Design Report Submittal Form

Project Title:

ECOnnectivity

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Project Summary

In cities around the world, precious resources are thrown to the wayside as waste with no possibility of further utilization. This is especially true for the organic fraction of both municipal solid waste and wastewater bio-solids produced in the United States, which contain useful energy and chemicals within. Unfortunately, the widespread implementation of systems that take advantage of such resources have been hindered by a lack connectivity between waste generators, haulers, treatment facilities, and government permitting. Fortunately, ECOnnectivity, while still in its early stages of development, is here to begin helping to overcome these social obstacles. ECOnnectivity is a big data based software, utilizing the internet of things (IOT), which virtually links waste entities in ways that facilitates the sharing of organic wastes and the resources derived from them. It does this by gathering and storing data from each waste entity to calculate mass and energy balances, economic analysis, optimized waste collection routes, and eventually much more. With the ability to store large amounts of data onto a central server, ECOnnectivity will also serve communities as a decision support system (DSS) for large-scale projects in an attempt to reduce wastefulness while increasing the sustainability of future cities. Though ECOnnectivity has prospects of spreading to much wider areas of interest, this report will focus on the use of a rudimentary version of the software to examine the usefulness of transporting source separated organics produced by commercial-scale organic waste generators in Lafayette Parish to the three wastewater treatment plants (WWTP) in Lafayette for energy recovery through anaerobic digestion.

To begin, optimized routes were created through Lafayette Parish based on road miles traveled, capacity of nearby digesters located at WWTPs, and greatest net positive energy production. These may seem like conflicting objective, but the results show that increasing any of these parameters will cause an increase in the system as a whole. These optimized routes would then be relayed to waste haulers in the area using the Google Maps API on a handheld GPS. Next, an economic analysis was run for each waste entity based on research of the process. This resulted in a best-case scenario for Lafayette Parish that covered a total of 337 road miles for one holistic pickup, collecting 9377 tons of organic food waste per year, producing 0.66 MW of net power. While this is considered a small-scale power plant, it represents the powering of roughly 950 residential homes or 160 commercial businesses. When looking at the results of the economic analysis, ECOnnectivity showed that while the waste haulers are able to turn a profit of $400,500 per year, the WWTPs would need government subsidies of $13.30 per ton of organic waste treated. This corresponds to $185,000 per year, to reach a reasonable payback period of roughly 12 years under the assumed conditions of waste generation, capital cost, and operation and maintenance cost.

Introduction

The growth of our cities is inherently accompanied by the increasing production of organic wastes such as food waste, yard clippings, animal manure, wastewater bio-solids, and many more. Lafayette Parish, the project area chosen for this case study, does not deviate from this pattern. As the second most densely populated parish in south-central Louisiana, Lafayette Parish is the state's hub city regarding the interaction between oil-and-gas, commerce, education, health services, living, and entertainment sectors in the southern region of the state. This has led to Lafayette Parish becoming one of the largest producers of organic waste in Southern Louisiana.

These organic wastes have many useful resources locked within such as heat, electricity, and chemicals, but as of now, there are very few systems in place for the recovery of these resources. In 2014, the United States EPA estimated that the single largest component of municipal solid waste (MSW) being placed into landfills are food-related wastes [1], reflecting a one-dimensional mindset in terms of organic waste treatment. Years of focusing solely on the disposal of organics has resulted in the unnecessary expenditure of land space, an inefficient use of valuable resources and greater than necessary greenhouse gas (GHG) emissions. As fossil fuels and other nonrenewable resources are used up, focusing our attention on ways to more effectively harness the energy within our wastes will become increasingly important. Currently Lafayette Parish disposes their municipal solid waste to landfills in the surrounding parishes, which have historically provided Lafayette Parish with a reliable service but does not capitalize on the intelligent utilization of land space or recycling of organic waste into useful energy and fertilizer.

Currently there are three WWTPs in Lafayette Parish that treat sewage sludge by anaerobic digestion. The biogas produced in this system is high in methane content, which is flared to the atmosphere to lower greenhouse gas exposure. Another product of anaerobic digestion is the production of biosolids containing high levels of nitrates. These solids are then brought to landfills to be land applied. While this process is successful in the disposal of waste, it is one-dimensional by not capitalizing on the energy potential of digesting organic waste. Sewage sludge co-digested with other forms of organic waste, such as food waste, increases the biogas production of each waste vector, resulting in a complementary relationship that should be tapped.

All this wastefulness can be contributed to two main factors. Firstly, digestion of sewage sludge alone does not produce enough biogas to be profitable for the WWTP after capital costs to install turbine generators to produce electricity is paid. Secondly, a lack of connectivity between organic waste generators, waste haulers, and WWTP prohibit the treatment facilities from receiving additional feedstock to increase biogas production to profitable levels. The ECOnnectivity network (**Figure 1**) is designed to solve both of these problems.

Problems Addressed

Of the many challenges preventing implementation of systems for resource recovery from organic waste, the most direct problem that must be overcome is the lack of connectivity between waste generators, haulers, and treatment facilities. The connectivity of an interactive network provides solutions that are crucial for the implementation and development of sustainability projects [2] [3]. Interactive connectivity allows: (1) quicker assessment of project status, and immediate actions on group decisions; (2) practitioners and theorists to dynamically search for better project directions; and (3) the discovery of untapped facilities and resources that may be key tools for progress. Adding data analytics within an interactive network creates a decision support system (DSS) aspect that allows for the modeling of metrics such as bioenergy potential, mass balances, and environmental impact estimates. Using the Internet of Things (IOT) platform and geographical information system (GIS) analytics, ECOnnectivity caters an interactive citywide network of organic wastes generators, haulers, and processors to implement a sustainable system of waste management and utilization in the city of Lafayette.

Due to ECOnnectivity's ability to process large amounts of data, managers of waste in the community would be aided in the resolution of complex problems. Population growth is inevitably complicating previously simple issues, and as stated here, "...so much depends on how we build our cities: not just environmental impacts, but our social well-being, our economic vitality, our sense of community and connectedness. Fundamentally, the way we shape cities is a manifestation of the kind of humanity we bring to bear," [4]. As new entities begin to use ECOnnectivity, larger amounts of information will be gathered, which in turn will enable the DSS to more accurately advise managers and important decision makers in the community. As humans develop increasingly intricate systems, this kind of connectivity will likely become a necessary role in shaping new legislation and infrastructures. If effectuated to serve the future appropriately, ECOnnectivity's opportunities are endless.

