Strategies for Converting Landfill Gas to Renewable Energy and Reducing the Carbon Footprint: A Case Study of Southeast Texas

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List of Abbreviations

BTU	British Thermal Unit
CEPCI	Chemical Engineering Plant Cost Index
CF	Carbon footprint
CH_4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
EIQ	Emissions inventory questionnaire
EPA	Environmental Protection Agency
GHG	Greenhouse gases
GWP	Global warming potential
IRR	Internal rate of return
KWH	Kilowatt-hour
LandGEM	Landfill Gas Emissions Model
LFG	Landfill gas
LMOP	Landfill Methane Outreach Program
LNG	Liquefied natural gas
MSW	Municipal solid waste
N_2O	Nitrous oxide
NG	Natural gas
NMOC	Nonmethane organic compound
PPMV	Parts per million by volume
RNG	Renewable natural gas
SCF	Standard cubic feet
VOC	Volatile organic compound

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Abstract: Landfills contribute to climate change primarily through the release of GHGs, particularly CH_4 and CO_2, into the atmosphere. The U.S. EPA is actively engaged in efforts to minimize landfills' carbon footprint and promote renewable energy projects that harness LFG. This study investigates three LFG conversion strategies, flaring, electricity generation, and RNG in a case study of the Golden Triangle Landfill in Beaumont, Texas. Three scenarios of LFG emissions were simulated using the EPA's LFG Simulation Model. Notably, one scenario simulates an increase in the annual waste acceptance rate from 1993 to 2021, followed by a subsequent decrease from 2022 to 2040. The simulated values align closely with the 2021 real landfill data. Each strategy's equipment is designed to calculate capital investments, operational costs, carbon footprint reductions, and potential profits. The electricity generation strategy stands out by achieving profitability from its inaugural year of operation, even without carbon credit market trading or carbon tax credit profits. This strategy anticipates reaching its highest profit of $9,622,257 by 2035, based on an electricity price rate of $0.125/kWh. In contrast, the RNG strategy, while eventually profitable, requires a longer timeline to break even due to its higher initial investment. It becomes profitable in its tenth year without carbon credit market trading or carbon tax credit profits, or in its fifth year with carbon credit market trading (at $40/ton). The RNG strategy boasts the most substantial carbon footprint reduction, cutting 1,073,195 tons of emissions, equating to an 89% reduction rate by 2035. Meanwhile, the electricity generation and flaring strategies also contribute significantly, reducing carbon footprints by 997,272 tons with an 83% reduction rate by 2035. This study underscores the vast untapped potential within landfills, particularly in converting their emissions into electricity, from both economic and environmental standpoints.

Keywords: Landfill gas; Renewable energy; Carbon footprint reduction; Capital; Cost; Profit

1. Introduction

A landfill is a carefully engineered site designated for the disposal of solid waste materials, both household and industrial, which are no longer useful or safe for regular recycling or disposal methods. Landfills are an essential component of waste management systems in many countries worldwide, providing a means to contain and manage the ever-growing volume of waste generated by human activities [1]. MSW Landfills are the most common type of landfill and accept household garbage, non-hazardous waste from businesses, and construction debris. MSW Landfills, often depicted as the byproduct of human consumption and waste, hold within them a concealed resource with the potential to address both environmental challenges and our energy requirements.

LFG is a gaseous mixture that forms within landfills as a result of the decomposition of organic waste materials. It primarily consists of CH_4 and CO_2, along with traces of other gases such as VOCs and small amounts of nitrogen, oxygen, and hydrogen [2] as shown in Figure 1. In addition, CH_4 is a potent GHG at least 25 times more effective than CO_2 at trapping heat in the atmosphere over a 100-year period [3]. Its release into the atmosphere contributes to global warming and climate change.

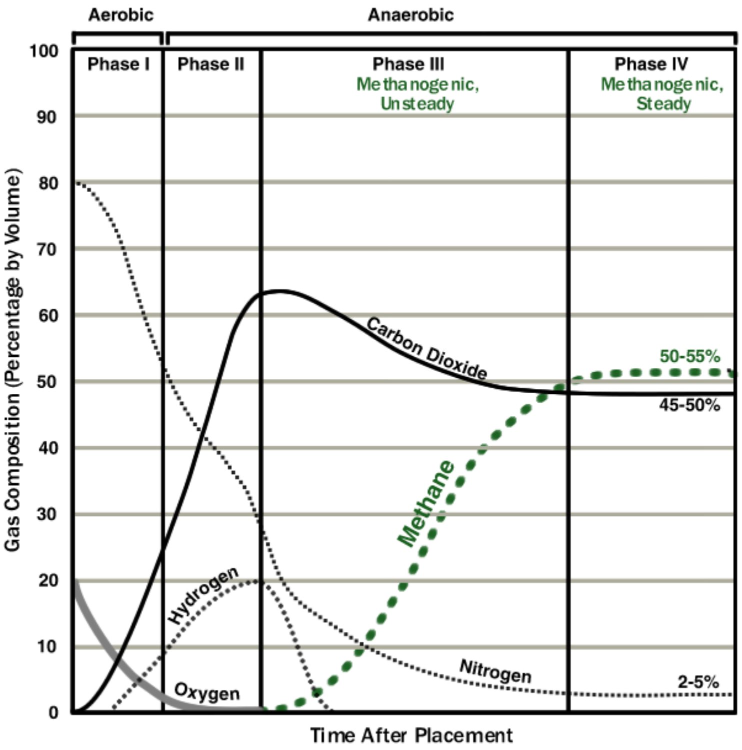


Figure 1. The Changes in Typical LFG Composition after Waste Placement [2]

Global warming and climate change refer to the long-term alterations in Earth's average temperature and weather patterns. These changes have far-reaching impacts on both the environment and humanity. Rising temperatures lead to the melting of polar ice caps and glaciers, causing sea levels to rise and resulting in coastal flooding. Extreme weather events, such as hurricanes, droughts, and heatwaves, become more frequent and severe, threatening ecosystems and agriculture. Climate change also disrupts ecosystems, endangering plant and animal species, and affects human health through increased heat-related illnesses, disease spread, and food and water shortages.

In the United States, MSW Landfills ranked as the third-largest contributor to human-generated CH_4 emissions in 2021, comprising roughly 14.3 percent of these emissions, as shown in Figure 2. This quantity of CH_4 released from MSW landfills during that year was roughly equivalent to the GHG emissions produced by nearly 23.1 million gasoline-powered passenger vehicles driven for a full year or the CO_2 emissions from the energy consumption of nearly 13.1 million homes over the same period. At the same time, CH_4 emissions from MSW landfills represent a lost opportunity to capture and use a significant energy resource.

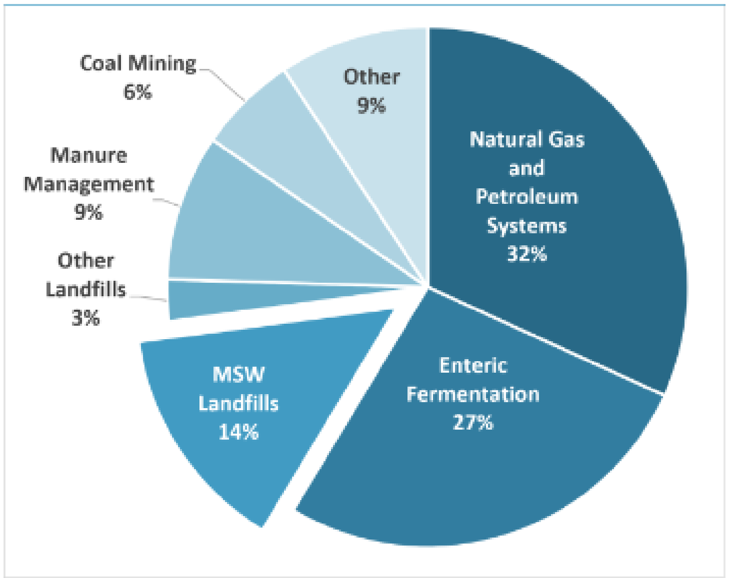


Figure 2. 2021 U.S. Methane Emissions, By Source [4]

The carbon footprint refers to the total amount of greenhouse gases, primarily CO_2 and other gases like CH_4 and N_2O, that are emitted into the atmosphere as a result of human activities, such as energy production, transportation, manufacturing, and waste management. It is typically measured in units of CO_{2e}, which express the total warming impact of all GHGs in terms of their equivalent effect on climate change [5].

Reducing the carbon footprint in landfills is of paramount importance for these reasons. Landfills are notable sources of CH_4 emissions, and mitigating these emissions significantly contributes to the global effort to combat climate change. Beyond environmental protection, reducing CH_4 emissions improves air quality, mitigates odors, reduces the risk of explosions in landfills, and mitigates health risks, fostering healthier and more pleasant living conditions for nearby communities. Moreover, this reduction unlocks the potential to harness valuable CH_4 as a clean energy resource, diminishing reliance on fossil fuels and promoting resource conservation. Compliance with regulatory standards and the principles of sustainable waste management underscore the significance of this endeavor, emphasizing landfill facilities as opportunities for responsible waste handling, resource recovery, and environmental stewardship. Ultimately, the pursuit of reduced carbon footprints in landfills aligns with global responsibility, reflecting a commitment to addressing pressing environmental challenges and advancing a more sustainable and resilient future for all [6].

The LMOP is a voluntary program in the United States administered by the EPA [7]. LMOP's primary goal is to reduce CH_4 emissions from landfills, promote the beneficial use of methane as a valuable energy resource, and mitigate the environmental impact of CH_4. By partnering with landfill owners, operators, and stakeholders, LMOP strives to curtail methane release through the implementation of state-of-the-art capture and control technologies. Moreover, LMOP's extensive technical assistance, public awareness campaigns, and collaborative partnerships further amplify its positive impact, ensuring that the program continues to be an essential catalyst in transforming landfills from environmental liabilities into sources of clean energy and environmental responsibility.

There are many options available for converting LFG into energy. Different types of LFG energy projects are grouped below into three broad categories – Electricity Generation, Direct Use of Medium-Btu Gas, and RNG [2], as shown in Figure 3.

LFG is used for electricity applications because of its relatively low cost, high efficiency and size ranges that complement the gas output of many landfills. A variety of technologies, including reciprocating internal combustion engines, turbines, microturbines and fuel cells, can be used to generate electricity for onsite use and/or sale to the grid. In smaller-scale landfill gas-to-energy projects, internal combustion engines are commonly used. These engines burn methane gas to drive a generator, producing electricity. These systems are dependable and relatively simple, making them suitable for smaller landfills. Larger landfills with higher gas production may use gas turbines. These turbines operate at higher temperatures and are more efficient than gas engines. They produce electricity by expanding the hot, high-pressure gas through a turbine to drive a generator. Moreover, cogeneration, also known as CHP, projects use LFG to generate both electricity and thermal energy, usually in the form of steam or hot water [2].

LFG can be used directly to substitute or supplement other fuels like natural gas, coal, or fuel oil. This involves channeling LFG to nearby facilities where it serves as a direct fuel source for boilers, dryers, kilns, greenhouses, and various thermal applications. The versatility of LFG extends to evaporating leachate, making it a practical solution for landfills where traditional leachate disposal methods are unavailable or cost prohibitive. LFG combustion may provide a more accessible method for leachate evaporation in these cases. Moreover, innovative applications of medium-Btu gas encompass a wide array of industries, including pottery and glass-blowing kilns, greenhouse heating, and waste paint evaporation. Current sectors benefiting from LFG integration range from auto manufacturing, chemical production, and food processing to pharmaceuticals, cement production, and wastewater treatment, underscoring its diverse utility in promoting sustainable and eco-friendly practices across numerous sectors [2].

LFG holds the potential to undergo treatment processes that elevate its methane content while reducing its CO_2, nitrogen, oxygen, and steam components, thereby transforming it into RNG, a high-Btu gas. RNG can seamlessly replace fossil natural gas and finds applications as pipeline-quality gas, CNG, or LNG. The utilization avenues for RNG are diverse, spanning thermal applications, electricity generation, and vehicle fuel. RNG can be employed on-site at the landfill where it originates or introduced into natural gas transmission and distribution networks for transportation to alternative locations. This transformation of LFG into RNG represents a sustainable and eco-conscious approach, offering clean energy alternatives and contributing to reduced greenhouse gas emissions sectors [2].

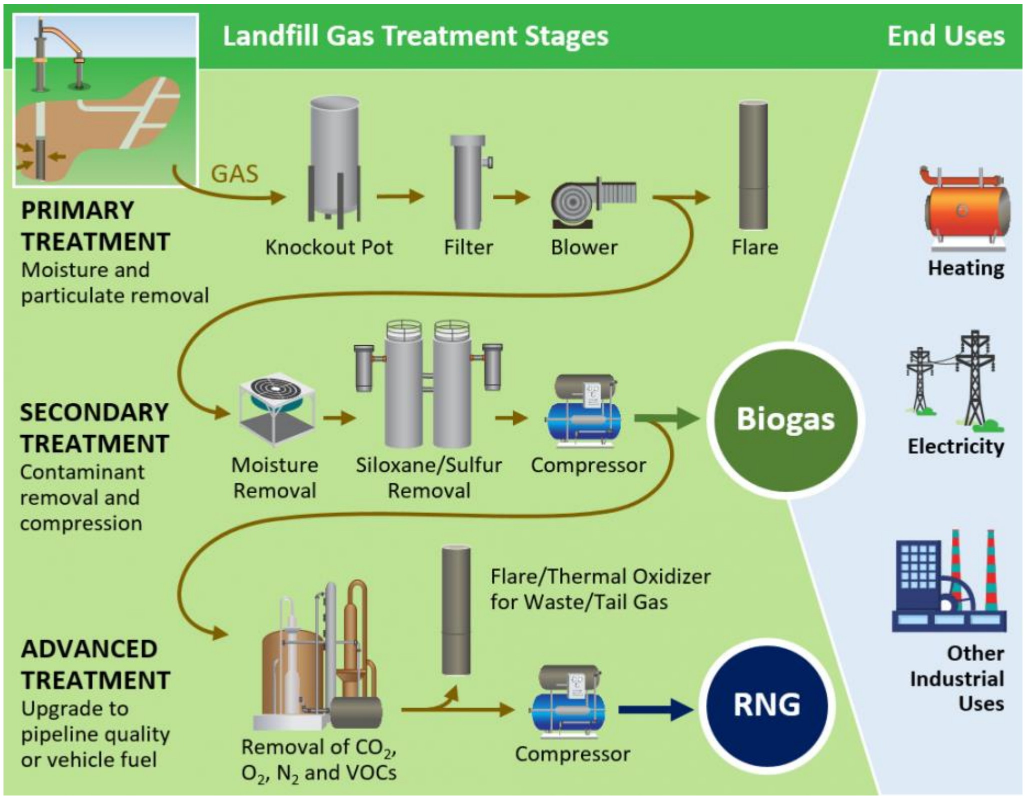
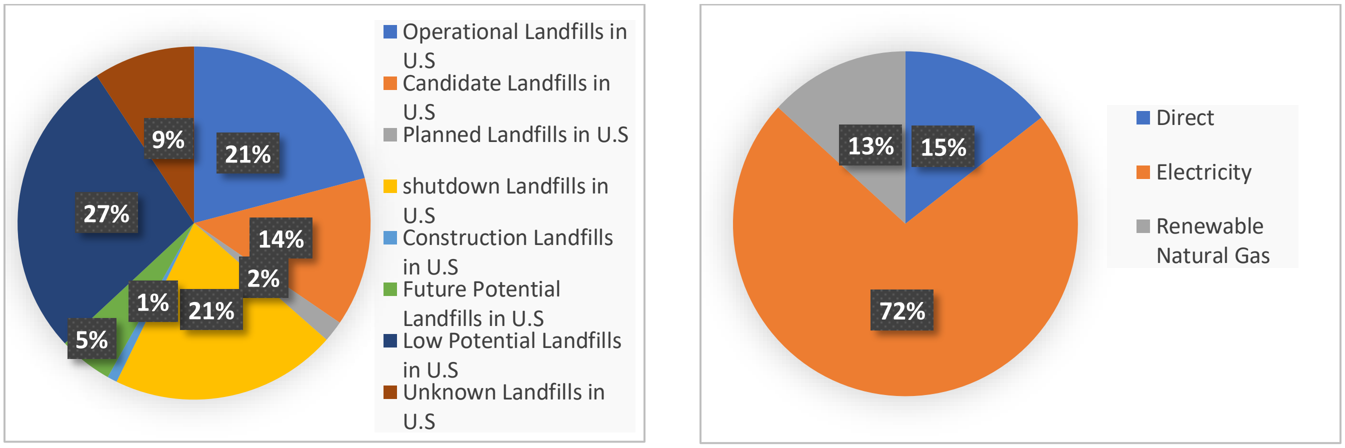


Figure 3. Three Stages of Landfill Gas Treatment [8]

In Figure 4(a), it is evident that low potential landfills (951) account for approximately 27% of the total landfills in the U.S., indicating that slightly over one-quarter of the landfills lack the feasibility for methane renewable energy development, potentially missing utilizing this valuable energy resource for industrial and residential purposes. In contrast, operational landfills (719) make up about 21% of the total U.S. landfills, indicating that they are already harnessing methane for renewable energy generation. Furthermore, candidate landfills (470), future potential landfills (170), planned landfills (67), and construction landfills (31) collectively represent 22% of all landfills in the U.S., equivalent to the proportion occupied by operational landfills. This suggests that these potential landfill sites hold promise for future methane capture and reduction initiatives. There is still untapped potential within this group of landfills to reduce methane emissions and exploit the available space for further development and sustainability efforts in waste management.

