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

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Abstract

A quantitative system dynamics model was created to evaluate the economic and environmental tradeoffs between biomass to electricity and to liquid fuel using MSW biomass in the state of California as a case study. From an environmental perspective, landfilling represents the worst use of MSW over time, generating more greenhouse gas (GHG) emissions compared to converting MSW to liquid fuel or to electricity. MSW to ethanol results in the greatest displacement of GHG emissions per dollar spent compared to MSW to electricity. MSW to ethanol could save the state of California approximately $60 billion in energy costs by 2050 compared to landfilling, while also reducing GHG emissions state-wide by approximately 140 million metric tons during that timeframe. MSW conversion to electricity creates a significant cost within the state's electricity sector, although some conversion technologies are cost competitive with existing renewable generation.

ACKNOWLEDGMENTS

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NOMENCLATURE

DC	Direct Combustion
GHG	Greenhouse Gas
IGCC	Integrated Gasification Combined Cycle
MSW	Municipal Solid Waste
SNL	Sandia National Laboratories
WBEM	Waste Biomass to Energy Model

1. INTRODUCTION

Increasing concern regarding the cost, security, and environmental impacts of fossil fuel energy use drives research and development towards discovering the most strategic uses of energy derived from biomass. This phenomenon is evident by the motivations and actions of policymakers at both the federal and state levels. The Renewable Fuel Standard (RFS2) sets biofuel consumption goals for the transportation sector to encourage alternative transportation fuel markets, to stimulate alternative fuel and vehicle innovation, and to encourage the adoption of alternative and flex fuel vehicles (US Environmental Protection Agency 2010). The ultimate goals of the RFS2 mandate include a reduction of 138 million metric tons (MMT) of transportation sector greenhouse gases (GHGs) and a reduction in annual petroleum consumption by approximately 13.6 billion gallons by 2022 (US Environmental Protection Agency 2010). At the state level, the renewable portfolio standard (CaRPS) in California was codified in 2011 to require electric utilities to increase their procurement of eligible renewable energy resources to total one third of their electricity generation by 2020 (California Public Utilities Commission 2011). Similar to RFS2, the CaRPS program goals included the displacement of existing fossil fuel-based electricity sources, reducing GHG emissions, while also encouraging renewable energy innovation in California (California Public Utilities Commission 2011). In pursuit of these biomass-derived energy objectives, California's Bioenergy Action Plan is authored by several state agencies and discusses the state's strategies and goals for potential biomass-derived energy (O'Neill 2012). Current analysis in the field of biomass to energy has begun to explore the theoretical limitations of biomass to energy through biomass resource availability assessments. At least 29 states have conducted biomass resource assessments, and at the national level, the US Department of Energy sponsors the Billion Ton Study which predicts county-level biomass resource availability, nation-wide from now until 2035 (US Department of Agriculture 2013b, US Department of Energy 2011). These biomass resource assessments indicate a desire to understand the potential for biomass to energy, and an overarching need for greater quantitative analysis capabilities concerning the cost, environmental impacts, and energy sector impacts of converting available biomass resources into energy.

The majority of current biomass to energy analyses focus on either the conversion of biomass to liquid fuel, or on the conversion of biomass to electricity energy, rather than considering the strengths and drawbacks of these pathways side by side. In 2006, Farrell *et al.* used the Energy and Resources Group Biofuel Analysis Meta-Model to evaluate the life cycle GHG and energetic effects of converting biomass to ethanol in the transportation sector. Also in 2006, Lin and Tanaka published a review of the current status of the conversion of biomass, and other resources, to transportation ethanol via biochemical conversion (Lin and Tanaka). In addition, a large body of literature is currently devoted to the evaluation of the RFS2 mandate; these efforts focus on the conversion of biomass resources to liquid transportation fuel, analyzing the mandate from an environmental, economic, and technology readiness standpoint (National Research Council 2009, Schnepf and Yacobucci 2012, Wakeley 2009, Westbrook 2013, and others). In the field of biomass-derived electricity, a 1995 analysis examined the technology readiness and economic potential of converting woody biomass to electricity via integrated gasification combined cycle (IGCC) technology, finding that at that time, while the proof of concept of the conversion technology existed, it had yet to be proven at a larger scale

(Bridgwater 1995). In addition, detailed techno-economic and state of the art assessments of biomass-derived electricity have been explored in more recent years (Lora 2009, Walter 2007). Although these studies provide important insight into the potential of biomass-derived energy, the variety of available energy conversion technologies along with regional diversities in existing energy supplies, in fuel costs, and in biomass resources suggest considering biomass-derived liquid fuel and electricity pathways in competition rather than in isolation. Preliminary biomass-derived energy analysis has begun to explore the economic and environmental tradeoffs of the production of electricity versus liquid fuels. In 2010, Campbell and Block evaluated the competing pathways of waste sugarcane cellulose (bagasse) to electricity with bagasse to cellulosic ethanol on a Brazilian nationwide basis using a linear approach. The study concluded that converting bagasse to electricity could represent approximately 40% of the nation's domestic electricity production, while the cellulosic ethanol pathway represented approximately 2.7% of the 2006 US transportation fuel consumption on an energy basis. The authors concluded that the conversion of bagasse to electricity could represent a better use of waste biomass resources in Brazil at that point in time. In 2009, Campbell *et al*. conducted a life-cycle assessment of GHG emissions and of land use efficiency for energy crop production, comparing the use cases of fueling either electric vehicles or ethanol-fueled vehicles. The authors observed greater net transportation energy output per hectare of crop production and greater life cycle GHG emissions offsets in the electric vehicle case compared to the 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 static system modeling in tandem with spreadsheet model calculations to account for economic and GHG emission effects. However, these studies do not yet capture energy system dynamics such as regional supply chain biomass availability and the required feedstock transportation infrastructure together with the costs and efficiencies of the appropriate conversion technologies, nor do they account for future uncertainties of these parameters.

A diverse set of biomass resources can be utilized for energy purposes. The California Bioenergy Action Plan and ORNL's Billion Ton Study consider biomass resources including energy crops, agricultural residues, forest residues, and urban residues (O'Neill 2012, US Department of Energy 2011). Energy crops are whole plants that are grown specifically for conversion to an energy carrier. Like conventional food crops, energy crops require resources such as arable land, fresh water, and nutrition for growth. Energy crops also require a growing season, as well as man-power to plant, maintain, and harvest the crops, all of which require time and energy. Some of these needs are significant and may ultimately make their use infeasible. For example, Bridgwater concluded that the conversion of woody biomass to electricity via IGCC conversion would only be economical if the process as carried out using either a low-cost waste biomass source, or if there was a formal subsidy structure in place (Bridgwater 1995). Due to these obstacles, biomass waste streams often represent an attractive alternative. Agricultural residues are often considered a waste biomass resource for energy conversion even though they may be traditionally used as either soil amendments to stabilize soil and to add to soil nutrition, or as livestock fodder following crop harvest (Schnepf 2012, USDA-NRCS 2002). Concerns regarding the deterioration of arable soil quality and erosion that result from removal of agricultural residues have led to research and modeling efforts to better understand the potential consequences of residue removal for energy conversion (US Department of Agriculture 2002, Nelson 2002). These efforts help in estimating how much biomass may potentially be safely removed from agricultural land for energy conversion, however these estimates vary by soil type, crop type, weather conditions, and by agricultural practices, and therefore are complex to calculate and coordinate on a large scale. It is also unclear whether new transportation infrastructure would be required to collect, handle, and transport crop residues from each individual field to a more central location for energy conversion. Agricultural residues have the additional limitation of being seasonal and regional, further constraining their potential reliability as an energy feedstock. Forest residues are wastes generated from existing commercial forest harvest practices, and from forest thinning efforts aimed at managing forest fire hazards (US Department of Energy 2011). Forest residue biomass collection drawbacks include resource-intensive collection that is largely done manually, as well as the potential need for new infrastructure to collect, handle, and transport the biomass. Due to these limitations of energy crops, agricultural residues, and forest residues as biomass-derived energy resources, the utilization of lower cost waste biomass resources with existing supply chain transportation infrastructures, such as municipal solid wastes (MSW), should be considered as potential energy sources. MSW is currently a zero cost waste biomass resource with a pre-existing supply chain infrastructure. The accumulation of MSW in landfill poses both economic and environmental costs to local and national communities that could be avoided if this biomass resource was diverted for other purposes. It is clear that policymakers are interested in MSW as a potential energy feedstock. For example, the conversion of MSW to electricity is eligible under the CaRPS if an approved IGCC conversion technology is utilized (California Energy Commission 2013). At the national level, the RFS2 mandate already allows blenders to receive biofuels mandate credits for the production of biofuels produced from cellulosic portions of MSW (US Environmental Protection Agency 2010). In 2010, the US Department of Energy's Biomass Program completed a case design summary for the production of liquid fuels from MSW via an IGCC conversion and has since directed funding to further explore this biomass to energy pathway and to investigate its practice at a commercial scale (US Department of Energy 2010). To a limited extent, MSW to energy modeling efforts have begun to explore the potential of MSW to energy in North America. Utilizing these models, studies have concluded that on a per unit energy basis, the direct combustion (DC) of municipal solid waste to generate electricity had a lower life cycle GHG impact compared to capturing and combusting landfill gas (LFG) to electricity, depending on the LFG capture efficiency (Kaplan 2009, Morris 2010). One of these studies assumed a flat national MSW mix based on available data from the US Environmental Protection Agency (EPA) and also considered the displacement of emissions from existing, or business as usual (BAU), electricity sources in North American Electric Reliability Council regions (Kaplan 2009). Both studies assumed flat one-way distances to represent the MSW biomass supply chain structure. Although these studies take a significant step towards a better understanding of the potential environmental impacts of MSW to electricity in comparison to LFG to electricity, including an economic perspective would be useful as well when developing future biomass to energy strategies.

Over the past 50 years California has made substantial progress in MSW diversion, composting or recycling over 60% of its MSW through programs 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 paper waste, organic material, and mixed plastics which could be converted to energy, and while interest in diverting this MSW as a potential low cost and low impact energy resource is prevalent, detailed MSW-to-energy quantitative modeling and planning efforts remain limited (California Integrated Waste Management Board 2009). This study performs a quantitative parametric analysis of the displacement of BAU electricity and liquid fuel energy sources with MSW-derived energy, and the resulting economic and GHG emission impacts of these changes over time using California as a case study. These environmental and economic impacts are evaluated across a range of MSW to energy pathways against the baseline pathway of landfilling MSW. The economic and GHG emission cost or benefit of a given energy pathway will depend, in part, on the state of the conversion technologies available, the cost of existing energy sources, the costs of converting biomass to energy, and how these parameters change over time. This study utilizes a parametric approach to evaluate each energy pathway across an appropriate range of these future uncertainties. The goal of this study is to inform robust, long-term strategic planning of biomass to energy at the national, state, and local levels for the US by providing the systems view of the economic and environmental impacts of the conversion and the displacement of existing energy sources.

2. MODEL DESCRIPTION

The Waste Biomass to Energy Pathway Model (WBEM) tracks the generation and use of MSW in California from 2010 until 2050. Figure 1 represents a high-level representation of the WBEM model structure, which is designed to capture the system dynamics of three competing pathways of MSW to 1) landfill, 2) electricity, and 3) liquid fuel. These three pathways have economic costs and environmental impacts, such as GHG emissions, associated with them. The WBEM calculates these factors in order to determine which MSW pathway is the most beneficial given an objective, such as reductions in GHG emissions or in cost savings per unit energy produced in a particular energy sector.

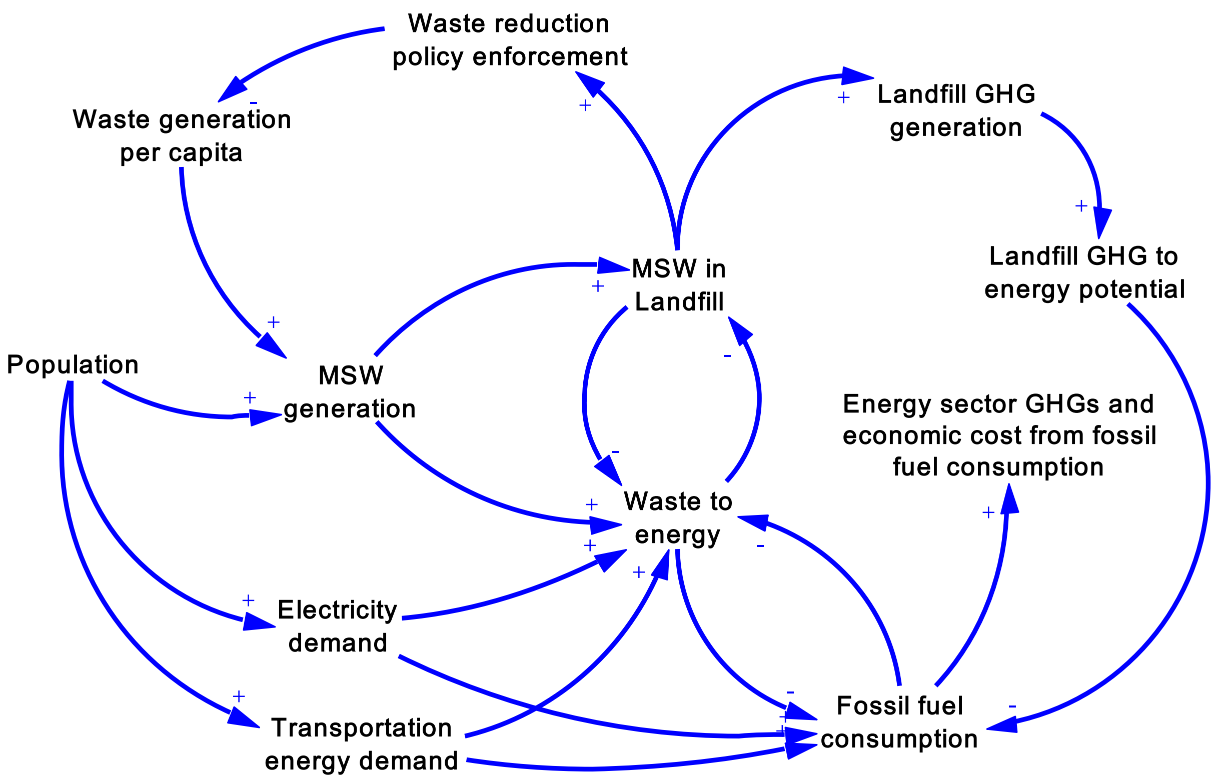

Figure 1. High-level Waste Biomass to Energy Pathway Model (WBEM) representation.