Description of System

Inputs & Outputs

The first input that the system will need are GIS shapefiles containing location specific information for the area of interest, in this case Lafayette Parish roads, commercial organic waste generators, and WWTPs. Next, weights of the organic fraction of solid waste produced by varying sources will be measured and wirelessly uploaded to the ECOnnectivity server along with individual truck capacities. This input is dynamic in nature and will require hardware to be constantly monitored. For the preliminary model used in this report, the organic fraction of solid waste produced by each commercial scale generator in Lafayette Parish was estimated using values with respect to each different type of source [5]. The static data inputs that will be needed for the DSS to calculate expenditures include the energy content [6] and cost [7] of diesel, fuel economy of typical garbage trucks [6], energy content of feedstock [8] [9] [10] [11], typical costs [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25](capital and O&M) and revenues of each entity.

Based on these inputs, ECOnnectivity will begin by breaking the area of interest's shapefiles into zones, each containing a WWTP. Next, ECOnnectivitiy's private server will output customized visual interfaces depending on their respective usefulness to each type of client, allowing them to easily track the progress of the system. This will provide a platform for increasing connectivity of community resources and aid in the waste treatment decision-making processes. For waste haulers, the model will output optimal routes based on maximized energy production potential, a cost analysis of their service, updated availability of waste in their respective zone, and permitting needed to facilitate the pickup process. WWTPs will be provided with anaerobic digester capacities for their plant incorporated with incoming deliveries, biogas generation, net financial gain for the facility, and further permitting information needed to take on the new sources of waste. City planners will be given a full economic analysis including job creation, costs and revenues, sustainability, statuses of ongoing permitting processes, and new city zoning suggestions. Finally, waste generators will have access to a constantly updated website displaying their contributions to the community to show that their efforts are making a difference both locally and globally.

Mass and Energy Balances

To solve both the mass and energy balances, the model begins by finding the shortest possible routes within each zone through a GIS software system, e.g., ArcGIS or QGIS, using pgRouting [26] to calculate route distances in miles. Based on the simple capacity balance given in Eq. (1-1), only the routes that do not cause anaerobic digesters to store biosolids beyond their capacity are considered.

Eq. 1-1	Net [C] = Available [C] - Required [C]
Eq. 1-2	Available [C] = Digester [C] x 2 (digesters/set) x 365 (days/year) / Retention time* (days)
Eq. 1-3	Required [C] = Food waste [V] + Sewage sludge [V]
Eq. 1-4	Food waste [V] = Food waste [M] / 750 (lbs FW/yard^3)
Eq. 1-5	Sewage sludge [V] = Digester influent** [V] x 365 (days/year)

[C] = Anaerobic digester capacity
[V] = volume
[M] = mass
**Retention time = 25 days*
***Digester influent given by WWTP*

Once outputted, the route distance in miles is used to calculate the energy consumption involved in transporting the organic waste between generators and treatment plants (Eq. (2-6)). Likewise, the weights of organic wastes produced from each pickup along the route will be used to estimate the energy production (Eq. (2-2)) [8] [9] [10] [11]. Finally, ECOnnectivity will calculate a net energy value by taking the difference between the energy produced and the energy consumed (Eq. (2-1)). This allows the DSS to generate a route minimizing driving distance while maximizing biogas production i.e. the largest net production of energy, all while taking into consideration the tank capacity of delivery trucks as well as anaerobic digesters.

Eq. 2-1	Net [E] = Produced [E] - Consumed [E]
Eq. 2-2	Produced [E] = Vol. solids co-digested feedstock [M] x VS co-digested feedstock* [E]
Eq. 2-3	VS co-digested feedstock [M] = Food waste [M] + Sewage sludge [M]
Eq. 2-4	Food waste [M] = SUM(Participating waste generators [M])
Eq. 2-5	Sewage sludge [M] = Sewage sludge [V] x 1400 (kg/m^3)
Eq. 2-6	Consumed [E] = Road [D] / 2.7 (miles/gallon) x diesel**[E] x 52 (pickups/year)

[E] = energy
[M] = mass
[V] = volume
[D] = distance
**based on %VS removed from feedstock*
***128488 (BTU/gal)*

System Functioning Mechanisms

Our system consists of multiple components all working together to optimize the detection and collection of waste from local waste generators. At each waste generator (grocery stores, restaurants, etc.) a solar-powered waste bin will be placed to report information back to the server. The bin will utilize an infrared sensor to estimate volume and a scale to measure weight, both connected to a small single board computer (like a raspberry pi). The server will be able to handle a multitude of tasks. It hosts a small program that listens for messages from all the sensors, and updates the database accordingly. The database will hold not only individual sensor information, but also information on the system as a network (sensor/driver locations within zones, waste per sensor/truck/zone, etc.). The server will also host a webapp (link: Https://sankyr.github.io/ECOnnectivity) that the drivers will use to see all available waste locations and their route through a google map while other participants can use to see live data on production.

A key component in optimizing fuel consumption is creating the shortest path for waste pickup. Our technique utilized two complementary open-source software: QGIS (GIS platform), and postgreSQL (database platform). These two platforms allow for quick calculations of big data to be displayed geospatially. PostgreSQL's extensions, PostGIS and pgRouting [26], provided the geospatial routing and zoning functionality necessary in completing the following tasks. This is detailed in **Figure 3**. The first step ECOnnectivity takes in optimizing routes is establishing zones around each WWTP. To tackle this, a topology of the area's road network is created through pgRouting, defining every node and edge. Then a polygon is created around the WWTP with a cost-specific radius (in our case, road distance). Once the zone creation algorithm is fully developed there will be multiple variables considered other than just road distance. For example, other variables will include digester capacity, over capacity in other zones, one-way streets, etc. The final step is finding the shortest path for each zone between every waste generator, with the final destination being the WWTP. Utilizing the topology created from the road network, nodes representing the waste generators and WWTP are injected into the road network, and the shortest round-trip path via edges is calculated.