Moreover, it becomes evident that almost three-quarters of landfill projects prioritize electricity generation strategy, underscoring its prominence as the primary approach for methane utilization, as shown in Figure 4(b). The utilization of Medium-Btu Gas for direct use and the RNG production both correspond to identical percentages, signifying an equitable distribution in the adoption of these alternative strategies.

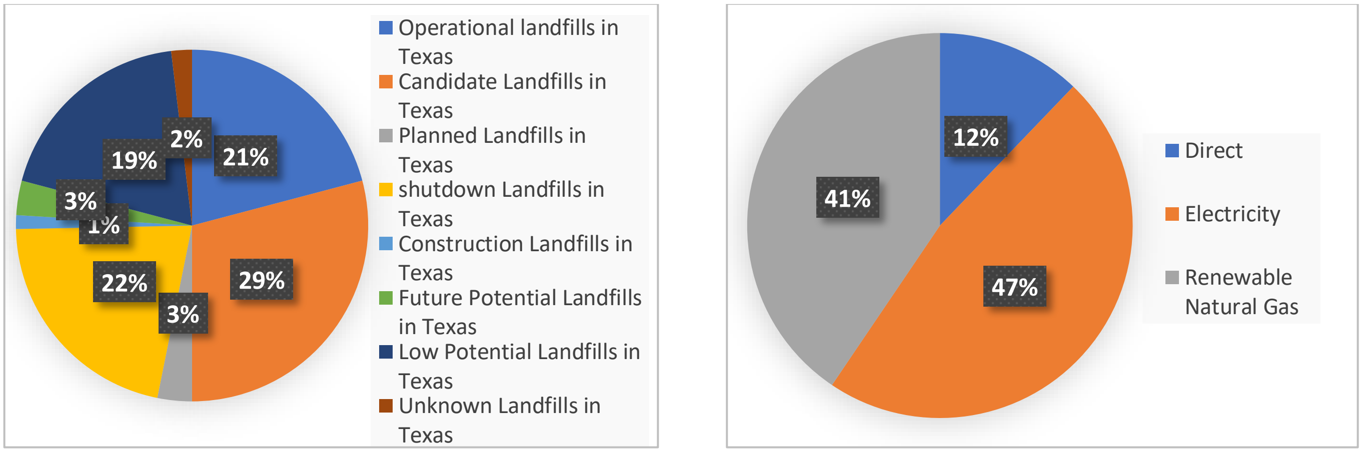


(a) The Percentage of Current Landfill Status in U.S. (b) Percentage of Project Type Category in U.S.

Figure 4. 2022 U.S. Landfill Information, By Source [9]

In the state of Texas, low potential landfills, totaling thirty in number, constitute approximately 19% of the state's landfills, signaling that less than 20% of the landfills present challenges for methane energy harnessing, as shown in Figure 5(a). However, operational landfills, numbering thirty-three, account for approximately 21% of the total landfills in Texas, demonstrating their proactive engagement in harnessing methane for renewable energy generation. Additionally, the combined category of candidate landfills (46), future potential landfills (5), planned landfills (5), and construction landfills (2) collectively constitute 36% of all landfills in Texas. This proportion is 1.5 times greater than that occupied by operational landfills, signifying immense untapped potential within this cluster of landfills. These figures underscore a promising opportunity to reduce methane emissions significantly and maximize available space for further development, fostering sustainability in waste management practices throughout the state of Texas.

Furthermore, it is noteworthy that 47% of these projects prioritize electricity generation, while 41% opt for the RNG approach, as depicted in Figure 5(b). This showcases the prominence of RNG as the primary strategy for methane utilization in the state of Texas, emphasizing its significant contribution to the overall energy landscape in Texas. The allocation of resources towards RNG underscores its environmental benefits and economic viability as a clean fuel alternative, thereby contributing to both climate change mitigation and resource conservation efforts within Texas. Additionally, it is noteworthy that 12% of projects in Texas employ Medium-Btu Gas for direct use, mirroring the proportion seen at the national level. This reflects a diversified approach to methane utilization, catering to a range of industries and applications, promoting sustainable practices and energy innovation in the state.



(a) The Percentage of Current Landfill Status in Texas (b) Percentage of Project Type Category in Texas

Figure 5. 2022 Texas State Landfill Information, By Source [9]

In the economic policies, U.S. federal incentive programs, such as the 45Q carbon tax credit, play a pivotal role in the nation's portfolio of laws aimed at curbing GHG emissions. The 45Q program extends tax credits to entities that capture and store CO_2 or utilize it for enhanced oil recovery. These credits incentivize companies and industries to invest in technologies for capturing CO_2 emissions from various sources, including industrial facilities and power plants. By leveraging financial incentives and promoting technological innovation, federal policies like the 45Q carbon tax credit are essential components of the broader strategy to combat climate change and drive the transition towards a more sustainable and environmentally conscious future [10]. Furthermore, the commitment to battling climate change goes beyond federal regulations, with individual states supplementing these efforts with their own tailored programs. States have the flexibility to set carbon reduction goals, establish renewable energy portfolio standards, and support initiatives that enhance energy efficiency. Federal programs, coupled with state-level initiatives, encourage the adoption of renewable energy sources. Mechanisms like the Production Tax Credit and the Investment Tax Credit [10] provide crucial financial incentives for renewable energy projects, enhancing their economic viability and contributing to the expansion of the clean energy sector. This multipronged approach reflects the comprehensive strategy required to address climate change and underscores the pivotal role of government policies in ushering in a sustainable and environmentally conscious future.

In this project, we embark on a comprehensive investigation centered around a compelling case study: the Gloden Triangle Landfill located in southeastern Texas. Our aim is to delve into the intricacies of carbon footprint reduction strategies, capital investments, operational costs, and profitability associated with three distinct approaches: flaring, electricity generation, and RNG production. We recognize that each strategy presents a unique blend of environmental, economic, and operational factors. Furthermore, our analysis extends beyond the confines of pure sustainability by considering the crucial aspect of incentivization. We evaluate the carbon benefits of these strategies by harnessing the power of policy tools such as the 45Q carbon tax credits, which offer financial incentives for carbon capture and storage, and explore the potential of trading carbon credits within the market. By addressing these multifaceted dimensions, our project not only sheds light on the practical and financial implications of different landfill gas utilization strategies but also contributes to the broader conversation about fostering sustainable waste management practices and reducing the carbon footprint—an endeavor that holds immense significance in the context of environmental conservation, climate change mitigation, and the quest for a more sustainable and resilient future.

2. A Case Study of Southeast Texas

2.1 Background

In the process of looking for ways to reduce carbon emissions, it is important to consider pathways that can be profitable for investors. This is, of course, because investors care much more about making money than they do reducing carbon emissions. Additionally, a solution with a wide range of applications can have a greater overarching impact than an individualized one, even if it loses some efficacy in exchange. The easiest way to satisfy the first of these conditions is to use emissions to produce something that can be sold by the owner, be it electricity or purified gas.

Both of these can be produced from MSW landfills, of which there are over 2,600 across the United States [11]. Many of these are prime locations for the collection and conversion of emissions, as the systems used for these processes are already used in other projects. The question, then, is how to encourage adoption of these technologies in those landfills that do not already use them. One option is an economic analysis of each method of treatment following the collection of the gas, namely flaring, electricity generation, or RNG production. To do this, we decided to choose a landfill as the basis for our analysis, to ensure that our work was realistic and reasonable. The best choice was a landfill known as the Golden Triangle Landfill, a local landfill with a fairly average capacity that makes it perfect to serve as a general representation of landfills in the US.

The selection of the Golden Triangle Landfill for this project was based on a number of factors that collectively make it a perfect fit. Firstly, Beaumont is a coastal city in Southeast Texas, within the Beaumont–Port Arthur metropolitan statistical area and a population of 115,282 at the 2020 census [12]. Beaumont is home to Lamar University. There are 4 MSW landfills in the Beaumont–Port Arthur metropolitan, including three candidates in open status and one low potential with a closed status). Among these, only one candidate, the Golden Triangle Landfill, has the LFG collection system, and it is currently capable of capturing 20% of its LFG emission.

According to the LMOP database [13], Golden Triangle Landfill generated 5.39 million standard cubic feet (mmscf) of LFG in 2020. Of this gas, 1.143 mmscf were captured by the collection systems already in place in the landfill. It has a design capacity of 17,358,975 tons, of which there are currently 10,952,530 tons in place. The landfill opened in 1993 and is projected to reach its capacity around the year 2042. It currently spans 116.9 acres of its designated 235 acres. It is owned and operated by Republic Services, Inc [14]. As a landfill serving a fairly populated area, it is fairly large, but not on the level of the largest landfills in the United States. Similarly, it is significantly larger than the landfills that serve smaller, more rural towns and cities. This is valuable because a more average case will be similar enough compared to the largest and smallest landfills to draw a connection, whereas applying the results from the largest landfill in the US to the smallest ones is much less likely to remain accurate. For example, larger landfills have a much greater incentive to employ methods with more expensive equipment due to the economy of scale. For smaller landfills, it will be harder to employ these same methods as the prohibitive cost of this equipment will be impossible to recoup. A landfill that lands somewhere between these two, like the Golden Triangle Landfill, will benefit from the economy of scale while still sometimes struggling to recoup high investment costs.

Secondly, Golden Triangle Landfill is uniquely positioned to take advantage of its untapped landfill gas resources. Not only does it have a gas collection system in place, but it also enjoys proximity to two ideal potential end users, West Beaumont Gas Plant and Goodyear Beaumont Chemical Plant, both within a 3-mile radius, as shown in Figure 6. These facilities have substantial natural gas needs for their primary energy sources, offering potential avenues for more lucrative alternatives in RNG production beyond simple pipeline injection. Although this project assumes pipeline injection for most applications to ensure gas quality standards are met, the presence of these nearby consumers underscores the landfill's potential for diversified and potentially more profitable use of its gas resources.

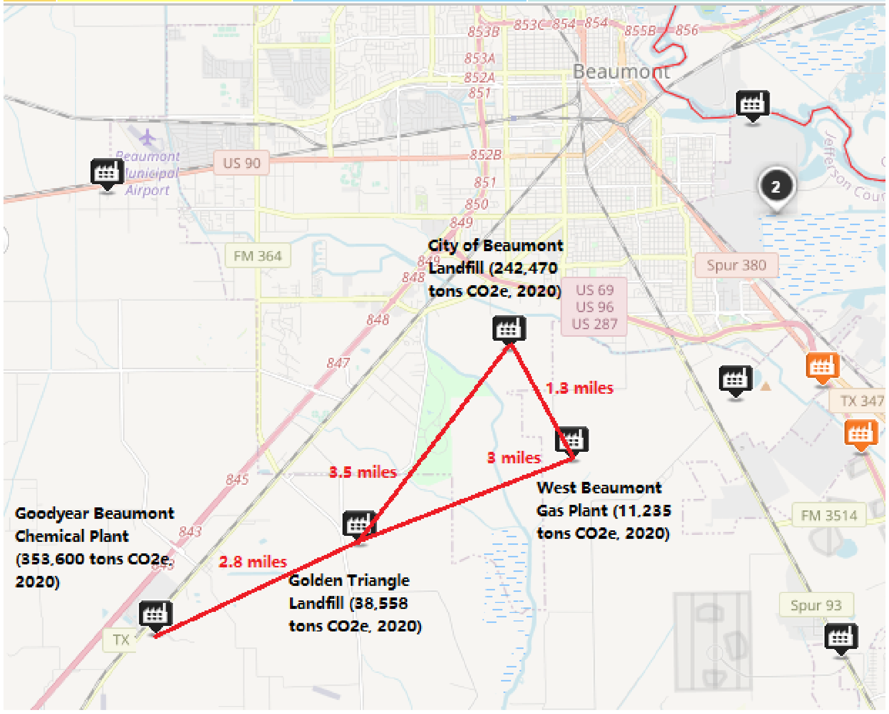


Figure 6. The Potential End Users in Golden Triangle Landfill Case [15]

Moreover, a core facet of engineering ethics centers on community engagement and giving back to the local residents. Therefore, the choice of a landfill with a meaningful impact on its surroundings was essential. The Golden Triangle Landfill's proximity to Beaumont, Texas positions it to make a tangible difference in reducing its carbon footprint, thereby enhancing the quality of life for the community it serves. Furthermore, the installation, use, and maintenance of energy producing facilities generate income for the surrounding communities, resulting in job creation and economic benefits for the area.

The economic analysis was done in three parts to give a proper representation of the benefits and costs of each treatment method. First, the equipment to be used for each method was determined and prices for them were found. Then, the carbon footprint reduction of each method was calculated based on the theoretical difference between the footprint of the method and that of the landfill with no collection system in order to apply the results of the study to a broad range of sites, the fact that the Golden Triangle Landfill already has a collection system in place was ignored for this calculation. Then, the profits of each method were calculated, using the price of the product for the generation of electricity or RNG as well as the additional price of carbon credits based on three market estimates [16]. These numbers were used as they are contingent on market demand, whereas the 45Q carbon tax credit, for example, depends on government funding which can be inconsistent and unreliable. All three methods were used to compare and contrast three different methods of treatment in order to identify the pros and cons of each.

2.2 Three Strategies for LFG Treatment

LFG Flaring is the most basic form of treatment. The gas is first collected, then run through a knockout drum to remove liquid water and a filter to remove large particulate solids. After removal of solids and liquids, landfill gas can be flared, converting its high methane content into carbon dioxide [2]. The tradeoff for this is the limited profitability: no product is being made. The capital investment is low to match, so any financial positive from this option comes from the valuation of carbon footprint reduction.

The second method, electricity generation, requires the removal of sulfurous compounds in addition to the primary treatment required for flaring. This treatment creates biogas, a medium-BTU gas with a number of applications [2]. Projects of other sizes may benefit from different methods of electricity generation, for example, a larger process may be more efficient when using a gas turbine. In this case, it will be burned in an internal combustion engine and used to generate electricity. Electricity is in high demand in Southeast Texas, and electricity itself will always be a valuable product with high demand. This option is included as it makes a product with intrinsically high value that is independent from the value of carbon footprint reduction.

The third and final method requires the removal of the carbon dioxide in addition to the treatment needed for the generation of electricity. This produces methane of sufficient purity to be used as natural gas, and as such is referred to as renewable natural gas. This can be sold as natural gas directly or simply injected into pipelines. Converting landfill gas into RNG is the most optimistic solution of the three. It has the most significant reduction in carbon footprint of the three methods, but it is also the most expensive. Compared to electricity generation, it has a higher investment requirement as well as a less profitable product, meaning it is much more reliant on the value of carbon footprint reduction. Unfortunately, the market for trading carbon credits in the United States is much less robust than that of Europe, and the reliance of tax credits on governmental regulation makes it a less reliable source of income in the long term [17]. However, if regulatory policies include significant credit for carbon footprint reduction, the generation of RNG may find itself as the most profitable of the three options presented in this paper.

