Capturing Value From Natural Gas: Mitigating the Flaring of Natural Gas in North Dakota

A comprehensive report on pathways for mitigation of natural gas flaring

Energy and the Environment Certificate
Duke University
Design Capstone Report

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Abstract:

Gas flaring, which has increased dramatically in the United States due to the shale gas and oil boom, poses a large environmental danger as well as economic waste. Due to the lack of infrastructure in certain areas and un-feasibility of transporting natural gas in other areas, much of the gas found in oil focused plays is flared. To address this issue in the most time effective and broad scope manner possible, three different approaches were taken to solve this issue. The approaches taken involve utilizing the flare gas to produce feedstock, producing electricity and flue gas to do on sight enhanced oil recovery, and transporting the gas to act as fuel for logistics and distribution companies. These methods were chosen due to their potential economic and technological feasibility, factors crucial in solving such an issue. The actual applicability and feasibility of each method varied, yet overall could be met with success given certain circumstances.

Introduction:

Everyday natural gas is being flared into the atmosphere at oil recovery sites around the world. This flare gas is not only an air pollutant, but is also a valuable potential source of energy that is being lost. The purpose of this report is to provide oil production groups with alternative uses for these natural gases that are currently being flared. Such alternatives will help these productions groups comply with increasingly stringent regulations by eliminating flaring and providing both environmentally beneficial and economically profitable returns for the production groups.

The bulk of this study is focused on the Bakken Shale formation in North Dakota; an area known for its oil production. North Dakota as a state is responsible for approximately 40% of all natural gas flaring in the United States.

Flare Gas Problem:

Flammable natural gas is flared at oil and gas wellheads during the extraction process in an effort to reduce the negative impacts of venting excess gas into our atmosphere. On a worldwide scale, annually over 140 billion cubic meters of natural gas is flared resulting in more than 350 million tons of CO2 emissions *(World Bank, 2015)*. The following countries represent the five largest producers of flare gas: Russia, Nigeria, Iran, Iraq & the United States *(World Bank, 2012)*. Within the United States, (1) North Dakota and (2) Texas are by far the biggest producers of flare gas. Flaring in North Dakota's Bakken and in Texas's Eagle Ford in 2013 combined to produce the equivalent CO2 production of 1.5 million cars (*Earthworks, 2014*).

Though the environmental problems created as a direct result of flaring are significant, even more staggering are the amount of economic opportunities lost from flaring the wasted gas. Annually, the amount of lost flare gas worldwide is equivalent to over 20% of the United States' total natural gas energy consumption *(World Bank, 2015)*. Solving this hurdle requires an economically feasible and profitable solution that is attractive to established oil & gas companies. According to publicly accessible company data, North Dakota oil companies have flared more than $854 million (96 billion cubic feet) of natural gas since 2010 (*Earthworks, 2014*). In 2013 alone, 12 companies in the Bakken region flared more than 3 billion cubic feet of gas, with 8 of the top 10 flaring more than 35% of their total volume production (*Earthworks, 2014*).

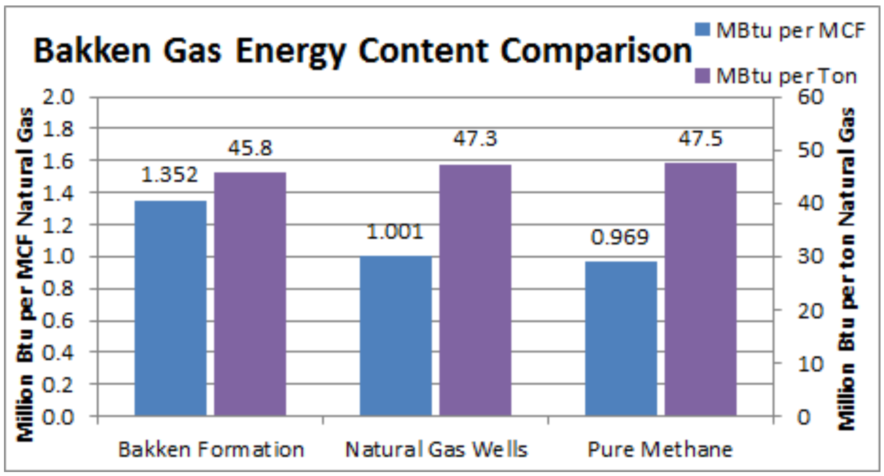
Bakken Natural Gas Composition Analysis:

As one of the most important energy source in the U.S., natural gas has very high heat content. However, the actual amount of heat to be harvest depends on the composition of the gas mixture. Understanding the gas composition would enhance the estimation of the energy that is wasted from flare gas as well as estimating the environmental impact of the greenhouse gases and other pollutants. This section is devoted in provide an overlook of the flare gas content of the Bakken formation of North Dakota.

