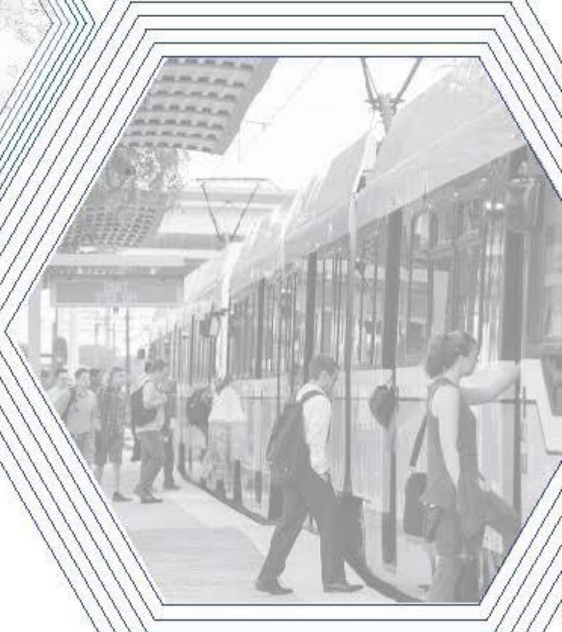
PRIORITIZING ORGANIC WASTE TO ENERGY – RENEWABLE (POWER) FRAMEWORK: REACHING THE NEXT TECHNOLOGY READINESS LEVELS
FINAL PROJECT REPORT

Melanie Sattler, Opeyemi Adelegan, Ardeshir Anjomani, Mehrdad Arabi, Arpita Bhatt, Mithila Chakraborty, Victoria Chen, Kate Hyun, Bahareh Nasirian, Doreen Ntiamoah-Asare, Asma Rony



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Center for Transportation Equity, Decisions & Dollars

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UNIVERSITY OF TEXAS AT ARLINGTON

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- North Central Texas Council of Governments (NCTCOG): Tamara Cook and Breanne Johnson
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- Waste Management of Texas, Inc.: Charles Rivette, P.E.
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16. Abstract

Developed in our previous CTEDD-funded project, the Prioritizing Organic Waste to Energy-Renewable (POWER) Framework (previously called the “Food & Flora Waste to Fleet Fuel (F^4) Framework”) helps cities/regions assess the economic feasibility of co-digesting organic wastes for energy recovery (including renewable natural gas or electricity for fleets) using existing anaerobic digester infrastructure. Leveraging our previous work, the project described herein aimed to advance the Technology Readiness Level (TRL) of the POWER Framework from TRL 5 “Integrated components demonstrated in a laboratory environment” to TRL 8 “Technology proven in operational environment,” by accomplishing the following objectives:

1) Forming and soliciting input from a multi-disciplinary Advisory Group of state/regional government officials and industry representatives in transportation, solid waste management, wastewater, and agriculture (farm digesters), to guide advancement of the POWER Framework from TRL 5 to 8.
2) Upgrading the POWER Framework to Version 2.0 via improvements arising from the previous project, Advisory Group recommendations, and case studies (Obj. 3).
3) Conducting case studies for two additional communities for conversion of organic wastes to renewable energy, including fleet fuel, and showcasing the use of the POWER Framework Version 2.0 to estimate costs, energy/fuel produced, and emission benefits.

The Advisory Group included officials from states/regions (North Central Texas, Southern Nevada/Las Vegas, and Vermont) with demonstrated commitment to food waste diversion, as well as the President of the Texas Natural Gas Vehicle Alliance, and an engineer with Waste Management, Inc.

POWER Tool upgrades included additional digester types (on-farm and industrial/stand alone, as well as water resource recovery facility); additional organic wastes (fats/oils/grease, manure, and crop residuals, as well as food, yard, and sludge); additional biogas end uses (grid electricity and pipeline renewable natural gas, or RNG; as well as vehicle fuel – electricity and RNG). GIS inputs were automated using the GIS Toolbox. The code for the Optimization Tool was revised to make it more flexible and to incorporate the changes in the POWER Framework (e.g. inclusion of farm digesters and stand-alone industrial digesters); a Graphical User Interface was also created for the Optimization Tool.

Upgrades to the POWER Framework were tested using case studies for Vermont and Las Vegas. For the Vermont case study, the Optimization Tool narrowed the list of 17 potential sites to 7 optimal sites. For the Las Vegas case study, from the 23 existing and potential sites, the optimization chose 1-10 preferred sites, depending on the scenario. The case study results for both Vermont and Las Vegas showed the following:

- More biogas was produced from digesting organics compared to landfilling; this is due to a higher fraction of gas being captured, and a higher methane content of the gas.
- Digesting organic waste would reduce greenhouse gas emissions compared to the regular power mix and use of landfill gas. Traditional air pollutants from digestion were slightly higher than the regular power mix, likely due to greater impurities in digester gas, except for PM 2.5. Traditional air pollutants from digester gas combustion are lower than those from landfill gas.
- “NET COSTS” for anaerobic digestion were negative, indicating that the benefits outweigh the costs. In estimating the “Total Benefits,” it was assumed that all potential credits are obtained. This may be overly optimistic for actual cases.
- Net benefits for digestion were estimated to be greater than for landfilling.

The Las Vegas case study showed that FOG waste has the highest overall benefit/cost savings per ton of waste digested, due to its higher energy density compared to other wastes.

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Chapter 1: Introduction

1.1 Project Goal and Objectives

In a previous project funded by CTEDD, UTA developed the Prioritizing Organic Waste to Energy-Renewable (POWER) Framework (Figs. 1.1 and 1.2) (previously called the "Food & Flora Waste to Fleet Fuel (F^4) Framework"), to help communities make the best use of existing infrastructure (water resource recovery facility digesters) to convert food/yard waste to biogas for renewable natural gas (RNG) fuel or electricity. Leveraging this previous work, the **overall goal** of the project described here was to facilitate conversion of organic wastes to renewable energy, by advancing the POWER Framework Technology Readiness Level (TRL) from TRL 5 "Integrated components demonstrated in a laboratory environment" to TRL 8 "Technology proven in operational environment." To ensure that the framework is broadly applicable, the previous framework was upgraded to include additional types of digesters, waste, and energy end uses, and 2 additional case studies were conducted. Specific **objectives** were to:

1) Form and solicit input from a multi-disciplinary Advisory Group of state/regional government officials and industry representatives in transportation, solid waste management, wastewater, and agriculture (farm digesters), to guide advancement of the POWER Framework from TRL 5 to 8.
2) Upgrade the POWER Framework to Version 2.0 via improvements arising from the previous project, Advisory Group recommendations, and case studies (Obj. 3).
3) Conduct case studies for two additional communities for conversion of organic wastes to renewable energy, including fleet fuel, and showcase the use of the POWER Framework Version 2.0 to estimate costs, energy/fuel produced, and emission benefits.

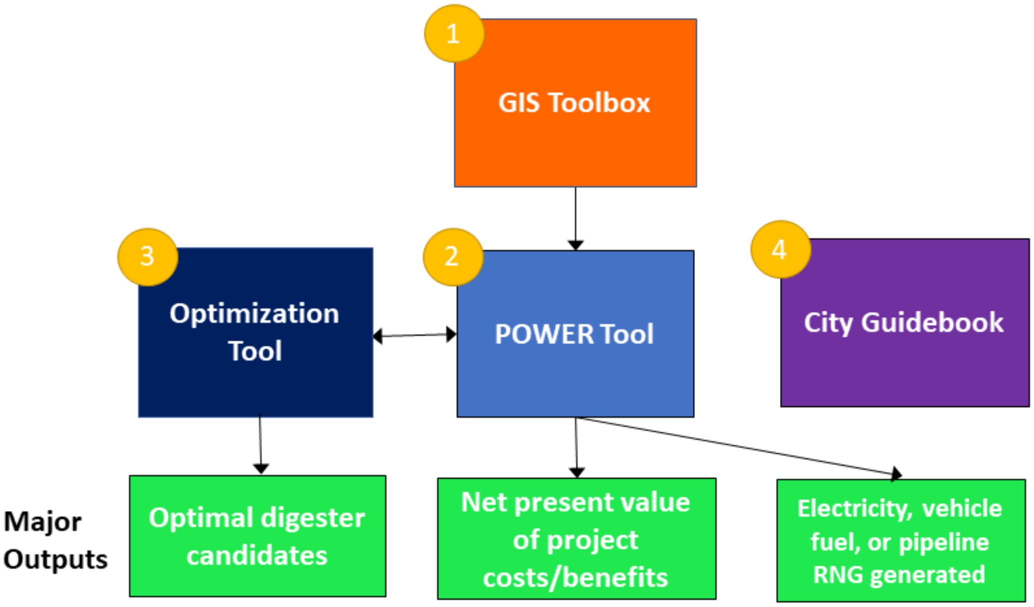


Figure 1.1 POWER Framework Components

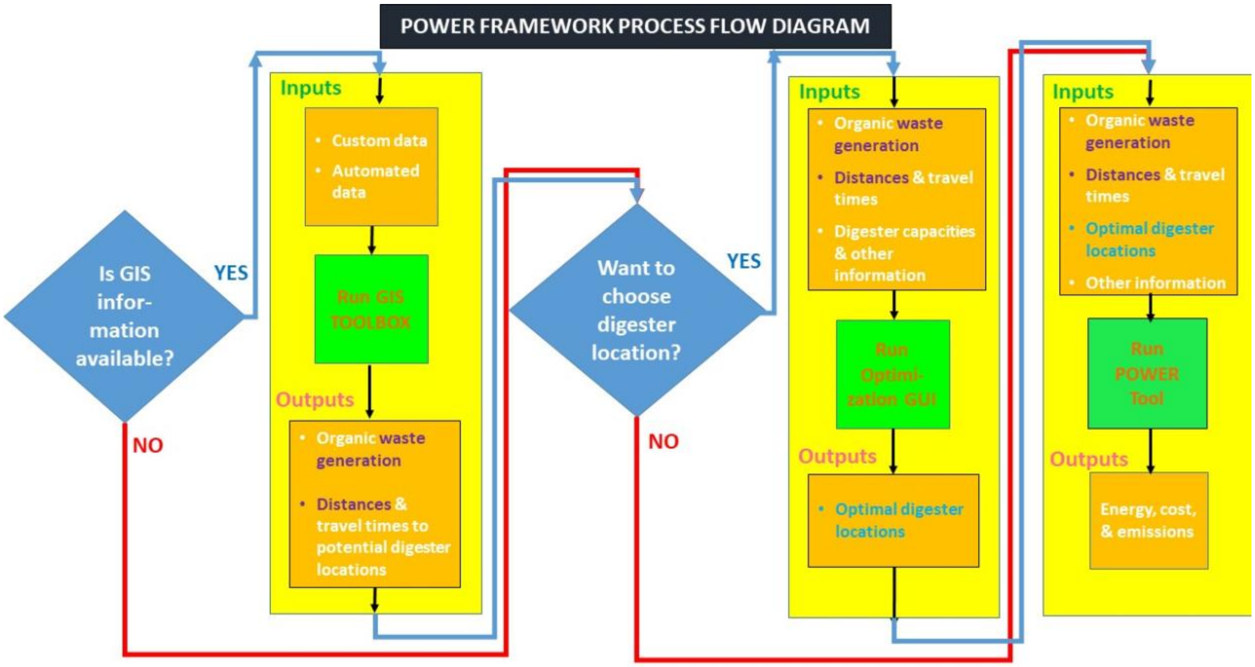


Fig 1.2 POWER Framework Process Flow Diagram

The project addressed the ***CTEDD objective of innovative use of cutting-edge technology*** to provide renewable fuel for fleets. It also provided outreach to policy makers through the collaborations with Advisory Group members, and education of future leaders of the transportation field (7 Ph.D. students, including 5 women and 2 minorities).

1.2 Background

As a part of a sustainable future, many cities are considering renewable energy. Biogas is a promising option, which can be cleaned for use in natural gas vehicles, upgraded to pipeline-quality renewable natural gas, burned to generate electricity for electric vehicles or other purposes, or used for direct heating. Use of renewable natural gas in vehicles reduces emissions particularly compared to diesel vehicles (NCTCOG, 2019a). Fleets are attractive targets for alternate fuels like biogas because many vehicles are able to take advantage of the installation of a refueling station, which is typically costly.

Organic waste generation and diversion is another challenge many cities and regions are facing due to urbanization. If waste is diverted to make biogas, urban waste volume is reduced, freeing up landfill space. Nationwide, 22% of the waste that goes to landfills is food waste, and 7.8% is yard waste (US EPA, 2018). According to EPA’s Food Recovery Hierarchy, if food waste cannot be reduced or used to feed hungry people or animals, the next priority is using it to generate energy, rather than composting or sending it to the landfill (US EPA, 2019).

Many cities already have anaerobic digesters (AD) that convert sewage sludge at water resource recovery facilities (WRRFs) to biogas. Using this existing infrastructure, organic wastes like food, yard, and fats/oils/grease (FOG) can be co-digested to increase biogas production. According to the US Environmental Protection Agency (EPA), 63 anaerobic digesters (AD) at WRRFs in the US were co-digesting food waste in 2019 (US EPA, 2021). With ADs located at over 1200 WWRFs (US EPA, non-dated a)), substantial potential exists for expanding co-digestion of organic wastes.

Additionally, food, yard, and FOG wastes can be co-digested at existing on-farm digesters, which are already processing crop residues and manure. As of 2019, 248 on-farm digesters were operating in the US, with 10 co-digesting food waste. Finally, food, yard, and FOG wastes can be co-digested at stand-alone digesters; 45 were co-digesting food waste in 2019 (US EPA, 2021).

As shown in Figure 1.1, the "Prioritizing Organic Waste to Energy-Renewable (POWER) Framework" can help cities/regions assess the feasibility of co-digesting organic wastes at existing or new WWRF digesters, on-farm digesters, or stand-alone digesters. The POWER Framework consists of 4 components: 1) GIS Toolbox, 2) POWER Tool, 3) Optimization Tool, 4) City guidebook entitled "Anaerobic Digestion of City Food and Yard Waste: Answers to 10 Critical Questions." The POWER Framework:

- Helps cities/regions assess the economic feasibility of co-digesting organic wastes for energy recovery,
- Considers existing and new digesters at wastewater recovery facilities, farms, industries, and other locations,
- Models the costs and emissions from the entire anaerobic digestion system and compares with current practices of landfilling and composting,
- Selects optimal digester location when more than one is available.

1.2.1 Contribution of the POWER Framework to the Body of Knowledge

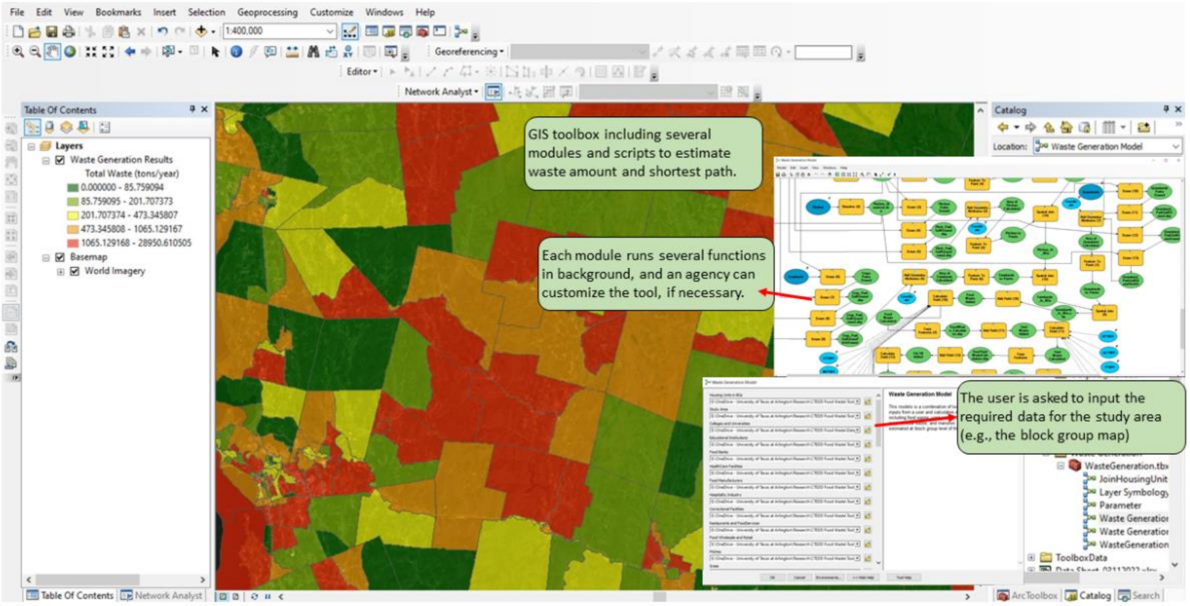
Prior to the POWER Framework, there was not a model for determining the best use of existing digester infrastructure for organic waste to fuel conversion. Several general models are available to facilitate municipal solid waste management decisions in the US, including the Solid Waste Optimization Lifecycle Framework (SWOLF, NCSU, 2014) and Municipal Solid Waste Decision Support Tool (MSW-DST, RTI International, 2012); these models, however, do not consider use of existing digester infrastructure to convert organic waste to fleet fuel. In addition, prior to the POWER Framework, there was not a user-friendly model for estimating fuel production from organic waste and costs/benefits. EPA's Co-Digestion Economic Analysis Tool (Co-EAT, Rock and Ricketts, 2017) requires 78 input values, many of which are not readily available. An EXCEL-based model that assesses farm-based AD/biogas systems is available for Ontario, CA, as well as the AD Budget Calculator, but neither includes food/yard waste co-digestion, nor does optimization of regions to supply digester feedstock (Anderson et al., 2015; Washington State University, non-dated).

1.3 POWER Framework Components

POWER Framework components, shown in Fig. 1.1, are briefly introduced here, with more in-depth information provided in Ch. 2-4.

1.3.1 GIS Toolbox

The automated geographic information system (GIS) Toolbox (Fig. 1.3) allows users to estimate quantities of organic wastes potentially collected for digestion. For seven food-waste generator categories (e.g. K-12 educational institutions, food banks, food manufacturers/processors, restaurants & food services), US EPA's Excess Food Opportunities map is used to provide institution-specific food-waste generation values in tons/year. For other food waste-generator categories, as well as yard-waste and farm-waste generator categories, waste production per block group is estimated by multiplying a waste generation rate (from literature) by an activity level per block group, obtained from various GIS information sources, including the US Census Bureau and Open Street Map (OSM). In addition, the GIS shortest path algorithm is used to route waste to AD facilities for any region in the US.



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Layers

☑ Waste Generation Results

Total Waste (tons/year)

- 🟩 0.000000 - 85.759094
- 🟩 85.759095 - 201.707373
- 🟨 201.707374 - 473.345807
- 🟧 473.345808 - 1065.129167
- 🟥 1065.129168 - 28950.610505

☑ Basemap

☑ World Imagery

GIS toolbox including several modules and scripts to estimate waste amount and shortest path.

Each module runs several functions in background, and an agency can customize the tool, if necessary.

The user is asked to input the required data for the study area (e.g., the block group map)

Figure 1.3 GIS Toolbox

1.3.2 POWER Tool

The POWER Tool, a user-friendly Microsoft Excel spreadsheet, estimates the following for the anaerobic digestion process shown in Fig. 1.4: costs/benefits; pollutant emissions; and electricity, vehicle renewable natural gas (RNG), or pipeline RNG production. To gather data for the POWER Tool, interviews were conducted with personnel from WRRF, fleet services, and solid waste collection services from several cities; relevant literature was reviewed (>200 articles); and meetings were held with a multi-disciplinary advisory group. Information sources are referenced in the POWER Tool itself.

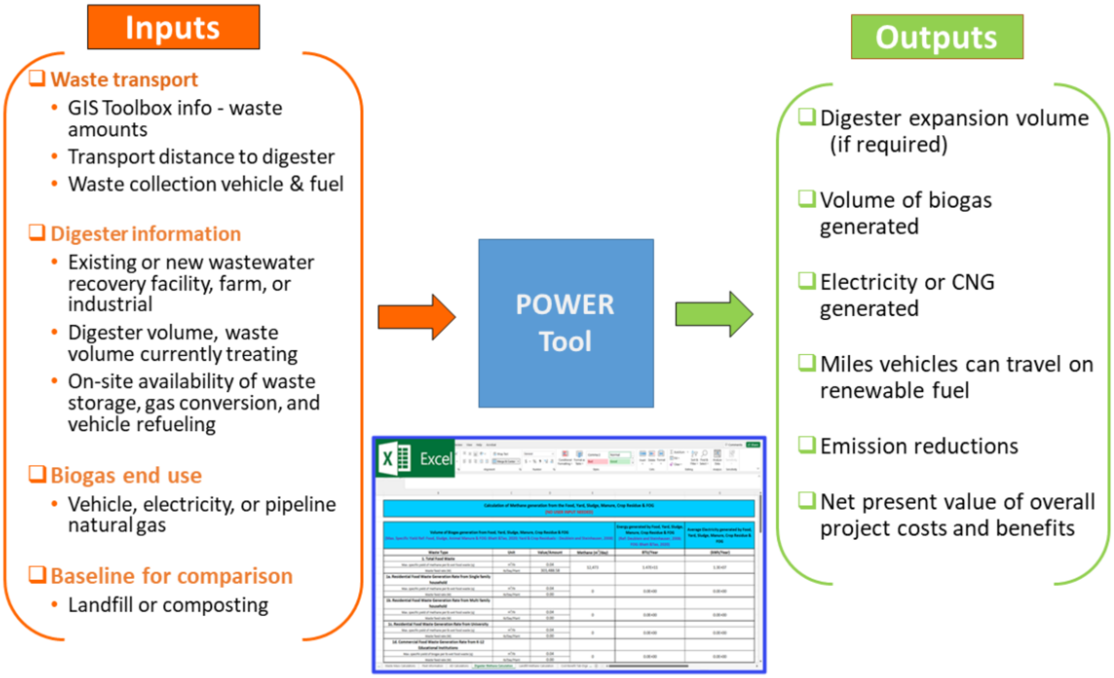


Figure 1.4. POWER Tool

Since the POWER Tool is a screening tool, inputs are limited, as shown in Fig. 1.4 (compared to 78 inputs for US EPA’s Co-Digestion Economic Analysis Tool, Co-EAT). Required inputs include distance of waste transport, as well as volume of waste being treated and excess capacity in existing digesters. The user can choose the categories of organic waste to evaluate, type of digester (WRRF, farm, or industrial), end use of biogas (electricity, vehicle RNG, or pipeline natural gas), type of vehicle if the end use is vehicle fuel, and baseline for comparison (landfilling or composting). Since the purpose of POWER Tool is screening, detailed impacts on digester performance and efficiency are not considered.

1.3.3 Optimization Tool

Using existing digester infrastructure to accommodate organic waste involves determining which digesters are the best candidates for co-digestion. The best candidates would provide the most biogas for the least cost. Determining this is not straightforward, however, because of the large number of potential digesters, waste collection routes, and variables that impact the cost. The 16-county region served by the North Central Texas Council of Governments, for example, has 9 existing ADs at WRRF. Trade-offs must be balanced between organic waste transportation costs; capital costs for expanding ADs, cleaning gas/generating electricity, and installing refueling stations; and on-going operation costs.

For example, as shown in Fig. 1.5, small capacity digesters in multiple locations may require lower transportation costs due to shorter distances between waste generators and digesters. However, higher capital costs would be necessary to add digester capacity and provide gas upgrading/conversion equipment and refueling stations at multiple facilities. A large digester could minimize the capital expansion costs (cost per unit of waste digested); however, higher transportation costs are expected since waste must be transported to the central facility.

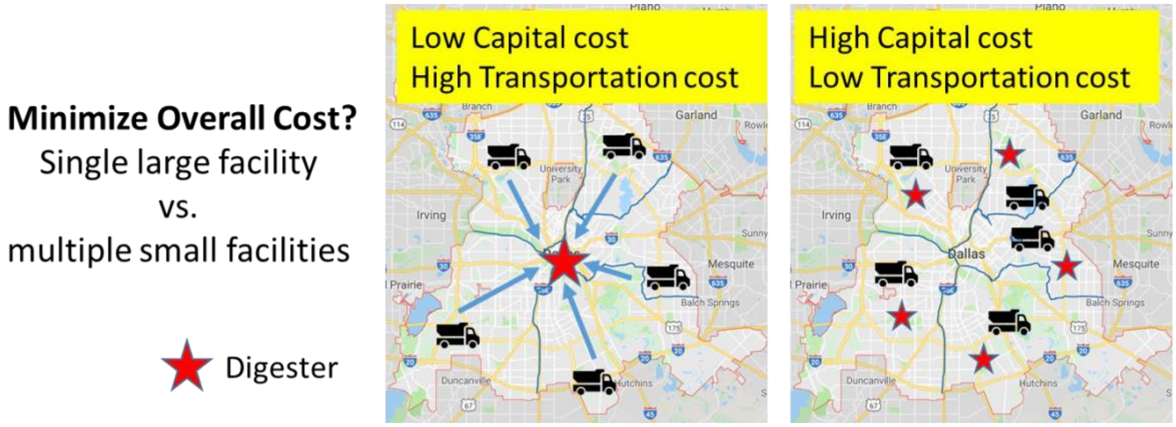


Figure 1.5 Optimization Extension balancing of transportation costs with digester facility capitalcosts

The Optimization Tool (developed using Python) with graphic user interface allows the user to determine the overall least-cost system of digesters for converting waste to energy. When more than one existing digester is available, the Optimization Tool determines the optimum region(s) of waste to send to each digester.

1.3.4 City Guidebook

The POWER Toolbox city guidebook, entitled “Anaerobic Digestion of City Food and Yard Waste: Answers to 10 Critical Questions,” addresses common questions that cities may face when considering diversion of food and yard waste from landfills. It is based on information from interviews with officials from seven US cities/states with successful food/yard waste collection programs (San Francisco, CA; Connecticut; Massachusetts; Southern Nevada; Austin, Texas; Vermont; and Washington State), as well as information from relevant literature. For example, two important questions cities commonly face are: What obstacles have cities encountered in separate collection of food and yard waste, and how have these obstacles been overcome? What incentives/penalties could my city use to encourage public participation in a separate collection of food and yard waste?

1.4 Work Accomplished Regarding Obj. 1 and 2

Work accomplished regarding Obj. 1 and 2, to upgrade the POWER Framework from TRL 5 to 8, is discussed below. Work accomplished regarding Obj. 3 (case studies) is discussed in Chapters 5-6.

1.4.1 Work Accomplished Regarding Obj. 1

The project Advisory Group consisted of officials from states/regions (North Central Texas, Southern Nevada/Las Vegas, and Vermont) with a demonstrated commitment to food waste diversion, many of whom provided input for the City Guidebook developed during the prior project. Advisory Group members also included President of the Texas Natural Gas Vehicle Alliance, and an engineer with Waste Management, Inc., one of the largest waste transport and management companies in the U.S. These members helped provide perspectives of the natural gas vehicle and waste management industries, respectively. The Advisory Group recommended POWER Framework upgrades and helped identify communities for case studies, as detailed below.

Table 1.1. Advisory Group members/project stakeholders

Organization		Advisory Group Member		
Type	**Name**	Name	**Title**	**Sector Representing**
Regional Government	North Central Texas Council of Governments (NCTCOG)	Tamara Cook (first part of project)	Senior Program Manager of Environment and Development	Environmental Resources (Solid Waste, Wastewater)
		Breanne Johnson	Planner I	
	DFW Clean Cities Coalition, NCTCOG	Lori Clark	Clean Cities Coordinator, Program Manager	Transportation
State Government	Nevada Division of Environmental Protection	Rachel Lewison (first part of project)	Southern Nevada Recycling Coordinator, Bureau of Sustainable Materials Management	Solid Waste
City Government	Public Works, Environmental Division – City of Las Vegas	Sharon Harney, Ph.D.	Environmental Laboratory & Compliance Manager	Wastewater
State Government	Vermont Department of Environmental Conservation	Amy Polaczyk	Wastewater Program Manager	Wastewater
		Nick Giannetti	Pretreatment Coordinator Watershed Management Division, Wastewater Program	Wastewater
	Vermont Agency of Agriculture, Food and Markets	Alex DePillis	Senior Agricultural Development Coordinator	Agriculture
Association of public and private interests	Texas Natural Gas Vehicle Alliance	Susan Shifflett	President	Transportation
Industry	Waste Management of Texas, Inc.	Charles Rivette, P.E.	Director, Planning and Project Development	Solid Waste, Transportation

Task 1.1 Conduct Advisory Group kick-off meeting to brainstorm ideas for improving the POWER Tool Framework. A virtual Advisory Group kick-off meeting was conducted Jan. 27, 2021. The project team provided an overview of the POWER Framework and results from the City of Dallas case study. The Advisory Group recommended a variety of improvements to the POWER Framework, many of which were incorporated into the final product, as discussed in Task 2.2.2 below.

Task 1.2 Conduct follow-up meetings with representatives from each state/region to identify case study participants. Following the kick-off meeting, virtual follow-up meetings were held with representatives from Vermont and Nevada to obtain recommendations of potential communities for case studies. For Vermont, a smaller region was chosen which contains industrial and water resource recovery facility digesters, as described in Ch. 5. For Nevada, the Las Vegas Valley was chosen as the case study area, as described in Ch. 6. Representatives from the case study regions were contacted for information as needed as we worked on the case studies. A final meeting was held with stakeholders from each state/region to present case study results.

Task 1.3 Conduct additional Advisory Group meetings to solicit feedback on POWER Framework improvements. A mid-project Advisory Group meeting was conducted on Nov. 5, 2021, via MS Teams. UTA gave a presentation on the updated version of the POWER Framework, and the group provided feedback on a variety of topics, e.g. renewable energy credits, sources of data for commercial yard waste generation, costs of yard waste grinding, common leachate treatment methods. At the final Advisory Group meeting, we presented the final GIS Toolbox, Optimization Tool and POWER Tool, as well as case-study results. We also discussed potential barriers to POWER Framework adoption and how to overcome them.

1.4.2 Work Accomplished Regarding Obj. 2

Task 2.1 Incorporate upgrades arising from the previous project.

- Automation of GIS inputs: National databases for GIS inputs were identified. Python codes were created to automatically pull GIS data into the Toolbox to estimate waste generation by block group. Python codes were also developed to convert geographical units (block group to waste truck route) and estimate shortest path from waste route to digester, landfill, or compost facilities, including travel time. This allows waste quantities and distances to be estimated quickly and easily for any region in the US. In addition, the user is allowed to input percent collection of residential and commercial waste. The GIS Toolbox is described in detail in Ch. 2.

- Update the Optimization Tool: The code for the Optimization Tool was revised to make it more flexible and to incorporate the changes in the POWER Framework (e.g. inclusion of farm digesters and stand-alone industrial digesters). The updates include the following:

  1) Flexible user-specified input parameters instead of fixed parameters in the code.
  2) Flexible number of waste collection zones.
  3) Flexible number of potential digester facility locations.
  4) Additional digester types, namely industrial and farm.
  5) Flexible size for new digesters.

6) Estimation of unused capacity at existing digesters.
7) Different types of garbage trucks.
8) Implementation of rigorously-derived cost parameters for transportation, new digesters, and facility capital and operating costs.
9) Simultaneous digester facility location optimization and garbage truck vehicle fleet size optimization.

A graphical user interface (GUI) was also created. The Optimization Tool is described in detail in Ch. 4.

- Improved flexibility in user inputs to the POWER Tool: To make the POWER Tool more flexible, the following additional options were added:
  - Digestion of residential or commercial food or yard waste only,
  - Digestion of fats, oil and grease (FOG), manure, and crop residuals, in addition to food/yard waste and sludge,
  - Use of farm and stand-alone industrial digesters, as well as water resource recovery facility (WRRF) digesters,
  - Fueling a mixture of electric and RNG vehicles (rather than all of one kind),
  - Use of excess gas, beyond what is required for fleets, for other purposes (electricity generation and pipeline RNG).

- Additional changes to the POWER Tool: Additional changes to the POWER Tool included refinement of emission estimates for all parts of the AD process, including pre-processing (e.g. grinding), gas impurities removal, and landfill and composting baselines. Additional credits for renewable energy production were also added.

- What-if scenarios and sensitivity analyses: Several what-if scenarios were examined using the Optimization Tool (e.g. different numbers of digesters with different types, varying distances). These were run using the City of Dallas case study, developed in the work funded with the previous grant, to ensure that the optimization was working properly. In addition, 5 scenarios were run for Las Vegas, with various types of waste (all food waste, casino food waste only, K-12 school food waste only, FOG, and all organic wastes). These are discussed in more detail in Ch. 6.

We contacted the Resource Conservation Council of the North Central Texas Council of Governments, composting and waste management companies, 5 large cities, and Advisory Group members to try to obtain information concerning improved yard waste generation rates for golf courses and parks, as well as food waste generation rates for multi-family housing. Improved rates were not found.

It was determined that estimation of payback time would be unduly complicated and time-consuming, and would not provide information much more valuable than cost/benefit information already being provided. Hence, payback time was not estimated.

Task 2.2 Incorporate upgrades recommended by the Advisory Group.

Task 2.2.1 Include agricultural/farm anaerobic digester option. Based on information provided by a consultant, regression equations were developed for estimating costs for farm digesters treating manure and crop residuals, as well as industrial/stand-alone digesters treating mixed organic waste. Additional information on waste generation rates and gas production from manure and crop residuals was also collected. Information was also collected on emissions from digesters in terms of pre-treatment and digestate treatment.

Task 2.2.2 Incorporate additional upgrades recommended by the Advisory Group. In Task 1.1, we solicited input from the Advisory Group on POWER Framework improvements. We evaluated the suggestions based on difficulty of inclusion (see Table A1) and found that most suggestions were feasible. The following suggestions from the Advisory Group were incorporated into the Basic Tool:

Suggestions concerning wastes:

- User allowed to select categories within food and yard (single family, multi-family, university, K-12 institutions, special event centers, corporate campuses, golf courses, parks, commercial lawns)
- Information provided for user on required C/N ratio

Suggestions concerning vehicles:

- Expanded reference vehicle choice (gasoline and diesel for all vehicle types), with which to compare RNG and electric vehicle emissions
- User choice of diesel, electric, or RNG garbage truck
- Different trucks added for collection of commercial waste (as opposed to residential)
- Addition of passenger trucks and commercial trucks as options to be fueled with electricity
- Information provided for user on market availability of vehicles
- User choose whether vehicle refueling stations/charging stations are already existing

Suggestions concerning cost analysis:

- Inclusion of California Low Carbon Fuel Standard (LCFS) credits and Oregon Clean Fuel Standard (CFS) credits
- Updating and verifying credit information
- User-input cost of electricity
- Cost/benefit per ton of carbon dioxide reduction

Other suggestions:

- Inclusion of waste pre-processing (storage, grinding)
- User chooses end uses of electricity generation (non-vehicle) and pipeline RNG
- Inclusion of costs and emissions for processing digestate (liquid/solid residual from anaerobic digestion)
- User chooses between landfilling and composting for baseline comparison

Task 2.3 Incorporate upgrades arising from the case studies. The Vermont case study required several additional improvements to the POWER Tool: the cost of manure, food waste, and yard waste storage; the option for adding turbine or engine capacity; cost of removing nitrogen or PFAS compounds from digestate (to avoid a water pollution problem).

1.5 Report Organization

The remaining chapters discuss various components of the POWER Framework, and case studies, as follows:

- Ch. 2 GIS Toolbox,
- Ch. 3 POWER Tool
- Ch. 4 Optimization Tool,
- Ch. 5 Case Study for Vermont,
- Ch. 6 Case Study for Las Vegas,
- Ch. 7 Conclusions and Recommendations

Chapters 2-4 describe in detail how the various components of the POWER Framework work, including sources of information used to develop them. The process used to upgrade the Framework from TRL 5 to 8 was discussed in Section 1.4, and thus is not discussed in Chapters 2-4. The 4th component of the POWER Framework, the City Guidebook, was developed during the previously-funded project, and was discussed in its project report, so is not discussed in this report.

Chapter 2: GIS Toolbox

The GIS Toolbox contains two toolboxes that include five model tools:

1. Waste Generation Toolbox
   - Housing Unit Model
   - Waste Generation Model
   - Layer Symbology
2. Network Analysis Toolbox
   - Origin Polygon to Point
   - Shortest Path Model

A combination of GIS tools and Python scripts are integrated to automatically:

- Pull GIS data and do a spatial analysis
- Calculate the estimated waste for geographical units (block groups), and
- Estimate the shortest path from waste route to the proposed digester(s).

Each of the 5 model tools listed above is discussed in turn.

2.1 Housing Unit Tool

The Housing Unit Tool determines the number of housing units of various types (e.g. single-family, multi-family) in each block group in the study area. The numbers of housing units are used to estimate the generated waste in the Waste Generation Tool, discussed in the next section.

The Housing Unit Tool requires a CSV file that includes the housing unit data from the US census and a shapefile that includes the block group polygon of the state of the study area. The model joins these two files, and the outcome is a shapefile with the number of housing units of various types in each block group. The data in the CSV file are as follows:

Housing Units of different types:

AL0AE001: Total

AL0AE002: 1, detached

AL0AE003: 1, attached

AL0AE004: 2

AL0AE005: 3 or 4

Used to calculate food waste and yard waste for single family households.

AL0AE006: 5 to 9

AL0AE007: 10 to 19

AL0AE008: 20 to 49

AL0AE009: 50 or more

Used to calculate food waste for multifamily households.

AL0AE010: Mobile home

AL0AE011: Boat, RV, van, etc.

2.2 Waste Generation Tool

2.2.1 Waste generation rate and GIS information used in waste generation estimates

The Waste Generation Tool uses the following basic equation to estimate waste production:

Waste produced per category = [**Waste generation rate**] * [**Activity level**/block group]
per block group (mass/year) (mass/activity/year)

Tables 2.1 - 2.3 show waste generation rates and sources of activity level data for food, yard, and agricultural waste, respectively. For all of the waste categories except "Special event centers & recreation facilities," GIS information is available via free national databases, most of which are provided as the default input that the Waste Generation Tool accesses automatically. For "Special event centers & recreation facilities," however, no free national database was available, so the user will need to input this information for their region. ArcGIS Business Analyst contains the information if the user has access to it.

It should be noted that POWER allows the user to specify the fraction of waste actually collected for digestion, landfilling, or composting. This can account for participation rates less than 100% (e.g. not all households participate), as well as diversion of waste to other end-uses (e.g. food waste used to feed hungry people).

For input data in polygon format (e.g. OSM data), the polygon is converted to a point (aka polygon centroid) to ensure the data is assigned to a single block group.

More information on the values reported in the "Rate" column is provided below.

Table 2.1 Food and FOG waste data sources

Food Waste Category	Waste Generation		GIS Data		
	Rate	Reference	Activity Data (per block group)	Source	Import in Toolbox
Single-family households (HH)	5 lb/household/ week	SWANA (2016)	Number of single-family households	US Census Bureau - ACS 2019, www.census.gov/	Default Input
Multi-family units	1 lb/unit/ week	SWANA (2006, 16)	Number of multi-family units		Default/ Input
Universities	0.39 lb/ student/ day	SWANA (2016)	Number of university students	Homeland Infrastructure Foundation-Level Data	Default Input
Other food waste categories*	Institution-specific, tons/yr	EPA Excess Food Opps. Map (US EPA non-dated a)	N/A (activity data is not needed because rate is provided in tons/year)	EPA Excess Food Opps. Map	Default Input
Special event centers & recreation facilities	150- 4200 lb/employee/ yr	NRDC (2017)	Number of employees per center	Locally specific	User Input (ArcGIS Business Analyst)
FOG (restaurants)	35.2 gal/ restaurant/ week	Moore and Myers (2010)	Number of restaurants	EPA Excess Food Opps. Map	Default Input

*Other food waste categories:

- Educational institutions (not universities),
- Correctional facilities,
- Food banks,
- Food manufacturers/processors,
- Food wholesale/retail,
- Health-care facilities,
- Hospitality industry,
- Restaurants/food services

Table 2.2 Yard waste data sources

Yard Waste Category	Waste Generation		GIS		
	Rate	Reference	Activity Data (per block group)	Source	Import in Toolbox
Single-family households	16 lb/household/week	SWANA (2016)	Number of households	US Census Bureau - ACS 2019, www.census.gov/	Default Input
Golf courses	269 lb/acre/ week	US EPA (non-dated b), State government info.	Acres	OSM	Default Input
Parks, grass land use*	538 lb/acre/ week		Acres		

*Includes commercial lawns, pitches, recreational land use, gardens

Table 2.3 Farm waste data sources

Waste Category	Waste Generation		GIS		
	Rate	Reference	Activity Data (per block group)	Source	Import in Toolbox
Croplands	10,000 kg/hectare/year	Lal (2004), based on US Corn Belt	Number of hectares	Cropland Data Layer - US Dept. of Agriculture	Default Input
Manure	Based on cows: 150 lb/animal/day, 1 animal/acre = 27.4 tons/acre/year	ASAE, 2003; OSU, 2015	Number of acres	Grassland/Pasture Data Layer - US Dept. of Agriculture	Default Input

2.2.1.1 Food waste generation rates

For food waste per **single-family household**, 5 lb/household/week (Table 2.1) is recommended by SWANA(2016) as a reasonable average for voluntary programs, although mandatory program average collection rates can go as high as 9 lb/household/week.

