Waste to Energy

Feasibility study of an on-campus anaerobic digester at Duke University

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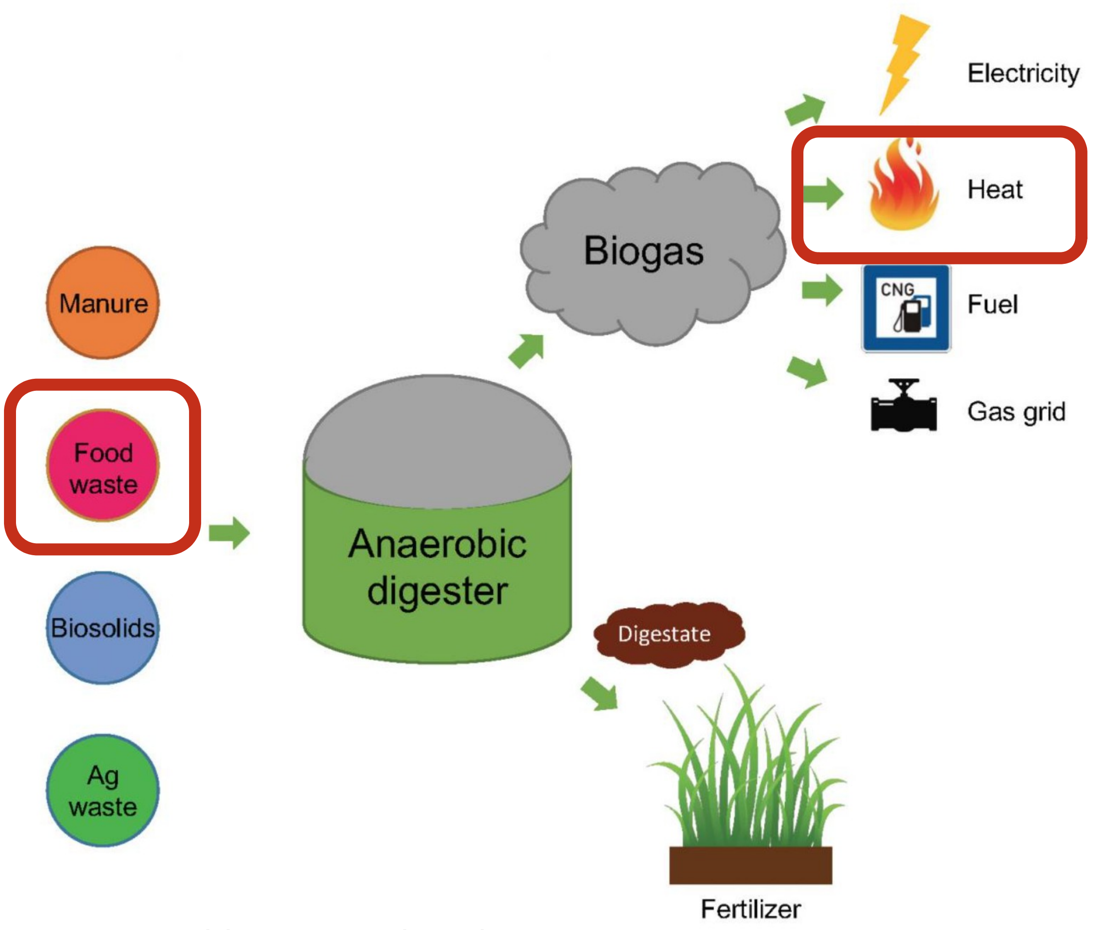
Waste to Energy: Motivation



Source: Ohio State University

Powering steam boilers with biogas

Duke Heats most of its buildings through
a centralized steam system

Picture: West Campus Steam Plant at Duke University

Methods

Physical Prototype

- Small scale prototype
- Proof of concept
- Objective: generate methane

Theoretical Modelling

- Economic, environmental, and social analysis on large scale scenarios
- Scenario 1: bottom-up approach
- Scenario 2: top-down approach

First Scenario: Bottom-Up Approach

- What can we do with Duke's food waste?
  - 200 – 600 tons of food waste annually
  - Low Volume Anaerobic Digester
  - Power a few central campus buildings

Second Scenario: Top-Down Approach

- Where can we make a big impact on campus?
  - Industrial Scale Anaerobic Digester
  - Opportunity: 2 West campus steam plant boilers need to be replaced
  - Duke food waste + community food waste

Top-Down Math Approach

Motivating Question: How many tons of food waste would we need to power one West Campus Steam Plant Boiler for a year?