3. LFG Emission Simulation

LandGEM is an automated estimation tool with a Microsoft Excel interface that can be used to estimate emissions rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from municipal solid waste landfills [18].

LandGEM uses the following first-order decomposition rate equation to estimate annual emissions over a time period [19].

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_i}{10}\right) e^{-kt_{ij}} \qquad \text{Eq. 1}$$

Where:

Q_{CH_4} = annual methane generation in the year of the calculation (m^3/year)

i = 1 year time increment

n = (year of the calculation) - (initial year of waste acceptance)

j = 0.1-year time increment

k = methane generation rate (year $^{-1}$)

L_0 = potential methane generation capacity (m^3/ton)

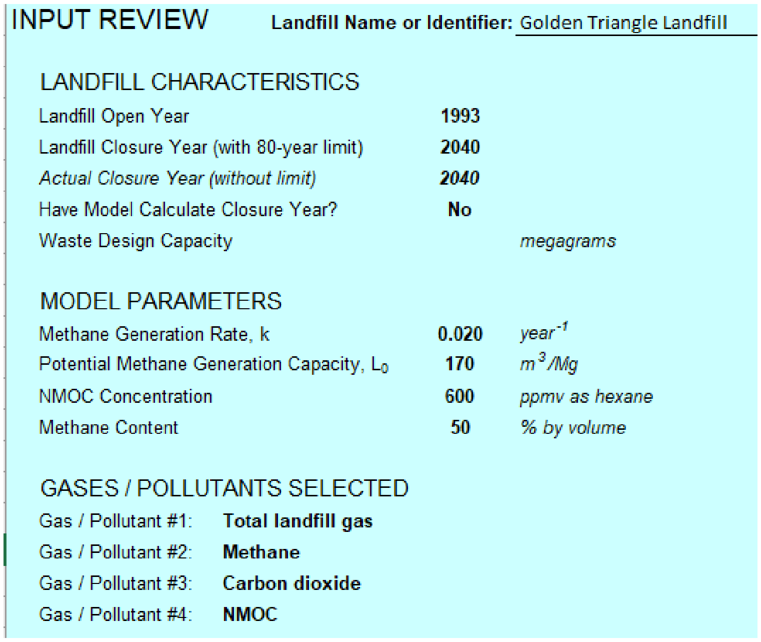
M_i = mass of waste accepted in the i^{th} year (ton)

t_{ij} = age of the j^{th} section of waste mass M_i accepted in the i^{th} year

3.1 Landfill Characteristics and Model Parameters

3.1.1 Landfill Open and Closure Years

Landfill Open Year is a required input and represents the year that the landfill began accepting waste. LandGEM uses the closure year of the landfill to determine the final year the landfill has accepted or is planning to accept waste, as shown in Figure 7.



INPUT REVIEW

Landfill Name or Identifier: Golden Triangle Landfill

LANDFILL CHARACTERISTICS

Landfill Open Year	**1993**	
Landfill Closure Year (with 80-year limit)	**2040**	
Actual Closure Year (without limit)	***2040***	
Have Model Calculate Closure Year?	**No**	
Waste Design Capacity		*megagrams*

MODEL PARAMETERS

Methane Generation Rate, k	**0.020**	*$year^{-1}$*
Potential Methane Generation Capacity, L_0	**170**	*m^3/Mg*
NMOC Concentration	**600**	*ppmv as hexane*
Methane Content	**50**	*% by volume*

GASES / POLLUTANTS SELECTED

Gas / Pollutant #1:	**Total landfill gas**
Gas / Pollutant #2:	**Methane**
Gas / Pollutant #3:	**Carbon dioxide**
Gas / Pollutant #4:	**NMOC**

Figure 7. Input Parameters for LandGEM Simulation

3.1.2 Methane Generation Rate (k)

The Methane Generation Rate, k, determines the rate of methane generation for the mass of waste in the landfill. The higher the value of k, the faster the methane generation rate increases and then decays over time. In our simulation, we employed the default value of "k = 0.02" to model this behavior.

3.1.3 Potential Methane Generation Capacity (L_0)

The Potential Methane Generation Capacity, L_0, depends only on the type and composition of waste placed in the landfill. The higher the cellulose content of the waste, the higher the value of L_0. In our simulation, we have adhered to the default value of $L_0 = 170$ m^3/ton as provided by LandGEM, which aligns with typical MSW characteristics and has been applied within our modeling endeavors.

3.1.4 Nonmethane Organic Compound Concentration

The NMOC Concentration in landfill gas is a function of the types of waste in the landfill and the extent of the reactions that produce various compounds from the anaerobic decomposition of waste. NMOC Concentration is measured in units of ppmv and is used by LandGEM only when NMOC emissions are being estimated. For the default inventory, the NMOC Concentration is set at 600 ppmv, assuming no co-disposal of hazardous waste has taken place. In our simulation, we have adhered to this default value of NMOC Concentration, maintaining it at 600 ppmv to model the relevant processes.

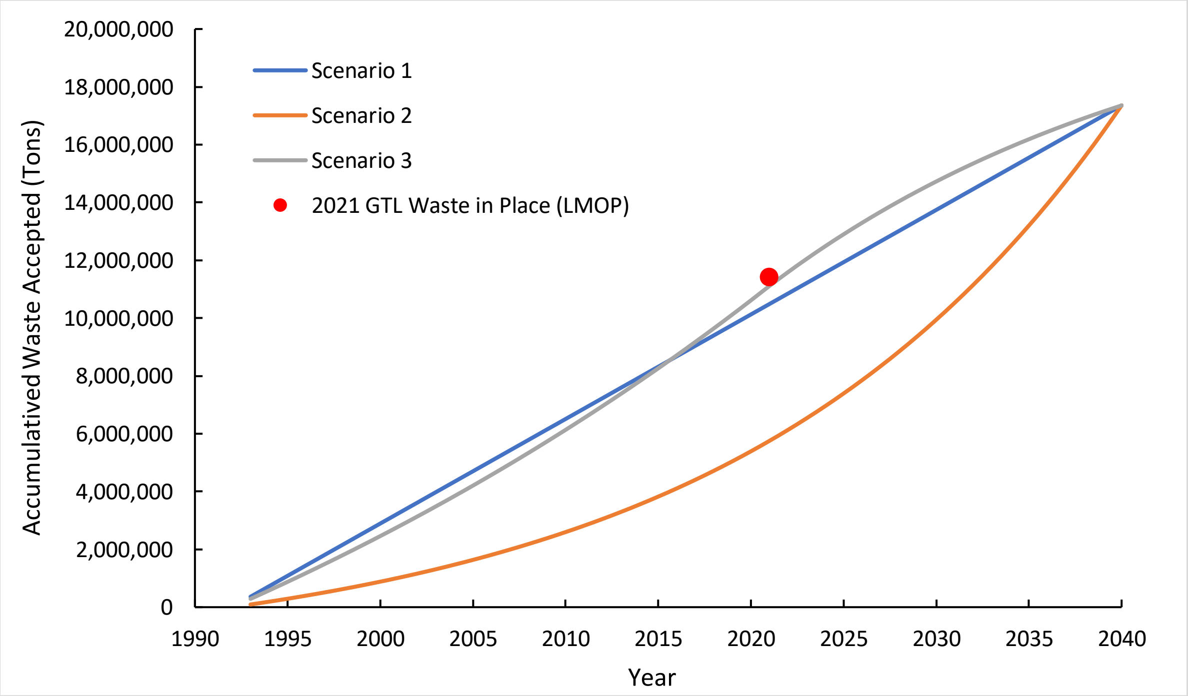
3.1.5 Methane Content

For LandGEM, landfill gas is assumed to be 50 percent CH_4 and 50 percent CO_2. According to data from LMOP, the methane percentage within the landfill gas at the Golden Triangle Landfill was reported as 51.4% in 2020. However, for the task of simplifying our simulation in this project, we have used a 50 percent methane content in the landfill gas.

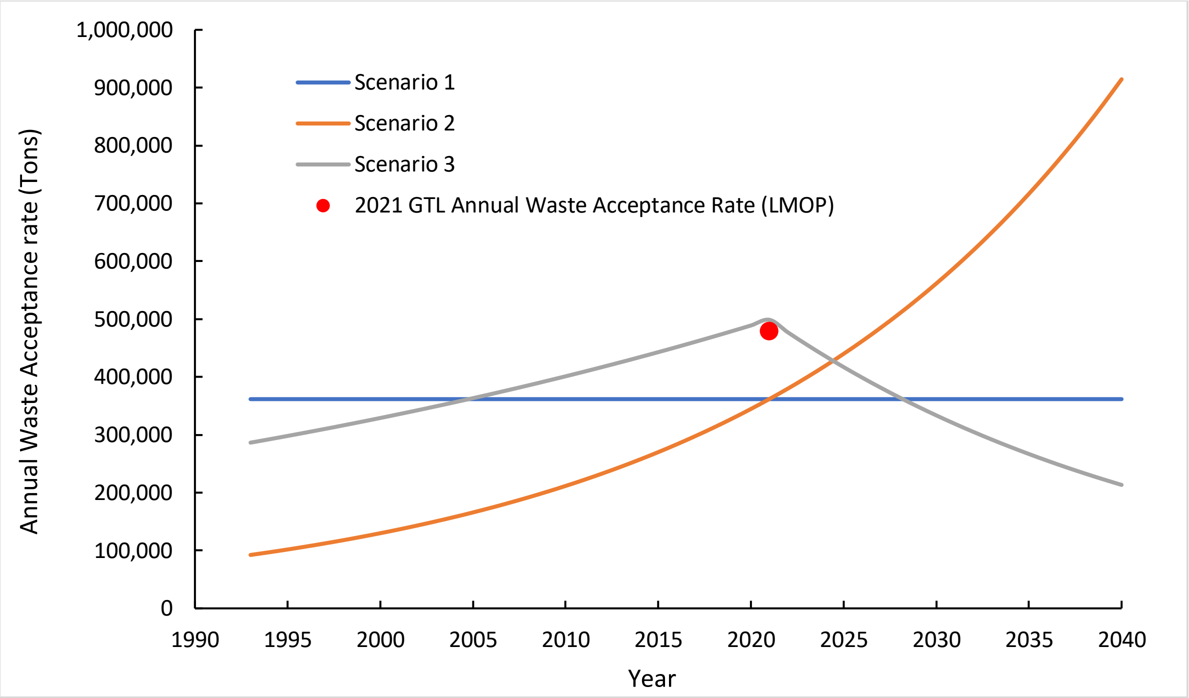
3.2 Scenarios of Waste Acceptance Rates

Due to the challenge of limited data availability, we formulated three distinct scenarios aimed at aligning waste intake projections with the scant publicly accessible information. Given that the landfill open year was 1993 and it is slated for closure in 2040, with a design capacity of 17,358,975 tons, Scenario 1 took a straightforward approach, assuming an even distribution of waste acceptance across each year from the landfill's commencement to its projected closure. In contrast, Scenario 2 designed a 5% annual increase in the landfill's waste acceptance rate, while Scenario 3 adopted a more nuanced strategy, projecting a 2% annual increase from 1993 to 2021, followed by a 4.4% annual decrease from 2022 to 2040.

To assess the alignment of these scenarios with the real Golden Triangle Landfill situation, two key indicators provided by LMOP were used: the 2021 waste in place and the annual waste acceptance rate at the Golden Triangle Landfill. Notably, Scenario 3 demonstrated a 2021 waste in place of 11,112,395 tons, mirroring the actual 2021 waste in place of 11,430,805 tons observed at the Golden Triangle Landfill, as shown in Figure 8 (a). Furthermore, Table 1, the 2021 annual waste acceptance rates for Scenario 1, Scenario 2, and Scenario 3 were simulated as 361,645 tons, 361,916 tons, and 498,732 tons, respectively. Remarkably, the value of Scenario 3 closely approximated the 2021 annual waste acceptance rate of 478,275 tons reported by LMOP for the Golden Triangle Landfill, as shown in Figure 8 (b). Hence, based on this alignment, we elected to adopt Scenario 3 as the most suitable representation for our project's annual waste acceptance rate simulation.



(a) Simulation of Accumulative Waste Acceptance in Golden Triangle Landfill



(b) Simulation of Annual Waste Acceptance Rate in Golden Triangle Landfill

Figure 8. Comparison of Three Scenarios Simulation and Real Golden Triangle Landfill

Table 1. Comparison of Three Scenarios and Real Annual Waste Acceptance Rate in Golden Triangle Landfill

Year	Annual Waste Acceptance Rate (tons per year)				Year	Annual Waste Acceptance Rate (tons per year)			
	LMOP	Scenario 1	Scenario 2	Scenario 3		LMOP	Scenario 1	Scenario 2	Scenario 3
1993		361,645	92,323	286,459	2017		361,645	297,749	460,752
1994		361,645	96,939	292,188	2018		361,645	312,637	469,967
1995		361,645	101,786	298,032	2019		361,645	328,269	479,366
1996		361,645	106,875	303,993	2020		361,645	344,682	488,953
1997		361,645	112,219	310,073	**2021**	**478,275**	**361,645**	**361,916**	**498,733**
1998		361,645	117,830	316,274	2022		361,645	380,012	476,938
1999		361,645	123,721	322,600	2023		361,645	399,013	456,096
2000		361,645	129,907	329,052	2024		361,645	418,963	436,164
2001		361,645	136,402	335,633	2025		361,645	439,911	417,104
2002		361,645	143,223	342,345	2026		361,645	461,907	398,877
2003		361,645	150,384	349,192	2027		361,645	485,002	381,446
2004		361,645	157,903	356,176	2028		361,645	509,252	364,776
2005		361,645	165,798	363,300	2029		361,645	534,715	348,836
2006		361,645	174,088	370,566	2030		361,645	561,451	333,592
2007		361,645	182,792	377,977	2031		361,645	589,523	319,014
2008		361,645	191,932	385,536	2032		361,645	618,999	305,073
2009		361,645	201,528	393,247	2033		361,645	649,949	291,741

2010		361,645	211,605	401,112	2034		361,645	682,447	278,992
2011		361,645	222,185	409,134	2035		361,645	716,569	266,800
2012		361,645	233,294	417,317	2036		361,645	752,398	255,141
2013		361,645	244,959	425,663	2037		361,645	790,018	243,991
2014		361,645	257,207	434,177	2038		361,645	829,518	233,329
2015		361,645	270,067	442,860	2039		361,645	870,994	223,132
2016		361,645	283,571	451,717	2040		361,645	914,544	213,381

3.3 Simulation of Landfill Gas in Scenario 3

Based on the annual waste acceptance rate of Scenario 3 as the simulated database, we conducted a comprehensive simulation using LandGEM to estimate the dynamics of CH_4, CO_2, and total LFG emissions over the landfill's operational timeline from 1993 to 2133. The results, illustrated in Figures 9 and 10, reveal a consistent upward trend in LFG emissions throughout this period, reaching their maximum with CH_4 emissions projected to peak at 2,513 tons (equivalent to 3,740,000 cubic meters) in 2040. Notably, the simulation extends our understanding of the timeline, showcasing that CH_4 generation persists exceeding 1,000 tons and equating to 25,000 tons of CO_2 emissions until 2087. This enduring CH_4 generation emphasizes the long-term environmental impact that concerns within the local area. Given our assumption of an equal blend of 50% CH_4 and 50% CO_2 (V: V), the CH_4 and CO_2 volume curves overlapped in Figure 10.

Furthermore, the simulated total LFG volume in 2021, standing at 5.49 million standard cubic feet per day (mmscfd), matched the actual LFG volume at the Golden Triangle Landfill, amounting to 5.39 mmscfd, as shown in Table 2. This alignment underscores the accuracy of our chosen Scenario 3 as the most representative scenario for our project. With this robust foundation in place, we are poised to use CH_4 generation data from 2024 to 2035 to design equipment specifications, calculate capital investments, operational costs, and potential profits, and estimate the carbon footprint reductions through the implementation of flaring, electricity generation, and RNG production strategies.