For food waste for **multi-family households**, food waste collection data is scarce. SWANA reported an average collection rate of 1.6 lb/household/week for San Francisco (SWANA, 2016), and 1.1 lb/household/week for Ontario, Canada (SWANA, 2006). Table 2.1 uses 1 lb/household/week as a conservative estimate. We contacted the Resource Conservation Council of the North Central Texas Council of Governments, composting and waste management companies, 5 large cities, and Advisory Group members to try to obtain information concerning improved food waste generation rates for multi-family housing (as well as yard waste generation rates for golf courses and parks). Improved rates were not found.

Since the range of waste generation rates for **special event centers and recreation facilities** provided by NRDC in Table 2.1 is very broad (150 – 4200 lb/employee/year), Table 2.4 categorizes these facilities into low, medium, and high waste producers based on the assumed amount of waste they produce.

Table 2.4 Special event centers and recreation facilities categorized by waste production

Types of special event center and recreation facilities assumed to fall in each waste production category	**Waste production**	
	Category	**Average amount (lb/employee/year)**
Performing arts, dance companies, orchestras & bands, music-entertainment, karaoke, kids' entertainment, circus companies, basketball clubs, professional sports clubs & promoters, soccer clubs, race tracks, music & live entertainment, museums, art centers, cultural centers, arboretums, botanical gardens, parks, arcades, bingo games, golf courses, recreation centers, skating rinks, bowling centers, family entertainment centers, and membership sports& recreation clubs	Low	150
Carnivals, concert venues, stadiums arenas & athletic fields, events-special, event centers, zoos, aquariums-public, picnic grounds, amusement places, water parks	Medium	2175
Concessionaires, fairgrounds	High	4200

2.2.1.2 Yard waste generation rates

For yard waste collection per **single-family household**, 16 lb/household/week (Table 2.2) represents anaverage of 6 municipal programs in the US and Canada (SWANA, 2016).

Yard waste for **golf courses** is assumed to be primarily grass clippings (rather than leaves or brush). An extensive search of peer-reviewed literature, government web sites, and other internetsites did not turn up a reliable value for grass clipping yield (mass/golf course area/time) for golfcourses. Several grass clipping yield values were found, presumably for presumably single-family lawns, from several government websites (e.g. CalRecycle, 2020; Franklin County Solid Waste Management District, 2019). These values were averaged to give 7 tons/acre/year, or 269 lb/acre/week. Although this value was for lawns, it was assumed to apply to golf courses also.

To obtain an improved estimate of waste generation from golf courses, golf courses in our case study area of Las Vegas were contacted via phone. Three golf courses were willing to provide information about their dumpster volume and frequency of waste collection, which gave an average estimate of 6 tons of yard waste/acre/year, which is just a bit lower than the estimate above (7 tons/acre/year). Since the Las Vegas climate is dry, it would be expected that yard waste production would be lower than other parts of the country. Hence, the 7 tons/acre/year factor was assumed to apply more broadly and was utilized for yard waste generation for golf courses for the GIS Toolbox.

Yard waste for **parks and commercial lawns** was assumed to include leaves and brush, as well as grass. An internet search did not yield any values for grass, leaves or brush from parks or commercial lawns (mass/area/time). We thus assumed that the 269 lb/acre/week value for single-family lawns applied to parks and commercial lawns as well. According to US EPA (non-dated b), yard waste is around 50% grass clippings, 25% brush, and 25% leaves. Doubling the 269 lb/acre/week value for grass, in order to account for brush and leaves, gives an average value of 538 lb/acre/week. Table 2.2 uses this value for parks and commercial lawns. Improved estimates of yard waste generation rates for parks and commercial lawns are recommended for future research.

In Table 2.2, OSM is recommended as a data source for areas of golf courses, parks and grass. Not all land uses are tagged in OSM, or may not be updated, so some local databases might have more complete data.

2.2.3 Waste Generation Tool GIS Procedure

The Waste Generation Tool GIS procedure is as follows:

1. The shapefile produced with the Housing Unit Tool is used as the first input.
2. A shapefile including a polygon representing the study area is used as an input for the user to clip the block group file.
3. A shapefile including the locations of colleges and universities is used as a default input (not asked from the user). Those with the positive enrollment numbers are selected. Total enrollment in each block group is calculated.
4. A shapefile including the locations of educational institutions from EPA is used as a default input. Average excess food for each location is calculated (because, for each location, there are two values representing low and high levels of excess food). Total amount of excess food from educational institutions in each block group is calculated.

5. A shapefile including the locations of food banks from EPA is used as a default input. Total amount of excess food from food banks in each block group is calculated.
6. A shapefile including the locations of healthcare facilities from EPA is used as a default input. Those with both the low and high excess food amount >0 are selected. Average excess food for each location is calculated. Total amount of excess food from healthcare facilities in each block group is calculated.
7. A shapefile including the locations of food manufacturers from EPA is used as a default input. Those with excess food amount >0 are selected. Average excess food for each location is calculated. Total amount of excess food from food manufacturers in each block group is calculated.
8. A shapefile including the locations of food wholesale and retail from EPA is used as a default input. Those with excess food amount >0 are selected. Average excess food for each location is calculated. Total amount of excess food from food wholesalers and retailers in each block group is calculated.
9. A shapefile including the locations of restaurants and food services from EPA is used as a default input. Those with excess food amount >0 are selected. Average excess food for each location is calculated. Total amount of excess food from restaurants and food services in each block group is calculated.
10. A shapefile including the locations of correctional facilities from EPA is used as a default input. Those with excess food amount >0 are selected. Average excess food for each location is calculated. Total amount of excess food from correctional facilities in each block group is calculated.
11. A shapefile including the locations of hospitality industries from EPA is used as a default input. Those with excess food amount >0 are selected. Average excess food for each location is calculated. Total amount of excess food from hospitality industries in each block group is calculated.
12. A shapefile including the locations of special event centers is used as a default input. Waste production rate for each location is calculated based on their NAICS code. Total waste for each location is calculated by multiplying the rate by the number of employees. Total waste generated from special event centers in each block group is calculated.
13. A shapefile including the locations of golf courses from OSM is used as a default input. The area of the golf courses is calculated. The golf courses are converted into points (the centroid of each golf course). Total area of golf courses in each block group is calculated.
14. A shapefile including the locations of parks from OSM is used as a default input. The area of the parks is calculated. The parks are converted into points (the centroid of each park). Total area of parks in each block group is calculated.
15. A shapefile including the locations of gardens from OSM is used as a default input. The area of the gardens is calculated. The gardens are converted into points (the centroid of each garden). Total area of gardens in each block group is calculated.
16. A shapefile including the locations of grass land uses from OSM is used as a default input. Golf course and park land uses are cut out of the grass land uses. The area of grassland use is

calculated. The grass land uses are converted into points (the centroid of each grass land use). Total area of grassland use in each block group is calculated.

17. A shapefile including the locations of pitches from OSM is used as a default input. Golf course, park and grass land uses are cut out of the pitches. The area of the pitches is calculated. The pitches are converted into points (the centroid of each pitch). Total area of pitches in each block group is calculated.
18. A shapefile including the locations of croplands from the Cropland Data Layer is used as a default input. Golf courses, parks, pitches, and grass land uses are cut out of the croplands. Area of the croplands is calculated. The croplands are converted into points (the centroid of each cropland). Total area of croplands in each block group is calculated.
19. A shapefile including the locations of grassland/pastures from Cropland Data Layer is used as the input. Golf courses, parks, pitches, and grass land uses are cut out of the grassland/pastures. Area of the grassland/pastures is calculated. The grassland/pastures are converted into points (the centroid of each grassland/pasture). The total area of grassland/pastures in each block group is calculated.
20. Food waste, yard waste, FOG waste, Crop residuals and manure are calculated for each block group. The waste collection ratio for each type of waste is asked from the user and its default value is one.

The waste from a block group was considered only if >20% of the block group land area was included in the study area. A percent corresponding to the percent of the block group included in the study area was used to calculate the waste in those block groups. For example, if 30% of the block group was in the study area, 30% of the estimated waste in the block group was used.

2.3 Output Demonstration Tool

This tool uses a default layer file that the user can choose to show the final output for each category of waste on the map. Default layer templates for each type of waste (food waste, yard waste, etc) are in a separate folder.

2.4 Shortest Path Tool

The GIS shortest path algorithm is used to route waste to AD facilities for any region in the US. The model needs 3 sets of inputs including the locations of origins, destinations, and road network. The toolbox converts the block group polygons into points and uses them as the origin of the analysis. The points representing the location of digesters are used as the input for the destination. The road network dataset is created for the study areas based on the road network extracted from OSM. The road network is required to have 3 information including direction of travel, length of the link, and travel time of the link. Travel time is calculated for each link by considering the length of the link and the speed of vehicles on the link. In this study, it is assumed that the speed on each link is equal to the speed limit on that link. The missing values of the link speed limit on the road network extracted from OSM are calculated by interpolation based on the existing speed limits of neighbor links that have the same road function type as the link with the missing value.

The Toolbox calculates the travel length and travel time between the centroid of each block group and the location of the waste treatment facilities by having the abovementioned inputs and using the shortest path algorithm. The final output of this toolbox is a spreadsheet with travel time, travel distance, and average travel speed or velocity for all sets of origins and destinations. Velocity is used to determine travel time, which is used in the estimation of cost (worker salary times time). Cost estimation is described in more detail in Ch. 3.

Chapter 3: POWER Tool

3.1 POWER Tool Overview

The Power Tool enables a city or regional government to evaluate the feasibility of using one digester to accommodate organic waste for conversion to energy. The user can choose to compare cost of digestion with cost of landfilling or composting. Fig. 1.3 summarizes the inputs and outputs of the POWER Tool.

Table 3.1 describes the various Excel spreadsheet tabs within the tool. The user should first read the tabs labeled "**User Guide**," "**Read me**," "**Necessary Information Needed**," and "**Acronyms Used.**"

The "**Quick Overview – Inputs & Outputs**" tab summarizes the main POWER Tool inputs and outputs. A ***user manual and tutorial video*** are available on the project website, showing the user how to input values on the "**Quick Overview – Inputs & Outputs**" tab. The user only needs to input information on this tab and the "**Waste Mass Calculations**" tab. The other tabs perform calculations, with the exception of the last five ("**CN Table**," "**Additional Resources**," "**Unit Conversions**," "**Bibliography**," and "**Help**"), which the user can access for additional information.

In terms of costs/benefits, it is assumed that the city transports the waste and owns and operates the digester(s) at the water resource recovery facility, as well as vehicles to be refueled. The city is assumed not to own farm and industrial/stand-alone digesters; the city pays to transport waste to these digesters and then pays a tipping fee. The city may or may not own the landfill and compost facility; costs of landfilling and composting are accounted for using tipping fees. The fee values do not distinguish whether landfill gas is captured and beneficially used.

Table 3.1 POWER Tool spreadsheet tab descriptions

Tab Name	Description
User Guide	General information about the POWER tool as well as the meaning of color-coded cells used in the spreadsheet.
Read Me	A table showing what tabs contain which information.
Necessary Information	A quick checklist of information that user must input to use the spreadsheet.
Acronyms Used	All acronyms used and their meanings are listed here.
Quick Overview – Inputs & Outputs	The only tab where user must INPUT values. Overall user INPUT, OUTPUT, benefits, revenues, losses, net benefit/cost, etc. are arranged here. It is the most important part of the POWER tool. With very limited INPUTs, the user can have an overview of all the OUTPUTS with overall benefit/cost information in terms of 50 years with 2% interest rate.
Waste Mass Calculations	Mass Calculations for food waste, residential and commercial food waste, yard waste, residential and commercial yard waste, corporate campus (food and yard), fats, oil and grease (FOG), Crop residue, Manure. C/N ratio check for selected waste type.

Fleet Information	All information about Fleets (fuel economy, mileage, cost of fuel, average lifespan, etc.) that can be refueled by generated biogas.
AD Calculations	Calculation for Anaerobic Digester (AD), including remaining capacity, volume, number of new digesters to be installed, etc.
Digester Methane Calculations	Detailed calculations about the amount of biogas generated from Anaerobic digestion of food waste, residential and commercial food waste, yard waste, residential and commercial yard waste, corporate campus (food and yard), Fats, oil and grease (FOG), Crop residue, Manure; conversion of biogas to energy, electricity; miles per year different vehicles can travel on biogas produced; number of vehicles that can be refueled by generated biogas; etc.
Landfill Methane Calculations	Detailed calculations about the amount of biogas generated from Landfilling of food waste, residential and commercial food waste, yard waste, residential and commercial yard waste, corporate campus (food and yard), Fats, oil and grease (FOG), Crop residue, Manure; conversion of biogas to energy, electricity; miles per year different vehicles can travel on biogas produced; number of vehicles that can be refueled by generated biogas; etc.
Cost-Benefit Tab_Digester	Detailed calculations for all individual cost and benefits in terms of Anaerobic Digestion including vehicle cost, credits and tipping fee.
Cost-Benefit Tab_Landfilling	Detailed calculations for all individual cost and benefits in terms of Landfilling including vehicles cost, tipping fee etc.
Cost-Benefit Tab_Composting	Detailed calculations for all individual cost and benefits in terms of Composting including vehicles cost, tipping fees etc.
Multichoice Vehicle	Calculations about all type of vehicles, credits, benefit of using biogas etc.
Emission-Waste Transport Vehicle	Emission from Waste Transporting Vehicle and calculation of social cost.
Emission-Preprocessing	Emission from Preprocessing steps and calculation of social cost.
Emission-AD	Emission during Anaerobic Digestion and calculation of social cost.
Emission-Solid-Liquid Residual	Emission from Anaerobic Digestion and baselines (landfill and composting) byproducts and calculation of social cost.
Emission-Impurities	Emission from impurities removal step and social cost.
Emission-Biogas Conversion	Emission from Biogas conversion processes and calculation of social cost.
Emission-GHG from Biogas Conversion	Emission of Green House Gases (GHG) during Biogas conversion processes and calculation of social cost.
Emission-Vehicles to be refueled	Emission from Biogas refueled vehicles and social cost calculation.
Emission-Combustion Pipeline NG	Emission from pipeline NG combustion and associated social cost calculation.
Total AD Emission	Total emission from Anaerobic Digestion and associated social cost.
Emission-Landfilling	Emission from Landfilling process and calculation of social cost.
Total Emission_Landfill	Total emission from Landfill and associated social cost.
Emission_Composting	Emission from Composting process and associated cost.
Total Emission_Composting	Total emission from Composting and associated social cost.
Comparison Emission	Comparison of emission from Anerobic digestion with baselines (landfilling and composting).

CN Table	C/N table for different feedstock.
Unit Conversion	Used units and their conversions.
Bibliography	List of references used.
Help	Contact information for questions regarding POWER Tool.

3.2 WASTE MASS Calculations ("**Waste Mass Calculations**" tab)

Waste masses are generally provided by the GIS Toolbox, as discussed in Ch. 2. These masses are then input into the appropriate yellow cells on the "**Waste Mass Calculations**" tab. The values from GIS assume 100% collection of waste generated. This assumes that 100% of persons participate in separating their organic waste from the rest of their trash and put it out for separate collection. It also assumes that no food waste is used to feed hungry people or animals. If desired, the values of waste collected can be multiplied by a fraction to account for <100% waste collection and/or other uses of waste (e.g. feeding to hungry people).

3.3 DIGESTER EXPANSION VOLUME Calculations ("**AD Calculations**" tab)

Digester expansion volume is calculated according to:

Digester Expansion Volume (MG) = [(Sum of volume of all wastes to be added in MG/ year) /(365 days/year) * (Residence time in days)] – (Existing digester volume in MG)

where wastes to be added include food, yard, sludge, cow manure, crop residue, and FOG. Residence times are as shown in the table below. Existing digester volume is a user input. When the digester expansion volume is estimated, sludge needed to provide microorganisms to seed a new digester is ignored.

Table 3.2. Digester residence times

Type of Digester	Residence time (days)	Reference
WWRF	40	Deublein and Steinhauser, 2008
Farm	18	Advisory Group
Industrial	17	Advisory Group

Volume of each kind waste to be added per year is calculated according to:

Volume of each kind waste to be added per year (MG/year) = (Mass of waste collected per

year from GIS or population) / (Average
waste density)

Mass of waste collected is a user input. Waste densities are shown in the table below.

Table 3.3. Waste densities

Type of Waste	**Density**					**1/Density**		**Reference**
	g/cm^3	Mg/m^3	lb/gal	lb/ft^3	lb/yd^3	MG/ton	MG/lb	
Food					1513	611	0.306	Miller, 2000
Yard					1568	633	0.317	McNulty and Kennedy, 1982; Gryc et al., 2011
Sludge	1	1	8.34	62.4	1686	681	0.341	N/A
Cow and pig manure (liquid)			8.4		1697	686	0.343	LPELC, 2021
Chicken manure (solid)				63	1701	687	0.344	Lorimor et al., 2004
Crop residuals		0.25			421	170	0.085	Worrell et al., 2016
Crop residuals		0.7			1179	476	0.238	Deublein and Steinhauser, 2008
FOG	0.9123	0.9123			1536	621	0.310	Keener (2008); City of Dothan, Alabama

3.4 Calculation of BIOGAS, ENERGY, ELECTRICITY GENERATED, AND VEHICLE MILES TRAVELLED ("**Digester Methane Calculations**" tab, "**Landfill Methane Calculations**" tab)

3.4.1 Volume of Methane Generated

Methane production is calculated according to (Deublein and Steinhauser, 2008):

$$Q_{CH4} = q * M * f_{CH4}$$

Where:

Q_{CH4} = Methane volumetric production rate, m^3/day

q = specific yield of biogas per lb wet food or yard waste, m^3/lb

M = waste feed rate, lb/day from "**Input/Output**" or "**Waste Mass Calculations**" tab

f_{CH4} = fraction methane, or fraction of biogas composed of methane

Values of q and f_{CH4} are shown in the table below.

Table 3.4 Maximum specific yields of biogas and fraction methane

Type of waste	**q** (m^3/lb raw material)	f_{CH4}	**Reference**
Food	0.073	0.56	Bhatt and Tao (2020)
Yard	0.076	0.65	Average of medians from leaves and grass: Deublein and Steinhauser (2008)
Sludge	0.015	0.6	Bhatt and Tao (2020)
Cow manure	0.014	0.65	Average from Deublein and Steinhauser (2008); Ileleji (2008); Senol (2020)
Pig manure	0.021	0.75	Average from Deublein and Steinhauser (2008); Ileleji (2008); Bhatt and Tao (2020)
Chicken manure	0.049	0.7	Average from Deublein and Steinhauser (2008); Ileleji (2008)
Crop residuals	0.135	0.7	Average from Deublein and Steinhauser (2008)
FOG	0.499	1	Bhatt and Tao (2020)

For landfills, methane is assumed to constitute 50% of the biogas (lower than for digesters). In addition, the amount of methane generated in landfills is multiplied by 0.5 to account for volume of methane collected being around 50% rather than 100%. 50% of the gas is assumed to be captured for the landfill, based on average decay rates for food and yard waste (de la Cruz and Barlaz, 2010), and varying landfill gas collection efficiency by year (Levis and Barlaz, 2011), vs. 100% for the digester.

3.4.2 Energy Generated

Energy generated is calculated according to:

Energy generated by waste (BTUs/year) = (Annual methane production, m^3/lb) * (Methane heating value, BTUs/ft^3) * $(1\ ft/0.3047\ m)^3$

Methane heating value = 910 Btu/ft^3 (net heating value of methane, EngineeringToolbox.com)

3.4.3 Electricity Generated

Electricity generated is calculated according to:

Electricity Generated (kWh/year) = Energy generated (BTUs/year) *

(Average conversion efficiency) /(3412 BTUs/kWh)

An average conversion efficiency of 0.2925 was used, representing the average of the values for a standard gas turbine, microturbine, reciprocating engine, and fuel cell, as shown in Table 3.5.

Table 3.5. Conversion efficiencies (EPA, 2016)

End Form of Energy	Electricity Generation Method	Conversion Efficiency
Electricity	Standard gas turbine (for digester gas)	0.26
	Microturbine	0.25
	Reciprocating engine	0.325
	Fuel cell	0.48
Vehicle RNG	N/A	0.875
Pipeline RNG	N/A	0.9

3.4.4 Miles Vehicles Can Travel on Renewable Fuel

Miles a vehicle can travel on renewable fuel are calculated according to:

Electric VMT = (kWh electricity generated) * (miles/gallon gasoline equivalent)
/ (33.7 kWh/gallon gasoline equivalent)
OR
Electric VMT = (kWh electricity generated) * (miles/gallon diesel equivalent)
/ (40.7 kWh/gallon diesel equivalent)

RNG VMT = (BTUs energy generated) * (miles/gallon gasoline equivalent)
/ (115,000 BTUs/gallon gasoline equivalent)
OR
RNG VMT = (BTUs energy generated) * (miles/gallon diesel equivalent)
(139,000 BTUs/gallon diesel equivalent)
(EngineeringToolbox.com)

Average fuel economy (miles/gallon) values were from AFLEET (Argonne National Lab), as shown in the table below. Emission factors for CNG are assumed to apply for RNG.

Table 3.6 Fleet information, including vehicles fueled on fuel (ANL, AFLEET) ("**Fleet Information**" tab)

Vehicle Category	Vehicle Fuel	Avg. Fuel Economy*	Fuel Unit	Cost of fuel ($/Fuel unit)	Average miles travelled per vehicle per year	Average Lifespan (Years)**
Passenger Car	Gasoline	26.2	Gallon	$2.68	12,400	11.8
	Diesel	31.4	Gallon	$2.92		
	EV	72.0	kWh	$0.11		
	CNG/RNG	24.9	GGE	$1.82		
Garbage Trucks	Diesel	1.7	Gallon	$2.92	23,400	12
	Electric	4.4	kWh	$0.11		
	CNG/RNG	1.5	GGE	$1.82		
Passenger Trucks	Gasoline	16.4	Gallon	$2.68	11,400	11.8
	Diesel	19.7	Gallon	$2.92		
	EV	44.3	kWh	$0.11		
	CNG/RNG	15.6	GGE	$1.82		
Light Commercial Truck	Gasoline	13.0	Gallon	$2.68	24,000	11.8
	Diesel	15.6	Gallon	$2.92		
	EV	33.7	kWh	$0.11		
	CNG/RNG	12.3	GGE	$1.82		

*Miles per diesel gallon equivalent (MPDGE) for electric garbage trucks; miles per gallon gasoline equivalent(MPGGE) for other electric vehicles.

** US DOE (2019), USF (2017)

3.4.5 Number of Vehicles Can Travel on Renewable Fuel

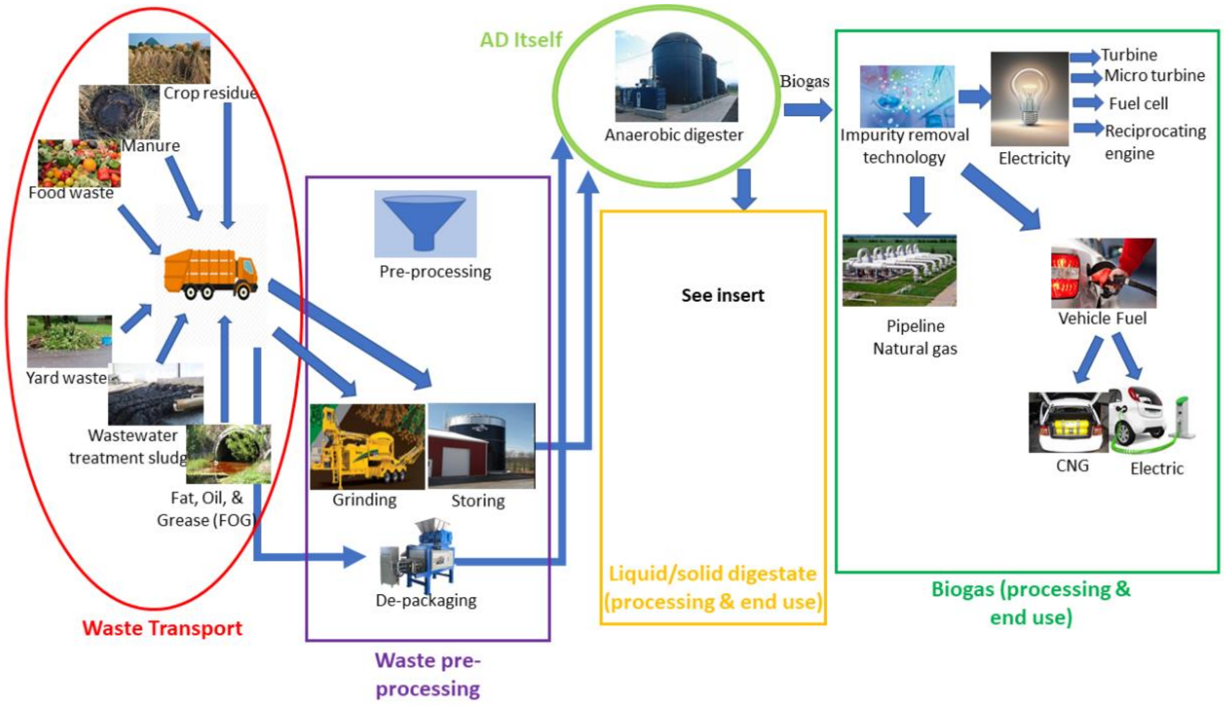
The number of vehicles that can travel on renewable fuel are calculated according to:

No. of vehicles can travel on renewable fuel = (Miles vehicles can travel on renewable fuel)/
(Average miles traveled per vehicle per year)

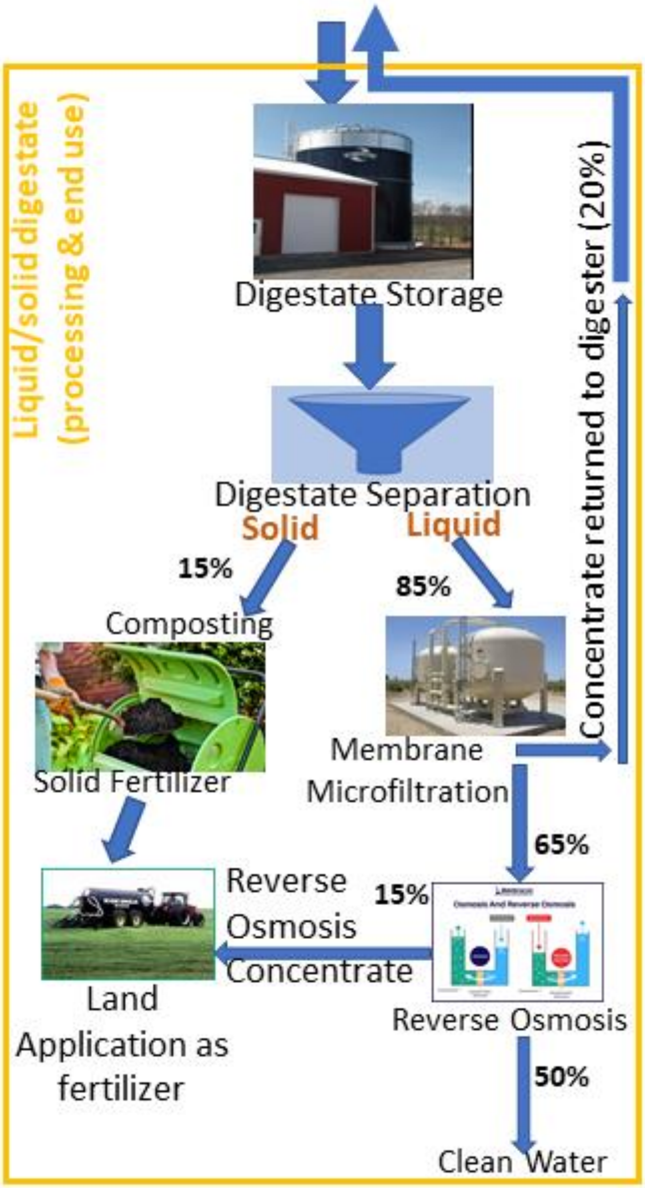
3.5 Calculation of EMISSIONS – WASTE TO ENERGY VIA ANAEROBIC DIGESTION (AD)

The POWER Tool considers emissions of four criteria pollutants (carbon monoxide, CO; nitrogen oxides, NOx; particulate matter, PM2.5 and PM10; and sulfur dioxide, SO_2), VOCs as a combined category, and greenhouse gases (carbon dioxide, CO_2; methane, CH_4, and nitrous oxide, N_2O). Strictly, the criteria pollutant is NO_2, but NOx (NO_2 + NO) was considered because NOx is most often reported in emission factors, since it contributes to ground-level ozone formation. The criteria pollutant ozone was not considered, because it is a secondary pollutant, not emitted directly by any sources. Lead was not considered, because few regions are non-attainment for the lead standard, and emission factors are not generally available for it. Specific VOCs and hazardous air pollutants (HAPs) were also not considered, due to the large number of them (188 HAPS).

Emissions are calculated for each part of the waste-to-energy process via AD, as shown in Figure 3.2 below.



(a) Overall AD Process



b) Digestate processing

Figure 3.2. AD Process Diagram

Table 3.7 summarizes the main categories of sub-processes associated with the overall AD waste-to-energy process and sources of emission factors. Emissions for each category of subprocesses are discussed in more detail below. Similar to the approach taken by EPA (2016), differences in biogas composition due to feedstock were not considered. In some cases, if emission factors were not available for VOCs, factors for hydrocarbons (HC) were used instead.

Table 3.7 Sources of emission factors for digestion, including waste transport and biogas use

Process Category			Emission Factor Source	
Major	**Sub**	**Sub-sub**	**Direct Emissions**	**Indirect Emissions**
Waste transport	N/A	N/A	Argonne National Lab's GREET Model (well-to-wheel emission factors include direct and indirect emissions)	
Digestion	**Waste pre processing**	**Grinding** (food, yard waste, crop residual, FOG)	Particulates from grinding, diesel fuel emissions (grinder similar to MoBark 6600, WV DEP, 2017)	N/A
		Storage	Manure – Lyng et al., 2018 Crop residues – Boulamanti et al. (2013) for maize	N/A
		Depackaging (food)	No direct emissions: contained unit	RecyclingWorks, 2014
	AD itself	**Water Resource Recovery Facility (WRRF)**	No direct emissions – unit is enclosed.	Amount of power consumed – estimated for heating, mixing, and pumping, based on conversations with Leonard Ripley, Ph.D., P.E., Freese and Nichols
		Farm – manure		Energy for operation of farm & industrial digesters was estimated using annual operating costs per ton of waste for 4 farm digesters, assuming that all operating costs went to electricity (Energy Vision estimates, 2021).
		Farm – crop		
		Industrial		
	Digestate post-processing	**Storage**	Preethi et al., 2020; Durdevic and Hulenic, 2020	N/A
		Solid-liquid separation	Aguirre-Villegas, Larson, Sharara, 2019	Lyons et al., 2021
		Treatment of liquid	Assume no direct air emissions from treatment via adsorption or absorption.	Electricity consumption for liquid digestate treatment taken from Timonena (2019).
		Composting of	See emissions in "Composting"	See emissions in "Composting" section (includes

		solids	section (includes land application as fertilizer)	land application as fertilizer)
	Digestate vs. commercial fertilizer baseline	N/A	For solids, already included in composting of solids number.	Assume energy used for application of fertilizer from digestate, compost, and commercial fertilizer is the same, so does not have to be considered.
Biogas Use	**Removal of gas impurities**	**Electricity**	None assumed from treatment (adsorption or absorption)	Patterson et al., 2011 (4.75% of energy content of biogas in the form of generated electricity; electricity emissions from Simapro)
		Vehicle RNG	Already included in conversion, EPA (2016)	
		Pipeline RNG		
	Biogas conversion	**Electricity**	EPA (2016)	Simapro
		Vehicle RNG		DOE, 2015
		Pipeline RNG		Greenblatt, 2015
	Combustion	**Electricity**	0	N/A
		Vehicle RNG	Argonne National Lab's AFLEET	
		Pipeline RNG	EPA's AP-42	
	Subtraction of baselines	**Electricity – regular power mix**	Simapro emission factors include direct and indirect emissions	
		Gasoline/diesel vehicles	Argonne National Lab's GREET Model (well-to-wheel emission factors include direct and indirect emissions)	
		Pipeline natural gas – non-renewable source	Simapro emission factors include direct and indirect emissions	

3.5.1 Waste Transportation Emissions (“**Emission – Waste Transport Vehicle**” tab)

Emissions from vehicles are calculated according to:

Emissions (kg/year) = (Emissions/mile) * (Vehicle miles travelled/year)

Vehicles transporting waste were assumed NOT to be operated with fuel from a digester or landfill; hence, emission factors (emissions/mile) for these vehicles were taken from Argonne National Lab’s GREET Model, as shown in Table 3.8. These factors are well-to-wheel, including emissions associated with producing the fuel as well as combusting it. Although trucks for transporting commercial yard waste and food waste are commonly diesel, emission factors were only available for gasoline vehicles, so these were used. Factors for CNG are assumed to apply to RNG.

Vehicle miles traveled per year to transport waste to the AD is calculated as follows:

VMT to transport waste to AD = Distance to AD * 2 * Number of trips to AD

Distance to AD is an input value. The factor of 2 accounts for the trips to and from the digester. The number of trips to the AD is estimated as follows:

Number of trips to AD = (Weight of waste to be transported)/(Truck capacity)

Table 3.8 also shows truck capacity.

Table 3.8 Capacity and well-to-wheel vehicle emission factors for waste transport vehicles (ANL, GREET)

Type of Vehicle	**Type of waste transported**	**Capacity (tons)**	**Fuel**	**Emissions from each category (GREET Values) (g/mi)**								
				CO	**NOx**	**PM10**	**PM2.5**	**SO_2**	**VOC**	**CH_4**	**CO_2**	**N_2O**
Garbage Truck	Residential – all kinds (food, yard, mixed)	12	Electric	0.60	0.77	0.01	0.01	0.30	0.22	5.00	0.14	0.02
			CNG/RNG	23.93	2.09	0.05178	0.04175	0.47	0.35	17.32	1770	0.04346
			Diesel	0.93	1.95	0.07519	0.0635	0.35	0.23	2.63	2120	0.00758
Passenger Truck (towing 16’ trailer)	Commercial yard waste	2.58	Gasoline	6.261	0.421	0.026	0.015	0.003	0.234	0.017	524	0.041
Light Commercial Truck (used to represent roll-off trucks)	Commercial food waste, FOG, manure, crop residual	4.25	Gasoline	2.624	0.142	0.023	0.011	0.002	0.185	0.012	429	0.01

3.5.2 Emissions from Digestion

3.5.2.1 Waste Pre-Processing Emissions

Waste-pre-processing processes considered were grinding (food, yard waste, crop residual, FOG), storage (all wastes), and depackaging (food waste).

Emissions from grinding. A grinder generates **direct** particulates both from grinding of waste and from combustion of diesel fuel to operate the grinder. Emission factors for particulates were averaged for a MoBark 1300 (760 hp), as shown in Table 3.9, with a 50% reduction in emissions from the grinding process itself due to water spray. Emissions for the MoBark 6600 (875 to 1200 hp), used for grinding food waste by the Eastern Bay Municipal Utility District and assumed as representative for food and other wastes, were not available (WV DEP, 2017). No **indirect** emissions result from grinding, because the grinder is diesel, which means it produces direct emissions only.

Table 3.9 Emissions from waste grinding (WV DEP, 2017)

Type of Emissions	Emissions (lb/hr)				
	CO	NOx	PM	SO_2	VOC
Diesel fuel combustion	14.24	11.49	0.62	1.56	1.63
Grinding process itself	0	0	1.62	0	0
TOTAL	14.24	11.49	2.24	1.56	1.63

Emissions from waste storage. **Direct** emissions from waste storage of manure are shown in Table 3.10, with values obtained from the Norwegian Biogas Model BioValueChain (Lyng et al., 2018). Methane emissions and N_2O emissions were multiplied by 28 and 298, respectively (the relative global warming potential of each compound compared to CO_2), to determine CO_2-equivalents.

Table 3.10 Emissions from manure waste storage (Lyng et al., 2018)

Manure type	Emission factors, kg/metric ton dry waste					Fraction total solids	Emission factors, kg/metric ton wet waste or digestate
	Methane		Nitrous oxide		Total		Total
	As CH_4	CO_2-eq.	as N_2O	CO_2-eq.	CO_2-eq.		CO_2-eq.
Cow	10.2	285.6	0.123	36.7	322.3	0.136	43.8
Pig	4.8	134.4	0.789	235.1	369.5	0.096	35.5
Average							39.7

Crop residues, food waste and FOG were assumed to be stored in covered containers with no emissions. No **indirect** emissions result from waste storage, because no electricity is needed.

Emissions from depackaging. No **direct** emissions are assumed to be produced from de-packaging because the unit is contained. For **indirect** emissions, electricity used for depackaging

(2.94 kWh/ton waste) was an average of the power requirements for several units (Recycling Works, 2014), as shown in Table 3.25 below (cost section). Emission factors for electricity production for the standard power mix from Simapro were then applied, as shown in Table 3.16.

3.5.2.2 Emissions from the AD Itself

Since the AD is a closed system, no **direct** emissions would be expected. **Indirect** emissions stem from use of electricity for digester heating, mixing, and pumping. Energy needed for heating, mixing, and pumping in WRRF digesters was estimated based on calculations described in Sattler et al. (2020).

3.5.2.3 Emissions from Processing Solid-Liquid Residual (Digestate)

Processes used for managing digestate are shown in Fig. 3.2(b). Table 3.11 below summarizes emission factors for the various parts of digestate processing. To simplify the analysis, since this is a screening tool, in terms of emissions from liquid treatment, no distinction is made between membrane microfiltration and reverse osmosis. It is thus assumed that the entire liquid amount 85% goes through both processes, when in actuality 20% (membrane concentrate) is recirculated back to the AD. This additional load on the AD is also not accounted for. It should be noted that no detail was provided regarding the 13 kg CO_2-eq. emission reduction per metric ton digestate applied, compared to commercial fertilizer. It is not known if the reduced nutrient value of compost from digestate, compared to commercial fertilizer, was taken into account. This value was applied to use of liquid digestate as fertilizer also.

Table 3.11 Emissions from digestate processing

Digestate processing step	**Digestate fraction reaching this step**	**Direct emission factor** (kg pollutant/ metric ton digestate)		**Indirect emission factor**	**Notes**	**Reference**
		CH_4	**CO_2-eq.**			
Storage	100%	2.485	69.58	No indirect emissions	No cover; average of digestate from cow and pig manure	Durdevic and Hulenic (2020)
		1.5	27.54		Pond storage, assumed open/no cover; food waste	Preethi et al. (2020)
		N/A	48.6		**Average**	
Solid-liquid separation	100%	N/A	21	Electricity requirement of 1.75 kWh/ton; emission factors for regular US power mix (Table 3.16)	N/A	**Direct**: Aguirre-Villegas et al. (2019); **Indirect**: Lyons et al. (2021)
Treatment of liquid phase	85%	Assume no direct air emissions from treatment via adsorption/absorption		Electricity requirement of 0.085 kWh/ton; emission factors for regular US power mix (Table 3.16).	N/A	Timonena (2019)
Composting of solid phase	15%	See emissions in "Composting" section (includes land application).			N/A	N/A
Use of RO concentrate as fertilizer	15%	N/A	13	Assume energy for application of fertilizer from digestate, compost, & commercial fertilizer is the same, so does not have to be considered.	Digestate replaces mineral fertilizer	Litmanen & Kirchmeyr (2014)

3.5.3 Emissions from Digester Gas Upgrading, Conversion, and Use

3.5.3.1 Emissions from Digester Gas Upgrading/Removal of Impurities

Direct emissions. Direct emissions from removal of impurities for electricity generation are assumed to be 0, since impurities are removed via adsorption or absorption, which would not generate any emissions. Emissions provided by EPA (2016), discussed in the next section, for upgrading digester gas to vehicle RNG and pipeline RNG include direct emissions from impurities removal.

Indirect emissions. Indirect emissions are generated from energy used to remove impurities. Energy needed to purify digester gas to form compressed RNG can range from 1.5 to 8% of the gas energy value; 4.75% was used as an average. (Patterson et al., 2011) This value was assumed to apply also to impurities removal from landfill gas, and for impurities removal for the end-uses of electricity generation and pipeline RNG. Electricity from the grid was assumed to supply the energy for impurities removal. Emissions from electricity generation for the standard US power mix are shown in Table 3.16.

3.5.3.2 Emissions from Digester Gas Conversion to Electricity, Vehicle RNG, or Pipeline RNG

Table 3.12 below shows emission factors for digester gas conversion. The factors are discussed in more detail below.

Table 3.12 Emission factors for digester gas conversion

Process Category		Emission Factor	
Major	**Sub**	**Direct**	**Indirect**
Electricity	Micro-turbine	EPA (2016)	2.4%* (US EIA, 2020a)
	Turbine		
	Engine		4.4%* (US EIA, 2020a)
	Fuel Cell		2%* (US EIA, 2020a)
Vehicle RNG	N/A		2%* (US DOE, 2015)
Pipeline RNG	N/A		2.5%* (Greenblatt, 2015)

*of energy content of biogas, in form of generated electricity (emissions from Simapro)

Direct emissions. Equations for direct emissions from various kinds of biogas conversion, as functions of conversion capacity, were obtained by plotting data from EPA (2016) and fitting regression curves to the data. The plots and regression curves are shown for various types of biogas conversion in Appendix A and summarized in Table 3.13.