Can break down into two questions…

1) How many cubic feet of natural gas does a full-time West Campus Steam Boiler use in a year?

2) How many cubic feet of natural gas equivalent can we expect from a ton of food waste?

$$Ft^3 \text{ Methane needed to run WCSP Boiler for 1 Year} \cdot \frac{\text{Ton of Food Waste}}{Ft^3\text{Methane}} = \text{Tons food waste needed to run WCSP Boiler for 1 Year}$$

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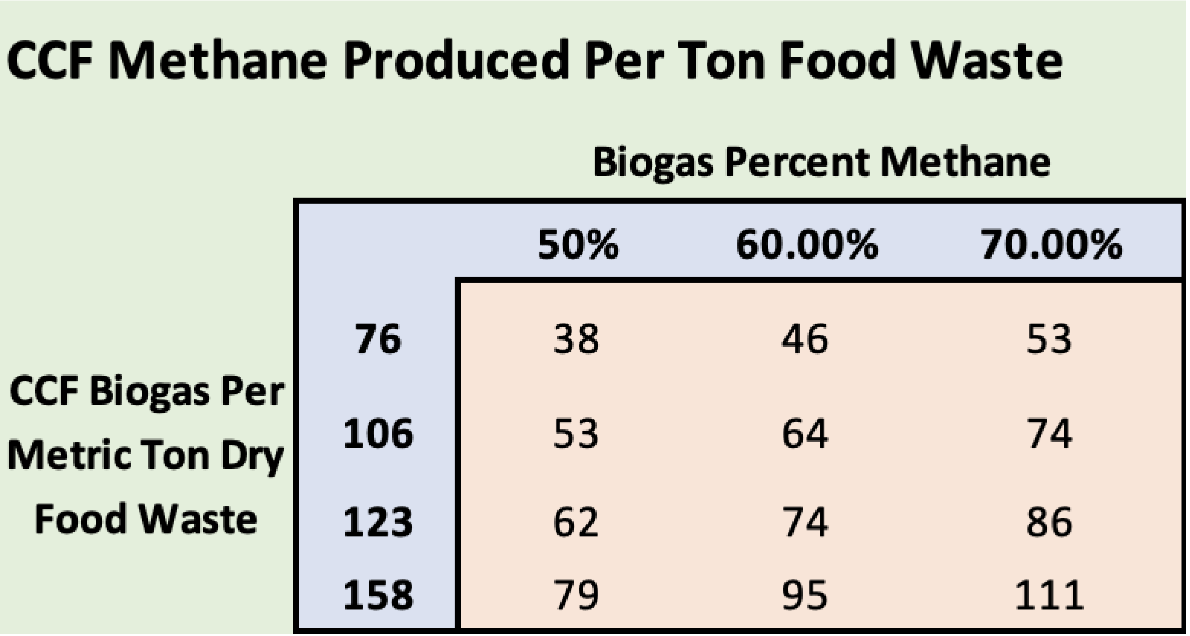
Sensitivity Math Approach



CCF Methane Produced Per Ton Food Waste

		Biogas Percent Methane		
		50%	60.00%	70.00%
CCF Biogas Per Metric Ton Dry Food Waste	76	38	46	53
	106	53	64	74
	123	62	74	86
	158	79	95	111

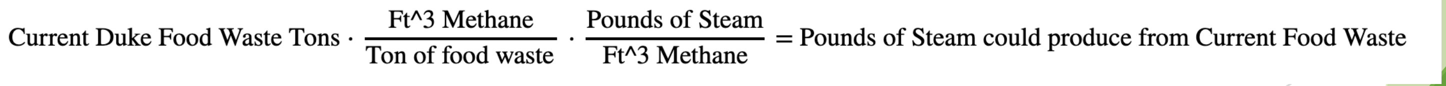
Bottom-Up Math Approach

Motivating Question: How many pounds of steam can we produce with the biogas collected from Duke's current food waste?