The California Department of Resources Recycling and Recovery (CalRecycle) periodically conducts waste characterization studies at state landfills to track the rate of waste generation, landfill size and location, locations where MSW is transported to and from, and the type of waste generated, ultimately populating an online database. This database was referenced to populate model MSW generation rate and type calculations (CalRecycle 2011). The WBEM calculates the MSW energy feedstock supply on a per person basis, estimating population growth according to current and historical US Census records (U.S. Census Bureau, Population Division 2009). For baseline model conditions, waste generation rate per person is constant over time;

however the model user can vary this rate over time to observe the effects of waste generation behavior on biomass to energy potential over time. MSW types that are considered suitable for energy conversion include paper, organic materials, and plastic. The remaining waste types: mixed, special, and inert are not considered suitable due to their chemical and physical compositions or due to the unknown nature of the waste (California Integrated Waste Management Board 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 source may be assumed to include the separation of paper, organics, and subcategories of plastics 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 from other waste types. The model user determines the amount of any waste type that will be diverted from landfilling for energy conversion. Prior to diversion, organic, paper, and plastic waste types may also be allocated for local recycling and/or composting programs. Mixed, special, and inert wastes are not able to be diverted for energy purposes and are always landfilled. In California, the WBEM captures MSW generation at the community level within 411 waste-producing jurisdictions and transported via a supply chain network to 130 active landfills, each landfill receiving waste from multiple jurisdictions. The MSW network tonnage data supporting the modeling of this supply chain was collected from the CalRecycle online database (CalRecycle 2011). The California MSW transportation network is complex (Figure 2); a landfill may receive MSW from as few as one to as many as 318 jurisdictions, while a given jurisdiction may send waste to as few as one to as many as 34 landfills (CalRecycle 2011).

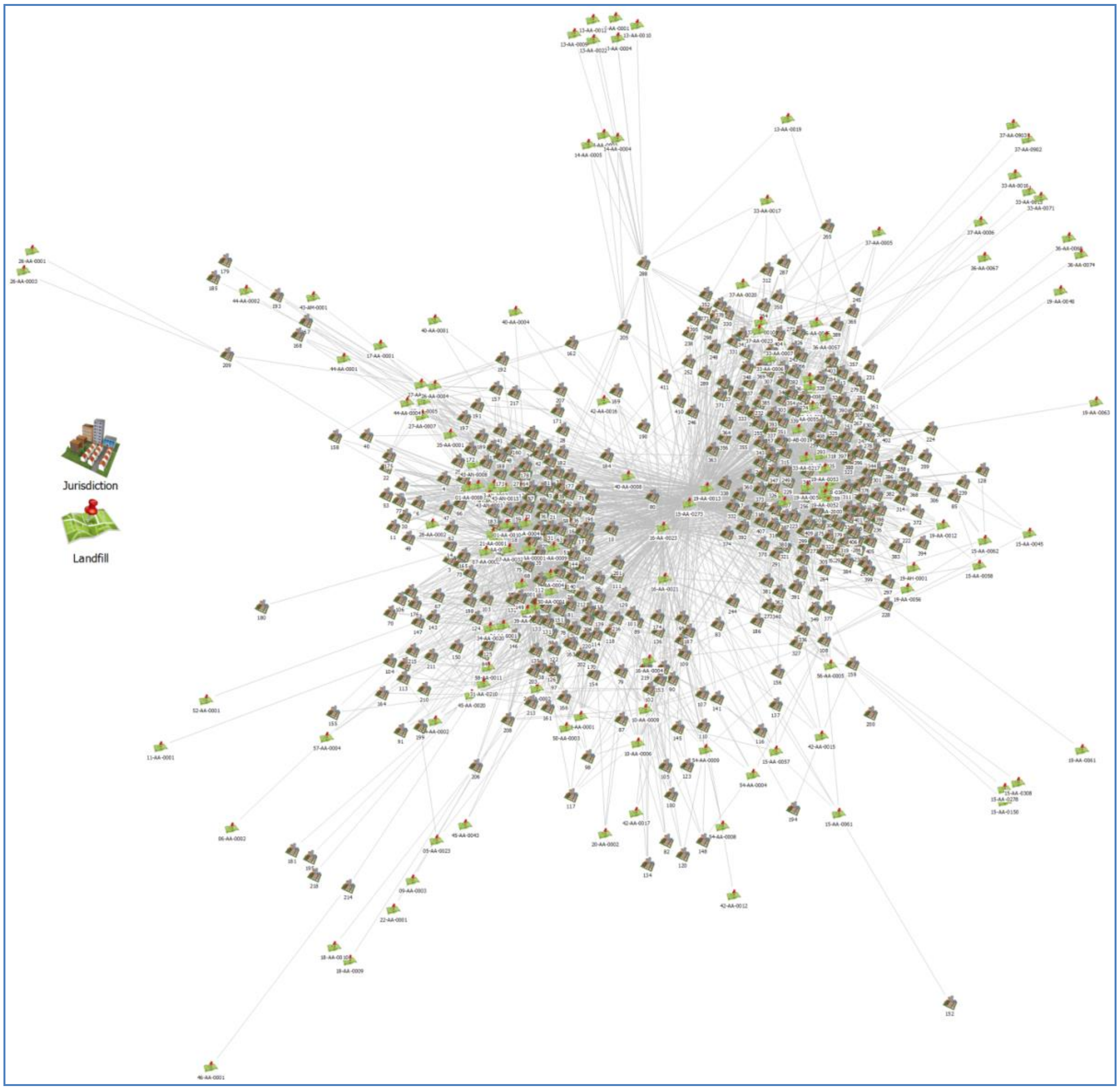

Figure 2. California jurisdiction to landfill network (not to scale).

Latitude and longitude coordinates of jurisdictions and of landfills were captured to calculate the total distance traveled via MSW truckload in the transportation network using a Great-circle distance algorithm (Google Moveable Type Scripts 2013, CalRecycle 2011). As a benchmark, actual road network distances were calculated for a sample set of jurisdictions and landfills.

Transportation costs of MSW transport were calculated on a per metric ton (MT) basis as a function of the total distance traveled, heavy duty truck capacity, fuel efficiency, diesel fuel cost, MSW density, and truck driver wage. Heavy duty truck capacity was assumed to be 20 cubic yards, assumed diesel fuel truck efficiency was 11.265 km/gallon, MSW density was assumed to be 0.045 metric tons per cubic yard, and diesel fuel cost was assumed to be $4.31 per gallon (Encyclopedia 2012, CalRecycle 2012, US Energy Information Administration 2012). Transportation costs and emissions associated with door to door pickup within a jurisdiction prior to distribution were ignored. MSW feedstock was assumed to have zero cost. Emissions associated with MSW heavy duty vehicle activity were calculated as described in Thorneloe *et al*., 2007 and in Wang, 2012.

2.1 MSW Supply Chain and Landfill Use

The landfilling of MSW in California represents the baseline model scenario. 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 GHGs over time due to decomposition, as well as land and air volume taken up by the waste over time, which is expressed by a displaced air space metric. Displaced air space is a commonly used metric 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 (Leonard *et al*. 2000), from landfill opening to closing (Figure 3).

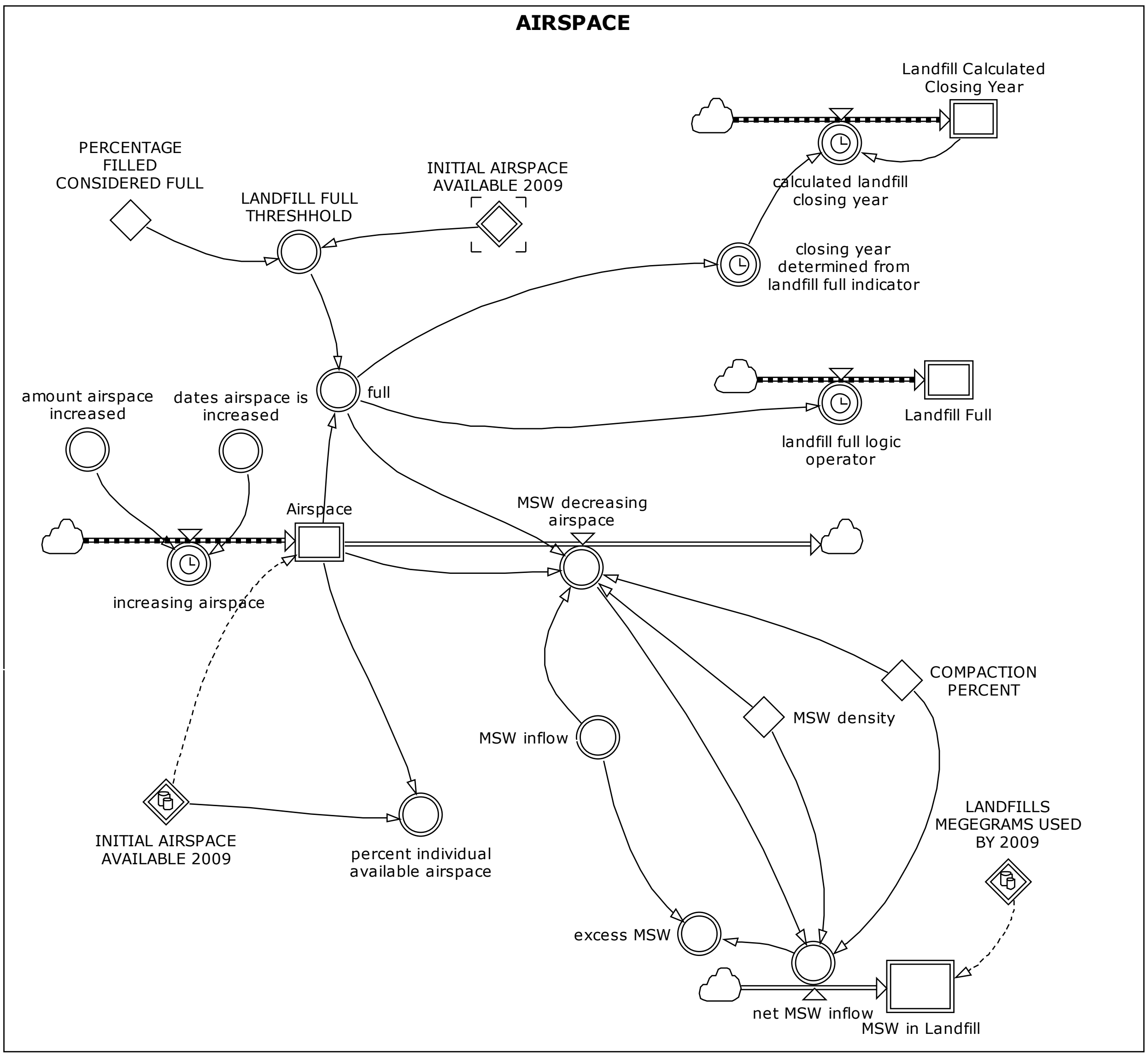

Figure 3. Snapshot of the MSW accumulation and compaction effects on available landfill airspace as calculated by the WBEM.

As described by Forrester, system dynamics employs "an alternating structure of reservoirs or levels interconnected by controlled flows" (Forrester 1961). These reservoirs are made operational by stocks, flow rates, decision functions and information channels, which are the collective building blocks of a system dynamics model, metaphorically described by Forrester as "bathtub dynamics." Stocks are the bathtubs themselves, decision functions are the automated or humanly controlled valves on the flows to and from bathtubs, and the information channels serve as pipes between stocks. In Figure 2, stocks are represented by rectangles, flow rates are the pipe and circle objects, other objects represent auxiliary functions for model clarity.