Emission estimates in EPA's report were for California, which currently has more stringent limits than the rest of the country; hence, emissions may be underestimated for locations outside California. However, these estimates may soon have utility for many regions in the U.S. The number (and severity) of ozone non-attainment areas are expected to increase after implementing the more stringent 2015 ozone standard.

The emissions for upgrading to Vehicle RNG and pipeline RNG include direct emissions from impurities removal. For vehicle RNG, hydrogen sulfide is removed, and methane and carbon dioxide are separated using a membrane. Upgrading for pipeline injection includes the aforementioned processes as well as removal of siloxanes and water vapor Emissions from burning RNG in a vehicle or appliance are accounted for separately in the next section, “Emissions from Digester Gas Use.”

Emissions for upgrading biogas for electricity production do not include emissions from impurities removal. Methane slip from engines and turbines is ignored. When emissions are combined for various end uses (electricity, pipeline RNG, etc.), reciprocating engines are used for emissions.

Indirect emissions. In terms of indirect emissions from biogas conversion, no energy is required for engines. For turbines, engines, and fuel cells, 2.4%, 4.4%, and 2% of the gas energy values is required for conversion, according to the sources in Table 3.12. For vehicle RNG and pipeline RNG, 2% and 2.5%, respectively, of the gas energy values are required for conversion. The percents were general values for gas conversion but were assumed to apply to digester gas and landfill gas. Electricity from the grid was assumed to supply the energy for biogas conversion.

Table 3.13 Regression equations for digester gas conversion emissions (US EPA, 2016)

End-use	**Type of Gas Conversion**	**Emissions, lb/MWh output** (turbines, reciprocating engines, fuel cells); **lb/MWh input** (Vehicle or pipeline RNG)					
		CO	**NOx**	**PM**	**SO_2**	**VOC**	**CO_2-eq.**
Electricity	Micro-turbine, Capacity in kW	$0.3606(Cap)^{-0.089}$	$0.3394(Cap)^{-0.089}$	$0.0212(Cap)^{-0.089}$	$1.4213(Cap)^{-0.089}$	$0.1697(Cap)^{-0.089}$	-248.9ln(Cap) + 3930.2
	Turbine, Cap. in MW	$0.066(Cap)^{-0.195}$	$0.5117(Cap)^{-0.195}$	$0.1981(Cap)^{-0.195}$	$1.0399(Cap)^{-0.196}$	$0.1155x^{-0.195}$	-562.9ln(Cap) + 7218.3
	Reciprocating Engine, Cap. kW	-0.226ln(Cap) + 3.1384	-0.064ln(Cap) + 0.8937	-0.021ln(Cap) + 0.291	-0.004ln(Cap) + 0.0624	-0.024ln(Cap) + 0.3325	-328.5ln(Cap) + 4575.7
	Fuel Cell	0.07	0.02	0.01	0.001	0.06	1451
Vehicle RNG	N/A	0.0137	0.0165	0.0036	0.0117	0.0018	122
Pipeline RNG	N/A	0.0042	0.0051	0.0011	0.0036	0.0006	101

3.5.3.3 Emissions from Digester Gas Use: Combustion of Vehicle RNG or Pipeline RNG

Although use of electricity does not produce any emissions, combustion of vehicle RNG or pipeline RNG does produce direct emissions that must be accounted for. It is assumed that pipeline RNG would be used in non-vehicle applications.

Tailpipe emissions for renewable compressed natural gas (assumed to be the same as for digester or landfill gas, since impurities have been removed) are accounted for using emission factors from AFLEET, as shown in Table 3.14 below. The emission factors were calculated by dividing lb/year values from AFLEET by miles travelled per year provided for each vehicle category in AFLEET. Emission factors are then multiplied by miles the vehicle can travel per year on biogas, calculated as explained in Section 3.4.4.

Table 3.14 Tailpipe emission factors for vehicles fueled with digester or landfill gas (AFLEET)

Vehicle	**Emission factor (g/mi)**					
	CO	**NOx**	**PM10**	**PM2.5**	**VOC**	**CO_2**
CNG/RNG Passenger car	1.278	0.018	0.034	0.006	0.067	0.067
CNG/RNG Garbage truck	21.230	0.166	0.150	0.026	0.054	0.054
CNG/RNG Passenger Truck	1.432	0.023	0.035	0.006	0.075	0.075
CNG/RNG Light Commercial Truck	1.306	0.024	0.036	0.006	0.084	0.084

Emissions from combusting pipeline RNG, which came from upgrading digester gas, are assumed to be similar to regular natural gas, since impurities have been removed, and emission factors for combustion of pipeline RNG resulting from digester gas were not available. Emission factors were taken from EPA AP-42's section on "Natural Gas Combustion" (Table 1.4-2 "Emissions for Criteria Pollutants and Greenhouse Gases"), and are shown in Table 3.15. Primary differences between combustion of pipeline RNG from digester gas and regular natural gas are likely to be in terms of VOCs and HAPs which result from impurities, and the POWER Tool does not estimate VOCs or HAPs individually anyway. These emission factors were also assumed to apply for combustion of landfill gas, as discussed in the next section.

Table 3.15 Emission factors for natural gas combustion (US EPA, 1998)

Pollutant	Emissions ($lb/10^6$ scf)
CO	84
NO_x	95
PM	7.6
SO_2	0.6
VOC	11
CO_2-eq.	120,000

Since combustion of vehicle RNG and pipeline RNG does not require any additional energy input beyond the gas itself, there are no indirect emissions.

3.5.3.4 Subtraction of emissions from baselines (electricity generated from the regular power mix, combustion of regular vehicle CNG and regular pipeline natural gas)

To estimate advantages of using electricity, vehicle RNG, or pipeline RNG produced from wastes, the life cycle emissions of non-renewable alternatives needed to be subtracted. Life cycle emissions include raw material acquisition (e.g. mining of coal for electricity generation), as well as the fuel use itself. Life-cycle emissions for **electricity – regular power mix and pipeline gas** (non-renewable source) were taken from Simapro and are shown in Table 3.16.

Table 3.16 Life-cycle emissions for electricity – regular power mix and pipeline gas (non-renewable source) from Simapro

Source	Emissions, mg				
	NOx	PM	SO_2	VOC	CO_2
US electricity, low voltage, per kWh	158	11.2	715	42.3	7590
Natural gas combustion, per m^3	1980	155.8	19,100	17.9	2,120,000

Life cycle emissions for **gasoline/diesel vehicles** were taken from GREET (well-to-wheel) and are shown in Table 3.17 below. Emission factors for diesel vehicles were only available for garbage trucks, so gasoline vehicles were used for the other vehicle categories. Emission factors are then multiplied by miles the vehicle can travel per year on biogas, calculated as explained in Section 3.5.4.

Table 3.17 Well-to-wheel vehicle emission factors for baseline gasoline vehicles (ANL, GREET)

Type of Vehicle	**Fuel**	**Emissions from each category (GREET Values) (g/mi)**								
		CO	**NOx**	**PM10**	**PM2.5**	**SO_2**	**VOC**	**CH_4**	**CO_2**	**N_2O**
Passenger Car	Gasoline	2.77	0.3	0.02227	0.01713	0.11	0.25	0.44	350	0.0181
Garbage Truck	Diesel	0.93	1.95	0.07519	0.0635	0.35	0.23	2.63	2120	0.00758
Passenger Truck	Gasoline	6.261	0.421	0.026	0.015	0.003	0.234	0.017	524	0.041
Light Commercial Truck	Gasoline	2.624	0.142	0.023	0.011	0.002	0.185	0.012	429	0.01

3.7 Calculation of EMISSIONS – LANDFILL BASELINE

Emissions are calculated for each part of the waste-to-energy process via landfill, as shown in Figure 3.3 below. Figure 3.3 is similar to 3.2 for AD, with the following exceptions:

- The waste transport distance to the landfill is different than the distance to the digester,
- Waste pre-processing for the landfill includes screening and compaction, rather than storage, grinding and de-packaging, as for the AD;
- Landfill operations include emissions from diesel equipment and waste decay;
- Gas composition is around 50% methane (compared to around 56%-73% for an AD);
- 50% of the gas is assumed to be captured for the landfill, based on average decay rates for food and yard waste (de la Cruz and Barlaz, 2010), and varying landfill gas collection efficiency by year (Levis and Barlaz, 2011), vs. 100% for the digester;
- Leachate pumping and treatment occur, which differs from solid-liquid residual processing for AD digestate;
- Removal of impurities and combusting landfill gas in a turbine or engine to generate electricity will generate different emissions than digester gas, due to different composition.

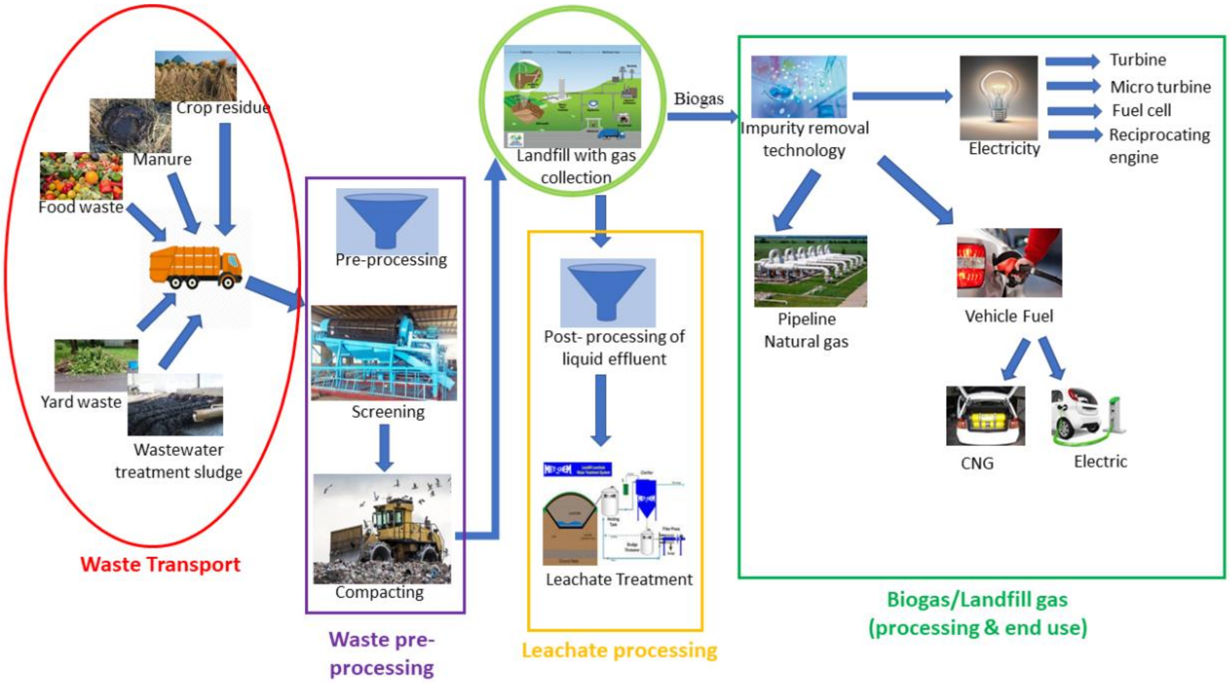


Figure 3.3 Landfill process diagram

Table 3.18 summarizes the main categories of sub-processes associated with the overall landfill waste-to-energy process and sources of emission factors. Emission factors that are identical to the AD table above are greyed out. Only the sections not greyed out will be discussed in more detail below.

Table 3.18 Emissions associated with landfill gas waste-to-energy

Process Category	**Process Sub-Category**	**Sub-Sub-Category**	**Source of emission factors**	
			Direct Emissions	**Indirect emissions**
Waste transportation	N/A	N/A	Argonne National Lab's GREET Model	
Landfill	Waste pre processing	Screening	N/A	N/A
	Landfill itself	Equipment, including compaction	Broun (2016)	N/A
		Waste decomposition	EPA	N/A
	Leachate processing	N/A	Assume no direct air emissions from treatment via adsorption or absorption.	Leachate pumping – Broun (2016) Treatment – Tsompanoglou et al. (2014)
Landfill Gas Use	Removal of gas impurities	Electricity	None assumed from treatment (adsorption or absorption)	Patterson et al. (2011)
		Vehicle RNG		
		Pipeline RNG		
	Biogas conversion	Electricity	US EPA (2008); Chen and Greene (2003)	Simapro
		Vehicle RNG	EPA (2016)	DOE (2015)
		Pipeline RNG		Greenblatt (2015)
	Combustion	Electricity	0	N/A
		Vehicle RNG	Argonne National Lab's AFLEET	
		Pipeline RNG	EPA's AP-42	
	Subtraction of baselines	Electricity – regular power mix	Simapro emission factors include direct and indirect emissions	
		Gasoline/diesel vehicles	Argonne National Lab's GREET Model (well-to-wheel emission factors include direct and indirect emissions)	
		Pipeline gas	Simapro emission factors include direct and indirect emissions	

3.7.1 Emissions from Landfilling

3.7.1.1 Emissions from Waste Pre-Processing for Landfilling

Screening out of inappropriate materials is assumed to occur by hand, resulting in no direct or indirect emissions due to energy consumption. Emissions from compaction are discussed in the next section "Emissions from the landfill itself."

3.7.1.2 Emissions from the Landfill Itself

Direct emissions of methane from landfills were estimated using EPA's methane inventory for landfills (https://www.epa.gov/lmop/frequent-questions-about-landfill-gas) and dividing by the amount of waste disposed of in landfills to get emissions/ton of waste.

Direct emissions from vehicles used at the landfill, including compaction, were taken from Broun (2016). Total diesel consumption is 1.23 L/ton of waste.

3.7.1.3 Emissions from Leachate Pumping and Treatment

Quantity of leachate generated was estimated by running the HELP model as follows.

1. From the EPA database of US landfills, two landfills were selected in each of the contiguous 48 states (not including Alaska and Hawaii), for a total of 96. The two cities in each state were selected to be far away from each other, to have varying conditions. Also, cities were chosen that had all the information needed to input into the model.
2. Once the landfill coordinates and address are specified, HELP automatically imports precipitation and evapotranspiration rates (as well as solar radiation), based on data from (NOAA) National Oceanic and Atmospheric Administration, and (NREL) National Renewable Energy Laboratory.
3. Landfill size/acres was obtained from the EPA landfill database.
4. The following values were input and held constant for all landfills, so that leachate generation would only be functions of precipitation, evapotranspiration, and landfill area:
    i. Waste thickness: 780 inches
    ii. Liner layer materials (from the Mansfield, TX landfill), with the corresponding thicknesses provided by HELP as shown in the table below:

Liner layer	Thickness (in.)	Material
Clay loam (moderate)	6	Loamy clay
Barrier soil liner	12	Fine sand
Geomembrane liner	0.05	HDPE membrane
Drainage net (0.5 cm geonet)	12	Geosynthetic drainage membrane
Barrier soil liner	12	Liner soil (high) - materials with low porosity e.g. fine clay.

iii. Drainage length: 1518 ft. (value for Mansfield, TX landfill)
iv. Drainage slope: 3% (value for Mansfield, TX landfill)
v. Subject to runoff: 0% (0% of runoff was assumed for worst case scenario, assuming that all precipitation seeped into the landfill)
vi. Initial moisture: No
vii. Years of simulation: 30
viii. Geomembrane pinhole density: 1 per acre
ix. Geomembrane installation defects: 10 per acre

The annual average leachate volume was then divided by landfill area to determine leachate volume per acre. The difference between average annual precipitation and annual average evapotranspiration was then plotted versus leachate volume per acre, as shown in Fig. 3.4. The regression equation shown on the figure is included in the POWER Tool to estimate leachate generation based on user values input for annual average precipitation, annual average evapotranspiration, and landfill area.

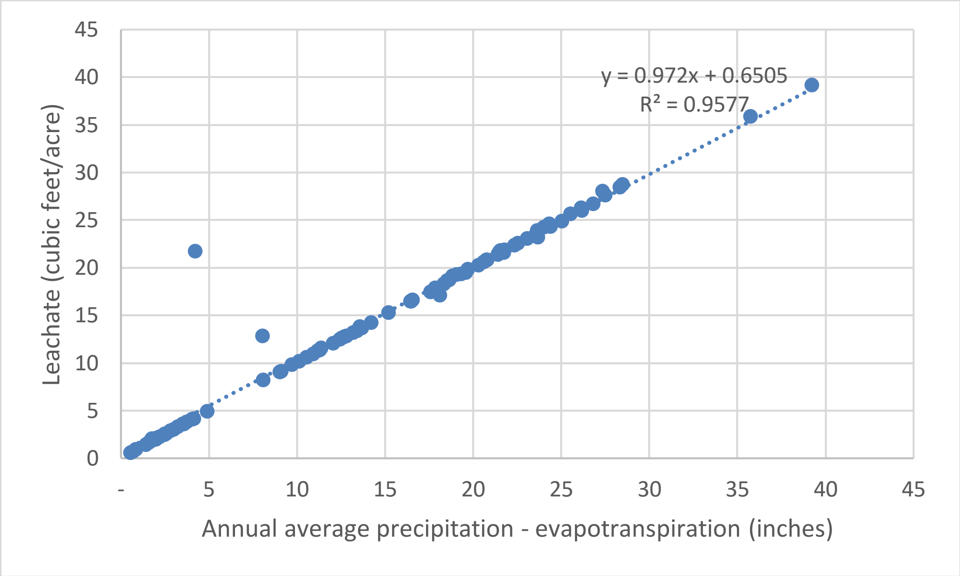


Figure 3.4 Leachate generation vs. annual average precipitation - evapotranspiration

Leachate is assumed to be treated via adsorption or absorption, resulting in no **direct** emissions.

Indirect emissions from leachate **pumping** were taken from Broun (2016) (0.182 kWh per ton of waste). **Indirect** emissions from **leachate treatment** were based on electricity consumption (regular power mix) of 0.129 kWh/gallon of leachate treated, according to Tsompanoglou et al. (2014), who assumed treatment at a water resource recovery facility using primary treatment, sequencing batch reactors, reverse osmosis, and evaporation.

3.7.2 Emissions from Landfill Gas Use

As shown in Table 3.18, emissions from landfill gas use are assumed to be the same as for digester gas use, with the exception of direct emissions from conversion of landfill gas to electricity. Emissions from conversion of landfill gas to electricity, shown in Table 3.19, were taken from US EPA (2008) and Chen and Greene (2003). The CO_2-eq. value for reciprocating engines was assumed to apply to fuel cells as well.

Table 3.19 Emission factors for electricity production from landfill gas

Pollutant	Emission factor for electricity production from landfill gas, lb/MWh
Nitrogen oxides (NO_x)$^+$	2.5
Particulate matter (PM)$^+$	0.4
Sulfur dioxide (SO_2)*	0.027
Volatile organic compounds (VOCs)*	0.86
Carbon dioxide (CO_2) equivalents$^+$	2814 for reciprocating engines; 938+2814 = 3752 for turbines

$^+$EPA (2008), *Chen & Greene (2003)

Direct emissions from landfill gas to vehicle RNG and pipeline RNG were taken to be the same as for digester gas, because no numbers specific to landfill gas could be found.

3.8 Calculation of EMISSIONS – COMPOST BASELINE

Emissions are calculated for each part of the compost process, as shown in Figure 3.5 below. Figure 3.4 is similar to 3.2 for AD, with the following exceptions:

- The waste transport distance to the compost facility is different than the distance to the digester,
- Storage is not needed for the compost facility, because waste can be added anytime;
- Waste pre-processing includes shredding instead of grinding (both result in size reduction);
- Solids conversion occurs via composting rather than a digester; since composting is not enclosed, direct emissions occur;
- No gas is generated for collection/beneficial reuse;
- Post-processing of the solid product (compost) includes curing and screening, which is different than the post-processing of the solid product resulting from digestion;
- A baseline of emissions from regular fertilizer use must be subtracted, since compost replaces fertilizer.

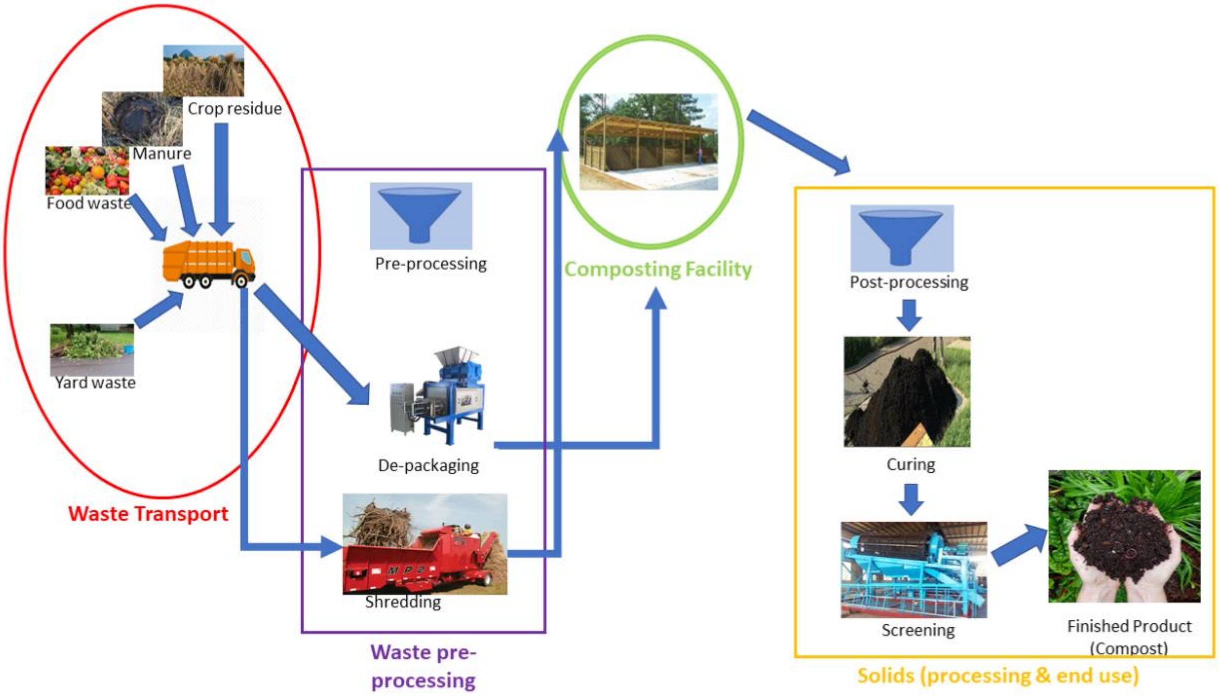


Figure 3.5 Compost process diagram

Table 3.20 summarizes the main categories of sub-processes associated composting and sources of emission factors. Sections of the table that are identical to the AD table above are greyed out. Since equipment used for shredding, moving waste during composting, and spreading compost as a fertilizer runs on diesel, emissions are direct instead of indirect. No information on emissions from post-processing steps of screening and curing was available, so these emissions were neglected.

Table 3.20. Sources of emission factors for composting

Process Category			Source of emission factors	
Major	**Sub**	**Sub-sub**	**Direct Emissions**	**Indirect Emissions**
Waste transportation	N/A		Argonne National Lab's GREET Model	
Composting	Waste pre processing	Shredding, turning	Boldrin et al. (2009)	N/A
		Depackaging	No direct emissions - unit is contained.	RecyclingWorks (2014)
	Composting itself	N/A	Boldrin et al. (2009)	N/A
	Compost post-processing	N/A	Neglect direct and indirect emissions from screening and curing	
	Use of compost vs. commercial fertilizer baseline	N/A	Boldrin et al. (2009)	N/A

Emission factors for composting are provided in Table 3.21. The lower nutrient content of compost compared to mineral fertilizers was accounted for in the substitution. 50% of compost was assumed to be applied for fertilizer purposes (offsetting use of commercial fertilizer), as opposed to applied for other purposes such as erosion control, according to Integrated Waste Management Consulting (2019). Upstream emission factors from Boldrin et al. (2009) accounted for provision of diesel fuel and electricity consumption by buildings on-site. Since these items were not accounted for in terms of digesters and landfills, they were not used for compost facilities to be consistent.

Table 3.21. Emissions associated with composting of garden waste (average for open & closed)

Category	**Processes Included**	**GHG emissions** (kg CO_2-eq./metric ton wet waste)	**Reference**
Pre-processing of waste and composting	• Depackaging	See Table 3.5.2.1	RecyclingWorks, 2014
	• Diesel emissions from shredding, front-end loaders, turning equipment • Emissions from waste degradation	82.75	Boldrin et al., 2009
Land application	• Diesel emissions from spreading • Nitrous oxide emissions from compost • Mineral fertilizer substituted • Carbon binding	-63.0	Boldrin et al., 2009

3.9 Calculation of COSTS and BENEFITS - AD

Table 3.22 summarizes the main categories of sub-processes associated with the overall AD waste-to-energy process and sources of cost/benefit information. Costs/benefits for each category of subprocesses are discussed in more detail below. The time frame is 50 years, which represents a reasonable estimate of the lifespan of a WRRF digester, according to our interviews. Standard engineering economy factor table values are used to convert annual costs topresent values as needed, assuming a 50-year project lifetime and 2% annual interest rate (representative average annual interest rate in US for past 10 years, Macrotrends).

Table 3.22. Costs for Digestion, Including Waste Transport and Biogas Use

Process Category			Source of Cost Information	
Major	Sub	Sub-sub	Capital Costs	Operating Costs
Waste transport	N/A	N/A	N/A (vehicles already owned)	See Table 3.23
Digestion	Waste pre processing	**Grinding** (food, yard waste, crop residual, FOG?)	MoBark 6600 (assumed representative, used by EBMUD) - $910,000	$1/ton (CBI, 2020)
		Storage	NRCS (2003) for manure; assumed the same for other types of wastes	N/A
		Depackaging (food waste)	RecyclingWorks, 2014	RecyclingWorks (2014)
	AD itself	**Water Resource Recovery Facility (WRRF)**	Estimates based on information provided by Ripley, Shapoorian and Hossain (2020)	Estimates based on information provided by Ripley (2020)
		Farm – manure	Tipping fee of $16/ton used to cover capital and operating costs (EPA, 2021)	
		Farm – crop	Tipping fee of $28/ton used to cover capital and operating costs (EPA, 2021)	
		Industrial		
	Digestate post-processing	**Storage**	Drosg et al. (2015)	N/A
		Solid-liquid separation		Drosg et al. (2015)
		Treatment	Nutrients – Drosg et al. (2015) PFAS – CDM Smith (2020)	Nutrients – Drosg et al. (2015) PFAS – CDM Smith (2020)

	Use of digestate vs. commercial fertilizer baseline	N/A	Drosg et al. (2015)	Drosg et al. (2015)
Biogas Use	**Removal of gas impurities**	**Electricity**	EPA (2016)	
		Vehicle RNG		
		Pipeline RNG		
	Biogas conversion	**Electricity**	EPA (2016)	
		Vehicle RNG		
		Pipeline RNG		
	Combustion	**Electricity**	0 for generation of electricity at power plant. Vehicle cost: AFLEET. Charging station cost: US DOE, 2015.	0
		Vehicle RNG	Vehicle cost: AFLEET; refueling station cost: Shifflett (2021)	
		Pipeline RNG	0	
	Subtraction of baselines	**Electricity – regular power mix**	N/A	Average US electricity cost – chooseenergy.com (2021)
		Gasoline/diesel vehicles	Vehicle cost from AFLEET	Fuel cost from AFLEET
		Pipeline gas – non-renewable source	N/A	Statistica, 2021

3.9.1 Waste Transport Costs

It is assumed that no new trucks are needed for pick up of waste (existing trucks are used), so there are no capital costs. Waste transportation operating costs are estimated as follows:

Waste transport operating costs = Fuel costs + Personnel costs

Fuel costs are estimated according to:

Fuel cost = (Cost per unit of fuel) * (Units of fuel consumed)

Units of fuel consumed = (Vehicle miles traveled) / (Fuel economy)

Vehicle miles travelled = (Distance to AD, landfill, or compost facility one-way) * (Tons of waste collected)/ (Capacity of collection vehicle in tons) * (2 one-way trips/round trip)

Table 3.23 shows values used for cost per unit of fuel, fuel economy, and collection vehicle capacity. The distance to the AD, landfill, or compost facility, as well as the tons of waste collected, can be determined using GIS Toolbox. In terms of specifying the distance to the AD, landfill, or compost facility, routing of a garbage truck through a waste collection zone does not have to be considered because these routes can be assumed to be the same, regardless of the assigned destination (AD, landfill, or compost facility), and the cost would thus be subtracted out in calculating the difference in cost between the AD scenario and the baseline. Given the locations of the waste collection zones and the destination, round-trip distances from the centroid of each waste collection zone to each destination can be determined using the shortest path algorithm for the transportation network in ArcGIS.

Personnel costs are estimated as follows:

Personnel costs = (Driver wages) + (Helper wages)

Driver wages = (Driver salary/hour) * (Number of hours)

Helper wages = (Helper salary/hour) * (Number of hours)

Number of hours = (Vehicle miles traveled)/(velocity)

Driver salaries per hour are given in Table 3.23. Vehicle miles traveled is estimated using the equation above. Vehicle velocity can be estimated using the GIS Toolbox, as described in Ch. 2. If information is not available to estimate velocity using the Toolbox, then the garbage truck average velocity can be assumed to be 30 mi/hr.

Table 3.23 Waste collection vehicle operating cost information

Waste	Vehicle Category	Vehicle Fuel	Avg. Fuel Economy*	Fuel Unit	Cost of fuel ($/Fuel unit)	Capacity (tons)	Person-nel	Driver salary ($/hour)	Helper salary ($/hour)	References
Residential – all kinds (food, yard, mixed)	Garbage Truck	Diesel	1.7	Gallon	$2.92	12	Driver & helper	$20	$10.40	**Fuel economy** • Garbage trucks: A FLEET (ANL) • Roll-off trucks; Sandhu et al., 2015 • Pick-up truck: commercial web sites **Cost of fuel**: A FLEET (ANL) **Capacity**: • Garbage trucks: estimate from Advisory Group • Roll-off trucks: Sandhu et al., 2015 • 16’ trailer: commercial web sites **Driver salary**: Gillespie, 2016; Helper salary: ZipRecruiter, 2019
		Electric	4.4	kWh	$0.11					
		CNG/RNG	1.5	GGE	$1.82					
Commercial food waste, FOG, manure, crop residual	Roll-off truck	Diesel	4.4	Gallon	$2.92	4.25	Driver only	$20	N/A	
Commercial yard waste	Pick-up truck towing 16’ trailer	Diesel	14.5	Gallon	$2.92	2.58	Driver & helper	$10	$10	

*Miles per diesel gallon equivalent (MPDGE) for electric garbage trucks.

3.9.2 Costs of Digestion – Water Resource Recovery Facilities (WRRF)

3.9.2.1 Waste Pre-Processing Costs for Digestion

Waste storage Costs. Table 3.24 shows information on manure storage costs provided by NRCS (2003). Capital cost was plotted vs. capacity, as shown in Fig. 3.5. The following regression curve was fit to the data, and this curve is used to estimate waste storage costs in the POWER Tool:

$$\text{Storage capital cost (\$)} = 0.0149*(\text{Storage volume in gallons}) + 2194.2$$

Needed storage volumes is estimated based on waste mass, waste density, and a storage time of 30 days. Although the equation was developed from data for manure storage costs, it is assumed to apply to storage of other kinds of waste as well. Waste storage operating costs are assumed to be zero.

Table 3.24. Data used to develop regression equation for waste storage (NRCS, 2003)

Livestock type	Region	Number animals per farm	Storage unit size (gal)	Total installation cost ($)
Dairy 2,4	Dairy Belt	300	4,342,477	$65,137
Dairy 4	Dairy Belt	200	2,893,414	$52,081
Dairy 4	Dairy Belt	100	1,321,828	$23,793
Dairy 5	SE	100	1,580,733	$28,453
Dairy 5	SE	300	4,573,781	$68,607
Dairy 5	West	100	1,607,863	$28,942
Dairy 5	West	200	3,130,258	$46,954
Dairy 5	West	300	5,216,732	$78,251
Layers 2	SE	50,000	7,054,470	$105,817
Layers 2	SE	200,000	26,515,403	$397,731
Layers 2	SC	200,000	25,387,588	$380,814
Swine 1	SE	83 AU	1,165,377	$17,481
Swine 1	SE	248 AU	3,222,244	$48,334
Swine 1	NC-NE	415 AU	5,384,140	$80,762
Swine 1	NC-NE	2075 AU	26,408,062	$396,121
Swine 1	West	415 AU	6,577,275	$98,659
Swine 1	West	2075 AU	32,348,499	$485,227

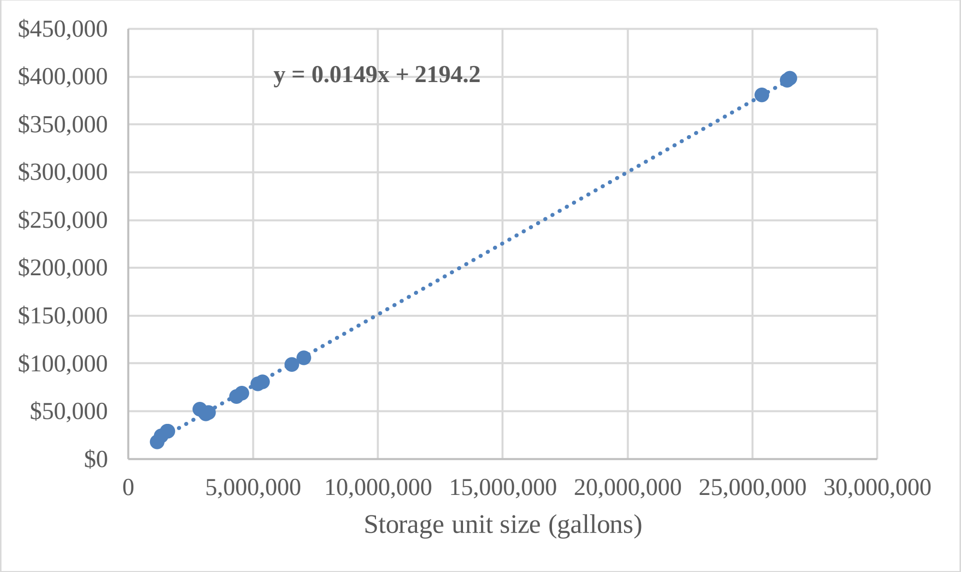


Figure 3.5 Regression Curve for Waste Storage Cost

Grinder. Based on conversion with a municipal utility processing food waste at their water resource recovery facility digester, a Mobark 6600 Grinder was used as a representative grinder for food waste, yard waste, and crop residuals, for AD, landfilling, and composting. A capital cost of $910,000 was used, with replacement every 5 years (permanufacturer), and operating cost of $1/ton (CBI, 2020).

Depackaging unit. Table 3.25 shows information for 6 different depackaging units, taken from "Summary of Food Depackaging Technologies," Recycling Works, Massachusetts (https://recyclingworksma.com/wp-content/uploads/2014/11/Depackaging_Combined_2014.pdf). Capacity in volume/hour was converted to tons/year when needed using an average density for food waste of 1513.5 lb/yd^3.

Table 3.25. Depackaging unit cost information

Model	*Capacity*	*Unit*	*Price ($)*	*Capacity (tons/year)*	*Power Requirements*	*Power Requirements (kw)*	*Kwh/year*	*Electricity Price ($/kwh)**	*Operation Cost ($/year)*	*Operation Cost ($/Ton)*
1	9	tons/ hour	$460,000	77,760	74.7 KW by 380 or 400 volt	74.7	645,408	$0.1419	$91,583	$1.18
2	205	ft^3/hr	$112,500	49,593	230 V/460 V/3ph/60 Hz	NA (no ampere mentioned)	NA		NA	NA
3	25	tons/ hour	$185,000	216,000	25 to 75 HP	37.3	322,142		$45,712	$0.21
4	up to 28	yd^3/hour	$285,000	183,074	NA	NA	NA		NA	NA
5	up to 30	yd^3/hour	$285,000	196,151	30 HP, 230/460 V, 3 PH	22.4	193,285		$27,427	$0.14
6	up to 10	yd^3/hour	$285,000	65,384	7.5 KW (10 HP), 460 V, 3 PH	7.5	64,800		$9,195	$0.14
Average										**$0.42**

*The average price of electricity was from https://www.chooseenergy.com/electricity-rates-by-state /.

Capital cost was divided by capacity (tons/year) and plotted vs. capacity, as shown in Fig. 3.6. The following regression curve was fit to the data, and this curve is used in the POWER Tool to estimate depackaging unit capital costs:

Depackaging capital cost ($) = [(-2E-05) * (Capacity, tons/year) + 5.2839] * (Capacity, tons/year)

Operating costs per ton were averaged for the 6 units; the average value ($0.42/ton) is used in the POWER Tool to estimate depackaging operating costs.

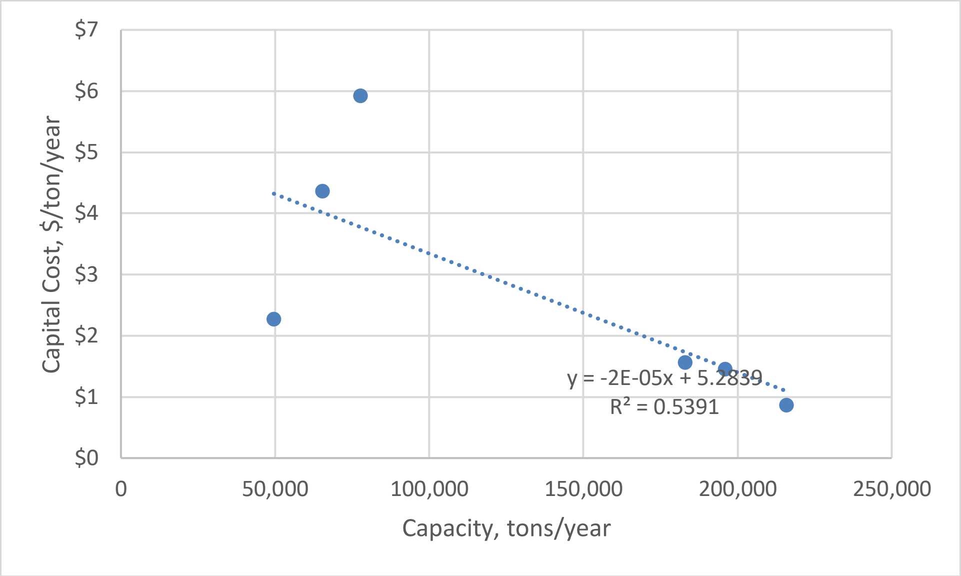


Figure 3.6. Regression equation for capital cost vs. capacity for depackaging units

3.9.2.2 Costs of WRRF AD Itself

3.9.2.2.1 WRRF AD Capital Costs

Dr. Leonard Ripley, Ph.D., P.E., Senior Environmental Engineer, Water/Wastewater Treatment and Reuse, Freeseand Nichols, Inc. provided advice concerning methods of estimating anaerobic digester capital and operating costs. Dr. Ripley has decades of experience in digesters at wastewater treatment plants.

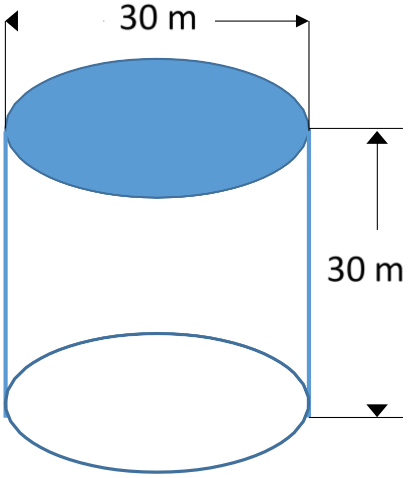


Figure 3.7. Cylindrical digester

Table 3.26 below estimates capital costs for a 30 m diameterx 30 m tall cylindrical concrete digester (5 million gallons, MG, as shown in Fig. 3.7), which is a common shape and size for new digesters today at wastewater treatment plants. It is assumed that if the waste volume is too large to fit in one digester, a second identical digester will be built. Additional 5.6 MG digesters will be added as needed toachieve the required capacity.

Table 3.26. Capital cost of a 30-meter concrete anerobic digester

Type of Cost	Specific Information	$ value
Concrete for walls and base (cubic yd)	2355	$706,556
Steel rebar for walls and base (ft)	168,679	$131,642
Mixer (LM20-20-96 model, Ovivo)	20 hp motor and 96-inch Hydrodisk	$340,000
Cover (Steel Cover, floating, Westech)	For 30 m tank diameter	$400,000
Subtotal Cost 1 ($)		**$1,578,198**
Other Costs	Heating, Pumping, Electrical:40% of Subtotal Cost [1]	$631,279
Subtotal Cost 2 ($)		**$2,209,477**
Consultants Cost	6% of Subtotal Cost [2]	$132,569
Contractors Cost	12.5% of Subtotal Cost [2]	$276,185
Foundation cost (including contractor)[3]		$500,000
Grand Total Cost ($)		**$3,118,230**

[1] Ripley (2020), [2] Shapoorian (2020), [3] Hossain (2020)

Concrete and steel rebar for a 30 m diameter x 30 m tall cylindrical concrete digester, as shown in Table 3.26, was estimated based on plans of existing digesters at the Village Creek Water

Resource Recovery Facility in Fort Worth, Texas, with height adjusted to 30 m tall (the actual digesters are 30 m in diameter but only about 10 m tall). Although additional rebar was added to a height of 30 m in the wall, the rebar diameter was not increased to be able to carry excess load associated with a taller digester wall.