Again, we can use our sensitivity analysis to estimate how much methane we can produce per ton of food waste.

Then we can use enthalpy calculations and assume standard efficiencies for converting from cubic feet methane to pounds of steam.

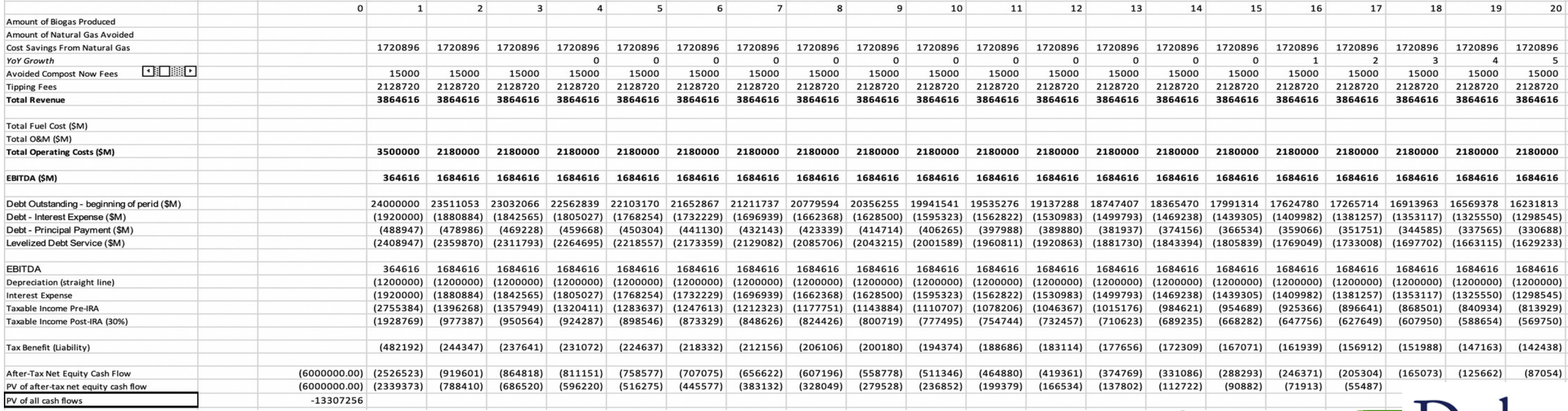
Once get pounds of steam per ton of food waste we can multiply by the tons of waste we have available to get the total potential steam output of our current waste.



$$\text{Current Duke Food Waste Tons} \cdot \frac{\text{Ft\^{}3 Methane}}{\text{Ton of food waste}} \cdot \frac{\text{Pounds of Steam}}{\text{Ft\^{}3 Methane}} = \text{Pounds of Steam could produce from Current Food Waste}$$

NPV Analysis - Relevant Inputs

- NPV: Net Present Value of the Project. Is it profitable?
- Relevant Inputs: food waste, biogas volume produced from food waste, CH4 content in biogas, natural gas being replaced, cost savings from natural gas replacement + compost now savings



