Georgia Institute of Technology

Landfill Gas Recovery for Energy in the United States: A contextual case study of three states' approaches

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Contents

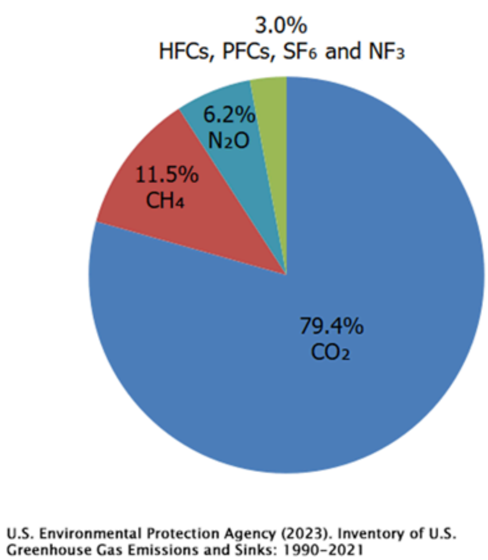
List of Tables

List of Figures

Introduction

Globally, methane (CH_4) is the second most abundant human-influenced greenhouse gas (GHG) after carbon dioxide (CO_2), as shown in Figure 1 (IPCC, Climate Change 2013: The Physical Science Basis, 2013). While methane's 12-year atmospheric lifetime is significantly shorter than that of CO_2, methane from landfill gas (LFG) has approximately 27 times the radiative efficiency, or global warming potential, over a 100-year period when compared to CO_2, but around 80 times over a 20-year period. (IPCC, 2021). On a per pound basis, methane environmental impacts are greater than those of CO_2 in the near term. As shown in Figure 1, landfills account for 15% of anthropogenic methane (CH_4) emissions in the United States. Methane generation comes from the decay of organic waste in landfills in an anerobic environment (EPA, 2024).

Landfill usage in the US has only grown by 9% from 1980 to 2018, a timeframe when population increased by 42% and waste disposal increased by 83% (US Population Growth Rate 1950-2024, 2024) (EPA, National Overview: Facts and Figures on Materials, Wastes and Recycling, 2024). Composting, incineration, recycling, and other food management systems are the waste disposal streams that grew to manage waste generation (EPA, National Overview: Facts and Figures on Materials, Wastes and Recycling, 2024). This report assesses the economic feasibility and effectiveness of policy instruments to implement LFG recovery projects as a climate mitigation measure by looking at case studies, databases, and existing policies.



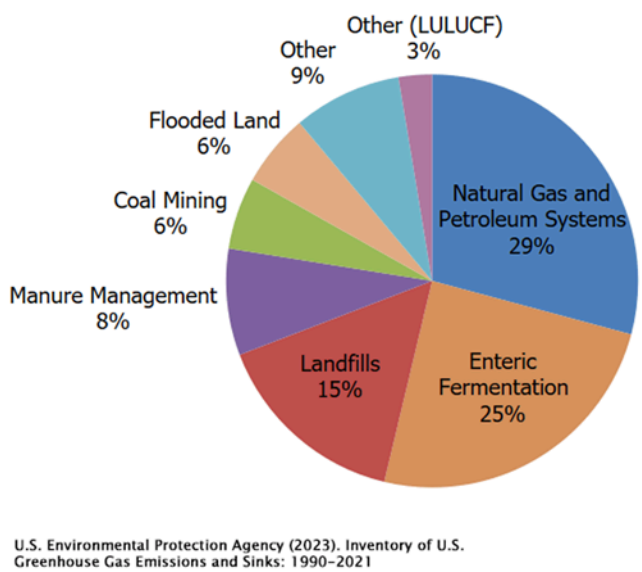


Figure 1. Overview of US Greenhouse Gas Emissions (left) and US Methane Emissions by Source (right) (EPA, 2024).

Landfills produce a variety of gases as waste decomposes. Figure 2 shows some of the gases and relative concentrations that can be expected in LFG (LMOP, LFG Energy Project

Development Handbook, 2024). The gases present in landfills change over time as the environment changes from aerobic to anerobic. LFG collection is optimal for methane concentrations of 50%. Therefore, collection typically begins after Phases I, II, and III are complete, which is 1-3 years after waste is in place (LMOP, LFG Energy Project Development Handbook, 2024) CO_2, Nitrogen, and other trace gases make up the remainder of the LFG, with up to 50% CO_2.

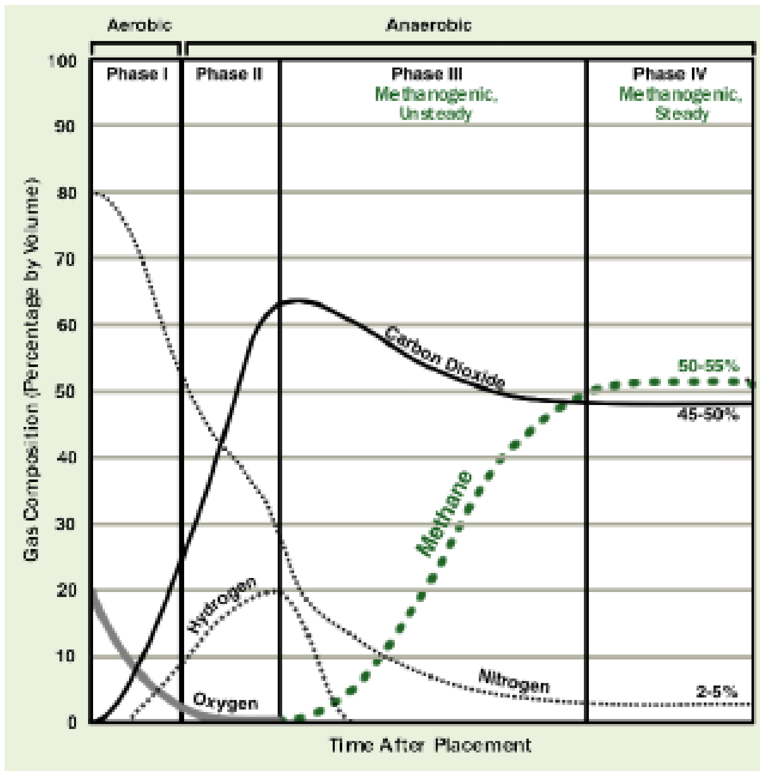


Figure 2. Gas production during waste decomposition in landfills (LMOP, LFG Energy Project Development Handbook, 2024)

US based research and development for LFG recovery began in the 1970s A case study of the Palos Verdes LFG Development Project outlines the initial successes and difficulties with LFG recovery, specifically with refinement of LFG for natural gas pipeline injections. This is discussed later in the report.

Figure 3 depicts LFG recovery from collection through end-use. LFG is collected by installing a series of vertical and horizontal pipelines in a closed landfill cell and then transporting the gas to a central location for processing and use. Recovered LFG has a variety of end-uses including electricity production, direct use in boilers or dryers, natural gas pipeline injections, or conversion into renewable natural gas (RNG). (LMOP, EPA, 2024)The US demonstrates stakeholder acceptance and technical feasibility with 518 LFG capture sites currently in operation, and 460 listed candidate landfills (EPA, 2024).

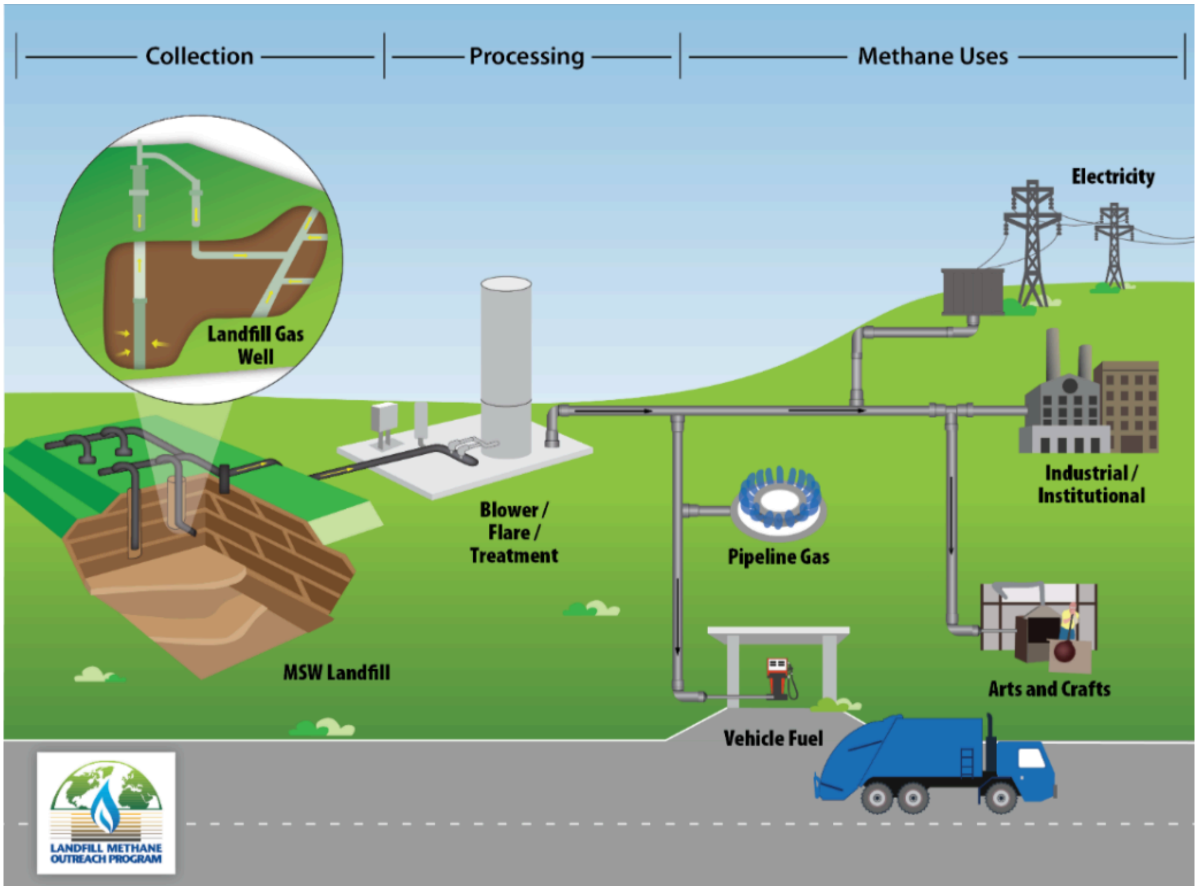


Figure 3. Process Diagram of LFG recovery from collection through end use (LMOP, EPA, 2024).

The primary benefit of LFG capture and use projects is the avoided emissions resulting from replacement of non-renewable fuel sources for electricity generation or fuel: for every megawatt (MW) of electricity generated from LFG, the volume of fuel source with equivalent thermal heat capacity to generate that MW of electricity or gallon of fuel is not extracted and subsequently burned elsewhere. To the extent that LFG displaces coal, oil, or natural gas-fueled electricity, CO_2e emissions are avoided. The average LFG project in Georgia avoids 0.013 Megatons (MT) of tons of CO_2e annually (EPA, 2024). In a state like Texas – the largest producer of landfill methane in the U.S., the potential for avoided emissions is magnitudes higher (EPA, 2022 Greenhouse Gas Emissions From Large Facilities, 2024).

Additional positive externalities result from these source displacements, such as reduced particulate matter and other criteria pollutants, leading to improved air quality and health improvements. This is discussed further in Equity Impacts.

The infrastructure required for LFG recovery is shown in Figure 3 and includes a pipeline and blower system to collect LFG, a flare system, LFG processing, and a pipeline to distribute the recovered LFG. Because landfills that generate enough methane for LFG recovery projects are required to flare methane, the infrastructure cost for LFG collection and flaring is excluded from the cost analysis of LFG recovery projects for this report. Infrastructure investments can be minimized by reducing the distance between the LFG treatment equipment and the final use point of the recovered LFG. Pipeline construction is a financial barrier with respect to RNG pipeline injections and direct use application (Oil & Gas Journal, 2023).

Methodology

Landfill gas project viability was studied along 2 dimensions: analyzing the USA-wide data present in the Landfill Methan Outreach Program (LMOP) database to extract trends for reasons why projects succeed, and the other learning about policies which contribute to said success. For the former, a correlation matrix of LMOP factors was created, and was used to identify aspects of landfills which correlated to whether they remained open or not. In addition, Levelized Cost of Energy (LCOE) calculations varying relevant parameters were completed to assess economic feasibility. The policy analysis focuses on incentives the three states chosen for case study provided for LFG projects and assessed the potential for further support, usually in the economic and permitting sense.

Data Science

The data science approach stemmed from the need to understand and characterize the litany of projects, both open and closed, within the EPA's LMOP database. The database is organized by factors such as ownership type, project type category, etc. Using Python, a numerically encoded the entirety of the database was created and derived the correlation matrix in Appendix C. Of primary interest are high value positive or negative correlations with current project status, which led to exploration of landfill design capacity/waste in place, LFG volumes generated, and the types of projects. Other data within the database informed LCOE or equivalent calculations.

Policy

In addition to the aforementioned statistical approach, this study explores federal and state-level policies that drive the creation of new LFG projects and either sustain or terminate existing projects. At the federal level, the EPA implements regulations governing landfill design and operation as authorized by the Clean Air Act (CAA) and the Resource Conservation and Recovery Act (RCRA) implemented in 1970 and 1976, respectively. Landfill design requirements include a lining to manage methane migration and leachate and an LFG collection and flaring system for landfills of a certain size. The system used to collect LFG for required flaring is used in the LFG recovery process, creating a baseline incentive for LFG projects since monitoring and collection is already in place at these landfills (EPA, 2024).

Not all landfills meet the criteria to produce enough methane content in the biogas to justify LFG projects. The LMOP handbook includes guidelines for LFG projects. Additional landfill requirements for LFG capture include (LMOP, LFG Energy Project Development Handbook, 2024):

- At least 1 million tons of waste in place
- A depth of at least 50 feet

- Continued operation or closing within the last 5 years
- At least 25 inches of annual precipitation
- Sufficient organic content to produce LFG

Municipal solid waste (MSW) landfills are the best candidates for LFG projects because they have the highest percentage of organic waste. Construction or hazardous waste landfills, in particular, will not have the organic content necessary for methane production. Unfortunately, this also means that federal regulation does not require construction landfills to monitor and collect methane, a policy that warrants further research and, implementation (EPA, 2024).

Due to the benefits of reducing CO_2 and other pollutant emissions, LFG capture has been subsidized through tax credits and grants. Georgia landfills have utilized federal funding from the American Recovery and Reinvestment Act (2009), particularly through a $15 million grant to fund an LFG to vehicle fuel project in 2010 under the Clean Cities Alternative Fuel and Vehicles Grant Program (DOE, 2010).

The LMOP Landfill and Project Database was analyzed to establish adoption rates for LFG projects on a state level. This graph, shown in Figure 5, informed state selection for the case study. The x-axis plots capacity in each state, which is defined as the number of active landfill gas projects plus the number of candidate landfills in each state. The criteria for candidate landfills are set by the EPA through LMOP as described above. States range from as few as 2 candidate landfills in Wyoming to as 83 in California (LMOP, LMOP Landfill and Project Database, 2024). The adoption rates ranged from 0% in Hawaii and Wyoming to 92% in New York, with an average adoption rate in the US of approximately 50%. Only select states are labeled to provide an idea of adoption rates in the US, data for each state can be referenced in Appendix A.

