Comparative Life-Cycle Assessment of Anaerobic Digestion of Municipal Solid Waste at Zero Waste Energy Development Company in San Jose, California

Sarah L. Nordahl

ABSTRACT

The Zero Waste Energy Development Company (ZWEDC) in San Jose, California performs anaerobic digestion as part of a city-wide sustainable waste management strategy. This study uses life-cycle assessments to quantify the greenhouse gas (GHG) emissions reduction benefit derived from incorporating anaerobic digestion into waste management as compared to traditional waste management methods. Two scenarios were considered: current waste management with anaerobic digestion and a base-case scenario representing waste management using landfilling and composting exclusively. The life-cycle assessment determined that anaerobic digestion reduced GHG emissions by about three times relative to the base-case scenario. Net GHG emission rates in the anaerobic digestion scenario were negative because of two processes offsetting emissions: carbon storage in compost and electricity generation from biogas, a by-product of anaerobic digestion. The base-case scenario yielded positive net GHG emission rates largely due to high emissions from landfilling. Avoided landfill emissions and further offsets from anaerobic digestion at ZWEDC has substantially reduced the carbon footprint of San Jose's waste management industry. The results demonstrated the significant environmental benefits provided by anaerobic digestion and suggest that expanding this practice could further reduce industry GHG emissions and climate change impact.

KEYWORDS

waste management, energy recovery, landfills, compost, life-cycle greenhouse gas emissions

INTRODUCTION

Anaerobic digestion (AD) is a biological process that involves converting organic municipal solid waste (MSW) into useful products, primarily energy and compost. It is the series of biochemical reactions including hydrolysis, acetogenesis, and methanogenesis that, from organic MSW, produces biogas consisting mostly of methane and carbon dioxide (Thelemis and Ulloa 2007). This occurs in landfills where the resulting biogas is either collected for energy conversion or burned in a flare. Under controlled conditions, biogas from AD, can be efficiently captured and converted into energy. This renewable energy source is relatively clean compared to fossil fuels (Khalid et al. 2011). The other product created by the AD process is biomaterial which is composted and then can be used in agriculture as a soil conditioner or fertilizer (Khalid et al. 2011). Various recent studies examining the AD process have proven that this option is a better form of waste management than simply landfilling waste with respect to climate change impact (Coventry et al. 2016, Milutinović et al. 2017). Implemented effectively, AD can serve as an efficient and beneficial method of waste management as well as energy production.

California offers an appropriate environment to implement commercially-viable AD and experiment with methods to overcome the various barriers that deter commercialization. Currently, only 15% of California's organic waste is diverted from landfills for energy production (Kirchstetter and Scown 2015). Cost and economic aspects of AD serve as a significant barrier to further expansion and successful commercial implementation. Study of local laws and economics, particularly concerning energy prices and electricity tariffs, can allow for effective market integration of this process to overcome this barrier (Braber 1995). California has various clean energy policies promoting sustainability goals that align with energy production from MSW. AD can help California meet its Renewable Portfolio Standard, the most recent of which outlined the state's vision that retail and publicly owned utilities obtain 50% of their electricity from renewable sources by 2030 (De León 2015). AD could diversify the state's energy mix and assist municipal governments in obtaining their own sustainability goals. There is clear potential for AD expansion in California, but additional concerns need to be addressed, including regulatory challenges, technical challenges, air pollution concerns, high capital costs, long retention times, and a variety of uncertainties related to power reliability (Park et al. 2005, Kichstetter and Scown 2015).

The San Jose-based Zero Waste Energy Development Company (ZWEDC) is attempting to resolve these issues and achieve profitable, effective AD commercialization. ZWEDC is the largest facility of its kind in the world. The city of San Jose itself has a population of a little over one million residents and the greater Santa Clara county has a total population of close to two million residents (California Department of Finance 2017). ZWEDC processes about 100,000 tons of organic MSW from this population area per year. ZWEDC has plans to expand its current capacity to 180,000 tons per year, in order to help the City of San José achieve its goal of diverting 100% of landfill waste. However, until the operations can be modeled effectively, the total environmental and economic benefits of the facility working at both its current and future commercial-level capacity are uncertain.

In this study, I performed a life-cycle assessment with respect to GHG emissions to identify strengths and weaknesses of ZWEDC operations in order to both quantify the climate change mitigation benefit provided by ZWEDC. Incorporating data collected from the larger research team studying ZWEDC into an R-based model, I determined the net reduction in life-cycle GHG emissions for the areas serviced by ZWEDC due to the facility's operations. I compare the GHG footprint produced by LCAs of two different scenarios: a base-case scenario in which all MSW is landfilled or directly composted, what would otherwise be occurring without ZWEDC, and an AD scenario, in which ZWEDC operates at current capacity. Further analyses of the conducted LCAs demonstrates which aspects of both waste management scenarios contribute most to GHG emissions. This research reveals the benefits of incorporating AD into waste management and potential focus areas for optimizing future expansion and scale-up of ZWEDC operations.

Anaerobic digestion systems

There are two primary types of solid waste AD systems: wet and dry. Wet digesters have a total solids value of no more than 16% while dry digesters consist of 22-40% total solids (Ward 2008). Wet digesters involve cycling the waste through complex machinery using pumps, while dry digesters keep the waste materials stationary in an air-tight chamber to which micro-organisms are added via sprinklers (Di Mario et al. 2017, Zero Waste Energy Development Company 2017). Several studies have shown that wet AD yields slightly more biogas, but perhaps at the cost of general production efficiency (Li et al. 2011, Di Maria et al. 2012). In another more recent study, dry and wet AD demonstrated similar biogas outputs (Chiumenti et al. 2017). There is a current shift towards dry AD and away from wet AD due to its greater efficiency and lower costs (De Baere 2000).

ZWEDC facility

The ZWEDC facility currently uses a dry digestion system that has the capacity to process 100,000 tons of solid waste and generate 1.8 MW per year (Zero Waste Energy Development Company 2017). This system began operating in 2013 and demonstrated initial success, yielding more biogas than originally expected. By using a dry, rather than wet digester, ZWEDC reduces pre-processing and operation costs and minimizes maintenance time.

All communities that are serviced by ZWEDC are included within the scope of this study. While a majority of the MSW accepted at ZWEDC originates in the City of San Jose, the facility also accepts MSW from the City of Palo Alto and a few other sources in Santa Clara County. Most of San Jose's MSW food waste as well as Palo Alto's residential green waste is sent to ZWEDC. Various companies and organizations within Santa Clara County, including grocery stores and private retailers, also send organic solid waste to ZWEDC.

ZWEDC maintains relationships with two other waste facilities: Newby Island Landfill and ZBEST. The locations of these facilities can be viewed in Figure 1. Newby Island Landfill is located in the city of Milpitas, about 15 km from the center of San Jose. It sorts incoming waste from a larger service area and sends organic waste to ZWEDC. Similarly, ZWEDC sorts incoming hauls and sends all non-organic materials to Newby Island Landfill. ZBEST is a large compost facility located in the city of Gilroy. ZWEDC sends yard waste that is not compatible with the digester and post-AD biomaterials to ZBEST.