Number of digesters needed = (Digester expansion volume)/(Volume per digester) ("**AD Calculations**" tab)

Volume for 30 m diameter x 30 m tall digester = 5.6 MG (Ripley, 2020)
Number of digesters needed = (Digester volume needed)/5.6

The required carbon/nitrogen ratio and moisture content of the digester feedstock is not considered.

3.9.2.2.2 WRRF AD Operating Costs

Operating costs are estimated for new digesters only, not for the existing digesters, which are already treating sludge (additional operating costs for adding food and yard waste to the existing digesters are not considered).

AD Operating Cost = **Mixing Cost** + **Pumping Cost** + **Heating Cost**

Mixing Cost ($/day) = Motor hp * (hours of operation/day) * (2545 BTU/hr/hp) / (3412BTU/kWh) / (Motor efficiency) * $0.11/kWh

Where:
Motor hp = 20 hp (EBMUD WRRF)
Hours of operation/day = 3-4 (EBMUD WRRF)
Motor efficiency = 80% (Webber, 2007)
$0.11/kWh = average cost of commercial power in the US for 2019 (EIA, 2020b)

Mixing Cost ($/ton) = Mixing cost ($/day)/(Sludge feed rate, tons/day)
Sludge feed rate = 15 tons/day (EBMUD WRRF)

Pumping Cost ($/day) = Pump hp * (hours of operation/day) * (2545 BTU/hr/hp) / (3412 BTU/kWh) / (Pump efficiency) * $0.11/kWh

where:
Pump hp = 15 hp (EBMUD WRRF)
Hours of operation/day = 3-4 (EBMUD WRRF)
Motor efficiency = 80%

(Webber, 2007)
$0.11/kWh = average cost of commercial power in the US for 2019 (EIA, 2020b)

Pumping Cost ($/ton) = Pumping cost ($/day)/(Sludge feed rate, tons/day)Sludge feed rate = 15 tons/day (EBMUD WRRF)

Heating Cost ($/year) = [(**Heat needed to raise temperature of waste**) + (**Heat needed to compensate for losses**)] (hours of operation/day) * / (3412 BTU/kWh) / (Efficiency of electric resistance heating) * $0.11/kWh

Heat needed to raise temperature of waste (BTUs) = (annual waste mass in lb) * (waste heat capacity) * [95°F - (average annual outdoor temp.)]

where
Waste heat capacity (assumed same as water, since food has high water content) = 1 Btu/lb/°F = 2000 Btu/(English ton of waste)/°F (Metcalf and Eddy, 2004)
95°F = 35°C = Mid-range of mesophilic temperatures (30-40°C); mesophilic digesters are most common, from our survey of WRRF with digesters

Heat needed to compensate for losses = (**Heat loss through new digester roof and floor**) + (**Heat loss through new digester walls**)

Heat loss through new digester roof and floor, MMBtus/yr/digester = 17.0 * (95°F - average annual outdoor temp); 17.0 comes from digester dimensions and heat transfer coefficient values for concrete digester base and roof from Metcalf and Eddy (2004).

Heat loss through new digester walls, MMBtus/yr/digester = 30 * (95°F - average annual outdoor temp); 30 comes from digester dimensions and heat transfer coefficient value for concrete digester walls from Metcalf and Eddy (2004).

Heat loss through existing digesters due to addition of food/yard waste is not accounted for.

Hours of operation/day = 24
Efficiency of electric resistance heating = 100% (US DOE, n.d.)
$0.11/kWh = average cost of commercial power in the US for 2019 (EIA, 2020b)

3.9.2.3 Costs of Digestate Processing

Table 3.27 provides net costs (combined capital and operating costs, including nutrient value) for the following scenarios:

1. Solid-liquid separation (screw press), PFAS removal, and separate land application of solid fraction and liquid phase.
2. Solid-liquid separation (decanter centrifuge), treatment of liquid phase

(ultrafiltration/reverse osmosis, evaporation, or nitrogen removal), and PFAS removal.

The basic costs without PFAS removal are from a study that considered a model biogas plant treating 50% manure and 50% corn silage (KTBL, 2008). The basic costs were increased by 37%, based on a study which found that average biosolids management cost increased by approximately 37% in response to PFAS concerns (CDM Smith, 2000). Storage costs are also included.

Table 3.27. Digestate processing costs (Drosg et al., 2015)

Process	**Cost (2008$/m^3 digestate)**
Solid: Solid-liquid separation, PFAS removal, and land application	$4.50
Solid: Composting of digestate	Tipping fee (Table 3.32)
Liquid: Solid-liquid separation, treatment of liquid phase & PFAS removal	$11.80

The benefit of not having to pay for commercial fertilizer was accounted for (University of Illinois, 2021). The lower nutrient content of compost compared to mineral fertilizers was accounted for in the substitution. 50% of compost was assumed to be applied for fertilizer purposes (offsetting use of commercial fertilizer), as opposed to applied for other purposes such as erosion control, according to Integrated Waste Management Consulting (2019).

3.9.3 Costs for Digester Gas Upgrading, Conversion, and Use - Water Resource Recovery Facilities (WRRF)

Table 3.28 shows capital and operating costs for removal of impurities and gas conversion, taken from EPA (2016). Costs reflect emission control to California standards, so may currently be overestimates for the rest of the country, although the rest of the country is likely to move to California standards in the near future. Equations for costs of various kinds of biogas conversion, as functions of conversion capacity, were obtained by plotting data from EPA (2016) and fitting regression curves to the data. The plots and regression curves are shown for various types of biogas conversion in Appendix B and summarized in Table 3.28.

Table 3.28. Regression equations for emissions from digester gas upgrading and conversion (US EPA, 2016)

End-use	**Type of Gas Conversion**	**Cost, $**	
		Capital	**Operating**
Electricity	Micro-turbine, Capacity in kW	$0.0033(Cap) + 0.1307$	$0.1268(Cap)^{-0.306}$
	Gas Turbine, Capacity in MW	$2.0114(Cap) + 4.6154$	$0.0182(Cap)^{-0.187}$
	Reciprocating Engine, Capacity in kW	$0.0091(Cap)^{0.8331}$	$0.1043(Cap)^{-0.205}$
	Fuel Cell	$0.0246(Cap)^{0.7832}$	$0.2312(Cap)^{-0.217}$
Vehicle CNG/RNG	N/A	$1.0658(Cap)^{0.4796}$	$0.0722(Cap)^{0.6948}$
Pipeline RNG	N/A	$4.2681\ln(Cap) - 1.8694$	$0.0422(Cap) + 0.1975$

Table 3.29 shows costs for purchasing city fleet vehicles (electric or CNG/RNG, aswell as regular gasoline and diesel), taken from AFLEET Model, fleet managers, truck manufacturers, and Google for pickup trucks and cars. Vehicles are assumed to be replaced every 13 years, based on the vehicle lifetimes shown in Table 3.6 and conversations with a waste management company. The POWER Tool calculates the additional costs for purchasing electric vehicles or CNG/RNG vehicles with respect to the current vehicles (gasoline or diesel).

Table 3.29. Vehicle capital costs

Category	Sub-Category	Cost
Garbage Truck	Electric	$605,000
	Diesel	$210,000
	CNG/RNG	$290,000
Passenger Car	Gasoline	$20,000
	Diesel	$22,500
	Electric	$37,500
	CNG/RNG	$27,000
Passenger Truck	Gasoline	$20,000
	Diesel	$39,500
	CNG/RNG	$43,500
	Electric	$69,000
Light Commercial Truck	Gasoline	$32,000
	Diesel	$46,500
	CNG/RNG	$44,000
	Electric	$69,000

Electric charging station cost of $60,000 was used, which represents a ballpark cost for a DC fast charging single port unit and installation (US DOE, 2015). The $60,000 represents a medium cost unit, such as the 50kW Dual connector dual port Chademo/SAECombo (NCTCOG, 2019b). CNG/RNG fast fill refueling station costs (one dispenser) can range from $750,000 to $1.2 million; an average value of $975,000 was used (Shifflett, 2021).

3.9.2.3.1 Subtraction of Baselines (electricity generated from the regular power mix, regular pipeline natural gas, gasoline/diesel fuel and vehicles)

To estimate advantages of using electricity, RNG, or pipeline natural gas produced from wastes, the cost of non-renewable alternatives needed to be subtracted. Average US electricity cost from chooseenergy.com (2021) was $0.1419. Average price of natural gas from 2008-2020 in the US from statistica.com was $7.48/1000 cubic feet. The average cost of gasoline and diesel were taken from AFLEET as $2.68 and $2.92/gallon, respectively. The average costs for gasoline and diesel vehicles were shown in Table 3.29 above.

3.9.4 Benefits from Renewable Electricity and Fuel – Water Resource Recovery Facility (WRRF) Digesters

Figure 3.8 shows credits included in the POWER Tool for water resource recovery facility anaerobic digesters, for various end uses of biogas. It is assumed that the user of the POWER Tool (a city or regional government) does not own the digester if it is a farm or industrial digester, so no credit applies. Table 3.30 summarizes the type of generating facility, feedstock, and end use to which each credit applies, along with its value. Business Investment Tax Credit for hardware was not included.

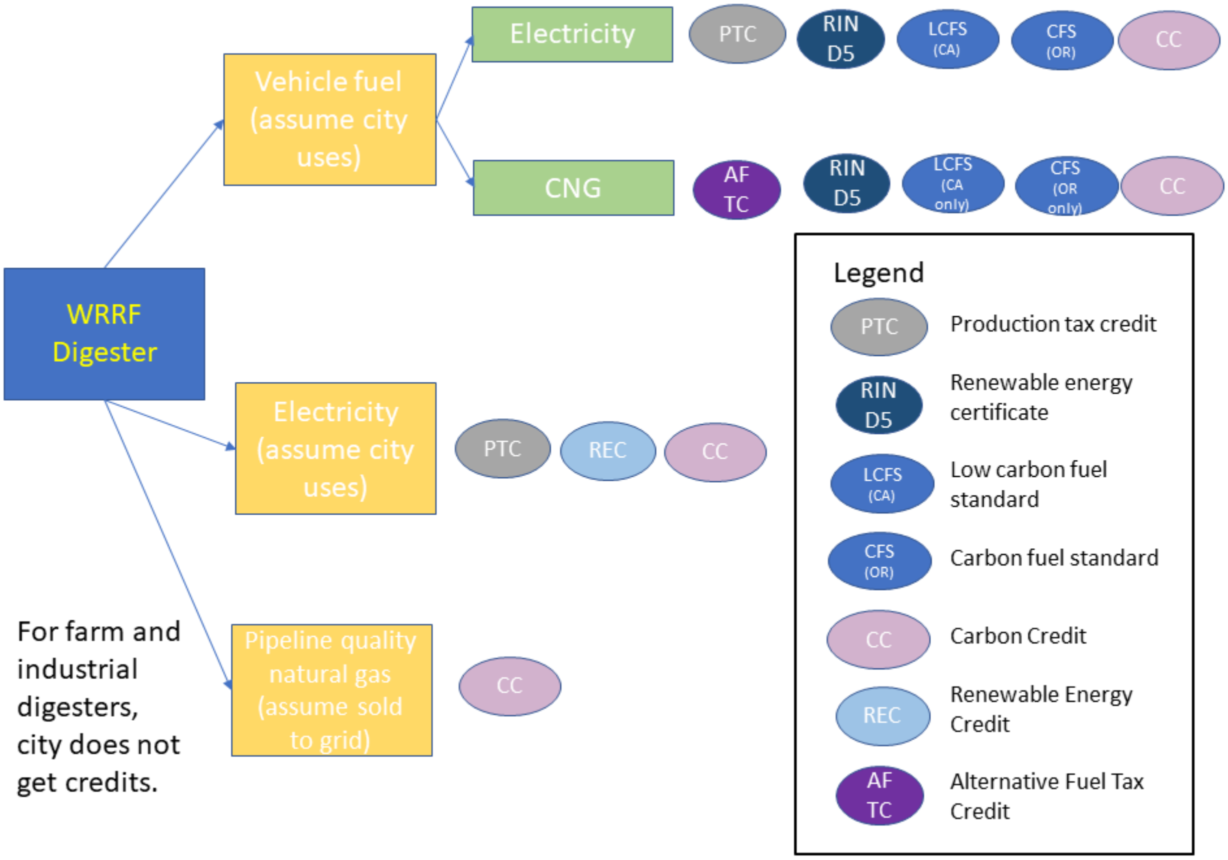


Figure 3.8. Credits included in the POWER Tool for anaerobic digesters

Table 3.30 Application and value of credits included in the POWER Tool for anaerobic digesters

Name of credit	Abbre-viation	Region	Applies to			Cost/Value
			Type of facility generating gas	Feedstock	End use of gas	
Production Tax Credit (IRS Section 45)	PTC	National	Landfill, WRRF, farm, industrial	MSW, Manure, **crop residual**	Electricity (for grid or vehicles)	1.3 cents/kWh
Renewable Energy Credit/Certificate	REC	National	Any	Any	Electricity (grid)	1 cent/kWh
Renewable Identification Number/Renewable Fuel Standard	RIN/RFS	National	MSW Landfill, livestock farms, WRRF, industrial	Categories (cellulosic, biomass, etc.) - Food waste qualifies for less valuable credit	Transportation fuel (RNG, not electricity)	$1.50/77,000 BTUs
Alternative Fuel Tax Credit	AFTC	National	MSW Landfill, livestock farms, WRRF, Organic Waste Management Operations (OWMO)	MSW, Manure, Crop residues	Transportation fuel (RNG only - not electricity)	50 cents /gallon
Low Carbon Fuel Standard	LCFS	California	MSW Landfill, livestock farms, WRRF, Organic Waste Management Operations (OWMO)	Biomass	Transportation fuel (RNG and electricity)	$199 /metric ton
Clean Fuel Standard	CFS	Oregon	Any	Any	Transportation fuel (RNG and electricity)	$145/ metric ton CO_2-e
Carbon Credit	CC	*	Any	Any	Any	$13.86 /ton

*California, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia

3.9.5 Costs for Farm and Industrial/Stand-Alone Digesters

The city is assumed not to own farm and industrial/stand-alone digesters; the city pays to transport waste to these digesters and then pays a tipping fee. Tipping fees of $16/ton and $28/ton are used for farm and industrial/stand-alone digesters, respectively (EPA, 2021). The tipping fee is assumed to cover capital and operating costs of waste pre-processing, digestion, processing of digestate, and biogas upgrading, conversion, and use. Since the city does not own the digesters, no benefits of credits are added.

3.9.6 Emission/Social Costs/Benefits

Social costs associated with all emissions are included in the Tool based on information from the Interagency Working Group on Social Cost of Carbon, United States Government (2010) and European Union Environmental Prices Handbook (version EU28, Bruynet al., 2018) as follows:

- For traditional air pollutants (VOCs, CO, NOx, PM10, PM2.5, SO_2), the value of reduced damage to human health, ecosystem services, buildings and materials, resource availability, and wellbeing
- For climate pollutants (CH_4, CO_2, N_2O), the value of reduced damage to agricultural productivity, human health, property (flood risk), and ecosystem services.

3.10 Calculation of COSTS – Landfill Baseline

Landfill transport costs were estimated similarly to those for digesters, as described in Section 3.9.1, except for the user specifying a different distance to the landfill on the Input/Output tab. Costs of pre-processing waste and constructing and operating the landfill, as well as benefits from any sales of landfill gas, are assumed to be accounted for through the tipping fee (Bolton, 2018). The fee values do not distinguish whether landfill gas is captured and beneficially used.

Table 3.31 shows regional landfill tipping fees included in the Tool. The user can also input their own specific value of landfill tipping fee.

Table 3.31 Regional landfill tipping fees (EREF, 2021)

Area (States)	Tipping Fee ($/ton)
National Average Tipping Fee	54.03
Pacific (AK, AZ, CA, HI, ID, OR, WA)	64.98
Northeast (CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT, VA, WV)	69.94
Midwest (IL, IN, IA, KS, MI, MN, MO, NE, OH, WI)	50.93
Mountains/Plains (CO, MT, ND, SD, UT, WY)	46.08
Southeast (AL, FL, GA, KY, MS, NC, SC, TN)	43.35
South Central (AR, LA, NM, OK, TX)	37.87

Landfill disposal costs ($/year) = (Tipping fee, $/ton) * (tons/year sent to landfill)

3.11 Calculation of COSTS – Composting Baseline

Compost transport costs are estimated similarly to those for digesters, as described in Section 3.9.1, except for the user specifying a different distance to the compost facility on the Input/Output tab. Costs of pre-processing waste and constructing and operating the compost facility are assumed to be accounted for through the tipping fee (Bolton, 2018). Table 3.32 shows compost tipping fees included in the Tool. The user can also input their own specific value of compost tipping fee.

Table 3.32. Compost tipping fees (Living Earth, Houston)

Category	Fee
10’ Trailer (1895 lb)	$40
12-16’ Trailer (5115-5335 lb)	$65
18’ trailer (5065 lb)	$95

Chapter 4: Optimization Tool

4.1 Problem description

Since the process of transporting and converting food and yard waste to renewable energy burdens different costs, it is necessary to employ a proper approach to identify optimized systems. In this regard, we propose a Mixed Integer Quadratic Problem (MIQP) to minimize the total cost of POWER process, including waste transportation cost, facility costs, and the expenses for digesters, while optimizing the location of digesters, the construction of new digesters, round trips of trucks for waste transportation, and the amount of transferred waste to each location over the planning horizon. In this problem, it is assumed that there is only one type of truck: a diesel garbage truck with 12 tons capacity and limited-service time per workday. Each truck transfers waste from a waste collection zone to a digestion location on a route. More than one truck with multiple trips can be assigned to each route. Moreover, it is assumed that trucks have already been bought, and they do not have purchase costs.

In this problem, there are four different types of digesters, including Farm Manure (FM), Farm Crop (FC), Water Resource Recovery Facility (WRRF), and Industrial (I) digesters. Digester costs include the capital cost of building a new digester, operating the waste treatment, and facility costs. Farm and industrial digesters do not have a fixed capacity, and consequently, they do not have fixed capital costs. Different capacities have different capital costs for building new digesters. Hence, we employ the dataset, including different capacities and corresponding costs, to fit a model for all three digesters. Linear regression models are fitted for the capital cost of farm manure, farm crop, and industrial digesters. The optimization model uses these fitted models to determine the farm and Industrial digesters' optimum capacity and corresponding capital cost.

4.2 Optimization Model

In this section, we propose an optimization model for the POWER problem. The objective function of the model equals minimizing digester facility cost + digester operating cost + digester capital cost + waste transportation cost. The digester facility cost includes two parts of fixed and variable costs. The fixed facility cost is the pre-treatment equipment cost. The variable facility cost is calculated based on the transported waste amount and the absence or presence of the grinder, storage & de-packing unit at the selected location. The digester operating cost is the waste treatment cost which is calculated for each ton of waste. The digester operating cost refers to the cost of building new a digester at each location. Finally, waste transportation cost is the cost of trucks for transferring waste to the digestion locations based on the fuel cost, driver salary, helper driver salary, and the number of the trucks' round trips. The constraints of the problem are presented in the following:

Constraint 1: Lower limit ≤ digester capacity ≤ upper limit; this constraint shows that the size of the new digester must be between the minimum and maximum allowable values.

Constraint 2: Transported waste to each new digester ≤ capacity of the new digester. This constraint means that the volume of the waste which is transported to the new digesters must be equal to or less than their capacity.

Constraint 3: Transported waste to the existing digesters ≤ unused capacity of the existing digesters; this constraint displays that amount of the transferred waste to the existing digesters must be equal to or less than their available capacity.

Constraint 4: Total transported waste to each location ≤ total waste demand; this constraint denotes that the total quantity of waste transported to each digester location must be equal to or less than the total volume of waste demand.

Constraint 5: Waste amount transported from each zone = waste demand at the zone. This constraint represents that the total volume of the waste transported from each zone must be equal to the waste demand at that zone.

Constraint 6: Transported waste by trucks ≤ total transportation capacity of trucks. This constraint symbolizes that the total waste amount transported by trucks from each zone to each location must be equal to or less than their total transportation capacity.

Constraint 7: Transported waste by trucks for each zone-location pair ≤ Total transportation capacity of trucks for the pair; this constraint symbolizes that the total transported waste by trucks from each zone to each digester location must be equal to or less than their transportation capacity from that zone to that digester location.

4.3 Graphical user interface (GUI)

In this section, we develop a GUI application to enable the user to control the optimization environment by button clicks and simple data entry. This application has two versions with and without time limitations. The optimization tool will find the optimal solution in the unlimited-time version, but execution time for large data sets may take more than an hour. The user can limit the run time in the limited-time version by selecting an option between 15minutes-30minutes and the optimization tool will find the best possible solution within the specified time limit. Figure 1 shows the master screen of the GUI application. When the application is opened, the user can upload the input file by clicking on the Browse button on the master screen. The input file is a prepared Excel file with five spreadsheets. The user needs to determine digestion locations and their type in the $A(a, l)$ matrix sheet. The total unused capacity of existing digesters at each location needs to be specified in the Unused Capacity sheet. The user must determine each zone's waste collection in the Waste sheet. In the Distance sheet, the user is asked to establish the distance between waste collection zones and digestion locations, and velocity corresponding to each distance. Lastly, in the Digester Facility Cost sheet, the user must enter the value of categorical variables for the absence of a grinder, waste storage, and de-packaging unit at each WRRF digestion location. All of the mentioned spreadsheets include filing instructions. Once the input file is uploaded, the user will be taken back to the master screen. In the first to fifth entries, the user needs to enter the maximum allowable number of new constructible digesters at each WRRF, farm manure, farm crop, and industrial digestion locations, respectively. In the sixth entry, the user must enter the number of workdays of the trucks per week. In the seventh entry, the user must enter the maximum allowed service time of the trucks, then click on the select an option drop down menu to choose model runtime from the available options. Finally, clicking on the Run button executes the optimization model, and the output is stored in the folder, including the input file.

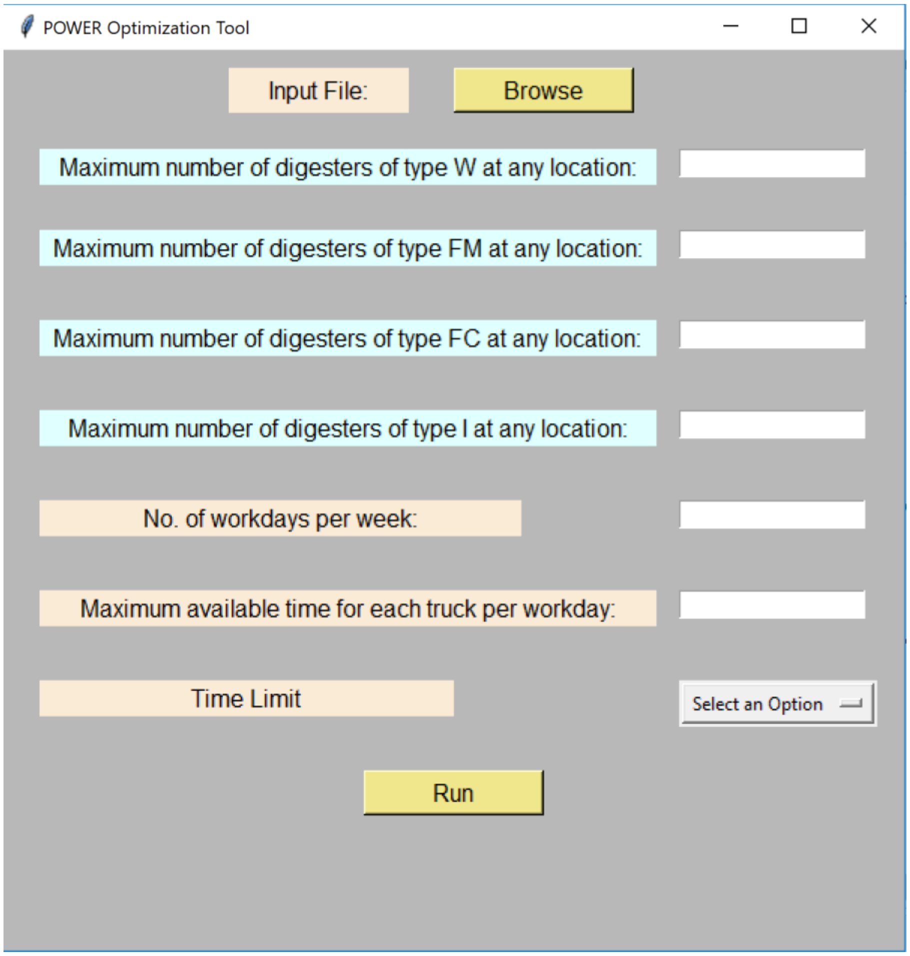


Figure 4.1. GUI application master screen

Chapter 5: Feasibility Study for Vermont

Using the upgraded POWER Framework, feasibility studies were conducted for 2 locations with demonstrated commitment to food waste diversion – Vermont and Las Vegas – both of whom provided input for the City Guidebook developed during the previous project. Ch. 5 discusses the feasibility study for Vermont, and Ch. 6 discusses the study for Las Vegas.

Vermont's food waste ban took effect on July 1, 2020, banning the disposal of food scraps in the trash or landfills, for residents and businesses. Currently, Vermont residents are encouraged to conduct at home composting, and businesses are encouraged to donate food waste when possible. (VDEC 2020a, b) An opportunity exists to initiate a program for diverting food waste to digesters.

The questions to be addressed by the Vermont feasibility study were:

- What are optimal locations of existing and new digesters for digesting all organics (food, yard, FOG, manure, crop residuals) in the study area?
- What would be the benefit in terms of energy/electricity, emissions and economics?

The approach and data inputs for addressing the questions above, as well as results, are discussed in more detail below.

5.1 Vermont Feasibility Study Area

The study area chosen within Vermont (Fig. 5.1) extends 50 miles from west to east and covers 528,700 acres. It includes Essex Junction and Chittenden on the western side and Montpelier on the eastern side and contains farm digesters and water resource recovery facility digesters.

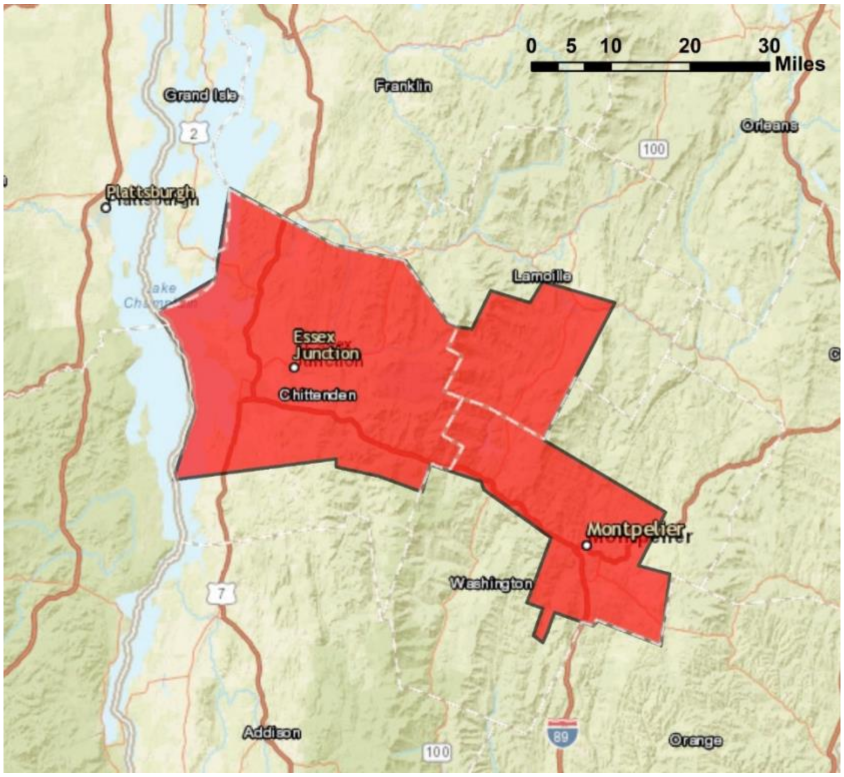


Figure 5.1 Vermont study area

Although a study entitled "Geotargeting Manure Digesters on Vermont Farms" was conducted previously by Stone Environmental, its goals were very different from our study. Stone's study aimed to identify the best 3-5 locations statewide for constructing new digesters to co-digest food waste and manure, based on feedstock availability and competitors (existing digesters and compost facilities). The Stone study did not consider:

- Digestion of other types of organics (yard waste, FOG, crop residuals),
- Non-farm digester locations (existing WRRF and stand- alone/industrial digesters, as well as potential new locations at WRRF without digesters, compost facilities, landfills, and industrial sites).
- Utilization of unused capacity of existing farm digesters,
- Amount of energy/electricity that could be produced,
- Potential emission reductions,
- Costs/benefits (other than utility line extensions).

5.2 Locations of existing and potential new digesters, and waste generation estimates, for the study area

Lists of digesters in the state of Vermont were obtained from the Vermont Dept. of Environmental Conservation, EPA AgStar database, and Vermont Agency of Natural Resources. Table 5.1 lists 17 locations of existing (E) and potential (P) new digesters in the study region, along with available capacities and equipment for pre-processing. Eight locations have existing digesters: 6 of these are located at WRRFs and 2 at breweries (counted as industrial). The WRRF at Stowe contains an ATAD (Autothermal Thermophilic Aerobic Digestion) digester, which is not currently operating, but could be converted to anaerobic digestion and utilized as a potential site. It was thus counted as a location with an existing digester. The Magic Hat (Zero Gravity) Digester in South Burlington digests brewery waste and food waste as part of a partnership with Casella and Purpose Energy, who own/run the digester. Vermont government officials provided information about current WRRF with digesters.

Table 5.1 also lists 9 potential locations for new digesters. 6 of these are WRRFs, one is a brewery, and two are FOG collection centers. Of the 6 WRRF locations, 3 actually have digesters (Barre, Burlington North, and Burlington South Airport). Considering them as potential sites represents a worst-case scenario, with 0 capacity remaining at existing digesters. Although landfills and composting facilities were considered as possible locations, none were located within the study area.

Table 5.1 Information about existing and potential digester locations in the Vermont study area

No.	Location		Type	Available Capacity, MG	Availability of waste pre-processing equipment			Annual Avg. Temp. (°F)	Notes
	No.	Name			Grind-er	Stor-age	Depack-aging unit		
1	EI01	Magic Hat Brewery	Ind.	0.016	No	Yes	No	N/A	Currently digests brewery waste and food waste
2	EI02	Fiddlehead Brewerie	Ind.	0.15	No	Yes	No	N/A	
3	PW01	Barre	WRRF	0	No	No	No	42.63	
4	EW03	Montpelier	WRRF	2.87	No	No	No	43	
5	PW03	South Burlington	WRRF	0	No	No	No	46.1	
6	PW09	Burlington North Ave.	WRRF	0	No	No	No	46.1	
7	PW04	Burlington Riverside	WRRF	0	No	No	No	46.1	
8	EW10	Stowe	WRRF	0.56	No	No	No	42.3	Aerobic; could be converted
9	PW06	Northfield	WRRF	0.33	No	No	No	42.5	Sequencing batch reactor, which could be converted
10	PW08	Milton	WRRF	0	No	No	No	45	
11	EW04	Burlington Main	WRRF	0.1	No	No	No	46.1	
12	EW08	Essex Junction	WRRF	1.4	No	No	No	45.2	
13	PF01	Baker Commodities	Ind. (FOG)	0	No	Yes	No	N/A	
14	PF02	City of Burlington	Ind. (FOG)	0	No	Yes	No	N/A	
15	PI01	Alchemist Brewery	Ind.	0	No	No	No	N/A	
16	EW11	Shelburne	WRRF	0.50	No	No	No	45.4	
17	EW12	Waterbury	WRRF	0.0083	No	No	No	44.1	

Notes:

- For the digester number, the first letter is E for existing, P for potential/new. The second letter is I for industrial, W for water resource recovery facility, and F for fats, oils, grease.
- Ind. indicates Industrial/stand-alone; WRRF indicates water resource recovery facility. Average annual temperature is needed only for WRRFs.

Figures 5.2-5.7 show the locations of the 8 existing and 9 potential new digesters included in the study, as well as waste generation estimates. **Digesters that were chosen by the optimization have their names provided.** Block groups with the highest total organic waste generation included those around Essex Junction and Montpelier. The pink circle slightly outside the study area to the southwest is located in a city which is counted in the study area. The waste generation estimates were obtained using the GIS Toolbox. Waste from special event centers was not included because we did not have access to GIS Business Analyst during the study period.

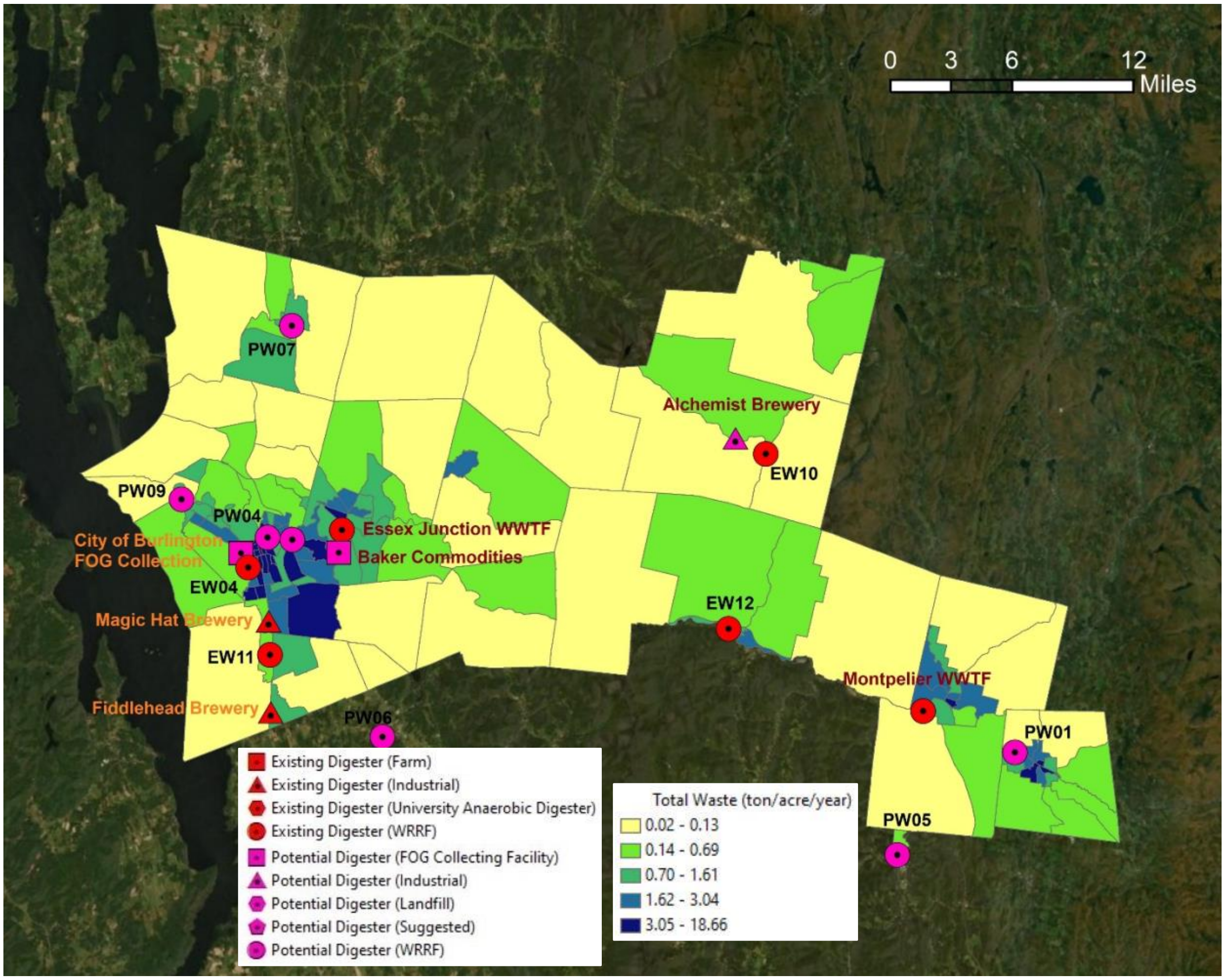


Figure 5.2. Total organic waste estimates, and locations of existing and potential digesters, for Vermont study area

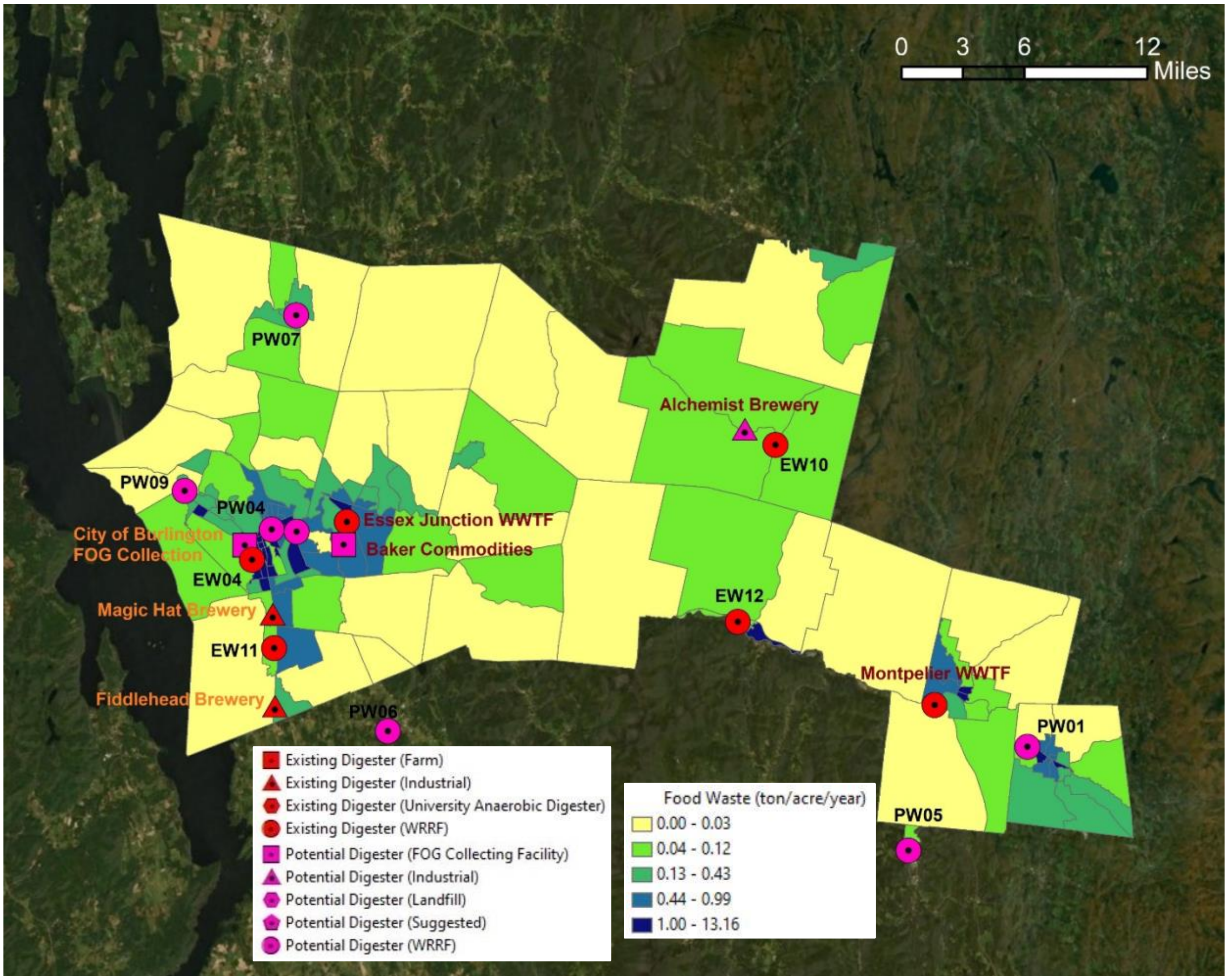


Figure 5.3. Food waste estimates, and locations of existing and potential digesters, for Vermont study area