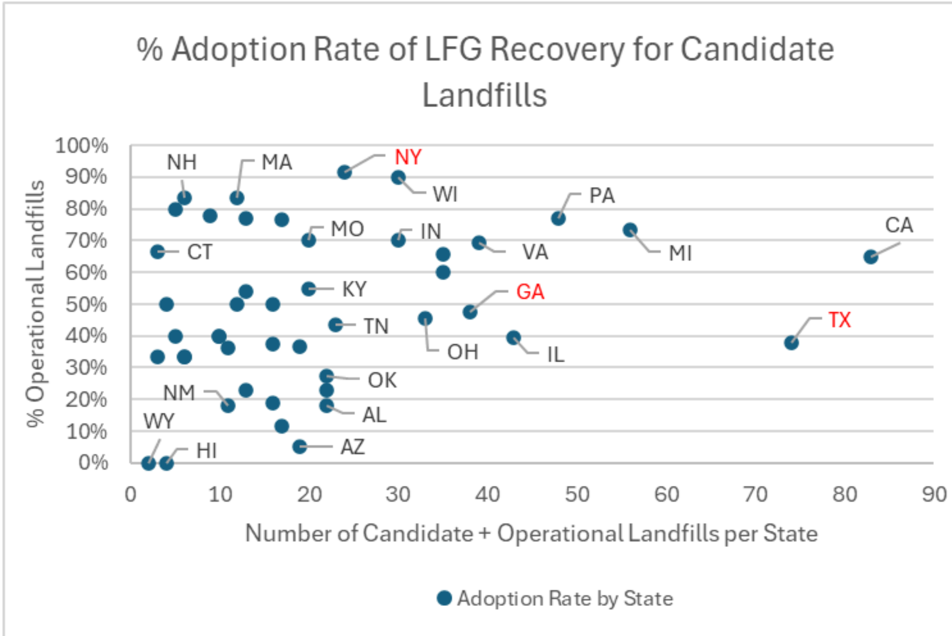


Figure 4. Adoption Rate of LFG Recovery by state (LMOP, LMOP Landfill and Project Database, 2024)

Georgia was chosen for analysis based on the research memo assignment and has an adoption rate of 47%. New York and Texas are points of comparison. New York has the highest rate of adoption at 92% and is a majority democrat state. Texas has a high potential for landfill gas recovery project implementation, Texas is an energy exporting state, and they are a majority republican state (Administration, 2021). This report will also further discuss policy instruments and equity concerns regarding LFG policies.

Analysis and Results

The analysis and results section begins by covering analysis of the LMOP database. Then, a cost analysis associated with LFG recovery projects is presented. The cost analysis covers capital and operational costs, LCOE, and a sensitivity analysis for pipeline distance for direct heat projects. A case study is presented to contextualize a project regarding landfill design and policy. Finally, a policy analysis assesses federal policy and three state policies, Georgia, New York, and Texas.

LMOP Analysis

Analysts used LMOP data to study the features of landfill design capacity/waste in place, LFG volumes generated, and the types of projects. In the case of landfill design capacity and waste in place, there is a bit of redundancy as the former puts a cap on the latter. As shown in the figure below, most landfill designs are usually less than 200 Mt of waste capacity. With that, a plot of mean waste in place versus the project status was generated to determine what the correlations present were. The bar chart below highlights a few things: (1) there is a trend for operational projects in the 10-25 MT size range, (2) shutdown projects have other considerations beyond simply waste in place.

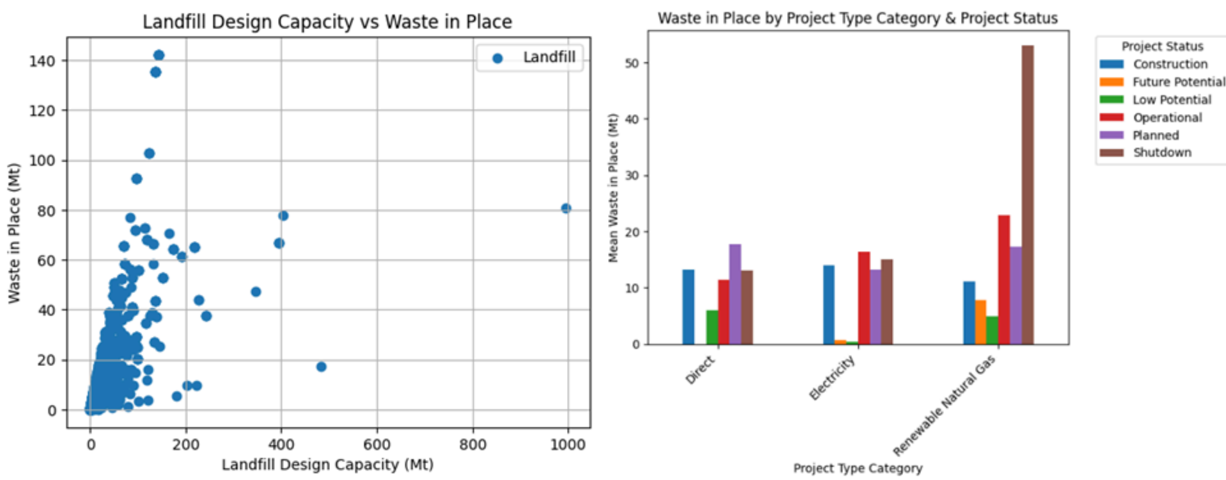


Figure 5. Landfill Design Capacity vs Waste in Place (L) and WIP by Project Status (R) (Also in Appendix C)

Given that looking at present waste volumes may not paint the whole picture, since there are factors such as landfill age and LFG flows to consider. As such, mean LFG Flow to projects may be found in the figure below. The LMOP database inconsistently reports LFG flow estimates for potential projects, but it can be noted that higher LFG generating projects tend to be more favored for RNG conversion projects over direct or electricity ones. However, the data remains inconclusive regarding project closures as the LFG flow to shutdown projects tends to mirror those in operation.

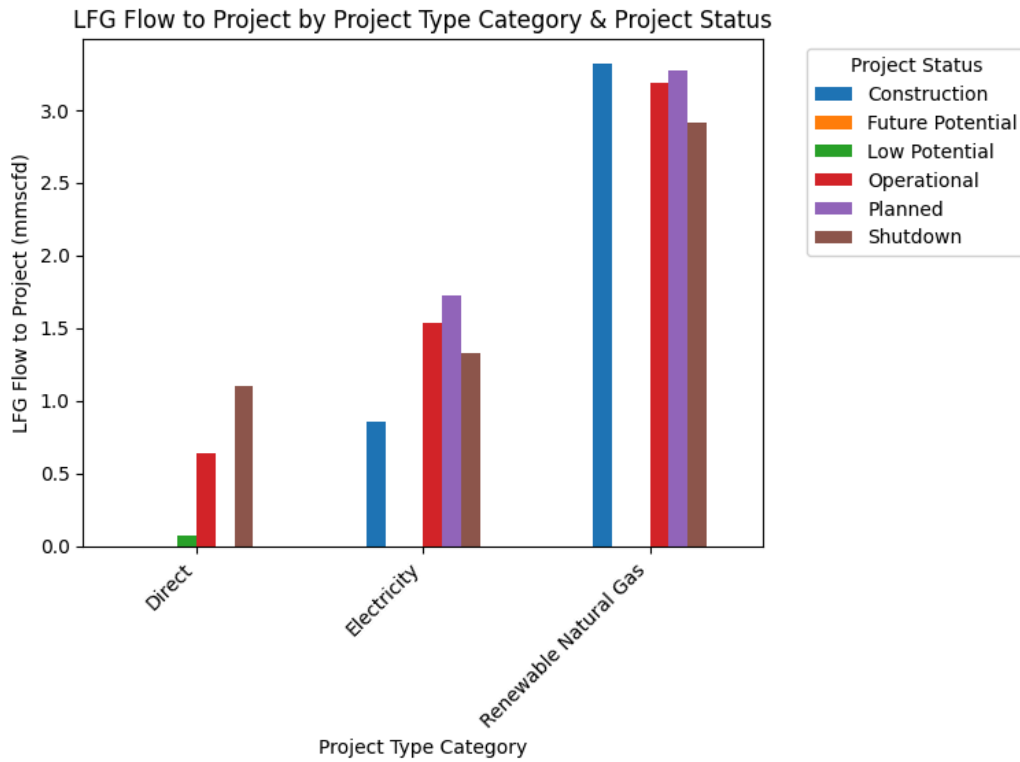


Figure 6. LFG Flow vs Project Status

Given the tends seen in the above figures regarding waste in place and LFG flow for different project types, a different conclusion may be drawn: project life may primarily be determined by factors outside of LMOP's database, the primary of which would be economic and policy.

Capital and Operational Cost

Table 1 summarizes the national average capital (CAPEX) and operation (OPEX) cost, of the different LFG projects as reported by the EPA (LMOP, LFG Energy Project Development Handbook, 2024). The table has recommendations for a project's potential size based on LFG flow range and the CAPEX and OPEX estimates are shown accordingly. The summarized values are from Sections 3 and 4 of the LFG handbook which relies on the modeling tool compiled by EPA (LMOP E.). Cost values are separated in accordance with project type and a given project size whenever applicable. Average values for the cost were calculated for the electric and direct costs. The cost for the landfill and LFG collection is not included. Values are shown in 2020 dollars as a base refence.

Table 1. CAPEX and OPEX Cost Matrix

Project Type Category	Project Type	Size		CAPEX		Yearly OPEX	
Electric	Microturbine	1>=	MW	3.40E+06	$/MW	3.40E+05	$/MW
	Small ICE	.8 >=	MW	2.90E+06	$/MW	3.20E+05	$/MW
	Large ICE	.8 <	MW	2.00E+06	$/MW	3.00E+05	$/MW

	Gas Turbine	3 <=	MW	1.70E+06	$/MW	1.90E+05	$/MW
	Average	**-**		**2.50E+06**	**$/MW**	**2.88E+05**	**$/MW**
Direct	-	1.44	mmscfd	5.07E+05	$/mmscfd	9.03E+04	$/mmscfd
		4.32	mmscfd	9.72E+05	$/mmscfd	1.25E+05	$/mmscfd
	Average	**2.88**	**mmscfd**	**7.40E+05**	**$/mmscfd**	**1.08E+05**	**$/mmscfd**
Renewable Natural Gas	**Gas Compression and treatment**	**-**		**5.03E+06**	**$/mmscfd**	**9.03E+05**	**$/mmscfd**
	Transportation 0.072 mmscfd	198	GGE/day			6.49E+02	$/GGE
	Transportation 0.216 mmscfd	594	GGE/day			1.50E+03	$/GGE
	Transportation 0.432 mmscfd	1188	GGE/day			2.59E+03	$/GGE
	Transportation 0.864 mmscfd	2377	GGE/day			4.59E+03	$/GGE
Gas Pipeline	Interconnect (add to gas pipeline)			400	k$	Negligible	
	Gas Pipeline			600 - 1000	k$/mile		
*GGE = Gasoline gallon equivalent. Transportation projects are a subset or RNG project.							

Levelized Cost of Energy Analysis

The average values for the LCOE or equivalent cost for all the projects from (LMOP, LMOP Landfill and Project Database, 2024) is shown in Figure 8. Since there are no subsidies or tax breaks added to the calculations these values represent some of the most expensive these projects will get. The projects show some sensitivity to the rate of return. Adding pipeline costs would increase the cost for the Direct and RNG projects (including the vehicle one). Average OPEX and CAPEX costs were used for the different project types and do not considered scaling based on flowrate of LFG assigned to the projects.

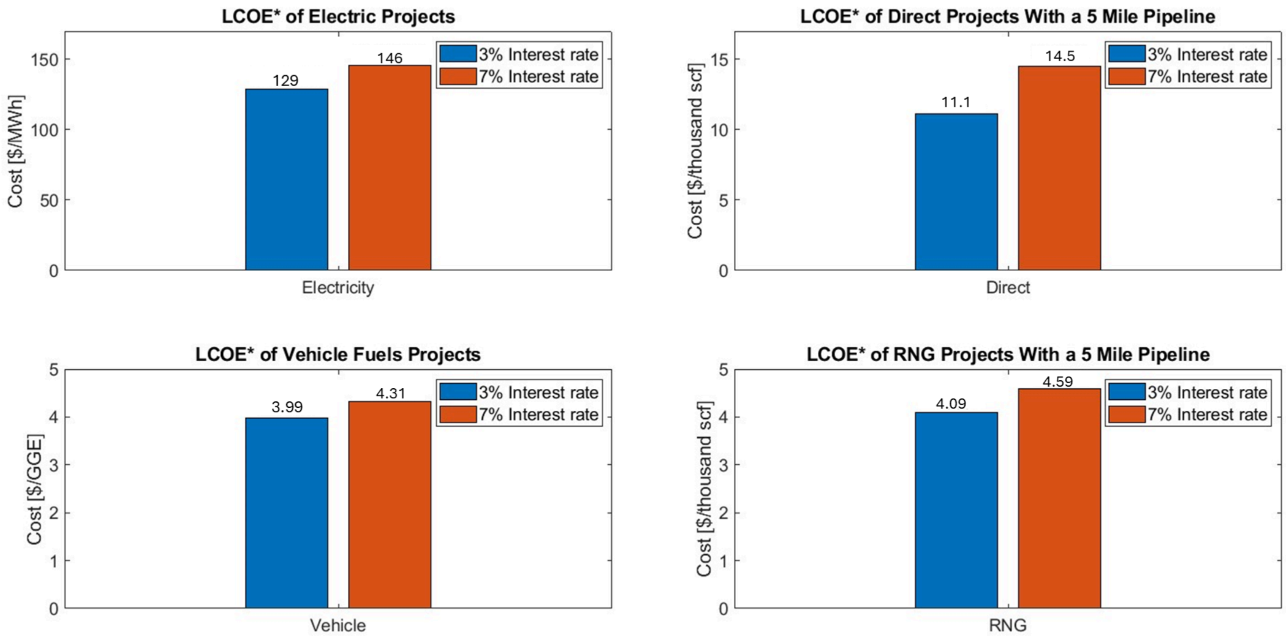


Figure 7. LCOE or Equivalent Results by Project Type

The values shown here are highly generalized and limited on the information available for the projects for, (LMOP, LMOP Landfill and Project Database, 2024). The addition of more information could have a significant impact on the costs. The addition of subsidies or savings will also have a significant impact on the cost projections. The results shown in Figure 8 are meant to show general trends. The direct heat projects are extremely sensitive to the length of the pipeline to be built. The same project shown here has a lifetime cost ranging from 0.46 to 0.52 $ per thousand-scf if no pipeline is to be built.

Cost Discussion

To contextualize the costs from the different projects the US average costs for electricity, natural gas, and gasoline are listed on Table 2. The costs calculated for the LFG projects are also listed on the Table.