Once operating, organic waste brought to participating WWTPs, seen in **Figure 2**, will be used as the feedstock for their anaerobic digesters in junction with the existing wastewater biosolids. Anaerobic digestion (AD) is a biological conversion process that converts complex organics to a final gaseous byproduct commonly known as biogas. The process begins with hydrolysis, or the breakdown of carbohydrates, proteins, and fats into simple sugars, amino acids, and fatty acids, respectively. Next, a group of bacteria known as acidogens converts the simple organics to acetic acid, hydrogen, carbon dioxide, and other volatile fatty acids (VFAs). Simultaneously, symbiotic groups of bacteria, the acetogens, convert the various VFAs into acetic acid that can be used as a carbon source for the last group of bacteria, the methanogens. The process finally ends when the methanogens convert acetic acid, hydrogen, and carbon dioxide into methane.

The final biogas consists mainly of methane (CH_4), hydrogen (H_2), and carbon dioxide (CO_2) with hydrogen sulfide (H_2S) as a trace gas. Because CO_2 and H_2S are low energy gasses that can quickly corrode machinery and cause harmful environmental effects, the methane must be treated before being converted into fuel or electricity. The proposed gas cleaning system is modeled closely to that of St. Landry Parish Solid Waste (St. Landry Parish, Louisiana), that has reported great success in capturing, cleaning, and storing biogas generated from their landfill. The first step is the removal of H_2S, a highly corrosive and foul-smelling gas that can produce SO_2 when burned–a known contributor to acid rain adverse health effects. An activated carbon filter can easily remove this constituent. At this point, the biogas still contains a fair amount of moisture that must be removed to improve the energy potential of the gas. This is accomplished by cooling the biogas to near freezing temperature of water to create a condensate trap, where the water will drop out of solution. The gas is then passed again through an activated carbon filter containing coconut shells to further remove sulfides and siloxanes. At this stage, most of the biogas is comprised of methane with about 15% carbon dioxide. Finally, to convert the biogas into useful power, it must be combusted within a contained chamber. Upon combustion, the biogas releases heat that will be used to evaporate water within a boiler. The water vapor rises and causes a turbine to rotate, producing mechanical work that can be used to generate electricity with a generator. Once created, the electricity will be placed into the electric grid to serve the community. The system design described above is summarized in **Figure 1**.

System Economics

To be considered economically viable, the system proposed through ECOnnectivity must be as cheap, or cheaper, to use than landfilling for all entities to have incentive to join. Therefore, the following business model has been proposed for the transportation and conversion of organic waste to energy.

To initiate this business model, waste generators must first source separate their organic waste into separate bins. To create incentives for this action, the local utility company would need to offer a premium rate of electricity to waste generators involved in the program. At this point, it is important to keep in mind that the decrease in electricity rates must outweigh the additional incurred cost of collection due to waste haulers making twice the number of weekly trips. A scenario has been envisioned in which the waste generation data stored on ECOnnectivity's server would be used to charge monthly pick-up fees based on the amount of waste produced by each individual generator, but changing the format of waste hauler contracts is an entirely different topic and will not be considered in this analysis. The only capital cost incurred by the waste generator during start-up would be the hardware needed to measure, store, and transfer organic waste generation data to the main server.

Next, the waste haulers would set up organic waste contracts with the waste generators that would be comparable to that of their current waste pick-up rates while still turning a profit considering the additional operation and maintenance cost of increasing the number of trips necessary for pick up. We assume that organic waste pick-ups can be scheduled on different days as the inorganic fraction so that no additional trucks would need to be purchased, nullifying capital cost for waste haulers. The waste hauler would then transport the organic waste to each zone's respective WWTP where a tipping fee based on the current tipping fee charged by landfills would be incurred. As to not to overbear the waste generator with additional costs, the waste hauler will enter into a contract with ECOnnectivity that charges an annual data holding fee based on the number of local generators. The waste hauler will likely be able to offset some of this cost by charging slightly higher collection fees to the generators.

Once received, the WWTP would pay for the conversion of the additional waste being placed into its anaerobic digesters, including pre-treatment, and sell the electricity produced. Of course, the WWTP would need to purchase pre-treatment equipment and technologies for biogas to electricity conversion, which will be the largest capital cost of this business model. Even with a high a capital cost, government tax credits will be given out for their purchase, helping to reduce the payback period of the WWTP's investment. Also, anytime renewable energy is created, a renewable identification number (RIN) is attached to it which helps the federal government keep track of renewable energy goals and where subsides must be paid out.

To tie all entities together, ECOnnectivity will take on the cost of buying a server and VPN to store and share data. The company will also produce and sell, by yearly subscription, a routing and navigation software to the waste haulers and a compliance tracking software (CTS) to the WWTPs. This business model is easily scalable to any size city, which can help communities decide on the scale at which they wish to operate and can approximate the necessary size of workforce needed to maintain the system.

Design Benefits

Ease of Operation

ECOnnectivity capitalizes on ease of integration. The IOT allows for continuous computing of large amounts of data on a private server and the algorithms can adapt as needed. Data is constantly being received from the waste generators and being sent to the waste haulers. Waste haulers have their routes automatically updated and can be visually accessed through a phone app. The system is virtually invisible to waste generators and the only change to daily routine would be separating the organic waste from the inorganic. The system calls for little maintenance other than occasional updates, as it is merely a server utilizing a non-tangible object (IOT).

Economic Development

The potential economic impact of this software can be grand; if the organic waste needed is available, it can continue to grow and benefit the community. The software not only keeps track of the waste that is being produced and collected, but also estimates the untapped local markets to help show an ideal growth point that can be easily sustained. This system helps employment in any environment, as well as lowers the total amount of organic waste that we let go as a country.

Ecological

In 2012, the world was producing an estimated 1.3 billion tons of MSW per year, and is expected to increase this value to 2.2 billion tons per year by 2025. As the production of MSW has increased with world population, society has developed many different methods for treating and disposing of solid waste such as landfilling, incineration, and composting [25]. Although these traditional methods accomplish the job of treatment/disposal, landfilling and composting require ample land space to implement and as cities continue to rapidly sprawl into the swamp; we are limiting our options of where to dump this waste. Instead of trucking it to further locations, bring it to a WWTP to produce a clean and renewable energy source (biogas) which helps divert organic waste from landfills to reduce GHG emissions, and produce a nutrient rich digestate that can be used to fertilize crops or as a soil conditioner to aid in reforestation [27].