Oil field associated gas, particularly that in the Bakken formation, is very rich in higher alkanes. According to North Dakota Pipeline Authority, one thousand cubic feet of raw natural gas from a Bakken/Three Forks contain around eight to twelve gallons of higher alkane (NDPA, 2012). As a result, natural gas collected at the well heads of Bakken formation, contains only approximately 68% natural gas, far lower than the volume concentration found in a typical natural gas well (90%-95%) as well as certain literature values of oil wells(81% and 86%) (Manbw, 2011)(Shell, 2004). The specific alkane components of Bakken formation natural gas are listed as the following:

		Higher Alkanes (Natural Gas Liquid)				
	Methane	Ethane	Propane	Butane	Pentane C5	Decane C10
Volume	1 MCF	10 Gallon				
Mass percentage	100.00%	46.99%	24.53%	14.79%	6.32%	7.37%
Chemical Conc.	68.30%	19.80%	7.00%	3.20%	1.10%	0.70%

Due to the higher heat content and heavier mass per molecule of higher alkanes, the lower methane concentration in the Bakken natural gas leads to slightly higher energy content per volume. yet, this is almost fully offset by the increase in mass. Based on the combustion heat and heat capacity of each chemicals, a model was constructed to calculate the composition impact of the energy content. The result found the Bakken oil associated gas contains 1.352 million Btu per MCF, or 45.8 million Btu per ton. This is approximately 35% more energy per MCF, but 3.2% less energy per ton when compared to natural gas produced from a typical natural gas wells.



Other typical impurities found in flare gas includes carbon dioxide (CO_2), water (H_2O), nitrogen (N_2) and hydrogen sulfide (H_2S). As natural product of natural gas combustion, CO_2 and H_2O are excluded from the calculation. N_2 is a stable gas content and found abundant in the atmosphere, thus involved neither in the combustion processes nor the bacteria fixation. H_2S is the major source of sulfur in oil and gas and would be oxidized to sulfur dioxide (SO_2). Both component would lead to decrease in the energy content of the natural gas, but the impact is marginal due to the low concentration found in natural gas (1% N_2 and H_2S would decrease the natural gas heat value by 0.81% and 0.54% respectively). In addition, an extra cost could be associated with desulfurization of the natural gas or the waste gas. High sulfur content is gas is also found corrosive to equipment. Study found relatively low sulfur content in the Bakken crude oil (~ 0.14% sulfur weight) as well as the associated gas (~ 10 ppm). (NDPC, 2014) (AFPM, 2014)

However, exceptions of high sulfur content have been reported. Current technologies, such as wet scrubbers have effectively lower the cost of both desulfurization and the emission allowance.

Regulations:

Regulatory policy is now in place at both the federal and state level to help combat the negative environmental impacts of natural gas flaring. At the federal level, the United States Environmental Protection Agency passed laws requiring control measures to be phased in for Reduced Emission Completions (RECs) by January 2015 *(EPA, 2012)*. The Bureau of Land Management also requires a 12.5% royalty (waived with pre-approved permits) for flaring on federal land *(GAO, 2010)*. Despite restrictions, at the state level North Dakota allows for gas to be flared for “up to a year without payment of royalties to private owners of the mineral rights or taxes to the state” *(Earthworks, 2014)*. These specific policies are outlined in the imposition of tax and payment of royalties section in N.D. Cent. Code § 38-08-06.4 on the control of gas and oil resources *(North Dakota Legislative Branch)*.

The North Dakota Industrial Commission has put in place a set of regulations, restrictions and resulting penalties for those who decide to continue to flare at high levels. The following are case specific examples of currently enacted policy efforts.

North Dakota Industrial Commission Goals:

1) Cut flaring to 5-10% of production volume by Q4 2020 from current ~22%
2) Improve communication between producers & midstream companies
3) Require detailed gas capture plans to obtain drilling permits

Regulation Noncompliance Violations:

1) Well production volume restrictions

    1) 200 barrels a day if below current threshold but above 60% captured

    2) 100 barrels a day if below 60% captured

Harsh Penalties & Fines:

1) Initial penalties start at $1000 a month

2) Failure to adhere to notices can increase penalties up to $12,500 per well per day

Exemptions from these rules and regulations can come at special request from members of industry to state officials. The following is guidance policy outlined in a recent North Dakota Industrial Commission order that states the most common reasons for exemption.