Table 2. Historic Utility/Gas/Gasoline Costs and Calculated LFG Project Costs

Year	Electricity Cost ($/MWh)				Natural Gas Cost ($/Thousand scf)	Gasoline Cost $/gallon
	Residential	Commercial	Industrial	All Sectors		
Annual Totals						
2014	125.2	**107.4**	**71**	101.20	5.6	3.44
2015	126.5	**106.4**	**69.1**	100.67	3.9	2.51
2016	125.5	**104.3**	**67.6**	99.13	3.5	2.25
2017	128.9	**106.6**	**68.8**	101.43	4.1	2.53
2018	128.7	**106.7**	**69.2**	101.53	4.2	2.82
2019	130.1	**106.8**	**68.1**	101.67	3.8	2.69
2020	131.5	**105.9**	**66.7**	101.37	3.3	2.26
2021	136.6	**112.2**	**71.8**	106.87	5.4	3.09
2022	150.4	**124.1**	**83.2**	119.23	7.7	4.06
2023	159.8	**127.4**	**80.6**	122.60	4.5	3.63
LFG Project Calculated Cost	128.7 - 145.6				Direct: 11.1 - 14.5 RNG: 4.09 - 4.59	3.99 - 4.31

https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_3
https://www.eia.gov/dnav/ng/hist/n3035us3m.htm
https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emm_epm0_pte_nus_dpg&f=m

For electric projects, the use of LFG as compared to the listed utility cost over the last 10 years would be more expensive, a trend that is changing as electricity prices increase. While this is true for the U.S. average, some states - such as New York - have higher electricity costs, making an LFG electric project more attractive. This trend is shown in Appendix C with New York having a large amount of LFG projects compared to both Texas and Georgia.

The prices as shown for direct heat are the ones with the highest disparity in the commercial cost. However, decreasing the pipeline length of the analysis would reduce initial capital cost for the project and reduce the project's expense, making these projects more competitive. Direct heat projects, while having the lowest CAPEX for LFG processing equipment can quickly increase in cost when adding the cost of pipelines. This makes it hard to justify the addition of long pipelines to the projects, limiting their application. A later section does an LCOE sensitivity analysis for varying flowrates.

The RNG cost appears to be competitive when compared to the most recent cost of natural gas. In fact, the cost of the RNG has been competitive over the last five years, which could be an indication of the increase in the construction of these projects shown in the LMOP data (LMOP, LMOP Landfill and Project Database, 2024) Appendix C. RNG projects are a lot less sensitive to pipeline length so even though the cost of the project would increase it would not be as significant as the direct heat project costs. The gasoline prices from the RNG projects are also close to those of the recent gasoline prices, making them an attractive installation. It is worth noting that the electric cost and gasoline costs will change with that of natural gas. As the natural gas market fluctuates it will affect the performance of these projects and might drive an increase or decrease in LFG project adoption.

Direct Heat and Pipeline Distance Sensitivity Analysis

The analysis presented claims that the direct heat projects are sensitive to pipeline parameters of distance and pipe diameter. An analysis was made to test out this sensitivity resulting on

Figure 9. Showing the calculated LCOE trend for a project with varying flowrate and a 5-mile pipeline under the current assumptions plotted with a blue line. This shows that there is an optimal project flowrate where your cost for the direct gas will be equal to that for natural gas, and thereafter several flows for which the project gas will be cheaper than NG. It is worth noting that the analysis does not account for equipment scaling and pipe size increasing the cost of the installation. A more realistic analysis under different assumptions would show a cost curve closer to the one drawn with the dashed line where a range of flows will result on cost savings but eventually the capital cost of the increasing equipment would outweigh the savings. Not to mention that as equipment and LFG production increases a market of end users needs to be available. Once this need is met any surplus product will just add to the cost. Similar conclusions apply to the other project types.

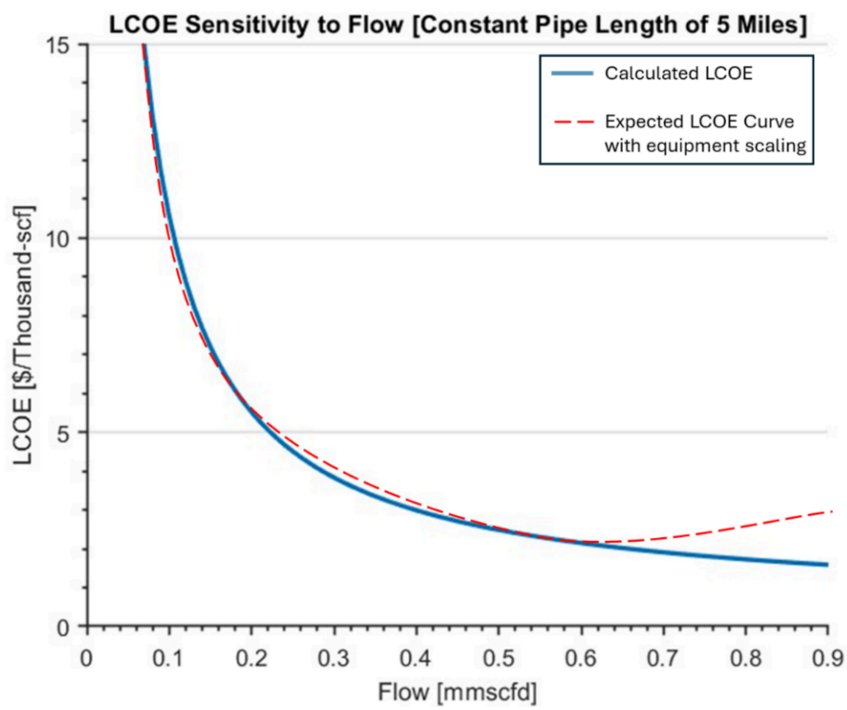


Figure 8. . LCOE Sensitivity to LFG Flow for a Direct Heat Project with Constant Pipe Length

Case Study: Palos Verdes LFG Development Project

A case study of the Palos Verdes LFG Development Project was analyzed to understand the mechanisms associated with the implementation of LFG projects. This project was completed in a landfill in Los Angeles County near the Pacific Ocean in collaboration with the EPA. The Palos Verdes LFG Development Project was the first commercial scale attempt in the US to inject refined landfill gas into a natural gas pipeline (Frank Bowerman, 1977). This project was completed in the mid-1970s during the oil embargo when the US government was looking to diversify energy sources. RCRA, which was enacted in 1976, provided federal regulation for methane migration control and leachate management. The researchers evaluated LFG collection system for ability to mitigate methane migration into nearby community buildings prior to the passage of RCRA (Frank Bowerman, 1977).

Pipeline injections of recovered LFG require quality controls above what is needed for direct use applications of recovered LFG. For this project, LFG had an energy density of 535 BTU/standard cubic foot (scf). To meet quality standards for injection into the nearby pipeline, the energy density was increased to 700 BTU/scf by reducing the volume of carbon dioxide and trace gases (Frank Bowerman, 1977).

Several problems were encountered during this project. First, the pipes used to collect the LFG induced air entrainment in the landfill. Introducing air disrupts the anerobic environment required for methane production and methane production dropped by 20%. The design of the collection pipes was modified to collect LFG from a minimum depth of 40 feet to solve the problem of air entrainment. LMOP standards still incorporate these design changes relative to the required depth of landfills for candidate projects (Frank Bowerman, 1977).

Second, chlorinated hydrocarbons in the LFG corroded the regeneration heat exchanger. Researchers replaced the steel heat exchanger with a nickel alloy heat exchanger. In general, LFG degrades equipment such as boilers and kilns more quickly than natural gas because LFG has higher percentages of trace gases, such as sulfides, ammonia, and non-methane organic compounds than natural gas (Frank Bowerman, 1977) (LMOP, LFG Energy Project Development Handbook, 2024) (Registry, 2001).

Finally, the researchers experimented with the optimal extraction rate. Extracting LFG at a high rate can reduce methane production. This point is relevant for present day operations because over-extraction can limit methane production and result in a project closing prior to planned closure dates.

Policy Analysis

As discussed above, federal policies such as the Clean Air Act and RCRA govern waste disposal and landfilling in the U.S. Additionally, several incentive programs have been applicable to LFG projects, with some ongoing. For example, Section 23 of the US tax code allows for a tax credit for renewable energy generated from approved sources. This tax credit is known as the Renewable Electricity Production Tax Credit (PTC), and it provides up to $0.015/kWh for electricity generated from LFG recovery for 10 years beginning on the year the equipment is placed in service. This tax incentive is available for projects that begin construction prior to December 31, 2024. (EPA, 2023) The PTC has been around since 1992 with modifications over time regarding the amount of the tax credit and the eligible technologies (Alvarez & Marsal Holdings, LLC, 2024).

Previously, the 2009 American Recovery and Reinvestment Act (ARRA) was an impetus for many landfill gas use projects. Section 1603 created grants for renewable energy projects from 2010 until 2018. This program offered renewable energy project developers cash payments in lieu of Investment Tax Credits (ITCs). Across the U.S., ARRA funded a total of 109,766 projects using $26.2 Billion (U.S. Treasury, 2018).

The 2010 Clean Cities Alternative Fuel and Vehicles Grant Program was one feature of this legislation that benefitted Georgians. Funded by the Department of Energy, this program focused on “clean” transportation projects with public-private partnerships. These had an average of a 2:1 public-to-private contribution ratio. Georgia received a $15 million grant, $13 million of which went to a DeKalb County Landfill LFG-to-fuel project. This project has since closed, but it reduced an estimated 1,200 tons of CO_2e (U.S. Treasury, 2018).

STATE	TOTAL # of PROJECTS	TOTAL FUNDING - Millions	TOTAL CAPACITY (MW)	LFG PROJECT - Millions	2010 Census Population - Millions	$ of LFG GRANTS per CAPITA	Cost per MW – all projects
CA	49,346	$7,046	8,378	$67.0	37.3	$1.80	$0.84
GA	**178**	**$197.5**	**248**	**$13.6**	**9.69**	**$1.41**	**$0.80**
NY	3,708	$751	1,063	$5.08	19.4	$0.26	$0.71
TX	743	$1,993	3,407	$5.51	25.1	$0.22	$0.59

Figure 9. Summary of 4 State LFG Project Funding from ARRA

Figure 9 is a brief summary of Section 1603 in the three comparison states. California has been added because of an interesting comparison in investments per capita. Georgia had $1.41 per capita in landfill gas projects from Section 1603. California was not much higher at $1.80. New York and Texas had much lower LFG investments in comparison, at just $0.26 and $0.22, respectively. While the ARRA grants supported far more wind and solar projects than LFG projects, the summary shows noteworthy progress across renewable projects. It also provided competitive costing per MW across states, supporting future similar projects, such as the Inflation Reduction Act of 2022 (U.S. Treasury, 2024)

Current U.S. policies which support new and existing landfill gas recovery and use projects rely primarily on supply-side instruments, such as Investment Tax Credits and Production Tax Credits, as well as organization and information instruments, such as EPA findings and the LMOP databases and handbooks. Even though the number of municipal solid waste landfills has decreased significantly from approximately 6,326 in 1990 to as few as 1,540 in 2013, the average *size* of landfills has increased, as seen in the aforementioned California case study. The continuous use of landfilling for waste management in the U.S. indicates that LFG projects will continue to be an important consideration for renewable electricity and power generation.

Georgia

Georgia policy relative to LFG recovery falls close to center on a national scale, but far more modest than New York for the purpose of this study. Specific policies contribute to the higher adoption rate of LFG capture in Georgia relative to other US states, notably, the Georgia Planning Act of 1989 and the Georgia Comprehensive Solid Waste Management Act of 1990. A requirement of the Planning Act is that all funding requests for MSW facilities or landfill permits must be accompanied by an MSW management plan. MSW management plans typically cover a 10-year period and outline current measures in place to manage MSW and any gaps in MSW planning. The Georgia Department of Community Affairs manages the Planning Act. The Georgia Department of Natural Resources Environmental Protection Division (EPD) manages the Solid Waste Management Act. Relative to the implementation of LFG capture, the EPD manages landfill permitting requirements and specifications and authorizes state funding and grants for landfill projects.

Although there are not state-level grants for LFG projects, Georgia offers an Energy Conservation Financing program to Georgia municipalities and select entities created by the Georgia General Assembly. The financing available is with a 1% interest rate reduction and a 1% closing fee to cover up to $25 million per borrower annually (Georgia Environmental Finance Authority, 2021).

Georgia's 2024 Priority Climate Action Plan – renamed the "Peach State Voluntary Emission Reduction Plan" (PSVERP) includes LFG projects as a priority measure for reducing statewide GHG emissions. The GHG reduction measure "Landfill gas management and utilization" is under the strategy of "Improve Waste Diversion and Landfill Management." This plan clearly counts on intersecting with federal PTCs to help incentivize LFG projects. The PSVERP specifies that LFG projects support the equity measures of "Improved Air Quality" and "Workforce Development" (GA DNR, 2024).

New York

New York has by far the most climate policies of our three comparison states. They have both a state-wide Climate Plan (the Climate Leadership and Community Protection Act of 2019) and a separate Energy Plan, as well as the NY State Climate Action Council Scoping Plan of 2022, which provides detailed guidance for how to comply with the 2019 statewide Climate Plan (New York State Climate Action Council, 2022). Goals include the reduction of economy-wide greenhouse gas emissions (GHGs) by 40% by 2030 and at least 85% by 2050 compared to 1990 levels. The Climate Act also requires investments in economic development and job creation to address equity concerns. New York also has goals of 70% renewable energy creation by 2030, 100% zero-emission electricity by 2040, and net-zero emissions statewide by 2050. It is unclear how some aspects of the state's energy use and waste management will affect these goals. For instance, the state currently produces only about 21% of the energy that it uses (EIA, 2023). Additionally, the state exports almost 30% of its MSW to other states (New York State Climate Action Council, 2022), raising questions about how much LFG methane the state is displacing, rather than actually eliminating.

New York also has numerous accompanying legislations, such as laws for reducing plastic bags (New York State Bag Waste Reduction Act) and requiring organic waste diversion for producers of 2 tons or more per week (Food Donation and Food Scraps Recycling Law) (New York State Climate Action Council, 2022). The implementation and efficacy of these laws – as well as financial structures to support them -- warrant future research, particularly since these were passed just before the Covid-19 pandemic in 2020.

New York has LFG collection projects operating in 22 out of 24 landfills in the state with the capability for LFG recovery. One likely reason for the high adoption rates in New York is the availability of state funded grants for LFG projects. These grants are issued under state policy DMM-SW-04-16 Landfill Gas Collection and Treatments Systems (NYS DEC, 2024). Grants cover 50% of the cost of LFG collection and treatment systems, with a cap of $2 million per grant (NYS DEC, 2024).

New York's 2024 Priority Climate Action Plan is named the "Climate Pollution Reduction Grant Program Priority Climate Action Plan," and it includes measures to "Reduce Fugitive Methane and Co-Pollutant Emissions from Landfills." This plan gives priority first to reducing or diverting organic waste, then to LFG electricity projects, in keeping with the state's overall clean energy and net-zero emissions long-term goals (NYS DEC, NYS ERDA, NYS DoS, 2024). Additionally, the overall high cost of electricity in New York may be a motivating factor for increasing local electricity generation and decreasing demand from other states (EIA, 2023).

Texas

Texas, while being the largest producer and consumer of energy in the U.S. (often several magnitudes more than other states), has minimal guidelines for management of landfills in general. There is a state Commission of Environmental Quality who monitors and regulates waste disposal, and there is a comprehensive statewide solid waste management law, similar to Georgia's. There are not, however, any laws as specific or far-reaching as those in New York. In 2002, the Texas Economic Development Act offered a franchise tax credit valued at $100 million or 10% of total capital costs for "clean energy projects"; however, the description is entirely misleading as the projects are actually fossil-fuel energy projects with carbon capture and storage, not renewable energy sources such as wind, solar, or LFG. (Texas Comptroller of Public Accounts, 2024). Anti-renewable energy bills continue to be introduced, despite Texas being the largest producer of wind energy in the country. While Texas did establish Renewable Portfolio Standards (RPS), it reached its target in 2008 – 7 years ahead of schedule – and has yet to re-establish them. RPS have not been needed for continued growth in wind energy projects, yet new ones could encourage non-wind projects, such as LFG (recall the 38% adoption rate) (Barbose, 2023). Texas has high potential for additional LFG projects, though the state is clearly relying on federal assistance to balance any extra costs for them.