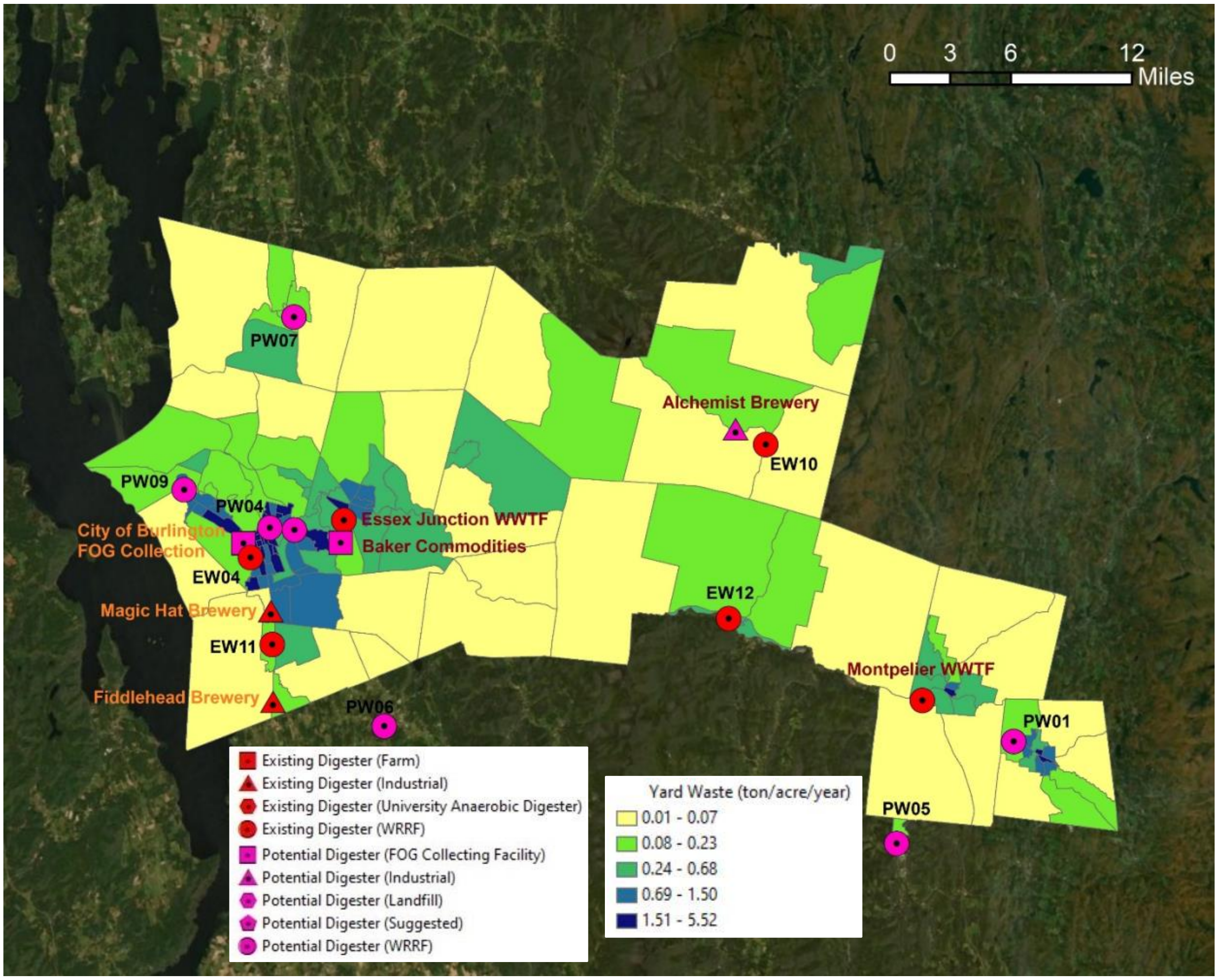


Figure 5.4. Yard waste estimates, and locations of existing and potential digesters, for Vermont study area

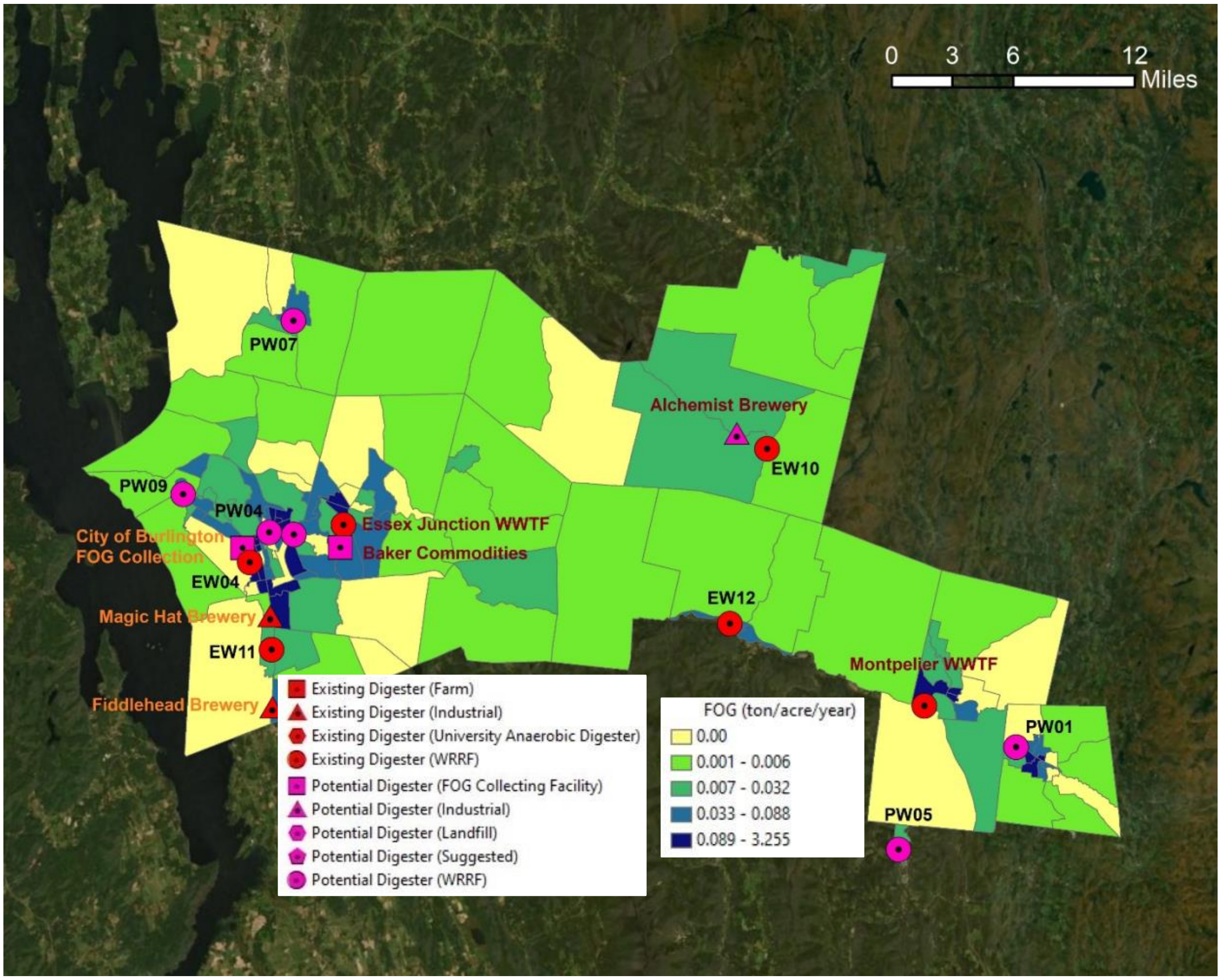


Figure 5.5. FOG waste estimates, and locations of existing and potential digesters, for Vermont study area

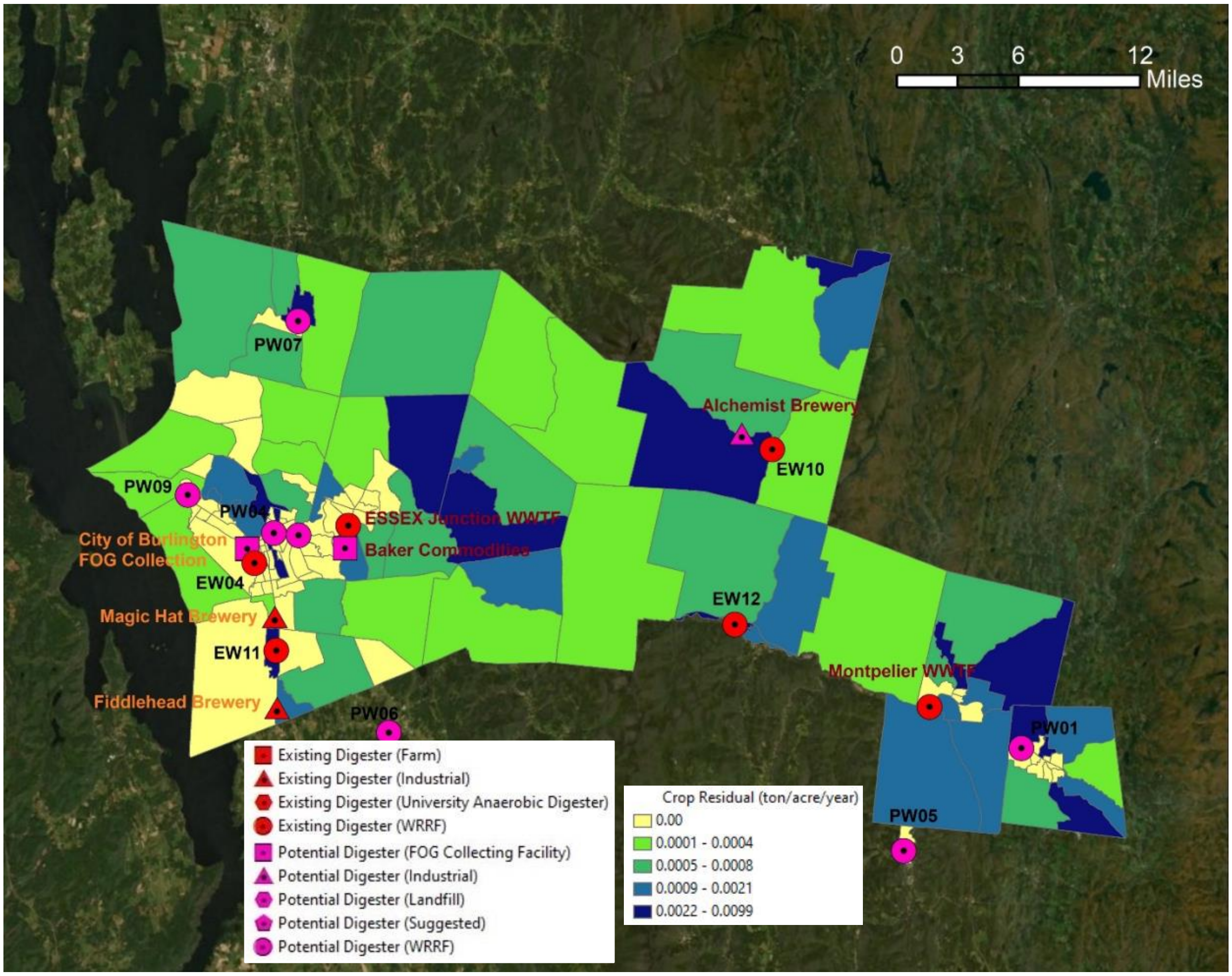


Figure 5.6. Crop residual waste estimates, and locations of existing and potential digesters, for Vermont study area

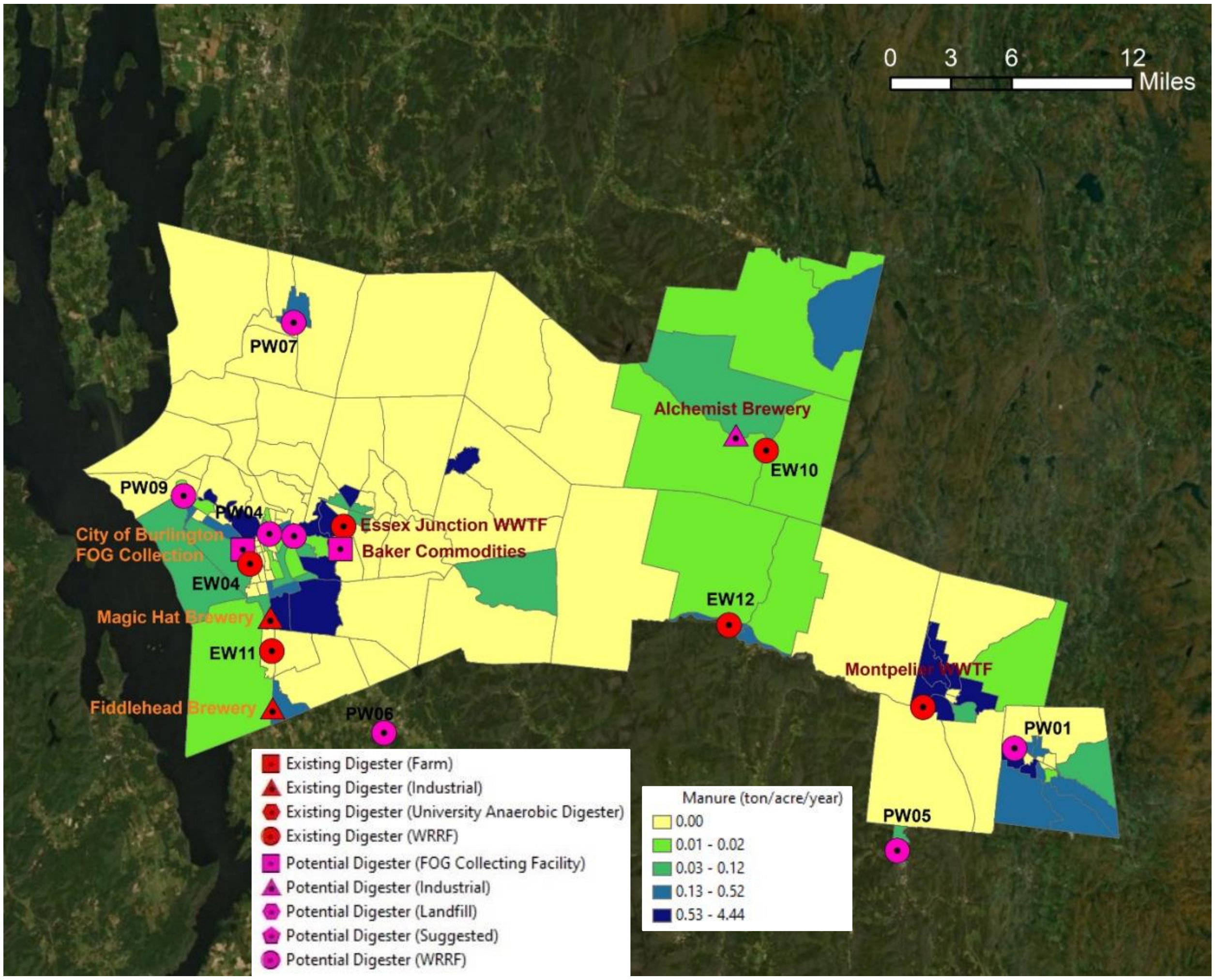


Figure 5.8. Manure waste estimates, and locations of existing and potential digesters, for Vermont study area

5.3 Determination of optimal locations of existing and new digesters for digesting all organics in the study area

The Optimization Tool was used to determine the optimal locations of existing and new digesters for digesting all organics in the study area. Inputs to the Optimization Tool included:

- Total waste generation by block group (from GIS Toolbox, as shown in Fig. 5.2),
- Transport distances and velocities (from GIS Toolbox) from each block group to the digester or landfill facility (baseline used as comparison),
- Capacity and pre-processing information from Table 5.1.

Optimization Tool outputs are shown in Table 5.2 and Figure 5.1 (chosen digester locations are indicated by labels with the name of the digester). Optimal digester locations include:

- Potential sites at 2 FOG collection centers and the Alchemist Brewery.
- Existing sites at Magic Hat Brewery and Fiddlehead Brewerie, as well as WRRFs at Montpelier and Essex Junction.

Table 5.2 Summary of optimal locations of existing and new digesters for digesting all organics in Vermont study area

Selected Location			**No. of Digesters**		**Waste amount (tons/year)**		
No.	**Name**	**Type**	**Existing**	**New**	**Existing digester**	**New digester**	**Total**
EI01	Magic Hat Brewery	Ind.	1	1	69	29,498	29,567
EI02	Fiddlehead Brewerie	Ind.	1	0	62.6	N/A	62.6
PF01	Baker Commodities	Ind.	N/A	2	N/A	49,004	49,004
PF02	City of Burlington	Ind.	N/A	1	N/A	29,768	29,768
PI01	Alchemist Brewery	Ind.	N/A	1	N/A	29,631	29,631
EW03	Montpelier	WRRF	1	0	11,966	N/A	11,966
EW08	Essex Junction	WRRF	1	0	5,838	N/A	5,838
TOTAL			**4**	**4**	**17,936**	**137,901**	**155,837**

All 5 industrial locations (2 existing and 3 potential) were chosen. Of the 6 WRRFs with existing capacity, the two locations chosen were the ones with the largest existing capacities of 2.87 and 1.4 million gallons (EW03 and EW08, respectively). In the 2 cases when a potential industrial digester was chosen (PF02 and PI01), an existing WRRF digester with excess capacity was available nearby, but the capacity was small (EW04 and EW10, respectively, with respective capacities of 0.1 and 0.56 MG). Pre-treatment equipment would need to have been added at the WRRF sites, and the small amount of capacity available did not justify the costs of adding pre-treatment equipment.

In terms of digester capital/operating vs. transport costs, transport costs were high enough that the optimization chose building a new digester at PI01 in the east over transporting waste to a digester in the west. However, transport costs were not high enough to force the optimization to select adding a digester at location PW07 in the north.

5.4 Determination of energy production, emissions, and costs/benefits for digesting waste at the optimal digesters

The POWER Tool was used to determine energy production, emissions, and costs/benefits for digesting all organic waste in the study area at the optimal digesters, compared to landfilling as the current business-is-usual scenario.

5.4.1 POWER Tool inputs

7 POWER Tool runs were conducted, one for each of the 7 optimal digester locations. Inputs related to the digesters themselves were the same as those shown in Table 5.1. Since the POWER Tool does not allow for capacity in existing industrial digesters, existing industrial digesters were input as farm digesters. This will be fixed in a future version of the Tool.

Table 5.3 shows waste and transport information used as inputs for the runs. The Optimization Tool does not distinguish among the kinds of organic waste; hence, the fractions of various kinds of waste (e.g. food waste, yard waste) to be sent to each digester were taken as the fractions of waste for the entire small study area, determined using GIS. The waste totals shown in Table 5.3 are the same as those shown in Table 5.2, from the optimization. Table 5.3 also shows average distance and speed for transport of waste from the block groups to each chosen digester; the distances and speeds were determined using the GIS Toolbox.

Table 5.3 Waste and transport inputs for the 7 runs for the Vermont case study

Selected Location		**Digester**	**Waste amount** (tons/year)						**Transport from block groups**	
No.	**Name**		**Food**	**Yard**	**Manure**	**Crop Residuals**	**FOG**	**Total**	**Average distance** (miles)	**Average speed** (miles/hour)
EI01	Magic Hat Brewery	Existing	19	31	17	0.2	2	69	18.7	45.1
		New	8235	13,348	7106	92.4	786	29,567	18.7	45.1
EI02	Fiddlehead Brewery	Existing	17	28	15	0.2	2	63	22.3	44.6
		New	17	28	15	0.2	2	63	22.3	44.6
PF01	Baker Commodities	New	13,648	22,123	11,777	153.2	1303	49,004	16.5	43.3
PF02	City of Burlington	New	8291	13,439	7154	93.1	791	29,768	17.7	39.1
PI01	Alchemist Brewery	New	8253	13,377	7121	92.6	788	29,631	33.3	53.5
EW03	Montpelier	Existing	3333	5402	2876	37.4	318	11,966	31.6	58.5
EW08	Essex Junction	Existing	1626	2636	1403	18.3	155	5,838	16.8	40.9
TOTAL			**48,399**	**78,448**	**41,762**	**543.2**	**4,620**	**155,968**	**N/A**	**N/A**

Table 5.4 shows inputs to the POWER Tool that were constant across all digester locations for the Vermont case study. Coventry is the location of the state's largest and only currently active landfill known as New England Waste Services Vermont or NEWSVT, which is owned and operated by Casella Waste Management. The landfill gas is used to power several methane combustion engines that produce electricity as part of Washington County Electric's grid. The Coventry Landfill is used as the baseline.

Table 5.4 POWER Tool inputs – constant across all digester locations for Vermont case study

Variable		Value	Data source
Major category	**Sub-category**		
Gas conversion and use	Cost of electricity (if something besides default is used)	N/A	N/A
	End use(s) of biogas	50% Garbage Truck 50% Electricity-Reciprocating Engines	N/A
	Technology to convert biogas to electricity	With Charging Station (Biogas to Electricity Standard Reciprocating Engine-Generator Set)	N/A
	Whether charging station or RNG refueling station is available	N/A	N/A
Transport	Fuel for waste collection vehicle	Diesel	
Baseline	Landfill or compost facility (name)	NEWSVT Landfill, Coventry	Landfill data in the USA
	User input tipping fee (if applicable)	N/A	N/A
	Average transport **distance** from block groups to baseline facility	74.5	GIS
	Average transport **speed** from block groups to baseline facility	55.71	GIS

5.4.2 POWER Tool outputs

Tables 5.5 – 5.8 show POWER Tool outputs for energy production, emissions, costs, and benefits for the Vermont case study, by digester location and total. Biogas, energy, and electricity production are proportional to the weight of waste sent to each digester, since the fraction of waste components is assumed to be the same for each digester. The right-hand column in Table 5.5 provides an estimate of the amount of electricity that would be produced, if all of the waste were used to generate electricity (the POWER Tool provides this as a useful piece of information, regardless of the chosen biogas end use). As shown in the bottom 3 lines of the table, more biogas was produced from digesting organics compared to landfilling; this is due to a higher fraction of gas being captured, and a higher methane content of the gas.

Table 5.5 POWER Tool outputs – Energy production for Vermont case study

Selected Location			**Energy Production**		
No.	**Name**	**Digester**	**Biogas** (m^3/day)	**Energy** (MMBTUs/year)	**100% Electricity** (MWh/yr)
EI01	Magic Hat Brewery	Existing	17	169	15
		New	7,360	72,795	6,241
EI02	Fiddlehead Brewery	Existing	16	154	13
PF01	Baker Commodities	New	12,199	120,653	10,343
PF02	City of Burlington	New	7,410	73,292	6,283
PI01	Alchemist Brewery	New	7,376	72,954	6,254
EW03	Montpelier	Existing	2,979	29,462	2,526
EW08	Essex Junction	Existing	1,453	14,374	1,232
DIGESTER TOTAL			**38,809**	**383,855**	**32,907**
Landfill Baseline			14,341	140,754	12,066
Difference: Digester – Landfill Baseline			**24,468**	**243,101**	**20,840**

As shown in Table 5.6, digesting organic waste would reduce greenhouse gas emissions compared to the regular power mix and use of landfill gas (the parentheses indicate negative numbers, or a reduction in emissions). Traditional air pollutants from digestion are slightly higher than the regular power mix, likely due to greater impurities in digester gas, except for PM 2.5. Traditional air pollutants from digester gas combustion are lower than those from landfill gas.

Table 5.6 POWER Tool outputs – Emissions for Vermont case study, compared to baseline of regular power mix

Selected Location			**Emissions (kg/year)**				
No.	**Name**	**Digester**	**VOCs**	**NOx**	**PM10**	**PM2.5**	**GHG**
EI01	Magic Hat Brewery	Existing	1	2	1	0	(1,783)
		New	234	491	187	(8)	(766,511)
EI02	Fiddlehead Brewery	Existing	1	2	1	0	(1,622)
PF01	Baker Commodities	New	355	724	286	(13)	(1,270,428)
PF02	City of Burlington	New	234	490	188	(8)	(771,735)
PI01	Alchemist Brewery	New	250	547	189	(7)	(768,177)
EW03	Montpelier	Existing	113	253	87	(3)	(325,653)
EW08	Essex Junction	Existing	57	127	47	(2)	(177,997)
TOTAL			**1,245**	**2,634**	**986**	**(39)**	**(4,083,905)**
Landfill baseline			7,891	69,389	1,429	327	630,062
Difference: Digester – Landfill Baseline			**(6,646)**	**(66,755)**	**(443)**	**(366)**	**(4,713,967)**

Note: ( ) shows emissions savings for using AD.

Table 5.7 summarizes overall costs for the Vermont case study. Costs are shown as positive, and benefits are shown in parentheses (negative costs). The “SUB-TOTAL” column shows out-of-pocket costs; “Emissions/Social Costs” are then added and “Total Benefits” are subtracted to get the overall “NET COSTS.” (Table 5.8 shows the credits that comprise the benefits in detail.) The “NET COSTS” for each of the digesters are negative, indicating that the benefits outweigh the costs. In estimating the “Total Benefits,” it was assumed that all the potential credits are obtained. This may be overly optimistic for actual cases.

As shown in the last 3 rows of Table 5.7, “NET COSTS” for digestion are estimated to be lower than those for landfilling. Benefits are not shown for landfilling, because the POWER Tool assumes that the city pays a tipping fee to the entity owning the landfill (not the city); any benefits accrue to that entity and are reflected in the tipping fee.

Table 5.7 POWER Tool outputs – Digester costs for Vermont case study

Selected Location			Costs (thousands of dollars)									
No.	**Name**	**Digester**	**Alt. Fuel Vehicles – Capital Costs**	**Waste Transport – Operating Costs**	**Pre-Processing Costs**	**AD Costs**	**Biogas Conversion Costs**	**SUB-TOTAL Out-of-pocket costs**	**Emissions/ Social Costs**	**Total Benefits**	**NET COSTS**
EI01	Magic Hat Brewery	Existing	$38	$16	$71	$60	$132	$317	$203	($753)	($233)
		New	$16,129	$6,908	$822	$25,933	$9,815	$59,607	$86,642	($323,947)	($177,698)
EI02	Fiddlehead Brewery	Existing	$34	$17	$71	$55	$126	$303	$184	($686)	($199)
PF01	Baker Commodities	New	$26,732	$10,213	$1,316	$42,982	$14,757	$96,000	$143,527	($536,914)	($297,387)
PF02	City of Burlington	New	$16,239	$6,859	$827	$26,110	$9,869	$59,904	$87,358	($326,154)	($178,892)
PI01	Alchemist Brewery	New	$16,164	$11,768	$823	$25,989	$9,833	$64,577	$87,066	($324,650)	($173,007)
EW03	Montpelier	Existing	$6,528	$4,415	$374	$41	$4,745	$16,103	$677	($131,109)	($114,329)
EW08	Essex Junction	Existing	$3,185	$1,261	$218	$60	$2,678	$7,402	$1,160	($63,965)	($55,403)
TOTAL			**$85,048**	**$41,457**	**$4,520**	**$121,230**	**$51,956**	**$304,213**	**$406,817**	**($1,708,178)**	**($997,148)**
Landfill baseline								**$468,077**	**$940,056**	**N/A**	**$1,340,699**
Difference: Digester – Landfill Baseline								**($8,620)**	**($533,240)**	N/A	**($2,379,304)**

Table 5.8 POWER Tool outputs – Digester benefits for Vermont case study

Selected Location			Benefits (thousands of dollars)						
No.	**Name**	**Digester**	**Fuel cost savings**	**Production tax credit**	**Renewable Energy Credits**	**LCFS Credits**	**CFS Credits**	**Carbon Credits**	**TOTAL**
EI01	Magic Hat Brewery	Existing	$104	$3	$2	$345	$251	$48	$753
		New	$44,521	$1,275	$981	$148,383	$108,118	$20,669	$323,947
EI02	Fiddlehead Brewery	Existing	$94	$3	$2	$314	$229	$44	$686
		New	$73,790	$2,113	$1,625	$245,932	$179,197	$34,257	$536,914
PF01	Baker Commodities	New	$44,825	$1,283	$987	$149,394	$108,855	$20,810	$326,154
PF02	City of Burlington	New	$44,618	$1,277	$983	$148,705	$108,353	$20,714	$324,650
PI01	Alchemist Brewery	New	$18,019	$516	$397	$60,054	$43,758	$8,365	$131,109
EW03	Montpelier	Existing	$8,791	$252	$194	$29,299	$21,348	$4,081	$63,965
TOTAL			**$234,762**	**$6,721**	**$5,170**	**$782,425**	**$570,109**	**$108,989**	**$1,708,178**

Chapter 6: Feasibility Study for Las Vegas

Using the upgraded POWER Framework, feasibility studies were conducted for 2 locations with demonstrated commitment to food waste diversion – Vermont and Las Vegas – both of whom provided input for the City Guidebook developed during the previous project. Ch. 5 discussed the feasibility study for Vermont, and this chapter discusses the study for Las Vegas.

6.1 Introduction

6.1.1 Study area

The boundary for the case study is the Las Vegas Valley, shown in Fig. 6.1 below. It from Spring Valley on the west to Boulder City on the east.

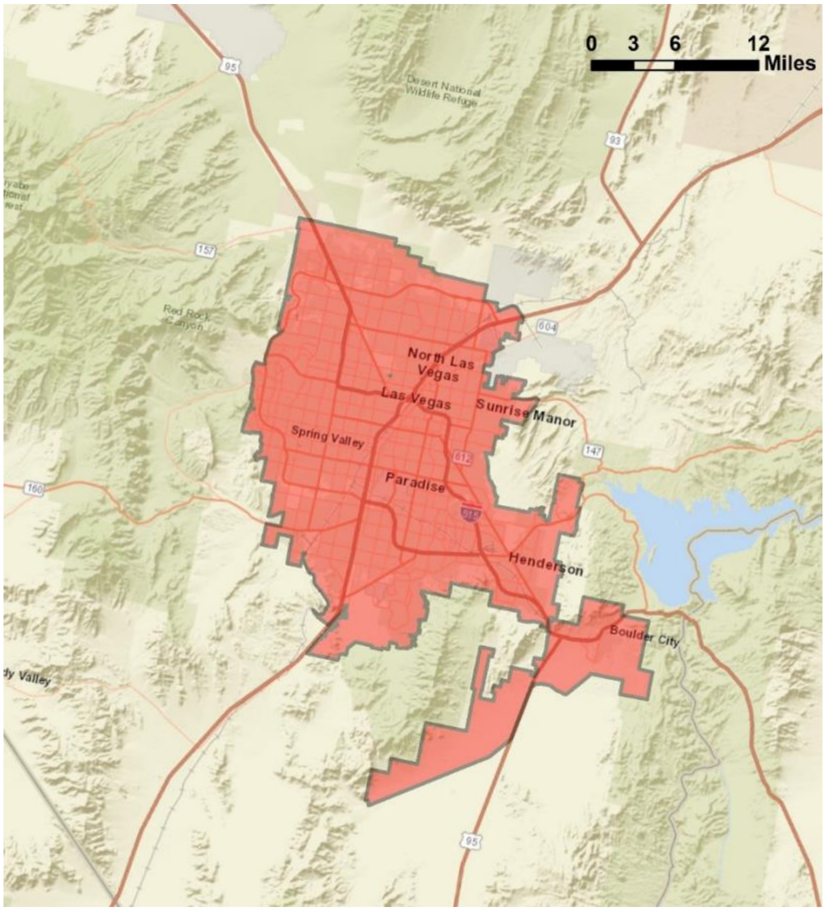


Figure 6.1 Las Vegas study area

6.1.2 Current waste generation and disposal issues in the Las Vegas Valley

This section highlights some of the current waste generation and disposal issues facing the Las Vegas Valley.

Food waste from casinos. Casinos are the largest producer of food waste in the Las Vegas Valley (25,398 tons per year, as of 2013), due to the regulatory constraints surrounding food safety (BioCycle, 2015). Food that is on-line, being available for self-service, is deemed non-edible if it is out and hot after 4 hours and thereby becomes food waste. Presently, the food waste is diverted from the landfill to a pig farm for livestock agriculture feed and compost. It should be noted that although composting produces a soil amendment, it does not produce energy.

Food waste from the school district. Food for the school district is prepared in a central kitchen, and then distributed to local schools. The central kitchen generates a large amount of food waste. The school district has expressed interest in sending this waste to an anaerobic digester to generate energy.

Digesters at WRRFs. 12 existing digesters are located at the City of Las Vegas Water Pollution Control Facility. FOG is currently collected separately from other trash and co-digested. However, there is no existing capacity to digest additional waste; new digesters would need to be added.

Landfill. The landfill that serves the Las Vegas Valley does capture landfill gas for energy. However, on average only 50% of methane generated from food waste is captured as landfill gas, with major losses before the gas collection and recovery system is installed, as well as leaks through the cover even after the system is installed. An anaerobic digester is an enclosed system, and thus captures all methane generated. In addition, due to more ideal conditions in the digester, a larger fraction of waste is converted to methane (around 60%) compared to a landfill (around 50%). Hence, an opportunity exists to increase renewable energy production via diversion of organic waste to digesters.

The current contract for waste hauling to the landfill extends to 2035. Hence, the city will not be able to divert organic waste from the landfill to a digester until then.

6.1.3 Questions to be addressed by the case study

The questions to be addressed by the Las Vegas feasibility study are:

- What is optimal location(s) of new digesters for digesting various categories of waste (all food, casino food only, K-12 school food only, FOG, total)?

- What would be the benefit for digesting the various categories of waste at the optimal location(s), in terms of energy/electricity, emissions and economics?

The approach and data inputs for addressing the questions above, as well as results, are discussed in more detail below.

6.2 Locations of existing and potential new digesters, and waste generation estimates, for the study area

Table 6.1 lists 23 locations of existing (E) and potential (P) new digesters in the study region, along with available equipment for pre-processing. Only one location has existing digesters (the City of Las Vegas Water Pollution Control Facility), but it has no available capacity. The 22 potential locations for new digesters include:

- 7 WRRFs without digesters,
- 3 compost facilities,
- 3 industrial sites (breweries),
- 2 sites where a large amount of waste is available but other candidate sites are not nearby,
- 3 FOG collection facilities,
- the school district central kitchen, a food bank, the pig farm where casino waste is currently taken, and the area landfill.

Brewery waste is a good candidate for anaerobic digestion. The breweries included were identified by US EPA (2022).

Table 6.1 Information about existing and potential digester locations in the Las Vegas study area

No.	Location			Type	Waste pre-processing equipment available?		
	No.	Owner/Operator	Name		Grinder	Storage	Depackaging unit
1	PK01	Clark County School District	Central kitchen	Ind.	Yes	Yes	No
2	PW01	City of Henderson	Kurt R. Segler Water Reclamation Facility	WRRF	No	No	No
3	PW02	Clark County Water Reclamation District	Desert Breeze Water Resource Center	WRRF	No	No	No
4	PW03	Clark County Water Reclamation District	Flamingo Water Resource Center	WRRF	No	No	No
5	PW04	City of Las Vegas	Bonanza Mojave Water Resource Center	WRRF	No	No	No
6	PW05	City of Las Vegas	Durango Hills Water Resource Center	WRRF	No	No	No
7	EW01	City of Las Vegas	Water Pollution Control Facility	WRRF	No	Yes	No
8	PW06	City of North Las Vegas	Water Reclamation Facility	WRRF	No	No	No
9	PW07	City of Henderson	Southwest Water Reclamation Facility	WRRF	No	No	No
10	PB01	Three Square	Three Square Food Bank	Ind.	No	No	No
11	PC01	Western Elite, Inc.	Compost facility	Ind.	No	No	No
12	PC02	Terra Firma Organics	Compost facility	Ind.	No	No	No
13	PC03	Viva La Compost	Compost facility	Ind.	No	No	No
14	PP01	Las Vegas Livestock LLC	Pig farm	Farm	No	No	No
15	PI01	Boulder Dam Brewing Co.	Brewing facility	Ind.	No	No	No
16	PI02	Triple 7	Restaurant and Microbrewery	Ind.	No	No	No
17	PI03	Tenaya Creek	Brewery	Ind.	No	No	No

18	PL01	APEX	Landfill	Ind.	No	No	No
19	PS01	N/A	Suggested Potential Digester – Vacant land at W. Cactus Ave	Ind.	No	No	No
20	PS02	N/A	Suggested Potential Digester - Vacant land at N. Durango Dr. and Maggie Ave.	Ind.	No	No	No
21	PF01	RenuOil of America	RenuOil (FOG Collecting, Recycling, and Supplier)	Ind.	No	No	No
22	PF02	Baker Commodities, Inc.	Baker Commodities (FOG Collecting, Recycling, and Supplier)	Ind.	No	No	No
23	PF03	Darling International	DAR PRO Solution (FOG Collecting, Recycling, and Supplier)	Ind.	No	No	No

Notes: For the digester number, the first letter is E for existing, P for potential/new. The second letter indicates the following:
K-kitchen
W-Waste water treatment facility or water recovery/reclamation facility
B-Food Bank
C-Compost facility
P-pig farm
I-industrial location such as a brewery
L-landfill site
S-suggested location
F-FOG collecting facility

Ind. indicates Industrial/stand-alone; WRRF indicates water resource recovery facility. Average annual temperature is needed only for WRRFs.

Figures 6.2 – 6.6 show the location of the one existing digester, and 22 potential new digester locations, in the study area. **Digesters that were chosen by the optimization have their names provided.** Waste generation estimates are also shown for the 5 waste scenarios (all food, casino food only, K-12 school food only, FOG, total). The waste generation estimates were obtained using the GIS Toolbox. Waste from special event centers was not included because we did not have access to GIS Business Analyst during the study period.