		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Amount of Biogas Produced																						
Amount of Natural Gas Avoided																						
Cost Savings From Natural Gas			1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896	1720896
YoY Growth						0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	4	5
Avoided Compost Now Fees			15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000
Tipping Fees			2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720	2128720
Total Revenue			**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**	**3864616**
Total Fuel Cost ($M)																						
Total O&M ($M)																						
Total Operating Costs ($M)			**3500000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**	**2180000**
EBITDA ($M)			**364616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**	**1684616**
Debt Outstanding - beginning of perid ($M)			24000000	23511053	23032066	22562839	22103170	21652867	21211737	20779594	20356255	19941541	19535276	19137288	18747407	18365470	17991314	17624780	17265714	16913963	16569378	16231813
Debt - Interest Expense ($M)			(1920000)	(1880884)	(1842565)	(1805027)	(1768254)	(1732229)	(1696939)	(1662368)	(1628500)	(1595323)	(1562822)	(1530983)	(1499793)	(1469238)	(1439305)	(1409982)	(1381257)	(1353117)	(1325550)	(1298545)
Debt - Principal Payment ($M)			(488947)	(478986)	(469228)	(459668)	(450304)	(441130)	(432143)	(423339)	(414714)	(406265)	(397988)	(389880)	(381937)	(374156)	(366534)	(359066)	(351751)	(344585)	(337565)	(330688)
Levelized Debt Service ($M)			(2408947)	(2359870)	(2311793)	(2264695)	(2218557)	(2173359)	(2129082)	(2085706)	(2043215)	(2001589)	(1960811)	(1920863)	(1881730)	(1843394)	(1805839)	(1769049)	(1733008)	(1697702)	(1663115)	(1629233)
EBITDA			364616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616	1684616
Depreciation (straight line)			(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)	(1200000)
Interest Expense			(1920000)	(1880884)	(1842565)	(1805027)	(1768254)	(1732229)	(1696939)	(1662368)	(1628500)	(1595323)	(1562822)	(1530983)	(1499793)	(1469238)	(1439305)	(1409982)	(1381257)	(1353117)	(1325550)	(1298545)
Taxable Income Pre-IRA			(2755384)	(1396268)	(1357949)	(1320411)	(1283637)	(1247613)	(1212323)	(1177751)	(1143884)	(1110707)	(1078206)	(1046367)	(1015176)	(984621)	(954689)	(925366)	(896641)	(868501)	(840934)	(813929)
Taxable Income Post-IRA (30%)			(1928769)	(977387)	(950564)	(924287)	(898546)	(873329)	(848626)	(824426)	(800719)	(777495)	(754744)	(732457)	(710623)	(689235)	(668282)	(647756)	(627649)	(607950)	(588654)	(569750)
Tax Benefit (Liability)			(482192)	(244347)	(237641)	(231072)	(224637)	(218332)	(212156)	(206106)	(200180)	(194374)	(188686)	(183114)	(177656)	(172309)	(167071)	(161939)	(156912)	(151988)	(147163)	(142438)
After-Tax Net Equity Cash Flow		(6000000.00)	(2526523)	(919601)	(864818)	(811151)	(758577)	(707075)	(656622)	(607196)	(558778)	(511346)	(464880)	(419361)	(374769)	(331086)	(288293)	(246371)	(205304)	(165073)	(125662)	(87054)
PV of after-tax net equity cash flow		(6000000.00)	(2339373)	(788410)	(686520)	(596220)	(516275)	(445577)	(383132)	(328049)	(279528)	(236852)	(199379)	(166534)	(137802)	(112722)	(90882)	(71913)	(55487)			
PV of all cash flows		-13307256																				

CAPEX & OPEX

Bottom-Up	Low	Medium	High
Food Waste (tons)	287.94 *Compost Now*	473.47 *Weighted Average*	659 *Duke University*
CAPEX	$200,000	$400,000	$600,000
OPEX (2% of CAPEX)	$4,000	$8,000	$12,000

Top Down	Low	Medium	High
Food Waste (tons)	31,789	53,218	107,289
CAPEX	$13M	$21.5M	$30M
OPEX (2% of CAPEX)	$854,000	$8,000	$12,000

Revenues

As biogas will be used on campus, 'revenues' will be indirect, received primarily from cost-savings

- Sources of Cost-Saving Measures Include:
  - Replace / Reduce natural gas in boilers
  - Eliminate composting partner
  - Renewable energy incentives (IRA bill – Investment Tax Credit of 30%)
  - Future Applications

- Methodology
  - % methane in biogas *(Literature)*
  - Top-down based on size of boiler being retrofit (*West Campus Boiler 5)*
  - Bottom-up approach based on amt of Duke Students' food waste
  - Saleable Co-Products of Biogas (Carbon Offset Credits, RECS/RFS)