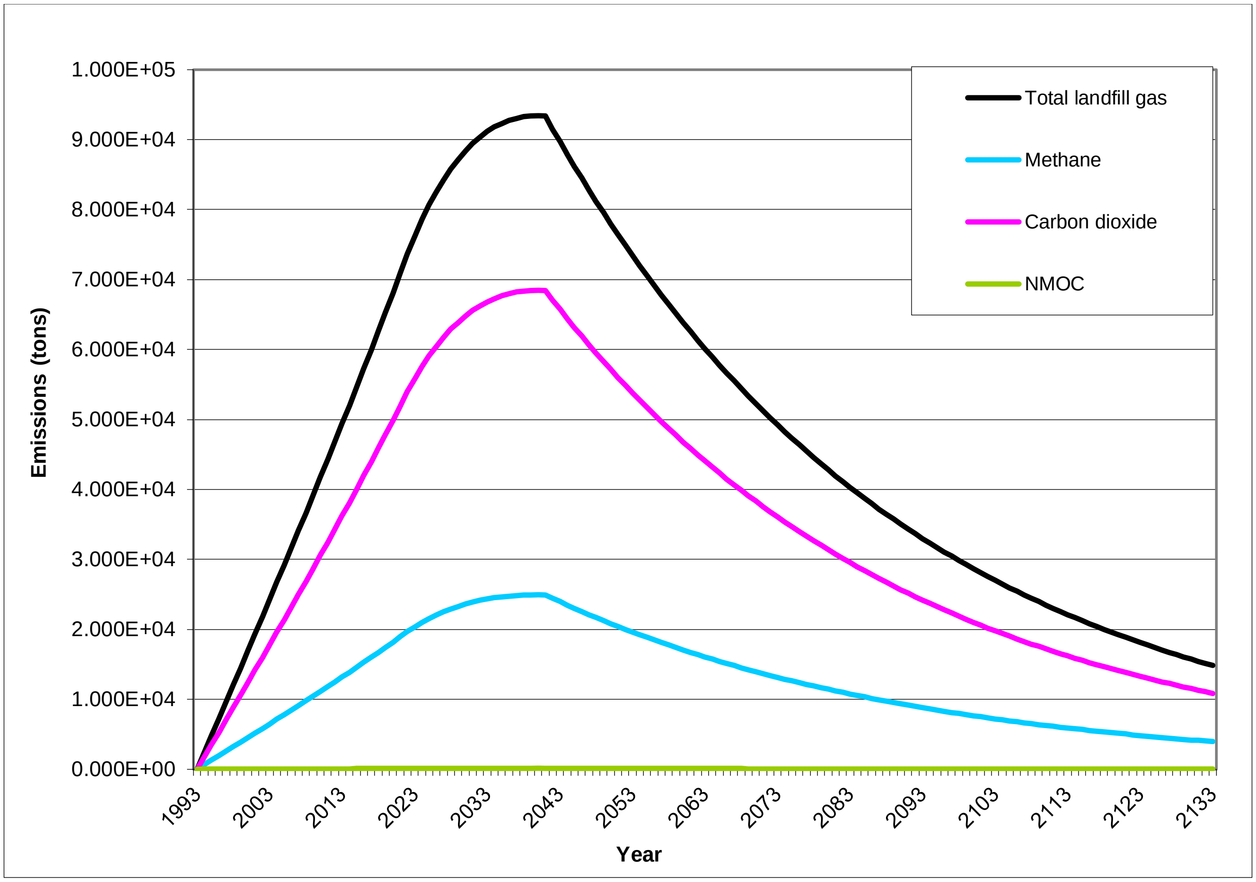


Figure 9. Simulation of Mass of Landfill Gas Emissions in Golden Triangle Landfill from 1993 to 2133

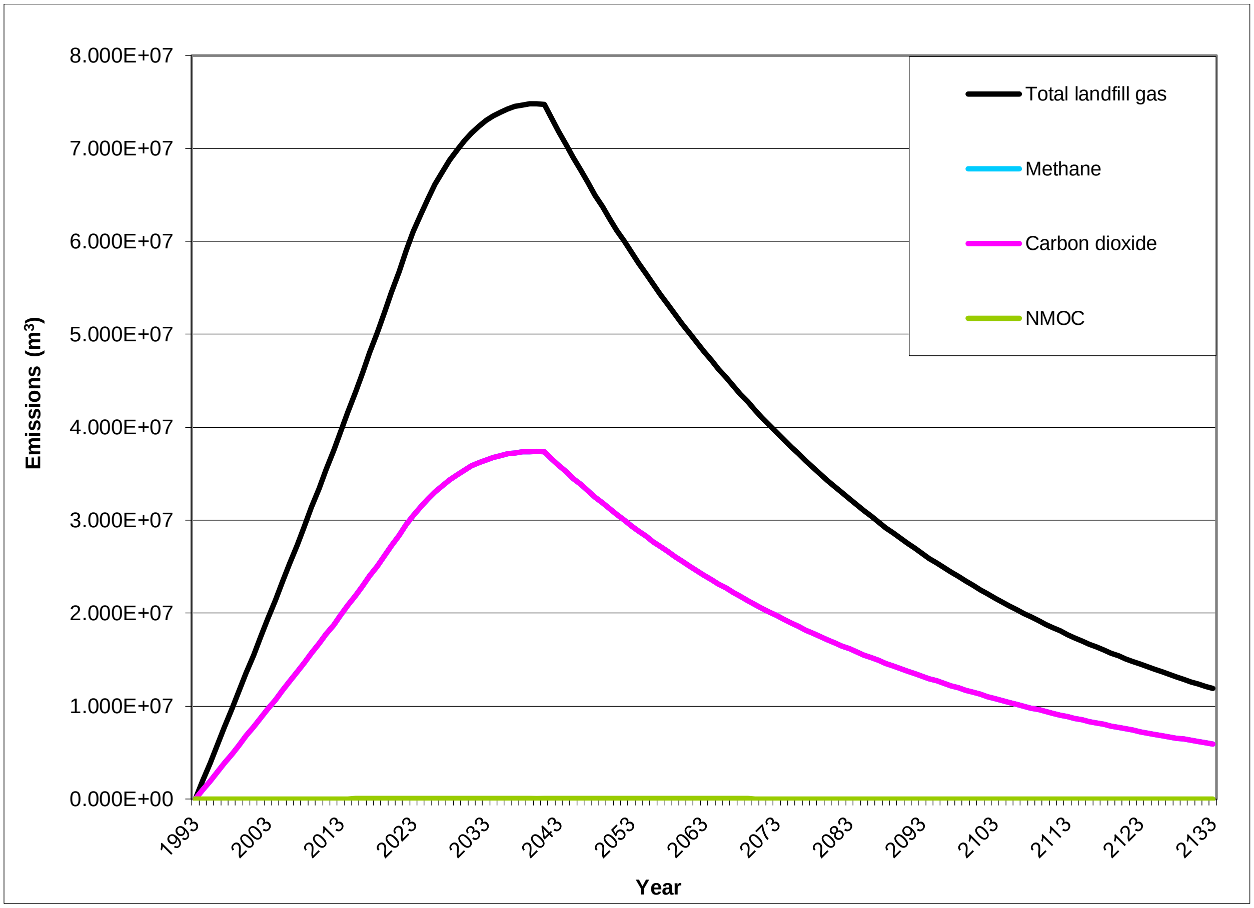


Figure 10. Simulation of Volume of Landfill Gas Emissions in Golden Triangle Landfill from 1993 to 2133

Table 2. Simulation of Total LFG, CH_4, and CO_2 from 2021 to 2041

Year	Total LFG			Methane		Carbon Dioxide	
	(Ton/year)	(m^3/year)	(mmscfd)	(Ton/year)	(m^3/year)	(Ton/year)	(m^3/year)
2021	7.086×10^4	5.674×10^7	5.49	1.893×10^4	2.837×10^7	5.193×10^4	2.837×10^7
2022	7.365×10^4	5.898×10^7	5.71	1.967×10^4	2.949×10^7	5.398×10^4	2.949×10^7
2023	7.621×10^4	6.102×10^7	5.90	2.036×10^4	3.051×10^7	5.585×10^4	3.051×10^7
2024	7.854×10^4	6.289×10^7	6.08	2.098×10^4	3.144×10^7	5.756×10^4	3.144×10^7
2025	8.065×10^4	6.458×10^7	6.25	2.154×10^4	3.229×10^7	5.911×10^4	3.229×10^7
2026	8.257×10^4	6.612×10^7	6.40	2.205×10^4	3.306×10^7	6.051×10^4	3.306×10^7
2027	8.429×10^4	6.749×10^7	6.53	2.251×10^4	3.375×10^7	6.177×10^4	3.375×10^7
2028	8.583×10^4	6.873×10^7	6.65	2.293×10^4	3.436×10^7	6.290×10^4	3.436×10^7
2029	8.720×10^4	6.983×10^7	6.76	2.329×10^4	3.491×10^7	6.391×10^4	3.491×10^7
2030	8.841×10^4	7.079×10^7	6.85	2.362×10^4	3.540×10^7	6.479×10^4	3.540×10^7
2031	8.947×10^4	7.164×10^7	6.93	2.390×10^4	3.582×10^7	6.557×10^4	3.582×10^7
2032	9.038×10^4	7.237×10^7	7.00	2.414×10^4	3.619×10^7	6.624×10^4	3.619×10^7
2033	9.116×10^4	7.299×10^7	7.06	2.435×10^4	3.650×10^7	6.681×10^4	3.650×10^7
2034	9.181×10^4	7.352×10^7	7.11	2.452×10^4	3.676×10^7	6.728×10^4	3.676×10^7
2035	9.234×10^4	7.394×10^7	7.15	2.466×10^4	3.697×10^7	6.767×10^4	3.697×10^7
2036	9.275×10^4	7.427×10^7	7.19	2.478×10^4	3.714×10^7	6.798×10^4	3.714×10^7
2037	9.307×10^4	7.452×10^7	7.21	2.486×10^4	3.726×10^7	6.821×10^4	3.726×10^7
2038	9.328×10^4	7.469×10^7	7.23	2.492×10^4	3.735×10^7	6.836×10^4	3.735×10^7
2039	9.339×10^4	7.478×10^7	7.24	2.495×10^4	3.739×10^7	6.845×10^4	3.739×10^7
2040	9.342×10^4	7.481×10^7	7.24	2.495×10^4	3.740×10^7	6.847×10^4	3.740×10^7
2041	9.337×10^4	7.476×10^7	7.23	2.494×10^4	3.738×10^7	6.843×10^4	3.738×10^7

4. Equipment Designs

In this section, we will discuss the sizes and costs of the equipment in the three strategies. Additionally, there will be some discussion of why each piece of equipment was chosen for use as well as the purposes they serve.

LFG is collected through vertical and horizontal piping buried in an MSW landfill. The LFG is then processed and treated for use. Primary treatment of the gas serves to get rid of the easiest contaminants, such as condensed water and large particulate matter. The product of this step is only fit for flaring, which serves to convert the methane in the gas to carbon dioxide, reducing its environmental impact significantly. A step further involves the washing of the gas and its compression, serving to remove siloxanes and other sulfurous compounds. This product, called biogas, is burned for a purpose, be it to harness the heat directly or to generate electricity. The final step is the purification of the methane to yield pipeline-quality natural gas [2].

This can be achieved in many ways, but in this case, a membrane was used, mainly to focus on the separation of carbon dioxide and methane. These are not the only methods of treatment for landfill gas, nor do we claim them to be the best, they are simply what we decided to use. This set of equipment allows for our delineation of three different pathways to carbon footprint reduction. Flaring, electricity generation, and RNG production are three different methods that each have their own characteristics, costs, benefits, and drawbacks. Each is more complex than the last, requiring more specialized equipment and more stringent purification to meet the necessary standards. However, they still build off each other, and most of the equipment used for the initial stages will also be used for the later stages.

The following equations are used to calculate the bare module cost of each piece of equipment [20].

$$\log_{10} C_p^0 = K_1 + K_2 * \log_{10}(A) + K_3[\log_{10}(A)]^2 \quad \text{Eq. 2}$$

$$C_{BM} = C_p^0 * F_{BM} = C_p^0 * (B_1 + B_2 * F_M * F_P) \quad \text{Eq. 3}$$

Where:

C_p^0 = Purchase cost of equipment

$K_{1,2,3}$ = Constant values dependent on equipment type

A = Capacity Factor dependent on equipment type

C_{BM} = Bare module cost

F_{BM} = Bare module factor, constant value from table

$B_{1,2}$ = Constant values dependent on equipment type

F_M = Material of construction factor

F_P = Pressure factor

The bare module cost of a piece of equipment is given in 2001 dollars. To account for inflation, the CEPCI is used to calculate the new dollar amounts. Because the CEPCI is based on real-world data, it does not exist for the year 2024 at the time of writing. Instead, the year 2020's value was used and an increase of 3% per year was applied to account for some inflation. Of course, this means the values reported are not a perfect reflection of real-world numbers, but it is believed that the approximation is close enough to suffice. The bare module cost is the cost of the equipment itself. As a rule of thumb, the cost of installing this module in an existing facility usually costs about 18% of the bare module cost, including contingency costs and fees [20]. Therefore, the total module cost can be found by multiplying the bare module cost by 1.18. The sum of these total module costs will be considered as the equipment cost for each method.

The equipment used for this project was taken directly from Figure 3. The only clarification necessary is that for advanced treatment a membrane is used for the final purification of methane to be sold as RNG. The description of how the cost of each piece of equipment was calculated will be explained in the following section. In addition to Equations. 2 and 3, various equipment that is in use in landfills across the US was scaled down according to proportional flowrates to find the necessary capacity for the Golden Triangle Landfill's level of output. Furthermore, some pieces were simply priced equivalent to similar units found on online marketplace forums. These methods were all aimed at simplifying calculations to allow for easy replication, as the goal of this project is to be applicable to a wide variety of landfills across the US.

Golden Triangle Landfill is currently capable of capturing 20% of its landfill gas emission. To provide a more diverse analysis, it was assumed that over the first 5 years of the project's lifespan, the capture rate would gradually increase, starting at 20% and increasing to 40%, 60%, 80%, and finally 90%. Finally, the economics of options outside the 90% rate can only be estimated based on revenue, as the equipment is sized for a 90% capture rate, obfuscating any economic analysis of other possibilities. Also, the costs of installing improved collection systems are not considered in this project due to time and scope constraints.

4.1 Flaring Strategy

The fundamental treatment method for LFG involves safe flaring, a process utilized for carbon footprint reduction. Flaring entails the controlled combustion of the gas, effectively converting CH_4 present in the gas to CO_2.

4.1.1 Knockout Drum

The design of a knockout drum is primarily aimed at preventing the entrainment of liquid droplets into the vapor stream. In the context of this project, the drum serves the crucial function of extracting liquid water droplets from the LFG flow. The quantity of liquid present is so minimal that it warrants the use of a petite, uniformly sized drum, chosen as a precautionary measure in case of unexpected increases in liquid content. This specific drum has a diameter of 0.5 meters and a height of 2 meters. These parameters were employed alongside equations 2 and 3 to calculate the price of the knockout drum, as detailed in Table 3 [20].

Table 3. Parameters Values of Knockout Drum Equipment Design

Parameters	Units	Values
k_1		3.4974
k_2		0.4485
k_3		0.1074
volume (V)	m^3	0.785
F_P		1
F_m		1
B_1		2.25
B_2		1.82

The volume (V) serves as the capacity factor in the Eq. 2, more generally known as A. The rest of the values are constants. By applying the equation as well as the CEPCI inflation proportion, the final value for the cost of the knockout drum came out to $11,511.

4.1.2 Filter

The sole additional equipment used for purification at this stage is the filter, specifically the Shelco 12FOS2, a 20-inch Stainless Steel Filter with an approximate cost of $4,153 [21]. The collaborative function of these two equipment components is to effectively eliminate the primary contaminants found in the LFG, with a particular focus on liquid water and large particulate matter. Once this dual purification process is completed, the LFG is ready for flaring.