Despite this preference for fossil-fuel-based projects, Texas submitted a Priority Climate Action Plan in 2024. LFG play a smaller role than in the Georgia and New York plans as it is not combined with other waste measures and falls into a more general "Other Measures" category. The Texas plan recommends creating "biofuels through methane capture from landfills and wastewater treatment plants, or by using surplus biomass" – an afterthought. Thus, Texas is prioritizing using LFG for fuels, with the exception of combining biogas electricity projects with solar arrays at closed landfills. This is in direct opposition to the New York plan, which prioritizes electricity projects over fuel projects (Texas Commission on Environmental Quality, 2024).

Policy Discussion

Here, we can see how the three states' priority climate action plans compare and contrast. Georgia, New York, and Texas all filed Priority Climate Action Plans, and they all included landfill gas initiatives in their plans. All three plans also included other waste measures, such as organic waste reduction or diversion. However, the exact characterizations and goals in each plan vary.

	Preparer	Key Policies	Note
GEORGIA	GA DNR, Environmental Protection Division	"LFG management and utilization"	Clearly paired with waste diversion/composting and recycling
NEW YORK	NYS Dept of Environmental Conservation, NYS Energy Research and Development Authority, NYS Dept of State	Priority to LFG electricity projects; goal of adding 10 projects in 5 years	Only one with a separate state climate plan and state energy plan
TEXAS	Texas Commission of Environmental Quality	Priority to LFG for biofuels (pipeline), or electricity at closed landfills with solar	38% adoption currently; most opportunity

Figure 10. PCAP Comparisons

New York stands out as having the only specific quantity project goal, set at creating 10 new projects within 5 years. They also prioritize the use of "bio-gas on-site" for electricity projects over refinement for renewable natural gas. New York is the only state of the three with an existing state-wide climate policy and a state energy and scoping plan. Texas, however, prioritized landfill gas projects for biofuels, and they only specify electricity projects at closed landfills and paired with solar. Texas also has by far the most opportunity for additional landfill gas capture and use projects due to its low adoption rate and overall number of candidate landfills.

Georgia's plan is broader in that no specific type of landfill gas projects is preferred over others. While this does not necessarily encourage the use of state funds for future LFG projects, it does provide flexibility for fuel, electricity, and industrial direct-use projects, appropriate for the growing industrial and renewable sectors in the state of Georgia.

Figure 12 adapts the categorization of policy instruments by Valentine, Brown, and Sovacool (2019) to compare and contrast the federal and state-level policies discussed throughout this paper. While not exhaustive, there are trends, including New York's strong reliance on regulations, Georgia's preference for organizational tools, and Texas's relative quiet. Of note is that many other federal and public-private partnerships exist at multiple levels. Furthermore, New York has a 92% adoption rate for LFG projects, so further grants may be best spent on different measures to avoid free rider projects (those that would happen without such a sizeable subsidy or, perhaps no subsidy at all).

Figure 11. Policy Instrument Choice Comparison - adapted from (Valentine, Brown, & Sovacool, 2019)

Equity Considerations

Of the 20 candidate LFG project sites in Georgia, six are located in counties with at least 80% of the population living in LIDAC areas (Low Income and Disadvantaged Communities), according to aggregated CEJST and EJ Screen data. Of those six counties over 80% LIDAC, five are considered 100% LIDAC. The resulting average percentage LIDAC among these candidate counties is 63%. The total population of those 20 counties was 1,536,768 according to 2020 U.S. Census data, with 734,490 of those individuals (48%) in designated LIDAC areas. Given the disproportionate risks to low-income individuals associated with climate change - particularly air quality and associated health risks such as asthma and other respiratory illnesses – the increased capture and use of landfill methane gas in lieu of flaring would offer significant risk reduction for these populations, both in the near and long-term future (EPA, 2021).

Both the county average and population average of the 20 candidate county locations in Georgia exceed the Biden Administration's Justice40 initiative requiring that at least 40% of overall Federal investments in specified strategies benefit disadvantaged communities (The White House, 2022). The landfill gas capture and use initiative falls under the categories of climate change and clean energy and energy efficiency, and potentially under training and workforce development. The Achievable estimations for CO_2e reductions in Georgia, therefore, exceed the Justice40 Initiative requirements for new investments in these measures.

In Texas, we see a similar trend to Georgia. New York, however, has an overall lower LIDAC population percentage in the state.

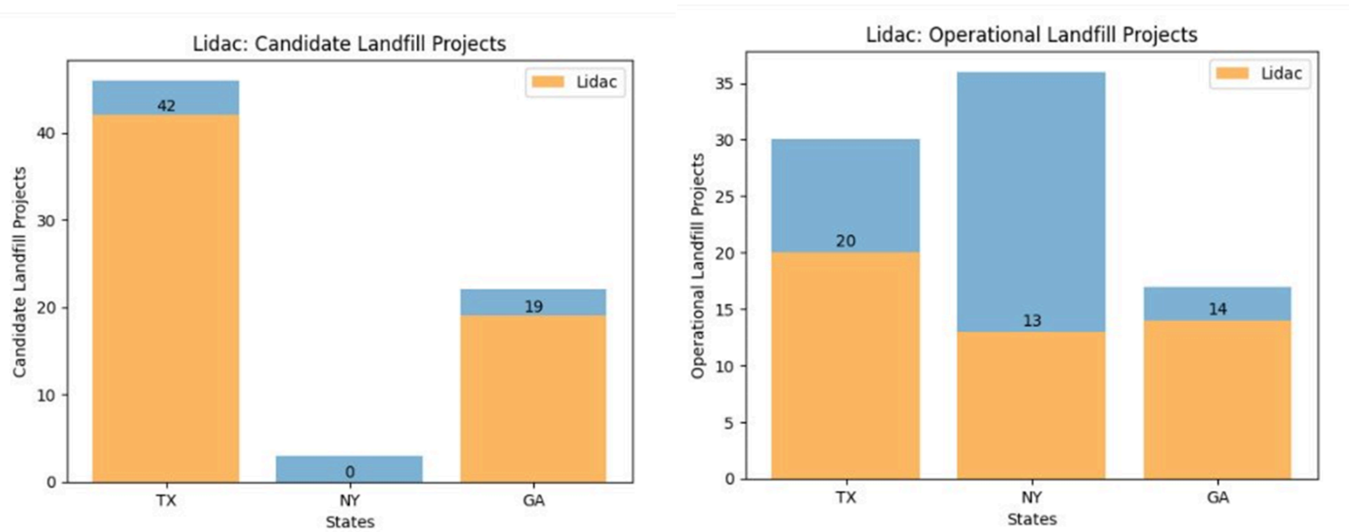


Figure 12. Percentage LIDAC LFG Projects by State

When comparing the equity concerns around operational and candidate landfill gas projects for our three states, we see some stark contrasts. Texas, being the largest state, has both the most current projects and by far the most potential projects in LIDAC areas. New York has the lowest, and Georgia falls between. Consider that Georgia's population is less than half that of New York's, but New York currently exports about 27% of their municipal solid waste. Georgia, however, accepts waste from other states.

The national trend is that 54% of U.S. landfills are in areas with a higher percentage of people of color or low-income residents than the national average. Both Texas and Georgia are exceeding that trend, while New York is below it (Enviormentl Integrity Project, 2023).

Jobs and Economic Factors

Since LFG capture facilities require, at minimum, up-front infrastructure investments at the landfill sites and more complex operations than LFG flaring, the measure offers temporary job creation during construction and permanent job creation as new sites begin operation, as discussed in Section 4. Employee skills from non-renewable electricity generation jobs would be at least minimally transferable since final electricity production uses existing technology. Additionally, 15 of the 20 candidate sites are publicly owned, allowing for direct pathways (i.e., a public/private partnership is not required) to funding and critical investment in disadvantaged communities should this initiative be adopted.

Equity Tradeoffs

There are some concerns of long-term tradeoffs between incentives for LFG collection and measures that will decrease organic material in landfills, such as composting. However, since all three states already have operating LFG facilities, baseline technology and workforce are available for new projects with immediate benefits to displace more-polluting electricity production from existing landfill waste, even if organic material composting increases more quickly than projected population growth and corresponding municipal solid waste landfilling.

It is not the aim of any environmental measure to increase energy costs, particularly to increase any electricity burden on LIDAC or other disadvantaged populations. The benefit of selling any LFG-produced electricity or fuel would only be considered beneficial to the community if a) the electricity cost is lower than that from other existing sources, or b) it can be transported and sold to other communities where it would decrease their energy costs. Regardless of potential electricity cost changes to the end user, however, communities adding LFG energy recovery projects would have a lower net cost of Clean Air Act compliance than those using methane flaring only due to the saleable good (electricity, fuel, or heat) produced from the compliance measure (USA EPA LMOP, 2023).The national trend is that 54% of U.S. landfills are in areas with a higher percentage of people of color or low-income residents than the national average. Both Texas and Georgia are exceeding that trend, while New York is below it (Environmental Integrity Project, 2023).

Discussion and Recommendations

Based on the analysis completed in this report, there are three key areas that warrant additional research discussion, use of LFG recovery as a mid-term climate solution, policy for landfill design, and the health impacts of LFG.

LFG Recovery as a Mid-term Climate Solution

Each of the Climate Action Plans reviewed in this report include measures to incentivize organic waste landfill diversion. Alternative methods to dispose of organic waste include composting and anerobic digestion. If the measures to divert organic waste from landfills succeed, new landfill cells are unlikely to produce enough methane for LFG recovery economically viable per the LCOE calculations above (LFG Energy Project Development Handbook, 2024). Because the source of methane in LFG is expected to reduce in the long-term, LFG recovery is not recommended as a long-term solution. Rather, this analysis indicates that LFG recovery is more appropriate as a medium-term solution. LFG recovery is an interim solution that can continue to be deployed to utilize the methane content of LFG as a fuel source from landfills that already have waste in place and waste that is put in place prior to the diversion of organic waste from municipal solid waste landfills.

Even with policy to incentivize the diversion of organic waste from landfills, the transition will take time. The supply chains for organic waste diversion are not able to support the flow of material if all organic waste is diverted from landfills rapidly. California recently began diverting organic waste from landfills and the supply chain deficiencies were revealed in that market. Examples include rows of compost that no one interested in purchasing or taking home, building facilities to process biogas and compost waste, and changing people's behavior regarding waste disposal (Taxin, 2024). What would you do with the compost from 200 tons/day of organic waste? Over time, one could postulate that the current supply of potting soil, construction fill dirt, compost for agriculture, etc. would be replaced with the compost from organic waste that has been diverted from landfills.

Policy for Landfill Design

Reflecting on the influence of past policy on landfill design and management can provide insight into changes that may be necessary to reduce greenhouse gas emissions. RCRA and the Clean Air Act are both federal legislation that was passed during the 1970s. During this time, the government was looking to manage the known negative externalities landfills of landfill gas migration, explosion hazards, and groundwater contamination (Frank Bowerman, 1977). An additional problem during the 1970s in the US was the oil embargo. At the time, the US government was looking to alternative sources of fuel. So, the generation of methane in landfills, with the intention of capturing for fuel, was encouraged by regulations on landfill design (Frank Bowerman, 1977). To solve those problems, RCRA mandated that new landfills would require a lining to control LFG migration and contamination of groundwater from leachate as well as an LFG collection system to flare LFG. Based on the LMOP database, these regulations shifted the design of landfills from small shallow local landfills to deeper large regional landfills.

The problem facing the governance of waste management today is managing the greenhouse gas emissions generated in landfills. Although LFG capture is the primary method to mitigate methane emissions from landfills, there is an alternative to LFG capture EPA should consider. As discussed above, disruption of the anerobic environment required to generate methane reduces the volume of methane in LFG. Is it viable to reduce methane generation in landfills by aerating landfill cells intentionally? What would be the impact on the composition of gases emitted from landfills and their health impacts? Methane could be eliminated in theory and would be replaced by biogenic CO_2, Nitrogen, Hydrogen, Oxygen, and an unknown mix of trace gases (LMOP, LFG Energy Project Development Handbook, 2024).

The problem facing the governance of waste management today is managing the greenhouse gas emissions generated in landfills. Although LFG capture is the primary method to mitigate methane emissions from landfills, there is an alternative to LFG capture EPA should consider. As discussed above, disruption of the anerobic environment required to generate methane reduces the volume of methane in LFG. Is it viable to reduce methane generation in landfills by aerating landfill cells intentionally? What would be the impact on the composition of gases emitted from landfills and their health impacts? Methane could be eliminated in theory and would be replaced by biogenic CO_2, Nitrogen, Hydrogen, Oxygen, and an unknown mix of trace gases (LMOP, LFG Energy Project Development Handbook, 2024).

Health Impacts of LFG

The LMOP Handbook fails to discuss the health concerns with trace gases that can be found in landfill gas such as ammonia, benzene, carbon monoxides, carbonyl sulfide, hexane, methyl ethyl ketone, sulfides, vinyl chloride, and xylenes. (Registry, 2001) For example, ammonia can cause health impacts of concentrations of 1700ppm (Rana Prathap Padappayil, 2023). Landfill gas typically contains 1,000 to 10,000 ppm of ammonia (Registry, 2001). During normal atmospheric mixing this level of ammonia concentration may not cause health impacts but the omission of this discussion adds from the extensive LMOP database has potential equity impacts as landfills are often located in LIDAC areas. Instead, the LMOP focuses on explosion hazards of methane, LFG migration, and groundwater contamination (LMOP, LFG Energy Project Development Handbook, 2024). Future research could consider a more detailed analysis of the impact of trace gases in LFG on surrounding communities.

Because landfills are often located in LIDAC, as presented in the policy analysis section, the health impacts of landfills have a potential for equity concerns. Future research could consider the impact of trace LFG gases on nearby communities. If research on intentional landfill aeration is pursued, the health impacts of changes in LFG composition should be considered in the Environmental Impact Analysis as required by the National Environmental Policy Act (NEPA).

Conclusion

Landfill design and management has an outsized impact on LFG generation, and thus the project cost structure. Our LCOE calculations show that these projects can be financially viable and could be a desirable alternative when prices increase in electric and natural gas markets. However, this is subject to change depending on the local market and ongoing policies. Underutilization or poor maintenance of the projects will quickly increase costs and reduce project cost benefits (which is something observed in the large datasets). LFG collection is a viable mid-term solution for which the modal shift towards more effective organic waste diversion results in its slow phase out. We recommend that policies moving forward reflect the current GHG emissions problems regarding present landfills in addition to other factors such as waste and leachate management that are already regulated. As new policy is considered, the health impacts of trace gases in LFG should be considered generally and through an equity lens.