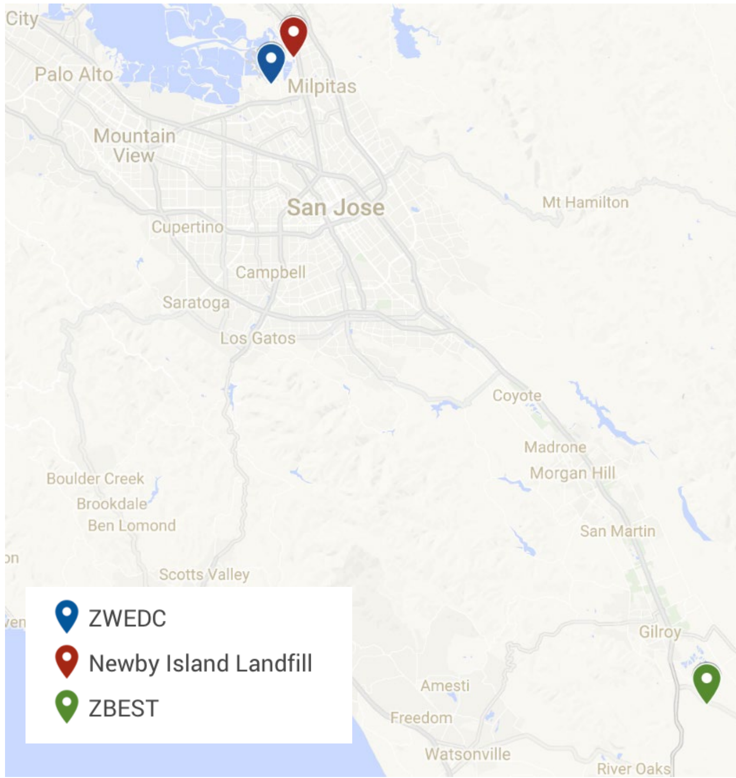


Figure 1. Partial map of Santa Clara County. This map shows the locations of the abovementioned facilities to demonstrate relative distances between San Jose and the facilities, as well as distances between facilities.

ZWEDC experiences problems with odor, offsite power sales, political barriers, and lack of buyers for its co-products, which include heat, gas, fertilizer, and compost (Zero Waste Energy Development Company 2017). Finding solutions to these issues is essential for successful further expansion of ZWEDC operations.

Methodology

Life-cycle assessment (LCA) is an internationally standardized method that is frequently used in environmental management to quantify the upstream and downstream environmental impacts from a particular product or process (Arena et al. 2003). Every stage in the life-cycle of the product or service is incorporated into the assessment to determine comprehensive environmental impact. Upstream effects refer to impacts from pre-consumption life-cycle stages including extraction, refining, and manufacturing; downstream effects refer to impacts from post-consumption stages such as disposal (Sound Resource Management Group 2009). By analyzing and aggregating the inputs and outputs of each stage over the life-cycle, an LCA quantifies the material and energy use in addition to the environmental effects associated with a particular product or activity (Arena et al. 2013). Application of this method varies case-by-case depending on a variety of factors specific to each study. The application of LCAs to waste management focuses primarily on downstream effects as environmental impacts from the production and distribution of municipal waste are exogenous to waste management systems. Analysis of these upstream effects do not offer an improved understanding of the environmental impact of waste management practices because they are associated with the products that become waste post-consumption (Vergara et al.2011). LCA is the most widely used method to evaluate environmental benefits and costs of waste management procedures and is therefore, an appropriate tool to examine ZWEDC's operation (Vergara et al. 2011).

Application of LCA in similar studies

LCA has been used in various similar studies to assess and compare waste management practices. LCA was used in a 2008 study in Phuket, Thailand to compare incineration to landfilling; the study concluded that incineration was the more efficient and environmental practice (Liamsanguan and Gheewala 2008). A 2016 LCA of waste management practices in Austin, Texas compared four scenarios: standard landfilling, landfilling and gas-to-energy conversion, advanced thermal recycling, and gasification (Coventry et al. 2016). The study compared these scenarios with respect to multiple metrics including acidification, eutrophication, global warming, human health, ozone depletion and photochemical smog. The disaggregated results of the LCA indicated which aspects of waste management are most harmful. The study concluded that gasification was least harmful with respect to all metrics. It also discovered that transport processes had less effect on LCA outcomes than beneficial uses of waste or recycling (Coventry et al. 2016). The study discussed in this paper similarly aims to reveal which aspects of waste management in San Jose will have the largest relative effect on the LCA through sensitivity analyses. Another study, performed in 2017 in Niš, Serbia, also considered four scenarios: landfilling without energy recovery, landfilling with recovery, incineration with recovery, and recovery via anaerobic digestion (Milutinović et al. 2017). It found LCA useful for comparing specific scenarios with respect to particular environmental metrics and identified recycling and anaerobic digestion as the most environmentally beneficial scenario (Milutinović et al. 2017). LCA is used equivalently in this study to compare two waste management scenarios to demonstrate the benefits of anaerobic digestion and quantify the reduction in GHG emissions due to ZWEDC operations in San Jose.

METHODS

LCAs were conducted of two different scenarios: the base-case scenario and the AD scenario. The base-case scenario describes traditional waste management: landfilling and some composting of organic MSW. The AD scenario describes waste management with integration of AD at ZWEDC operating at current capacity. The focus of the LCAs is on GHG emissions. To standardize results and make them comparable to findings from other studies reporting relative contributions to global warming, emissions were calculated in terms of kilograms of carbon dioxide equivalent (kg of CO2e). The life-cycle stages considered include: transportation, general operation of waste facilities, and energy production.

Sensitivity analyses were conducted on the LCA models for each scenario. These analyses revealed the relative impact each stage had on the net emissions total for each scenario. Such analysis makes it possible to directly compare life cycle stages both within and between scenarios.

Data collection

Data from May 26, 2016 to September 20, 2016 was used because over this period, reporting at ZWEDC was relatively complete and accurate. Emissions from transportation were calculated from data on distance traveled and weight of load carried. This information, among other details regarding the type of waste, is recorded at ZWEDC when accepting each incoming haul. It was assumed that all relevant waste is transported via diesel truck, the primary vehicle used for such transportation in San Jose. Emissions data from venting gas at ZWEDC are collected by the larger research team doing field work. Electricity offset credits were calculated based on average kg CO2e emitted by producing 1MWh of electricity from natural gas, the main energy supply in California (California Energy Commission 2017). Per-tonne of waste emissions and carbon storage at Newby Island Landfill were estimated considering direct methane emissions from landfill gas. Hypothetical landfill offset credits were also calculated to demonstrate electricity generation if thermal energy from the landfill flare was captured. Compost emissions and carbon storage were estimated from amount of waste composted. Further explanation of emissions calculations and emissions factors used can be found in Appendix A.

Scenario descriptions

AD scenario

The AD scenario describes waste management as it has been executed with a portion of organic MSW being sent to ZWEDC for anaerobic digestion (Figure 2). It was assumed that all waste sent from ZWEDC to Newby Island Landfill had no organic content and therefore would not create GHG emissions when decomposing in the landfill. Therefore, in this scenario, there are no emissions from the landfill. Emissions from landfilled waste that did not come from ZWEDC are outside the scope of this study. This study only considers the waste that was sent to ZWEDC.

The operation at ZWEDC was evaluated at its current capacity taking into account transportation of materials, operation of the digester, venting of extra gas, electricity production from biogas and distribution of outputs. Each aspect of the process was considered for its emissions or energy production. More in depth details of the process stages occurring at ZWEDC are described by Figure B1 in the appendix.