The maximum capacity for each active California landfill was referenced from CalRecycle to calculate if and when each landfill would reach full capacity over time (CalRecycle 2012). Landfill-associated GHG emissions were calculated as described by EPA's Landfill Gas Emissions Model (LandGEM) (LandGEM 2005). Estimated methane generation capacity, projected methane generation rate, precipitation conditions, and landfill type may be input as user-specified model parameters that influence landfill GHG emission rates. Future landfill GHG emissions are calculated based on model projections of MSW accumulation in landfill over time. LandGEM is commonly used to estimate future GHG emission rates of planned MSW landfills to ensure compliance with current air quality standards. LFG composition is approximately 50% methane, approximately 50% carbon dioxide (CO_2), with trace amounts of approximately 50 additional volatile organic and/or hazardous atmospheric pollutants. The Intergovernmental Panel on Climate Change has concluded that CO_2 emissions from landfilled organic material (paper and organic MSW) do not count towards a landfill's GHG footprint due to the CO_2 gas that would result from the aerobic decomposition occurring regardless of waste location (Intergovernmental Panel on Climate Change 2001). Landfill CO_2 emissions are calculated by the WBEM, however, here they are not included in landfill GHG calculations. Landfill methane emissions result from anaerobic decomposition reactions that would not otherwise occur outside of the landfill environment, and therefore do count towards the landfill's GHG footprint.

2.2 Business as Usual Energy Consumption

WBEM business as usual (BAU) energy use in California was modeled to represent existing electricity and transportation energy per person consumption in California in 2010. When a BAU energy source is displaced with energy derived from MSW, the monetary costs associated with that BAU energy source, such as raw materials and operations, are no longer included in calculating the total energy-associated costs in the state, and are displaced with the costs associated with the MSW to energy process. Similarly, the GHG emissions associated with the raw material collection, raw material processing, and generation of displaced BAU energy are no longer included in the total state GHG calculation, and are replaced by GHG emissions associated with MSW collection, processing, and conversion to energy. The model user may manually decide which of these BAU energy sources to displace with energy derived from MSW. In addition, the model user may decide how much of the available MSW is to be converted into energy.

California's BAU electric mix was modeled according to the California Energy Commission's 2009 Energy Almanac of 60.5% natural gas, 19.3% hydroelectricity, 6.3% nuclear, 5.9% wind, 4.0% geothermal, 1.3% biomass, 0.8% photovoltaic, 0.8% oil, 0.6% LFG, and 0.5% coal (California Energy Commission 2009). As energy demand grows over time as a function of electricity demand per person, the model user may choose how the electricity grid evolves over time, and what BAU sources are displaced by electricity derived from MSW. Costs associated with raw materials and operations of these 10 electricity sources were referenced from the US Energy Information Administration (EIA) (EIA 2010, EIA 2011). All US dollar (USD) values described in this analysis reference 2012 USD. The WBEM considers BAU electricity demand based on electricity demand per person in 2009 which was 6,063,166 gigajoules (GJ) per day, or 1,684,208 MWh per day (California Energy Commission 2009, US Census Bureau 2009). Life cycle GHG emissions associated with each electricity source were referenced from Argonne's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) spreadsheet model (Wang 2012).

The WBEM captures California's liquid fuel 2009 BAU transportation sector E10 demand at approximately 400 gallons per capita per year (US Department of Energy 2009, US Census Bureau 2009). E10 is a liquid fuel consisting of a volumetric blend of 90% gasoline and 10% ethanol. The ethanol share of E10 in 2009 consisted of a fermented mix of approximately 90% dry milled corn and 10% wet milled corn (Wang 2012). Modeled costs associated with the raw materials, refinement, conversion, and distribution of these transportation fuel sources were referenced from the EIA (US Energy Information administration 2011c). Life cycle GHG emissions for BAU liquid fuel sources were referenced from GREET (Wang 2012).

2.3 Energy Conversion

Alternative to the MSW to landfill baseline model scenario, MSW may be diverted for conversion to energy. Organic, paper, and plastic MSW types may be converted to electricity or to ethanol, providing an alternative electricity or liquid fuel source for California. For the purposes of this analysis, it is assumed that only currently landfilled organic and paper wastes are able to be diverted for energy conversion, and waste biomass currently being utilized for composting or recycling programs is not considered. It was outside of the project scope to consider locations of waste to energy conversion facilities, and while we do consider transportation costs and emissions from the transport of both MSW to landfill and of MSW to energy, it is assumed that the waste to energy facilities are co-located at each landfill site in the state, so these transportation emissions and costs are equivalent regardless of MSW pathway.

Waste to energy facilities do not currently exist at a large scale in California, and therefore the total costs associated with converting MSW to energy include an operational cost and a levelized capital cost. Levelized capital cost is calculated as a function of the facility capital cost, the discount rate, the anticipated operational lifetime of the facility, the capacity factor of the facility, and the expected annual hours of operation as described by the EIA (US Energy Information Administration 2011a). Due to a lack of energy conversion data specific to paper and organic MSW materials, MSW biomass feedstocks are represented by corn stover for energy conversion due to similarities in chemical composition and in their lower heating values (LHVs). For example, the weighted average of LHVs of the five most landfilled paper types nationally is equal to 17.52 Megajoules (MJ) per kg (Domalski *et al*. 1987), compared to a corn stover LHV of 17.21 MJ per kg (Wang 2012). 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 2012). Regarding organic MSW, according to the National Renewable Energy Laboratory (NREL) thermodynamic database, the LHVs and carbon content is highly variable among food types, in part 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 MSW in California as well. However, if a model user has more detailed data on input biomass, the model parameters can be adjusted accordingly. MSW-derived energy feedstocks were considered to have zero cost.

2.3.1 Organic and Paper MSW to Electricity

Organic and paper MSW that is diverted from landfill for energy conversion purposes may be converted to either liquid fuel or to electricity. This MSW may be converted to electricity by directly combusting (DC), or via integrated gasification combined cycle (IGCC) conversion. DC MSW conversion is assumed to be performed in a biomass bubbling fluidized bed (BBFB) facility as described by the EIA (2010). IGCC conversion involves the creation of synthesis gas, or syngas, and char from biomass under high temperature and high pressure conditions in the absence of oxygen, followed by the combustion of these products (2010). Creating syngas in this intermediate step is ultimately to reduce the GHG emissions from the conversion of biomass to electricity and to make the overall process more efficient and generate fewer pollutants. Although DC is currently the most common method used to convert biomass to electricity in California, many renewable energy portfolio standard programs, such as the CaRPS, only grant renewable energy credits for MSW-derived electricity generated via IGCC conversion methods California Energy Commission 2009). The energetic requirements, GHG emissions, and thermal efficiencies for each of these processes were determined by GREET (Wang 2012). The baseline thermal efficiency of the conversion of MSW to electricity is approximately 19% via DC technology and is approximately 37% for IGCC conversion (Wang 2012). Costs associated with levelized capital costs and operational costs for both DC and IGCC conversion methods were referenced from the EIA (US Energy Information Administration 2010). The modeled base capital cost of a 50 MW DC biomass to electricity facility was $3,760 per kW and the base capital cost of a 20 MW IGCC biomass to electricity plant was $7,573 per kW (US Energy Information Administration 2010). The operational cost baseline for DC conversion was modeled at $0.15 per kWh, and the operational cost baseline for IGCC conversion was modeled at $0.52 per kWh (US Energy Information Administration 2010). WBEM model users may divert any amount of MSW for conversion to electricity via either conversion technology, and the user may also displace any combination of baseline electricity sources with electricity derived from MSW.

2.3.2 Organics and Paper MSW to Liquid Fuel

The WBEM allows for the diversion of MSW for conversion into liquid fuel for use in California's transportation sector. For this energy pathway, biochemical and thermochemical conversion methods were considered. Biochemical and thermochemical conversion technologies modeled here are equivalent to those described in Humbird *et al*. (2011) and in Dutta *et al*. (2012) respectively. The energy requirements, GHG emissions, and thermal efficiencies for each of these processes were determined by GREET (Wang 2012). The baseline thermal efficiency of the conversion of MSW to liquid fuel is approximately 49% via biochemical technology and is approximately 50% for thermochemical conversion (Wang 2012). Costs associated with levelized capital costs and operational costs for both biochemical and thermochemical conversion methods were referenced from the EIA (US Energy Information Administration

2012). Due to variation in the estimated costs of biomass to ethanol in current literature, the capital and operational costs for biochemical and thermochemical conversion were considered to be equal (Humbird *et al.* 2011, Dutta *et al.* 2012). The modeled overnight capital cost for biochemical and thermochemical of MSW to ethanol was $1962 per gallon with an operational cost of $1.47 per gallon (US Energy Information Administration 2012).

Similar to MSW conversion to electricity, WBEM model users may divert any amount of MSW for conversion to liquid fuel via either conversion technology, and the user may also displace any combination of baseline gasoline or ethanol sources with ethanol derived from MSW.

3. RESULTS & DISCUSSION

3.1 Current WTE potential in California

WBEM model output determined the current potential for MSW to electricity, to liquid fuel, and to landfill in 2010, the first year of the model simulation. At the time of model data collection, 2010 was the most current complete data set available for incorporation into the model. California landfilled paper and organic MSW totaled approximately 46,000 metric tons per day in 2010. If this entire resource were converted to electricity through DC, it would produce approximately 34 million kWh per day; meeting 15% of California's residential electricity demand, and the equivalent of approximately 2 million households. Considering both operational and levelized capital costs, the DC conversion process cost would be approximately $5.2 million per day in 2010, not taking into account the displacement of current electricity sources. This electricity has the potential to displace several existing fossil fuel-based electricity sources. For example, combustion of organic and paper wastes can displace all of California's baseline coal-derived electricity, and all of its oil-derived electricity, or 3% of its natural gas-derived electricity.

If IGCC technology converts all organics and paper MSW to electricity, the potential yield would be approximately 65 million kWh per day, which would meet approximately 30% of the state's residential electricity demand, powering approximately 4 million average California households. Operational and levelized capital costs of this generation total approximately $16 million per day in 2010, and could potentially result in the displacement of 6.5% of California's natural gas-derived electricity.

Alternatively, paper and organic MSW in California may be converted to liquid fuel in the form of ethanol. In 2010, landfilled paper and organic MSW tonnage is sufficient to produce as much as 4 million gallons of ethanol per day utilizing either biochemical or thermochemical conversion methods. This volume represents approximately 90% of California's current ethanol demand from E10 gasohol use (US Department of Energy 2009). Here we assume that ethanol derived from waste displaces BAU E10 ethanol rather than gasoline. Operational and levelized capital costs of waste-derived ethanol production total approximately $5.7 to $5.8 million per day in 2010.

3.1.1 Waste paper and organic biomass to landfill in California

In 2010, the WBEM calculates that 46,000 metric tons of organic and paper MSW is transported per day via a one-way network distance of 1,400,352 km between the 411 communities and the 130 landfills in the state (CalRecycle 2012). By 2015, these wastes will have emitted approximately 24,000 metric tons of methane from its anaerobic decomposition in landfill. Figure 4 shows the changes in landfill airspace over time without the diversion of paper and organic wastes for energy conversion.

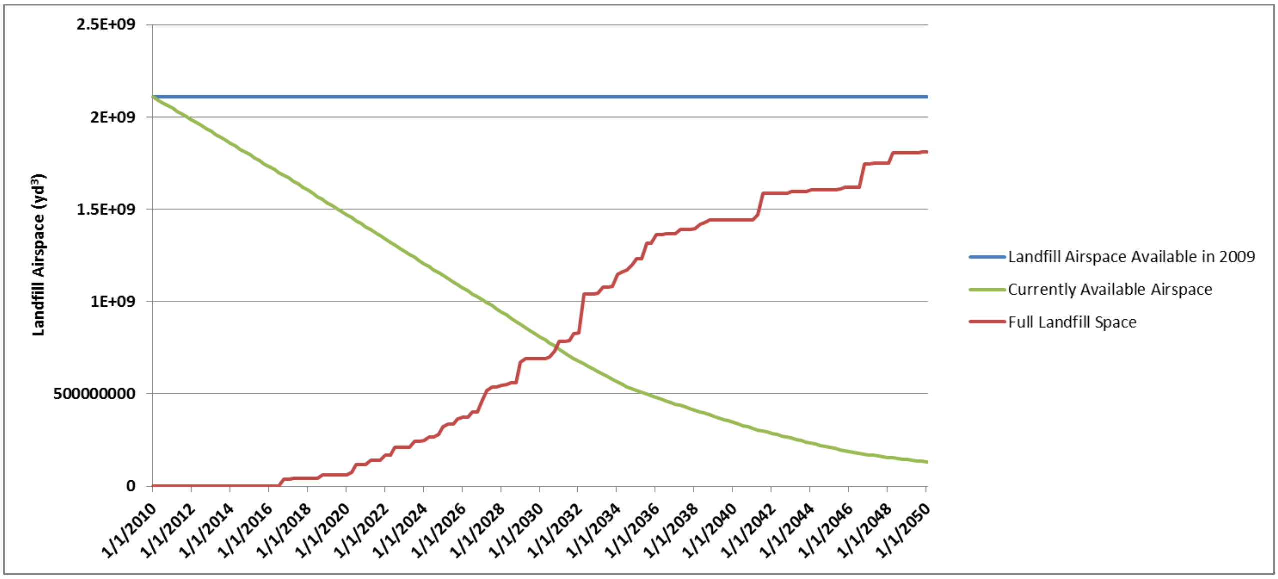

Figure 4. Representation of the changes in California landfill airspace over time with BAU MSW transportation. Paper and organics are transported to landfill and are not diverted to energy.