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Appendix A

State	Operational	Candidate	Adoption Rate by State	Candidate + Operational Landfills
WY	0	2	0%	2
HI	0	4	0%	4
AZ	1	18	5%	19
CO	2	15	12%	17
NM	2	9	18%	11
AL	4	18	18%	22
AR	3	13	19%	16
IA	5	17	23%	22
WV	3	10	23%	13
OK	6	16	27%	22
AK	1	2	33%	3
MT	2	4	33%	6
NV	2	4	33%	6
UT	4	7	36%	11
LA	7	12	37%	19
MS	6	10	38%	16
TX	28	46	38%	74
IL	17	26	40%	43
SD	2	3	40%	5
MN	4	6	40%	10
WA	4	6	40%	10
TN	10	13	43%	23
OH	15	18	45%	33
GA	18	20	47%	38
ND	2	2	50%	4
KS	6	6	50%	12
MD	8	8	50%	16
NE	7	6	54%	13
KY	11	9	55%	20
FL	21	14	60%	35
CA	54	29	65%	83
NC	23	12	66%	35
CT	2	1	67%	3
VA	27	12	69%	39
MO	14	6	70%	20
IN	21	9	70%	30
MI	41	15	73%	56
SC	13	4	76%	17

NJ	10	3	77%	13
PA	37	11	77%	48
OR	7	2	78%	9
ID	4	1	80%	5
NH	5	1	83%	6
MA	10	2	83%	12
WI	27	3	90%	30
NY	22	2	92%	24

Note: Maine, Rhode Island, Delaware, and Vermont are omitted because LMOP does not have data available on candidate landfills in these states.

Appendix B

Energy production and consumption by state, Georgia, New York, and Texas.

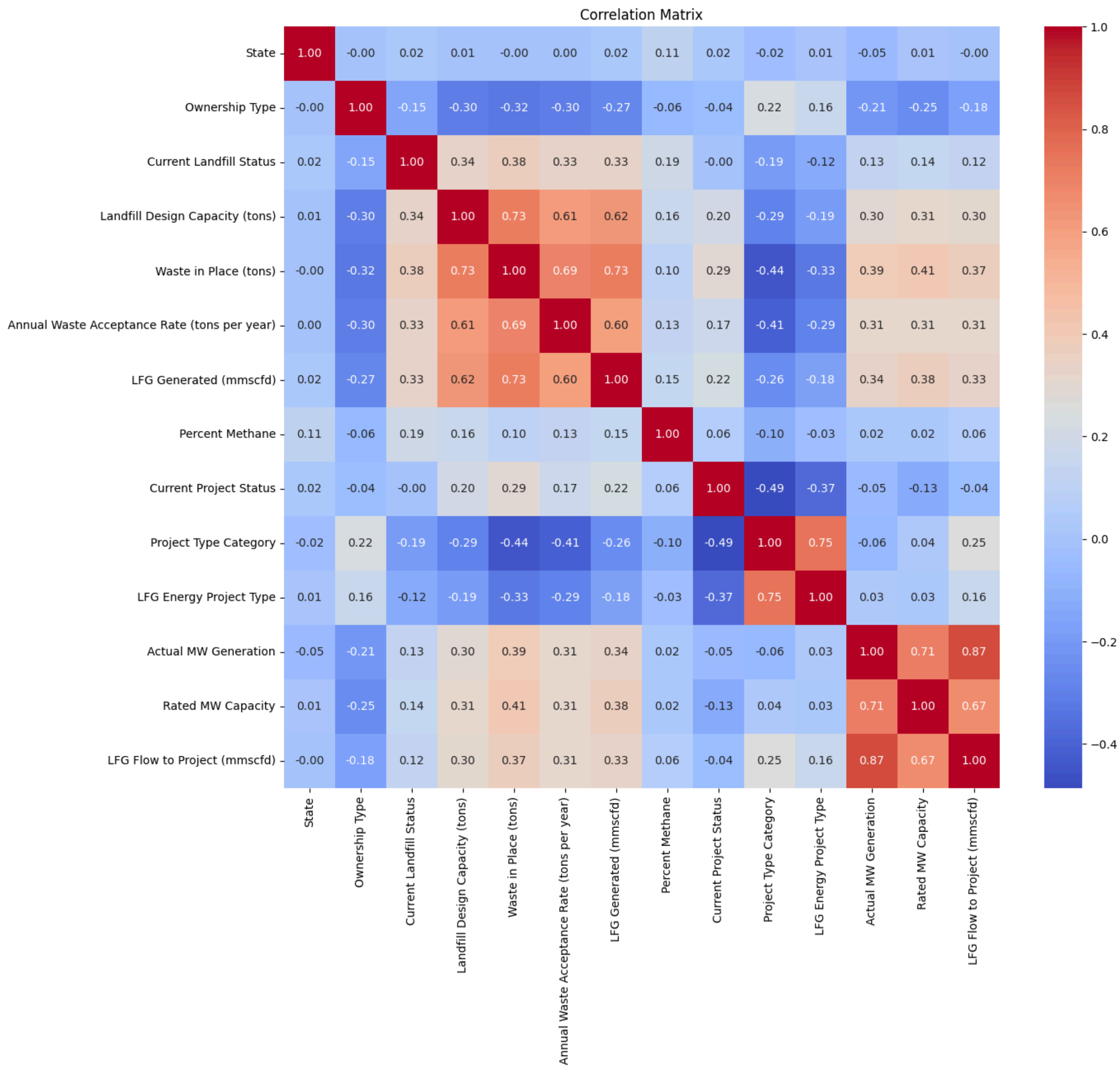
State	Produced	Consumed	Net
GA	671 trillion Btu	2,836 trillion Btu	-2165 trillion Btu
NY	761 trillion Btu	3,541 trillion Btu	-2780 trillion Btu
TX	23,844 trillion Btu	14,364 trillion Btu	9,480 trillion Btu

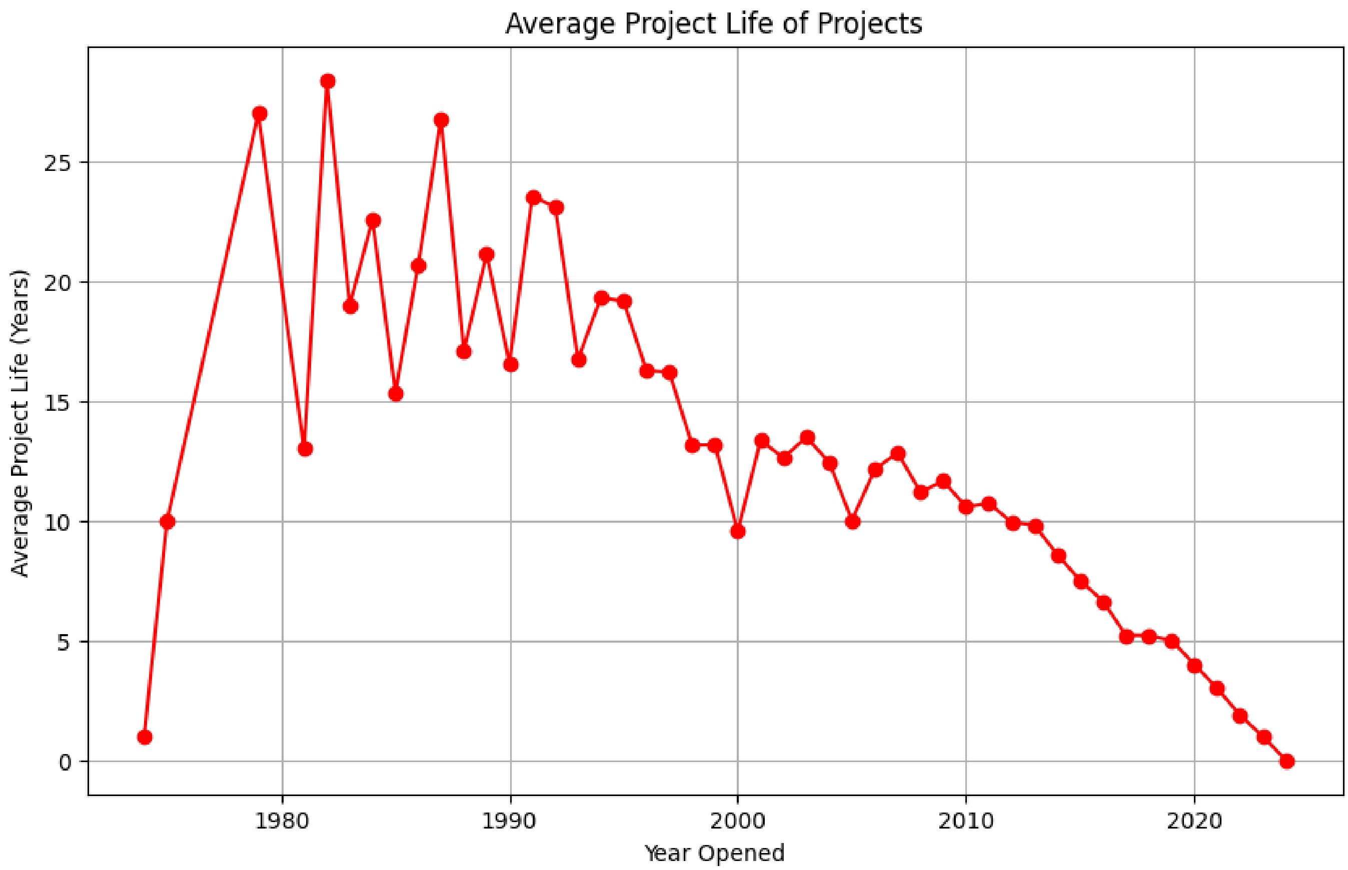
2021 Energy Production and Consumption by State (EIA, 2024)

From: U.S. Energy Information Administration. (2024). State Profiles and Energy Estimates. https://www.eia.gov/state/

Appendix C – Colab Generated Images

https://colab.research.google.com/drive/1nEysrMm5PC7AfIMxgi85VAeIBCWv28BU?usp=sharing#scrollTo=ZvG8y08HnpIA




Average Project Life of Projects
Average Project Life (Years)
0
5
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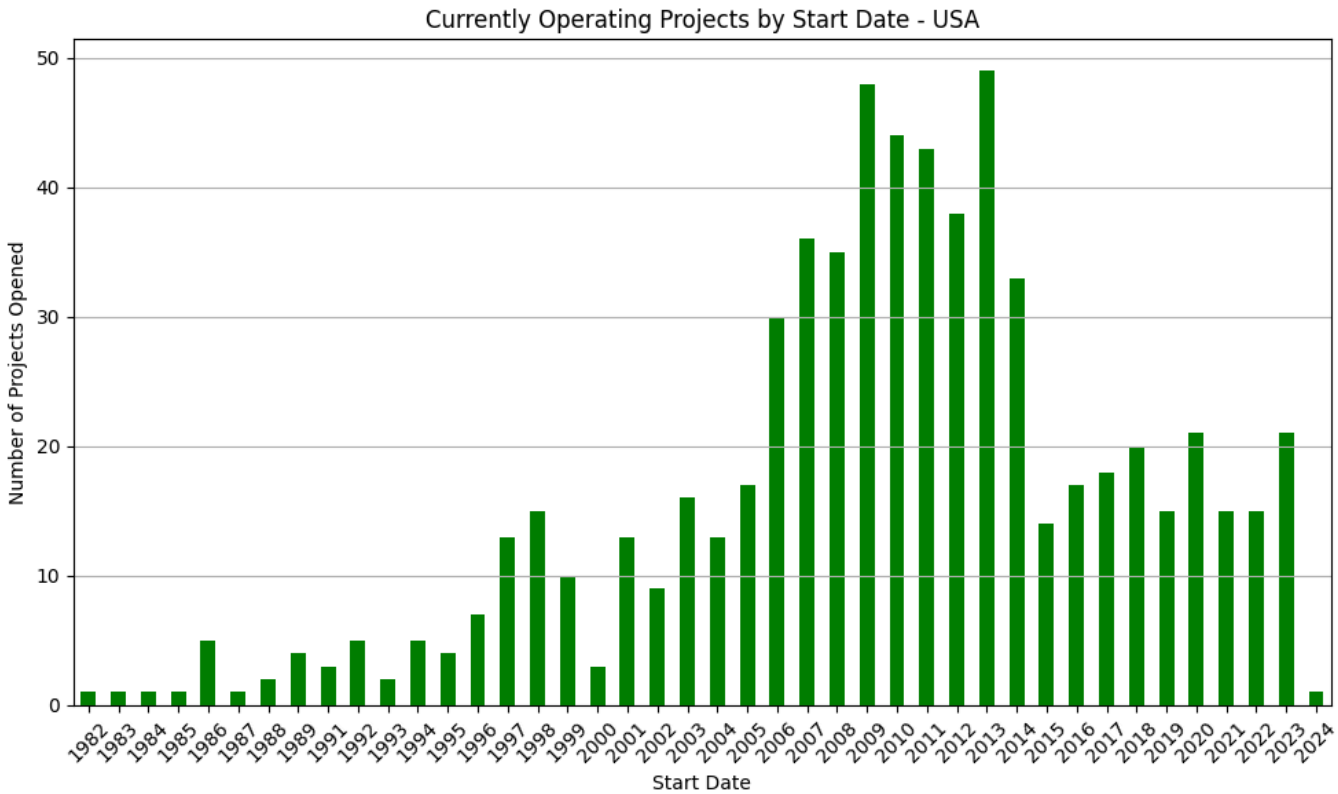
15
20
25
1980
1990
2000
2010
2020
Year Opened