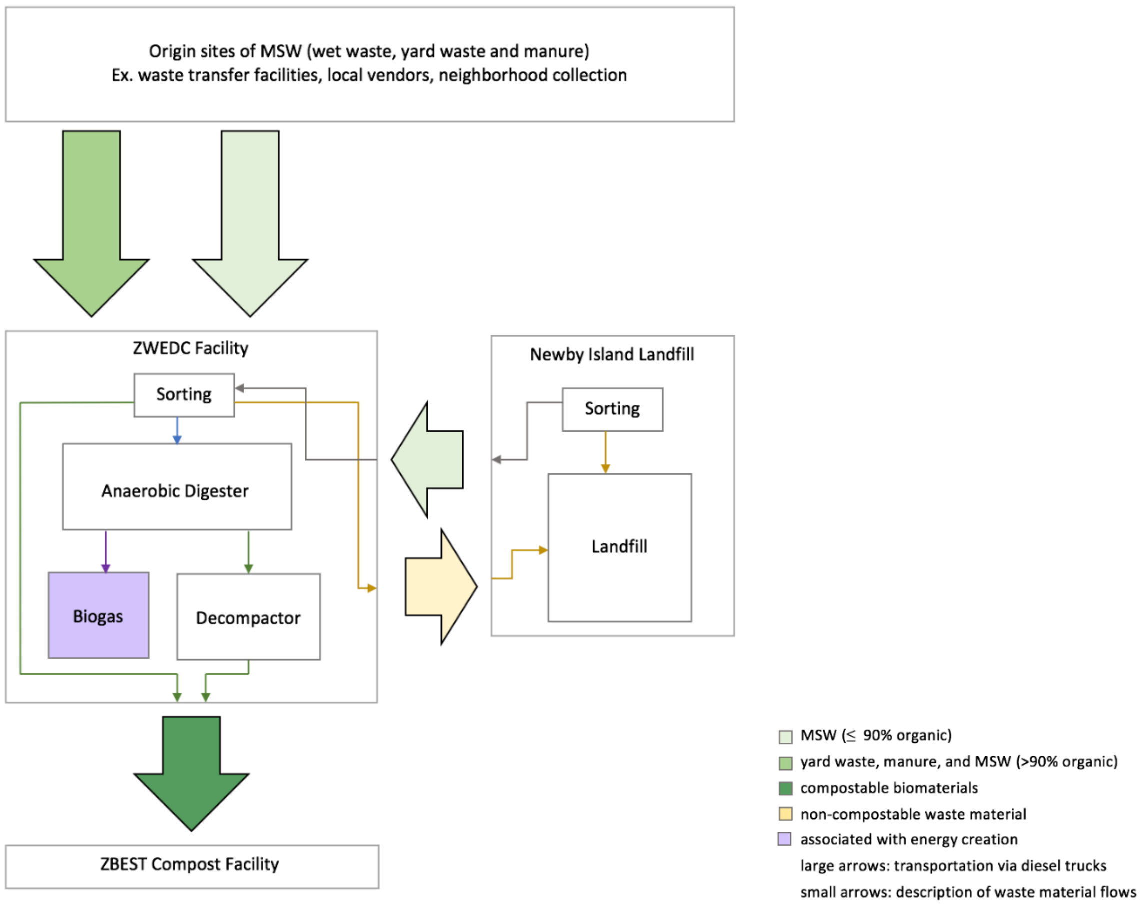


Figure 2. AD Scenario Flow Diagram. This diagram describes the processes analyzed in the AD scenario. Transportation (depicted by the large arrows), vented gas from the anaerobic digester, and the compost facility all contribute to emissions. Biogas collection at ZWEDC offsets these emissions by generating energy.

Base-case scenario

The base-case scenario describes waste management without anaerobic digestion at ZWEDC facility (Figure 3). The main form of MSW disposal in this scenario is landfilling and some composting. There are a few landfills that MSW from San Jose and Palo Alto is sent to: Newby Island Landfill, Monterey Peninsula Landfill and Guadalupe Disposal facility. For the purpose of this study, it was assumed that all MSW with an organics content of 90% or less received by ZWEDC would otherwise go to Newby Island Landfill, the closest disposal facility to the majority of the waste sources. All MSW with higher than 90% organics content, yard waste and manure was assumed to go straight to the compost facility, ZBEST. The LCA for the base-case scenario looks at GHG emissions from transportation of waste to their destination facilities and emissions from both the landfill and compost facility themselves. Newby Island Landfill collects landfill gas and flares it so carbon is emitted as carbon dioxide rather than methane which has a higher global warming potential. Newby Island Landfill does not perform gas-to-energy conversion, but total emissions were modelled both for the realistic base-case scenario, no energy conversion, and a modified, base-case scenario, as if Newby Island Landfill captured thermal energy from the flare and converted it to electricity.

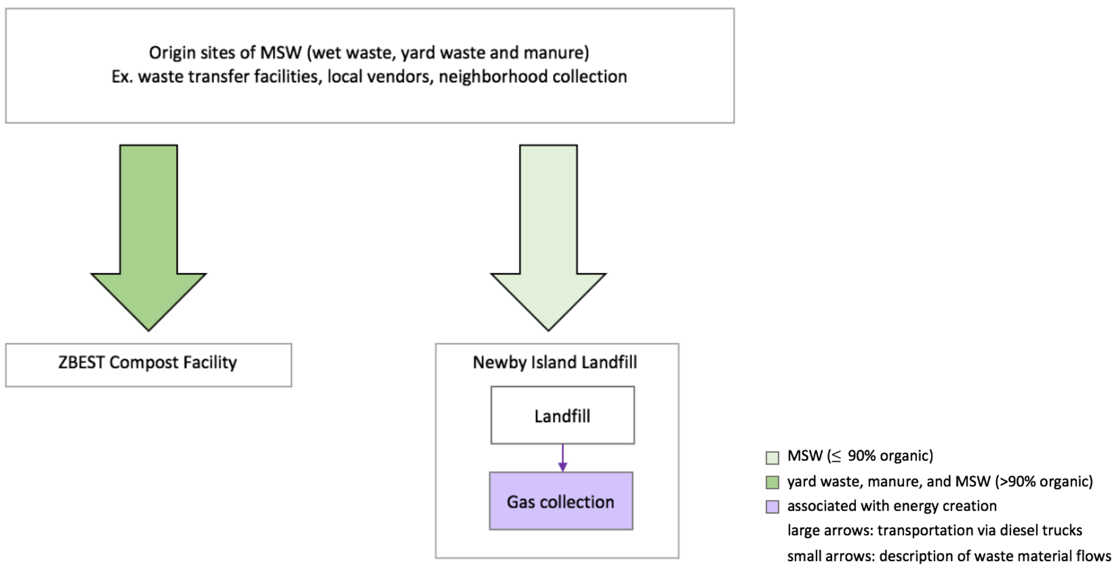


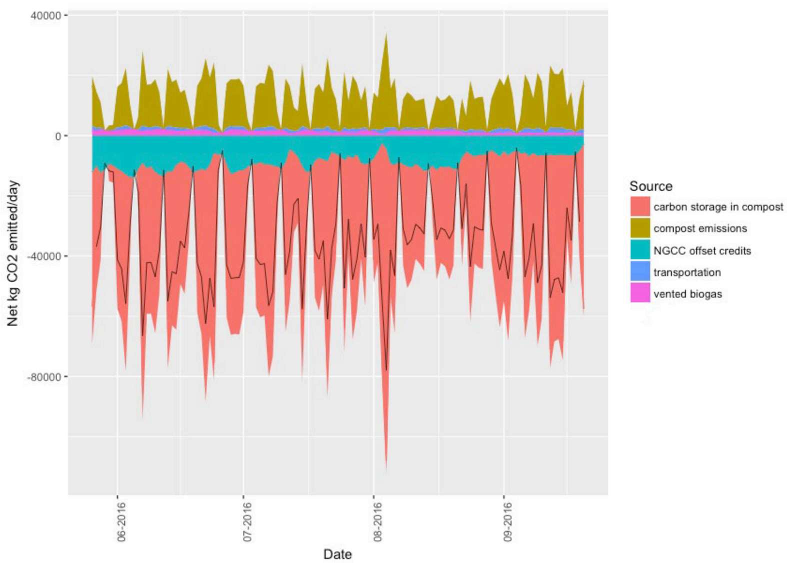
Figure 3. Base-case Flow Diagram. This diagram describes the processes analyzed in the base-case scenario LCA. Transportation (depicted by the large arrows), anaerobic decomposition of organic waste at the landfill, and the compost facility contribute to emissions. Landfill gas collection and conversion to electrical energy offsets these emissions by generating energy in the modified, hypothetical base-case scenario.