The WBEM does not create new landfill space, but it does track the consumption of existing state landfill space as MSW is generated over time. In 2010, approximately 2,107 million yd^3 of state landfill airspace is available. By 2050, 70 state landfills reach their maximum capacity, and only 6% of the 2010 available landfill airspace remains (Figure 4).

3.2 Waste to Energy Numerical Analysis

3.2.1 Parameterization

The potential benefits and drawbacks of converting MSW to energy will depend in part on the future economic and technological states of MSW conversion processes, and on the BAU energy sources it displaces. A set of key parameters were chosen to explore future uncertainty in the state of MSW to energy technology and cost, in model assumptions, and in electricity and liquid fuel market conditions. The basline values and distributions of these key model parameters are described in Table 1. These values defined a global sensitivity analysis and the techno-economic MSW to energy pathway parametric analyses. Parameters were varied across these distributions with a multiplier approach. For example, the baseline MSW generation rate per person was represented by historical data from 2009 as reported by CalRecycle. To represent variation in MSW generation per person over time, a multiplier scales the baseline value to calculate greater or lesser MSW generation (Table 1). Here, MSW generation per person ranges from zero to twice the baseline generation rate per person (Table 1).

Table 1. Baseline, minimum, and maximum model input values for parameterization.

Parameter	Baseline	Minimum	Maximum
Corn price	$4 per bushel	$2 per bushel	$10 per bushel
Natural Gas price	$4.11 per mmBTU	$2.05 per mmBTU	$13.36 per mmBTU
Waste to energy plant financial life	40 years	30 years	50 years
Waste to energy capital cost discount rate	5%	3%	10%
Waste to electricity DC energetic efficiency	19%	19%	38%
Waste to electricity DC operational cost	$0.15 per kWh	$0.04 per kWh	$0.15 per kWh
Waste to electricity DC facility capital cost	$3860 per kW capacity	$1930 per kW capacity	$3860 per kW capacity
Waste to electricity IGCC energetic efficiency	37%	37%	74%
Waste to electricity IGCC operational cost	$0.52 per kWh	$0.13 per kWh	$0.52 per kWh
Waste to electricity IGCC facility capital cost	$7573 per kW capacity	$3787 per kW capacity	$7573 per kW capacity
Waste to ethanol biochemical energetic efficiency	48%	48%	96%
Waste to ethanol thermochemical energetic efficiency	49%	49%	98%
Waste to ethanol operational cost	$1.47 per gallon EtOH	$0.38 per gallon EtOH	$1.47 per gallon EtOH
Waste to ethanol facility capital cost	$657 per gallon EtOH capacity	$329 per gallon EtOH capacity	$657 per gallon EtOH capacity

To capture future uncertainties in E10 ethanol price, corn price was parametrically varied from $2 per bushel to $10 per bushel to capture historical commodity price fluctuations over the past several decades. Historically, corn price did not rise above $7 per bushel since the year 1900; however this price was allowed to reach $10 in order to capture a broad range of future price uncertainty (US Department of Agriculture 2013a). A baseline corn price of $4.00 per corn bushel approximately reflected the 2013 received commodity price in the US (US Department of Agriculture 2013a). For MSW to electricity pathways, uncertainty in future BAU electricity generation was represented by variation in the price of natural gas. A baseline natural gas price of $4.11 per million BTU (mmBTU) was referenced from the reported price of natural gas delivered to the Pacific electric power sector in 2011 and was ranged from $2.05 per mmBTU to $13.36 mmBTU to represent historical fluctuations in natural gas price since 1990 (US Energy Information Administration 2012).

The future capital and operational costs of converting MSW to energy are unknown and therefore represent a significant economic uncertainty. To explore these future uncertainties, a series of economic parameters were explored in the parametric analysis including levelized capital and operational costs. Waste to energy plant financial life was ranged from a minimum of 30 years to a maximum of 50 years, with a baseline value of 40 years, and the capital cost discount rate was varied from 3% to 10%, with a baseline value of 5% (US Energy Information Administration 2010). MSW to electricity baseline capital costs for DC and for IGCC conversion methods were referenced from the EIA's projected estimates for new electricity plant planning, and were distributed such that the capital cost would never exceed its current estimated cost, but could decrease to half of the current value (US Energy Information Administration 2010). Similarly, MSW to energy operational cost baseline and maximum range values were represented by current estimates for DC and IGCC biomass power plants per the EIA, and minimum values were allowed to decrease to 25% of the current cost (US Energy Information Administration 2010). Baseline conversion efficiencies of MSW to electricity and of MSW to ethanol were referenced from efficiencies of the corresponding cellulosic conversion processes as described by Wang (2012). To capture future advances in waste to energy technologies, and to capture extreme technology advancement conditions, efficiency values were allowed to increase to approximately twice their current value. A baseline operational cost of cellulosic ethanol production of $1.47 per gallon was referenced from the EIA (US Energy Information Administration 2012). Operational liquid fuel conversion costs were not allowed to increase in the parametric analysis, but were ranged to 25% of the baseline value to represent extreme advances in the technologies and/or in subsidies that would lower the cost of conversion. Baseline capital costs for MSW to ethanol conversion were $657 per gallon ethanol capacity (US Energy Information Administration 2012).

3.2.2 Model Baseline

Electricity derived from MSW could, in theory, displace some fraction of any of the 10 existing electric energy sources in California. However, given its renewable electricity mandates, it is unlikely that California would displace its existing renewable electricity sources with electricity derived from MSW. Here we assume that MSW-derived electricity displaces BAU electricity derived from natural gas. For simplicity, when considering an MSW to energy pathway, it is assumed that all paper and organic wastes are diverted from landfill for energy conversion. When MSW is converted to energy, it is assumed that it is displacing an existing energy demand, rather than meeting an anticipated new demand. The WBEM calculates energy sector impact metrics based on this principle. For example, when calculating the net GHG impact of converting MSW to energy in a given energy sector, the WBEM eliminates GHGs resulting from processes being displaced, and instead includes GHGs resulting from the new MSW to energy process. Figure 5 demonstrates this net GHG impact resulting from the conversion of waste to electricity and to liquid fuel relative to the baseline case of sending paper and organic wastes to landfill. Here we have set the cumulative GHGs emitted from landfilling paper and organic MSW at zero over time to represent baseline GHG emissions, observing cumulative GHGs for MSW to energy pathways relative to this baseline. By 2050, if paper and organic wastes are landfilled, the resulting cumulative GHG emissions are approximately 1,750 MMT, mostly due to methane-producing anaerobic decomposition. Conversion of these wastes to either electricity or to liquid fuel results in net GHG reductions for California compared to landfilling (Figure 5). Relative to the baseline scenario, converting paper and organic MSW to electricity via DC results in a net GHG reduction of approximately 2000 MMT by 2050, and waste to electricity via IGCC conversion results in a net GHG reduction of approximately 2400 MMT by 2050 (Figure 5).

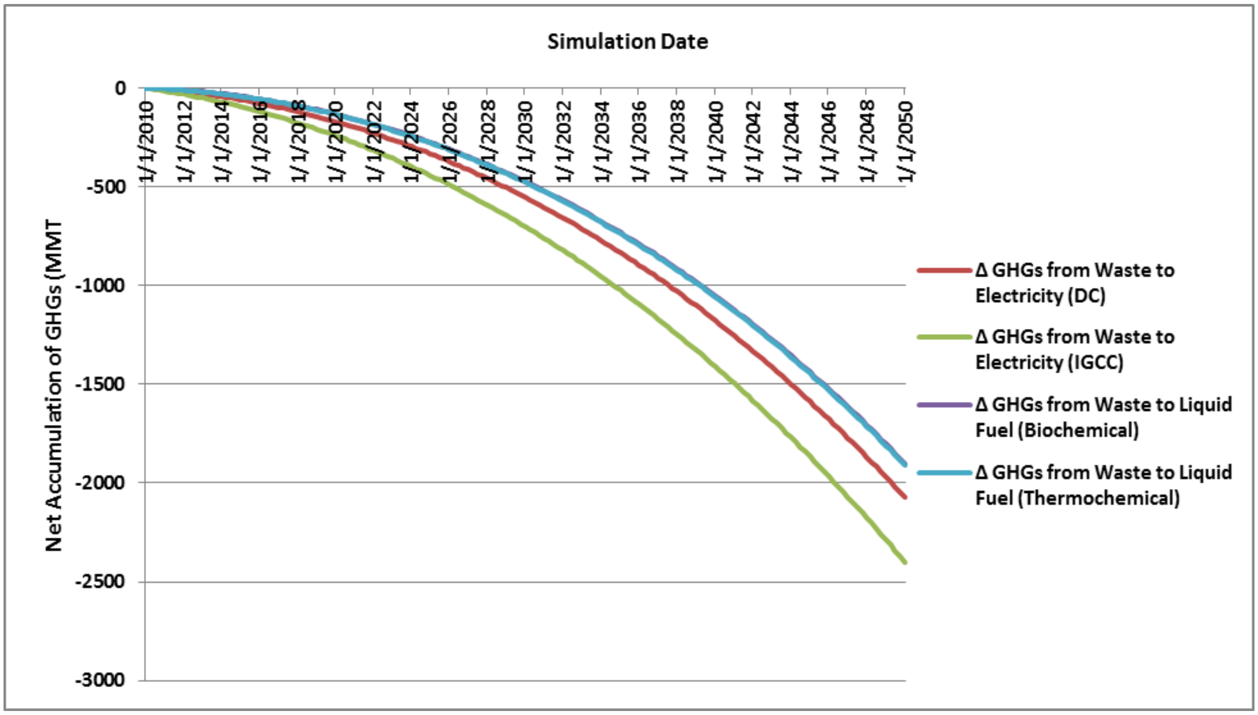

Figure 5. Net reductions of GHG over time in California as organic and paper MSW are diverted to electricity or to liquid fuel relative to the baseline GHG emissions resulting from landfilling these wastes.

Producing ethanol from paper and organic wastes also results in net reductions in GHGs in the transportation sector by 2050 of approximately 1900 MMT in each case (Figure 5). These observations indicate that under baseline model conditions, the landfilling of paper and organic MSW represents the least advantageous use of MSW from a GHG perspective and the diversion of these wastes to energy represents a potential GHG savings no matter what fuel or what conversion technology is chosen. Under baseline model conditions, waste to electricity via IGCC results in the greatest GHG savings of all possible MSW pathways, followed by conversion to electricity via DC, with somewhat reduced GHG savings observed with ethanol production.

By observing the accumulation of GHGs over time, the GHG emission advantages and disadvantages of each pathway become clear. For example, when paper and organic materials are landfilled, the methane-producing anaerobic reactions occur slowly, and cumulatively increase over time. Paper and organic MSW sent to landfill beginning in 2010 will have produced approximately 1,762 MMT of cumulative GHG by 2050 with methane gas representing the vast majority of these emissions. CO_2 emissions are not accounted for in the GHG calculations for either landfill or for MSW to energy conversion processes, and therefore landfill GHGs consist mostly of methane. MSW to energy pathways also produce methane, however not at the levels produced in landfill over time. In contrast with landfill GHG evolution, the majority of electricity sector GHG emissions are generated instantly when an energy source is converted to the carrier form, compared to the relatively slower generation of landfill GHGs which require time to evolve. These GHG emissions differences may only be observed over time. Similarly in the transportation sector, the majority of GHG emissions occur as a result of vehicle use on a relatively shorter timescale compared to landfill GHG emissions. Distinct GHG profiles also contribute to these MSW to energy pathway reductions. The cumulative GHG emissions from direct combustion of organic and paper wastes to electricity beginning in 2010 total approximately -311 MMT in 2050, and the cumulative GHG emissions from IGCC conversion of organic and paper wastes to electricity beginning in 2010 total approximately -637 MMT in 2050 relative to the projected BAU case. The electricity sector GHG reductions result from the loss of GHG emissions resulting from no longer producing electricity derived from natural gas that are now replaced by GHG emissions from the MSW to electricity conversion process. When compared to the baseline landfill GHG case, converting these MSW sources to electricity via DC and IGCC conversion results in a total GHG displacement of -2073 and -2400 MMT respectively in the electricity sector by 2050 (Figure 5). For MSW to electricity, the DC to electricity process generates more GHGs compared to the IGCC process on a per unit output energy basis. Additionally, the IGCC process is approximately twice as efficient as DC, displacing more natural gas in the process. The cumulative GHG emissions from biochemical conversion of organic and paper wastes to ethanol beginning in 2010 total approximately -137 MMT in 2050, and the cumulative GHG emissions from thermochemical conversion of organic and paper wastes to ethanol beginning in 2010 total approximately -146 MMT in 2050 relative to the projected BAU case. In the liquid fuel conversion case, a net GHG savings is observed for MSW to liquid fuel even though ethanol is displacing ethanol in E10. This difference results from the displacement of corn-based ethanol sources with MSW-derived ethanol. The majority of ethanol used in E10 transportation fuel is produced from corn, which generates a GHG footprint due to fertilizer use, farm equipment use, harvest, and transportation in addition to end use vehicle emissions (Wang 2012). When compared to the baseline landfill GHG accumulation, converting these MSW sources to liquid fuel via biochemical and thermochemical conversion results in a total GHG displacement of approximately -1900 and -2400 MMT respectively in the transportation sector by 2050 (Figure 5).

