divertible for energy conversion include paper, organic material, and plastic. Mixed, special, and inert waste types are not considered divertible to energy due to their chemical and physical composition or due to the unknown nature of the waste (CA Waste Characterization Study, 2009). The WBEM calculates the MSW biomass supply on a per person basis, calculating population growth according to current and historical US Census records (U.S. Census Bureau, Population Division, 2009). It is generally accepted among the MSW-to-energy research community that some degree of pre-sorting of MSW at the household or commercial level may be assumed to include the separation of paper, organics, and sub categories of plastic including recyclables and non-recyclables prior to curbside collection (McDougall *et al*., 2001). As a result, the WBEM assumes that paper, organic materials, and plastics may be diverted from landfills separately. The amount of each type of divertible waste to be designated to energy conversion may be determined by the model user. Prior to diversion, a model user may input parameters for the diversion of these three waste types for local recycling and/or composting programs prior to other pathways. It is assumed that mixed, special, and inert wastes are not able to be diverted and always continue to landfill as a default. MSW is generated at the city level from 411 jurisdictions and is transported to 130 active landfills, each landfill receiving waste from multiple jurisdictions. MSW network tonnage data was collected from the CalRecycle website (CalRecycle, 2011). Emissions and fuel costs associated with the collection and transportation of MSW by heavy duty truck, as well as those associated with landfill equipment operations were calculated as described in Thorneloe et al., 2007 and in Wang, 2011.

Displaced air space is a commonly used metric for representing the land and atmospheric area and volume taken up by landfill waste. The WBEM calculates displaced air space over time as MSW is generated and deposited in landfill, incorporating a 10% compaction rate, from landfill opening to closing (Figure 2).

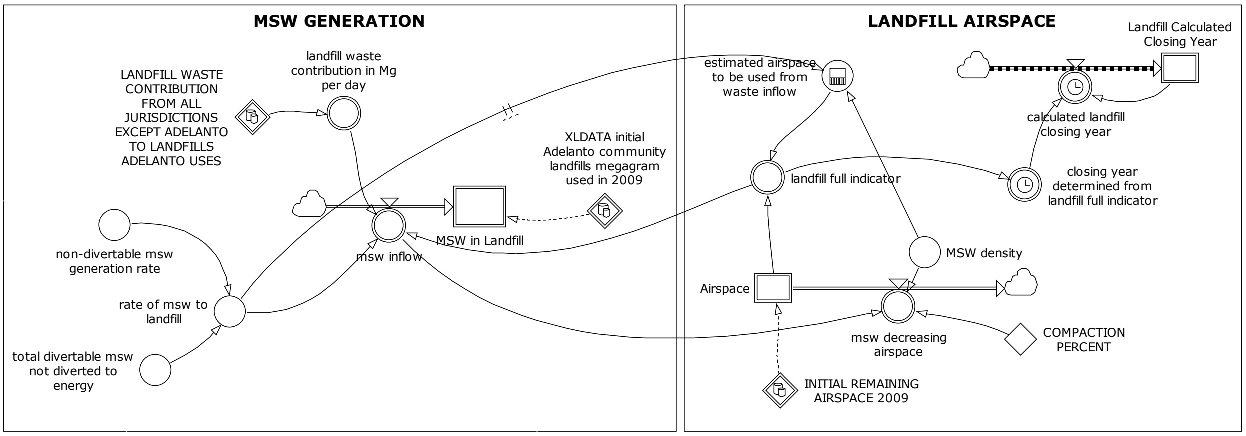

Figure 2. Portion of WBEM model. One community, Adelanto, and all MSW landfills it utilizes.

Opening dates and estimated closing dates for landfills were determined by CalRecycle (CalRecycle, 2011). Fees associated with MSW landfill disposal are also considered, including tipping fees paid at MSW transfer stations, as well as fees paid by municipalities per ton of MSW for landfill disposal. Landfill-associated emission calculations were modeled as described by the Environmental Protection Agency's (EPA) Landfill Gas Emissions Model (LandGEM) (LandGEM, 2005). Historical landfill GHG emissions were determined for each California landfill according to available historical landfill age, landfill capacity, and landfill environmental conditions. LandGEM settings for potential methane generation capacity, projected methane generation rate, environmental conditions, and landfill type may be input as user-specified model parameters. These data are incorporated with model-projected future landfill GHG emissions that are based on continual MSW deposits in landfill under the assumption that waste generation per person remains constant over time. A preliminary sample output of landfill methane quantity over time from one community calculated by LandGEM is shown in Figure 3.