Net Present Value of the Project – Bottom Up

Project NPV (Bottom-up)		CAPEX Scenarios		
		Low	Medium	High
Gas Production Scenarios	Low	$40,773	-$114,355	-$269,575
	Medium	$57,496	-$86,857	-$231,339
	High	$74,219	-$59,359	-$193,102

Takeaway: It is possible to attain a feasible project if ***capital costs are low.*** *These can be lowered through grants, philanthropic donations, research funding, etc.*

Net Present Value of the Project – Top Down

Project NPV (Top-down)	CAPEX Scenarios		
	Low	Medium	High
Baseline (378MN ft^3/yr)	$17.72M	-$3.74M	-$13.31M

Environmental Benefit Analysis

- Anaerobic Digestor Benefits
  - Reduction in GHG emissions
  - Fertilizer Production
  - Landfill avoidance

- ~2% of Duke's GHG emissions from solid waste disposal

- EPA Waste Reduction Model
  - Landfill vs Compost vs AD
  - Waste categorization
  - Transportation emission

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Potential CO2 offsets

Bottom Up	Food Waste(tons)	Net change CO2 emissions/MTC02E with NG offset
Low	288	-41.31
Medium	474	-164.86
High	659	-287.45

Top Down	Food Waste/tons	Net change CO2 emissions/MTC02E with NG offset
Low	31,789	-22163.47
Medium	53,218	-23056.36
High	107,289	-25309.34

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Social Benefit Analysis

- Campus as Lab
  - Learning outside of traditional classrooms
- Class Integration
  - Field Trips
  - Learning Modules
- Research
  - Interdisciplinary collaboration between labs on campus
- Jobs Created and Community Building
  - Full time employees
  - Build awareness within the community

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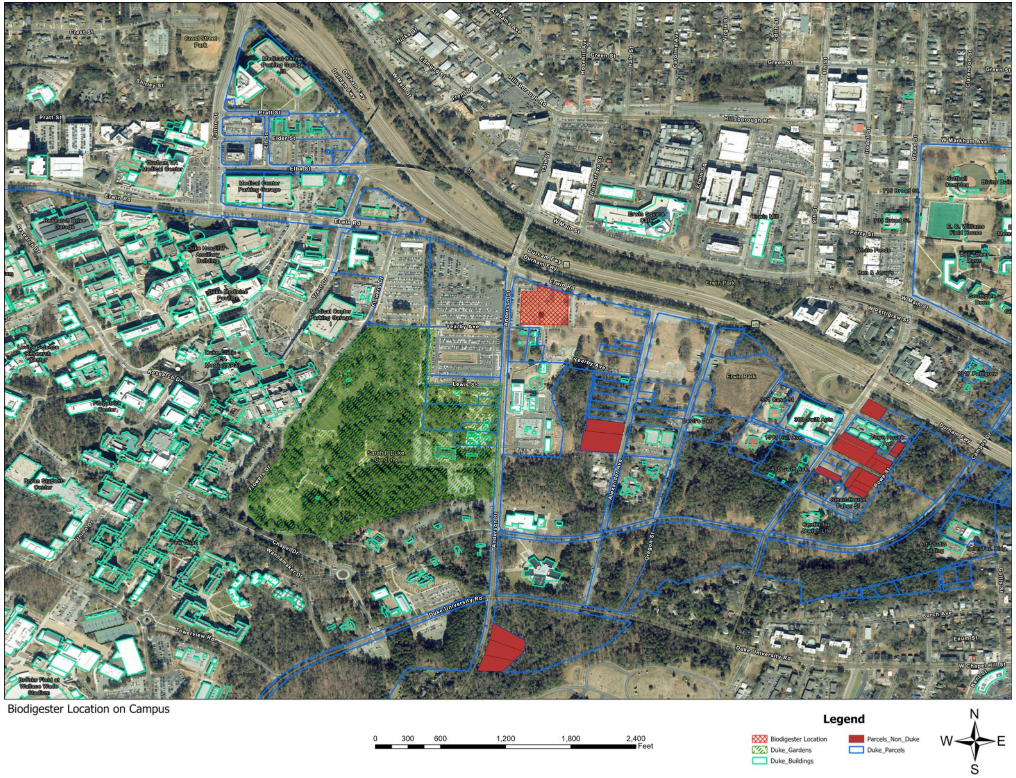
Location Analysis