Currently Operating Projects by Start Date - USA
Number of Projects Opened
Start Date
0
10
20
30
40
50
1982
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1988
1989
1991
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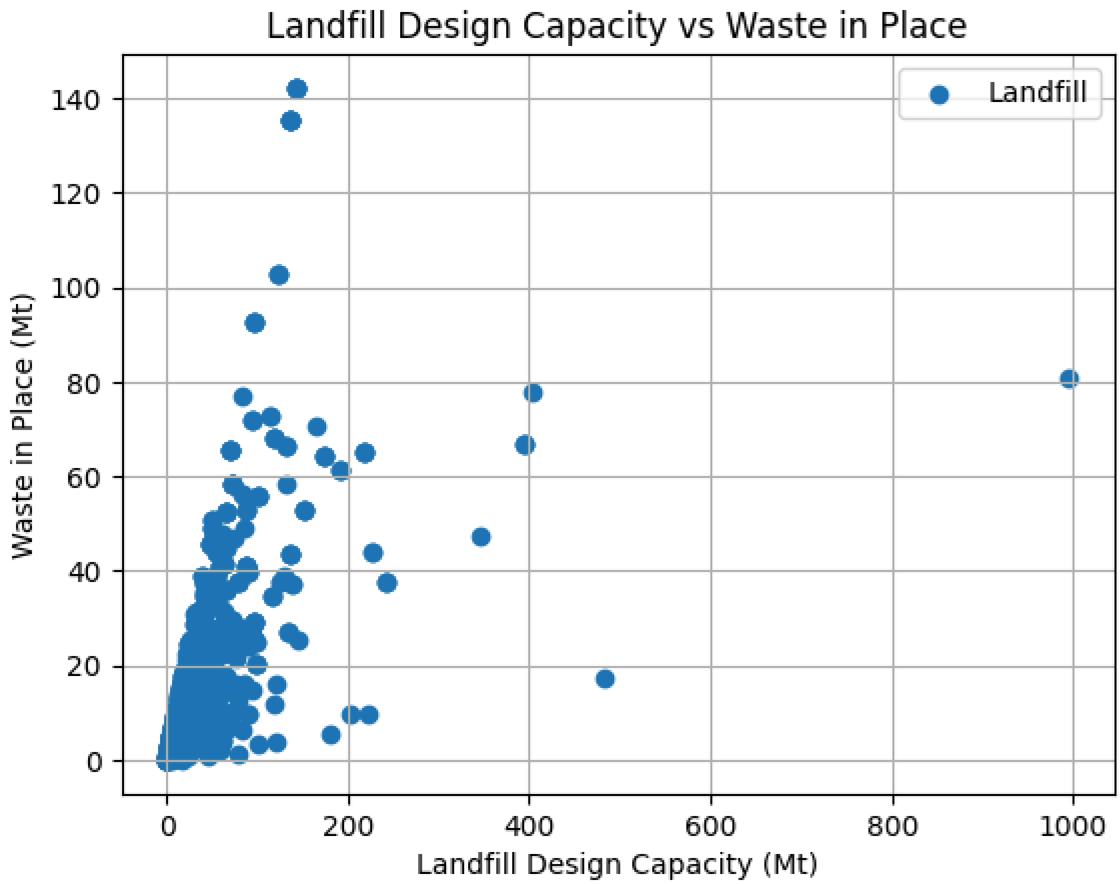
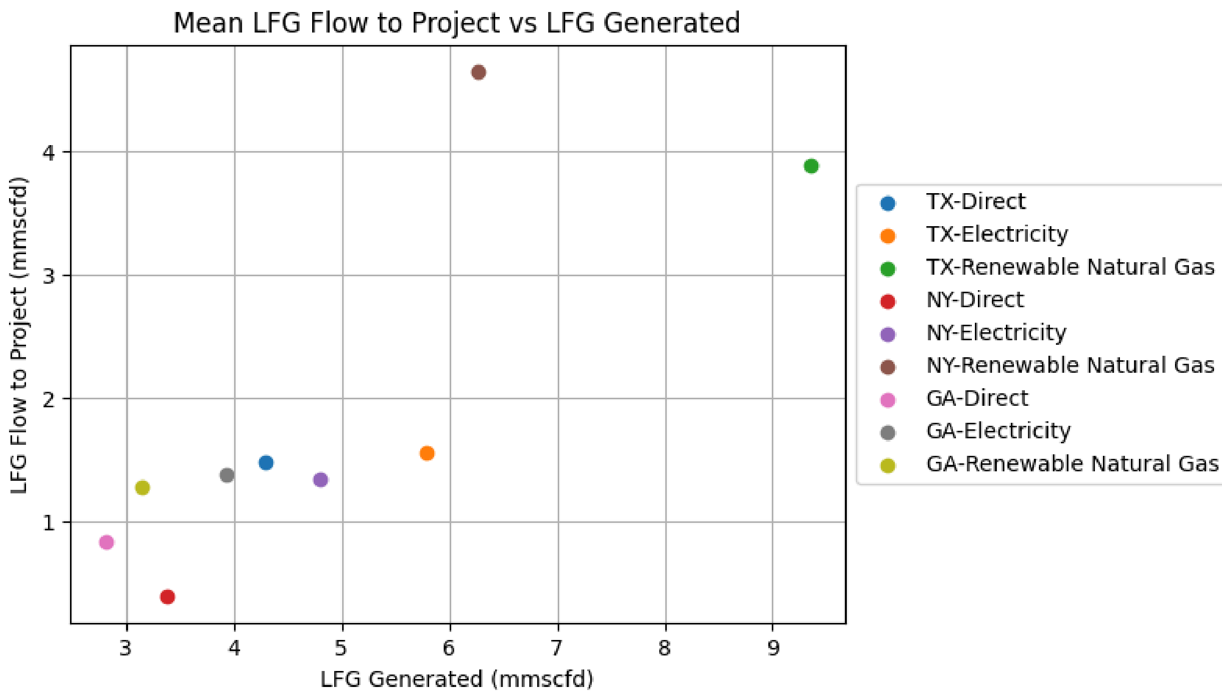
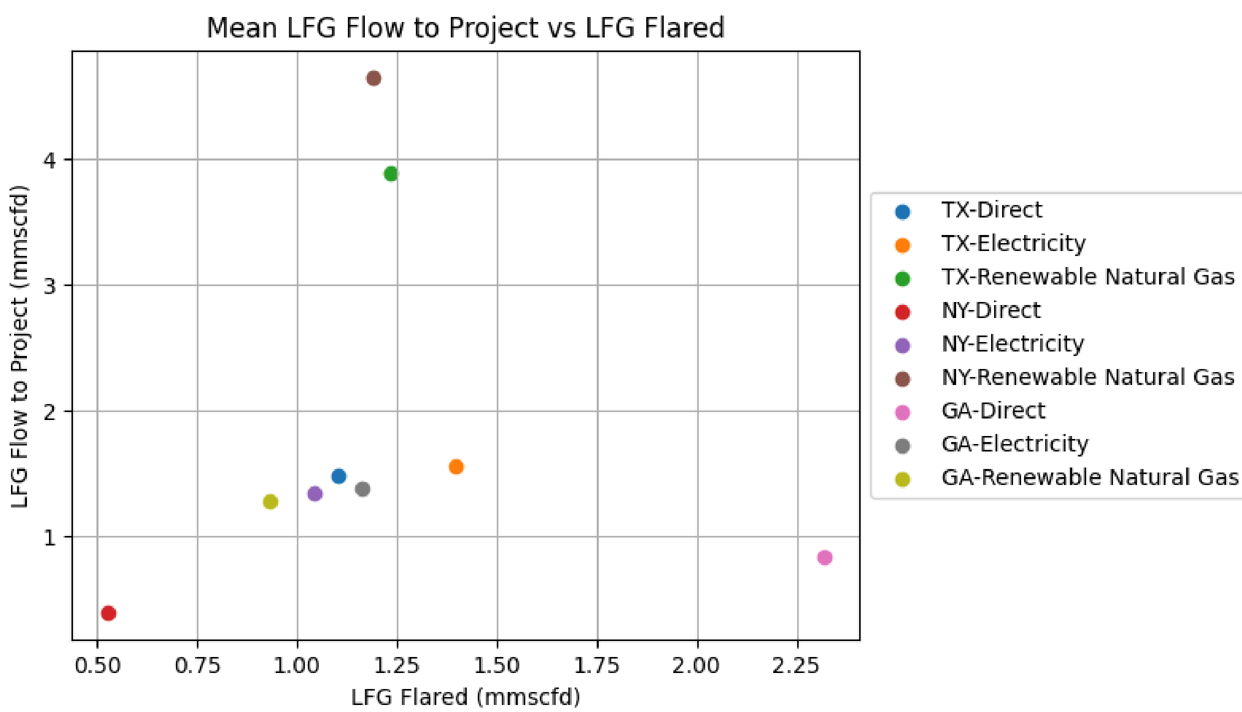
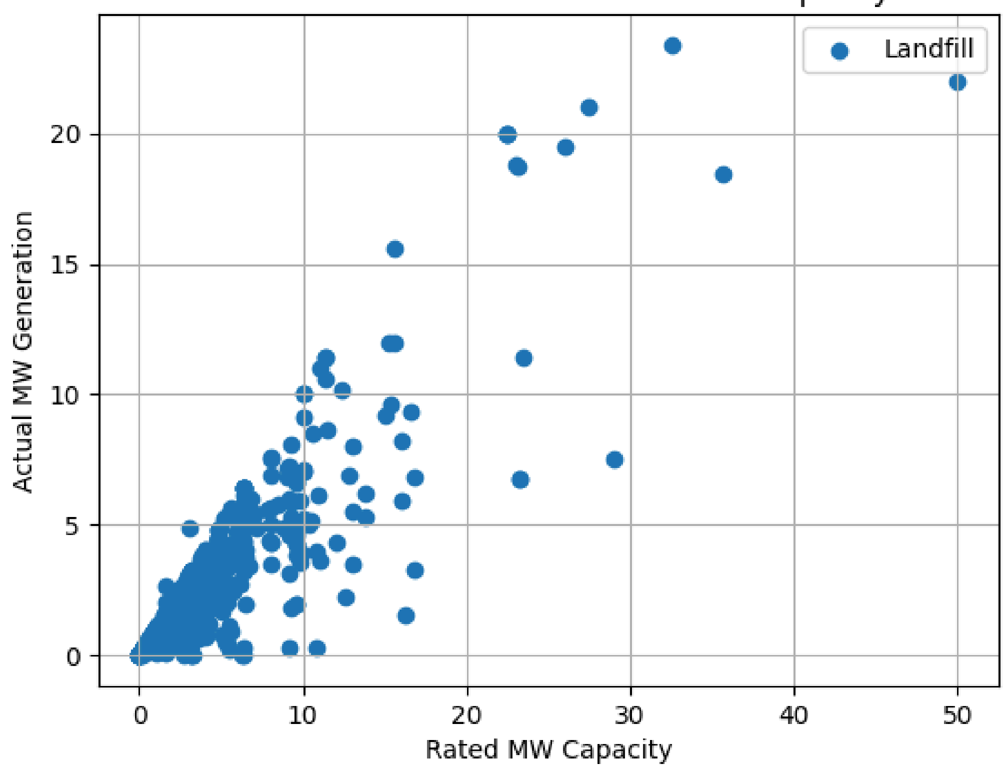

Landfill Design Capacity vs Waste in Place
Landfill
Waste in Place (Mt)
Landfill Design Capacity (Mt)
0
20
40
60
80
100
120
140
0
200
400
600
800
1000

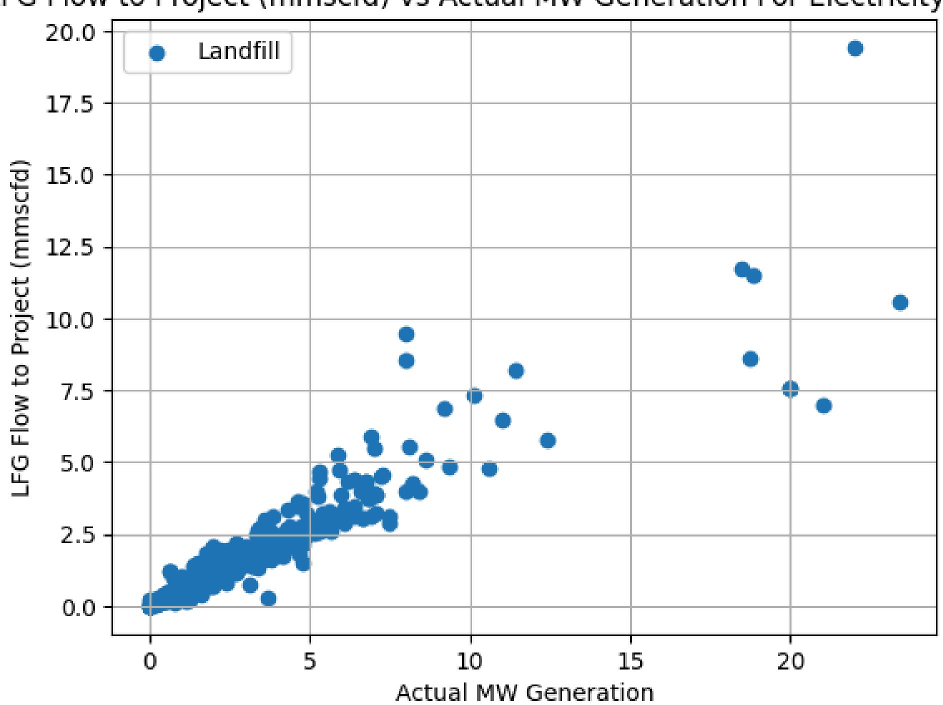

Mean LFG Flow to Project vs LFG Generated
LFG Flow to Project (mmscfd)
LFG Generated (mmscfd)
1
2
3
4
3
4
5
6
7
8
9
TX-Direct
TX-Electricity
TX-Renewable Natural Gas
NY-Direct
NY-Electricity
NY-Renewable Natural Gas
GA-Direct
GA-Electricity
GA-Renewable Natural Gas

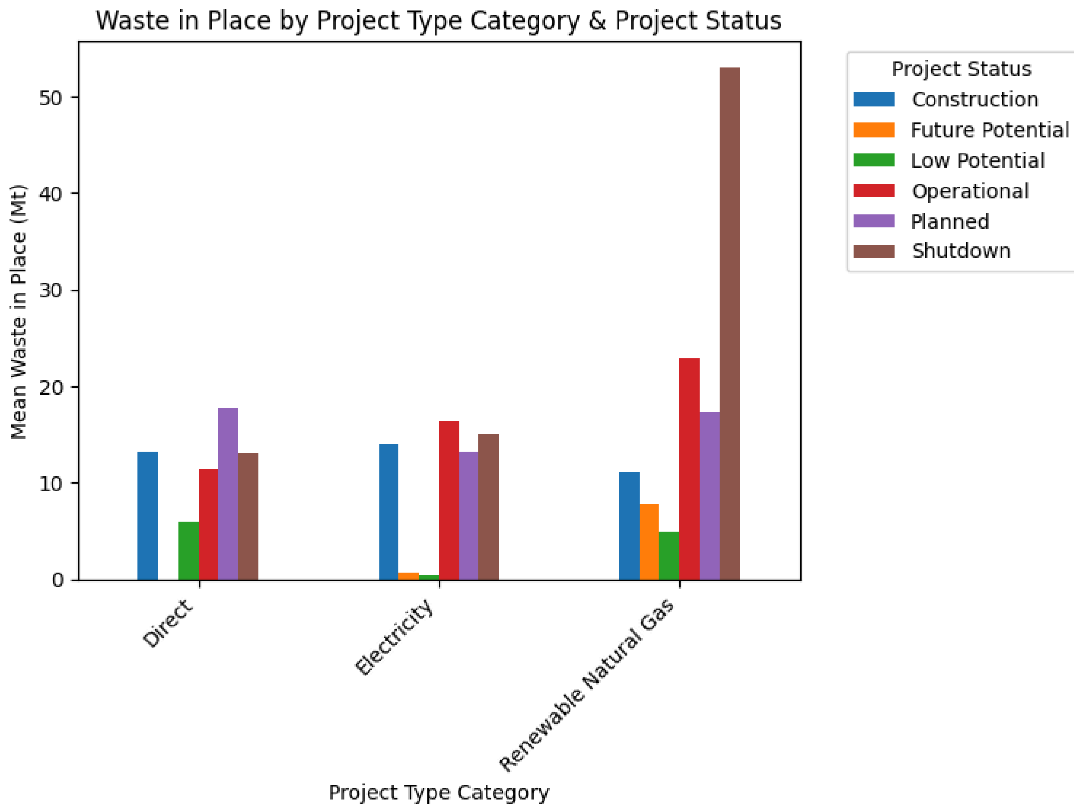

Mean LFG Flow to Project vs LFG Flared
LFG Flow to Project (mmscfd)
LFG Flared (mmscfd)
1
2
3
4
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
TX-Direct
TX-Electricity
TX-Renewable Natural Gas
NY-Direct
NY-Electricity
NY-Renewable Natural Gas
GA-Direct
GA-Electricity
GA-Renewable Natural Gas