Exemptions:

1) surface landowner, tribal, or federal government right-of-way delays

2) temporary midstream down-time for system upgrades and/or maintenance

3) federal regulatory restrictions or delays

4) safety issues

5) delayed access to electrical power

6) possible reservoir damage

Environmental Risks & Health Impacts:

Although flaring is far less than an ideal option, the process is an effective short-term solution to avoid simply venting natural gas into the atmosphere. The flaring process avoids releasing massive amounts of this methane and other dangerous chemical compounds, but that is not to say it is without its flaws. It creates significant byproducts of atmospheric contaminants that are damaging to our earth and overall well-being as well. Among the atmospheric contaminants produced are: oxides of nitrogen, carbon and sulphur ($NO2$, $CO2$, CO, $SO2$), particulate matter, hydrocarbons, ash, photochemical oxidants and hydrogen sulphide *(Obioh, 1999)*. While carbon based pollution certainly contributes to rising global temperatures, methane is responsible for trapping as much as 25 times more heat within our atmosphere *(Podesta, 2015)*.

Excess heat from flaring sites is known to also destroy the growth of surrounding vegetation, as well as do harm to other forms of life in the immediate area (e.g. birds). The atmospheric contaminants produced also exacerbate the growing problem of acid rain, which damages crop yields, depletes surrounding soil nutrients and erodes infrastructure.

This process can also have direct detrimental human health effects, as these air pollutants and atmospheric contaminants can cause cancer, neurological, reproductive / developmental effects, deformities in children, lung damage, skin problems, as well as negative effects on blood and blood-forming cells that can cause anemia, pancytopenia or leukemia *(Kindzierski, 2000)*.

Project Design Introductions:

Given the vast scope of the problem, three separate approaches were taken to solve this issue. Each approach looked at the issue a different way, leveraging different technologies to utilize flare gas in the most effective way.

Project #1

On-Site Flare Gas Utilization
Generating Electricity and Flue Gas for EOR

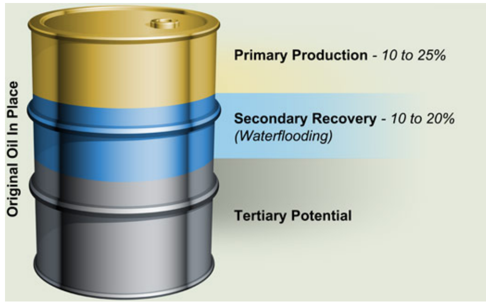
1.0 Introduction:

The purpose of this project design is to provide oil production groups with an on site system that will utilize flare gas in an enhanced oil recovery process. Ideally, this system will effectively eliminate flaring and provide an environmentally beneficial and economically profitable use for the natural gas that is currently being flared. The design we have come up with is intentioned to capture almost all flare gas at the wellhead, compress it, store it, then burn it to both generate electricity and flue gas. The flue gas we produce will then be used as a reinjection agent which will allow oil companies to better increase the yield of their oil field. We believe that leveraging existing and proven technologies in the process we have designed will both be technologically feasible and economically beneficial.

Mission Statement: *Our goal is to provide oil production groups with an on site system that will utilize flare gas in an enhanced oil recovery process. This system will effectively eliminate flaring and provide an environmentally beneficial and economically profitable use for the natural gas that is currently being flared.*

2.0 Project Background and Analysis

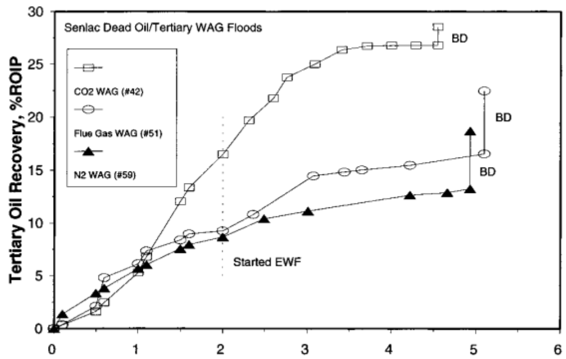
2.1 Enhanced oil recovery (EOR):