One study has shown that roughly 176.3 kg of CO_2 equivalent per ton of waste is emitted during landfill operations. When compared to the 31.4 kg of CO_2 equivalent per ton of waste emitted from biogas utilization of the AD process [11], diverting organic waste from landfills through the AD process shows promising potential to be a beneficial alternative that can better ensure a sustainable future.

Costs – Both Implementation & Operating Costs

ECOnnectivity's start-up costs is expected to be inexpensive from the use of open source software to negate any development cost, and the fact that most of the initially needed personnel are shareholders in the company. The only additional personnel needed during start-up would be a part time accountant to help keep track of the books, resulting in a cost of roughly $760 per year [15]. The cost of personnel will inevitably grow along with the company as more software developers, customer service and sales representatives, and administrators are hired on, but is not discussed in detail for this report. Next, funds equating to $74.15 will be needed to cover the cost of each set of scale-hardware placed at the generators' locations [12] [16] [19] [20] [21] [22]. The last cost incurred from the implementation of ECOnnectivity is the setup of the central server. This is expected cost $8,300 for a server with 24 terabytes of storage, which will be more than enough for Lafayette Parish. For more detailed calculations on the economic analysis for the set-up and first year's operation of ECOnnectivity, see **Table 2.1-2.4** in the appendix. All other cost associated with the ECOnnectivity network will be the responsibility of the individual waste entities.

For the three WWTPs considered in this simulation, a total of $2,156,680 will be needed to cover the capital cost for the turbine generators and pre-treatment equipment. Operation and maintenance for the newly installed equipment and compliance tracking software will cost the WWTP an additional $722,020 per year. The treatment facilities will also will need to take care of the cost of tipping fee to place the remaining digested biosolids into landfills. For the portion added by the source separated organic waste, this cost comes out to roughly $21,000 per year above what is currently being incurred from the wastewater biosolids alone.

As stated in a previous section, due to scheduling additional pick-up days for organic waste, the waste haulers involved in the ECOnnectivity network will not be forced to buy additional garbage trucks, and therefore will not pay a capital cost when joining the program. To take on the six extra routes per week needed to collect the organic waste, an increase of $377,200 will be needed for operation and maintenance costs. This includes the cost of diesel, driver's wages, the tipping fee paid to the WWTP, a data-holding fee and software subscription to ECOnnectivity, and occasional truck maintenance.

The last waste entity to discuss is the waste generators. To join the ECOnnectivity network, waste generators will be forced to buy the necessary hardware for the measurement and storage of organic waste production data. To produce a small profit to help with startup cost, ECOnnectivty will charge $120 per waste generator for the hardware and an installation fee. Because waste haulers will need to stop at each generator's location twice a week, an additional collection fee will be charged. The additional amount charged will be up to the waste generators and haulers when they set up their contract, but for the purposed of this report, $115 dollars has been chosen.

Using the cost estimates above, the expected profits for ECOnnectivity's first year in business is $87,400 dollars. With government subsidies of $13.30 per ton of waste treated, the WWTP will generate an additional $495,000 in profit per year with a payback period of just below 5 years. The waste haulers will immediately begin to make an additional profit of $400,000 per year on the new routes that it will service. The amount of money that will be saved by the waste generators in electricity cost is completely dependent on the amount of electricity consumed per year, but for the average commercial institution in Lafayette, a loss of around twenty dollars would be incurred. If a waste generator uses less than the average amount of electricity, larger losses will occur, but for very large consumers of electricity will actually save additional money. Looking at the residential source separation system in place for recyclable items, paying additional costs for a collection service is actually very well accepted when the generator feels good about what they are doing. This is even more likely to be the case for commercial businesses as they can advertise their business as "green" in an attempt to sell more of their goods or services. For detailed calculations used in the economic analysis, see **Tables 2.1-2.4** in the appendix.

Implementation Challenges

The implementation of ECOnnectivity has foreseeable issues that must be considered such as opposing political environments and economic dearth. Conservative communities may be reluctant to this change initially, but as other communities adopt similar systems as the norm, they will likely become more accepting if they see a chance for economic gain. The past eight years of the Obama administration have continually increased government subsidies and tax credits given for the production of renewable energy and related technologies, but under the new presidency, this trend is not expected to continue [24]. To add insult to injury, Louisiana is a generally known to be a conservative state with very few state subsidies for alternative energy technologies. This being the case, other states such as Washington or California are likely to be much better places for the startup of ECOnnectivity.

The next challenge that many places face when attempting to utilize WWTP as anaerobic co-digestion facilities is the high capital and operation and maintenance costs. This becomes a major problem when the amount of organic waste produced is miniscule compared to that of the wastewater biosolids, which is the case in Lafayette Parish and is expected to occur in most cities around the world. This causes the factor in which the payback period and operation and maintenance costs are raised to be much greater than that of biogas production. For example, if the amount of food waste generated and collected is doubled, the payback period and cost to cover the pretreatment doubles as well. However, the total biogas production, and thus the revenue from the sale of energy, only rises by a small fraction of that amount. This makes choosing the size of the pretreatment equipment and zoning very difficult. For this project, the results seem to hint that organic waste should not exceed 10% of the entire feedstock used. Greater amounts of organic waste results in a loss of yearly profit from increasing operation and maintenance cost while lower amounts decrease the specific biogas production [25] [28].