RESULTS

Net GHG Emissions from LCAs

I found that the average daily life-cycle GHG emissions for the AD scenario was -33983 kg CO2e and for the base-case scenario was estimated to be 15525 kg CO2e (Figure 4). I found that average daily net emissions, not considering offset credits, from the examined data was 13596 kg CO2e in the AD scenario and 18191 kg CO2e in the base-case scenario. Total offset credits for the AD Scenario was -47579 kg CO2e and for the base-case scenario was -14945 kg CO2e. The net emissions per-tonne of wet waste was -218 kg CO2e for the AD scenario and 100 kg CO2e for the base-case scenario.

(a)



(b)

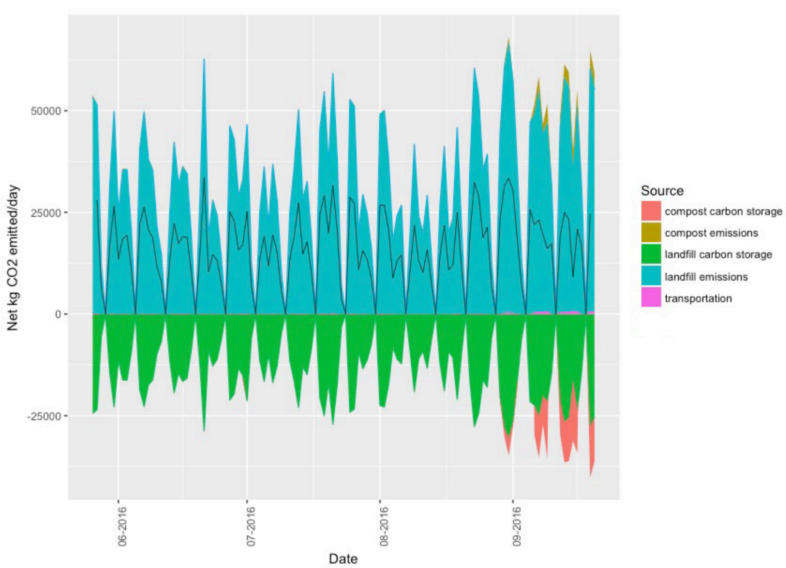


Figure 4. Daily GHG emissions. These graphs demonstrate the daily emissions broken down by life-cycle stage. The total area above the x-axis equals total emissions. The total area below the x-axis equals total offsets. The difference between these areas yields net GHG emissions. (a) This graph describes the AD scenario. “NGCC offset credits” refer to the emissions from a natural gas combined cycle power plant that were avoided because of electricity generation from biogas at ZWEDC. (b) This graph describes the base-case scenario.

Emissions by life-cycle stage

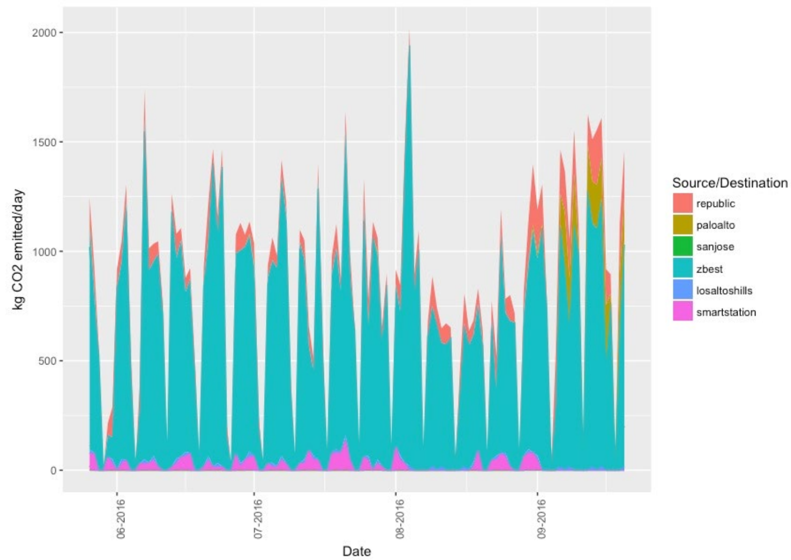
I further analyzed the model for each scenario to identify the life cycle stage that contributes most to net emissions. The daily average emissions by life cycle stage for both scenarios are listed in Table 1.

Table 1. Emissions by Life-Cycle Stage.

	Base-case scenario		AD scenario	
Life-Cycle Stage	**Average daily emissions (kg CO2e)**	**Relative contribution to net emissions**	**Average daily emissions (kg CO2e)**	**Relative contribution to net emissions**
Transportation	101	0.2%	832	1%
Landfill emissions (Newby)	29987	66%	0	0%
Carbon storage in landfill (Newby)	-13715	30%	0	0%
Venting biogas (ZWEDC)	-	-	1440	2%
Electricity generation from biogas (ZWEDC)	-	-	-8755	14%
Compost facility emissions (ZBEST)	384	0.8%	11324	19%
Carbon storage in compost (ZBEST)	- 1231	3%	-38824	64%
Net total	15525		-33983	

In the AD Scenario, the largest contributor to net emissions was carbon storage in compost (Table 1). The next most significant contributor was compost emissions. The average net daily effect of composting was -27500 kg CO2e. Considering the effects from composting combined, venting biogas was the highest emitting process and electricity generation from biogas was the second highest offsetting process. Transportation was the least significant contributor to emissions. Transportation to the compost facility, ZBEST, made up 84% of total transportation emissions (Figure 5).

(a)



(b)

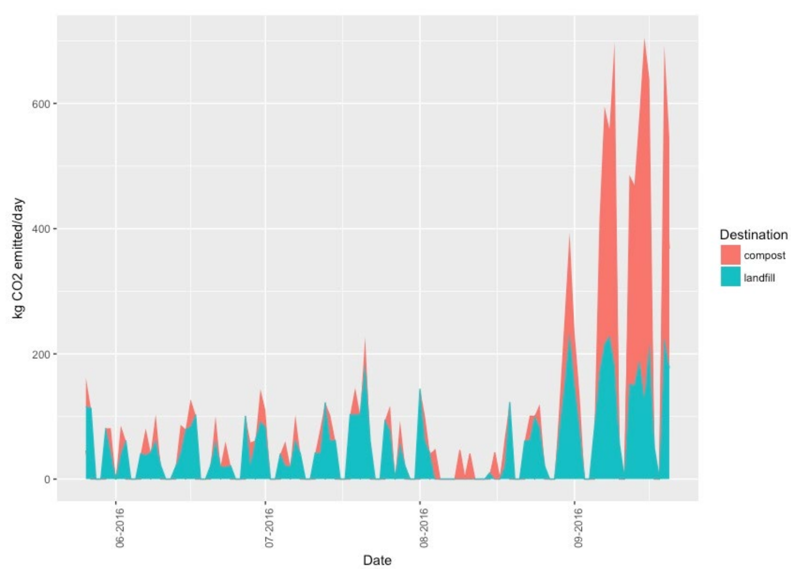


Figure 5. Daily GHG emissions from transportation. (a) This graph describes the AD scenario**.** The values plotted emissions from transporting waste over the distance between ZWEDC and the respective source/destination listed in the legend. (b) This graph describes the base-case scenario. The emissions shown come from transporting waste from its source to its destination, either ZBEST, the compost facility, or Newby Island Landfill, the landfill.