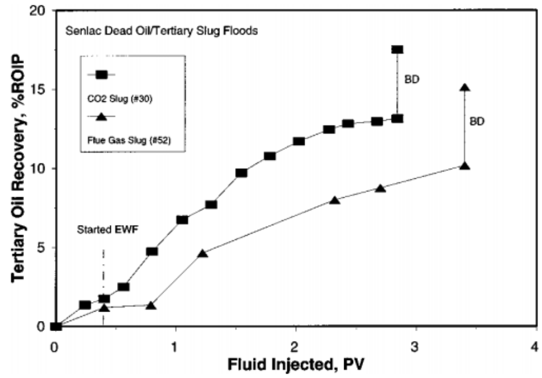


The avenue our technology will create a niche in the market is through addressing the growing demand by the oil industry to increase the yield of producing oil fields. Traditionally, oil production follows three stages; primary, secondary, and tertiary. Primary recovery is the first stage where oil production is simply a by product of drilling into the well formation and allowing the natural porosity of the rock create the flow of oil into the well pipe. In the case of North American onshore production this stage has very frequently entailed hydraulic fracturing, where the tight shale rock is made more porous by creating subsurface perforations and expanding them by injecting high pressure hydraulic fluid. This first stage typically recovers 10-25% of the total recoverable oil in a formation. Secondary recovery is the process of injecting some fluid, typically water, nitrogen gas or methane into the well to increase subsurface pressure which in turn increases porosity and flow rate. In the case of many onshore and offshore wells, particularly in North America, natural gas is re-injected into wells which are focused on oil to increase their yield. Secondary recovery typically increases yield by 10-20%. Finally, Tertiary recovery is the process of injecting high purity, temperature and pressure CO_2 into the well. This gas then becomes miscible with the oil below the surface and greatly increases recoverable amount of the well by almost 25%. Our project is a combination of secondary and tertiary recovery. Because flue gas is not >95% CO_2, this cannot be considered tertiary as flue gas will not be fully miscible with oil. However, given the relatively high concentration of CO_2 that we will be producing, our process could have some of the similar effects as tertiary recovery. And given the very high concentration of N_2 and increased sub-surface pressure, our project has many of the similar characteristics of secondary recovery.

2.2 Flue Gas Injection Analysis:

Flue gas is the purified exhaust of fuel combustion, with ~ 85% of N_2 and ~15% CO_2. Flue gas is selected considering the limited CO_2 availability in the area and the energy and cost advantage of avoiding large scale gas separation. Compared to pure CO_2 injection, which has a typical yield of 2 barrels of oil recovered per ton of carbon dioxide injected, flue gas injection is about half efficient in oil return by volume injection. However, considering the low concentration of CO_2 content in the flue gas, flue gas is much more efficient in terms of the amount of of CO_2 consumed. In addition, flue gas is a lower cost option compared to pure CO_2 injection. The high cost and inaccessibility of high quality of CO_2 has been a limiting factor of tertiary oil recovery. Using the readily available flue gas from onsite combustion would vastly decrease the cost of purification and separation of CO_2 from Nitrogen. Thus although the injection of larger amount of flue gas is more energy intensive, less energy will be required for the gas preparation compared to pure carbon dioxide injection. A study in United Kingdom shows that flue gas has a oil return efficiency between pure carbon dioxide and nitrogen injection, with approximately 50% recovery rate compared to CO_2 injection (Srivastave et al., 1999). This result is illustrated in the graphs below:





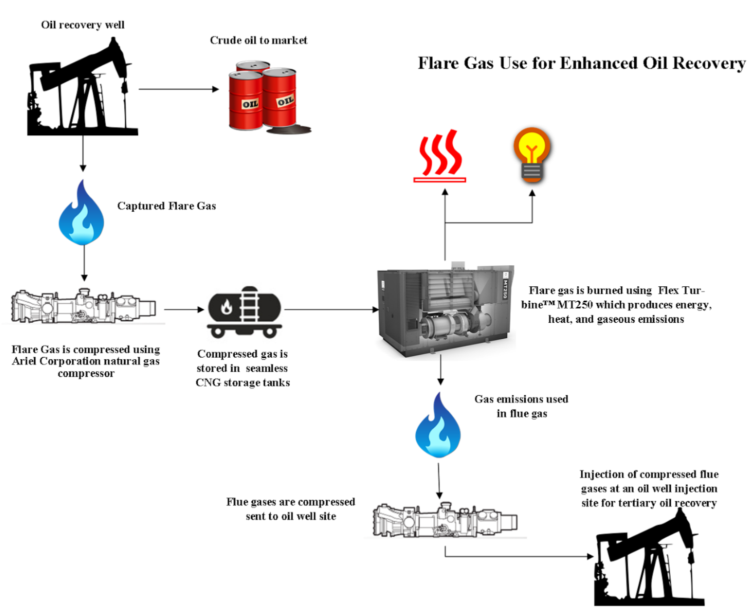
As previously discussed, associated gas from the Bakken Formation has a higher proportion of high alkane. As a result, a higher percentage of CO_2 is found in the combusted exhaust. Based on the calculated gas composition, complete combustion of **each ton of natural gas in air would require 17.24 ton of air and yields 15.43 ton of flue gas**, including 2.88 ton of CO_2 (18.6%) and 12.55 ton of N_2 (81.4%), as well as 2.02 ton of H_2O and 38 kg SO_2. In reality, a slightly lower amount of air will be supplied to exhaust the oxygen and prevent underground combustion and explosion during injection and enhanced oil recovery.