4.1.3 Flare

To determine the dimensions and costs associated with the flare, the EPA provides a handbook featuring tables that establish a relationship between size and cost. Table 4 is designed to complement the Equations. 4 and 5 and reference data [22].

$$\log_{10}(V_{max}) = \frac{(B_v+1,212)}{850} \qquad \text{Eq. 4}$$

$$D_{min} = 1.95\sqrt{\frac{Q_{tot}}{V_{max}}} \qquad \text{Eq. 5}$$

Where:

V_{max} = Maximum Permitted Velocity (ft/sec)

B_V = Net Heating Value of Vent Stream (Btu/scf)

D_{min} = Minimum permissible diameter of flare tip

Q_{tot} = Total Flow Rate of Vent Stream

Table 4. Maximum Permitted Velocity based on Net Heating Value

Option	Net Heating Value of Vent Stream, B_V	Maximum Permitted Velocity, V_{max}
	(Btu/scf)	(ft/sec)
1	≥ 300	< 60
2a	≥ 300 & $< 1,000$	$\log_{10}(V_{max}) = \frac{(B_v + 1,212)}{850}$
2b	$\geq 1,000$	< 400

The net heating value of a mixture of gases is calculated based on the heating value of each gas and its proportion in the mixture. Because for this project we are assuming that the landfill gas is a 50/50 mixture of CO_2 and CH_4, the heating value of the mixture is equal to the average of the heating values of each gas. CO_2 has a heating value of 0 Btu/scf as it is fully oxidized, while CH_4 has a heating value of about 1,010 Btu/scf [23]. Therefore, the net heating value of the mixture is about 505 Btu/scf, so Eq. 4 is used to calculate the maximum permissible velocity of the vent stream. Plugging in this value returns V_{max} as being approximately equal to 107 ft/sec. At the maximum flow, 90% of about 7.24 mmscfd will be flared off. This is equivalent to about 6.5 mmscfd, or about 4500 cubic feet per minute. Plugging these values into Eq. 5 returns a minimum diameter of about 12 inches, so a 12-inch flare tip will be used. Additionally, a flare height of 40 feet will be used as a standard safe height. Using a 12-inch diameter and a height of 40 feet returns a cost of $68,200. Assuming both a flare for use and a secondary backup are required, the total cost is $136,400.

4.2 Electricity Generation Strategy

The process of converting LFG into electricity represents a sort of middle-ground choice among the three strategies. After undergoing the same treatment steps as the flaring method, an additional washer is introduced to remove sulfurous compounds and siloxanes. Once these compounds are removed, the gas is transformed into biogas, suitable for direct-use applications. To generate electricity, the knockout drum and filter remain necessary, with the assumption that their sizes align with those used in the treatment process for flaring.

4.2.1 Washer

After the utilization of these equipment components, the treated gas undergoes a washing process. The washer's volume was determined to be 0.785 m^3 using an EIQ report from North Texas Municipal Water District’s 121 Regional Disposal Facility [24]. To accommodate the altered usage conditions relative to the Golden Triangle Landfill, the washer's size was proportionally adjusted by comparing the LFG flow rates of both landfills. Referring to Table 3 and applying the equations 2 and 3, the calculated bare module cost stands at approximately $1,705. Considering the CEPCI and general inflation of costs, in addition to applying a multiplier of 5 due to the equipment's modular nature, the total cost reaches $12,895.

4.2.2 Internal Combustion Engine

The most expensive and important piece of equipment for electricity generation is the engine used. In this case an internal combustion engine is used based on the projected output of the engine, as shown in Table 5 [25].

Table 5. Parameters of Internal Combustion Engine Design

Project Component	Unit	Value
Gross capacity factor	%	93
System operating schedule	hours/year	8,147
Fuel use rate	Btu/kWh generated	13,000
Parasitic loss efficiency	%	88
Landfill gas heat content	Btu/ft^3	506
Turbine capacity	kW	5,129

The most important parameter for the computation of equipment costs is the turbine capacity, which stands at 5,129 kW. This critical value is used in conjunction with the other data presented in Table 6 [20] to derive the engine's cost through the application of Equations. 2 and 3. It is worth noting that in Table 6, the turbine capacity denoted as "W" has been rounded to 5,000 kW for simplifying calculations. This rounding is applied because the turbine capacity, while influencing both the engine cost and the electricity generation amount, has a relatively minor impact on the overall economic aspects of its operation. The estimated cost is approximately $4,164,614. Full inflation analysis including CEPCI increases this number to a total of $8,700,558.

Table 6. Parameters of Internal Combustion Engine Cost

Parameters	Units	Values
k_1		-21.7701
k_2		13.2175
k_3		1.5279
W	kW	5,000
F_P		1
F_m		3.5

4.3 RNG Production Strategy

Conversion of the biogas that is acceptable for use in electricity generation into fully realized RNG requires the separation of CO_2 from CH_4 to a sufficient purity to be injected into a pipeline. In this project, a selective physical membrane is used. In order to use this piece of equipment, a high pressure is needed, so a compressor is also necessary to compensate.

4.3.1 Compressor

The selected membrane for use in this project requires a feed pressure of 50 bar to purify NG to 98% pure [26]. Assuming that the remaining 2% is CO_2, this purity threshold is the minimum requirement for the gas to be classified as pipeline-quality NG. To increase the pressure of the gas from atmospheric pressure to 50 bar requires an estimated 400 horsepower compressor, equivalent to roughly 300 kW. This value, in conjunction with the data from Table 7 [20], was used in Eq. 2 to determine the compressor's cost, resulting in an estimated expense of $1,034,750. After accounting for CEPCI inflation and multiplying the cost by 5 to account for the modular approach, the total cost of compressors at this step amounts to $7,826,288.

Table 7. Parameters of Compressor Cost

Parameters	Units	Values
k_1		5.0355
k_2		-1.8002
k_3		0.8253
Capacity	kW	298.28
F_m		2.4

4.3.2 Membrane

The last equipment component used in purifying LFG is the carbon membrane. Table 8 provides comprehensive performance data for this membrane [26].

Table 8. Performances of Carbon Membrane

Feed Pressure	Membrane Area	Power Demand	Annual Capital-related Cost	OPEX	NG Processing Cost
(Bar)	(m^2)	(kW)	(\$)	(\$)	(\$/m^3 Sweet NG)
50	1.19×10^5	1,109	4.00×10^6	3.55×10^5	1.278×10^{-2}
60	1.06×10^5	1,154	3.78×10^6	3.69×10^5	1.219×10^{-2}
70	9.46×10^4	1,180	3.58×10^6	3.78×10^5	1.162×10^{-2}
80	8.94×10^4	1,238	3.54×10^6	3.96×10^5	1.156×10^{-2}
90	8.27×10^4	1,256	3.42×10^6	4.02×10^5	1.122×10^{-2}

In this case, a feed pressure of 50 bar will be used. The membrane area and power demand of the carbon membrane were proportionally decreased to be equivalent to the feed volume used in our project, resulting in the values used in Table 9 [26]. By simply multiplying the membrane area by its associated cost, an estimated expense of membrane is $323,950. As this data is sourced from 2018, adjusting for inflation via the CEPCI and incorporating a multiplier of 5 to account for the anticipated carbon capture expansion leads to a total cost of $2,450,195.

Table 9. Parameters of Carbon Membrane Cost

Parameters	Units	Values
Flow rate	m^3/h	1361.1
Membrane area	m^2	3239.5
Power demand	kW	30
Membrane Cost	\$/m^2	100

4.3.3 Pipeline

In order to sell the final RNG product, the integration of the landfill and treatment site with a pipeline becomes necessary. For the purposes of this project, it was assumed that this integration process would cost $2,000,000. It is worth noting that this expense could potentially be lower for the Golden Triangle Landfill, given the opportunity to sell directly to local end-users. Nevertheless, this cost estimate serves as a reminder that there will be financial considerations associated with pipeline integration, should the decision to produce RNG be pursued.

4.4 Comparison of Equipment Costs for Three Strategies

The comparative analysis of total estimated equipment costs for each of the three strategies is depicted in Figure 11, offering a nuanced breakdown of expenses. It is worth noting that the cost of flaring is significantly lower overall compared to the other two strategies, while RNG production and electricity generation strategies exhibit closer cost estimates. Among these options, the RNG production strategy emerges as the costliest, surpassing $12,000,000, a figure exceeding the electricity generation strategy by over $3,000,000. This difference can be attributed to the higher expenses associated with the compressor and membrane, which are necessary components for RNG production but not as costly for electricity generation. Additionally, pipeline integration fees constitute a substantial portion of the expenses. Interestingly, the specialized equipment mentioned earlier, such as the knockout drum, filter, flare, and washer, which are integral to every treatment method, appear comparatively inconsequential in terms of cost when juxtaposed with the expenditures tied to the more specialized equipment in each strategy.

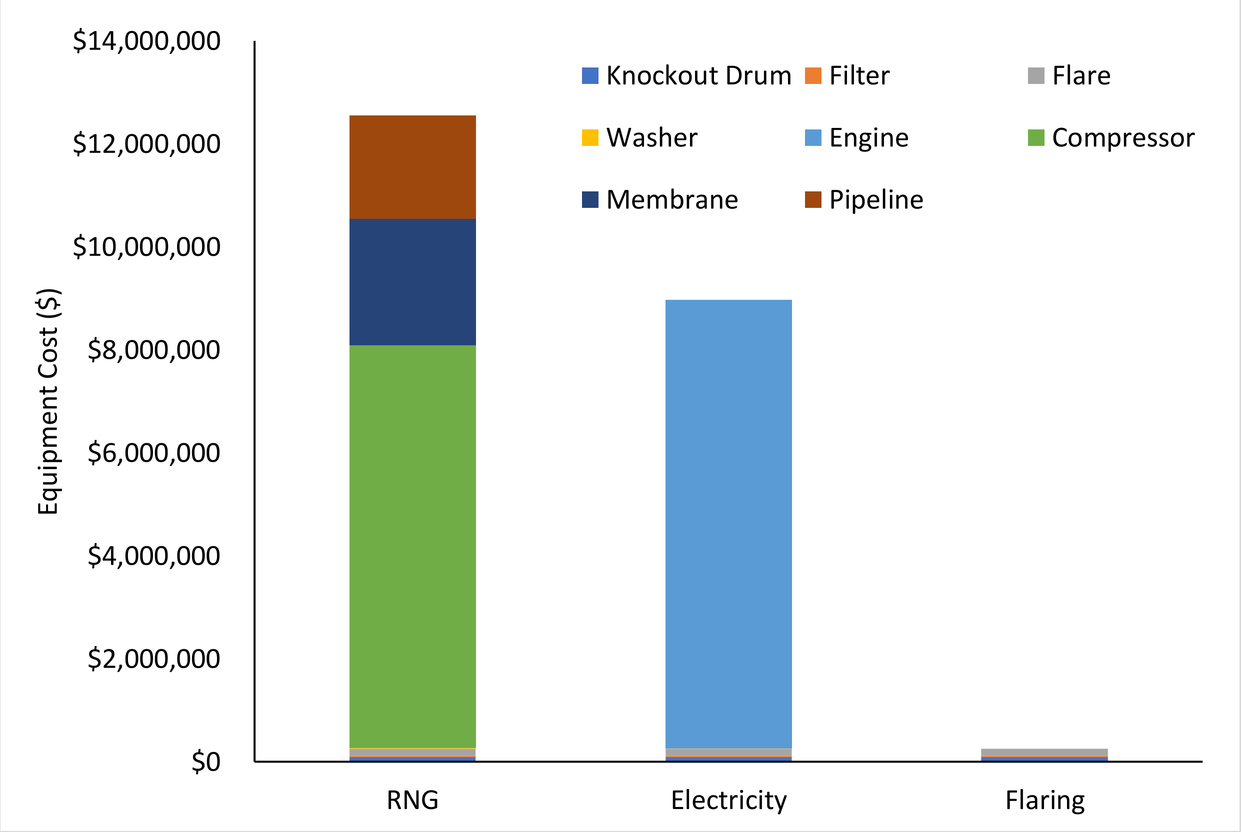


Figure 11. Comparison of Equipment Costs for Three Strategies

5. Carbon Footprint Reduction Calculation

In this section, we will investigate the computation of the total carbon footprint reduction for each LFG treatment strategy. This process can be straightforwardly divided into easily understandable steps. The baseline emissions data is sourced from the simulation data in Table 2. To calculate the actual emissions, our consideration is primarily focused on direct emissions and the carbon dioxide emission equivalents resulting from electricity consumption. The inevitable leakage of pipes was not considered. Direct emissions encompass the emissions from the flare in the flaring method, assuming that CH_4 is perfectly combusted into CO_2, as well as the emissions from the engine in the electricity generation method, under the same combustion assumption. It is important to acknowledge that LFG collection efficiency is less than 100%, so the LFG that remains uncollected must also be factored in. All emission values are reported in carbon dioxide equivalent (CO_{2e}), which accounts for the varying GWP of each gas. Methane, for instance, is assigned a GWP of 25, signifying that CH_4 has an environmental impact 25 times greater than that of CO_2.

The following equations are used to calculate the calculated CF values for all three strategies.

$$CF_{No\ Treatment\ CO_{2e}} = CF_{CO_2} + CF_{CH_4} \qquad \text{Eq. 6}$$

$$CF_{Actual\ Emissions} = CF_{No\ Treatment\ CO_{2e}} - CFR \qquad \text{Eq. 7}$$

$$CFR\ (\%) = \frac{CFR}{CF_{No\ Treatment\ CO_{2e}}} \times 100\% \qquad \text{Eq. 8}$$

Where:

$CF_{No\ Treatment\ CO_{2e}}$ = The total carbon footprint (CF) emission of Golden Triangle Landfill is directly release into the atmosphere

CF_{CO_2} = CO_2 is generated in Golden Triangle Landfill

CF_{CH_4} = CH_4 is generated in Golden Triangle Landfill, equivalent to $25CF_{CO_2}$

$CF_{Actual\ Emissions}$ = The actual CF emissions of Golden Triangle Landfill are emitted

CFR = Carbon footprint reduction, equivalent to the collected CH_4 carbon footprint by the collection system

CFR (%) = Carbon footprint reduction percentage

5.1 Flaring and Electricity Generation Strategies

The carbon footprint reduction is solely calculated based on the quantity of captured CH_4. Methane is intentionally combusted to generate CO_2, preventing the direct release of CH_4 into the atmosphere in the flaring strategy, and using heat to produce electricity in the electricity generation strategy. This commonality in the treatment of CH_4 in these two strategies results in identical calculations. The electricity generation method is considered to be self-sufficient in terms of electricity use, hence no Scope 2 carbon footprint is attributed to it [27]. To determine the carbon footprint for each year, emissions post-combustion were initially calculated. In these calculations, it is assumed that the combustion of LFG perfectly converts CH_4 into CO_2, thereby making the emissions consist solely of CO_2. This conversion significantly reduces the environmental impact since the global warming potential of CO_2 is 25 times lower than that of CH_4.

As illustrated in Table 10, as LFG capture efficiency gradually increases from 20% to 40%, 60%, 80%, and ultimately 90%, carbon footprint emissions are a significant decline. Correspondingly, the CFR percentage shows a steady rise, reaching 18%, 37%, 55%, 74%, and finally stabilizing at 83% when capture efficiency reaches 90%.

In addition, "Usable Credits [CO_{2e}]" is the difference between the carbon footprint column and the carbon footprint data reported to FLIGHT for 2020, which will be explained in detail later.