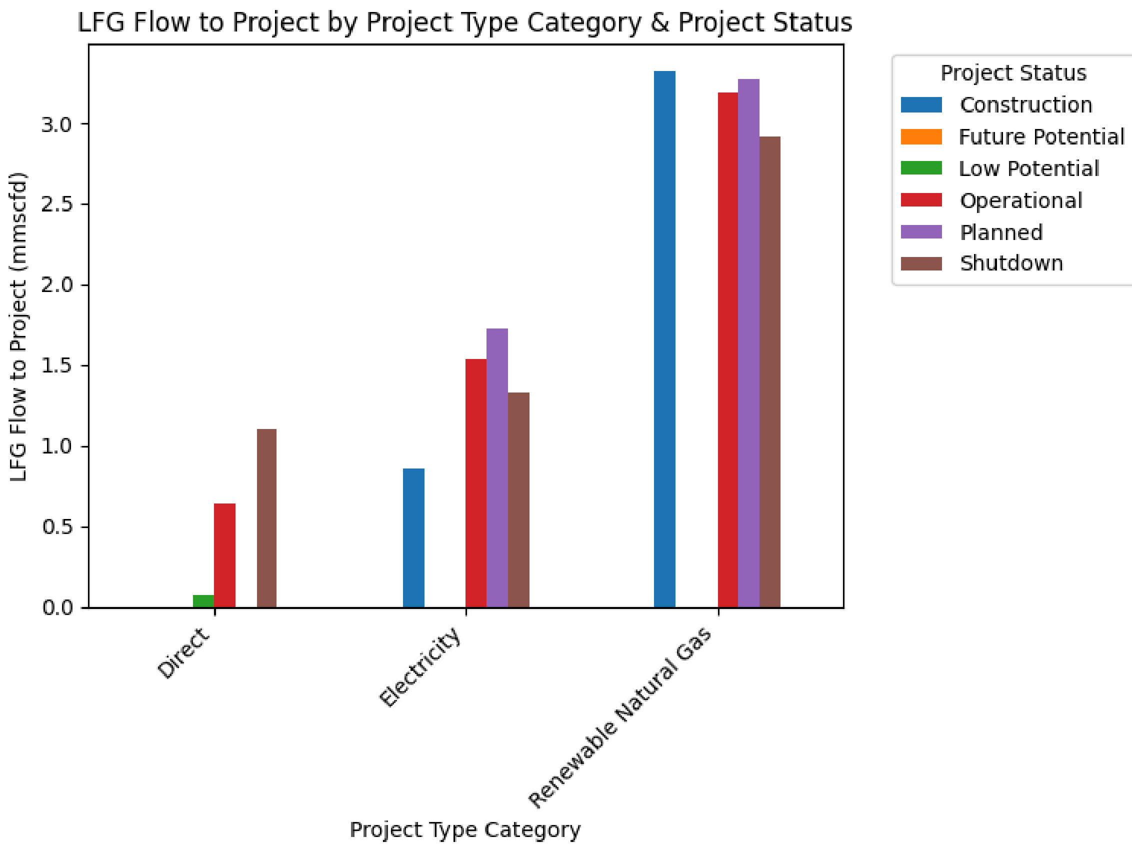
Actual MW Generation vs Rated MW Capacity



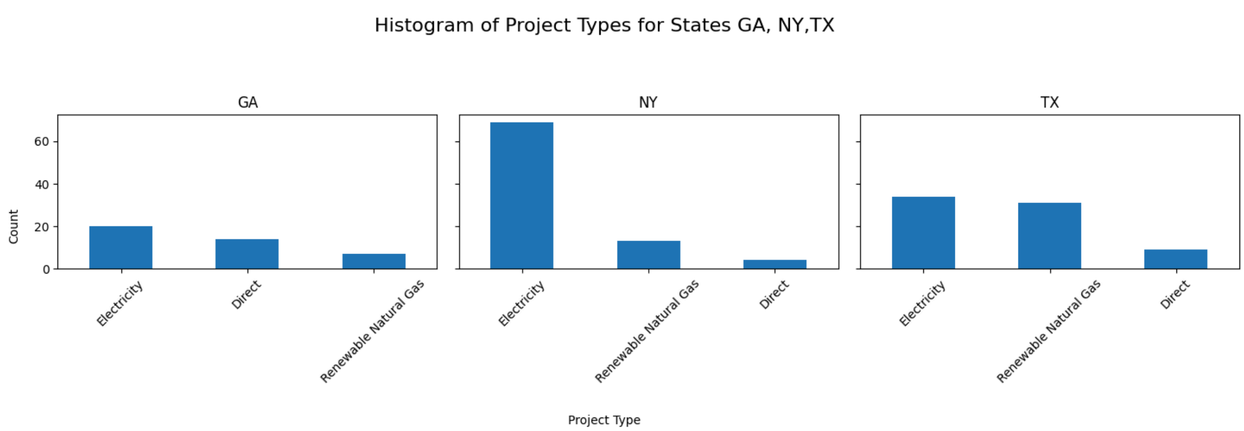
LFG Flow to Project (mmscfd) vs Actual MW Generation For Electricity Projects



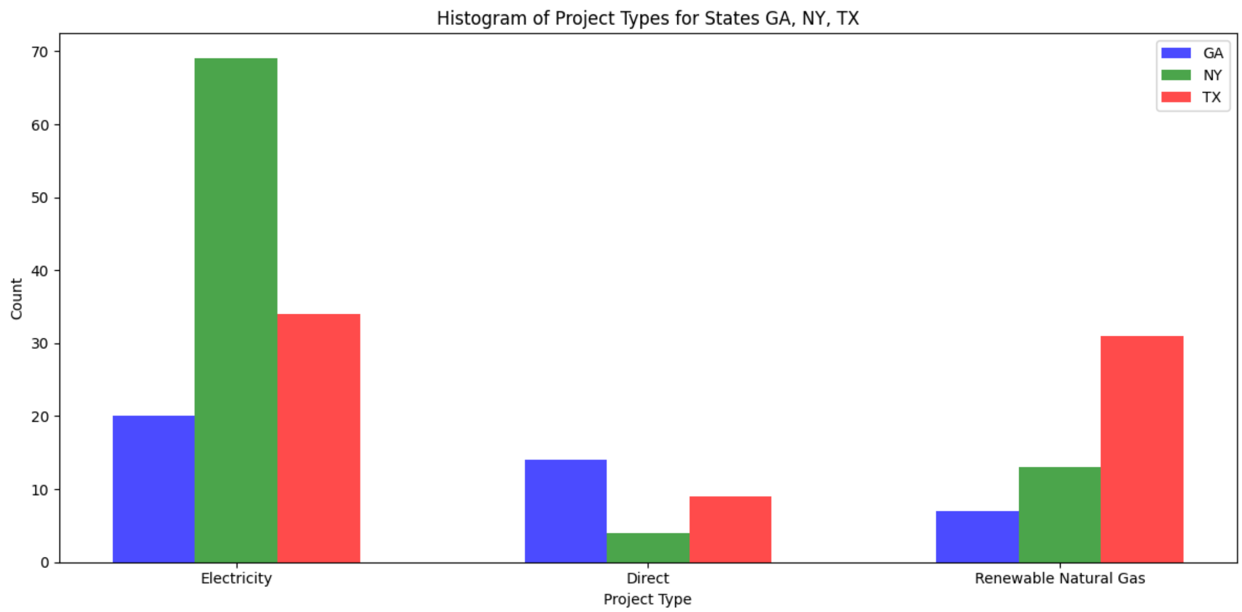

Waste in Place by Project Type Category & Project Status
Mean Waste in Place (Mt)
0
10
20
30
40
50
Direct
Electricity
Renewable Natural Gas
Project Type Category
Project Status
Construction
Future Potential
Low Potential
Operational
Planned
Shutdown



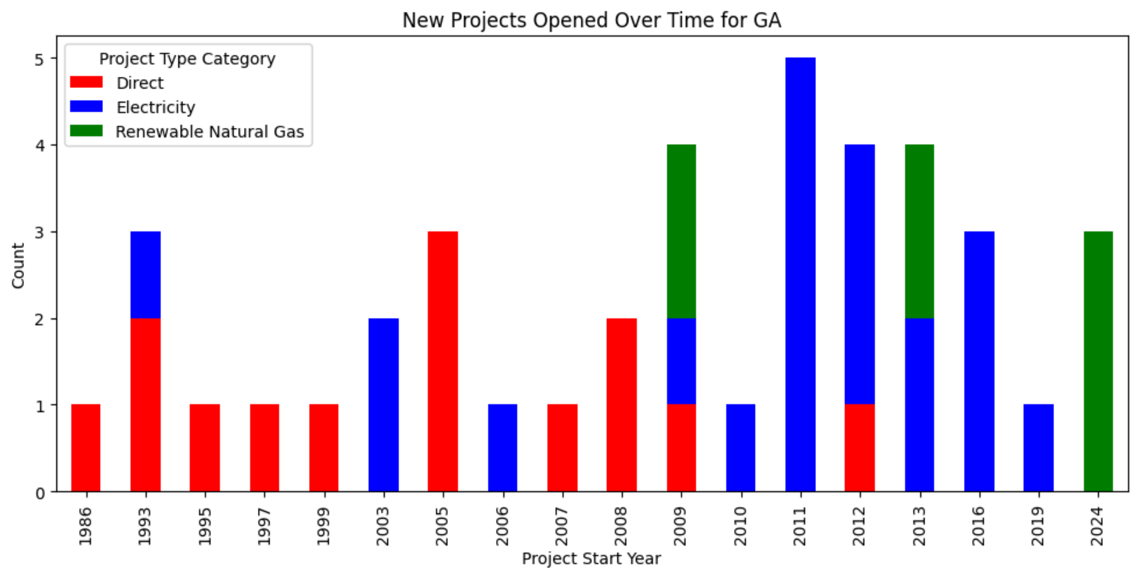
LFG Flow to Project by Project Type Category & Project Status
LFG Flow to Project (mmscfd)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Direct
Electricity
Renewable Natural Gas
Project Type Category
Project Status
Construction
Future Potential
Low Potential
Operational
Planned
Shutdown

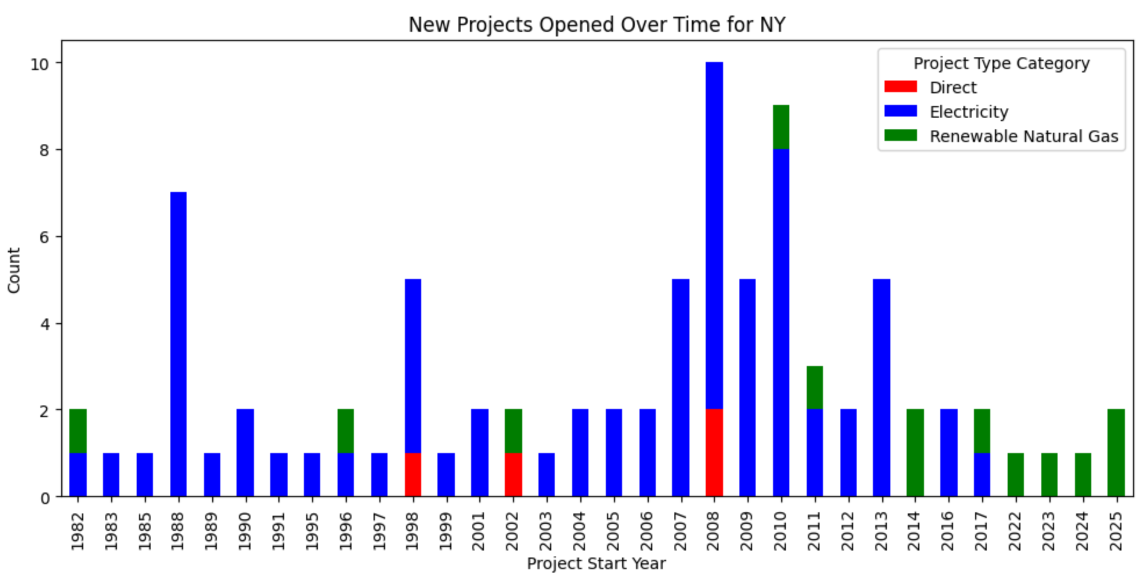


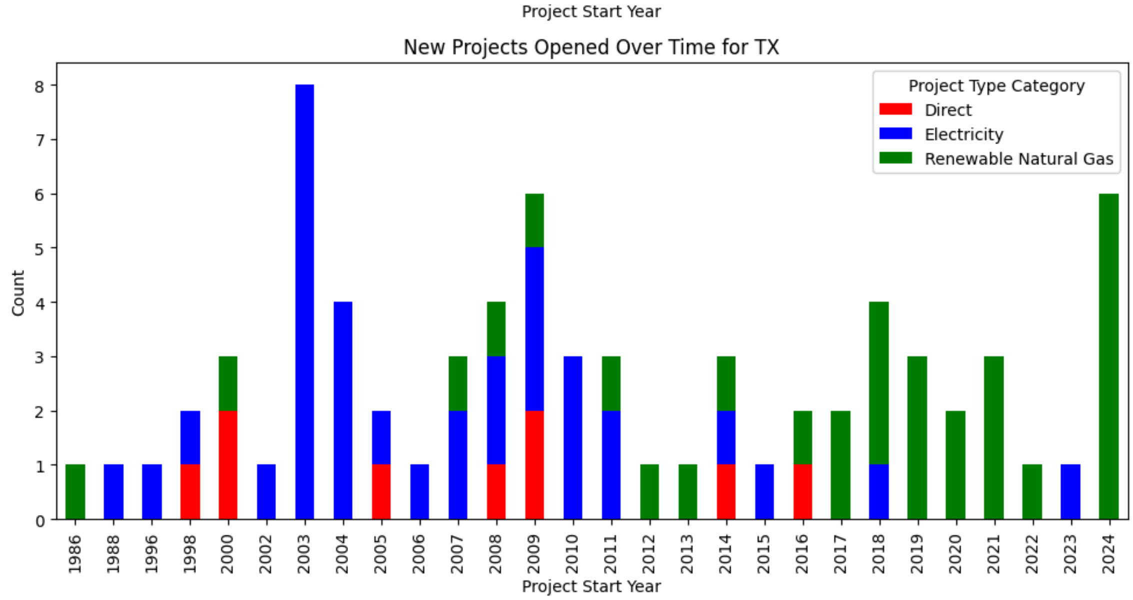
Histogram of Project Types for States GA, NY,TX
GA
NY
TX
Count
0
20
40
60
Electricity
Direct
Renewable Natural Gas
Electricity
Renewable Natural Gas
Direct
Electricity
Renewable Natural Gas
Direct
Project Type



Histogram of Project Types for States GA, NY, TX
GA
NY
TX
Count
70
60
50
40
30
20
10
0
Electricity
Direct
Renewable Natural Gas
Project Type


New Projects Opened Over Time for GA
Project Type Category
Direct
Electricity
Renewable Natural Gas
Count
Project Start Year
1986
1993
1995
1997
1999
2003
2005
2006
2007
2008
2009
2010
2011
2012
2013
2016
2019
2024


New Projects Opened Over Time for NY
Project Type Category
Direct
Electricity
Renewable Natural Gas
Count
Project Start Year


New Projects Opened Over Time for TX
Project Type Category
Direct
Electricity
Renewable Natural Gas
Count
Project Start Year