2.3 Field Analysis:

Our project is focusing on 9 oil and gas producing fields wells in Bowman County, North Dakota. The company which operates all of these fields is Continental Resources which is one of America's leading onshore tight oil exploration and production companies. Of particular note, it is important that Continental Resources is almost entirely focused on oil production, indicating a willingness to find alternative uses for natural gas encountered at each well. Each field has an average oil production of **38.4 barrels per day**. Additionally, each field uses an average of **83 barrels of water per day**. These fields were chosen due to their tight geographical grouping as well as their consistent and large volumes of gas flared, **209 thousand standard cubic feet per day**. Because these fields are mainly focused on oil production, most gas that is found during the production process is flared. Furthermore, their production of gas consistently exceeds their amount flared per day, indicating the potential to replace old technologies in exchange for our, potentially more efficient ones. It is important to note that many of these fields produce natural gas and sell it to existing pipeline infrastructure. But because pipeline infrastructure is limited in this region, the only practical means of dealing with the gas is to flare it. Data on our field is in our attached spreadsheet, Onsite Flare Utilization.

3.0 Technological process analysis:

3.1 Process Overview:



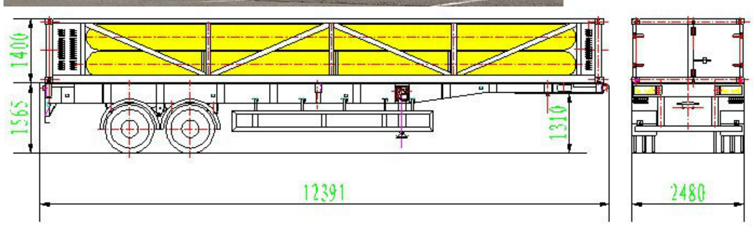
This project will be operated fully on site to avoid transportation cost. Gas collectors will be used to replace the flaring towers. The technical process is illustrated in the graph above. The originally flared gas will be capped, compressed and contained on the sizable scale. On site storage will be used to overcome the intermittency of flaring. Once sizable amount of flare gas is stored, it will be delivered to the turbine unit for combustion and electricity generation. Here the chemical energy will be convert to electricity and the flue gas exhaust will be harvested and cooled to separate water. Finally, the waste gas is recompressed on site and injected underground to enhance oil field pressure and viscosity, thus increase the oil recovery. The following sections will provide a detailed look at the parameters and the techniques we will be using through the EOR processes.

3.2 Gas Capture and Compression:

Based on the daily production index provided by North Dakota Oil and Gas Division, the nine sites selected for the case flares approximately 209 MCF on average per day. However, flaring events are highly intermittent and the emission is concentrated on a few hour window. Study in 2004 conducted by Shell Inc. found out that flow rate of the gas coming out of the system varies between 1500 and 7000 pounds per hour (Shell, 2004). The majority of time the flow rate ranges between 1500 - 2500 pounds per hour with spontaneous minute-long spikes peaking at 7000 pounds per hour. Based on average flow rate of 3000 pounds per hour, each well flares approximately 4 hours per day.