In the base-case scenario, the largest contributing stage to net emissions was landfill emissions. The next largest contributing stage was carbon storage in compost, followed by fugitive emissions from composting. Emission offsets from composting were 32 times lower in the base-case scenario than in the AD scenario. Transportation was the lowest emitting stage. Transportation to ZBEST made up 47% of total transportation emissions and transportation to

Newby Island Landfill made up 53% (Figure 5). Total transportation emissions in the base-case scenario were 5 times less significant with respect to net annual emissions compared to transportation emissions in the AD scenario.

In the AD scenario, avoided emissions due to electricity generation at ZWEDC were 8755 kg CO2e on average per day (Table 1). If Newby Island Landfill performed gas-to-energy conversion using collected landfill gas, it would have offset a daily average of around 4 kg CO2e. Electricity generation and subsequent emissions offsets in the base-case scenario would have been less than 1% of those achieved in the AD scenario. The change in average net emissions rate comparing the base-case scenario with and without gas-to-energy conversion is negligible.

DISCUSSION

My findings indicate significant environmental benefits from integrating AD into San Jose's waste management industry. There was a threefold reduction in average daily GHG emissions rate comparing the base-case and AD scenarios. Because of electricity production at ZWEDC and high carbon storage from increased composting, the AD scenario had a net negative emissions rate, -33983 kg CO2e per day (Table 1). The negative carbon footprint implies that in addition to offsetting direct life-cycle emissions in the AD scenario, other emissions outside the scope of this study were also offset. The base-case scenario, on the other hand, had a consistently positive net GHG emissions rate, 15525 kg CO2e per day. This difference in net GHG emissions rates is primarily attributable to the significance of offset credits achieved in the AD scenario and the significance of emissions from landfilling organic waste in the base-case scenario.

Offset credits in the scenarios were achieved through two processes: energy production from biogas at ZWEDC and carbon storage. Energy production from biogas yielded negative emissions in the model because the former created electricity which would have otherwise been produced through GHG emitting processes at a natural gas combined cycle power plant. Carbon storage, either at the landfill or in compost, also produced negative emissions because carbon that would otherwise be taking the form of a GHG in the atmosphere is sequestered in the ground. The AD scenario benefitted from offset credits from both of these processes while the base-case scenario only offset emissions through carbon storage. The net effect of landfilling was positive while the net effect of AD and composting were both negative. The AD scenario had net negative results because all organic waste was processed at ZWEDC and then composted. Alternatively, the base-case scenario had net positive results because most organic waste was landfilled and a minority of organic waste was composted. This explains why offsets derived from composting were much higher in the AD scenario than the base-case scenario. The rate of avoided emissions due to carbon storage in composting was 32 times higher in the AD scenario than in the base-case. The summed offsets in the AD scenario outweighed positive emissions, while high GHG emission rates from landfilling outweighed all offsets in the base-case scenario.

In the AD scenario, all of the landfill emissions are avoided while offsetting relatively high amounts of GHG emissions, thereby demonstrating AD's significant positive impact. Newby Island does not currently perform gas-to-energy conversion so the standard base-case scenario did not consider electricity generation at the landfill. However, a modified base-case scenario demonstrated that if Newby Island used a typical landfill gas turbine to generate electricity, the net impact of the landfill on GHG emissions rate would decrease by less than 1%. ZWEDC's AD biogas production capability would still be much more impactful in lowering net emissions, offsetting 8755 kg CO2e per day, than gas-to-energy conversion at the landfill, which would have offset only 4 kg C02e per day. This implies that expanding AD use in waste management has much higher potential for increasing climate change benefits than further developing or expanding landfill gas collection. This conclusion is also supported by results from the LCA conducted by Milutinović et al. in 2017. They found that global warming impact was about 9 times lower for a waste management strategy that involved AD and landfilling without energy recovery than a strategy that involved no AD and landfilling with energy recovery (Milutinović et al. 2017).

These results are further supported by other similar studies confirming the environmental value of AD (Chaterjee and Mazumder 2016, Escamilla-Alvadaro et. al 2017). A similar LCA which compared traditional landfilling to AD and biorefinery in Mexico found a reduction in global warming potential by a factor between 3 and 4 (Escamilla-Alvadaro et. al 2017). Similar to this study, my findings also concluded that net GHG emissions in the AD scenario were approximately three times lower than in the base-case scenario. Furthermore, the combined results of this study and Escamilla-Alvadaro's suggest a universal quality of AD and its potential for integration in a variety of places and on a variety of scales, as the context of Mexico and San Jose as study areas are fairly different.

The model further suggests that scaling up ZWEDC operations and commercializing AD could augment emissions reductions. However, scaling up ZWEDC operations will likely require more research and development to efficiently process a larger capacity of waste. A laboratory study of AD found that a digester working at its fullest capacity was most efficient in biogas generation when fed frequently and consistently (Challen Urbanic et al. 2011). This indicates that to maximize efficiency, any future expansion of the digester must be met with equivalent, consistent increases to feeding. More research is needed to understand how to best expand the capacity and improve ZWEDC's system for commercialization, but it seems that simply physically expanding the size of the current digester could increase GHG reduction benefits.

In addition to the complete LCA comparison, which shows that the ZWEDC system has the ability to improve carbon offsetting, the sensitivity analysis indicated which aspects of the overall process can be improved upon to lower emissions. Even marginal reductions to emissions can be valuable so it is important to consider each life-cycle stage: transporting materials, venting excess gas, generating electricity from biogas, landfilling organic materials and composting.

Transportation

Transportation is a well understood GHG emitting process. Relative to the other life-cycle stages, it is not a significant contributor to overall emissions, but improvement can still yield valuable benefits particularly in the real-life AD scenario. There are two primary methods by which transportation emissions can be reduced: improving fuel efficiency of the fleet of waste-transporting vehicles and minimizing distance traveled by these vehicles. By replacing or updating transportation vehicles to improve fuel economy, waste can be transported the same distance at a lower emission cost. This can be achieved by improving the energy efficiency of vehicle engines, retrofitting vehicles with control devices, and substituting diesel with alternative fuel sources (Caponi and Wong 2016). Not only could these strategies reduce GHG emissions, thereby lowering global warming impact, but they can also reduce local ambient air pollution (Caponi and Wong 2016). In addition to improving fleet fuel economy, transportation emissions can be reduced by minimizing distance waste must be transported. All biomaterials from ZWEDC are currently sent 72 km to ZBEST for composting; this movement contributes the most to overall transportation emissions. ZBEST is the closest compost facility with a large capacity which may explain why

ZWEDC sends materials to ZBEST rather than closer, smaller compost facilities. However, ZBEST is also owned by the same parent company as ZWEDC indicating a potential conflict of interest. Besides practicality, ZWEDC may have chosen to work with ZBEST rather than an assortment of smaller, more local facilities because of this business connection. The transportation emissions produced by moving waste to ZBEST could be significantly reduced by moving the facility to a closer location, opening a closer composting facility, or creating a composting facility at the same site as ZWEDC. Furthermore, improving sorting and labeling of waste can reduce transportation emissions by ensuring waste is transported to the correct destination from its origin and eliminating excessive transportation of waste between facilities, ZWEDC and Newby Island Landfill.