Appendix D – Batch LCOE Calculations Script

```
clc; clear all; close all; format shortE



%LCOE Calculations

Data = readtable('cleaned 1_LCOE_forCalcs_modV_Pipe.xlsx'); %'cleaned
1_LCOE_forCalcs.xlsx'

 Life_times = {'Avg_Project_Lifetime', 'Optimistic_Lifetime'};
 LCOEs = {'avg', 'opt'};

for i = 1:3386

   LCOE_3_avg(i,1) = 0; LCOE_3_opt(i,1) = 0;
   LCOE_7_avg(i,1) = 0; LCOE_7_opt(i,1) = 0;


 for p = 1:2

    Num_3 = 0;
    Num_7 = 0;

    Den_3 = 0;
    Den_7 = 0;

    if Data.(Life_times{p})(i) > 0
        for ii = 1:round(Data.(Life_times{p})(i))

            Num_3 = Data.OPEX_year(i)./((1+0.03).^ii) + Num_3;
            Num_7 = Data.OPEX_year(i)./((1+0.07).^ii) + Num_7;

            Den_3 = Data.Production(i)./((1+0.03).^ii) + Den_3;
            Den_7 = Data.Production(i)./((1+0.07).^ii) + Den_7;
        end

        if p == 1
            LCOE_3_avg(i,1) = (Data.CAPEX(i) + Num_3)./(Den_3);
            LCOE_7_avg(i,1) = (Data.CAPEX(i) + Num_7)./(Den_7);
        else
            LCOE_3_opt(i,1) = (Data.CAPEX(i) + Num_3)./(Den_3);
            LCOE_7_opt(i,1) = (Data.CAPEX(i) + Num_7)./(Den_7);
        end
    end %end if


end % end of loop
%
    if str2num(Data.PLantUseCheck{i}) == 1
        if str2num(Data.Plant_Usage{i}) <= 0.02
```

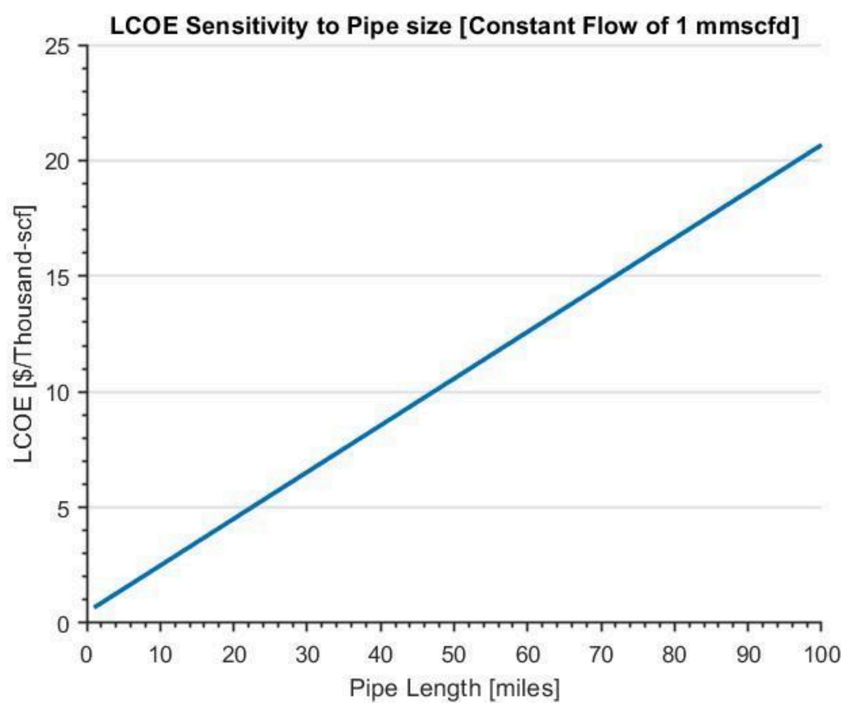
```
            LCOE_7_opt(i,1) = NaN; LCOE_3_opt(i,1) = NaN;
            LCOE_7_avg(i,1) = NaN; LCOE_3_avg(i,1) = NaN;
        end
    end


end

LCOEs = [LCOE_3_avg, LCOE_7_avg, LCOE_3_opt, LCOE_7_opt];
LCOEs(isinf(LCOEs)) = NaN;
LCOE_tabl = array2table(LCOEs,"VariableNames", {'LCOE_3_avg', 'LCOE_7_avg',
'LCOE_3_opt', 'LCOE_7_opt'});
```

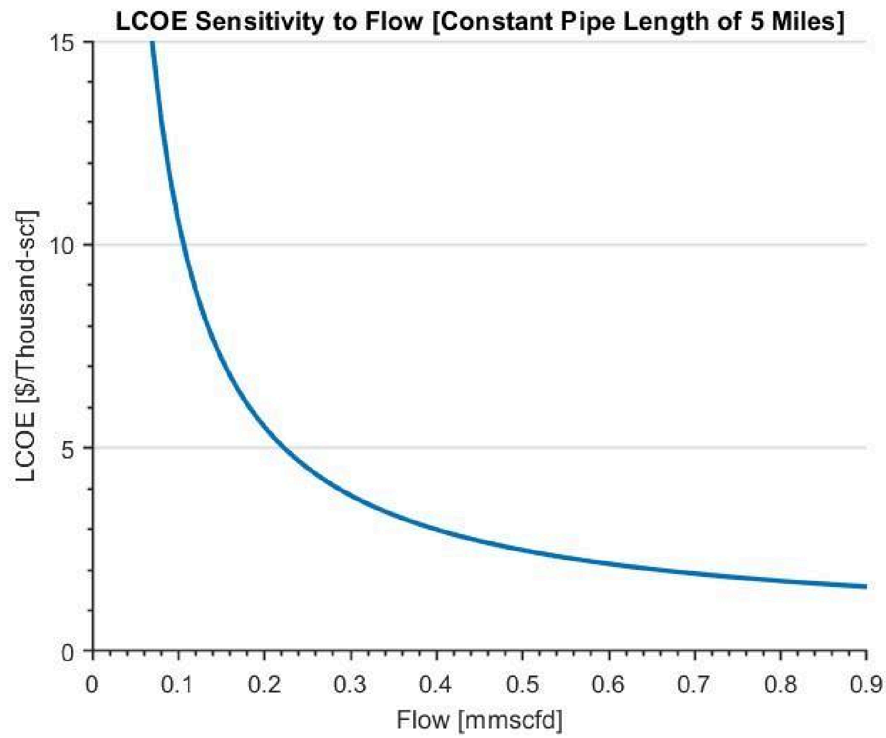
Appendix E – Direct Heat Sensitivity Script (with Images)

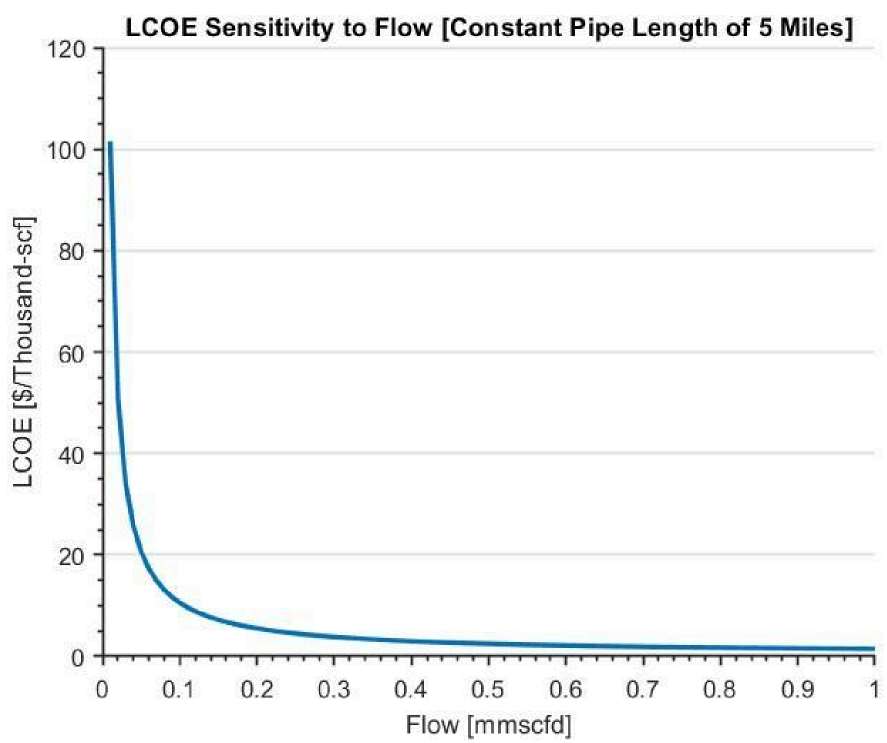
```
clc; clear all; close all


CAPEX_direct = 739583.33; %$/mmscfd
CAPEX_pipe = 880700; %$/mile
OPEX = 107638.89; %$/mmscfd-year
r = 3; % -
LF = 15; %years

NG_price = 4.6;

flow = 0.1:.01:6.2; %mmscfd [flow vector to step through]


for i = 1:length(flow)

    dif = 100;
    pipe = 150; %miles
    d_pipe = .1;

    while dif > 0.001
        pipe = pipe-d_pipe;
        LCOE = Direct_LCOE(CAPEX_direct,CAPEX_pipe,OPEX,r,LF,flow(i),pipe);
        dif = LCOE-NG_price;


    end

    pipe_final(i) = pipe;

end

%% Plot
figure (1)
plot(flow, pipe_final, 'LineWidth', 2)
title('Optimal Flow vs Pipe Length to Achieve LCOE of 4.6 $/Thousand-scf')
xlabel('Flow [mmscfd]')
ylabel('Pipe Length [miles]')

set(gca, 'Box', 'off', 'TickDir', 'out', ...
    'XMinorTick', 'on', 'YMinorTick', 'on', 'YGrid', 'on', ...
     'LineWidth', 1)
hold off
%% Now a quick LCOE to Pipe Length sesnitivity study

pipes = 1:100;

flow_LCOE = 1; %mmscfd

for i = 1:length(pipes)
    LCOEs(i) = Direct_LCOE(CAPEX_direct,CAPEX_pipe,OPEX,r,LF,flow_LCOE,pipes(i));
```

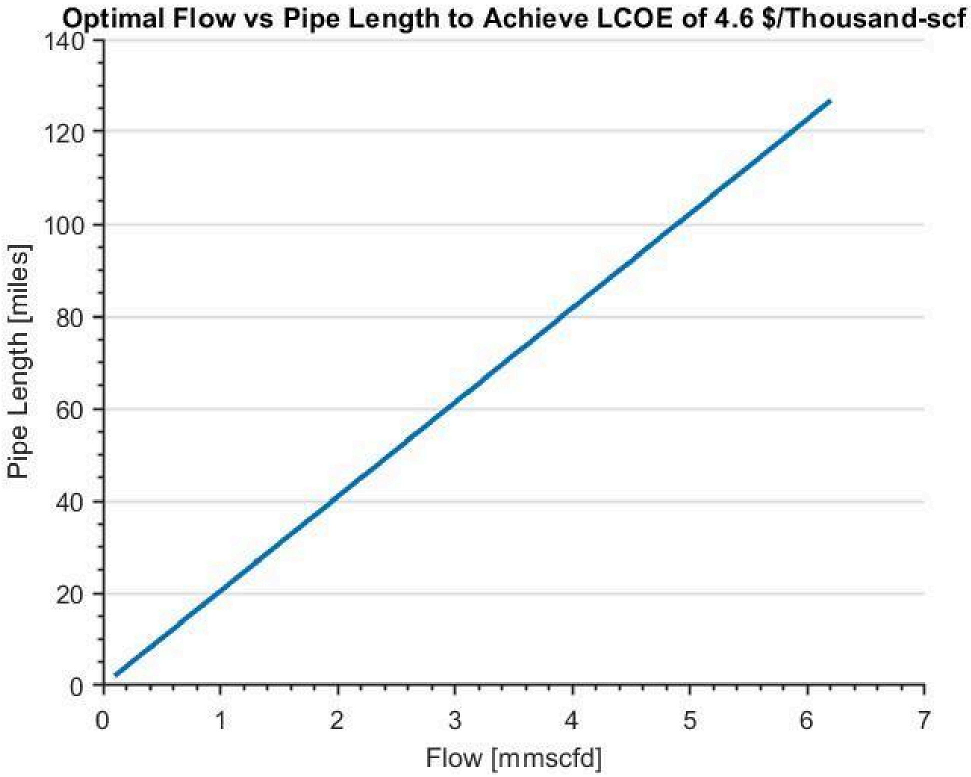
```
end

figure (2)
plot(pipes, LCOEs, 'LineWidth', 2)
title('LCOE Sensitivity to Pipe size [Constant Flow of 1 mmscfd]')
xlabel('Pipe Length [miles]')
ylabel('LCOE [$/Thousand-scf]')

set(gca, 'Box', 'off', 'TickDir', 'out', ...
    'XMinorTick', 'on', 'YMinorTick', 'on', 'YGrid', 'on', ...
     'LineWidth', 1)


%% Now one holding Pipelength constant and switching flow

flow_array = 0.01:0.01:1;

pipe = 5; %mmscfd

for i = 1:length(flow_array)
    LCOEs_flow(i) =
Direct_LCOE(CAPEX_direct,CAPEX_pipe,OPEX,r,LF,flow_array(i),pipe);
end

figure (3)
plot(flow_array, LCOEs_flow, 'LineWidth', 2)
title('LCOE Sensitivity to Flow [Constant Pipe Length of 5 Miles]')
xlabel('Flow [mmscfd]')
ylabel('LCOE [$/Thousand-scf]')

set(gca, 'Box', 'off', 'TickDir', 'out', ...
    'XMinorTick', 'on', 'YMinorTick', 'on', 'YGrid', 'on', ...
     'LineWidth', 1)


figure (4)
plot(flow_array, LCOEs_flow, 'LineWidth', 2)
title('LCOE Sensitivity to Flow [Constant Pipe Length of 5 Miles]')
xlabel('Flow [mmscfd]')
ylabel('LCOE [$/Thousand-scf]')

set(gca, 'Box', 'off', 'TickDir', 'out', ...
    'XMinorTick', 'on', 'YMinorTick', 'on', 'YGrid', 'on', ...
     'LineWidth', 1)
xlim([0, 0.9])
ylim([0, 15])

---------------------------
function LCOE = Direct_LCOE(CAPEX_direct, CAPEX_pipe, OPEX, r, LF, flow, pipe)
%Function to calculate the LCOE cost of a direct heat project
%Inputs: CAPEX [$/mmscfd]; CAPEX_pipe [$/ile]; OPEX [$/mmscfd-year]; r [%];
%LF [years], flow [mmscfd]; pipe [miles]

    %
    tot_CAPEX =flow*CAPEX_direct +pipe*CAPEX_pipe;
```

```
    num = 0; den = 0;
    for i = 1:LF
        num = (OPEX.*flow./((1+r./100).^i))+num;
        den = (flow.*365./((1+r./100).^i))+den;
    end

    LCOE = ((tot_CAPEX+num)./den)./1000;


End
```




LCOE Sensitivity to Flow [Constant Pipe Length of 5 Miles]
LCOE [$/Thousand-scf]
Flow [mmscfd]
0
5
10
15
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


LCOE Sensitivity to Flow [Constant Pipe Length of 5 Miles]
LCOE [$/Thousand-scf]
Flow [mmscfd]
0
20
40
60
80
100
120
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Optimal Flow vs Pipe Length to Achieve LCOE of 4.6 $/Thousand-scf
Pipe Length [miles]
Flow [mmscfd]
0
20
40
60
80
100
120
140
0
1
2
3
4
5
6
7