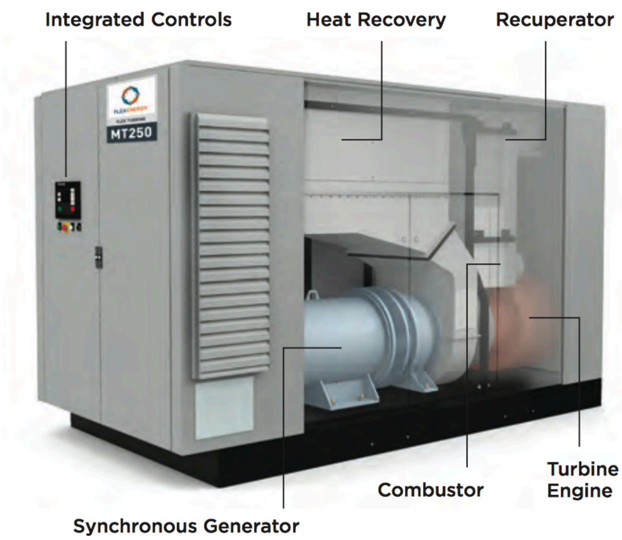
To capture the majority of flare gas and compress it to a sizable volume, the Ariel Corp 6 Throw JGA/6 Compressor has rated power will be used for the project. The compressor had a rated power of 840 boiler horsepower (BHP), which sufficiently accommodates the maximum flow rate of 7000 pounds (660 BHP). The natural gas will be compressed to 2.5MPa and delivered to storage. An industrial standard flowmeter will be installed to monitor the gas flow prior to compression. In events or emergence, or extreme large flow, the excessive amount natural gas will be released to reduce pressure to diverted to the compressor for re-compressing the exhaust gas if not combustion and injection take places.

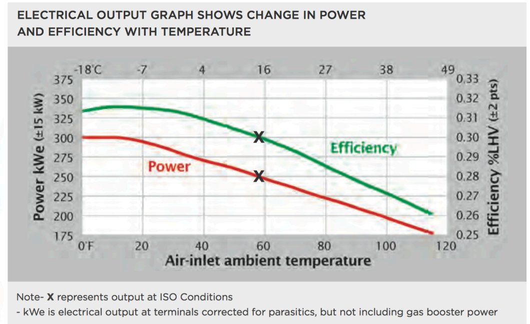
3.3 Gas Storage:



Compressed flare gas will now come to the storage tanks at a pressure of 25 MPa. The gas will be stored in a 12 tube container set manufactured by Yukun Machinery Equipment Co., Ltd. in China. The tube sets are 40 feet in length and weighs 3.8 ton without loading. The container set will be capable of storing 294,000 standard cubic feet (scf) of flare gas at a pressure of 25 MPa. This helps to solve the intermittency problem of flare gas. Using the accompanied semi-trailer, the tank can be delivered to the turbine for combustion and electricity generation.

3.4 Gas Combustion:

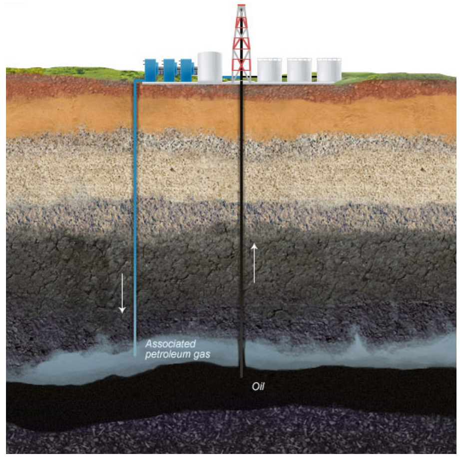




Nominal heat rate (HHV)	13,341 kJ/kWh without gas booster 13,800 kJ/kWh with gas booster
Voltage	480 VAC/400 VAC
Frequency	60 Hz/50 Hz
Type of service	3 phase, wye, 4 wire
Grid-isolated regulation (steady state)	±0.50% nominal voltage ±0.50% nominal frequency
Transient handling (linear loads) (recovery within 5 seconds)	±10% nominal voltage max ±5 Hz frequency max

For the combustion process we have chosen to use the FlexTurbine M250. The advantages of using this turbine system are two fold. First, the technology can operate at a high level of efficiency even using a dirty fuel source, such as flare gas. At a rate of 2,483 scf/hour, the FlexTurbine will generate 250 kw/hour and will produce 40,000 scf/hour of flue gas and 4,000 scf of hot water steam. Operating at an efficiency of 30% (13,341 kj/kwh nominal heating value), provides efficient reaction given cost. The second great advantage of this technology is the company is very willing to lease us the technology at a reasonable rate. While we have not been able to get the exact costs, the estimated annual cost of leasing such a turbine is $25,000 per year. We are very confident that this technology will provide our customers with a significant amount of electricity each year as well as the flue gas which we can use as a reinjection agent.