The net economic impact of waste conversion to electricity and waste to landfill is shown in Figure 6. Similarly to the GHG case, the WBEM eliminates costs resulting from processes being displaced, including the cost of currently used natural gas, the cost of corn ethanol feedstock, and the costs associated with transporting and converting these baseline sources while taking into account new costs associated with MSW to energy processes. Over time, the landfilling of paper and organic MSW represents a cumulative cost of approximately $78,500 million USD. This baseline cost results from tipping fees charged on a per ton basis and the cost of waste transportation. It should be noted that other costs may occur as a result of landfilling waste, including landfill permitting and maintenance fees, however sufficient data were not available regarding these costs, and therefore the economic impacts of landfilling waste may be underestimated. To compare the cost of alternative uses of MSW to that of landfill, here we have set the cumulative cost of landfilling paper and organic MSW over time at zero to represent the baseline scenario, and calculate cumulative costs for MSW to energy pathways relative to this baseline. The conversion of paper and organic waste to electricity via the IGCC method represents a net cost for California of approximately $650,000 million USD relative to the baseline case, and conversion to electricity via DC with a net cost of $120,000 million USD relative to the baseline case (Figure 6).

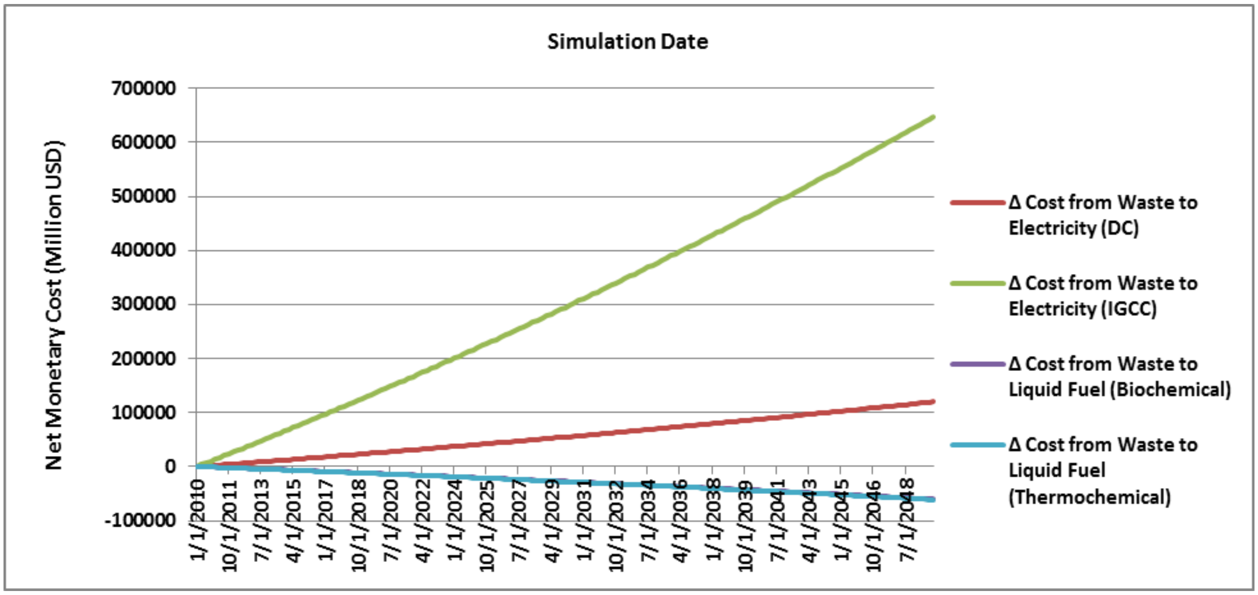

Figure 6. Net reductions of economic costs over time in California as organic and paper MSW are diverted to electricity or to liquid fuel relative to the baseline costs of landfilling these wastes.

IGCC conversion is more expensive than DC on a per unit energy basis and is more thermally efficient, and therefore more electricity is produced in the IGCC case, resulting in a greater overall electricity sector cost compared to DC conversion if all paper and organic MSW is utilized. MSW conversion to ethanol is economical compared to MSW landfilling with both biochemical and thermochemical methods performing similarly for costs, creating a cost savings of approximately $60,000 to $61,000 million USD by 2050 (Figure 6). Since MSW is considered to have zero cost, the economic benefit of eliminating corn ethanol feedstock commodity and production costs outweighs the incremental cost of producing ethanol from a cellulosic feedstock. In addition, ethanol transportation costs are reduced as the total fuel distances traveled are reduced by having ethanol operations in-state.

It should be noted that these MSW to energy results are highly dependent on baseline model assumptions listed in detail in Table 1, which includes the consistency of current commodity prices, the costs of waste to energy conversion and the efficiencies of these processes. In addition, we assume that California individuals generate the same amount of waste over time, and that electricity and transportation fuel demands remain the same per person.

3.2.3 Sensitivity Analysis

A global sensitivity analysis was performed to determine which model parameters drive the greatest change in the output metrics. The analysis included a Monte Carlo simulation set of 1000 points utilizing a random Latin Hypercube sampling of parameters across a uniform distribution from the ranges listed in Table 1. Following Monte Carlo simulation, each parameter and metric combination received a Spearman rank correlation coefficient to represent the degree to which variability in a given metric corresponded to change in a given parameter. Coefficient values of +1 or of -1 represented perfect positive or negative correlations respectively, while a coefficient value of 0 indicated no correlation between parameter and metric pairs. Table 2 lists the sensitivity analysis results for waste to liquid fuel and Table 3 lists these results for waste to electricity.

Table 2. Spearman rank correlation coefficients for key output MSW to liquid fuel metrics (columns) with regards to model parameters (rows) in the year 2050.

Parameter	MSW to EtOH via biochemical cumulative GHG emissions in 2050	MSW to EtOH via gasification cumulative GHG emissions in 2050	MSW to EtOH via biochemical cumulative economic cost in 2050	MSW to EtOH via thermochemical cumulative economic cost in 2050
Corn price	0.0	0.0	-0.45	-0.45
MSW to EtOH biochemical conversion efficiency	-0.34	0.0	-0.36	0.0
MSW to EtOH thermochemical conversion efficiency	0.0	-0.27	0.0	-0.36
MSW to EtOH operational cost	0.0	0.0	0.32	0.32

MSW to ethanol net cumulative GHG emissions in 2050 were highly sensitive to their conversion efficiencies represented by coefficients of -0.34 and -0.27 for biochemical and thermochemical conversion methods respectively. Costs were sensitive to the cost of the energy source being displaced (corn price) with a coefficient value of -0.45. This metric is also sensitive to the efficiency of the waste to energy process with a coefficient value of -0.36 for both conversion methods. Costs were also sensitive to energy operational costs with a coefficient value of 0.32. Sensitivities of these metrics to changes in levelized capital costs of waste to ethanol plants were also characterized (data not shown). Cumulative economic cost of waste to ethanol was also sensitive to changes in the levelized capital cost of the waste to ethanol plant.

Table 3. Spearman rank correlation coefficients for key output MSW to electricity metrics (columns) with regards to model parameters (rows) in the year 2050.

Parameter	MSW to electricity via DC cumulative GHG emissions in 2050	MSW to electricity via IGCC cumulative GHG emissions in 2050	MSW to electricity via DC cumulative economic cost in 2050	MSW to electricity via IGCC cumulative economic cost in 2050
Natural gas price	0.0	0.0	-0.60	-0.24
MSW to electricity DC conversion efficiency	-0.32	0.0	-0.3	0.0
MSW to electricity IGCC conversion efficiency	0.0	-0.34	0.0	-0.18
MSW to electricity DC operational cost	0.0	0.0	0.36	0.0
MSW to electricity IGCC operational cost	0.0	0.0	0.0	0.48

Similarly to the waste to liquid fuel scenario, net cumulative GHG emissions in 2050 due to the conversion of waste to electricity were highly sensitive to their conversion efficiencies with correlation coefficient values of -0.32 and -0.34 for DC and IGCC conversion respectively. Net cumulative costs of waste to electricity via DC and IGCC on the electricity sector were sensitive to the price of the BAU electricity source being displaced, with coefficient values of -0.6 and -0.24 respectively, the efficiency of energy conversion, with coefficient values of -0.3 and -0.18 respectively, and the conversion operational costs with coefficient values of 0.36 and 0.48 respectively. Sensitivity was also measured for the parameter of levelized capital cost of waste to electricity plants. Cumulative economic cost of DC of MSW to electricity was more sensitive to changes in levelized capital cost compared to electricity conversion via IGCC (data not shown). This difference is likely due to the relatively high operational cost of the IGCC method compared to the DC method. Levelized capital cost sensitivity was also analyzed (data not shown). Similarly to analysis by the EIA, levelized capital cost was found to be most sensitive to variation in conversion facility discount rate and capital cost, and was not sensitive to variation in the MSW to energy facility financial life or in the considered plant capacity factor (US Energy Information Agency 2012).

3.2.4 Parametric Analysis

3.2.4.1 Electricity

Under baseline model conditions, the displacement of natural gas generated electricity with electricity derived from paper and organics MSW via direct combustion or via gasification result in reductions in electricity sector GHGs and in cost reductions compared to the baseline case of landfilling by 2050 (Figure 6, Figure 7). Within the electricity sector itself however, the cumulative capital and operational costs associated with displacing natural gas electricity with MSW-derived electricity are significant. Electricity derived from renewables is typically more costly than BAU electricity sources; however a parametric analysis may be applied to explore future cost conditions to determine under what circumstances, if any, MSW to electricity is cost competitive in the state of California within the electricity sector. According to the sensitivity analysis, the net electricity sector costs of MSW to electricity are sensitive to the capital and operational costs of MSW to electricity conversion and to the cost of the BAU electricity source being displaced (Table 3). These parameters may be varied in order to determine under what circumstances MSW to electricity becomes cost competitive for California. Figure 7 represents the 2050 net electricity sector monetary cost of converting paper and organic MSW to electricity via DC as a function of variation in the capital costs plus the operational costs (total cost) of conversion and of the price of natural gas. A net electricity sector cost is represented by positive values, while a net electricity sector savings (more favorable) is represented by negative values (Figure 7).

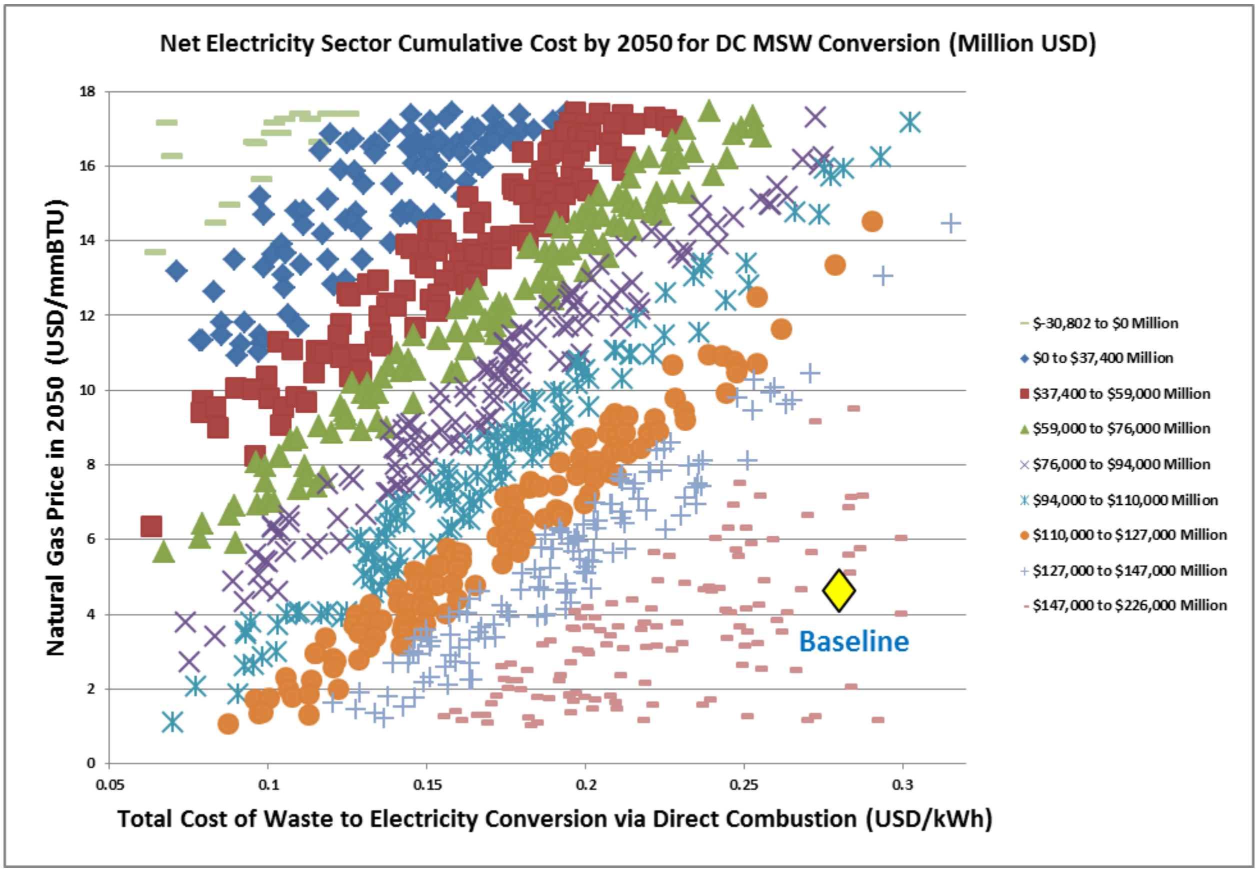

Figure 7. The cumulative electricity sector cost in 2050 as a function of variation in the total cost of converting paper and organic MSW to electricity by DC and of the cost of natural gas. The baseline case is indicated with yellow diamond.