Biodigester Location on Campus

Central Campus:

- Low transportation times
- Unused open space
- On campus

Identified Loads for Produced Biogas:

- Nasher Museum
- Jordan Building (Duke Police Station)

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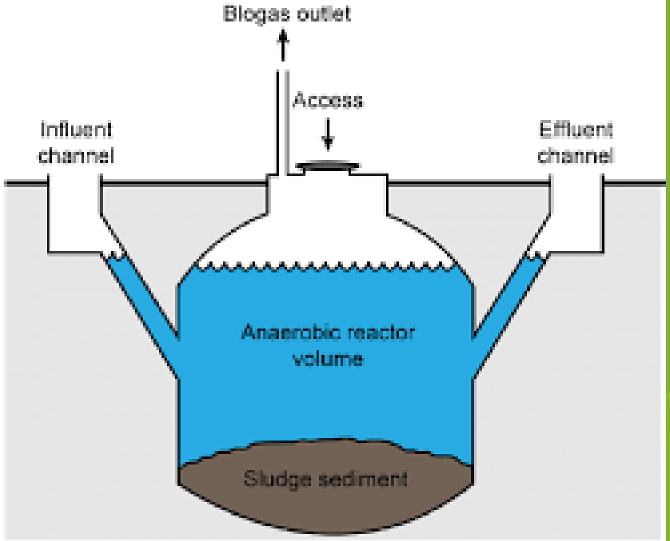
Engineering Team Goals

- Functional prototype
- Biogas production
- Gas composition analysis
- POC: Optimization and design improvement



Technical Risks and Risk Mitigants

Risk	Mitigation Strategy
• Biogas loss through leakage • Would directly offset emission reductions	• Operated beneath fume hood • Used high quality clamps and seals • Tested system for leaks before operation
• Meeting gas purity requirements	• Tested 3 different samples: • 1.) Food waste • 2.) Food waste + manure • 3.) Food waste + compost
• Overheating of solar thermal collector	• Performed thermal modeling and preliminary testing

First Prototype

Components

- 5-gallon container
- Gas-outlet: Vinyl tubing, Hose Clamps and Valves
- Balloon

Testing Results

- Gas Leakage
- Stagnant mixture

Biogas Analysis: Flowchart

FEEDSTOCK

- Cow manure + Food waste
- Compost + Food waste
- Food waste

Gas sample bag
(temporary storage)

Exetainer
(long-term storage)

Autosampler vial
(prior to analysis)

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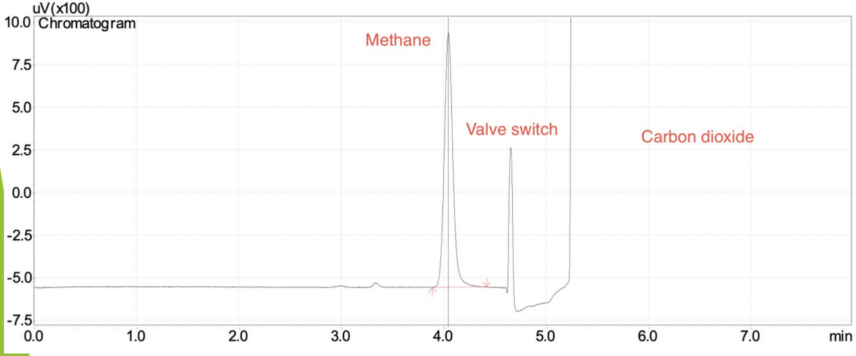
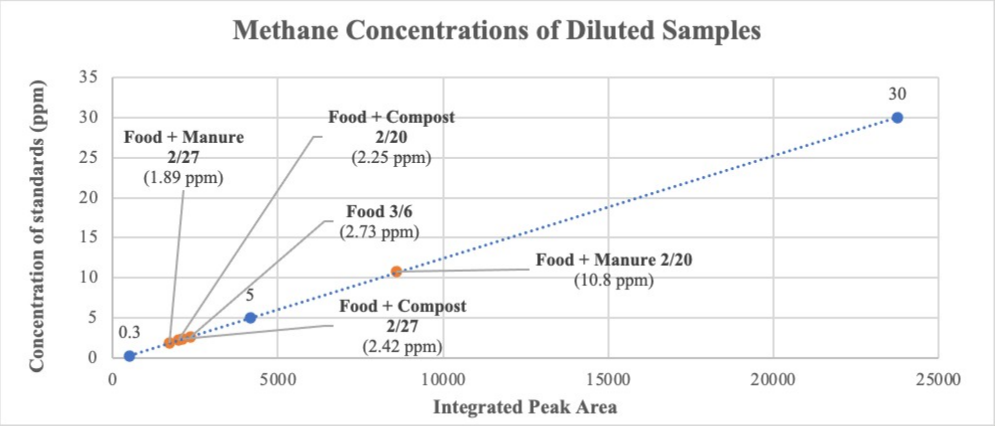
Biogas Analysis (I)