3.5 Flue Gas Reinjection:



Once the flare gas has been used to generate electricity, the product of this process will be flue gas. Collecting that flue gas at the exhaust end of the combustion process will allow us to then recompress the gas and inject it directly back into the well via reinjection manifolds. this high pressure flue gas will hopefully increase the yield of the oil field significantly. Gas desulfurized will be compressed and pressurized to 8.17 MPa to meet the flue gas enhanced oil recovery standard. This can be done using ArielCorp 4 Throw JGA/4 with rated power of 540 horsepower (the same JFA/6 for flare gas compression will suffice as well).

4.0 Environmental Impact Analysis

For each of the nine Continental Resources wells used in this analysis, there are 209,000 cubic feet of gas flared per day. This translates into 76,285,000 cubic feet of natural gas per year, or approximately 2268 tons of natural gas per year. Currently these gases are being combusted which emits a number of greenhouse gas emissions. As stated in the chemistry analysis, for each ton of this gas that is combusted in the presence of air, 2.876 tons of CO_2, 12.55 tons of N_2, 2.202 tons of H_2O, and 38kg of SO_2 are produced. Of particular interest to environmental impact analysis are the emissions of CO_2 and SO_2. By capturing and recycling the natural gas for use in flue gas, approximately 6,490 tons of CO_2 and 86.18 tons of SO_2 would be no longer be emitted into the atmosphere each year.

An equivalent amount of greenhouse gas emissions highlighted above would likely be saved in addition to the emissions saved by flare gas capture. This is based on the assumption that the flare gas used in on site power generation is replacing another source of power generation that uses natural gas and produces comparable emissions.

In addition to gaseous emissions, this system also has the potential to save water resources surrounding the area of well sites. The process of flue gas enhanced oil recovery would be replacing secondary and tertiary enhanced oil recovery techniques which utilize water and carbon dioxide, respectively. On average 945,000 gallons of water are used per well site per year. With the elimination of this demand for water there would also be a complete reduction in all emissions related to processing and transportation of that water.

Data used from North Dakota Industrial Commission

5.0 Business Model and Plan:

Business Structure:

To deploy our technology in a manner which will meet commercial success and bring value to our founders, we have found that a lease and release model would be best suited. Thus, the broad terms of any contract reached with an oil firm would be an Owner's Engineering Agreement, which would guarantee total control of our intellectual property. Furthermore, to maintain tax efficiency and lure investors the company's structure would be that of an Master Limited Partnership. The benefits of a Master Limited Partnership is that it practically makes any shareholder in the company a Partner in the business who is entitled to any cash distributions the company makes. In addition to that, Shareholders do not need to pay capital gains tax on distributions until the total distributions collected reaches the par value of equity, allowing for the shareholder to defer tax liabilities. This structure, in addition to the lease and release model would enable our business to start-up with little paid-in capital as well as grow significantly quickly without much more capital. However, given that we are forgoing equity in the majority of our Property Plant and Equipment, we lose a significant amount of the upside. But given the initial high-capital requirements and our shareholders risk profile, we believe the lease and release model to be the best suited.

Deployment Plan:

Our business plan moving forward is comprised of 3 stages and will take an estimated 2 years.

Stage 1 (6 months): From inception, we will need 6 months to do further research and development on our technology. Specifically, we will need to secure our procurement efforts with specific vendors who offer the most attractive terms and technology. While we have done a fair deal of analysis, more will need to be done. Additionally, in this first stage we will involve field testing, where we will conduct small scale tests on the technologies we choose to ensure they could withstand the parameters of our process design.

Stage 2 (1 Year): This stage will largely comprise of ensuring that our company has the necessary federal and state licenses to operate safely and freely. This will require a deal of litigation to ensure we meet all the requirements we must as well as have done so in the most cost efficient manner. Additionally, at this stage we plan on approaching either a large domestic oilfield services or parts manufacturing company to partner with. We believe partnering with a large well established organization will add legitimacy to our efforts as well as ensure that we have the ability to approach larger companies with our technology. Some of these companies include National Oilwell Varco, Schlumberger, Halliburton or Weatherford.

Stage 3 (6 Months): In this final stage we plan to do our first commercial demonstration and then fully go to market with our technology. To do the demonstration application, this may require approaching an independent exploration and production company and offering them exclusive terms for a given number of the first units we produce.

Using this business structure and roll out plan, we believe that our technology has the best chances of being commercially successful and will bring significant value to our founders.

5.1 Economic Analysis

An analysis of the financials of our technology reveals an attractive and economically viable venture. Below is a table with the investment and cost details.