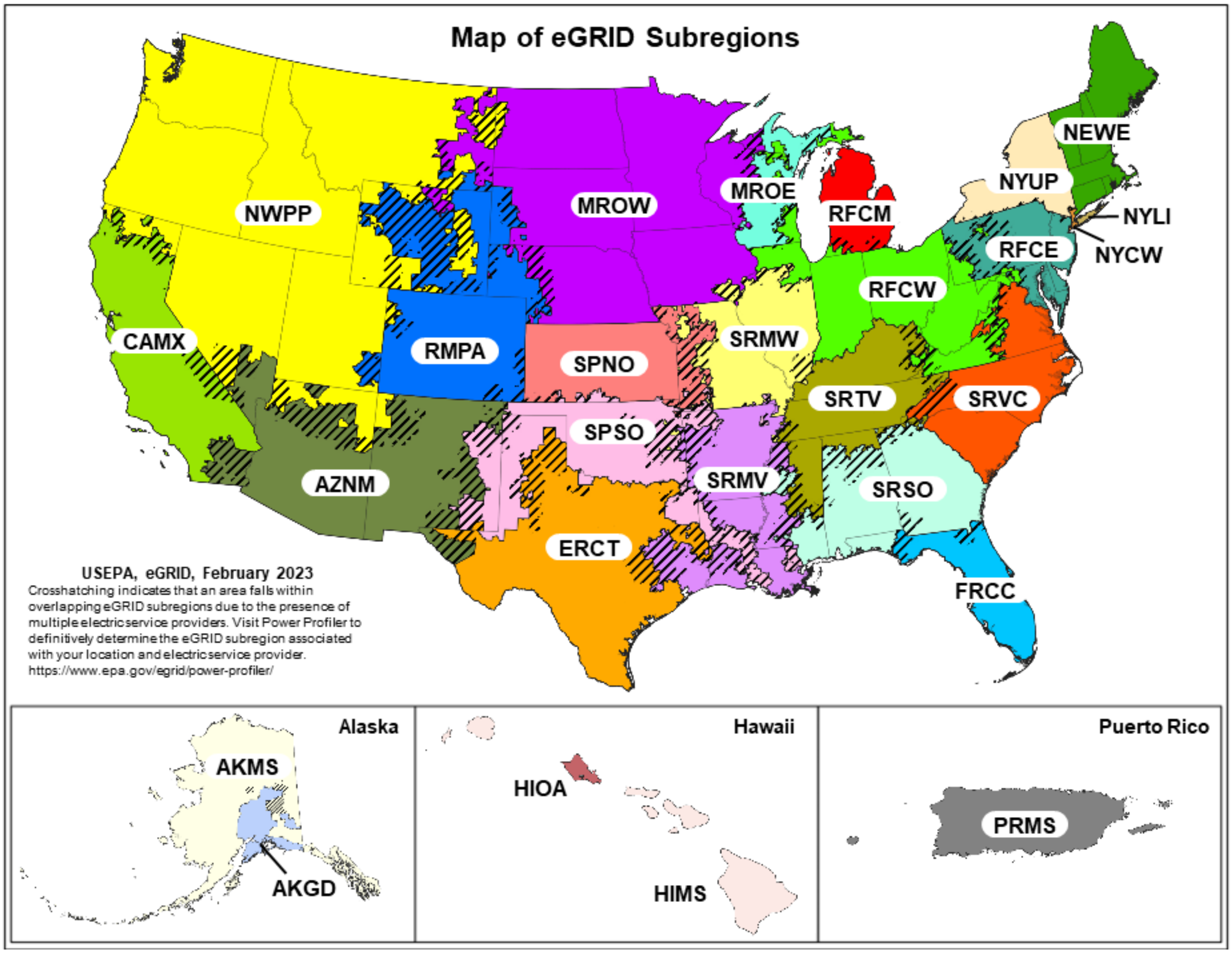
Table 10. Carbon Footprint Reduction Calculations

	No Treatment [CO_{2e}]	Flaring/Electricity Generation Strategy				RNG Production Strategy			
		CF [CO_{2e}]	CFR [CO_{2e}]	Usable Credits [CO_{2e}]	CFR (%) [CO_{2e}]	CF [CO_{2e}]	CFR [CO_{2e}]	Usable Credits [CO_{2e}]	CFR (%) [CO_{2e}]
Year	Tons/year					Tons/year			
2024	1.02×10^{6}	8.33×10^{5}	1.88×10^{5}	0	18%	8.24×10^{5}	1.97×10^{5}	0	19%
2025	1.05×10^{6}	6.61×10^{5}	3.87×10^{5}	0	37%	6.36×10^{5}	4.12×10^{5}	0	39%
2026	1.07×10^{6}	4.79×10^{5}	5.95×10^{5}	0	55%	4.37×10^{5}	6.37×10^{5}	0	59%
2027	1.10×10^{6}	2.87×10^{5}	8.09×10^{5}	0	74%	2.26×10^{5}	8.69×10^{5}	4.35×10^{3}	79%
2028	1.12×10^{6}	1.89×10^{5}	9.27×10^{5}	4.19×10^{4}	83%	1.19×10^{5}	9.97×10^{5}	1.12×10^{5}	89%
2029	1.13×10^{6}	1.92×10^{5}	9.42×10^{5}	3.88×10^{4}	83%	1.21×10^{5}	1.01×10^{6}	1.10×10^{5}	89%
2030	1.15×10^{6}	1.95×10^{5}	9.55×10^{5}	3.62×10^{4}	83%	1.22×10^{5}	1.03×10^{6}	1.09×10^{5}	89%
2031	1.16×10^{6}	1.97×10^{5}	9.66×10^{5}	3.39×10^{4}	83%	1.23×10^{5}	1.04×10^{6}	1.07×10^{5}	89%
2032	1.17×10^{6}	1.99×10^{5}	9.76×10^{5}	3.19×10^{4}	83%	1.25×10^{5}	1.05×10^{6}	1.06×10^{5}	89%
2033	1.19×10^{6}	2.01×10^{5}	9.85×10^{5}	3.01×10^{4}	83%	1.26×10^{5}	1.06×10^{6}	1.05×10^{5}	89%
2034	1.19×10^{6}	2.02×10^{5}	9.92×10^{5}	2.87×10^{4}	83%	1.27×10^{5}	1.07×10^{6}	1.04×10^{5}	89%
2035	1.20×10^{6}	2.03×10^{5}	9.97×10^{5}	2.75×10^{4}	83%	1.27×10^{5}	1.07×10^{6}	1.03×10^{5}	89%

5.2 RNG Production Strategy

The production of RNG presents a different carbon footprint when compared to the other two strategies because the ultimate fate of the gas is not combustion and emission into the atmosphere. In this process, a membrane is used to separate CH_4 and CO_2 in the LFG into two distinct streams where the purified CH_4 is sold as RNG, while CO_2 can be reserved for storage or utilization, although these specific solutions are beyond the scope of this project. Crucially, neither of these gases will be emitted into the atmosphere. Due to this, the only emissions in this case beyond that of the uncaptured LFG come from Scope 2 emissions of electricity usage. The Golden Triangle Landfill, located in Southeast Texas, operates within the SRMV electric grid, as indicated in Figure 12 [28].

The SRMV electricity grid was reported to have emissions of 0.3667 kg CO_2/kWh in 2019 [29]. This specific value is used in this case, even if it has changed over time. The total electricity load of the compressor and the membrane amounts to approximately 380 kW. Therefore, this setup results in Scope 2 emissions of about 0.14 tons CO_{2e} / hour. Given that LFG emissions occur continuously, it is assumed that this process will operate continuously for simplicity's sake. Consequently, the electricity CO_{2e} emissions are calculated by determining the annual kWh usage and multiplying it by the associated emissions. This is then multiplied by up to 5, accounting for each year of capture efficiency increase. In comparison to the other two strategies, this strategy exhibits a significantly lower carbon footprint due to the absence of Scope 1 emissions from the captured LFG.


Map of eGRID Subregions

USEPA, eGRID, February 2023
Crosshatching indicates that an area falls within overlapping eGRID subregions due to the presence of multiple electric service providers. Visit Power Profiler to definitively determine the eGRID subregion associated with your location and electric service provider.
https://www.epa.gov/egrid/power-profiler/

Figure 12. Electricity Grid Map

The quantity of electricity related CO_{2e} emissions in the RNG production strategy is lower than the amount of combusted CH_4 used to generate CO_2 in the flaring and electricity generation strategies, as depicted in Table 10. Consequently, as LFG capture efficiency progressively climbs from 20% to 40%, 60%, 80%, and ultimately 90%, carbon footprint emissions witness a notable reduction. In a corresponding fashion, the CFR percentage exhibits a consistent increase, reaching 19%, 39%, 59%, 79%, and finally stabilizing at 89% when capture efficiency achieves 90%.

Figure 13 displays the relationship between the carbon footprint of the three strategies. Over time, the carbon footprint of an untreated landfill increases due to the constant intake of waste from the communities it serves, and this is reflected in the gradual increase of untreated emissions.

Over the first five years, the emissions of each method decrease as the efficiency of collection increases. Once collection has reached its peak in year 5, carbon footprint sees a gradual increase caused by an increase in LFG emission volume. Throughout the lifetime of the project, RNG production always carries a lesser carbon footprint than flaring/electricity generation, and this difference is only increased if scope 2 emissions are not taken into account.

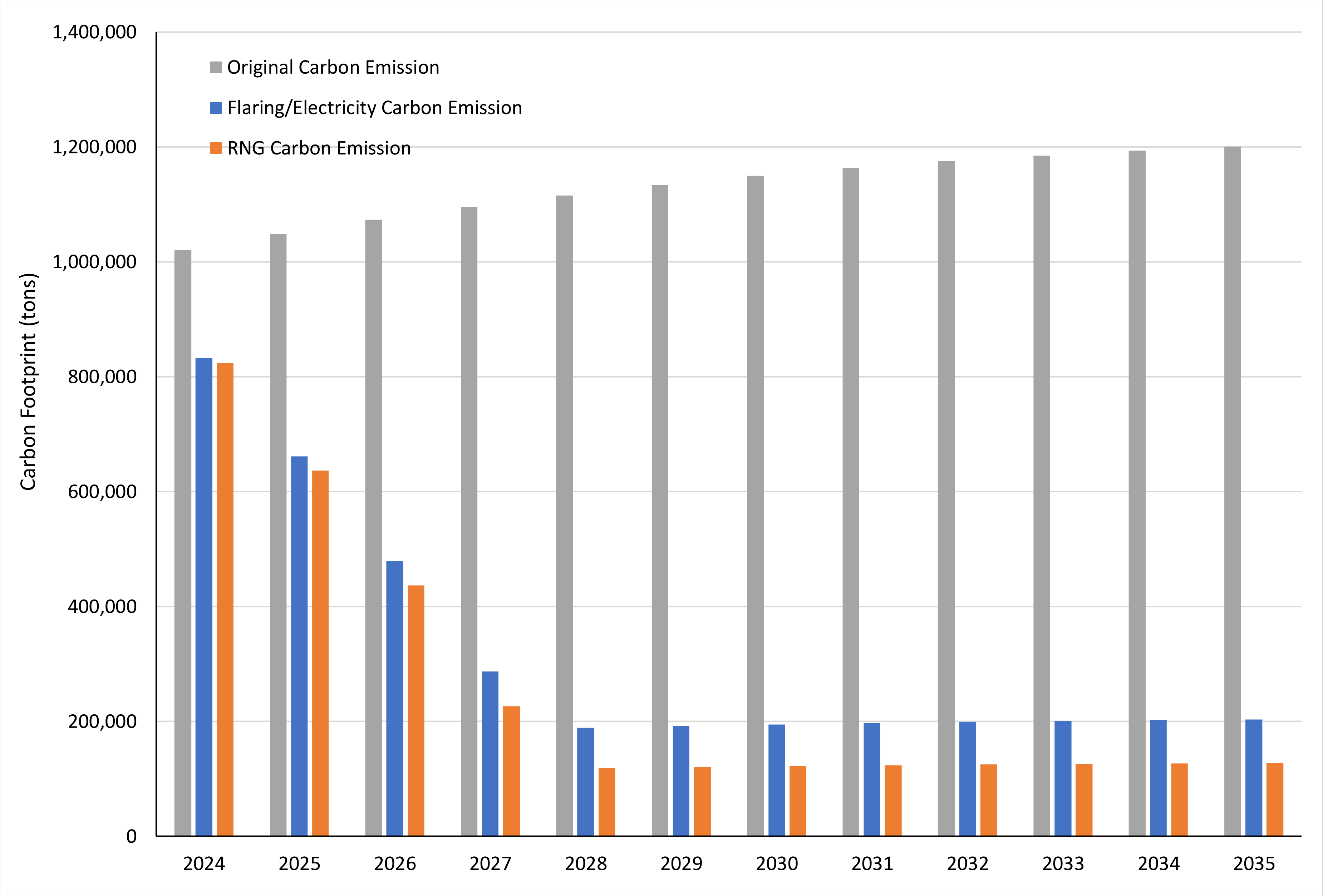


Figure 13. The Changes of Carbon Footprint Reduction for Each Strategy in 12 years

6. Economic Benefits Calculation

This section will discuss the calculation methodology and present the outcomes regarding the economic benefits of each strategy. These economics are based on three key components: capital investments, operational costs, and the profits associated with each strategy. Furthermore, the profit breakdown will encompass a discussion of the carbon credit market trading and government tax credits. A comparison of each strategy will also be included, as highlighting the differences between the three strategies is an important part of the goal of this project.

6.1 Capital Investment

The capital investment associated with a project is a reflection of the total dollar amount that must be invested in the earliest stages of that project. Related costs can come from a vast number of sources, with them generally being one-time costs. The Golden Triangle Landfill itself has enough of a foundation in place that many of these costs can be ignored. For example, the costs associated with installing equipment in a grassroots facility do not apply, saving a fair amount of money in this way. Additionally, the cost associated with increasing the efficiency of the collection systems from its existing 20% to a final value of 90% are not considered. The reasoning behind this is twofold: any number of technologies could be used to improve collection, and our focus is on the treatment methods themselves, not collection. Therefore, the capital investment of each method is equal to the total costs associated with its equipment, as all other costs are annual and as such are not included. As a reminder, the equipment costs of each method and thus their required investments are presented in Figure 11.

Table 11. Capital Investment of Three Strategies

	Flaring	Electricity Generation	RNG Production
Knockout Drum	$87,065	$87,065	$87,065
Filter	$31,418	$31,418	$31,418
Flare	$136,400	$136,400	$136,400
Washer	$0	$12,895	$12,895
Internal Combustion Engine	$0	$8,700,558	$0
Compressor	$0	$0	$7,826,288
Membrane	$0	$0	$2,450,195
Pipeline	$0	$0	$2,000,000
Total	$254,883	$8,968,335	$12,544,261

Table 11 provides that the Flaring approach has the lowest total capital investment among the three strategies, amounting to $254,883. This is primarily due to its simplicity and minimal equipment requirements.

Conversely, the Electricity Generation strategy involves more substantial investments, particularly in an Internal Combustion Engine, which accounts for the majority of the expenses at $8,700,558. Other components include a Knockout Drum, a Filter, a Flare, and a Washer, totaling $8,968,335. The capital investment is considerably higher compared to Flaring due to the specialized equipment necessary for electricity generation. Lastly, the RNG Production strategy requires the most significant capital investment of $12,544,261, attributed to the procurement of a Compressor, Membrane, and Pipeline, which are pivotal for the conversion of landfill gas into renewable natural gas. Despite the higher initial cost, this strategy holds the promise of significant long-term returns, particularly through the sale of the RNG produced.

6.2 Operating Costs

The operating expenses for each strategy are divided into three parts: maintenance, electricity, and labor. These elements are computed separately, and their collective sum for each year represents the total operating costs. This section will delve into the methodology used to calculate each part for every LFG treatment strategy.

6.2.1 Maintenance Costs

To calculate the maintenance costs for each year, we started the process by calculating the depreciation of the initial investment over time. We assumed that, starting with the total capital investment in the first year of the project, the value would depreciate by 10% annually in a straight-line depreciation scheme, with an assumed minimum depreciated value of 10% of the total [30]. Subsequently, the maintenance cost for each year was calculated as 10% of this depreciated value [31]. The maintenance costs for the flaring strategy range from $25,500 to $2,550, while the maintenance costs for electricity generation strategy will decrease from $900,000 to $90,000. The maintenance costs for RNG production strategy will decrease from $12,600,000 to $1,260,000, as shown in Tables 12-14. These maintenance cost values directly correlate with the capital investment for each strategy, with RNG production incurring the highest maintenance costs and the flaring strategy the lowest.