APPENDIX

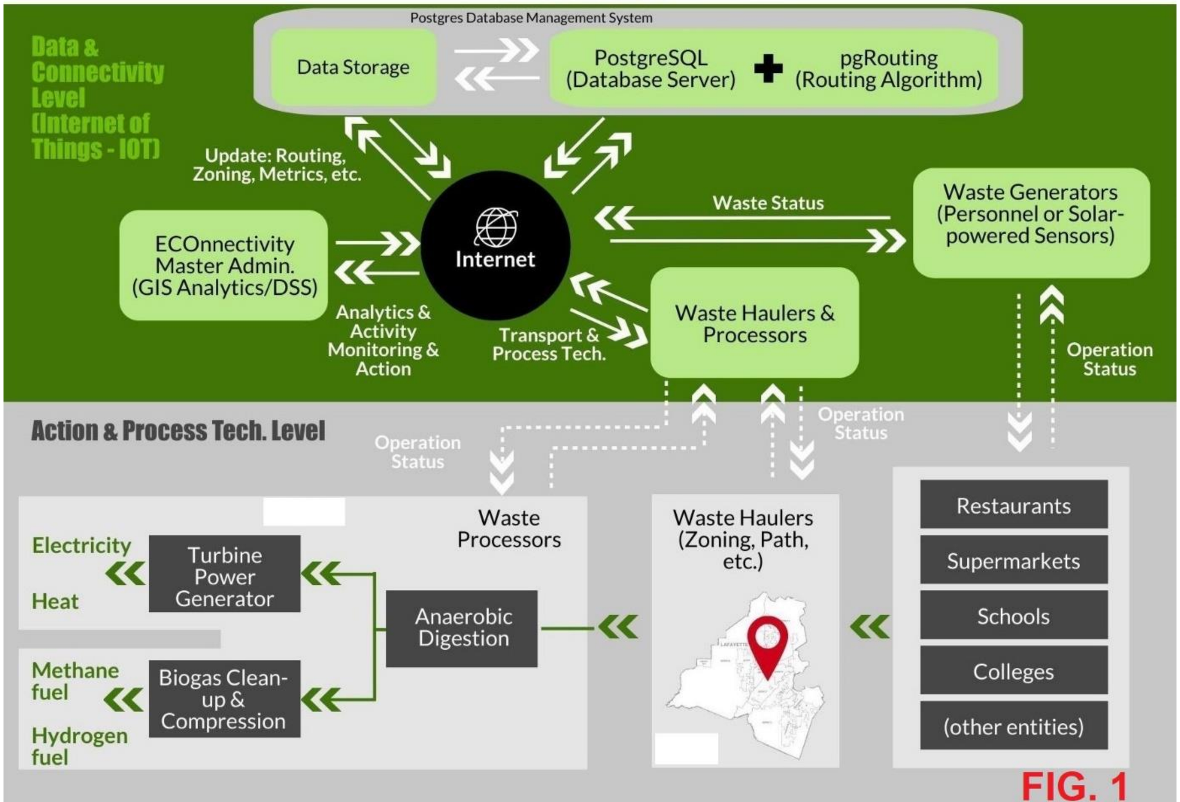


FIG. 1

Technologies: (1) Anaerobic Digestion, (2) Biogas Clean-up & Compression, (3) Turbine Power Generation, (4) Solar-powered Embedded Waste Level Sensors, (5) IOT