- The area of the CH_4 standards peaks in the chromatogram was obtained and a standard calibration curve was created
- The samples' peak areas were fitted to the curve to obtain the methane concentrations in the samples





Biogas Analysis (II)

- Use of cow manure increased methane production four-fold compared to the next best feedstock
- Methane concentrations decreased with time due to the lack of new feedstock
- Methane concentrations obtained not large enough to be used in a boiler without natural gas cofiring

	Cow Manure + Food Waste	**Compost + Food Waste**	**Food Waste**
Week 1	10.8	2.65	-
Week 2	2.35	3.01	-
Week 3	-	-	2.73

Final Prototype

Vessel Redesign

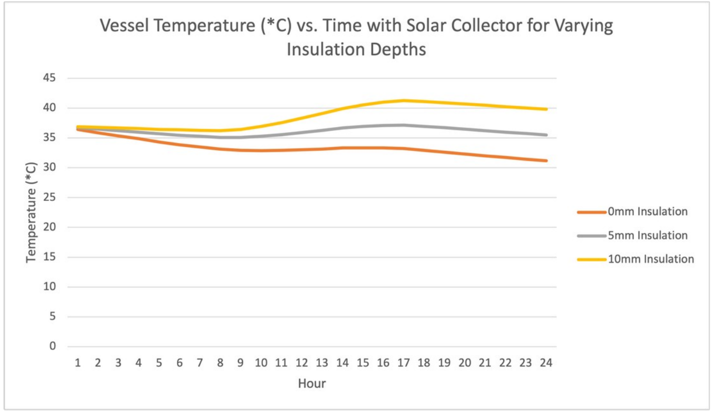
Thermal management

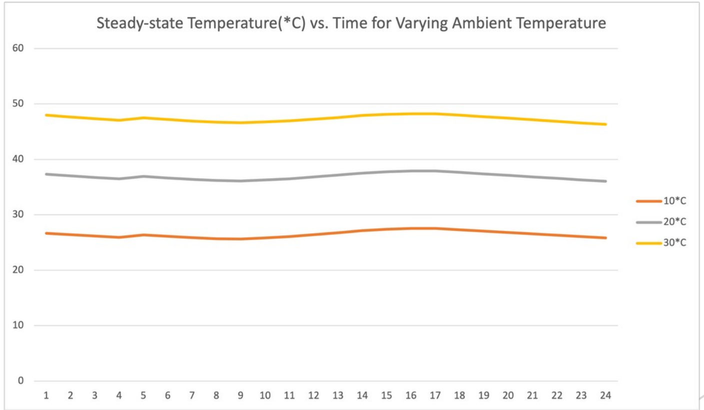
Mechanical mixing

Waste inlet and outlet

Thermal Management

- Optimal efficiency: 30ºC-40ºC
- Medium-thickness insulation with solar collector yields best results
- Black paint for additional heat absorption