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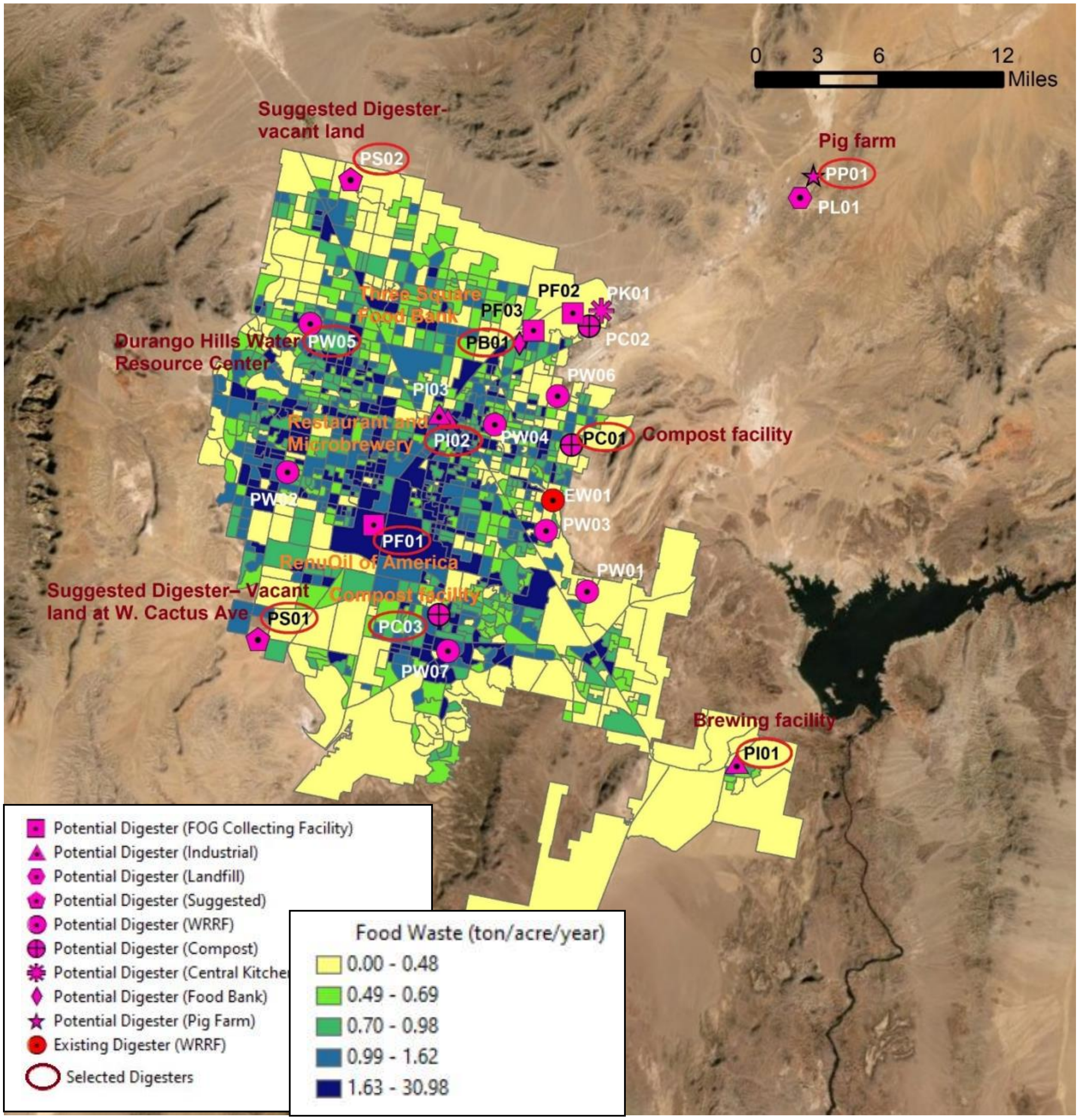

Figure 6.2. All food waste estimates, and locations of existing and potential digesters, for Las Vegas Valley

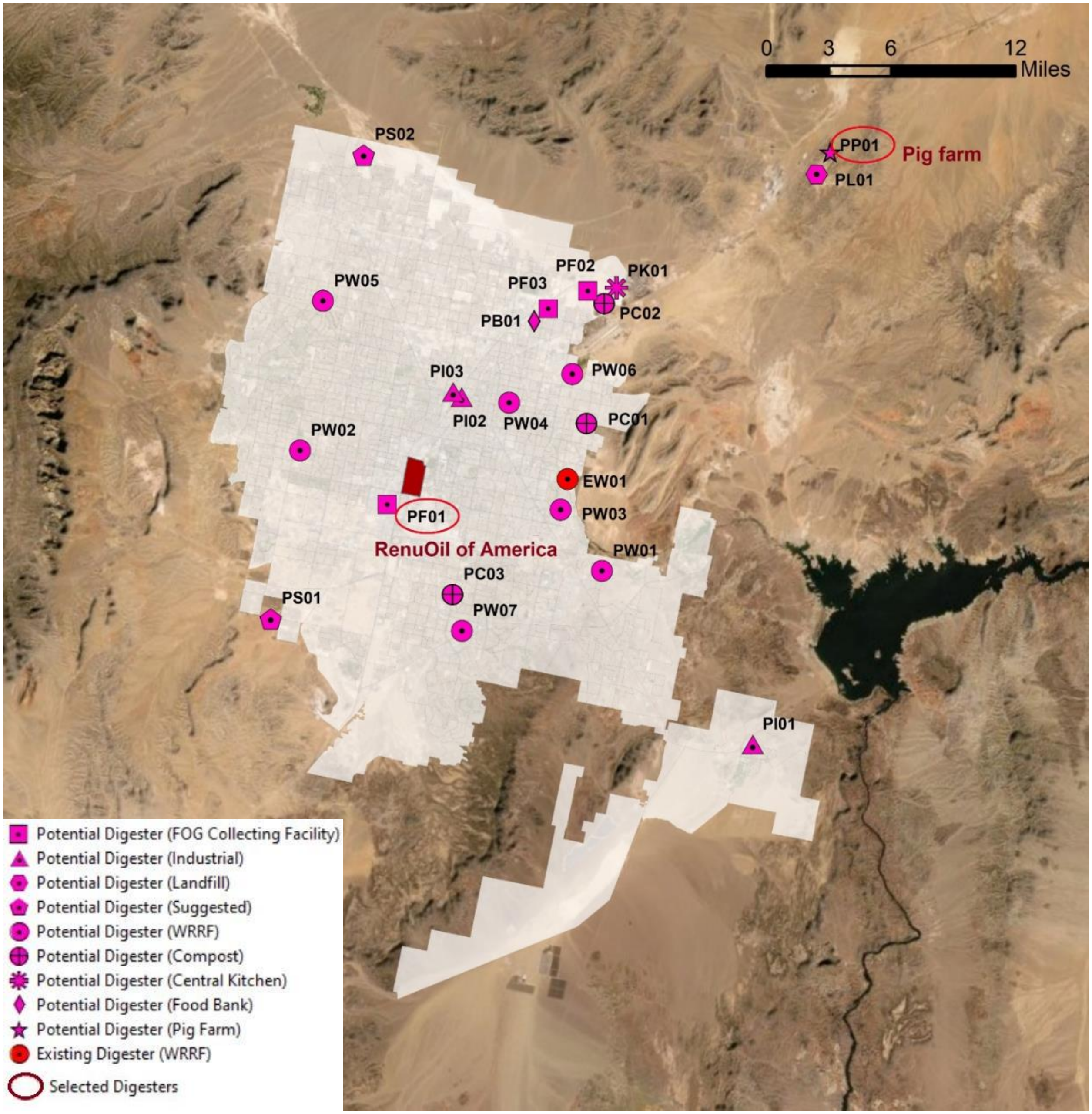

Figure 6.3. Casino food waste estimates, and locations of existing and potential digesters, for Las Vegas Valley

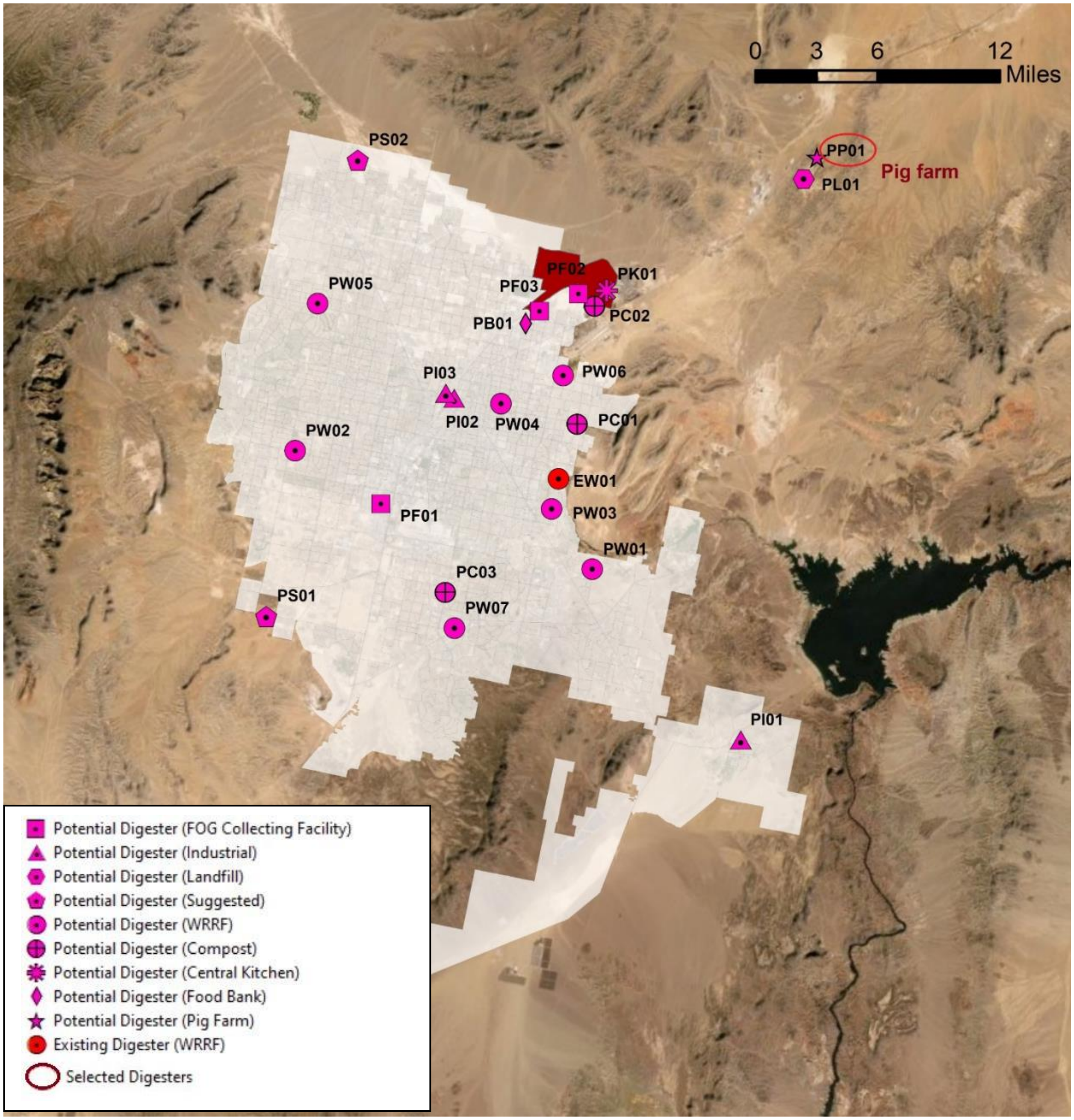

Figure 6.4. K-12 school food waste estimates, and locations of existing and potential digesters, for Las Vegas Valley

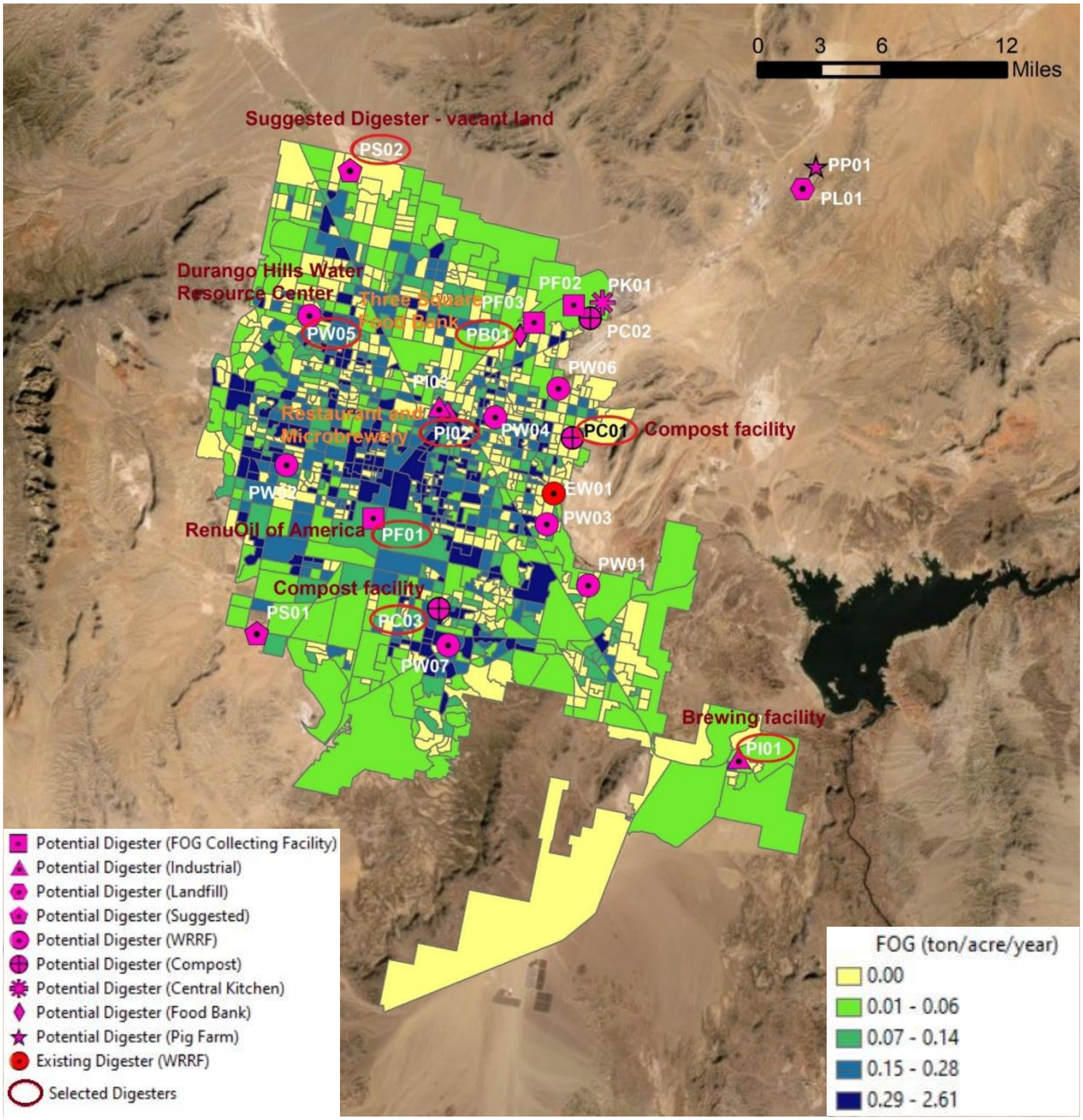

Figure 6.5. FOG food waste estimates, and locations of existing and potential digesters, for Las Vegas Valley

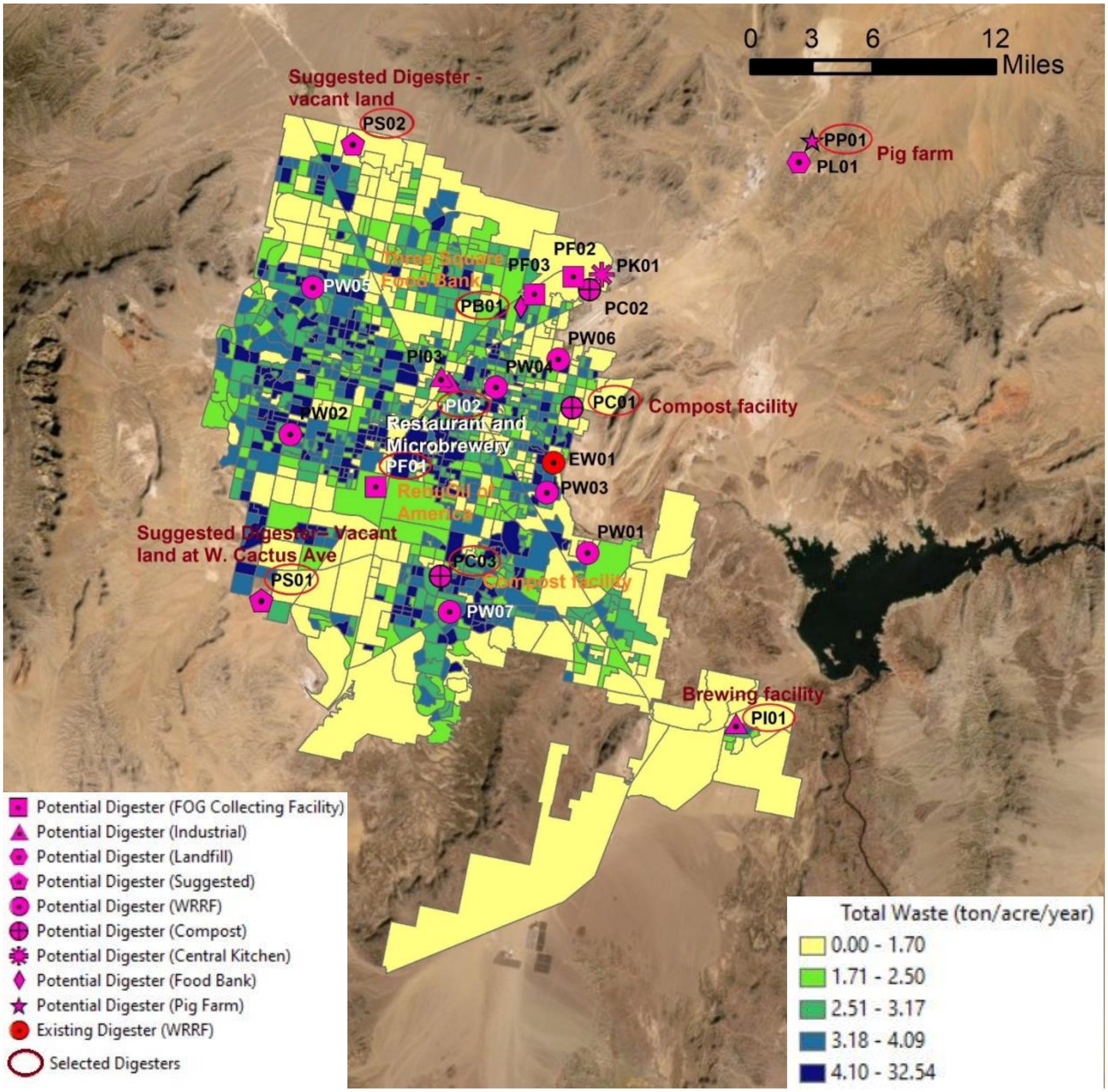

Figure 6.6. All organic waste estimates, and locations of existing and potential digesters, for Las Vegas Valley

6.2 Determination of optimal locations of new digesters for various waste scenarios

The Optimization Tool was used to determine the optimal locations of new digesters for the 5 waste scenarios: all food, casino food only, K-12 school food only, FOG, total). Inputs to the Optimization Tool included:

- Total waste generation by block group (from GIS Toolbox, as shown in Figs. 6.2 – 6.5),
- Transport distances and velocities (from GIS Toolbox) from each block group to the digester or landfill facility (landfill was used as a baseline for comparison),
- Capacity and pre-processing information from Table 6.1.

Optimization Tool outputs for the 5 scenarios are shown in Tables 6.2 – 6.6 and Figures 6.2 – 6.6 (chosen digester locations are indicated by labels with the name of the digester). Average distances and speeds from block groups to the chosen digesters, determined using the GIS Toolbox, are also shown in Tables 6.2 – 6.6.

Table 6.2 Summary of **optimal locations** of new digesters, along with transport information, for **all food waste scenario**, Las Vegas Valley

Selected Location		**No. of digest-ers**	**Food waste** (tons/ year)	**Transport from block groups**	
No.	**Name**			**Average distance** (miles)	**Average speed** (miles/hour)
PP01	Pig farm	1	103,631	29.6	62.7
PB01	Three Square Food Bank	1	13,892	12.9	50.2
PC01	Western Elite, Inc. Compost Facility	1	14,460	13.1	45.5
PC03	Viva La Compost	2	38,471	13.3	50.1
PF01	RenuOil of America	1	29,694	10.5	46.0
PI01	Boulder Dam Brewing Co.	1	5,513	27.3	55.7
PI02	Triple 7 Restaurant and Microbrewery	1	29,676	9.7	49.3
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	1	11,048	17.6	48.3
PS02	Suggested Potential Digester - Vacant land at N. Durango Dr. and Maggie Ave.	1	9,605	20.3	50.4
PW05	City of Las Vegas Durango Hills Water Resource Center	1	26,732	15.8	13.7
TOTAL		**11**	**282,722**	**N/A**	**N/A**

Table 6.3 Summary of **optimal locations** of new digesters, along with transport information, for **casino food waste scenario**, Las Vegas Valley

Selected Location		**No. of digesters**	**Food waste** (tons/ year)	**Transport from block groups**	
No.	**Name**			**Average distance** (miles)	**Average speed** (miles/hour)
PP01	Pig farm	1	28,080	27.7	67.4
PF01	RenuOil of America	1	2,973	2.8	38.1
TOTAL		**2**	**33,580**	**N/A**	**N/A**

Table 6.4 Summary of **optimal locations** of new digesters, along with transport information, for **K-12 school food waste scenario**, Las Vegas Valley

Selected Location		**No. of digesters**	**Food waste** (tons/ year)	**Transport from block groups**	
No.	**Name**			**Average distance** (miles)	**Average speed** (miles/hour)
PP01	Pig farm	1	631	13.1	73.7
TOTAL		**1**	**631**	**N/A**	**N/A**

Table 6.5 Summary of **optimal locations** of new digesters, along with transport information, for **FOG waste scenario**, Las Vegas Valley

Selected Location		**No. of digesters**	**FOG waste** (tons/ year)	**Transport from block groups**	
No.	**Name**			**Average distance** (miles)	**Average speed** (miles/hour)
PB01	Three Square Food Bank	1	3061	12.9	50.2
PC01	Western Elite, Inc. Compost Facility	1	2007	13.1	45.5
PC03	Viva La Compost	1	5549	13.3	50.1
PF01	RenuOil of America	1	7541	10.5	46.0
PI01	Boulder Dam Brewing Co.	1	695	27.3	55.7
PI02	Triple 7 Restaurant and Microbrewery	1	5457	9.7	49.3
PS02	Suggested Potential Digester - Vacant land at N. Durango Dr. and Maggie Ave.	1	1000	20.3	50.4
PW05	City of Las Vegas Durango Hills Water Resource Center	1	4511	15.8	13.7
TOTAL		**8**	**29,821**	**N/A**	**N/A**

Table 6.6 Summary of **optimal locations** of new digesters along with transport information, for **all organic waste scenario**, Las Vegas Valley

Selected Location		No. of digest-ers	Total waste (tons/ year)	Transport from block groups	
No.	**Name**			**Average distance** (miles)	**Average speed** (miles/hour)
PP01	Pig farm	2	434,259	29.6	62.7
PB01	Three Square Food Bank	1	16,594	12.9	50.2
PC01	Western Elite, Inc. Compost Facility	1	29,662	13.1	45.5
PC03	Viva La Compost	2	59,517	13.3	50.1
PF01	RenuOil of America	2	59,454	10.5	46.0
PI01	Boulder Dam Brewing Co.	1	16,603	27.3	55.7
PI02	Triple 7 Restaurant and Microbrewery	2	59,484	9.7	49.3
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	1	9,546	17.6	48.3
PS02	Suggested Potential Digester - Vacant land at N. Durango Dr. and Maggie Ave.	1	29,612	20.3	50.4
TOTAL		**13**	**714,731**	**N/A**	**N/A**

Table 6.7 summarizes the locations chosen for each scenario. High points of Table 6.7 include:

i. From 23 existing and potential sites, the optimization narrowed the number to 1-10, depending on the scenario.

ii. Only one WRRF location was chosen (Durango Hills Water Resource Center), for the all-food-waste and FOG scenarios.

iii. The food bank location and 2 of the 3 compost facility locations were chosen for the all-food-waste, FOG, and all-waste scenarios.

iv. The pig farm, which is located adjacent to the landfill, was the most frequently selected site – it was selected for all scenarios except FOG – although the landfill site itself was not chosen.

v. All 3 of the industrial locations were breweries; 2 of these were chosen for the all-food-waste, FOG, and all-waste scenarios.

vi. The 2 suggested locations (near block groups with high waste generation) were chosen for the all-food-waste and all-waste scenarios, and one was also chosen for the FOG scenario.

vii. Of the 3 FOG collection sites, one location was chosen for all scenarios except K-12 food waste.

Table 6.7 Summary of digester locations chosen for each scenario

No.	Location		Type	Chosen as Optimal for Scenario				
	No.	Name		All food	Casino food	K-12 food	FOG	All waste
1	PK01	Central kitchen	Ind.					
2	PW01	Kurt R. Segler Water Reclamation Facility	WRRF					
3	PW02	Desert Breeze Water Resource Center	WRRF					
4	PW03	Flamingo Water Resource Center	WRRF					
5	PW04	Bonanza Mojave Water Resource Center	WRRF					
6	PW05	Durango Hills Water Resource Center	WRRF	X			X	
7	EW01	Water Pollution Control Facility	WRRF					
8	PW06	Water Reclamation Facility	WRRF					
9	PW07	Southwest Water Reclamation Facility	WRRF					
10	PB01	Three Square Food Bank	Ind.	X			X	X
11	PC01	Compost facility	Ind.	X			X	X
12	PC02	Compost facility	Ind.					
13	PC03	Compost facility	Ind.	X			X	X
14	PP01	Pig farm	Farm	X	X	X		X
15	PI01	Brewing facility	Ind.	X			X	X
16	PI02	Restaurant and Microbrewery	Ind.	X			X	X
17	PI03	Brewery	Ind.					
18	PL01	Landfill	Ind.					
19	PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	Ind.	X				X
20	PS02	Suggested Potential Digester - Vacant land at N. Durango Dr. and Maggie Ave.	Ind.	X			X	X
21	PF01	RenuOil (FOG Collecting, Recycling, and Supplier)	Ind.	X	X		X	X
22	PF02	Baker Commodities (FOG Collecting, Recycling, and Supplier)	Ind.					
23	PF03	DAR PRO Solution (FOG Collecting, Recycling, and Supplier)	Ind.					
Total				**10**	**2**	**1**	**8**	**9**

6.3 Determination of energy production, emissions, and costs/benefits for digesting Las Vegas' waste at the optimal digesters

The POWER Tool was used to determine energy production, emissions, and costs/benefits for digesting waste for the 5 scenarios at the optimal digesters.

6.3.1 POWER Tool inputs for Las Vegas scenarios

A separate POWER Tool run was conducted for each row in Tables 6.2 through 6.6, using information listed in the row (waste amount, digester, distance, and speed) as inputs. The Optimization Tool does not distinguish among the kinds of organic waste; hence, for the all-waste scenario, the fractions of various kinds of waste to be sent to each digester were taken as the fractions of waste for the entire study area, determined using GIS and shown in Table 6.8. Table 6.9 shows additional inputs that were the same across all digester locations. Inputs related to the digesters themselves were the same as those shown in Table 6.1.

Table 6.8 POWER Tool inputs - Masses in different waste categories for the all-waste scenario, Las Vegas Valley

Selected Location		Waste amount (tons/year)					
No.	**Name**	**Food**	**Yard**	**Manure**	**Crop Residuals**	**FOG**	**Total**
PP01	Pig farm	171,777	243,868	0	496	18,119	434,259
PB01	Three Square Food Bank	6564	9319	0	18	692	16,594
PC01	Western Elite, Inc. Compost Facility	11,733	16,657	0	34	1238	29,662
PC03	Viva La Compost	23,542	33,423	0	68	2483	59,517
PF01	RenuOil of America	23,518	33,388	0	68	2481	59,454
PI01	Boulder Dam Brewing Co.	6568	9324	0	19	693	16,603
PI02	Triple 7 Restaurant and Microbrewery	23,530	33,405	0	68	2482	59,484
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	3776	5361	0	11	398	9,546
PS02	Suggested Potential Digester - vacant land	11,713	16,629	0	34	1236	29,612
TOTAL							**714,731**

Table 6.9 POWER Tool inputs – constant across all digester locations, Las Vegas Valley

Variable		**Value**
Major category	**Sub-category**	
Digester	Annual ambient temperature (used to determine operating costs)	70°F
	End use(s) of biogas	50% Garbage Truck, 50% Electricity
	Technology to convert biogas to electricity	Standard Reciprocating Engine-Generator Set
	Whether charging station or RNG refueling station is available	Charging Station
	Fuel for collection vehicle	Diesel
Baseline - Landfill	Landfill (name)	Apex Landfill
	Waste transport vehicle	Diesel Garbage truck
Baseline – Compost	Compost facility (name)	Pig Farm
	Waste transport vehicle	Diesel Garbage Truck

Landfilling (APEX Landfill) was used as the current business-is-usual scenario for comparison, since most organic waste in the region is currently landfilled, except for the casino food waste scenario. Since the casino food waste is currently sent to a pig farm where a portion of it is composted, compost was chosen for the baseline for the casino food waste scenario. Table 6.10 shows average transport distance and speed for the various waste scenarios to the baseline. Additional inputs related to the baselines were shown in Table 6.9.

Table 6.10 POWER Tool inputs – distance and average speed to baseline, Las Vegas Valley

Waste Scenario	**Baseline facility**	**Transport to baseline facility**	
		Average distance (miles)	**Average speed** (miles/hour)
All food	Landfill	28.4	62
Casino food	Pig farm (compost)	26.5	67
K-12 school food	Landfill	11.9	74
FOG	Landfill	28.4	62
All organic wastes	Landfill	28.4	62

6.3.2 POWER Tool outputs for Las Vegas scenarios

Tables 6.11 – 6.30 show POWER Tool outputs for energy production, emissions, costs, and benefits for the 5 Las Vegas case studies, by digester location and total. Biogas, energy, and electricity production are proportional to the weight of waste sent to each digester, since the fraction of waste components is assumed to be the same for each digester. The middle column in Tables 6.11, 6.15, 6.19, 6.23, and 6.27 provide an estimate of the amount of electricity that would be produced, if all of the waste were used to generate electricity (the POWER Tool provides this as a useful piece of information, regardless of the chosen biogas end use). As shown in the bottom 3 lines of each table, more biogas was produced from digesting organics compared to landfilling; this is due to a higher fraction of gas being captured, and a higher methane content of the gas.

As shown in Tables 6.12, 6.16, 6.20, 6.24, and 6.28, digesting organic waste would reduce greenhouse gas emissions compared to the regular power mix and use of landfill gas (the parentheses indicate negative numbers, or a reduction in emissions). Traditional air pollutants from digestion are slightly higher than the regular power mix, likely due to greater impurities in digester gas, except for PM 2.5. Traditional air pollutants from digester gas combustion are lower than those from landfill gas.

Tables 6.13, 6.17, 6.21, 6.25, and 6.29 summarize overall costs for the Las Vegas case study. Costs are shown as positive, and benefits are shown in parentheses (negative costs). The “SUB-TOTAL” column shows out-of-pocket costs; “Emissions/Social Costs” are then added and “Total Benefits” are subtracted to get the overall “NET COSTS.” Tables 6.14, 6.18, 6.22, 6.26, and 6.30 show the credits that comprise the benefits in detail. The “NET COSTS” for each of the digesters are negative, indicating that the benefits outweigh the costs. In estimating the “Total Benefits,” it was assumed that all the potential credits are obtained. This may be overly optimistic for actual cases.

As shown in the last 3 rows of Tables 6.13, 6.17, 6.21, 6.25, and 6.29, “NET COSTS” for digestion are estimated to be lower than those for landfilling. Benefits are not shown for landfilling, because the POWER Tool assumes that the city pays a tipping fee to the entity owning the landfill (not the city); any benefits accrue to that entity and are reflected in the tipping fee.

Table 6.11 POWER Tool outputs – **Energy Production**, **all food waste** scenario, Las Vegas Valley

Selected Location		**Energy Production**				
No.	**Name**	**Biogas** (m^3/day)	**Energy** (MMBTUs/ year)	**Electricity** (MWh/yr)	**Vehicle miles travelled**	**Number of vehicles refueled**
PP01	Pig farm	23,962	281,658	24,146	978,878	42
PB01	Three Square Food Bank	3,129	36,775	3,153	127,807	5
PC01	Western Elite, Inc. Compost Facility	3,256	38,276	3,281	133,027	6
PC03	Viva La Compost	8,664	101,836	8,730	353,923	15
PF01	RenuOil of America	6,687	78,603	6,738	273,179	12
PI01	Boulder Dam Brewing Co.	1,241	14,592	1,251	50,714	2
PI02	Triple 7 Restaurant and Microbrewery	6,683	78,555	6,734	273,011	12
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	2,488	29,244	2,507	101,636	4
PS02	Suggested Potential Digester - vacant land	2,163	25,425	2,180	88,363	4
PW05	City of Las Vegas Durango Hills Water Resource Center	6,020	70,763	6,066	245,931	11
DIGESTER TOTAL		**64,293**	**755,727**	**64,786**	**2,626,469**	**113**
Landfill baseline		25,946	304,959	26,143	1,059,932	45
Difference: Digester – Landfill Baseline		**38,3487**	**450,7768**	**38,643**	**1,556,537**	**68**

Table 6.12 POWER Tool outputs – **Emissions**, **all food waste** scenario, Las Vegas Valley

Selected Location		**Emissions (kg/year)**				
No.	**Name**	**VOCs**	**NOx**	**PM10**	**PM2.5**	**GHG**
PP01	Pig farm	775	1597	575	(27)	(3,036,403)
PB01	Three Square Food Bank	128	274	105	(4)	(397,803)
PC01	Western Elite, Inc. Compost Facility	133	283	109	(4)	(414,048)
PC03	Viva La Compost	307	631	249	(11)	(1,101,593)
PF01	RenuOil of America	243	502	201	(9)	(850,275)
PI01	Boulder Dam Brewing Co.	60	136	47	(1)	(157,850)
PI02	Triple 7 Restaurant and Microbrewery	242	498	200	(9)	(849,754)
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	107	233	87	(3)	(316,344)
PS02	Suggested Potential Digester - vacant land	96	210	77	(3)	(275,032)
PW05	City of Las Vegas Durango Hills Water Resource Center	405	1741	431	(7.6)	(765,466)
DIGESTER TOTAL		**2,496**	**6,104**	**2,082**	**(79)**	**(8,164,568)**
Landfill baseline		13,460	119,084	2,292	364	(6,440,511)
Difference: Digester – Landfill						

Table 6.13 POWER Tool outputs – Digester **costs**, **all food waste** scenario, Las Vegas Valley

Selected Location			**Costs (thousands of dollars)**							
No.	**Name**	**Alt. Fuel Vehicles - Capital**	**Waste Transport – Operating**	**AD**	**Pre-Processing**	**Biogas Conversion**	**SUB-TOTAL Out-of-pocket costs**	**Emissions/ Social Costs**	**Total Benefits**	**NET COSTS**
PP01	Pig farm	$62,405	$35,402	$55,774	$14,550	$29,301	**$197,432**	$189,363	$1,016,090	($629,295)
PB01	Three Square Food Bank	$8,148	$2,179	$12,223	$7,366	$5,667	**$35,583**	$41,382	$132,666	($55,701)
PC01	Western Elite, Inc. Compost Facility	$8,481	$2,362	$12,723	$7,376	$5,852	**$36,794**	$43,070	$138,084	($58,220)
PC03	Viva La Compost	$22,563	$6,226	$33,849	$7,793	$12,869	**$83,300**	$114,471	$367,378	($169,607)
PF01	RenuOil of America	$17,416	$3,890	$26,127	$7,643	$10,442	**$65,518**	$88,361	$283,564	($129,685)
PI01	Boulder Dam Brewing Co.	$3,233	$1,783	$4,850	$7,215	$2,710	**$19,791**	$16,456	$52,642	($16,395)
PI02	Triple 7 Restaurant and Microbrewery	$17,405	$3,524	$26,111	$7,643	$10,437	**$65,120**	$88,301	$283,390	($129,969)
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	$6,479	$2,396	$9,720	$7,315	$4,717	**$30,627**	$32,929	$105,500	($41,944)
PS02	Suggested Potential Digester - vacant land	$5,633	$2,363	$8,451	$7,289	$4,217	**$27,953**	$28,639	$91,722	($35,130)
PW05	City of Las Vegas Durango Hills Water Resource Center*	$15,678	$5,134	$23,521	$7,591	$9,594	**$80,753**	$2,159	$255,280	($172,368)
DIGESTER TOTAL		**$167,441**	**$65,259**	**$213,348**	**$81,782**	**$95,806**	**$623,636**	**$645,131**	**$2,152,111**	**($883,344)**
Landfill baseline							$661,398	$1,549,870	N/A	$2,211,269
Difference: Digester – Landfill Baseline							($37,762)	($904,739)	$2,152,111	($3,094,613)

*Tipping fee was used for cost of WRRF digester.

Table 6.14 POWER Tool outputs – Digester **benefits**, **all food waste** scenario, Las Vegas Valley

Selected Location		**Benefits (thousands of dollars)**					
No.	**Name**	**Fuel cost savings**	**Prod-uction tax credit**	**Renewable Energy Credits**	**LCFS Credits**	**CFS Credits**	**TOTAL Benefits**
PP01	Pig farm	$172,259	$4,932	$3,794	$483,099	$352,007	$1,016,090
PB01	Three Square Food Bank	$22,491	$644	$495	$63,076	$45,960	$132,666
PC01	Western Elite, Inc. Compost Facility	$23,409	$670	$516	$65,652	$47,837	$138,084
PC03	Viva La Compost	$62,282	$1,783	$1,372	$174,669	$127,272	$367,378
PF01	RenuOil of America	$48,073	$1,376	$1,059	$134,820	$98,236	$283,564
PI01	Boulder Dam Brewing Co.	$8,925	$256	$197	$25,029	$18,237	$52,642
PI02	Triple 7 Restaurant and Microbrewery	$48,043	$1,375	$1,058	$134,737	$98,176	$283,390
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	$17,885	$512	$394	$50,160	$36,549	$105,500
PS02	Suggested Potential Digester - vacant land	$15,550	$445	$342	$43,609	$31,776	$91,722
PW05	City of Las Vegas Durango Hills Water Resource Center	$43,278	$1,239	$953	$121,373	$88,437	$255,280
DIGESTER TOTAL		**$462,196**	**$13,233**	**$10,179**	**$1,296,224**	**$944,485**	**$2,726,316**

Table 6.15 POWER Tool outputs – **Energy Production**, **casino food waste** scenario, Las Vegas Valley

Selected Location		**Energy Production**				
No.	**Name**	**Biogas** (m^3/day)	**Energy** (MMBTUs/year)	**Electricity** (MWh/yr)	**Vehicle miles travelled**	**Number of vehicles refueled**
PP01	Pig farm	6,948	81,666	7,001	283,822	12
PF01	RenuOil of America	670	7,870	675	27,353	1
DIGESTER TOTAL		**7,618**	**89,536**	**7,676**	**311,175**	**13**
Landfill baseline		3,330	39,142	3,356	136,022	6
Difference: Digester – Landfill Baseline		**4,288**	**50,394**	**4,320**	**175,153**	**7**

Table 6.16 POWER Tool outputs – **Emissions**, **casino food waste** scenario, Las Vegas Valley

Selected Location		**Emissions (kg/year)**				
No.	**Name**	**VOCs**	**NOx**	**PM10**	**PM2.5**	**GHG**
PP01	Pig farm	275	599	208	(8)	(873,026)
PF01	RenuOil of America	32	70	27	(1)	(85,136)
DIGESTER TOTAL		**307**	**669**	**235**	**(9)**	**(958,162)**
Landfill baseline		1,753	15,479	300	48	(841,878)
Difference: Digester – Landfill Baseline		**(1,446)**	**(14,810)**	**(65)**	**(57)**	**(116,284)**

Table 6.17 POWER Tool outputs – Digester **costs**, **casino food waste** scenario, Las Vegas Valley

Selected Location			Costs (thousands of dollars)							
No.	**Name**	**Alt. Fuel Vehicles - Capital**	**Waste Transport - Operating**	**AD**	**Pre-Processing**	**Biogas Conversion**	**SUB-TOTAL Out-of-pocket Costs**	**Emissions / Social Costs**	**Total Benefits**	**NET COSTS**
PP01	Pig farm	$18,094	$11,138	$17,788	$9,280	$10,769	$67,069	$60,133	$294,612	**($167,410)**
PF01	RenuOil of America	$1,744	$110	$2,616	$7,169	$1,667	$13,306	$8,864	$28,392	**($6,222)**
DIGESTER TOTAL		**$19,838**	**$11,249**	**$20,404**	**$16,449**	**$12,436**	**$80,376**	**$68,997**	**$323,004**	**($173,631)**
Landfill baseline							$225,109	$96,203	N/A	321,312
Difference: Digester – Landfill Baseline							**($144,733)**	**($27,206)**	**$323,004**	**($494,943)**

Table 6.18 POWER Tool outputs – Digester **benefits**, **casino food waste** scenario, Las Vegas Valley

Selected Location		Benefits (thousands of dollars)					
No.	**Name**	**Fuel cost savings**	**Production tax credit**	**Renewable Energy Credits**	**LCFS Credits**	**CFS Credits**	**TOTAL**
PP01	Pig farm	$49,946	$1,430	$1,100	$140,073	$102,063	$294,612
PB01	RenuOil of America	$4,813	$138	$106	$13,499	$9,836	$28,392
DIGESTER TOTAL		**$54,759**	**$1,568**	**$1,206**	**$153,572**	**$111,899**	**$323,004**

Table 6.19 POWER Tool outputs – **Energy Production**, **K-12 school food waste** scenario, Las Vegas Valley

Selected Location		**Energy Production**				
No.	**Name**	**Biogas** (m^3/day)	**Energy** (MMBTUs/ year)	**Electricity** (MWh/yr)	**Vehicle miles travelled**	**Number of vehicles refueled**
PP01	Pig farm	766	9,006	772	31,300	1
DIGESTER TOTAL		**766**	**9,006**	**772**	**31,300**	**1**
Landfill baseline		271	3191	274	10,931	0
Difference: Digester – Landfill Baseline		**495**	**5,815**	**498**	**20,369**	**1**

Table 6.20 POWER Tool outputs – **Emissions**, **K-12 school food waste** scenario, Las Vegas Valley

Selected Location		**Emissions (kg/year)**				
No.	**Name**	**VOCs**	**NOx**	**PM10**	**PM2.5**	**GHG**
PP01	Pig farm	39	88	31	(1)	(87,045)
DIGESTER TOTAL		**9**	**88**	**31**	**(1)**	**(87,045)**
Landfill baseline		169	1467	31	5	(84,680)
Difference: Digester – Landfill Baseline		**(130)**	**(1,379)**	**0**	**(6)**	**(2,364)**

Table 6.21 POWER Tool outputs – Digester **costs**, **K-12 school food waste** scenario, Las Vegas Valley

Selected Location			Costs (thousands of dollars)								
No.	**Name**	**Alt. Fuel Vehicles - Capital**	**Waste Tran-sport – Oper-ating**	**AD**	**Pre-Processing**	**Biogas Conversion**	**SUB-TOTAL Out-of-pocket Costs**	**Emissions / Social Costs**	**Total Benefits**	**NET COSTS**
PP01	Pig farm	$ 1995	$1160	$3988	$7366	$1852	$16,361	$13,042	$32,489	($3,086)
DIGESTER TOTAL		**$ 1995**	**$1160**	**$3988**	**$7366**	**$1852**	**$16,361**	**$13,042**	**$32,489**	**($3,086)**
Landfill baseline							$45,939	$16,622	N/A	$62,560
Difference: Digester – Landfill Baseline							**($29,578)**	**($3,580)**	**$32,489**	**($65,646)**

Table 6.22 POWER Tool outputs – Digester **benefits**, **K-12 school food waste** scenario, Las Vegas Valley

Selected Location		Benefits					
No.	**Name**	**Fuel cost savings**	**Prod-uction tax credit**	**Renewable Energy Credits**	**LCFS Credits**	**CFS Credits**	**TOTAL**
PP01	Pig farm	$5508	$158	$121	$15,447	$11,255	$32,489
DIGESTER TOTAL		**$5508**	**$158**	**$121**	**$15,447**	**$11,255**	**$32,489**

Table 6.23 POWER Tool outputs – **Energy Production**, **FOG waste** scenario, Las Vegas Valley

Selected Location		**Energy Production**				
No.	**Name**	**Biogas** (m^3/day)	**Energy** (MMBTUs /year)	**Electricity** (MWh/yr)	**Vehicle miles travelled**	**Number of vehicles refueled**
PB01	Three Square Food Bank	5,853	68,799	5,898	239,105	10
PC01	Western Elite, Inc. Compost Facility	3,839	45,123	3,868	156,820	7
PC03	Viva La Compost	10,612	124,731	10,693	433,490	19
PF01	RenuOil of America	14,421	169,510	14,532	589,117	25
PI01	Boulder Dam Brewing Co.	1,328	15,613	1,338	54,261	2
PI02	Triple 7 Restaurant and Microbrewery	10,436	122,672	10,516	426,335	18
PS02	Suggested Potential Digester - vacant land	1,912	22,476	1,927	78,112	3
PW05	City of Las Vegas Durango Hills Water Resource Center	8,627	101,398	8,693	352,405	15
DIGESTER TOTAL		**57,028**	**670,322**	**57,465**	**2,329,645**	**99**
Landfill baseline		12,100	142,231	12,193	494,301	21
Difference: Digester – Landfill Baseline		**44,928**	**528,091**	**45,272**	**1,835,344**	**78**