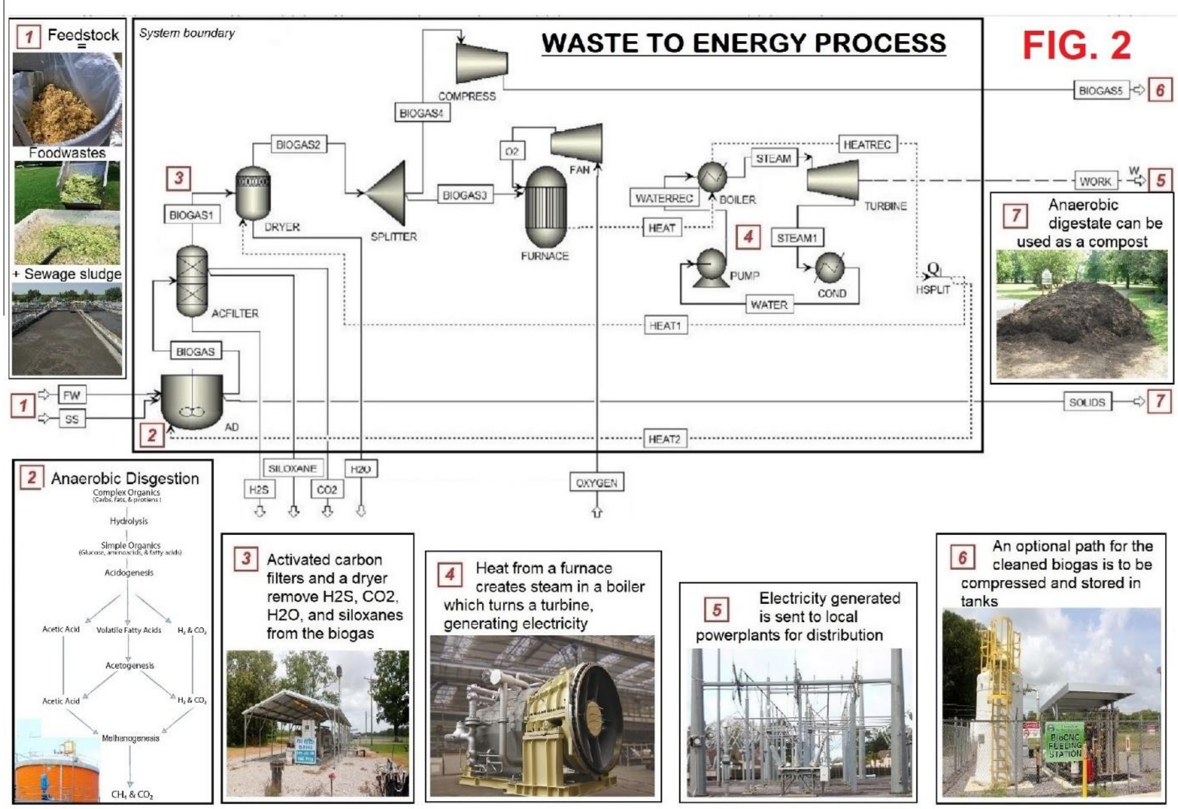
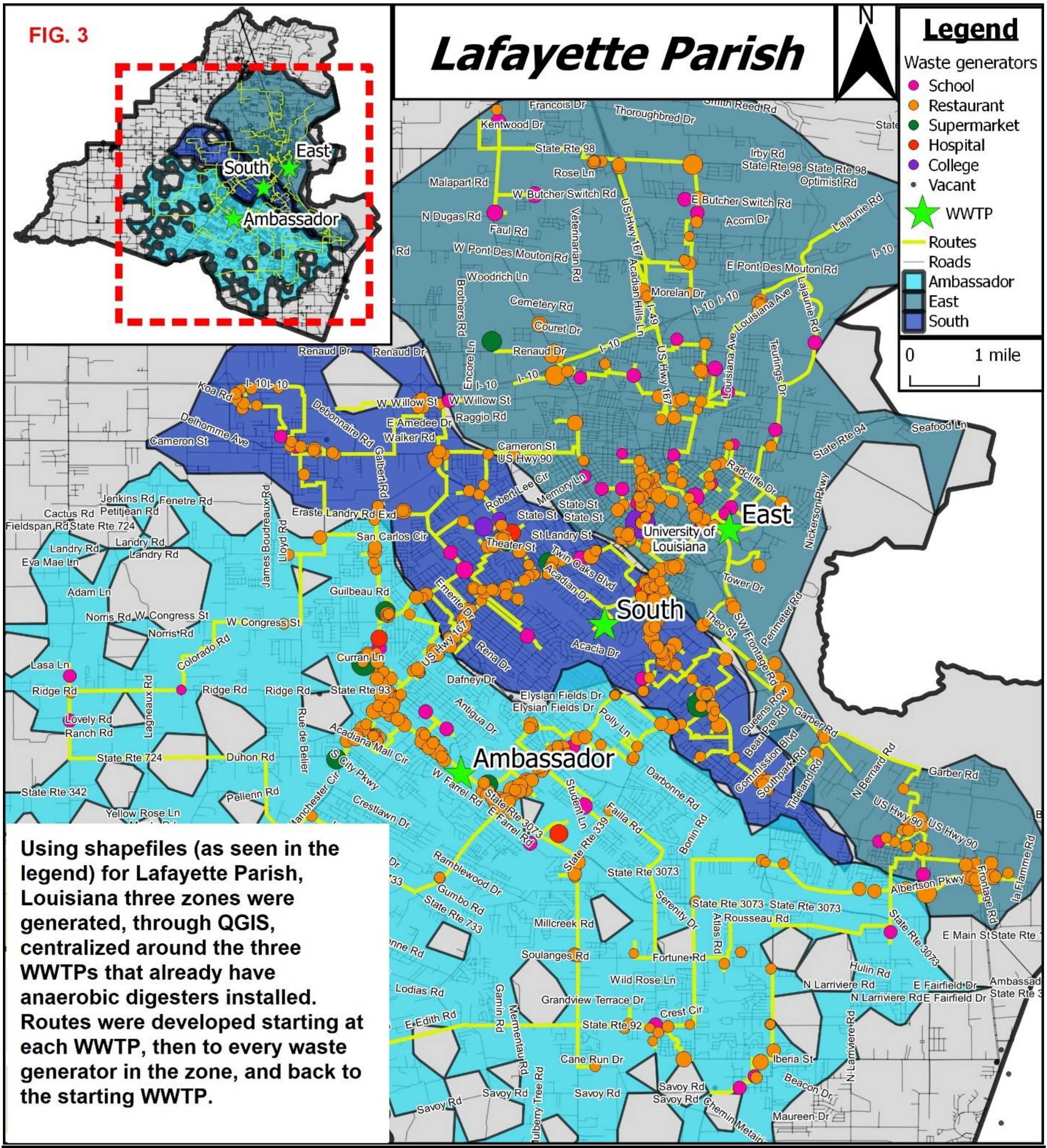


FIG. 2



Using shapefiles (as seen in the legend) for Lafayette Parish, Louisiana three zones were generated, through QGIS, centralized around the three WWTPs that already have anaerobic digesters installed. Routes were developed starting at each WWTP, then to every waste generator in the zone, and back to the starting WWTP.

Funciton	***Description***
cv.clean.advanced algorithm	-Clean topology of TIGER/Line road Shapefile for use in pgRouting
pgr_createTopology	-Create road Topology within database
ST_Transform	-Set projection in order to calculate road distance in meters
ST_Length	-Calculate road distance in meters
pgr_drivingdistance	-Find borders of zones by using set radius r *(road length) with wwtp as center
pgr_pointsAsPolygon	-Create visual representation of each zone
upgr_vnodes [26]	-Inject wwtp and waste generators as virtual nodes
pgr_tsp	-Find most efficient order to visit each waste generator and wwtp
pgr_trspViaEdges	-Calculate shortest path (in road miles) and visualize in QGIS

Totals

WWTP	Net Energy (MWh/yr)	Food Waste (Tons/yr)	Sewage Sludge (Tons/yr)	Net Capacity (yd3/yr)
Ambassador	4882	3249	40940	26511
East	3512	3528	28359	45417
South	5696	2590	49255	-5281
TOTAL	14090	9367	118554	66647

End of Year	ECOnnectivity Server profit	Waste Generator Profit	Waste Hauler Profit	WWTP Profit
1	$87356	$-380328	$426393	$-1661210
3	$208056	$-999624	$1279179	$-670210
5	$328756	$-1618920	$2131965	$320790

Represents profit for all respective participating parties

Table 1.1 Waste Generation Estimates

Values from database		*Values from WWTP*	
Generator	Ug	Zone	Id
College residential (cr)	20000	Ambassador	26528
College non-residential (cnr)	1000-5000		
Hospital (h)	128-186	East	18376
Restaurant (r)	1-249		
School (sc)	2-2321	South	31917
Supermarket (su)	100-499		

Parameters from literature

Parameter	Description	Unit	Value
FWr, FWsu	FW of restaurants or supermarkets	tons/yr-employees	1.5
FWh	FW of hospitals	tons/yr-beds	0.62415
FWcr	FW of residential colleges	tons/yr-students	0.070875
FWcnr, FWsc	FW of non-residential colleges/schools	tons/yr-students	0.0189
Das	Density of sewage sludge	kg/m^3	1400

Food waste produced (tons/yr)		Sewage sludge produced (tons/yr)
Ug x FWx	Zone	Id x Das
3249	Ambassador	40940
3538	East	28359
2590	South	49255