Baseline model conditions are represented by a yellow diamond, indicating a natural gas price of $4.11 per mmBTU and a total MSW to electricity cost of $0.26 per kWh (Figure 7). Under these baseline conditions, by 2050, converting organics and paper MSW to electricity via DC will cost the state's electricity sector an additional cumulative $200,000 million USD more than using BAU electricity sources. This increase accounts for the cost of transporting MSW, the capital and operational costs of converting MSW to electricity, and any savings associated with natural gas displacement. As expected from the sensitivity analysis, the parametric analysis indicates that the cost of MSW conversion and the price of the displaced electricity source are both key drivers of this economic impact (Figure 7). A cost savings may be achieved under conditions of sustained high natural gas prices together with reduced MSW conversion costs. For MSW-derived electricity via direct combustion to reach an economic breakeven point respective to BAU electricity generation, natural gas prices would need to be sustained at a price of approximately $15 per mmBTU between 2010 and 2050. In addition, the total cost of DC MSW conversion would need to decrease from $0.26 per kWh to approximately $0.10 per kWh or lower (Figure 7). Both of these conditions must be met in order for MSW DC to electricity to reach an economic breakeven point within the state's electricity sector. Historically, natural gas price has never risen above $10 per mmBTU in the US, and the price has only risen above $8 per mmBTU between 2004 and 2008 in the past several decades, indicating that the sustained natural gas prices necessary to reach this economic breakeven point are unlikely (US Energy Information Agency 2012). The future price of natural gas is uncertain, and may not be effectively controlled without significant policy intervention. However, the conversion cost of MSW to electricity is dependent on several factors that may be influenced either by technology advances or by policy. In accordance with the sensitivity analysis findings, the parametric approach may be applied to understand uncertainty in the total cost of MSW to electricity conversion via DC as a function of the conversion efficiency and of the operational cost (Figure 8).

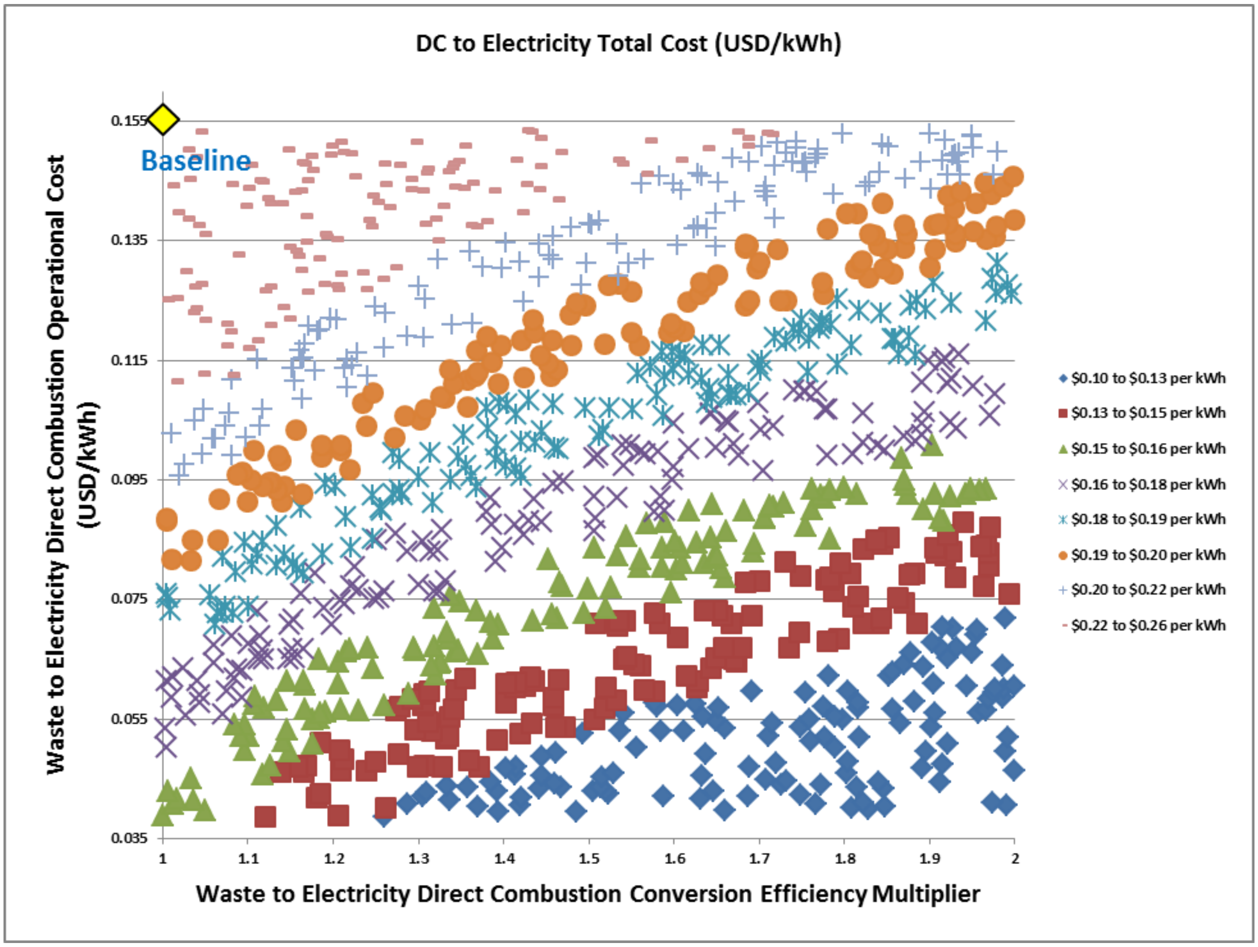

Figure 8. Plot of the total cost of organic and paper MSW to electricity via direct combustion conversion in USD/kWh as a function of variation in the operational cost and the conversion efficiency.

Technology advancements in the DC conversion of cellulosic biomass sources are represented by the conversion efficiency multiplier parameter on the x-axis, while reductions in operational costs per kWh (y-axis) could result from either an up-scaling of the process or other system efficiencies, or due to savings resulting from government subsidies or rebates (Figure 8). Both the operational cost of conversion and the conversion efficiency influence the total conversion cost, however the operational cost is the stronger driver for this metric (Figure 8). In order to reduce the total cost of DC conversion from $0.27 to $0.10 per kWh, the operational cost would need to decrease from $0.15 per kWh to approximately $0.07 per kWh and the conversion efficiency would need to increase by at least 50%, from 19% process efficiency to at least 30% efficiency if all organic and paper MSW is to be converted (Figure 8). Historically, simple cycle steam turbine electricity generation technology has the ability to reach these efficiencies with other electricity source fuels such as coal; however it is unclear how efficiency modifications to biomass DC conversion would affect the overall cost of the process, or if they would currently be possible for biomass conversion.

Since the DC conversion method is not currently eligible under the California RPS, utilities and municipalities interested in converting MSW to electricity may wish to explore other conversion technologies. In anticipation of this need, the parametric analysis was applied to the IGCC conversion of paper and organic MSW to electricity (Figure 9). Figure 9 represents the net electricity sector costs of converting paper and organic wastes to electricity via IGCC as a function of the total cost of conversion and the price of natural gas.

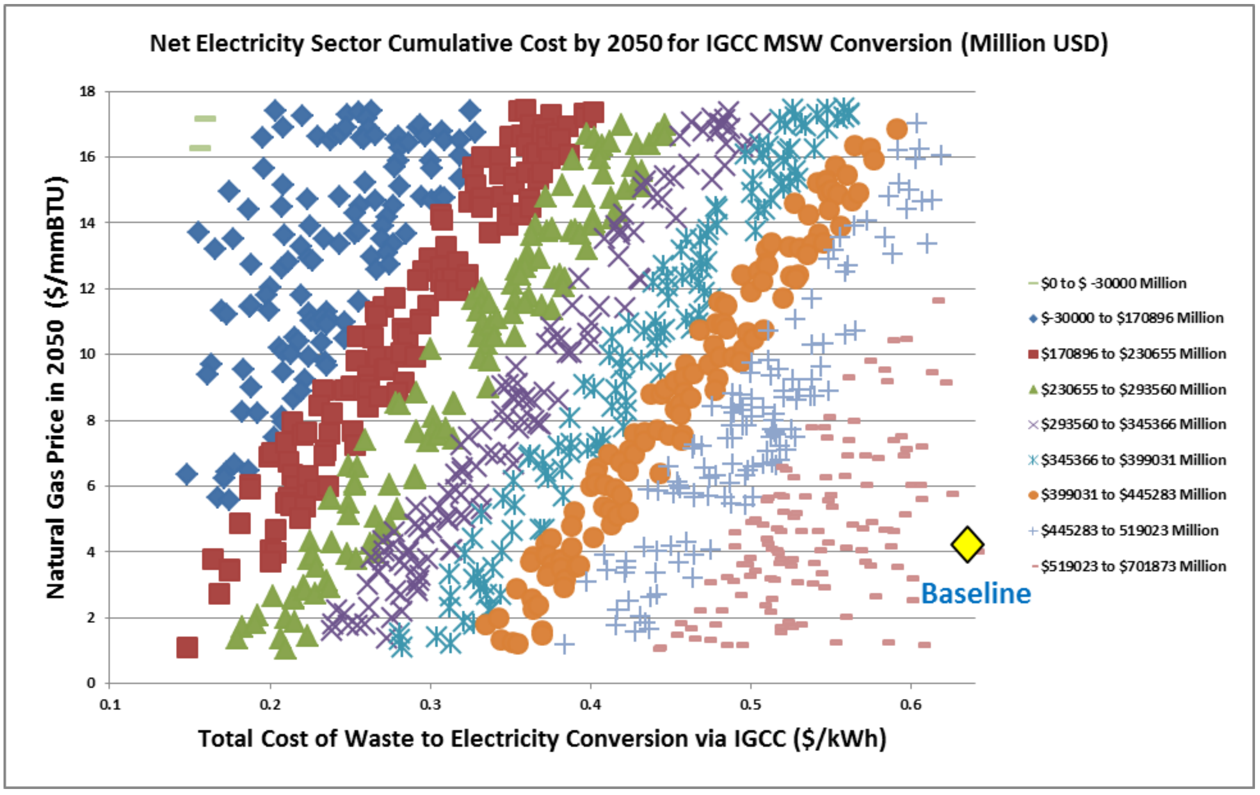

Figure 9. The cumulative electricity sector economic impact in 2050 resulting from varying the total cost of converting waste paper and organic biomass to electricity by IGCC conversion and varying the future cost of natural gas. The baseline case is indicated with a yellow diamond.

Baseline conditions are represented by a yellow diamond, indicating a natural gas price of $4.11 per mmBTU and a total MSW to electricity conversion cost of $0.63 per kWh (Figure 9). Similar to DC conversion, the IGCC parametric analysis indicates that the cost of MSW conversion and the price of the electricity source being displaced are key drivers of the electricity sector economic impact (Figure 9). However, due to the higher cost of IGCC conversion per kWh, the total conversion cost is a more significant driver for overall electricity sector economic impact compared to that observed in the DC method case. Under baseline conditions, by 2050, converting all organics and paper MSW to electricity via IGCC conversion will cost California's electricity sector approximately $700,000 million more than it would have utilizing only BAU electricity sources. Similar to DC conversion, the parametric analysis indicates that the IGCC to electricity process reaches an economic breakeven point under conditions of sustained high natural gas prices together with significantly reduced conversion costs. For this process to be cost competitive with BAU electricity generation in the state, sustained natural gas prices of at least $16 per mmBTU are required between 2010 and 2050. In addition, the total cost of IGCC conversion would need to decrease from $0.63 per kWh to $0.15 per kWh or lower (Figure 9). As noted above, a sustained increase in natural gas price is unlikely in light of historical data. Figure 10 describes the total IGCC conversion cost as a function of the MSW to electricity operational cost and of the conversion efficiency.