ZWEDC efficiency

To increase emissions reduction benefits of AD, two components of ZWEDC operation should also be addressed: biogas venting and biogas conversion to energy. The former is a negative contribution to net emissions reduction so developments that reduce the amount of biogas vented can increase environmental benefits. In contrast, biogas conversion is a positive contribution; therefore, further improving methods of biogas generation and conversion will also increase net emissions reduction. By increasing the environmental benefit derived from developing and optimizing ZWEDC operations, ZWEDC efficiency and process performance is increased. One potential method for improving process performance may involve more careful sorting, waste selection and co-digestion because different waste types have varied biogas yields (Burnley et al. 2012, Chaterjee and Mazumder 2016). Since capacity of the digester is physically limited, optimizing ZWEDC and maximizing biogas generation will likely include selecting the optimal waste inputs. One LCA study found that AD yielded net per-tonne of waste emissions to be -109 kg CO2e for paper waste, -183 kg CO2e for food waste, and -147 kg CO2e for yard waste (Burnley et al. 2012). At first glance, these values compared to my more general results of net per-tonne of organic MSW emissions of -218 kg CO2e imply that waste selection at ZWEDC may already be optimized. However, differences in LCA application or emissions factors used between Burnley's study and this study may explain the higher value I found. Additionally, differences in emissions from other life-cycle stages serve as confounding factors when comparing these two studies.

Burnley's study proves the variability in GHG emissions reductions according to waste type. Therefore, higher selectivity of high-yield organic waste materials could potentially have higher biogas yields and therefore be more effective at offsetting net emissions.

Landfill efficiency

Closer examination of the base-case scenario and the results of its sensitivity analysis offers greater understanding of landfill efficiency. The results demonstrated that Newby Island Landfill could reduce their GHG footprint only slightly by implementing gas-to-energy systems. Because Newby Island currently only flares collected landfill gas, without use of a gas turbine and generator, the facility is not benefiting from the albeit limited potential to harness energy. Even if the landfill was equipped with gas-to-energy technology, the offset credits from electricity generation would be less than 1% of net landfill emissions, 16272 kg CO2e per day taking into account emissions and carbon storage. This demonstrates potential for development and improvement in landfill gas collection and gas-to-energy programs.

Composting

The net effect of composting had the most significant impact on net emissions in the AD scenario. The value of composting was bolstered by AD which extracted additional benefits from organic waste before composting by generating electricity. Composting had a lesser impact on net emissions in the base-case scenario because fewer materials were composted. The significance of composting to net emissions suggests that composting more organic waste, even without AD, instead of landfilling can yield great GHG emissions reduction benefits to waste management strategies. This claim is substantiated by several studies. An LCA comparing disposal options for food waste from a global perspective (Kim and Kim 2010). This study determined that 1 tonne of food waste produced 123 kg CO2e when composted and 1010 kg CO2e when landfilled demonstrating GHG emissions reduction benefits from composting (Kim and Kim 2010). The study fails to address carbon storage in compost which explain the positive emissions value for composted waste. Similarly, an LCA conducted in Tehran, Iran concluded that composting reduced climate change impact by 60% when compared to landfilling (Abduli et al. 2011). With respect to GHG emissions and climate change impact, composting is a better alternative disposal process for organic waste than landfilling.

Limitations

As the model requires various simplifying assumptions, the exact results of each LCA do not precisely describe the actual global warming potential or net emissions rate from each scenario or life-cycle stage considered. However, for the purpose of this study, the values are an important comparison tool when juxtaposing AD and landfills. This limitation is standard with the LCA methodology, but results are still significant and have relevant implications.

Specifically, model accuracy was limited by assumptions made regarding landfilling and composting. Exact data on landfill procedures, emission rates and energy creation were difficult to acquire, so certain values were estimated within the model. Additionally, landfill emission factors are widely variable in existing literature (Lee et al. 2017, EPA 2018). The accuracy of the results could have been improved by taking direct measurements of landfill gas yields, methane content of landfill gas and landfill gas collection efficiency at Newby Island Landfill. There is also a range of reported compost emission factors in existing literature (Pipattti et al. 2006, EPA 2018). This study would have benefitted from direct measurements of emissions at ZBEST. Furthermore, GHG emissions and carbon storage both in compost and at landfills varies with waste type. Model accuracy could have been improved with more specific information on incoming waste to ZWEDC.

Various assumptions were also made for the base-case scenario, particularly concerning where waste would otherwise be transported if not to ZWEDC. In actuality, a portion of MSW would likely be sent to other landfills besides Newby Island Landfill, the closest landfill to ZWEDC. Therefore, transportation emissions were likely slightly underestimated. Additionally, other landfills may actually perform gas-to-energy conversion and would then provide actual offset credits in the base-case scenario. A base-case LCA analysis considering waste processing at other landfills besides Newby Island might provide different results that would likely still extend support in favor of AD as a means to lower GHG emissions.

Future Directions

Overall expansion of the scope of the model, could yield information about annual net emissions or per-tonne emissions from different waste management strategies on a statewide or even national scale. This would quantify aggregate emissions from integrated waste management strategies so that they are comparable to GHG emissions or climate change impact from other industries.

The LCA model and methods used in this study can be applied and modified for analysis of other sites in future research. For application of this model to other case studies, it is important to consider energy mix for electricity generation; this affects the value of electricity offset credits and their relative contribution to net emissions. For example, in areas where electricity is generated primarily via pulverized coal plants, offset credits would be higher than in this study since there is a larger emission rate associated with electricity generated from coal plants than natural gas plants (Jaramillo et al. 2007).

Broader Implications

The integration of AD into municipal waste management strategies on a commercial scale can yield significant environmental benefits and contribute to local climate change mitigation goals. Several comprehensive studies examining a variety of waste management strategies have consistently concluded that strategies which incorporate AD yield the most environmental benefits with respect to climate change as a metric (Lombardi et a. 2015, Sadhukhan and Martinez-Hernandez 2017). Furthermore, the results of this study demonstrate that AD's biogas generation at ZWEDC has the potential to be a relevant renewable energy source and that expanding the AD process could contribute to meeting California's energy goals. The environmental achievements of ZWEDC in San Jose, the third biggest city in California by population, implies opportunity for similar and even greater success in other parts of California as well. There are currently about 16 facilities performing anaerobic digestion in California of which ZWEDC is the largest (CalRecycle 2017). Increasing the number of such facilities and their processing capacity can provide significant support in reducing the carbon footprint of the waste management industry in California.

ACKNOWLEDGEMENTS

This project would not have been possible without the enthusiasm and commitment of Patina Mendez, Kurt Spreyer, Alison Ecker and Leslie McGinnis. Thanks to Patina Mendez's guidance and connections, I was able to find a project mentor after struggling to develop a feasible research plan on my own. Alison Ecker patiently advised me through many meetings and e-mails, providing me important feedback and encouraging me to push through stressful moments. Corinne Scown, my mentor, offered me a position in her research group at Lawrence Berkeley Laboratory. She helped me narrow my focus and execute ideas. Ekpa Akpan, my employer at the City of San Jose, provided me resources and funding, allowing me to study R and environmental modeling. Lastly, I am thankful for the support, feedback, and camaraderie I received from my peers: Ashley Sutton, Annemarie Peacock, Sophia Leiker, Bessie Liu, Steven Wong and Mark Hashimoto.

REFERENCES

Abduli, M., A. Naghib, M. Yonesi, and A. Akbari. 2011. Life cycle assessment (LCA) of solid waste management strategies in Tehran: landfill and composting plus landfill. Environmental Monitoring and Assessment 178:487–498.