Ug = Generator's respective unit (students/beds/employees)   Id = Digester influent (m^3/yr)   FWx = Mass of food waste per unit, by sector x (tons/year-Ug)

Table 1.2 Capacity

Values from WWTP

Zone	Cd	Id
Ambassador	2392.8	35040
East	2701.6	24272.5
South	1485.3	42157.5

Parameters from literature

Parameter	Description	Unit	Value
Rt	Retention time	Days	25
Dfw	Density of food waste	lbs/yd^3	750

Available capacity (yd^3/year)	Required capacity (yd^3/year)	
Cd x 2* x 365 / Rt	Zone	(Mfw** / Dfw) + Id
69871.1	Ambassador	43360.2
78887.4	East	33470.1
43371.9	South	48652.9

Cd = Capacity per digester (yd^3)   Id = Digester influent (yd^3/yr)   Mfw = Mass of food waste (lbs/yr)

*2 digesters per set at each WWTP
**Value calculated in Table 1.1

Table 1.3 Energy

Values from database

Zone	Mfw*	Mss*	Dr
Ambassador	3249	40940	95
East	3538	28359	86
South	2590	49255	156

Parameters from literature

Parameter	Description	Unit	Value
Ecd	Energy content of diesel	BTU / gal	128488
Ecm	Energy content of methane	MJ / m^3	40.34
Mt	Mileage of truck	miles / gal	2.7
Mvs	Methane content of VS	L CH4 / g VS	0.326
Rvs	Reduction of VS	ton VS degraded / ton VS	0.69
%vs	% VS of wet co-digestate	ton VS / ton wet co-digestate	0.049

E produced (MWh/year)		E consumed (MWh/year)
(Mfw + Mss) x %vs x Rvs x Mvs x Ecm	Zone	Dr / Mt x Ecd
4951	Amb.	69
3574	East	62
5809	South	113

Mfw* = Mass of food waste (tons/yr)   Mss* = Mass of sewage sludge (tons/yr)   Dr = Distance of route (miles/yr)

*Value calculated in Table 1.1

Table 2.1 ECOnnectivity

Values from database

Ng	Nh	Nhw
589	3	30

Parameters from literature

Parameter	Description	Unit	Value
Ac	Pay rate for accountant	$ / hour	25
Dr	Data holding revenue	$ / Ng-year	100
Hc	Hardware setup cost	$ / Ng	74.15
Hr	Hardware setup revenue	$ / Ng	120
Sr	Software subscription revenue	$ / Nh-year	2000
Sec	Server setup cost	$	3800

Revenue ($ / year)			Cost ($ / year)		
Software	*Hardware***	*Data*	*Server***	*Hardware***	*Data*
Sr x Nh	Hr x Ng	Dr x Ng	Sec	Hc x Ng	Ac x Nhw
6000	70680	58900	3800	43674	750

Ng = Number of participating waste generators   Nh = Number of participating waste hauler companies   Nhw = Number of hours worked per year* by accountant

*Assuming 5 hours per week for 2 weeks during startup and 4 weeks during tax season
**One-time setup fee, not per year

Table 2.2 Waste Generators

Values from database

Ng	%e	Cc
589	0.2	1320

Parameters from literature

Parameter	Description	Unit	Value
Ec	Cost of commercial electricity	$ / kWh	86712
Ed	Average commercial electricity demand	kWh / yr	0.0458

Revenue ($ / year)	Cost ($ / year)	
Electricity savings	*Contract*	*Hardware***
Ng x %e x Ec x Ed	Ng x Cc	Ng x Hr*
467832	777480	70680

Ng = Number of participating waste generators   %e = % decrease in electricity rate   Cc = Contract cost ($ / yr-Ng)   Hr* = Hardware setup cost ($ / yr-Ng)

*Value from Table 2.1
**One-time setup fee, not per year

Table 2.3 Waste Haulers

Values from database

Ng	Sdr*	Smfw*	Nhw
589	337	9377	2496

Parameters from literature

Parameter	Description	Unit	Value
Dc	Data holding cost	$ / Ng-year	100
Fc	Fuel cost	$ / mile	0.79
Hc	Pay rate of hauler	$ / hour	16.55
Mc	Maintenance cost	$ / mile	0.73
T	Tipping fee	$ / Smfw*	26.7

Revenue ($ / year)	Cost ($ / year)				
Contract	*Gas*	*Maintenance*	*Tipping*	Wages	*Data*
Ng x Cc***	Sdr* x Fc	Sdr* x Mc	Smfw* x T	Nhw x Hc	Ng x Dc
777480	266	246	250366	41309	58900

Ng = Number of participating waste generators   Cc*** = Contract cost ($ / yr-Ng)   Sdr* = Sum of route distance (miles/year)   Smfw* = Sum of FW mass (tons/year)   Nhw = Number of hours worked per year** by haulers

*Summed from Table 1.3
**Assuming 8 hours per week per route, with 6 routes per week
***From Table 2.2

Table 2.4 Wastewater Treatment Plants

Values from database

Ep*	Smfw*	%e
14334000	9377	0.2

Parameters from literature

Parameter	Description	Unit	Value
%r	% removal	ton dry / ton wet	0.916
Ec	Cost of commercial electricity	$ / kWh	0.0753
Oc	Operation & maintenance cost	$ / ton FW	77
Pc	Pre-treatment cost	$ / ton FW	230
T	Tipping fee	$ / ton FW	26.7
Tw	Tipping fee at WWTP	$ / ton FW	40

Revenue ($ / year)		Cost ($ / year)		
Tipping	*Electricity*	*Pretreatment***	*Operation & maintenance*	*Tipping*
Smfw* x Tw	(Ep* x Ec) x (1 - %e)	Smfw* x Pc	Smfw* x Oc	Smfw* x (1 - %r) x T
375080	863480	2156710	722029	21031

Ep* = Sum of energy produced (kWh/year)   Smfw* = Sum of FW mass (tons/year)   %e = % decrease in electricity rate

*Summed from Table 1.3
**One-time fee, not per year

Bibliography

[1] X. Chen, R. T. Romano and R. Zhang, "Anaerobic Digestion of Selected Food Wastes for Biogas Production," *International Journal of Agricultural & Biological Engineering,* vol. 3, no. 4, pp. 61-72, June 2009.