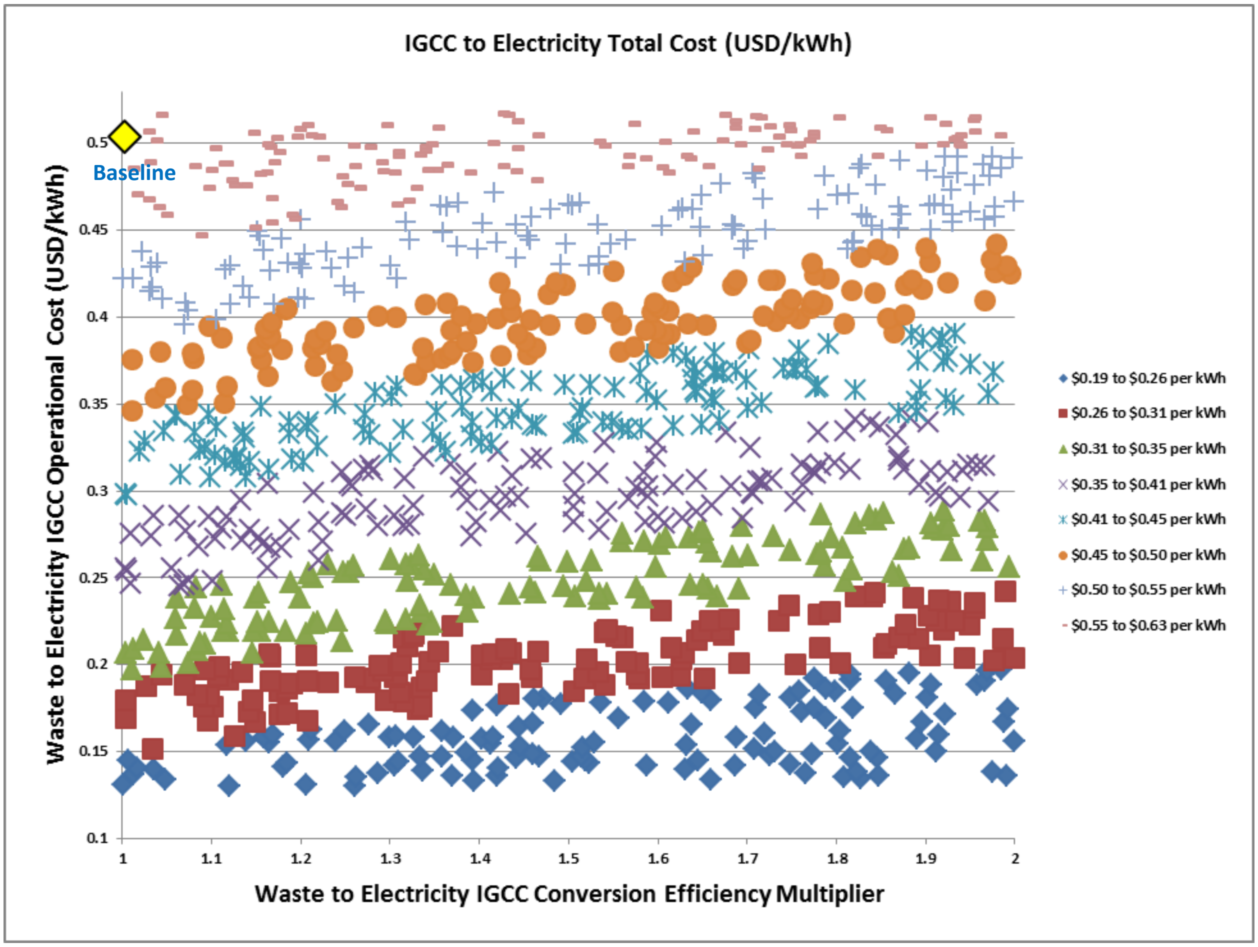

Figure 10. Plot of the total cost of organic and paper MSW to electricity via IGCC conversion in USD/kWh as a function of the operational cost and the conversion efficiency.

The total cost of IGCC conversion of MSW to electricity is more strongly driven by the operational cost compared to the efficiency of the process (Figure 10). This relationship is similar to that of DC conversion to electricity, however in the IGCC case, the efficiency is a much less significant driving force in the overall process cost. This observation is likely the result of the greater cost of the IGCC conversion process compared to that of DC. In order to reach a total IGCC conversion cost of $0.15 per kWh, the operational cost could need to decrease by more than 75%, which is greater than the range of values explored here (Figure 10).

3.2.4.2 Liquid fuel

Current ethanol liquid fuel demand in the California transportation sector may be displaced by ethanol derived from paper and organic MSW via biochemical or via thermochemical conversion methods. Both conversion processes result in reductions in transportation sector GHGs by 2050 (Figure 5). Under baseline model conditions, biochemical and thermochemical of paper and organic MSW results in a net economic cost in the transportation sector (Figure 6). A parametric representation of the cost of the conversion of paper and organic MSW to ethanol via biochemical as a function of corn price and of total conversion cost is shown in Figure 11. Baseline conditions are described by a corn price of $4 per bushel and a total conversion cost of $1.47 per gallon ethanol and are indicated by a yellow diamond (Figure 11).

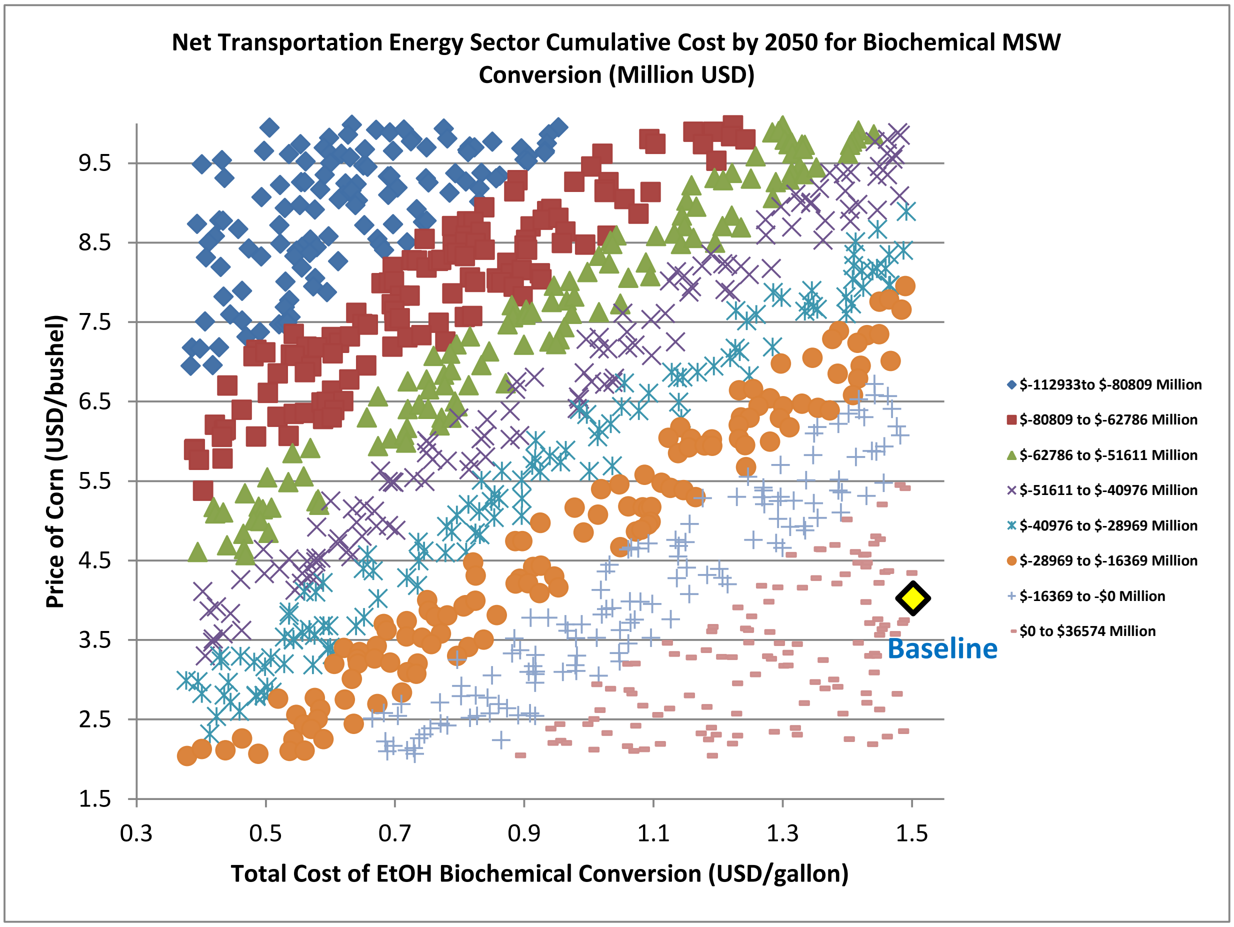

Figure 11. The cumulative transportation sector economic impact in 2050 resulting from varying the total cost of converting waste paper and organic biomass to EtOH via biochemical and varying the future price of corn.

At baseline corn price, biochemical conversion of MSW to ethanol is not economical for the transportation sector at the baseline total conversion cost (Figure 11). Both the total cost of energy conversion and the price of BAU source being displaced are driving forces in determining this economic breakeven point in the transportation sector in California (Figure 11). At this corn price, the total biochemical conversion cost would need to decrease from $1.47 per gallon to approximately $1.20 per gallon to reach an economic breakeven point in 2050 within the transportation sector (Figure 11). If the conversion cost remains constant at $1.47 per gallon, BAU corn price would need to increase from $4 per bushel to approximately $5.50 per bushel over time to create a MSW biochemical economic breakeven point (Figure 11). Historically, corn has risen above this benchmark price to $6.89 in 2013; however this price was unusually high from a historical perspective (US Department of Agriculture 2013). Under baseline conditions, by 2050, converting all organics and paper MSW to ethanol via biochemical will cost California's transportation sector approximately $18,000 million more than it would have utilizing only corn-based ethanol. A similar analysis was performed for MSW conversion to ethanol via thermochemical conversion (Figure 12).

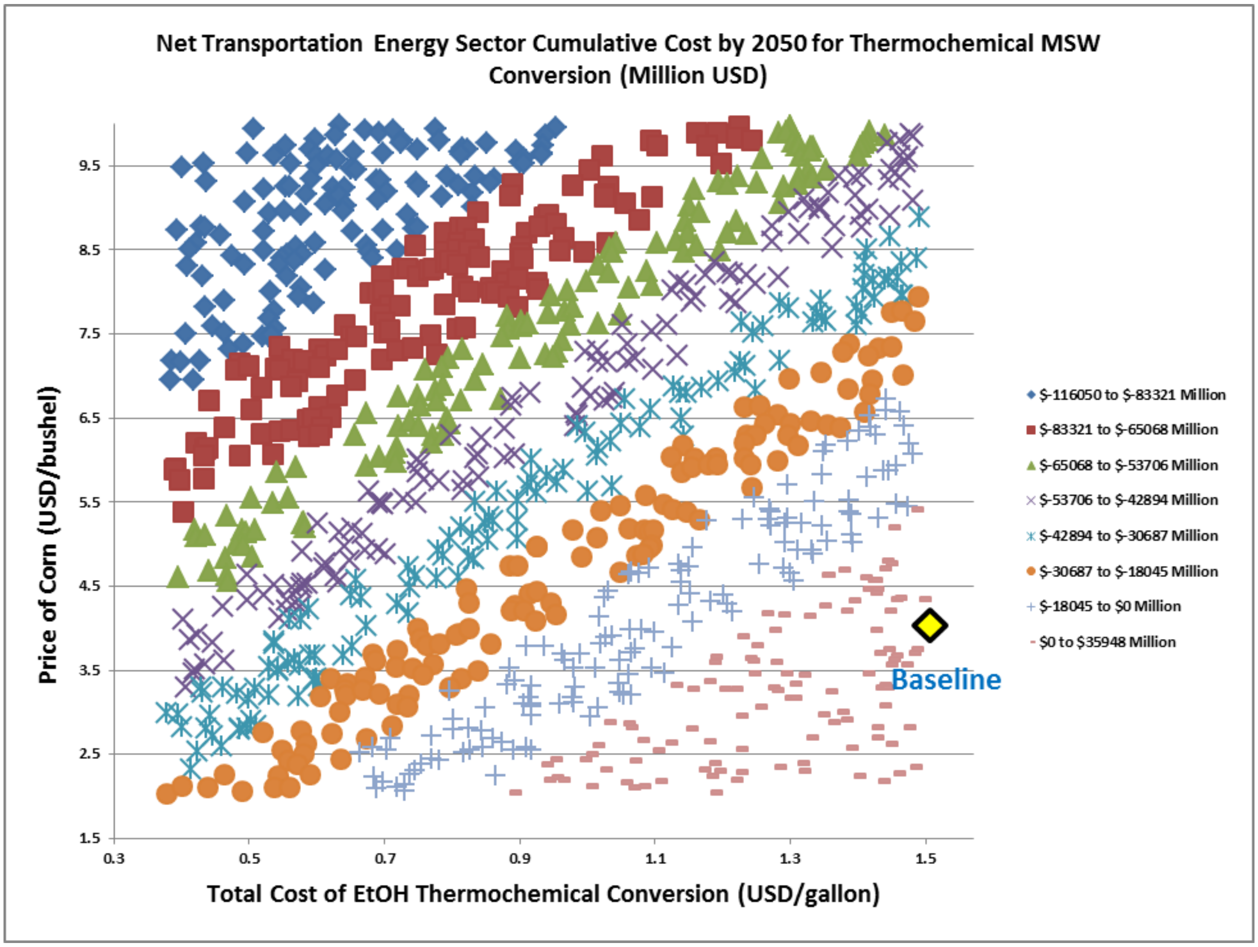

Figure 12. The cumulative transportation sector economic impact in 2050 resulting from varying the total cost of converting waste paper and organic biomass to EtOH via thermochemical conversion and varying the price of corn.