Table 12. Annual Costs for Flaring Strategy in 12 Years Lifetime

Year	Capital	Depreciation	Maintenance	Flare Fuel Cost	Labor	Total Expense
2024	$254,883	$254,883	$25,488	$3,600	$200,730	$229,818
2025	$0	$229,395	$22,939	$3,708	$206,752	$233,399
2026	$0	$203,906	$20,391	$3,819	$212,954	$237,164
2027	$0	$178,418	$17,842	$3,934	$219,343	$241,119
2028	$0	$152,930	$15,293	$4,052	$225,923	$245,268
2029	$0	$127,442	$12,744	$4,173	$232,701	$249,619
2030	$0	$101,953	$10,195	$4,299	$239,682	$254,176
2031	$0	$76,465	$7,646	$4,428	$246,873	$258,947
2032	$0	$50,977	$5,098	$4,560	$254,279	$263,937
2033	$0	$25,488	$2,549	$4,697	$261,907	$269,153
2034	$0	$0	$2,549	$4,838	$269,764	$277,151
2035	$0	$0	$2,549	$4,983	$277,857	$285,389

Table 13. Annual Costs for Electricity Generation Strategy in 12 Years Lifetime

Year	Capital	Depreciation	Maintenance	Labor	Total Expense
2024	$8,968,335	$8,968,335	$896,834	$200,730	$1,097,564
2025	$0	$8,071,502	$807,150	$206,752	$1,013,902
2026	$0	$7,174,668	$717,467	$212,954	$930,421
2027	$0	$6,277,835	$627,783	$219,343	$847,127
2028	$0	$5,381,001	$538,100	$225,923	$764,023
2029	$0	$4,484,168	$448,417	$232,701	$681,118
2030	$0	$3,587,334	$358,733	$239,682	$598,416
2031	$0	$2,690,501	$269,050	$246,873	$515,923
2032	$0	$1,793,667	$179,367	$254,279	$433,645
2033	$0	$896,834	$89,683	$261,907	$351,590
2034	$0	$0	$89,683	$269,764	$359,448
2035	$0	$0	$89,683	$277,857	$367,541

Table 14. Annual Costs for RNG Production Strategy in 12 Years Lifetime

				Operational		
Year	Capital	Depreciation	Maintenance	Electricity	Labor	Total Expense
2024	$12,544,261	$12,544,261	$1,254,426	$416,319	$200,730	$1,871,475
2025	$0	$11,289,835	$1,128,983	$832,638	$206,752	$2,168,373
2026	$0	$10,035,409	$1,003,541	$1,248,957	$212,954	$2,465,452
2027	$0	$8,780,983	$878,098	$1,665,276	$219,343	$2,762,717
2028	$0	$7,526,557	$752,656	$2,081,595	$225,923	$3,060,174
2029	$0	$6,272,131	$627,213	$2,102,411	$232,701	$2,962,325
2030	$0	$5,017,704	$501,770	$2,123,435	$239,682	$2,864,888
2031	$0	$3,763,278	$376,328	$2,144,669	$246,873	$2,767,870
2032	$0	$2,508,852	$250,885	$2,166,116	$254,279	$2,671,280
2033	$0	$1,254,426	$125,443	$2,187,777	$261,907	$2,575,127
2034	$0	$0	$125,443	$2,209,655	$269,764	$2,604,862
2035	$0	$0	$125,443	$2,231,752	$277,857	$2,635,051

6.2.2 Flare Fuel Costs

The process of flaring LFG consumes minimal electricity; however, maintaining a continuous burn in the flare does incur operational costs. For the sake of simplicity, we assumed that both the operational and backup flares will run continuously to prevent any underestimation of costs. This is a reasonable assumption, considering the estimated annual fuel cost of $1,800 [32]. All other related expenses are excluded from this calculation. Taking these considerations into account, the total cost of flaring for the first-year amounts to $3,600, with a yearly increment of 3% projected over the lifetime of the project.

6.2.3 Electricity Consumption

The calculation of yearly electricity costs assumed that only the electricity consumed by the equipment specific to each strategy would be considered. Therefore, electricity used for general lighting, air conditioning, and other amenities is excluded from these calculations, as these costs can vary significantly and are much cheaper in comparison to the values being utilized. An electricity cost of $0.125/kWh is used [31]. It is also assumed that all operations will run continuously without stopping.

The electricity consumption of each strategy was approached differently. Firstly, for the RNG Production strategy, the primary electricity-consuming equipment is the compressor. Each compressor, designed to compress an amount of gas equivalent to roughly 20% of the LFG generated by the landfill to a pressure of 50 bar, requires an approximate load of 400 horsepower, equivalent to 300 kW. Additionally, an additional linear reduction of about 30 kW for the membrane application is included alongside the calculated compressor load. Lastly, the remaining equipment is estimated to consume approximately 50 kW of electricity.

In the electricity generation strategy, instead of incurring costs for the electricity used, it is subtracted from the total electricity generated, which can be sold. This electricity usage is simply the 50-kW estimated for the remaining equipment mentioned in the previous paragraph. On the other hand, for the flaring strategy, electricity consumption is negligible since the blower used in the collection system to boost the pressure of the LFG line falls outside the scope of this project.

6.2.4 Labor

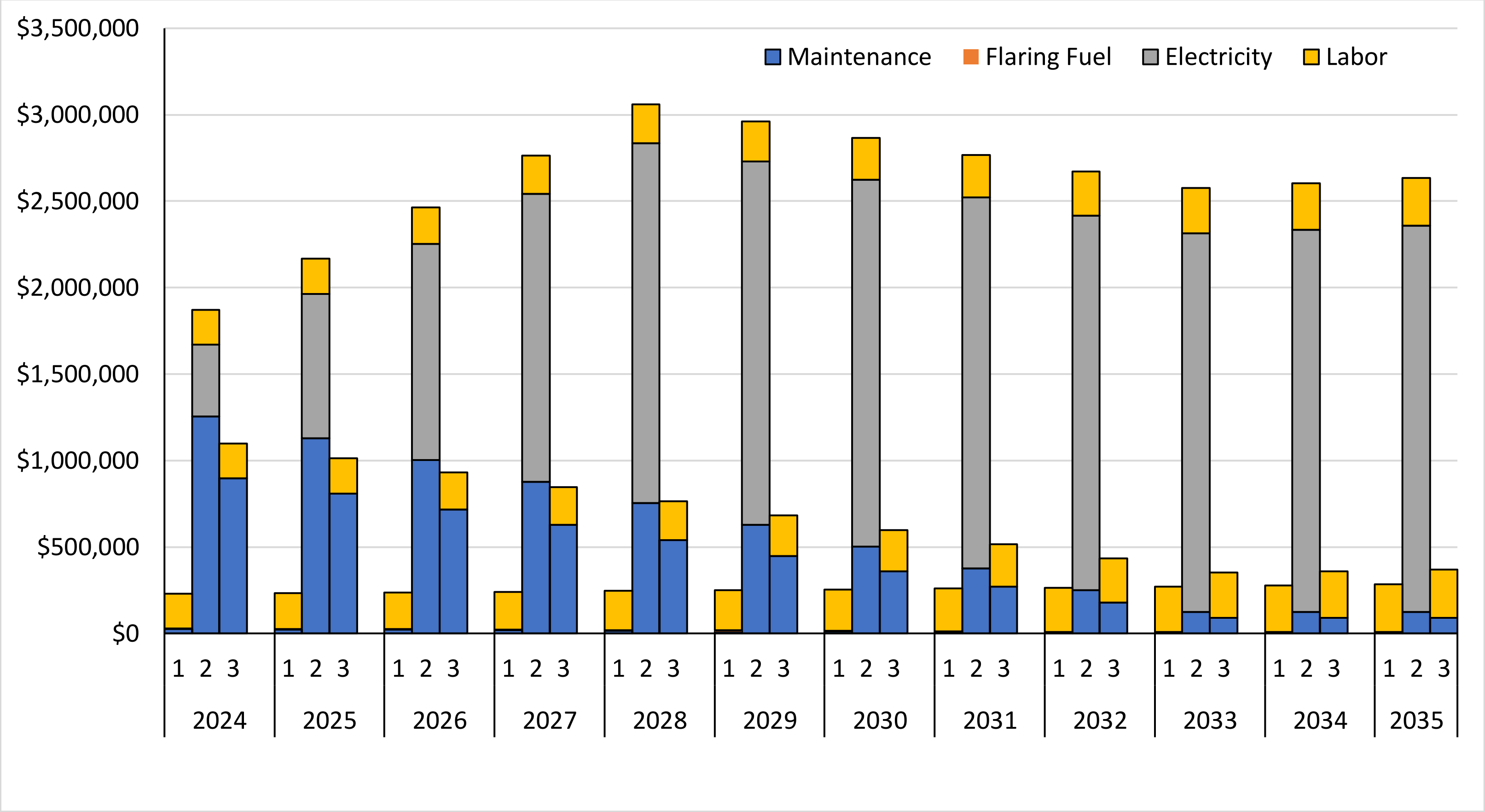
The computation of labor costs for each strategy was intentionally kept simple, focusing solely on the expense of operator labor. All calculations were made under the assumption of employing 3 operators. It is important to note that this cost can substantially differ depending on factors like location, and it may be possible to train existing landfill staff to manage the equipment, potentially reducing expenses.

For this analysis, a base salary of $66,910 per operator was adopted, with an annual increase of 3% [20]. Nonetheless, it is crucial to acknowledge that operator salaries can significantly fluctuate based on geographical factors. Hence, the actual costs should be customized to the specific circumstances of each project.

In the case of the flaring strategy, the predominant yearly expenditure pertains to labor fees. However, for the RNG production strategy, the cost dynamics evolve differently. As LFG collection and utilization increase, there is a gradual increment in electricity expenses. Notably, these expenses surpass the maintenance costs by 2026, making electricity costs the central economic factor for this strategy.

On the other hand, the electricity generation strategy follows a distinctive trajectory. The maintenance cost decreases gradually due to depreciation, eventually yielding to an intriguing shift. By 2032, labor fees outstrip maintenance costs, emerging as the primary annual expense for this approach, as illustrated in Figure 14.

These trends underscore the dynamic nature of the economic aspects within each strategy. Notably, the RNG production strategy exhibits the highest annual operating cost among the three. This is primarily attributed to the gradual decrease in maintenance costs due to depreciation, coupled with a concurrent rise in labor fees. Consequently, the distinction in annual operating costs between the flaring and electricity generation strategies gradually diminishes. Significantly, both the flaring and electricity generation strategies exhibit relatively lower annual operating costs.



Note: 1 – Flaring Strategy; 2 – RNG Production Strategy; 3 – Electricity Generation Strategy.

Figure 14. Annual Costs for Each Strategy in 12 Years Lifetime

6.3 Raw Profits

This section discusses the raw profits associated with each strategy, specifically the revenue generated through the sale of their respective products. Consequently, our focus in this section will be directed towards the production of RNG and electricity generation, as the flaring strategy does not yield a sellable product, thus exempting it from this discussion. In the context of RNG production, the pricing of the product is subject to significant fluctuations. Thus, the outcomes presented in this section are contingent upon prevailing market prices for these products.

6.3.1 RNG Production Raw Profit

The revenue from the sale of RNG is directly influenced by both the amount of RNG produced and its market price, typically linked to natural gas prices. Our choice of $4/MMBtu stems from the observation that, in most cases, natural gas prices typically fall within the range of $2-$6/MMBtu, with $4 representing a stable midpoint [33]. Table 15 provides insight into the production of RNG and its price when sold at $4/MMBtu, given that it is assumed that each cubic foot of methane is approximately 1,050 Btus [34]. The sales value undergoes substantial growth during the initial 5 years due to enhanced collection efficiency. Over time, it gradually rises in tandem with increasing LFG emissions from the landfill. Upon full operation of the RNG production strategy, the raw profit is estimated to reach approximately $4,800,000 annually.

Table 15. Raw Profit of RNG Production Strategy

Year	RNG Flow	Raw Profit
	tons/year	$
2024	7,854	$916,891.22
2025	16,130	$1,883,060.42
2026	24,771	$2,891,946.93
2027	33,716	$3,935,823.72
2028	38,624	$4,509,154.10
2029	39,240	$4,581,321.56
2030	39,785	$4,644,304.07
2031	40,262	$4,700,069.83
2032	40,671	$4,747,962.78
2033	41,022	$4,788,638.99
2034	41,315	$4,823,410.58
2035	41,553	$4,850,965.43

6.3.2 Electricity Generation Profit

The conversion factor used for turning LFG into electricity is outlined in Table 5, where 13,000 Btus yield 1 kWh. The estimated electricity consumption for each collection increment, mirroring the approach for RNG production, is set at 380 kW for simplicity in calculation. The electricity used in the process is deducted from the electricity product, and the surplus electricity is sold at a rate of $0.125/kWh [31]. The outcomes of these calculations are presented in Table 16. As seen in the data, electricity generation experiences a similar pattern to RNG production, with significant growth in the initial years due to enhanced collection efficiency, followed by gradual increases over the project's extended lifespan. With the electricity generation strategy in full operation, the anticipated annual raw profit amounts to around $9,800,000. This reflects the economic dynamics associated with electricity generation from LFG.

Table 16. Raw Profit of Electricity Generation Strategy

Year	Electricity Used	Electricity Product	Electricity Sold	Raw Profit
	kWh	kWh	kWh	$
2024	3.33×10^6	1.79×10^7	1.46×10^7	$1,825,976
2025	6.66×10^6	3.68×10^7	3.02×10^7	$3,772,463
2026	9.99×10^6	5.66×10^7	4.66×10^7	$5,823,417
2027	1.33×10^7	7.70×10^7	6.37×10^7	$7,959,941
2028	1.50×10^7	8.82×10^7	7.32×10^7	$9,153,884
2029	1.50×10^7	8.96×10^7	7.46×10^7	$9,330,373
2030	1.50×10^7	9.09×10^7	7.59×10^7	$9,484,399
2031	1.50×10^7	9.20×10^7	7.70×10^7	$9,620,777
2032	1.50×10^7	9.29×10^7	7.79×10^7	$9,737,901
2033	1.50×10^7	9.37×10^7	7.87×10^7	$9,837,376
2034	1.50×10^7	9.44×10^7	7.94×10^7	$9,922,411
2035	1.50×10^7	9.49×10^7	7.99×10^7	$9,989,798

6.4 Potential Profits

Aside from the profits obtained through product sales in each strategy, the reduction of the landfill's carbon footprint can also be considered valuable. However, this type of profit is more abstract compared to standard product sales and deserves a distinct discussion in this section. Two primary avenues for realizing the value of carbon footprint reduction are governmental incentives (such as 45Q Carbon Tax Credit) and the open carbon trading markets. Each pathway will be explored here, but it is important to note that the profitability in this context is contingent on the decisions made by the owner of an LFG project.

6.4.1 45Q Carbon Tax Credit

The 45Q Carbon Tax Credit is a tax credit for projects that capture carbon emissions, offering a range of credit values depending on project-specific conditions [16]. These values span from a minimum of \$12/metric ton CO_{2e} to a maximum of \$180/metric ton CO_{2e}. This is by far the highest potential source of income for this project, and in fact the reason for the analyzed lifespan being 12 years is because that is the length of time after installation that this credit is valid. However, as this credit's availability is contingent on local government funding, it was not further explored in the context of the Golden Triangle Landfill project.

6.4.2 Carbon Credit Market Trading

The concept of Carbon Credits involves companies being allocated specific emissions quotas, with the option to sell any unused allowances to other companies. While this system is primarily applied to high-GWP gases, including organic compounds, CO_2, and CH_4. This study explored three distinct carbon credit price points, each rooted in different sectors and industries. The lowest price, set at \$6/ton, originates from financial services companies, while the mid-range of \$25/ton is dictated by energy companies. Economists and climate experts set the high price at \$40/ton [35].

The figures presented in Figures 15 and 16 illustrate the prospective profits of each strategy over time at these various carbon credit prices. Interestingly, these carbon credit prices seem to have a negligible effect on the ultimate profits of the electricity generation strategy, suggesting that revenue from electricity sales significantly outweighs that from carbon credit market trading. However, for the RNG production strategy, the higher price of \$40/ton notably amplifies overall profitability. This implies that, for this project, revenue generated from carbon credit market trading surpasses that from RNG sales, as evident in Figure 16.