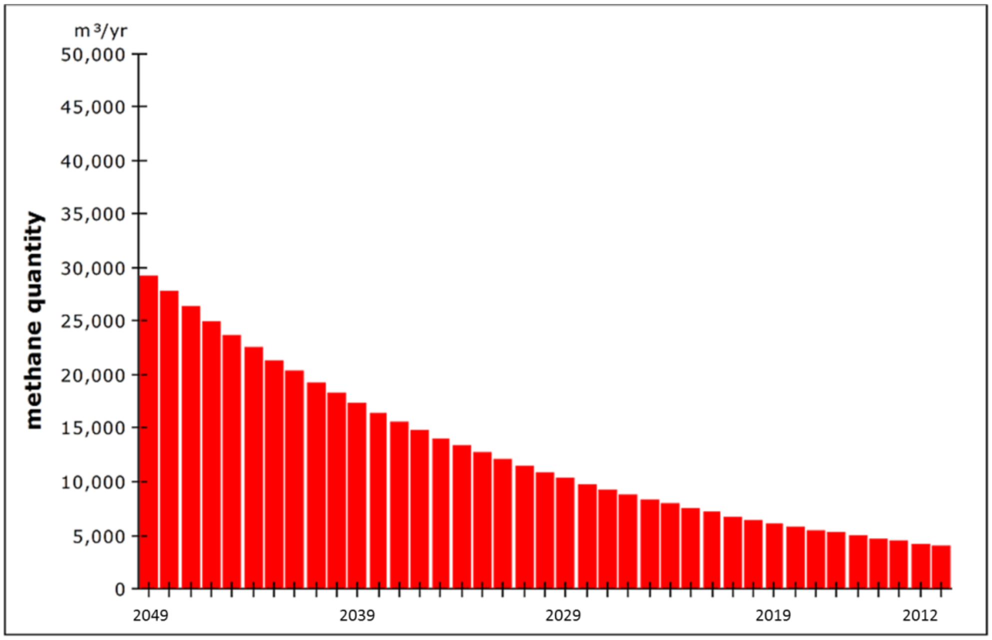

Figure 3. Preliminary sample landfill methane quantity model output from landfills receiving MSW from one community: Adelanto, CA. Calendar year is represented on the x-axis. In 2049 for example, methane landfill emissions include those from MSW deposited in landfill during 2049, as predicted by the model, plus landfill emissions resulting from previous MSW deposited in landfill in previous years as it continues to decay.

LandGEM is commonly used for MSW landfill planning estimates of GHG emission rates for total landfill gas, methane, carbon dioxide, non-methane organic compounds, and other air pollutants from MSW landfills. Under LandGEM default conditions, landfill gas composition is approximately 50% methane, 50% carbon dioxide, with trace amounts of 50 additional volatile organic and/or hazardous atmospheric pollutants.