Arena, U., M. L. Mastellone, and F. Perugini. 2003. The environmental performance of alternative solid waste management options: a life cycle assessment study. Chemical Engineering journal 96:207–222.

Braber, K. 1995. Anaerobic digestion of municipal solid waste: A modern waste disposal option on the verge of breakthrough. Biomass and Bioenergy 9:365–376.

Bove, R. and P. Lunghi. 2006. Electric power generation from landfill gas using traditional and innovative technologies. Energy Conversion and Management 47:1391-1401.

Burnley, S., R. Phillips, and T. Coleman. 2012. Carbon and life cycle implications of thermal recovery from the organic fractions of municipal waste. International Journal of Life Cycle Assessment 17:1015–1027.

California Department of Finance. 2017. E-5 Population and Housing Estimated for Cities, Counties and the State. (Accessed 29 March 2018). http://www.sanjoseca.gov/DocumentCenter/View/72712.

California Energy Commission. 2016. Total System Electric Generation. (Accessed 6 Dec 2017). http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html.

CalRecycle. 2017. California Anaerobic Digestion Projects. (Accessed 16 March 2018). http://www.calrecycle.ca.gov/organics/conversion/ADProjects.pdf.

Canty, A. and B. Ripley. 2017. boot: Bootstrap R (S-Plus) Functions. R package version 1.3-20.

Caponi, F., and M. Wong. 2016. Southern California landfill operator plays a big role in cleaning the air. MSW Management 26:40–45.

Challen Urbanic, J. m., B. VanOpstal, and W. Parker. 2011. Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste (OFMSW)-Full Scale vs. Laboratory Results. Journal of Solid Waste Technology & Management 37:33–39.

Chatterjee, B., and D. Mazumder. 2016. Anaerobic digestion for the stabilization of the organic fraction of municipal solid waste: A review. Environmental Reviews 24:426–459.

Chiumenti, A., F. da Borso, and S. Limina. 2017. Dry anaerobic digestion of cow manure and agricultural products in a full-scale plant: Efficiency and comparison with wet fermentation. Waste Management.

Coventry, Z., R. Tize, and A. Karunanithi. 2016. Comparative life cycle assessment of solid waste management strategies. Clean Technologies & Environmental Policy 18:1515–1524.

Davison, A. C. and D. V. Hinkley. 1997. Bootstrap Methods and Their Applications. Cambridge University Press, Cambridge. ISBN 0-521-57391-2.

De Baere, L. 2000. Anaerobic digestion of solid waste: state-of-the-art. Water Science and Technology 41:283–290.

De León, K. 2015. Clean Energy and Pollution Reduction Act of 2015.

Di Maria, F., M. Barratta, F. Bianconi, P. Placidi, and D. Passeri. 2017. Solid anaerobic digestion batch with liquid digestate recirculation and wet anaerobic digestion of organic waste: Comparison of system performances and identification of microbial guilds. Waste Management 59:172–180.

Di Maria, F., A. Sordi, and C. Micale. 2012. Energy production from mechanical biological treatment and Composting plants exploiting solid anaerobic digestion batch: An Italian case study. Energy Conversion and Management 56:112–120.

Dowle, M. and A. Srinivasan. 2017. data.table: Extension of `data.frame`. R package version 1.10.4-3. https://CRAN.R-project.org/package=data.table.

Dutky S. and M. Maechler. 2013. bitops: Bitwise Operations. R package version 1.0-6. https://CRAN.R-project.org/package=bitops.

EPA. 2018. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM). WARM v14.

Escamilla-Alvadaro, C., H. M. Poggi-Varaldo, and M. T. Ponce-Noyola. 2017. Bioenergy and bioproducts from municipal organic waste as alternative to landfilling: a comparative life cycle assessment with prospective application to Mexico. Environmental Science and Pollution Research 24:25602–25617.

Grothendieck, G. 2014. gsubfn: Utilities for strings and function arguments. R package version 0.6-6. https://CRAN.R-project.org/package=gsubfn.

Grothendieck, G., L. Kates, and T. Petzoldt. 2016. proto: Prototype Object-Based Programming. R package version 1.0.0. https://CRAN.R-project.org/package=proto.

Hiebert, J. 2016. udunits2: Udunits-2 Bindings for R. R package version 0.13. https://CRAN.R-project.org/package=udunits2.

Holm-Nielsen, J. B., T. Al Seadi, and P. Oleskowicz-Popiel. 2009. The future of anaerobic digestion and biogas utilization. Bioresource Technology 100:5478–5484.

Jaramillo, P., W. M. Griffin, and H. S. Matthews. 2007. Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation. Environmental Science & Technology 41:6290–6296.

Khalid, A., M. Arshad, M. Anjum, T. Mahmood, and L. Dawson. 2011. The anaerobic digestion of solid organic waste. Waste Management 31:1737–1744.

Kim, M. and J. Kim. 2010. Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Science of the Total Environment 408:3998-4006.

Kirchstetter, T. and C. Scown. 2015. ZWEDC facility grant proposal. Lawrence Berkeley National Laboratory.

Lang, D.T. 2014. RJSONIO: Serialize R objects to JSON, JavaScript Object Notation. R package version 1.3-0. https://CRAN.R-project.org/package=RJSONIO.

Lang, D.T. and the CRAN team. 2018. RCurl: General Network (HTTP/FTP/...) Client Interface for R. R package version 1.95-4.10. https://CRAN.R-project.org/package=RCurl.

Lee, U., J. Han, and M. Wang. 2017. Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. Journal of Cleaner Production 166:335-342.

Li, Y., S. Y. Park, and J. Zhu. 2011. Solid-state anaerobic digestion for methane production from organic waste. Renewable and Sustainable Energy Reviews 15:821–826.

Liamsanguan, C., and S. H. Gheewala. 2008. LCA: A decision support tool for environmental assessment of MSW management systems. Journal of Environmental Management 87:132–138.

Lombardi, L., E. Carnevale, and A. Corti. 2015. Comparison of different biological treatment scenarios for the organic fraction of municipal solid waste. International Journal of Environmental Science & Technology 12:1–14.

Mata-Alvarez, J., S. Macé, and P. Llabrés. 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Bioresource Technology 74:3–16.

Milutinović, B., G. Stefanović, P. S. Đekić, I. Mijailović, and M. Tomić. 2017. Environmental assessment of waste management scenarios with energy recovery using life cycle assessment and multi-criteria analysis. Energy 137:917–926.

Müller, K. 2017. bindrcpp: An 'Rcpp' Interface to Active Bindings. R package version 0.2. https://CRAN.R-project.org/package=bindrcpp.

Park, C., C. Lee, S. Kim, Y. Chen, and H. A. Chase. 2005. Upgrading of anaerobic digestion by incorporating two different hydrolysis processes. Journal of Bioscience and Bioengineering 100:164–167.

Pipatti, R., J. Alves, Q. Gao, C. Cabrera, K. Mareckova, H. Oonk, E. Scheehle, C. Sharma, A. Smith, P. Svardal, and M. Yamada. 2006. Biological Treatment of Solid Waste. IPCC Guidelines for National Greenhouse Gas Inventories 5:4.1-4.8.

Plate, T. and R. Heiberger. 2016. abind: Combine Multidimensional Arrays. R package version 1.4-5. https://CRAN.R-project.org/package=abind.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

R Core Team. 2017. RStudio version 1.0.153. R Foundation for Statistical Computing, Vienna, Austria.

Ryan, J.A. and J. M. Ulrich. 2017. xts: eXtensible Time Series. R package version 0.10-1. https://CRAN.R-project.org/package=xts.