Comparing the final profits of all three strategies, including carbon credit market trading (\$40/ton), it is apparent that the electricity generation strategy is substantially more profitable, as depicted in Figure 17. Notably, the use of carbon credits in the flaring strategy renders its profitability nearly equivalent to that of the RNG production strategy.

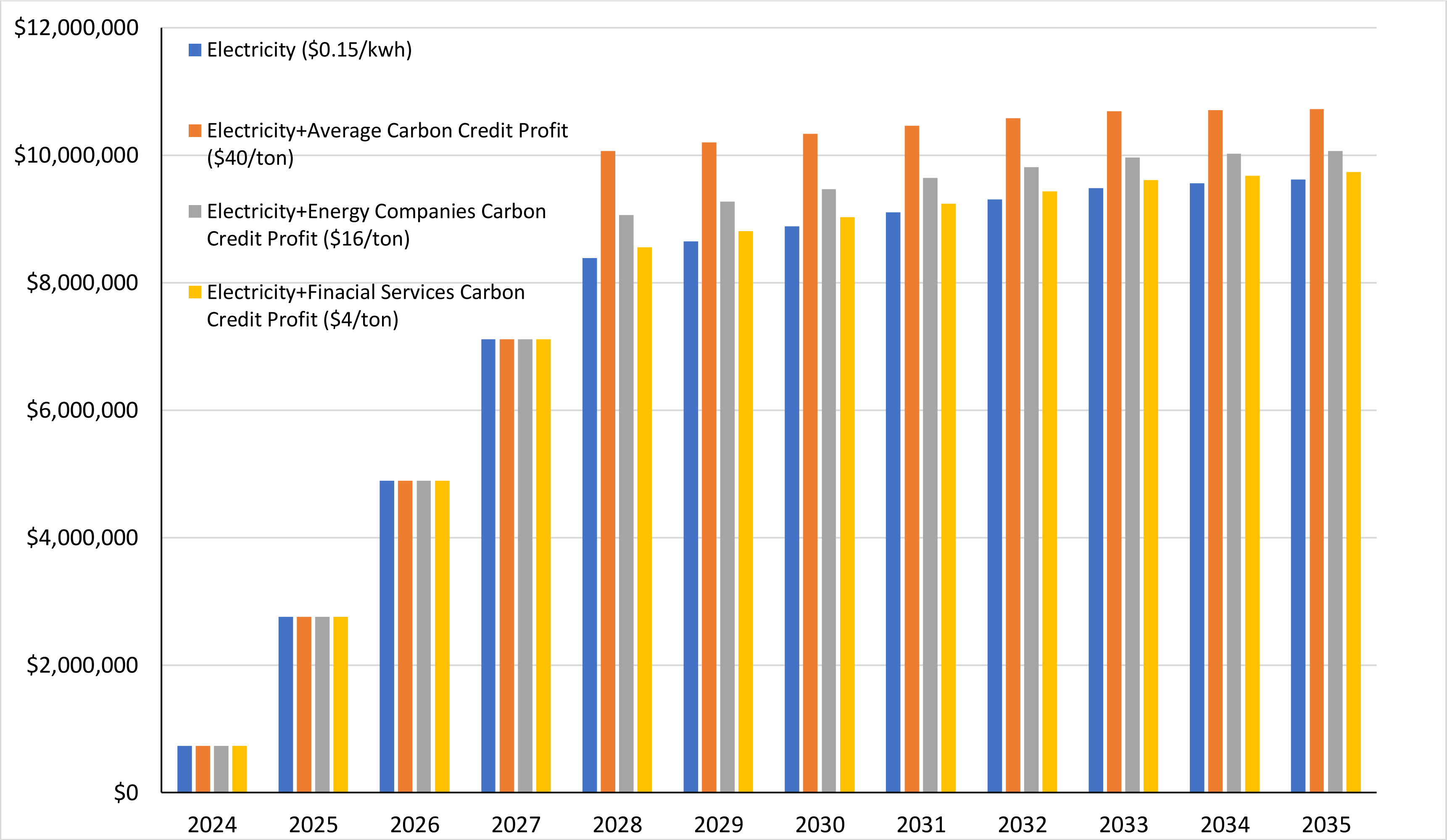


Figure 15. Annual Profit with Carbon Credits of Electricity Generation Strategy

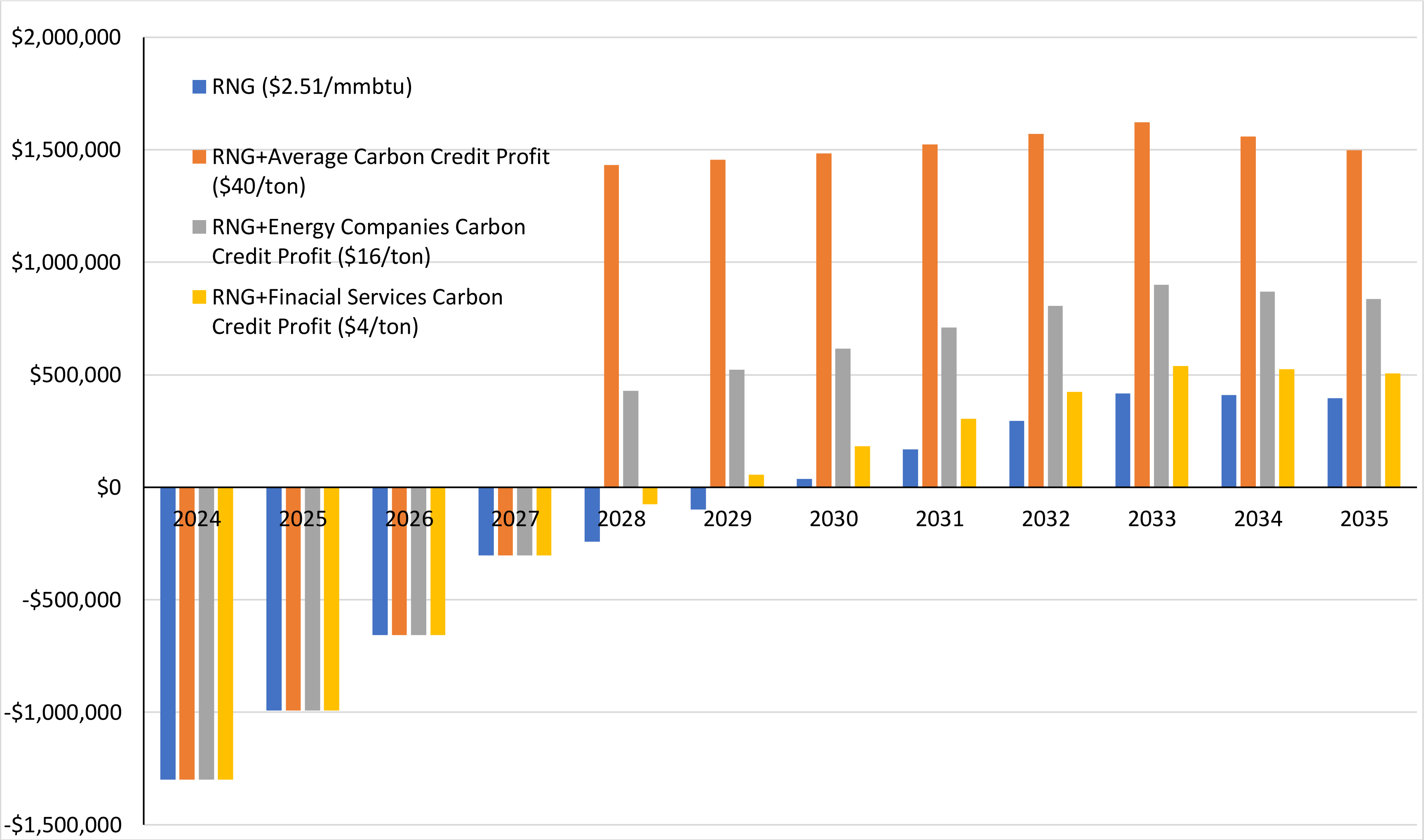


Figure 16. Annual Profit with Carbon Credits of RNG Production Strategy

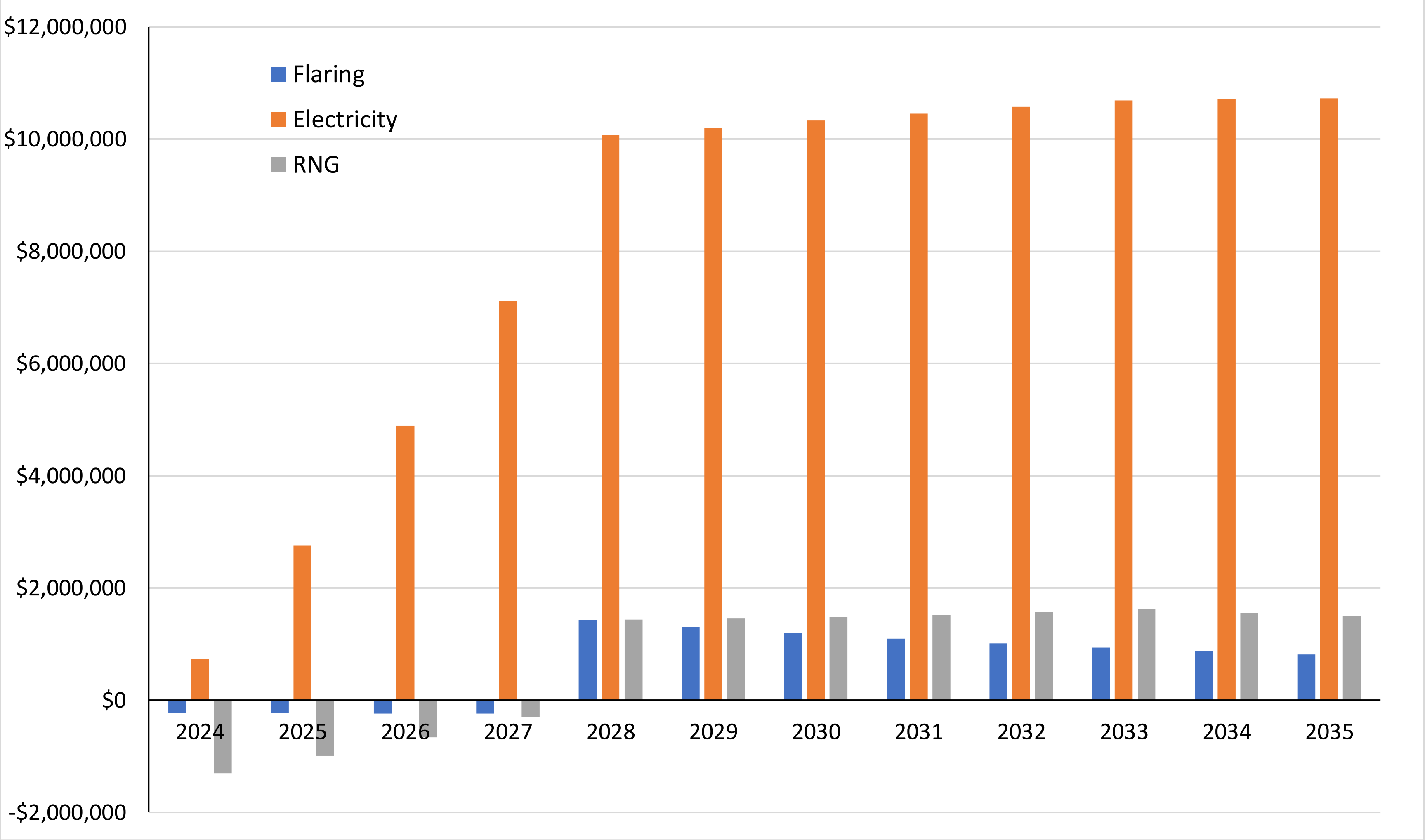


Figure 17. Annual Profit $40/ton Carbon Credits of Each Strategy

6.5 Internal Rate of Return

The internal rate of return (IRR) is a financial metric used to assess the profitability of an investment by quantifying the interest gained over the lifetime of project. In this case, we calculated the carbon credit price required to achieve a 7% IRR, which is considered a reasonable return.

The outcomes of this analysis are presented in Table 17. When using LFG for RNG production, a substantial initial investment is necessary, requiring a relatively high price of \$170/ton of CO_{2e} to reach a 7% IRR. On the other hand, the flaring strategy, with its lower initial investment in comparison to its carbon footprint reduction, can attain the same IRR with a lower price of \$5/ton.

Electricity generation strategy differs from the other strategies as its product holds high intrinsic value. Therefore, it naturally achieves an IRR of 39% even without factoring in carbon credits. Consequently, carbon credits primarily serve as an additional source of profitability for this strategy.

Table 17. Carbon Credit Prices for 7% IRR of Each Strategy

Strategy	Carbon Credit Price (\$)	IRR (%)
RNG Production	170	7
Electricity Generation	0	39
Flaring	5	7

7. Conclusion

The foundation of this report was built on the simulation used to predict waste acceptance and annual LFG emissions, particularly within the context of the Golden Triangle Landfill case study. Commencing with publicly accessible data, Scenario 3, which features a gradual increase and subsequent decrease in the waste acceptance rate, demonstrated the closest alignment with the actual landfill conditions. This scenario furnished the crucial data on yearly LFG emissions, forming the basis for the subsequent phases of the project.

The capital investment associated with each treatment strategy is predominantly influenced by the procurement and installation expenses for the necessary equipment. During the initial 5 years, an assumption is made that LFG collection efficiency experiences growth. In a comparative analysis of the strategies, direct flaring of LFG necessitates the most economical capital investment, while the conversion of LFG into RNG carries the highest costs. Electricity generation from LFG falls between these two extremes, with its investment magnitude closely aligned with the RNG conversion approach, rather than the more cost-effective flaring strategy.

When evaluating the carbon footprint reduction of each strategy, it is possible to dissect the carbon footprint into distinct components, including CO_2 emissions, CH_4 emissions, and Scope-2 emissions arising from electricity consumption. In both flaring and electricity generation approaches, LFG combustion leads to the conversion of CH_4 into CO_2, contributing to carbon emissions. However, for the conversion to RNG, the employed membrane effectively prevents the release of both CH_4 and CO_2, resulting in emissions solely from Scope-2 sources. This distinction underscores that RNG conversion yields the highest reduction in carbon footprint. Nevertheless, flaring and electricity generation methods are not far behind, achieving long-term reductions of 89% and 83%, respectively.

The profits generated by each strategy can be categorized into two groups based on their reliance on income sources beyond the sale of a tangible product. In the electricity generation strategy, it excels in both categories: electricity production itself is notably profitable, there is a local demand, and it constitutes a substantial portion of potential profits. Carbon credit market trading complements these gains. Conversely, for RNG production strategy, the initial investment size is such that depending solely on the product is insufficient to recover the initial costs. Here, the addition of carbon credit value makes a more significant difference compared to other strategies, but it remains challenging to achieve substantial profitability at current prices. Flaring, devoid of a sellable product, benefits from its low initial investment. With the assistance of carbon credits, it can still be profitable.

Every strategy for LFG treatment comes with its own set of advantages and weaknesses. At the prices considered in this study, the substantial initial investment needed for RNG production can be a significant barrier. Nevertheless, the product itself holds utility, and it boasts the highest carbon footprint reduction, indicating significant potential if market conditions are favorable. Flaring, with its cost-effectiveness and substantial carbon footprint reduction, presents a compelling option for widespread use with a focus on environmental impact. Meanwhile, the electricity generation strategy stands out as a highly profitable approach while also contributing significantly to carbon footprint reduction. Therefore, given the conditions assessed in this study, the utilization of LFG for electricity generation emerges as the recommended strategy overall.

The results of this study can be furthered in a number of ways. Transitioning the labor calculation into a formulaic approach would provide a more precise cost projection. Additionally, employing a more realistic operating schedule, as opposed to continuous operation, would yield more accurate outcomes. Altering equipment choices, such as incorporating distillation, could influence both costs and profits.

References:

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