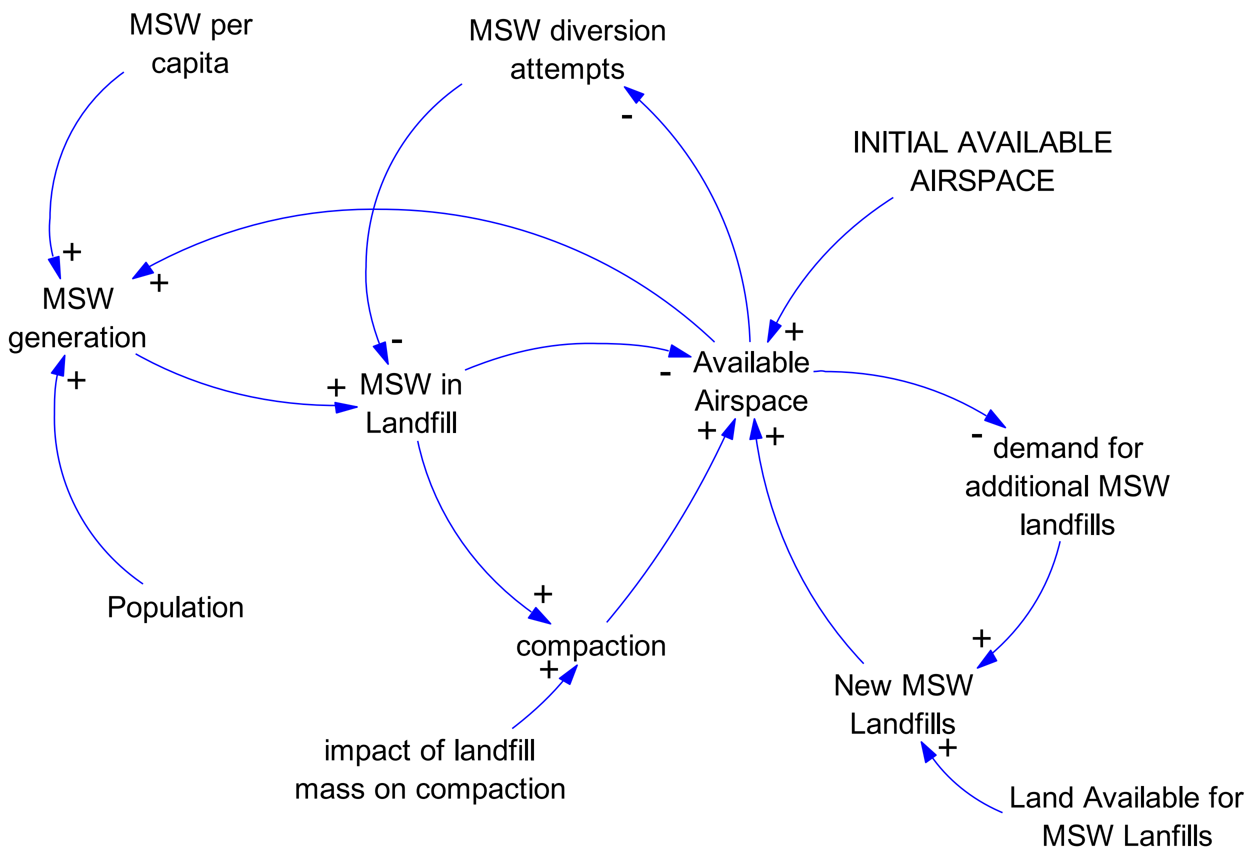

Figure 4. WBEM MSW supply chain causal loop relationships.

Figure 4 highlights some of the MSW supply chain causal loops found in the WBEM. As MSW is generated on a per person basis, it contributes to MSW in landfill where it displaces air space as it accumulates and compacts over time. Diversion of MSW to either energy conversion or to local recycling and composting programs decreases MSW going to landfill, increasing the available landfill space. The demand for additional landfills increases as MSW fills up the initially available air space available, creating a demand for new landfills.

Energy Conversion

Organics and Paper to Electricity

Waste organic and paper material that is diverted from the landfill for energy conversion purposes may be converted to either liquid fuel or to electricity. For the conversion of waste organic matter and paper biomass to electricity, gasification and direct combustion conversion technologies were considered. Although direct combustion is by far the most common conversion technology used to date for the conversion of biomass to electricity in California (CA Energy Almanac, 2009), many renewable portfolio standard programs, such as that in CA, only allow electricity generated from gasification of MSW to be eligible for renewable energy credits. A state or region may wish to explore biomass to energy options that are eligible for energy credits, even if some technologies are still at a pilot stage of development; therefore the WBEM allows the user to choose which conversion technology is used. All MSW-derived energy feedstock biomass is considered to be zero cost.

Due to a lack of energy conversion data specific to paper and organic materials, these MSW biomass feedstocks are represented by corn stover for electricity and ethanol conversion due to similarities in chemical composition and in LHVs. For example, the weighted average of LHVs of the tons of the five most landfilled paper types is equal to 17.52 Megajoules per kg (Domalski *et al*., 1987), compared to a corn stover LHV of 17.21 Megajoules per kg (Wang *et al*., 2011). Percent carbon content by weight of the same paper products is 42.2% (Domalski *et al*., 1987), and corn stover carbon content by weight 43.7% (Wang *et al*., 2011). According to the NREL thermodynamic database, the LHVs and carbon content is highly variable among food types which is partly due to variations in water content (Domalski *et al*., 1987). Due to the lack of granularity in organic waste biomass by type available, corn stover is used as a proxy for organic waste as well. However, if a model user has more detailed data on input biomass, the model parameters can be adjusted accordingly. Energy requirements, GHGs, and energy conversion efficiencies were determined by GREET (Wang, 2011).