[2] M. S. Ruhin, G. Drishya and K. S. Harish, "A Survey on Smart Garbage Management in Cities using IoT," *Internation Journal of Engineering and Computer Science,* vol. 5, no. 11, pp. 18749-18754, November 2016.

[3] D. Hoornweg and P. Bhada-Tata, "What a Waste: A Global Review of Solid Waste Management," *Urban Development Series, No. 15,* March 2012.

[4] P. Calthorpe, *The Power of Introverts,* 2017.

[5] MDOEP, "Identification, Characterization, and Mapping of Food Waste and Food Waste Generators in Massachusetts," Massachusetts Department of Environmental Protection, Boston, 2002.

[6] US-DOE, "Fuel Properties Comparison," 2014. [Online]. Available: https:\\www.afdc.energy.gov/fuels/fuel_properties.php. [Accessed 2017].

[7] U. E. I. Administration, "Weekly retail diesel prices," US DOE, 16 Oct 2017. [Online]. Available: https://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_w.htm. [Accessed Oct 2017].

[8] W. C. Kuo-Dahab, *Anaerobic Co-Digestion of Food Waste and Sewage Sludge: Bench-Scale Study,* Amherst, 2013.

[9] J. Weeks, "Future of Recycling," *CQ Researcher,* vol. 17, no. 44, 2007.

[10] Engineering Tool Box, "Fossil and Alertnative Fuels-Energy COntent," The Engineering Tool Box, [Online]. Available: https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html. [Accessed October 2017].

[11] W. Long, Z. Baoning, Y. Hairong, L. Yanping, Z. Dexun and L. Xiujin, "Comparative Investigations on Pilot-scale Anaerobic Digestion of Food Waste at 30C and 25C," *International Journal of Agricultural & Biological Engineering,* pp. 109-117, January 2016.

[12] "Breadboard," Amazon, 2017. [Online]. Available: https://www.amazon.com/Solderless-BreadBoard-tie-points-200PTS-Haobase/dp/B0195V3682/ref=pd_lpo_vtph_21_lp_img_3?_encoding=UTF8&psc=1&refRID=WYRYRDTT49RCY45B205K. [Accessed Oct 2017].

[13] "Choose Your SaferVPN Plan," Safer Social Ltd, 2017. [Online]. Available: https://www.safervpn.com/business/pricing. [Accessed October 2017].

[14] "Commercial service rates," Waste Management, Inc., 2017. [Online]. Available: http://www.wm.com/location/california/bay_area/castrovalley/commercial/rates.jsp.

[Accessed Oct 2017].

[15] "Hourly Rate for Certification: Certified Public Accountant (CPA)," Payscale, 2017. [Online]. Available: https://www.payscale.com/research/US/Certification=Certified_Public_Accountant_(CPA)/Hourly_Rate. [Accessed October 2017].

[16] "IR break beam sensor," Adafruit, 2017. [Online]. Available: https://www.adafruit.com/product/2168?gclid=EAIaIQobChMIxsaz44v01gIVwlqGCh0p-gTeEAYYASABEgLAMfD_BwE. [Accessed Oct 2017].

[17] Ivy Computer, Inc., "Routing," Ivy Computer, Inc., 2017. [Online]. Available: http://www.trashflow.com/products/routing.php. [Accessed Oct 2017].

[18] J. D. Popovec, "Retail Landlords Keep Pushing Rents Up," nreionline.com, 7 Oct 2015. [Online]. Available: http://www.nreionline.com/retail/retail-landlords-keep-pushing-rents. [Accessed Oct 2017].

[19] "Raspberry Pi Zero W," Adafruit, 2017. [Online]. Available: https://www.adafruit.com/product/3400. [Accessed Oct 2017].

[20] "SD Card," Amazon, 2017. [Online]. Available: https://www.amazon.com/Transcend-Flash-Memory-Card-TS2GSDC/dp/B000FGNM6I/ref=sr_1_2?s=pc&ie=UTF8&qid=1508121368&sr=1-2&keywords=sd-card&refinements=p_n_feature_two_browse-bin%3A6518302011%2Cp_36%3A1253503011. [Accessed Oct 2017].

[21] "Solderless wires," Amazon, 2017. [Online]. Available: https://www.amazon.com/Solderless-Flexible-Breadboard-Jumper-100pcs/dp/B005TZJ0AM/ref=pd_bxgy_328_img_2?_encoding=UTF8&pd_rd_i=B005TZJ0AM&pd_rd_r=M6S8F3N87CM407447Y5K&pd_rd_w=zQmFN&pd_rd_wg=2YzT6&psc=1&refRID=M6S8F3N87CM407447Y5K. [Accessed Oct 2017].

[22] "Solar panel," Adafruit, 2017. [Online]. Available: https://www.adafruit.com/product/200?gclid=EAIaIQobChMIl5e7pMP01gIVAkSGCh2fwg7AEAQYASABEgJ04_D_BwE. [Accessed Oct 2017].

[23] "CPI Inflation Calculator," 2017. [Online]. Available: https://www.bls.gov/data/inflation_calculator.htm. [Accessed October 2017].

[24] I. Smith, "Tax Subsidies For Renewables Now Far Outpaces Fossil Fuels," RealClear Media Group, 28 April 2017. [Online]. Available: http://www.realclearenergy.org/articles/2017/04/28/tax_subsidies_for_renewables_now_far_outpaces_fossil_fuels_110217.html. [Accessed October 2017].

[25] L. Arsova, "Anaerobic Digestion of Food Waste: Current Status, problems and an Alternative Product," New York City, 2010.

[26] R. O. Obe and L. S. Hsu, pgRouting A Practical Guide, Chugiak, AK: Loacte Press LLC, 2017.

[27] D. Bodamer, "14 Charts from the EPA's Latests MSW Estimates," 16 November 2016. [Online].

[28] E. Iacovidou, . D.-G. Ohandja and N. Voulvoulis, "Food waste co-digestion with sewage sludge e Realising its potential in the UK," *Journal of Environmental Management,* vol. 112, pp. 267-274, 2012.