Sadhukhan, J., and E. Martinez-Hernandez. 2017. Material flow and sustainability analyses of biorefining of municipal solid waste. Bioresource Technology 243:135–146.

Sarkar, D. 2008. Lattice: Multivariate Data Visualization with R. Springer, New York. ISBN 978-0-387-75968-5.

Soetaert, K., T. Petzoldt, and R. W. Setzer. 2010. Solving Differential Equations in R: Package deSolve. Journal of Statistical Software. 33(9):1-25. http://www.jstatsoft.org/v33/i09/.

Sound Resource Management Group. 2009. Environmental Life Cycle Assessment of Waste Management Strategies with a Zero Waste Objective: Study of the Solid Waste Management System in Metro Vancouver, British Columbia.

Themelis, N. J., and P. A. Ulloa. 2007. Methane generation in landfills. Renewable Energy 32:1243–1257.

Vergara, S. E., A. Damgaard, and A. Horvath. 2011. Boundaries matter: Greenhouse gas emission reductions from alternative waste treatment strategies for California's municipal solid waste. Resources, Conservation and Recycling 57:87–97.

Ward, A. J., P. J. Hobbs, P. J. Holliman, and D. L. Jones. 2008. Optimisation of the anaerobic digestion of agricultural resources. Bioresource Technology 99:7928–7940.

Warnes, G. R., B. Bolker, G. Gorjanc, G. Grothendieck, A. Korosec, T. Lumley, D. MacQueen, A. Magnusson, and J. Rogers. 2017. gdata: Various R Programming Tools for Data Manipulation. R package version 2.18.0. https://CRAN.R-project.org/package=gdata.

Wickham, H. 2009. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, NewYork.

Wickham, H. 2011. The Split-Apply-Combine Strategy for Data Analysis. Journal of Statistical Software, 40(1), 1-29. http://www.jstatsoft.org/v40/i01/.

Wickham, H. 2017. scales: Scale Functions for Visualization. R package version 0.5.0. https://CRAN.R-project.org/package=scales.

Wickham, H., R. Francois, L. Henry, and K. Müller. 2017. dplyr: A Grammar of Data Manipulation. R package version 0.7.4. https://CRAN.R-project.org/package=dplyr.

Zeileis, A. and G. Grothendieck. 2005. zoo: S3 Infrastructure for Regular and Irregular Time Series. Journal of Statistical Software. 14(6):1-27.

Zero Waste Energy Development Company. Technology. 2017. http://zwedc.com/technology.

APPENDIX A: Emissions Calculations and Assumptions

Transportation

For each haul of waste or materials, ZWEDC records weight, origin and destination. I used distance traveled and tonnage to determine total diesel usage and subsequent emissions. Emissions from vehicle idling at origins and destinations was also taken into account. I assumed idling time to be 30 minutes.

ZWEDC

A larger research team studying ZWEDC measured GHG emissions from venting biogas and electricity output in kWh. Generated electricity was converted into avoided emissions using a carbon intensity of 393 g CO_2e per kWh which is typical of a standard natural gas combined cycle power plant (Kirchstetter and Scown 2015).

Landfilling

Waste diverted to the landfill was assumed to be mixed MSW. I assumed 16% of original carbon in landfilled mixed MSW was emitted as methane and 19% was stored in the landfill (EPA 2018). Original carbon was calculated based on carbon content of waste as reported by ZWEDC. Landfill gas collection efficiency was assumed to be 66% based on the average efficiency for California regulated landfill processing mixed MSW (EPA 2018). CO_2 emissions from landfilled organic waste were not taken into account because carbon in waste is considered contemporary or biogenic. Biogenic carbon is not considered as an impact on climate change when emitted as CO_2 (EPA 2018).

Theoretical electricity generation in the base-case scenario was calculated assuming 28% electrical efficiency which is typical of gas turbine used at landfills (Bove and Lunghi 2006). Newby Island reported flare energy to be 500 BTU per standard cubic foot of landfill gas. Landfill gas was assumed to be 50% methane and 50% CO_2 (EPA 2018). The carbon intensity of 393 g CO2e per kWh was used again to determine potential avoided emissions in the base-case scenario.

Composting

To calculate composting impacts on net GHG emissions, it was assumed composting feedstock was similar to yard waste. Composting produces two GHGs: methane and dinitrogen monoxide (N2O) (EPA 2018). I assumed that per ton of feedstock composted, 0.0139 tonnes of CO2e from methane were emitted, 0.0609 tonnes of CO2e from N2O were emitted and 0.24 tonnes of CO2e were stored (EPA 2018).

APPENDIX B: Detailed ZWEDC Process Flows

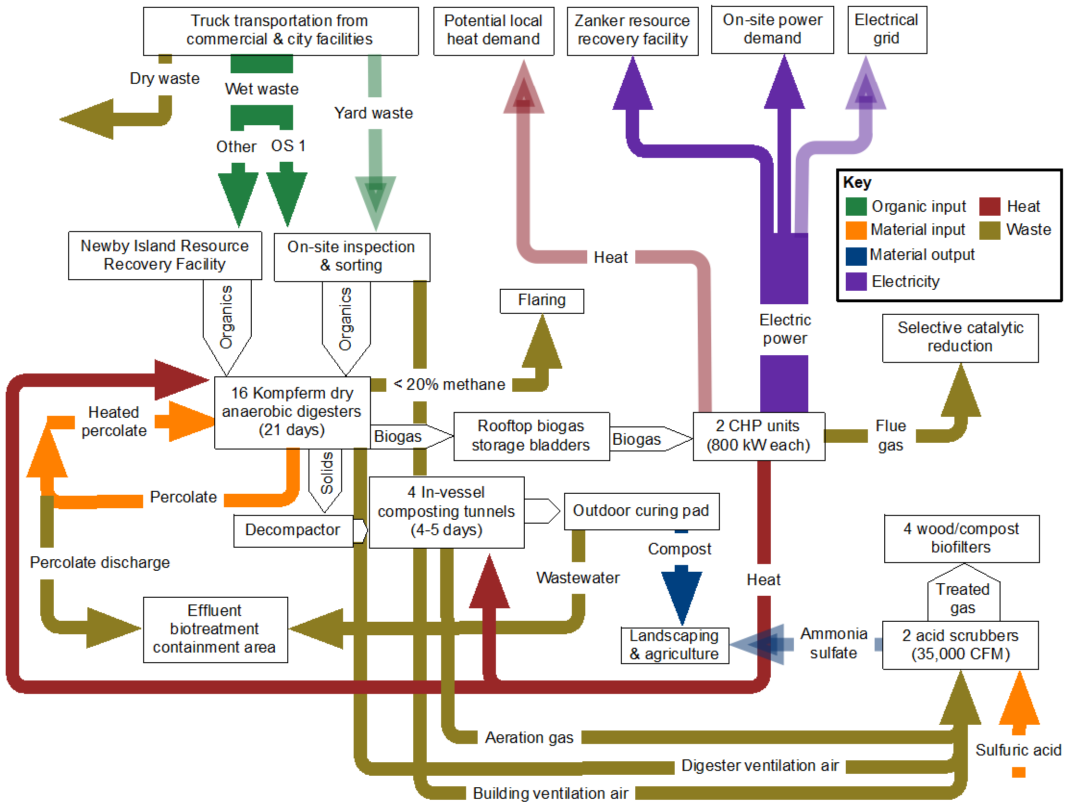


Figure B1. ZWEDC Process Flow Diagram (Current Capacity and Planned Flows). This figure offers a more in depth understanding of the material and energy flows occurring in the AD scenario. The specifics of the ZWEDC facility processes are outlined.