Table 6.24 POWER Tool outputs – **Emissions**, **FOG waste** scenario, Las Vegas Valley

Selected Location		**Emissions (kg/year)**				
No.	**Name**	**VOCs**	**NOx**	**PM10**	**PM2.5**	**GHG**
PB01	Three Square Food Bank	203	402	177	(8)	(658,186)
PC01	Western Elite, Inc. Compost Facility	142	287	124	(5)	(431,678)
PC03	Viva La Compost	334	637	291	(15)	(1,193,269)
PF01	RenuOil of America	429	798	375	(20)	(1,621,664)
PI01	Boulder Dam Brewing Co.	57	121	50	(2)	(149,364)
PI02	Triple 7 Restaurant and Microbrewery	329	626	287	(14)	(1,173,573)
PS02	Suggested Potential Digester - vacant land	78	164	68	(3)	(215,018)
PW05	City of Las Vegas Durango Hills Water Resource Center	279	536	245	(12)	(800,086)
DIGESTER TOTAL		**1851**	**3571**	**1617**	**(79)**	**(6,242,838)**
Landfill baseline		10,477	90,910	1897	303	(5,349,393)
Difference: Digester – Landfill Baseline		**(8626)**	**(87,339)**	**(280)**	**(382)**	**(893,445)**

Table 6.25 POWER Tool outputs – Digester **costs**, **FOG waste** scenario, Las Vegas Valley

Selected Location			Costs (thousands of dollars)							
No.	Name	Alt. Fuel Vehicles - Capital	Waste Transport – Operating	AD	Pre-Processing	Biogas Conversion	SUB-TOTAL Out-of-pocket Costs	Emissions/ Social Costs	Total Benefits	NET COSTS
PB01	Three Square Food Bank	$15,243	$737	$2,693	$0	$9,379	$28,052	$5,869	$248,196	($214,275)
PC01	Western Elite, Inc. Compost Facility	$9,997	$515	$1,766	$0	$6,679	$18,957	$3,872	$162,782	($139,953)
PC03	Viva La Compost	$27,636	$1,379	$4,882	$0	$15,159	$49,056	$10,550	$449,969	($390,363)
PF01	RenuOil of America	$37,557	$1,547	$6,635	$0	$19,426	$65,165	$14,269	$611,513	($532,079)
PI01	Boulder Dam Brewing Co.	$3,459	$337	$611	$0	$2,860	$7,267	$1,363	$56,323	($47,693)
PI02	Triple 7 Restaurant and Microbrewery	$27,179	$999	$4,802	$0	$14,957	$47,937	$10,373	$442,542	($384,232)
PS02	Suggested Potential Digester - vacant land	$4,980	$377	$880	$0	$3,822	$10,059	$1,950	$81,082	($69,073)
PW05	City of Las Vegas Durango Hills Water Resource Center	$22,466	$1,336	$3,969	$0	$12,824	$40,595	$8588	$365,796	($316,613)
DIGESTER TOTAL		**$148,517**	**$7,227**	**$26,238**	**$0**	**$85,106**	**$267,088**	**$56,834**	**$2,418,203**	**($2,094,281)**
Landfill baseline							$181,704	$174,916	N/A	$356,620
Difference: Digester – Landfill Baseline							**$85,384**	**($118,082)**	**$2,418,203**	**($2,450,901)**

Table 6.26 POWER Tool outputs – Digester **benefits**, **FOG waste** scenario, Las Vegas Valley

Selected Location		**Benefits (thousands of dollars)**					
No.	**Name**	**Fuel cost savings**	**Prod-uction tax credit**	**Renewable Energy Credits**	**LCFS Credits**	**CFS Credits**	**TOTAL**
PB01	Three Square Food Bank	$42,077	$1,205	$927	$118,004	$85,983	$248,196
PC01	Western Elite, Inc. Compost Facility	$27,597	$790	$608	$77,394	$56,393	$162,782
PC03	Viva La Compost	$76,284	$2,184	$1,680	$213,937	$155,884	$449,969
PF01	RenuOil of America	$103,671	$2,968	$2,283	$290,743	$211,848	$611,513
PI01	Boulder Dam Brewing Co.	$9,549	$273	$210	$26,779	$19,512	$56,323
PI02	Triple 7 Restaurant and Microbrewery	$75,025	$2,148	$1,652	$210,406	$153,311	$442,542
PS02	Suggested Potential Digester - vacant land	$13,746	$394	$303	$38,550	$28,089	$81,082
PW05	City of Las Vegas Durango Hills Water Resource Center	$62,014	$1,775	$1,366	$173,917	$126,724	$365,796
TOTAL		**$409,963**	**$11,737**	**$9,029**	**$1,149,730**	**$837,744**	**$2,418,203**

Table 6.27 POWER Tool outputs – **Energy Production**, **all organic waste** scenario, Las Vegas Valley

Selected Location		**Energy Production**				
No.	**Name**	**Biogas** (m^3/day)	**Energy** (MMBTUs/year)	**Electricity** (MWh/yr)	**Vehicle miles travelled**	**Number of vehicles refueled**
PP01	Pig farm	139,970	1,394,663	119,560	4,847,031	207
PB01	Three Square Food Bank	5,335	53,129	4,555	184,644	8
PC01	Western Elite, Inc. Compost Facility	9,536	94,968	8,141	330,052	14
PC03	Viva La Compost	19,133	190,551	16,335	662,243	28
PF01	RenuOil of America	19,113	190,351	16,318	661,547	28
PI01	Boulder Dam Brewing Co.	5,338	53,158	4,557	184,747	8
PI02	Triple 7 Restaurant and Microbrewery	19,122	190,447	16,326	661,882	28
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	3,069	30,561	2,620	106,214	5
PS02	Suggested Potential Digester - vacant land	9,519	94,808	8,128	329,496	14
DIGESTER TOTAL		**230,134**	**2,292,635**	**196,540**	**7,967,856**	**341**
Landfill baseline		84,735	837,379	71,786	2,934,294.29	125
Difference: Digester – Landfill Baseline		**145,399**	**1,455,256**	**124,754**	**5,033,562**	**216**

Table 6.28 POWER Tool outputs – **Emissions**, **all organic waste** scenario, Las Vegas Valley

Selected Location		**Emissions (kg/year)**				
No.	**Name**	**VOCs**	**NOx**	**PM10**	**PM2.5**	**GHG**
PP01	Pig farm	5,630	25,622	6,012	(141)	(14,706,066)
PB01	Three Square Food Bank	284	1,146	298	(6)	(560,406)
PC01	Western Elite, Inc. Compost Facility	481	1,981	509	(10)	(1,001,726)
PC03	Viva La Compost	904	3,809	968	(21)	(2,009,945)
PF01	RenuOil of America	897	3,786	966	(21)	(2,007,832)
PI01	Boulder Dam Brewing Co.	293	1,178	298	(5)	(560,717)
PI02	Triple 7 Restaurant and Microbrewery	896	3,782	967	(21)	(2,008,850)
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	173	686	178	(3)	(322,364)
PS02	Suggested Potential Digester - vacant land	489	2,005	509	(10)	(1,000,040)
DIGESTER TOTAL		**10,046**	**43,995**	**10,705**	**(240)**	**(24,177,945)**
Landfill baseline		44,462	392,031	7,656	1,220	(21,556,912)
Difference: Digester – Landfill Baseline		**(34,416)**	**(348,036)**	**3,049**	**(1,460)**	**(2,621,033)**

Table 6.29 POWER Tool outputs – Digester **costs**, **all organic waste** scenario, Las Vegas Valley

Selected Location			Costs (thousands of dollars)							
No.	**Name**	**Alt. Fuel Vehicles - Capital**	**Waste Tran-sport – Opera-ting**	**AD**	**Pre-Pro-cessing**	**Biogas Con-version**	**SUB-TOTAL Out-of-pocket Costs**	**Emissions / Social Costs**	**Total Benefits**	**NET COSTS**
PP01	Pig farm	$309,005	$150,676	$221,757	$36,313	$107,219	$824,970	$754,810	$5,768,829	($4,189,049)
PB01	Three Square Food Bank	$11,771	$2,603	$14,601	$7,857	$7,616	$44,448	$49,527	$2,197,847	($2,103,872)
PC01	Western Elite, Inc. Compost Facility	$21,041	$4,845	$26,099	$8,386	$12,163	$72,534	$88,463	$331,632	($170,635)
PC03	Viva La Compost	$42,219	$9,470	$52,366	$9,592	$21,355	$135,002	$177,336	$648,256	($335,918)
PF01	RenuOil of America	$42,175	$7,788	$52,311	$9,590	$21,337	$133,201	$177,113	$788,705	($478,391)
PI01	Boulder Dam Brewing Co.	$11,778	$5,372	$14,609	$7,857	$7,620	$47,236	$49,611	$422,534	($325,687)
PI02	Triple 7 Restaurant and Microbrewery	$42,196	$7,064	$52,338	$9,591	$21,345	$132,534	$177,192	$586,309	($276,583)
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	$6,771	$2,070	$8,399	$7,571	$4,886	$29,697	$28,521	$362,414	($304,196)
PS02	Suggested Potential Digester - vacant land	$21,006	$7,287	$26,055	$8,384	$12,147	$74,879	$88,365	$297,919	($134,675)
DIGESTER TOTAL		**$507,962**	**$197,175**	**$468,533**	**$105,142**	**$215,688**	**$1,494,499**	**$1,590,937**	**$6,252,696**	**($3,167,260)**
Landfill baseline							$4,274,250	$1,930,172	N/A	$6,204,422
Difference: Digester – Landfill Baseline							**($2,779,751)**	**($339,235)**	**$6,252,696**	**($9,371,682)**

Table 6.30 POWER Tool outputs – Digester **benefits**, **all organic waste** scenario, Las Vegas Valley

Selected Location		Benefits					
No.	**Name**	**Fuel cost savings**	**Prod-uction tax credit**	**Renewable Energy Credits**	**LCFS Credits**	**CFS Credits**	**TOTAL**
PP01	Pig farm	$852,961	$24,421	$18,785	$2,821,901	$2,050,761	$5,768,829
PB01	Three Square Food Bank	$32,493	$930	$716	$107,549	$2,056,159	$2,197,847
PC01	Western Elite, Inc. Compost Facility	$58,081	$1,663	$1,279	$192,244	$78,365	$331,632
PC03	Viva La Compost	$116,539	$3,337	$2,567	$385,735	$140,078	$648,256
PF01	RenuOil of America	$116,416	$3,333	$2,564	$385,329	$281,063	$788,705
PI01	Boulder Dam Brewing Co.	$32,511	$931	$716	$107,609	$280,767	$422,534
PI02	Triple 7 Restaurant and Microbrewery	$116,475	$3,335	$2,565	$385,525	$78,409	$586,309
PS01	Suggested Potential Digester – Vacant land at W. Cactus Ave	$18,691	$535	$412	$61,866	$280,910	$362,414
PS02	Suggested Potential Digester - vacant land	$57,983	$1,660	$1,277	$191,921	$45,078	$297,919
DIGESTER TOTAL		**$1,402,152**	**$40,144**	**$30,880**	**$4,639,678**	**$139,842**	**$6,252,696**

Table 6.31 summarizes waste input and outputs (energy, emissions, and costs) for the 5 Las Vegas scenarios. Costs and benefits are provided not only overall for the scenario but also per ton of waste processed.

The “all organic waste” scenario produces the most energy, followed by the “all food waste” scenario (28% of that for “all organic waste”) and the “FOG” scenario (25% of that for “all organic waste.”) It should be noted that the FOG scenario produces almost as much energy as the “all food waste” scenario, but with only around 10% of the waste mass, due to the high energy density of FOG waste.

Even though the FOG and “all food waste” scenarios produce comparable energy, the overall savings are much greater for the FOG scenario ($2.1 million) compared to the “all food waste” scenario ($0.88 million), due to lower waste transport costs and AD tipping fee costs for the FOG scenario, due to lower waste mass.

In terms of costs/benefits per ton of waste processed, FOG has higher out-of-pocket costs, due to greater gas production per ton of waste: the greater gas production means greater costs per ton in terms of purchasing alternate fuel vehicles to be refueled with the gas and greater gas conversion costs. However, the greater gas production also means greater benefits per ton of waste processed ($81.09) compared to the other scenarios, and greater net savings ($71.59). Hence, FOG should be prioritized in terms of waste use.

Table 6.31 Input/Output Summary for Las Vegas Scenarios

Input/ Output Category	**Specific output**	**Scenario**				
		All food waste	**Casino food waste**	**K-12 school food waste**	**FOG**	**All organic waste**
Waste mass	Input – tons/year	282,722	33,580	631	29,821	714,731
Energy	Biogas, m^3/day	64,293	7,618	495	57,028	230,134
	Energy, MMBtu	755,727	89,536	5,815	670,322	2,292,635
	Electricity, MWh	64,786	7,676	498	57,465	196,540
	Vehicle miles travelled	2,626,469	311,175	20,369	2,329,645	7,967,856
	Vehicles refueled	113	13	1	99	341
	% energy compared to all organic scenario	28%	3.9%	0.25%	25%	100%
Emissions, kg/year	VOCs	2504	307	39	1851	10,046
	NOx	6133	669	88	3571	43,995
	PM10	2081	235	31	1617	10,705
	PM2.5	(79)	(9)	(1)	(79)	(240)
	CO_2	(8,164,568)	(958,162)	(87,045)	(6,242,838)	(24,177,945)
	% CO_2 emission benefit compared to all organic scenario	34%	4.0%	0.36%	26%	100%
Costs, thousands of dollars	Subtotal out-of-pocket costs	$623,636	$80,376	$16,361	$267,088	$1,494,499
	Emissions/social costs	$645,131	$68,997	$13,042	$56,834	$1,590,937
	Total benefits	$2,152,111	$323,004	$32,489	$2,418,203	$6,252,696
	Net costs/savings	($883,334)	($173,631)	($3,086)	($2,134,876)	($3,167,260)
	% net costs/savings compared to all organic scenario	(28%)	(5.5%)	(0.10%)	(66%)	(100%)
Costs, $/ton of waste	Subtotal out-of-pocket costs	$2.21	$2.39	$25.93	$8.96	$2.09
	Emissions/social costs	$2.28	$2.05	$20.67	$1.91	$2.23
	Total benefits	$7.61	$9.62	$51.49	$81.09	$8.75
	Net costs/savings	($3.12)	($5.17)	($4.89)	($71.59)	($4.43)

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

- The POWER Framework serves as a method to assess the feasibility of co-digesting organic wastes in existing or new digesters (water resource recovery facilities, farm, and industrial/stand-alone).
- The GIS Toolbox provides a method for estimating organic waste to becollected for digestion.
- POWER Tool provides information about anaerobic digestion cost, life-cycle pollutant emissions, and electricity/renewable vehicle fuel/pipeline renewable gas produced.
- The Optimization Tool can select optimal digester locations, and the amount of waste to send to each.
- In this project, substantial upgrades were made to the GIS Toolbox, POWER Tool, and Optimization Tool. These upgrades were tested using case studies for Vermont and Las Vegas.
- For the Vermont case study, the Optimization Tool narrowed the list of 17 potential sites to 7 optimal sites. For the Las Vegas case study, from the 23 existing and potential sites, the optimization chose 1-10 preferred sites, depending on the scenario.
- The case study results for both Vermont and Las Vegas showed the following:
    - More biogas was produced from digesting organics compared to landfilling; this is due to a higher fraction of gas being captured, and a higher methane content of the gas.
    - Digesting organic waste would reduce greenhouse gas emissions compared to the regular power mix and use of landfill gas. Traditional air pollutants from digestion were slightly higher than the regular power mix, likely due to greater impurities in digester gas, except for PM 2.5. Traditional air pollutants from digester gas combustion are lower than those from landfill gas.
    - The “NET COSTS” for each of the digesters was negative, indicating that the benefits outweigh the costs. In estimating the “Total Benefits,” it was assumed that all the potential credits are obtained. This may be overly optimistic for actual cases.
    - “NET COSTS” for digestion were estimated to be lower than those for landfilling.
- The Las Vegas case study showed that FOG waste has the highest overall benefit/cost savings per ton of waste digested, due to its higher energy density compared to other wastes.

7.2 Recommendations for future work

Improvements to incorporate into the next version of the POWER Framework include:

GIS Toolbox

- Collect improved data on food-waste generation rates for multi-family housing, as well as yard-waste generation for parks and commercial lawns.
- Find a free source of information for special event centers.

POWER Tool

- Add an option for direct use of biogas for generating hot water/steam, heat, or cooking fuel.
- Add option to retrofit vehicles to take RNG.
- Include forest waste.
- Add option for reducing transportation costs via a transfer station.
- Add net energy balance.
- Add CO_2 emissions from consumption of diesel fuel for grinding.
- Size water resource recovery facility digesters based on organic loading. This would require costs to be adjusted based on different structural requirements.

Optimization Tool

- Allow user to select whether charging station is present (this would lower capital costs if it was present already).
- Calculate the digester tipping fee that would be required to cover the costs of transportation and digestion.
- Conduct additional sensitivity analyses.

Integration of the 3 components

- Based on Optimization output, automate computation of resulting optimal digester capacity needed, energy production, emissions, and other costs. This would obviate the need for many subsequent POWER Tool runs.

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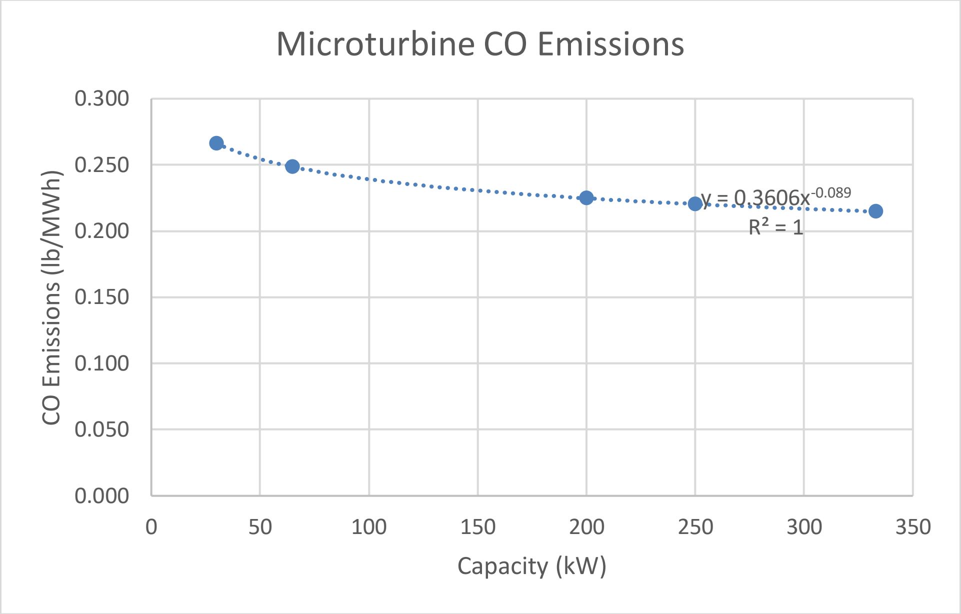
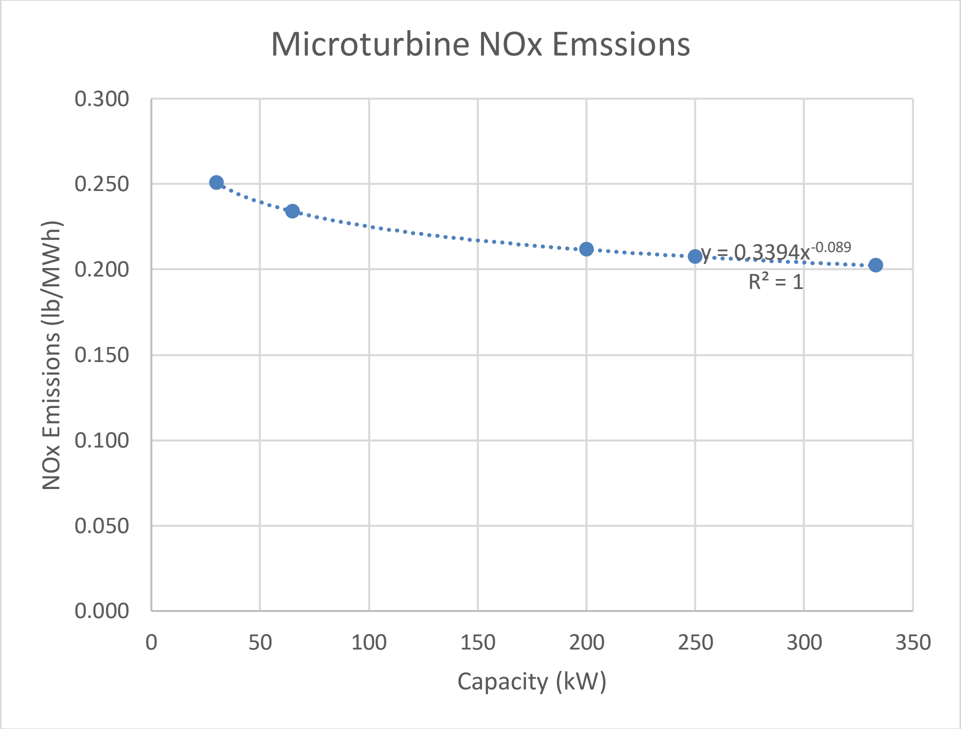
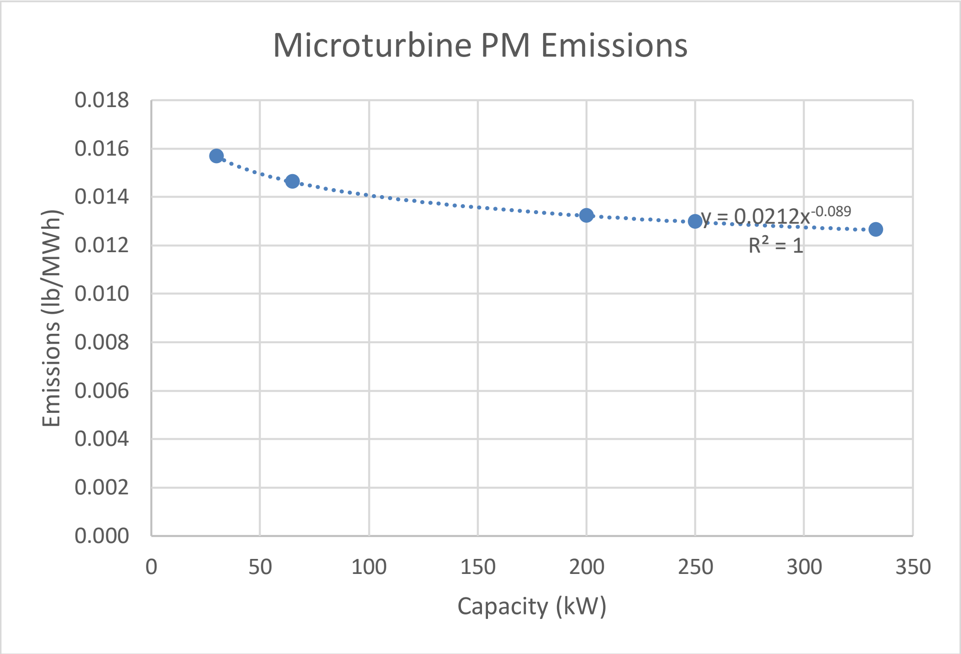
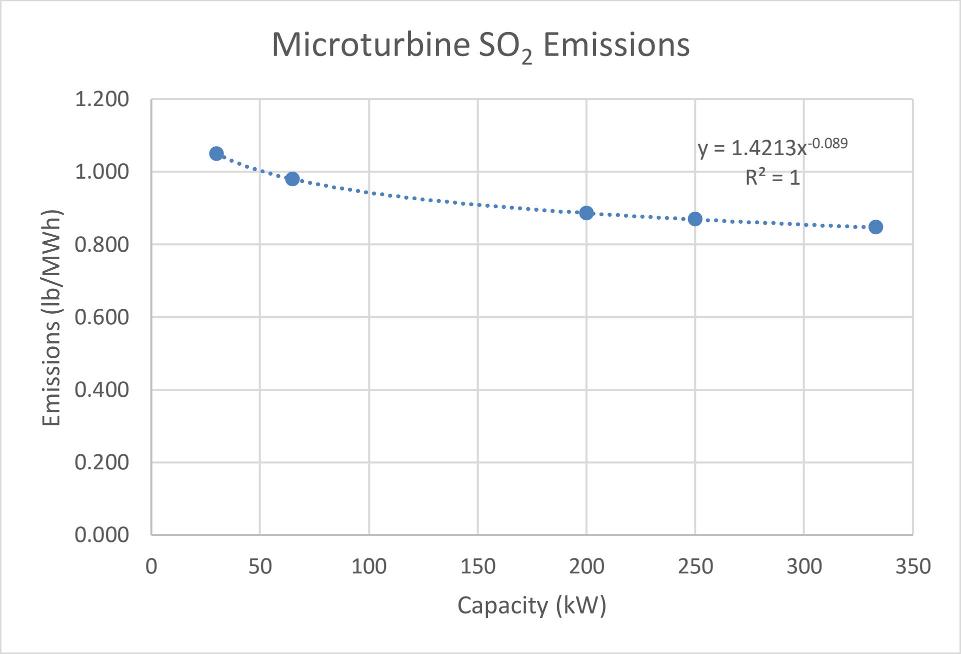
Appendix A: Regression Curves for Emissions from Biogas Conversion

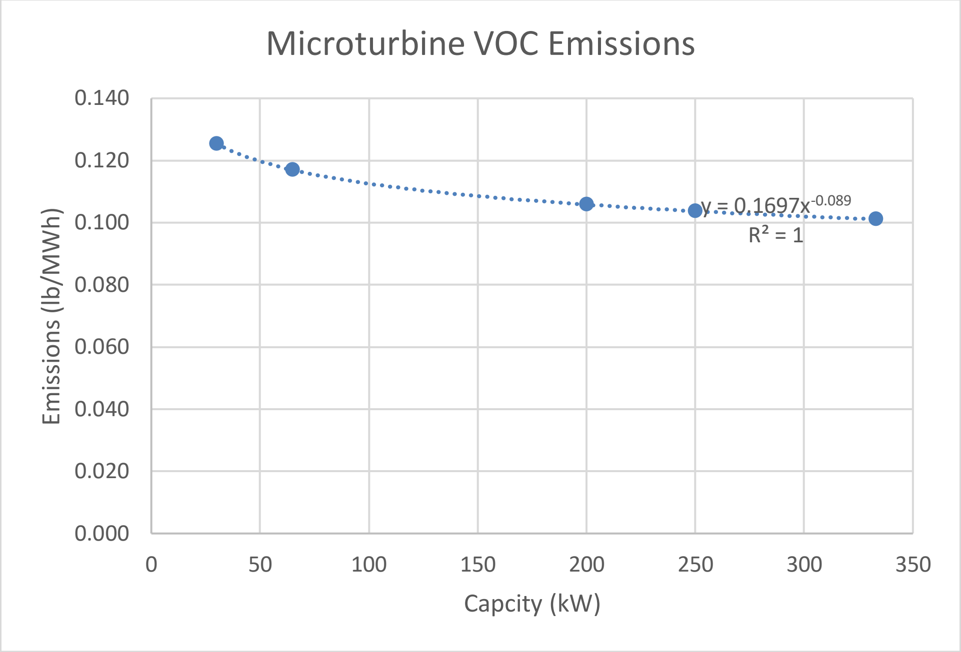
Microturbines (30-330 kW)

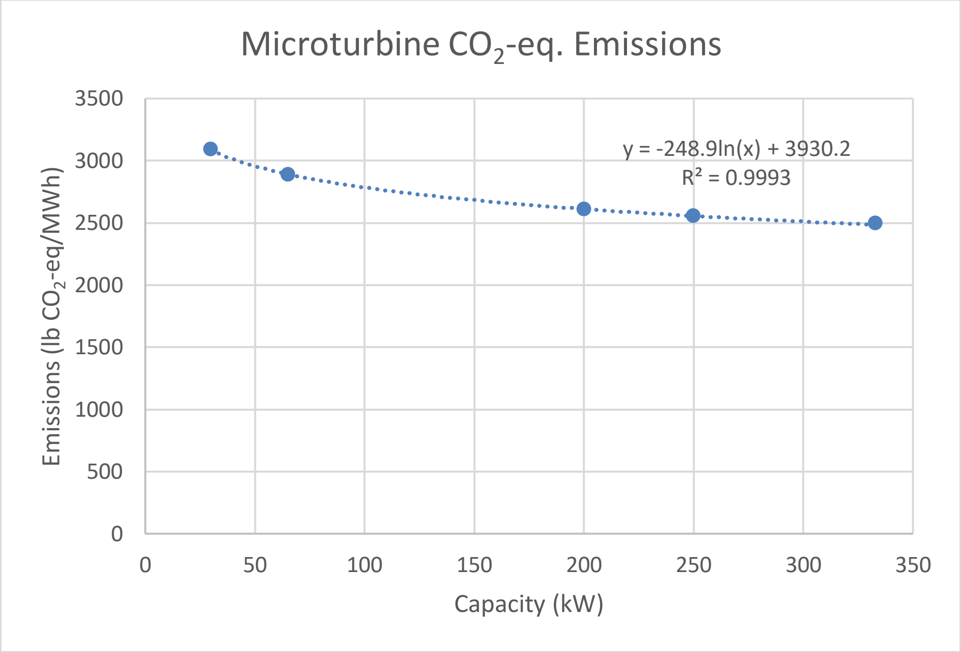




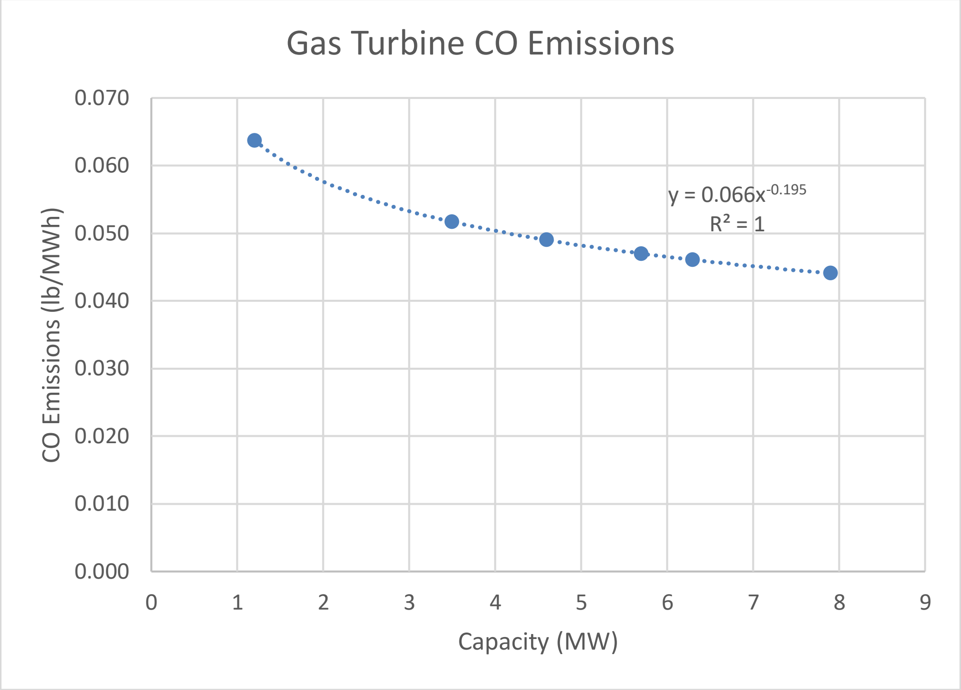

Microturbine PM Emissions
Emissions (lb/MWh)
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
50
100
150
200
250
300
350
Capacity (kW)
y = 0.0212x^-0.089
R² = 1

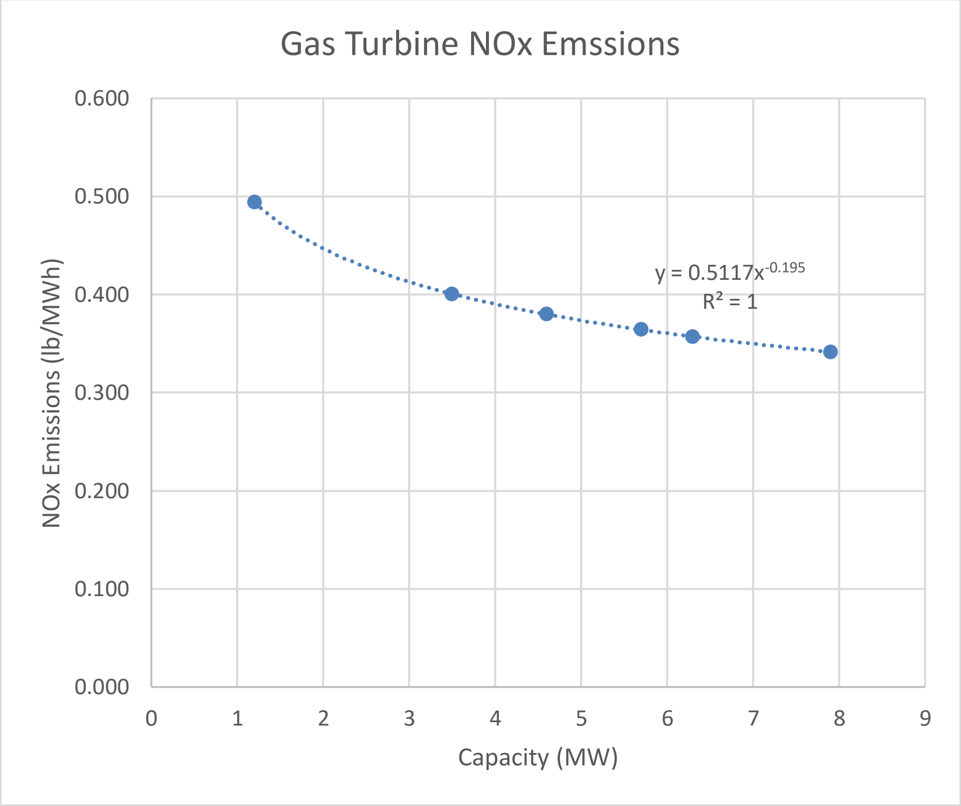

Microturbine SO2 Emissions
Emissions (lb/MWh)
1.200
1.000
0.800
0.600
0.400
0.200
0.000
0
50
100
150
200
250
300
350
Capacity (kW)
y = 1.4213x^-0.089
R² = 1

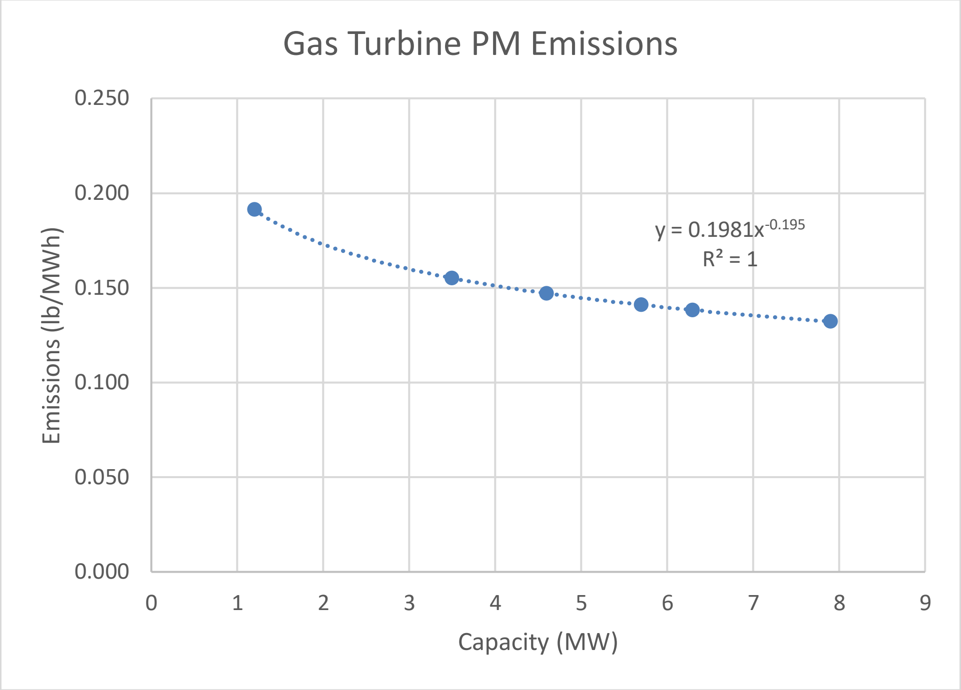

Microturbine VOC Emissions
Emissions (lb/MWh)
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0
50
100
150
200
250
300
350
Capcity (kW)
$y = 0.1697x^{-0.089}$
$R^2 = 1$

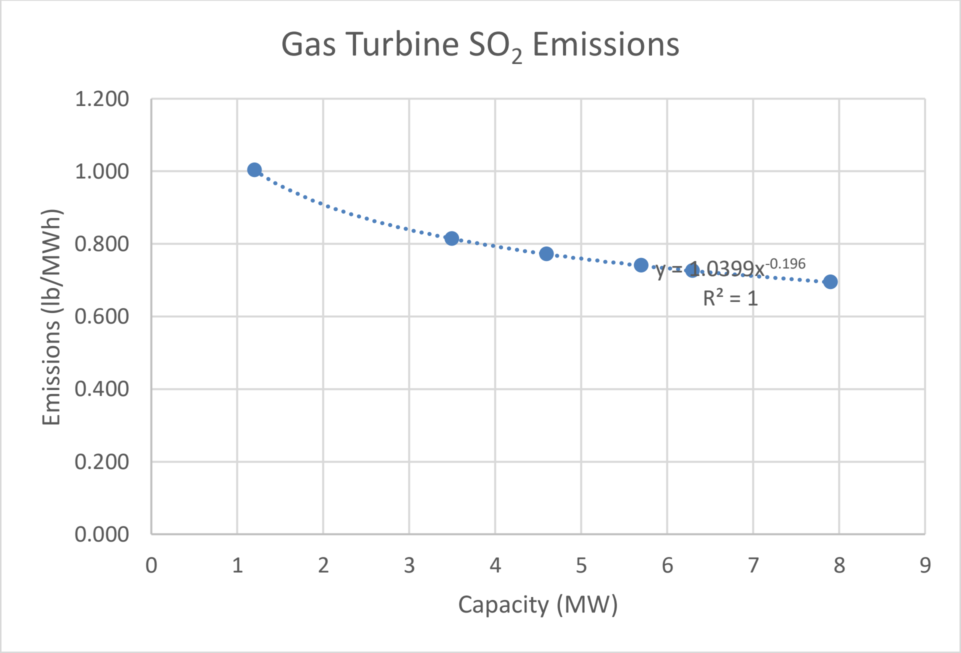

Microturbine CO_2-eq. Emissions
Emissions (lb CO_2-eq/MWh)
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350
Capacity (kW)
$y = -248.9\ln(x) + 3930.2$
$R^2 = 0.9993$

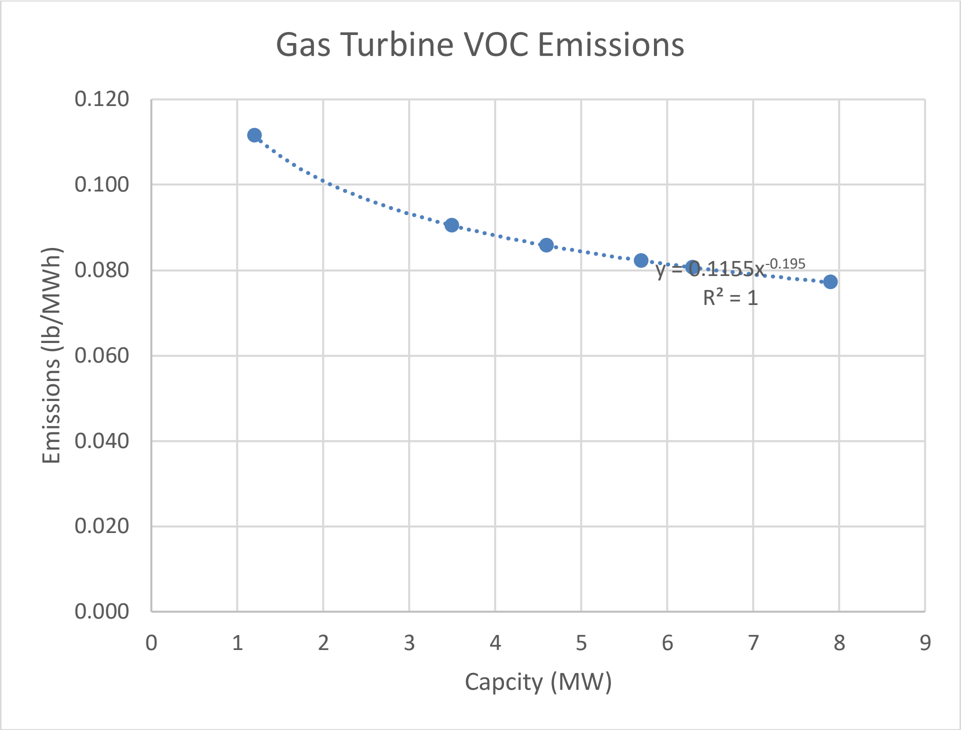
Turbines (1-5 MW)