Since the biochemical and thermochemical processes were considered to be of similar cost, similar conclusions regarding the economic breakeven point as for biochemical conversion are made for thermochemical conversion. Similarly to the conversion of waste to electricity, the total conversion cost of MSW to ethanol could be influenced by a variety of means, including those that are technology-based and policy-based. Figure 13 describes the total MSW to ethanol conversion cost as a function of the MSW to operational cost and of the conversion efficiency.

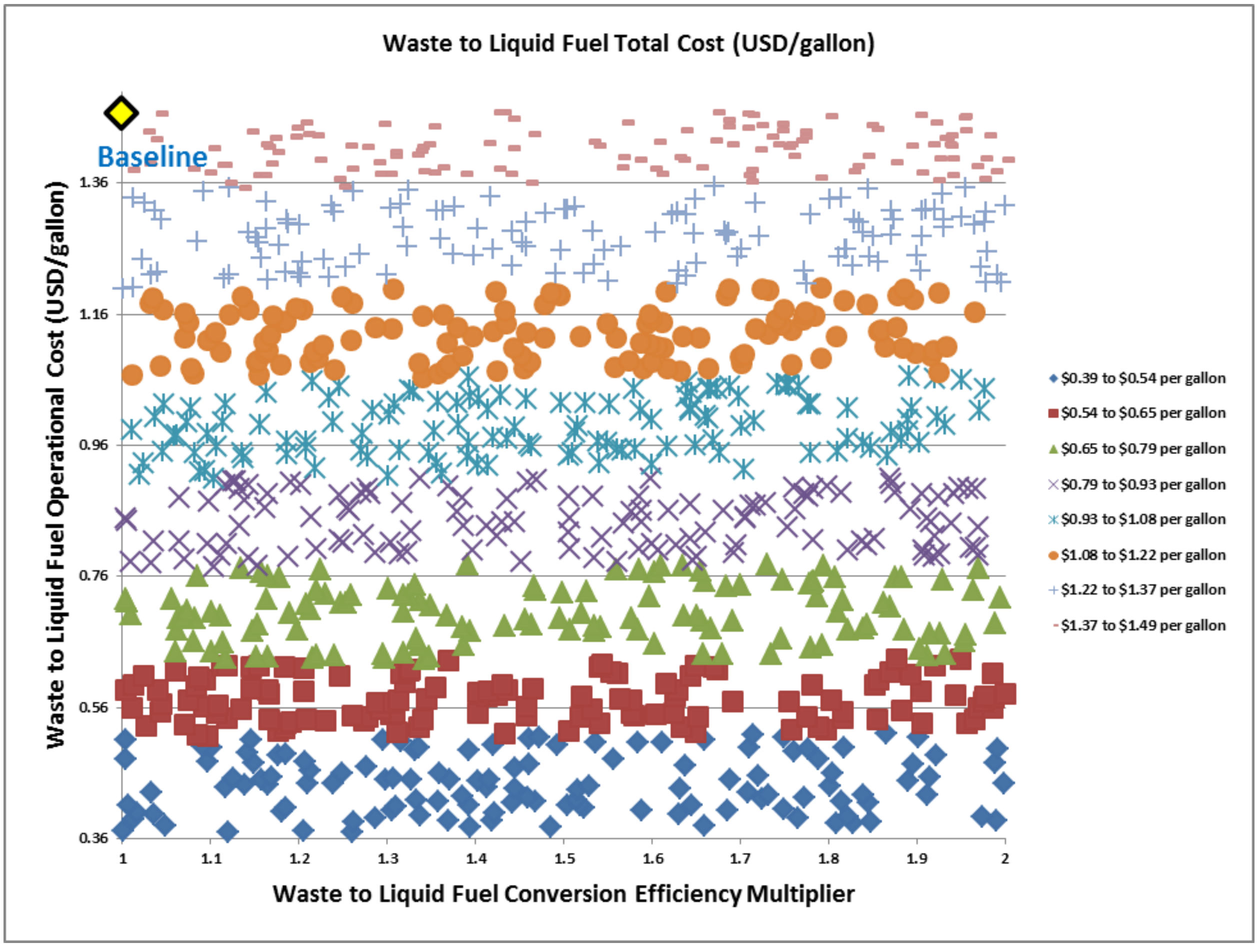

Figure 13. The total cost of organic and paper MSW to liquid fuel (USD/gallon) as a function of the operational cost of MSW to liquid fuel and of the efficiency of the conversion process.

In order to reach an economic breakeven point total conversion cost of $1.20 per gallon, the operational cost could need to decrease from $1.47 to approximately $1.15 per gallon regardless of any technology advancements that affect conversion efficiency (Figure 13).

3. CONCLUSIONS

A significant amount of cellulosic-based MSW is currently transported to landfill in California. The model baseline and parametric analyses indicate that compared to the alternative pathways of converting that waste to electricity or to liquid fuel, landfilling this MSW is the most disadvantageous use of these wastes from an environmental perspective. In addition, some alternative uses of this MSW may even represent an economic advantage for the state under certain conditions.

Although the conversion of MSW paper and organic sources to electricity in California result in a net reduction in electricity sector GHGs, as evident by historical market conditions, it is unlikely that either DC or IGCC of these MSW sources would be economical for the state compared to the baseline scenario, assuming that no new significant renewable electricity capacity is brought online in the meantime. The incorporation of renewable energy sources into the grid is rarely economical. The EIA provides cost estimates for new online electrical capacity that includes capital costs (US Energy Information Agency 2012). The EIA reports that new renewable electricity costs are estimated at $0.087 for conventional wind, $0.22 per kWh for offshore wind, $0.14 per kWh for photovoltaic, $0.26 per kWh for solar thermal, and $0.09 per kWh for new hydroelectricity. Under baseline WBEM conditions considered here, a DC of paper and organics MSW total cost of $0.26 per kWh is already cost competitive with solar thermal and is almost cost competitive with offshore wind. Increases in MSW to electricity thermal efficiency subsidizing MSW to electricity operational costs could make DC more cost competitive with other renewable electricity sources such as photovoltaic generation. Despite these potential advantages, the DC of MSW in California is not currently eligible under the CaRPS, and therefore it is unlikely that utility companies would invest in waste to energy capabilities using this technology. Instead, the IGCC conversion is eligible under the CaRPS and is therefore more likely to be utilized if waste to electricity is implemented in California. However, due to its high cost, the IGCC waste to electricity conversion would require extreme market and subsidy conditions in order to be economical. The decrease in total IGCC cost from $0.63 per kWh to $0.15 per kWh in the IGCC case may require significant government subsidy to become economical over the baseline scenario; however as noted above, renewable electricity sources are not typically economical compared to conventional fossil-based electricity generation. IGCC conversion may be attractive due to its higher process efficiency compared to DC, enabling more progress towards the state's RPS goal in general, and therefore the state could consider MSW among its renewable options as it continues to make progress towards its renewable electricity and landfill reduction goals.

Under baseline conditions, the creation of ethanol from paper and organic MSW results in a state-wide GHG savings with either biochemical or thermochemical conversion. Within the transportation sector, an economic cost is associated with these processes compared to BAU ethanol consumption. As a result, in order to create a cost savings for liquid fuel conversion, investment is required in either the conversion technology, or in the form of a rebate or subsidy to discount the operational costs.

From a cost benefit perspective, it is difficult to compare and contrast energy use in the transportation sector, i.e. miles on the road, to electricity, i.e. hours of lights on for example, without common metrics such as GHG reductions or economic savings. At the same time, these metric values are variable for each energy pathway analyzed. It may be possible to combine these two metrics to calculate a cost-benefit metric for each pathway. For example, a pathway's cumulative GHG emissions savings may be combined with cumulative net cost to calculate a GHG emissions savings per dollar spent. Under baseline conditions, waste to landfill results in a positive accumulation of GHG emissions, resulting in a GHG cost of 0.022 MMT GHG emitted per million dollar spent in the landfill sector, and 0.022 MMT GHGs are added to the environment per million USD spent sending waste to landfill. In contrast, MSW to electricity processes have significant net costs, however they result in a reduction of GHGs from the electricity sector compared to the predicted emissions occurring if the current electricity mix is simply scaled up over time to meet demand. Under baseline model conditions, waste to electricity via DC removes 0.0016 MMT of GHGs from the electricity sector per million USD spent by 2050. Waste to electricity via IGCC removes 0.0009 MMT per million USD spent under baseline model conditions. This reduction is not as significant as the DC pathway due to the high cost of the IGCC process. If paper and organic wastes are converted to ethanol, at the baseline price of $4 per bushel the biochemical pathway yields the reduction of 0.0075 MMT GHGs per million dollars spent while the thermochemical pathway yields the reduction of 0.0084 MMT of GHGs per million dollars spent. Using this metric, the thermochemical conversion of paper and organic MSW to ethanol represents the waste to energy pathway with the greatest displacement of GHGs per dollar invested compared to all other MSW pathways considered. Following this pathway, waste to liquid fuel via biochemical yields the second greatest GHG reduction per dollar spent, followed by waste to electricity via DC. The least effective considered waste to energy pathway in terms of GHGs displaced per dollar invested is MSW to electricity via IGCC.

As mentioned previously, MSW may alleviate one of the current concerns regarding biomass to energy investments in general relates to the reliability of the biomass feedstock. Although the optimization of MSW to energy facilities was outside of the analysis scope, it is worth estimating how much MSW in California is available compared to the estimated capacities of new biomass to energy facilities. According to the EIA, new cellulosic biomass to liquid fuel facilities are assumed to accept approximately 1700 tons of biomass per day with a generation capacity of approximately 3700 barrels of ethanol per day (US Energy Information Administration 2012). In California, the WBEM predicts approximately 38,556 metric tons of organic and paper biomass to be produced per day in the state, distributed across 100 landfills. Therefore, if a MSW to ethanol facility were built at each existing landfill site, it would receive approximately a fourth of the biomass needed for full capacity ethanol production. Based on these data, the state may wish to build approximately 25 MSW to ethanol facilities to ensure continual operation at full capacity. Further analysis could identify the optimal locations for these facilities based on MSW source locations.

DC biomass to electricity facilities are assumed to accept approximately 2,000 tons of biomass per day, depending on moisture content, with a generation capacity of 50 MW net electricity (US Energy Information Administration 2010). IGCC biomass to electricity facilities are assumed to accept approximately 370 to 500 tons of biomass per day, depending on moisture content, with a generation capacity of 20 MW net electricity (US Energy Information Administration 2010). The DC conversion biomass demand is similar to that of ethanol production from biomass, so a waste to energy facility location strategy would be similar. In the case of IGCC conversion to electricity, estimated biomass demand is well aligned with the existing distribution of MSW to landfill, and therefore MSW to energy facilities could potentially be built at landfill sites as modeled by the WBEM.

Additional factors may drive decisions towards one energy pathway or another. For example, California imports the majority of its natural gas (US Energy Information Agency 2012). The reduction in natural gas importing resulting from waste conversion to electricity would be relatively small, only eliminating the need for approximately 4% of the state's current demand, however with the large historical variation in natural gas price over the past several decades, the state may be interested in developing an electricity demand buffer with waste to electricity, while at the same time significantly reducing the amount of waste sent to landfill. Although California was used as a case study for this analysis, the impacts of MSW to energy may vary with the existing energy source profile in a given geographical area, and the cost versus the carbon impact may change depending on the energy source being displaced. In this study, we have chosen to displace natural gas as an electricity source. However, natural gas has a relatively low carbon-intensity. If a more carbon-intensive electricity source were to be displaced by MSW, the observed GHG savings in the electricity sector would be greater. Similarly, the ethanol produced from converting paper and organic MSW to liquid fuel could be used to displace more carbon-intensive transportation sector energy sources such as petroleum. In California, the volume of ethanol produced from converting all paper and organic wastes to liquid fuel could displace conventional gasohol to meet the fuel demands of 3 to 4 million E85 flex fuel vehicles, assuming an annual volumetric blend of E67 in these vehicles rather than meeting E10 ethanol demand (US Department of Energy 2012). The importing of ethanol may be an additional factor to consider. Currently, California's ethanol nameplate production capacity is approximately 250 million gallons per year, producing only 16% of the state's current ethanol demand (Nebraska 2013). A large-scale MSW to ethanol activity involving the state's organic and paper wastes could significantly increase the state's nameplate capacity and meet 90% of the current in-state transportation E10 ethanol demand.

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