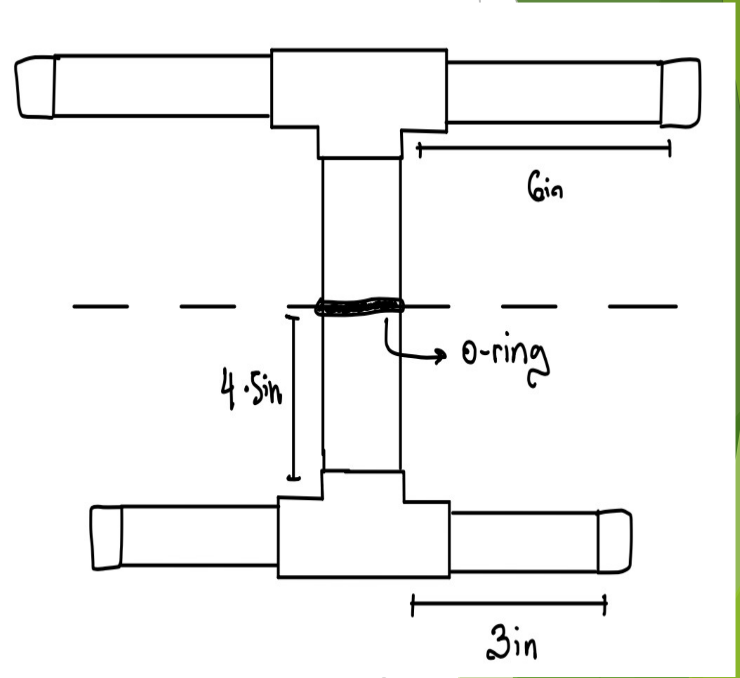


Vessel Redesign

- Schedule 40 PVC
  - Pressure Rating of 140 psi > 15 psi
  - Pressure Gauge and Relief Valve
- Airtight and Oxygen Free
  - Anaerobic Digestion
  - Internal Gas Storage

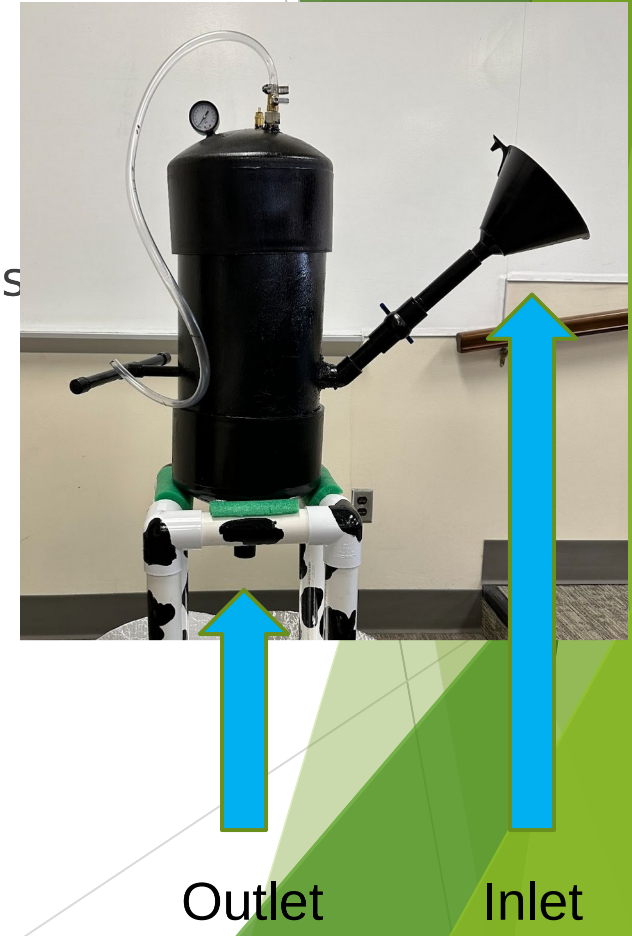
Mechanical Mixing

- To agitate the feedstock mixtur
- ½ inch PVC pipes
- At the bottom for watertightnes
- O-ring seal



Inlet and Outlet

- Inlet and outlet valves provide easy access to central chamber
- Inlet located in biodigester midsection
  - Used to add feedstock
- Outlet positioned on bottom face
  - Used to remove old waste



Future Improvements

Active temperature monitoring

Automatic mixing

Advanced materials

Works Cited