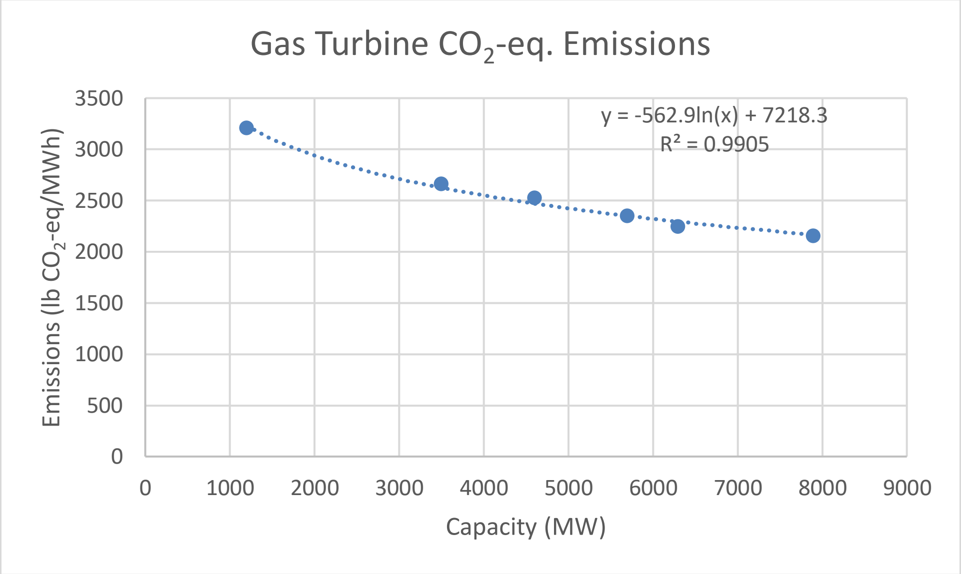




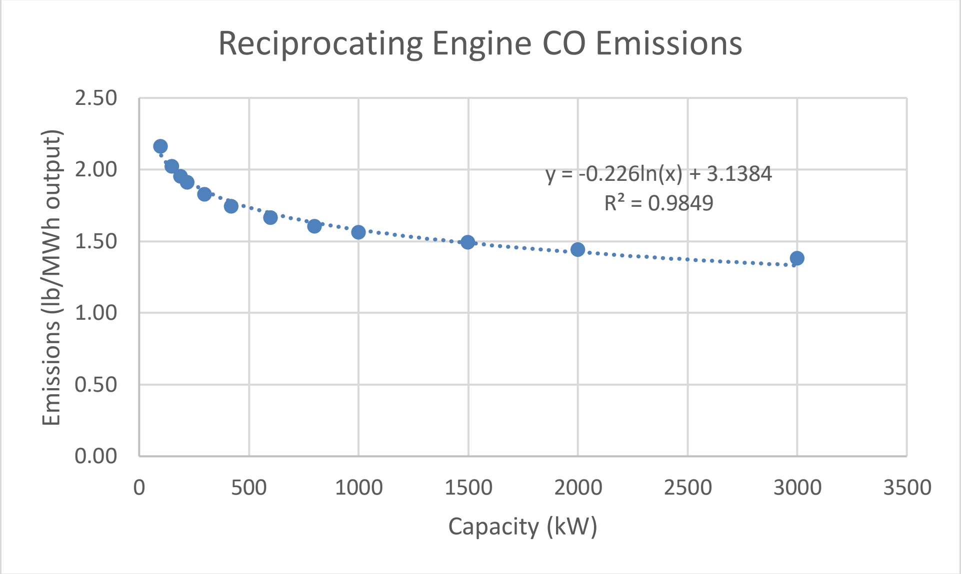

Gas Turbine PM Emissions
0.250
0.200
0.150
0.100
0.050
0.000
Emissions (lb/MWh)
$y = 0.1981x^{-0.195}$
$R^2 = 1$
0
1
2
3
4
5
6
7
8
9
Capacity (MW)

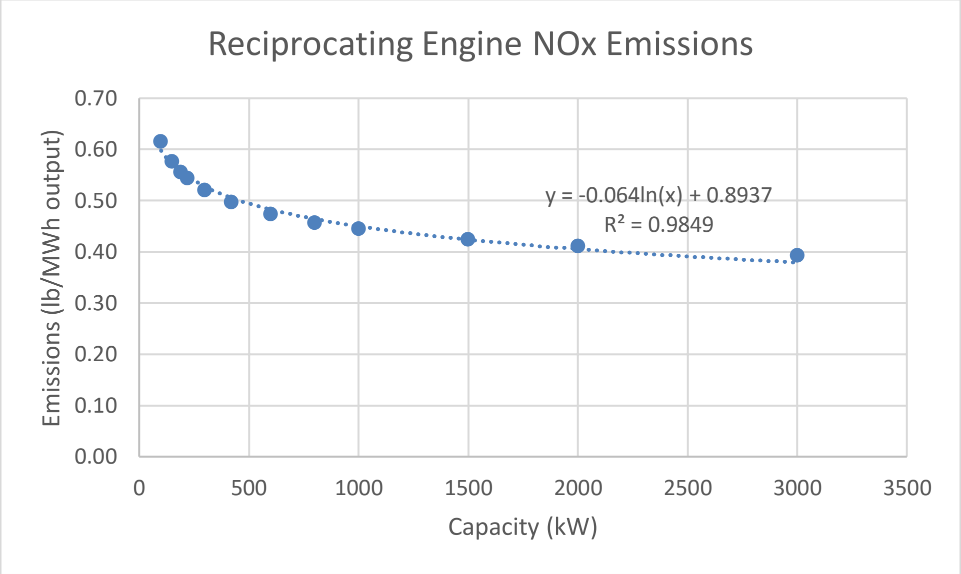

Gas Turbine SO_2 Emissions
1.200
1.000
0.800
0.600
0.400
0.200
0.000
Emissions (lb/MWh)
$y = 1.0399x^{-0.196}$
$R^2 = 1$
0
1
2
3
4
5
6
7
8
9
Capacity (MW)

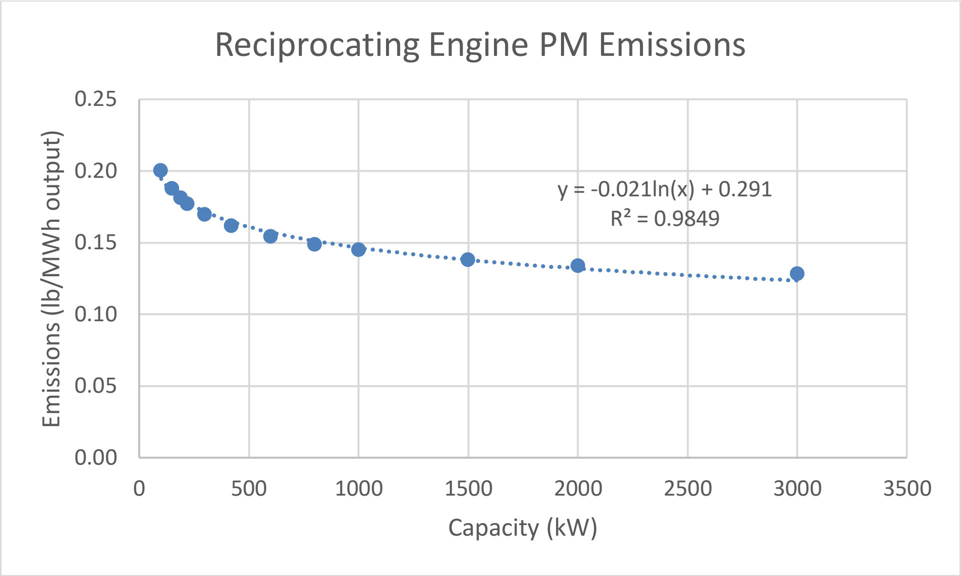

Gas Turbine VOC Emissions
Emissions (lb/MWh)
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0
1
2
3
4
5
6
7
8
9
Capcity (MW)
y = 0.1155x-0.195
R² = 1

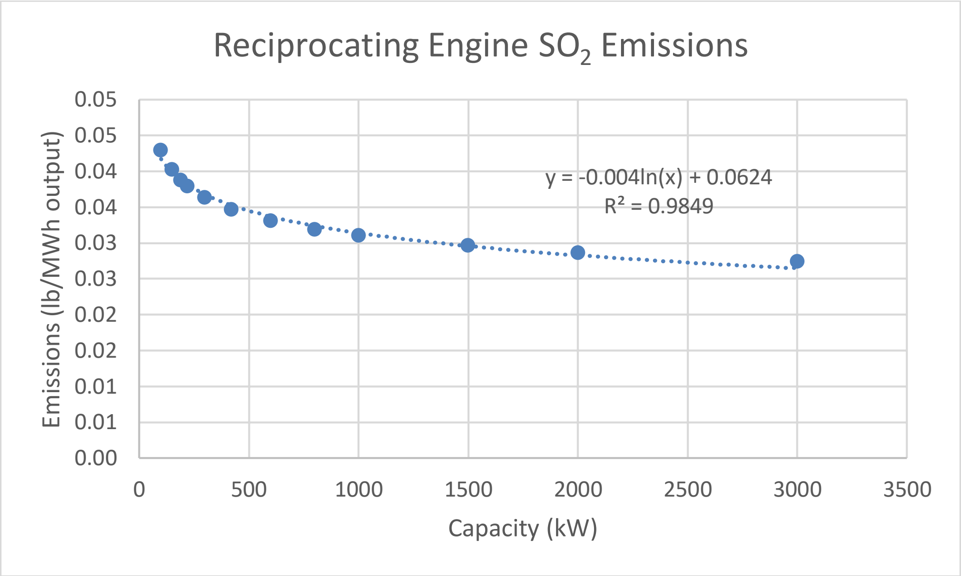

Gas Turbine CO2-eq. Emissions
Emissions (lb CO2-eq/MWh)
3500
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Capacity (MW)
y = -562.9ln(x) + 7218.3
R² = 0.9905

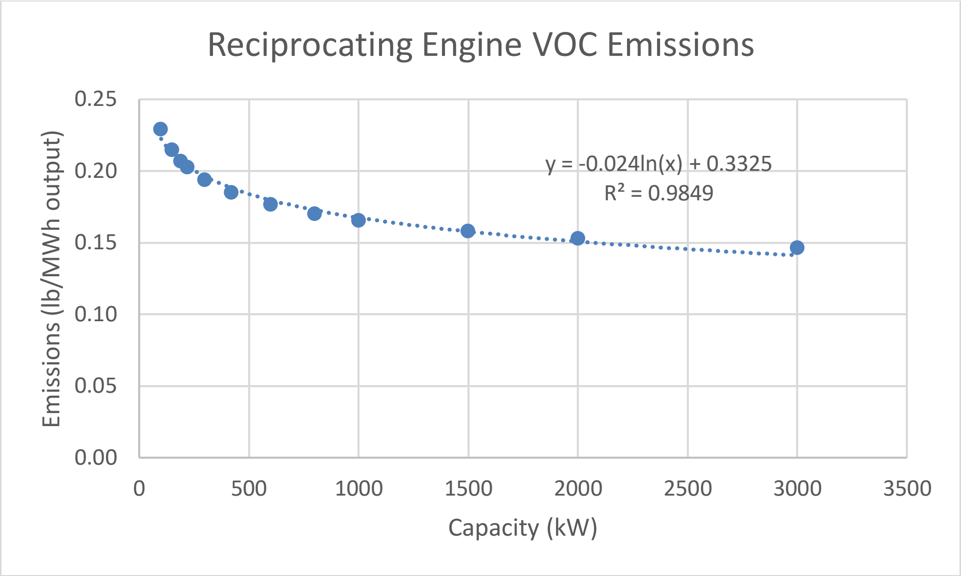
Reciprocating Engines

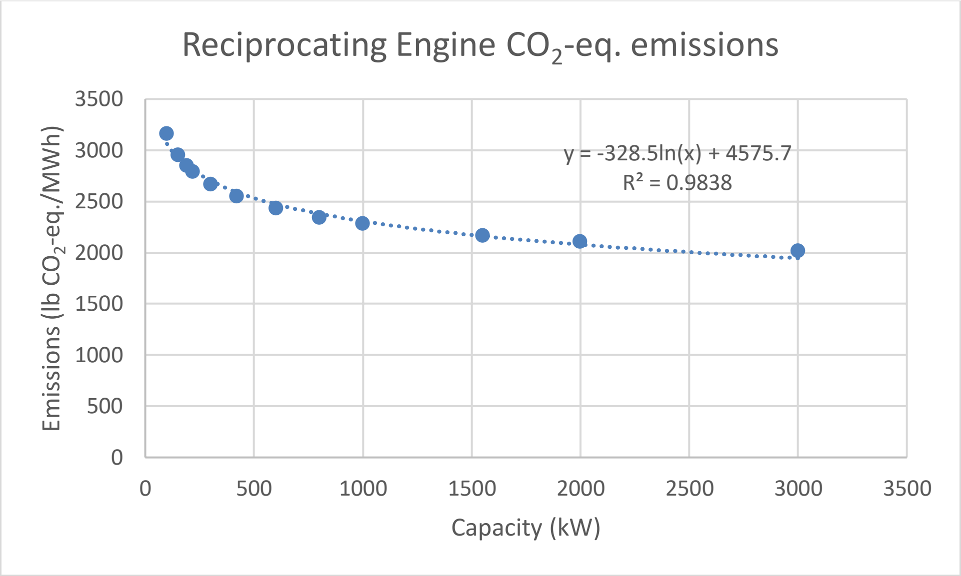





Reciprocating Engine PM Emissions
Emissions (lb/MWh output)
0.25
0.20
0.15
0.10
0.05
0.00
0
500
1000
1500
2000
2500
3000
3500
Capacity (kW)
y = -0.021ln(x) + 0.291
R² = 0.9849


Reciprocating Engine SO2 Emissions
Emissions (lb/MWh output)
0.05
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
0
500
1000
1500
2000
2500
3000
3500
Capacity (kW)
y = -0.004ln(x) + 0.0624
R² = 0.9849


Reciprocating Engine VOC Emissions
Emissions (lb/MWh output)
0.25
0.20
0.15
0.10
0.05
0.00
0
500
1000
1500
2000
2500
3000
3500
Capacity (kW)
y = -0.024ln(x) + 0.3325
R² = 0.9849


Reciprocating Engine CO2-eq. emissions
Emissions (lb CO2-eq./MWh)
3500
3000
2500
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
3500
Capacity (kW)
y = -328.5ln(x) + 4575.7
R² = 0.9838

Fuel Cells

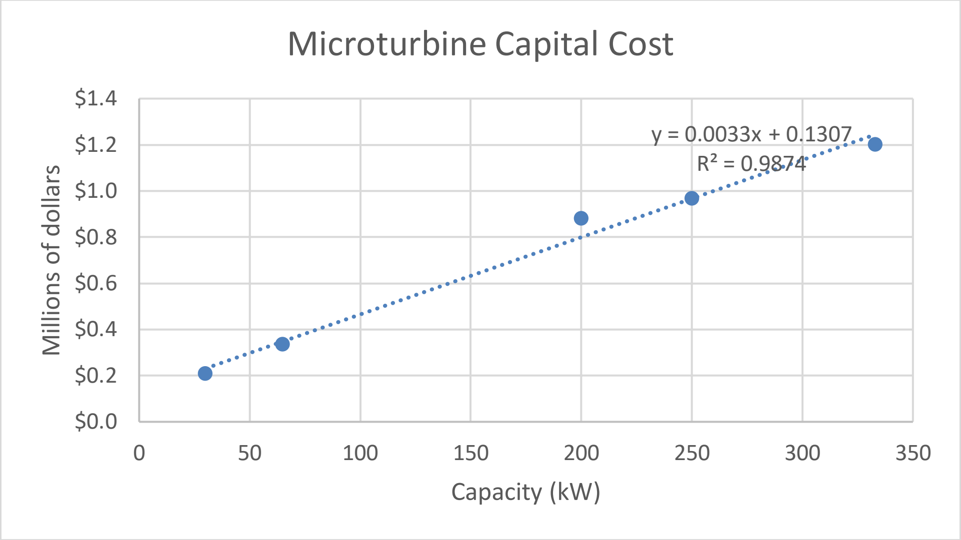
Pollutant	Emissions (lb/MWh output)
CO	0.07
NOx	0.02
PM	0.01
SO_2	0.001
VOC	0.06
CO_2-eq.	1451

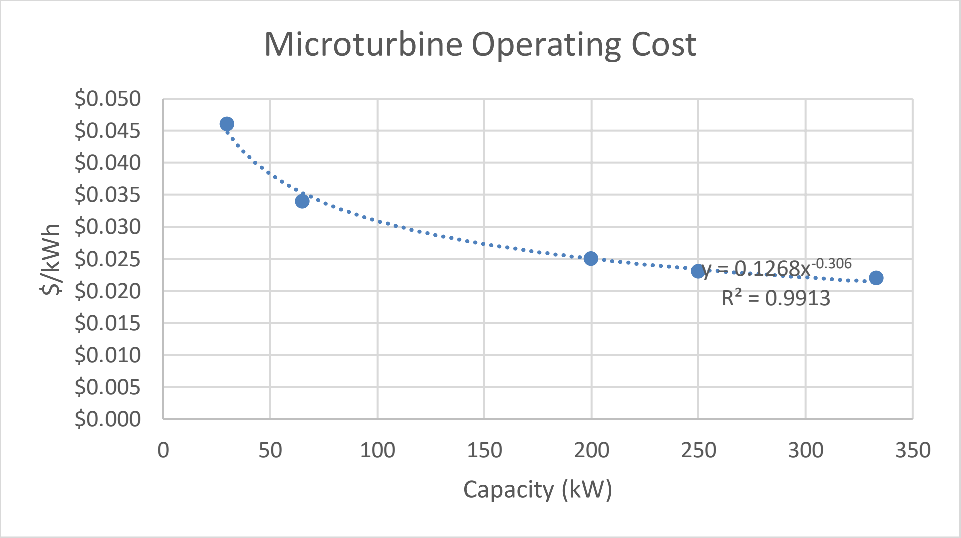
Compressed RNG

Pollutant	Emissions (lb/MWh output)
CO	0.0137
NOx	0.0165
PM	0.0036
SO_2	0.0117
VOC	0.0018
CO_2-eq.	122

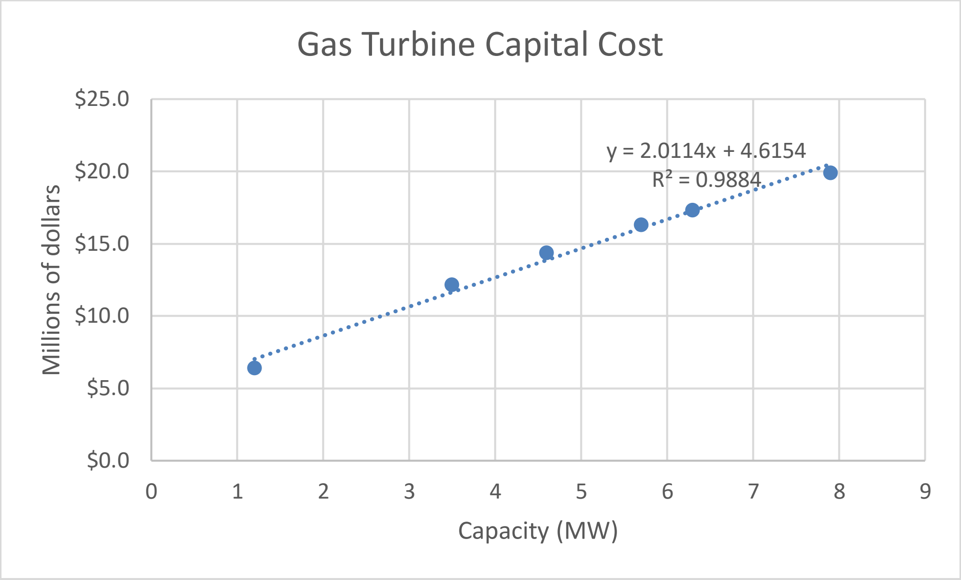
Appendix B: Regression Curves for Costs of Biogas Conversion

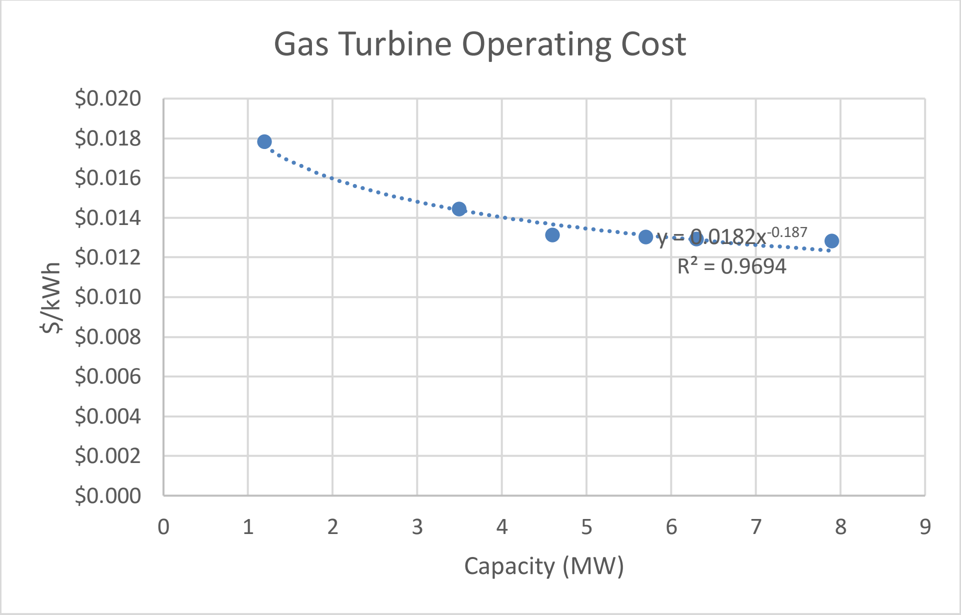
Microturbines (30-330 kW)



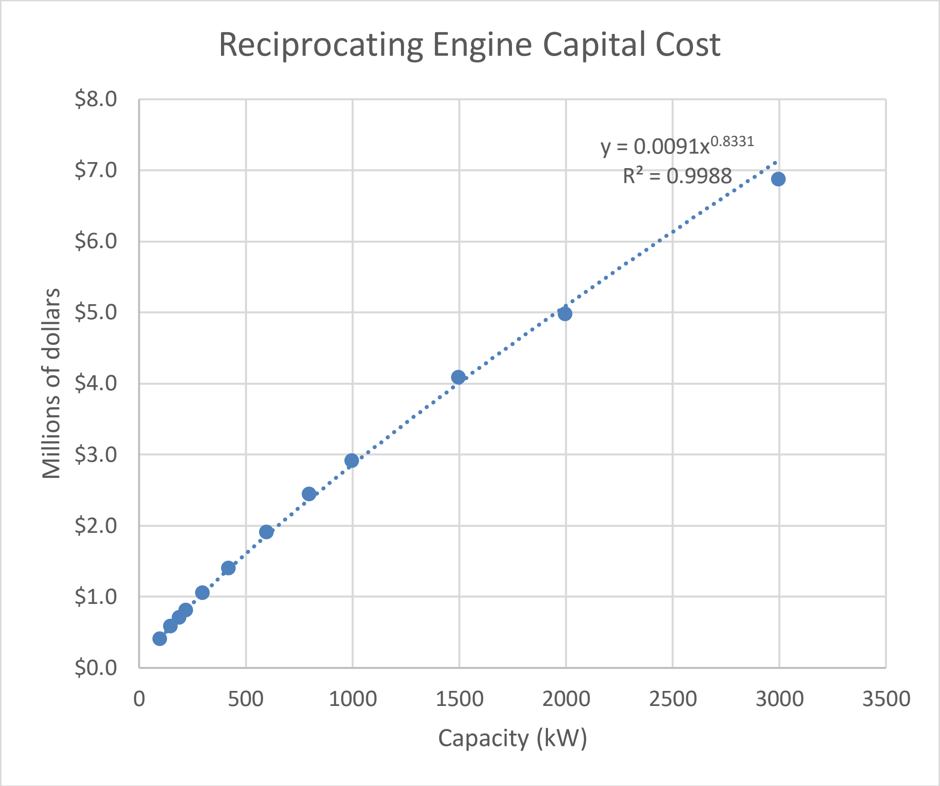


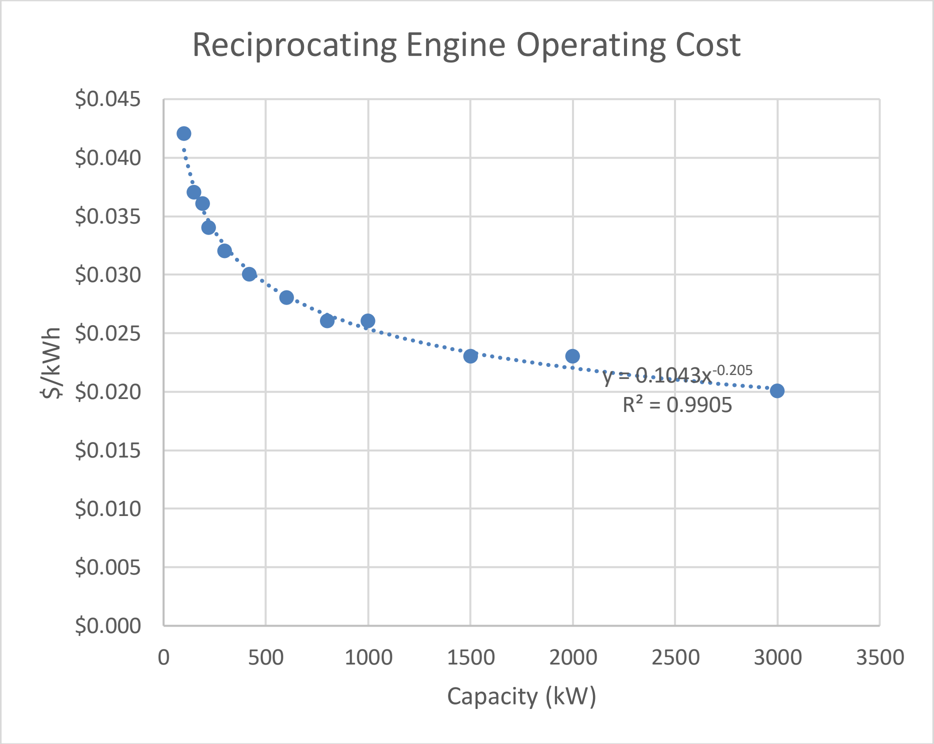
Turbines (1-5 MW)



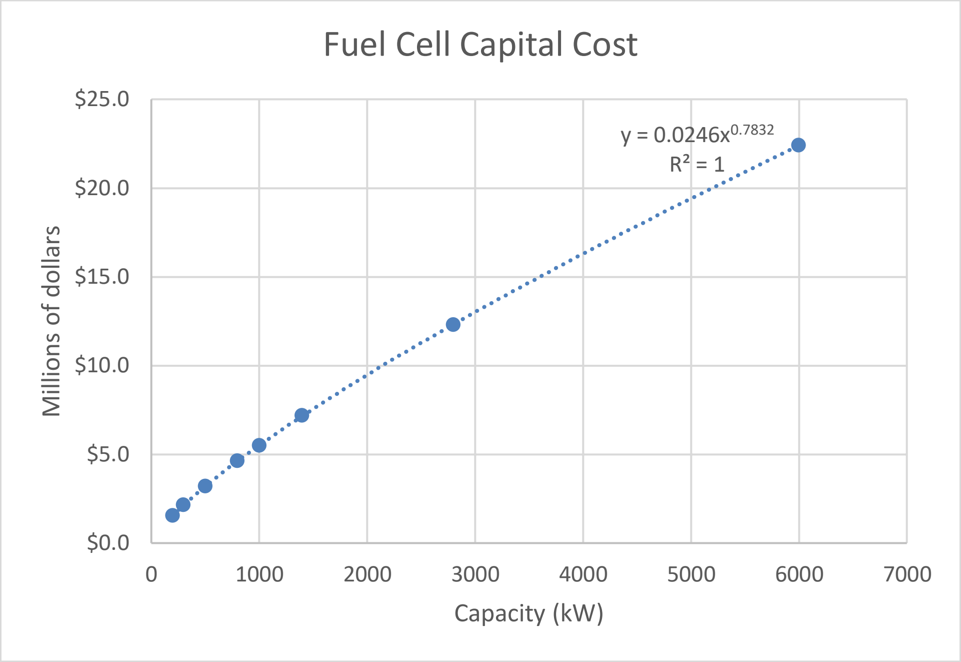


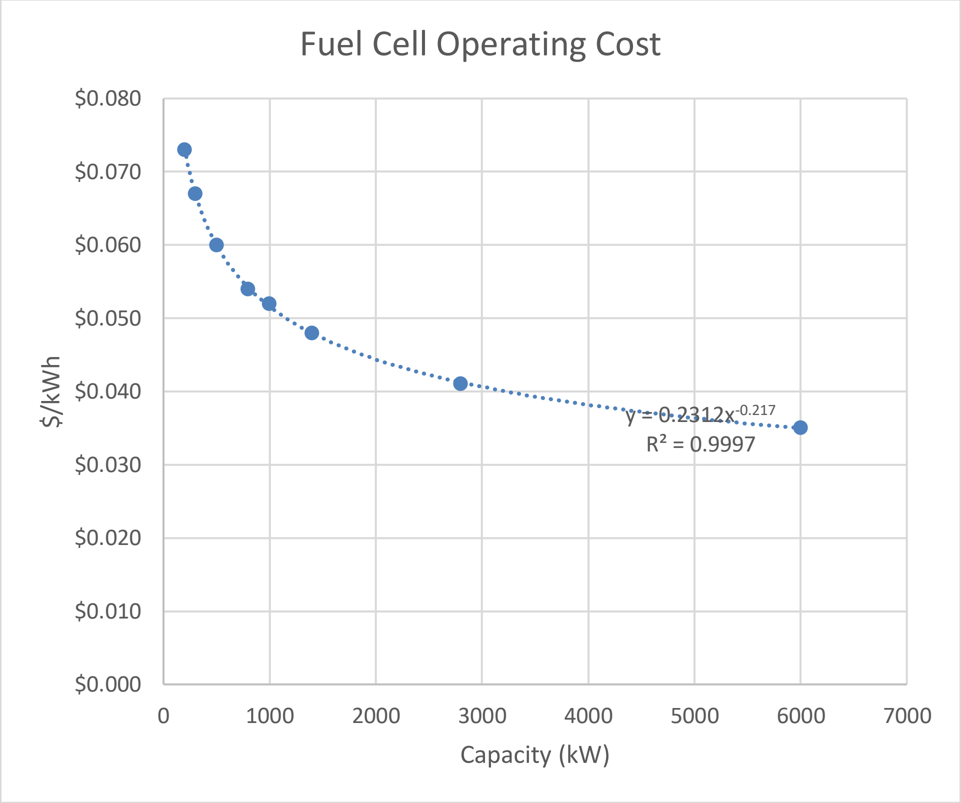
Reciprocating Engines



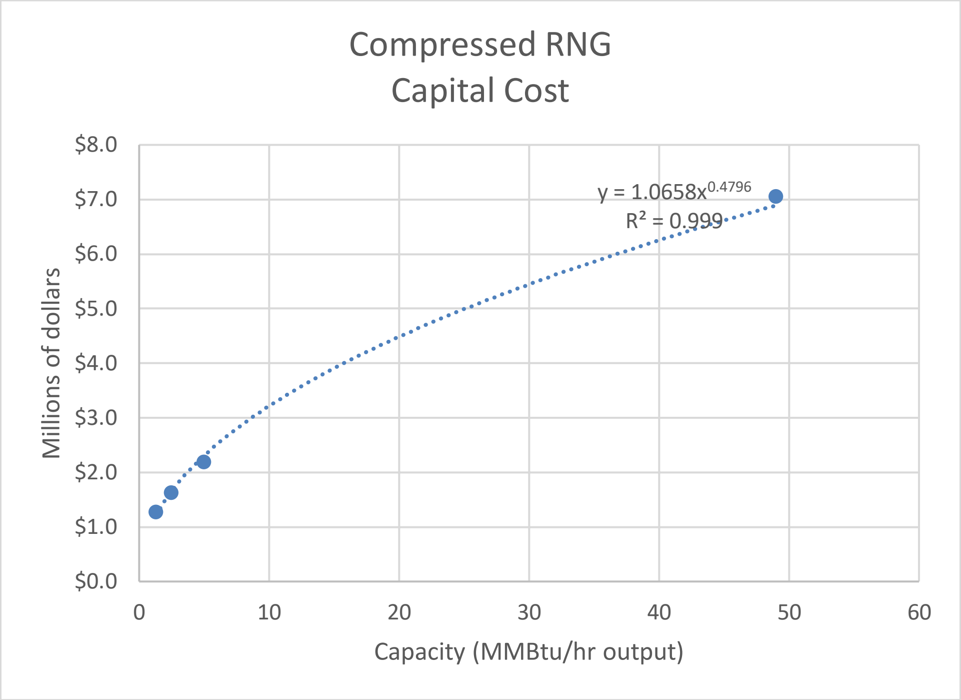


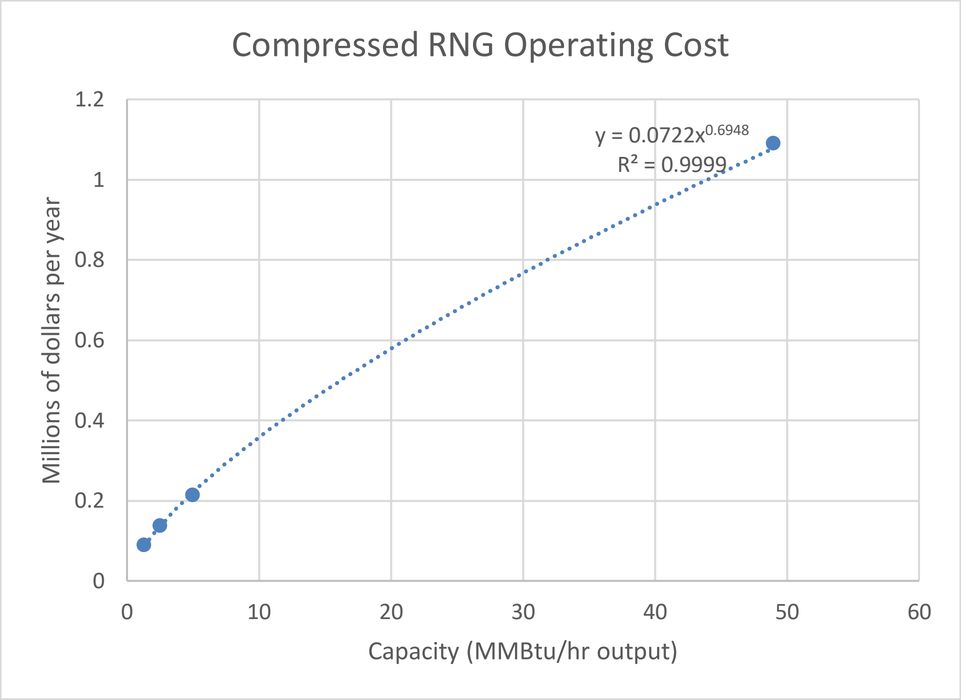
Fuel Cells


Fuel Cell Capital Cost
y = 0.0246x^0.7832
R² = 1
Millions of dollars
$25.0
$20.0
$15.0
$10.0
$5.0
$0.0
0
1000
2000
3000
4000
5000
6000
7000
Capacity (kW)


Fuel Cell Operating Cost
y = 0.2312x^-0.217
R² = 0.9997
$/kWh
$0.080
$0.070
$0.060
$0.050
$0.040
$0.030
$0.020
$0.010
$0.000
0
1000
2000
3000
4000
5000
6000
7000
Capacity (kW)

Compressed RNG





Appendix C: Technology Transfer

Technology transfer to project stakeholders occurred via project Advisory Group meetings, as described Ch. 1. The list of Advisory Group members was shown in Table 1.1.

In addition, the following presentations and papers were used for technology transfer:

List of conference presentations (with a paper):

Sattler, Melanie L.; Bhatt, Arpita H.; Hyun, Kate; Nasirian, Bahareh; Behseresht, Ali; Chakraborty, Mithila; Chen, Victoria C. P. "Development of a Cost Optimization Algorithm for Food and Flora Waste to Fleet Fuel (F^4)," 2021 INFORMS Service Science Conference, Virtual, Aug. 2021.

List of conference presentations (without a paper, reverse chronological order):

Sattler, Melanie; Adelegan, Opeyemi; Anjomani, Ardeshir; Arabi, Mehrdad; Bhatt, Arpita; Chakraborty, Mithila; Chen, Victoria; Hyun, Kate; Nasirian, Bahar; Ntiamoah-Asare, Doreen; Rony, Asma. "POWER (Prioritizing Organic Waste to Energy-Renewable) Framework: Evaluating Options for Organics Waste Diversion," Intercontinental Landfill Research Symposium, Asheville, NC, Sept. 2022.

Sattler, Melanie; Adelegan, Opeyemi; Anjomani, Ardeshir; Arabi, Mehrdad; Bhatt, Arpita; Chakraborty, Mithila; Chen, Victoria; Hyun, Kate; Nasirian, Bahar; Ntiamoah-Asare, Doreen; Rony, Asma. "Prioritizing Organic Waste to Energy- Renewable: POWER Framework." Air & Waste Management Association 115th Annual Conference, San Francisco, California, June 2022.

Ntiamoah-Asare, Doreen; Adelegan, Opeyemi; Chakraborty, Mithila; Arabi, Mehrdad; Nasirian, Bahar; Sattler, Melanie; Chen, Victoria; Bhatt, Arpita; Hyun, Kate. "Prioritizing Organic Waste to Energy-Renewable: Development and Application of the POWER Framework," Poster at College of Engineering Innovation Day, April 2022 https://uta.engineering/innovationday/project-2022.php?p=15&h=d733d1b4c62ba763d3ea6f233d2d924c.

Bhatt, A.; Sattler, M.; Hyun, K., Chen, V.; Anjomani, A.; Chakraborty, M.; Raven, N.; Behseresht, A.; Mehrdad, A.; Nasirian, B.; Rony, A. "Prioritizing Organic Waste to Energy-Renewable: Development and Application of the POWER Tool," Poster, Global Waste Management Symposium, Indian Wells, CA, Feb. 2022.

Chakraborty, Mithila; Boskabadi, Azam; Raven, Nic; Behseresht, Ali; Anjomani, Ardeshir; Sattler, Melanie. "Food and Flora Waste to Fleet Fuel: Development and Application of the F^4 Framework," Poster, UTA College of Engineering Innovation Day, April 2021. https://uta.engineering/innovationday/project.php?p=17&h=36b5ae3aa49499cb7ef2d193f631665b .

Other Presentations:

Sattler, Melanie; Adelegan, Opeyemi; Anjomani, Ardeshir; Arabi, Mehrdad; Bhatt, Arpita; Chakraborty, Mithila; Chen, Victoria; Hyun, Kate; Nasirian, Bahar; Ntiamoah-Asare, Doreen; Rony, Asma. “Prioritizing Organic Waste to Energy- Renewable: POWER Framework.” Presentation for the North Texas Food Policy Alliance, March 2022.

Bhatt, Arpita. Presentation for International Environmental Engineering Webinar Series "ENVIRO WEBTALK 2021” sponsored by Lovely Professional University, Punjab, India, May 2021.

Sattler, Melanie; Anjomani, Ardeshir; Arabi, Mehrdad; Behseresht, Ali; Bhatt, Arpita; Boksabadi, Azam; Chakraborty, Mithila; Chen, Victoria; Hyun, Kate; Nasarian, Bahar; Raven, Nicholas; Rony, Asma. “Food & Flora Waste to Fleet Fuel: Development and Application of the F^4 Framework,” Presentation at virtual Regional Center of Excellence (RCE) North Texas Summit, https://sustainability.uta.edu/rce/2021-annual-summit/, March 2021.

Magazine Article:

Sattler, Melanie; Hyun, Kate; Bhatt, Arpita; Ardeshir Anjomani, Caroline Krejci, Victoria Chen, Mithila Chakraborty, Nic Raven, Ali Behseresht. “The POWER Toolbox: Aid for Assessing Anaerobic Digestion of Organics.” March 2022.

Book Chapter:

Hyun, K., Sattler, M., Bhatt, A., Nasirian, B., Behseresht, M., Chakraborty, A., Chen, V. “Development of a Cost Optimization Algorithm for Food and Flora Waste to Fleet Fuel (F^4)” In: Qiu, R., Lyons, K., Chen, W. (eds) *AI and Analytics for Smart Cities and Service Systems*. ICSS 2021. Lecture Notes in Operations Research. Springer, Cham, Nov. 2021, pp. 141-153. https://link-springer-com.ezproxy.uta.edu/chapter/10.1007/978-3-030-90275-9_12 .

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