As waste biomass is converted into electricity, it displaces current electricity sources. Current baseline California state electric mix and demand was determined from the California Energy Commission's CA energy almanac and includes biomass, coal, geothermal, hydroelectric, landfill gas, natural gas, nuclear, oil, photovoltaic, and wind electricity fuel sources (CA Energy Almanac, 2009). GREET was used to determine energy requirements and GHGs for each baseline electricity source except landfill gas, which was referenced by Sanscartier et al., 2011 (Wang, 2011). In real-time application, it is unknown whether waste-derived bioelectricity would offset baseline electrical mix, marginal electric mix, or future electricity generation that is planned but not yet built. In order to address any and all of these possibilities, the WBEM allows the user to determine what electricity sources it displaces in any possible configuration. This approach provides flexibility to a wide range of model applications, but also allows analysis for determining the most strategic allocation of biomass-derived electricity resources. Costs associated with electricity fuels, electricity conversion, and the price of electricity for baseline electricity sources were determined from the Energy Information Administration (EIA) (U.S. Energy Information Administration, 2011a).

Organics and Paper to Liquid Fuel

The WBEM also allows for the diversion of waste biomass for conversion into liquid fuel for use in the transportation sector. For the conversion of waste organic matter and paper biomass to electricity, gasification and fermentation conversion technologies were considered. Similarly to electricity, due to a lack of liquid fuel conversion data specific to paper and organic materials, and in order to quantitatively compare liquid fuel generation to electricity generation, these MSW biomass feedstocks are represented by corn stover for liquid fuel conversion due to similarities in chemical composition and in LHVs. The model user may choose the conversion technology to be used. Energy requirements, GHGs, and energy conversion efficiencies were determined by GREET (Wang, 2011). Costs associated with the fermentation conversion of cellulosic waste biomass to liquid fuel and resulting ethanol prices are as described by Humbird et al, 2011.

As waste biomass is converted to liquid fuel, it displaces currently used transportation fuel sources. Current baseline California state ethanol and gasoline demand was determined by information available from EIA to be approximately 2.5 million Megajoules per day in the transportation sector (2011b). According to GREET, national US ethanol production consists of a mix of approximately 90% dry milled corn and 10% wet milled corn (Wang, 2011). This baseline mix was used to approximate California state ethanol mix in the WBEM. If MSW biomass is converted to ethanol energy for use in the transportation sector, the model user may determine what baseline sources of ethanol production will be displaced. In addition, the current California state gasoline fuel demand of approximately 4.9 billion Megajoules per day was also incorporated into the WBEM in order to evaluate the costs and environmental consequences of gasoline liquid fuel displacement with MSW-derived liquid fuel (EIA, 2011c). It is unknown whether MSW-derived liquid fuel would displace fossil fuel-based transportation fuels, current ethanol sources, or some combination of these options, the model allows the user to allocate MSW-derived energy resources while also allowing for analysis to determine the most strategic allocation of energy resources based on cost, environmental impact, and other parameters. Conversion costs of baseline biomass resources to ethanol, ethanol prices, and costs associated with gasoline production and use were determined by Humbird et al. and EIA respectively

(2011; EIA, 2011). Costs associated with gasoline feedstock, refining, and retail price were determined by the EIA (2011c).

Discussion

This system dynamics methodology allows a quantitative exploration of tradeoffs between these pathways by considering dynamics and feedback across them over time. For example, the variety of current biomass to energy conversion technologies vary widely in terms of cost. As these technologies mature as a function of the amount of biomass converted, they may become more economical compared to others, shifting the flow of biomass types over time as a function of cost-benefit. System dynamics is also ideal for analyzing these competing pathways in the face of changing energy use and fuel price. For example, as the price of oil fluctuates in the case of liquid fuel, and as the price of coal or Natural Gas fluctuates in the case of electricity, which energy pathway would be better suited for waste biomass from a life-cycle cost perspective? This dynamic approach may also be used to determine how biomass may be able to make a significant environmental improvement. For example, diverting waste biomass to either liquid fuel or to electricity may displace existing energy sources. This displacement will have an environmental impact per amount of baseline energy demand displaced in either the electricity or transportation sectors. This metric may vary depending on the carbon intensity of the displaced energy fuel source. The carbon intensity of the displaced fuel source will vary geographically in the US, and also perhaps over time. This dynamic approach will be able to capture these phenomena, among others, as the WBEM nears completion. By capturing these dynamics, we expect to see variations in the most cost-effective and the most environmentally-effective uses of waste biomass over time. This capability will guide understanding of how waste-to-energy technologies could more strategically advance bioenergy in one state, which may be then extrapolated to consider waste to energy capabilities on a national level, and provide a flexible framework able to apply to waste streams beyond MSW, and to the strategic planning of other available biomass resources.

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