Building/Installation Costs	$20,000.00
Compressor Cost	$85,000.00
Storage Tank	$80,000.00
Total Investment	$185,000.00
Annual Turbine Lease Cost	$75,000.00
Yearly Operating and maintenance	$35,000.00
% of Equity	20%

Cost of Capital	$58,403.89
Yearly Costs	$168,403.89
Generator Capacity (kW)	250
Efficiency	30%
Uptime (Hours)	24
Total Electricity Production per Generator (kWh)	2,190,000.00
Total Gas Usage(mscf)	24,908.72
# of Generators needed/site	3
% of Electricity Used by Our Equipment	5%
Total Electricity Equipt. Consumes (kWh)	328,500.00
Total Electricity Sold to user (kWh)	6,241,500.00
Price of Electricity (kWh)	**$0.034**
Total Electricity Revenue	$212,211.00
Total Flue Gas Reinjected (mscf)	385,088.89
Increased Yield of Field (bbls/year)	19,607.38
Marginal Cost of Service per barrel	**$10.82**

EBITDA	**$102,211.00**
IRR	**57%**

For number verifications see Attached Onsite Flare Spreadsheet

Because we are only buying few assets, the initial capital we need is relatively low. As displayed in the figures above, the equity portion we plan on committing is 20%, thus leaving the rest of our financing to traditional bank means. Assuming a 4% rate and a 4 year term, this gives us an attractive cost of capital for the short term following our deployment. If contracts are unable to be extended past 4 years, or duration of the loan, our IRR is still above 20%. However, it is important to note that the effective marginal cost per barrel of our system is above $10. In calculating that we assumed that each tones of flue gas injected will produce 1 barrel of oil. For further explanation see the Flue Gas section above.

6.0 Conclusion:

Our project provides a unique way for domestic oil and gas producing companies to utilize flare gas in an economically and environmentally beneficial manner. Using existing technologies, our project has the high potential to be technically feasible and economically viable. Given the higher costs producers are already paying for electricity on site using diesel, our project definitely would provide value to the oil companies. Additionally, the flue gas we can re-inject for the oil producer will likely increase the total yield of the oil field, which obviously would provide value.

However, given the relatively high cost of our system and the potential for little yield increase, our technology would not be very practical. While it would be a means to generate electricity on site and use flare gas, the reinjection component adds significant risk of gas fouling which would yield the project worthless. Thus, at current oil prices below $60 a barrel, our project would not make much sense as it adds a $10 marginal cost per barrel. However, if oil prices begin to rise above their historical low, to say $75, then our technology would be practical and would add value.

Project #2

Using Flare Gas to Power FedEx

Dylan Brown| Isaac Fraynd | Ryder Quigley

1.0 Introduction

In this section of the report, we explore the last pathway to mitigate the flaring of natural gas. By creating a company focused on utilizing the natural gas for the transport of FedEx vehicles, an economically viable investment opportunity became apparent. The sections below will explore the following aspects in detail: (1) Company Structure and Partners, (2) Location and Sites, (3) Equipment Required, (4) Real Estate, (5) Environmental Analysis, (6) Financials.

2.0 Our Team

From the beginning, our Team's mission was to mitigate the harmful effects of natural gas flaring. With that in mind, we sought to combine the most efficient technologies in order to combat this problem head on. Settling on the unique solution to power FedEx's fleet vehicles with natural gas came through partnerships with other companies, FedEx's demand for fuel, their national presence (and proximity to North Dakota), and need for physical locations. By connecting natural gas capture, compression, transport, and a distribution center, our Team has created a way to mitigate the flaring of natural gas, reduce dependence on gasoline for transport, improved FedEx's green image, all while turning an investment profit. In the same way as the Enhanced Oil Recovery team (EOR), our structure is best served by a Master Limited Partnership (MLP). The details and benefits of the MLP structure are outlined in EOR Section 5.0.

2.1 Partnerships

Our Team is pleased to be working with some of the top companies in the world. FedEx, an international delivery service, has a unique need for fuel and a desire to be green. Their reliance on physical distribution centers across the country makes them a prime candidate for this opportunity. Wrightspeed, an electric powertrain manufacturer, allows the natural gas to be used for transport. It is important to note that although FedEx is the company of choice for this report, there are many other companies that could be potential users of this structure.

2.1.1 FedEx

FedEx, an American global courier delivery service, is considered a world leader. Covering over 220 countries and connecting more than 99% of the world's GDP, FedEx combines technology, transportation, information, and ideas in order to deliver the world's packages. They operate a fleet of approximately 47,500 motorized vehicles (FedEx).

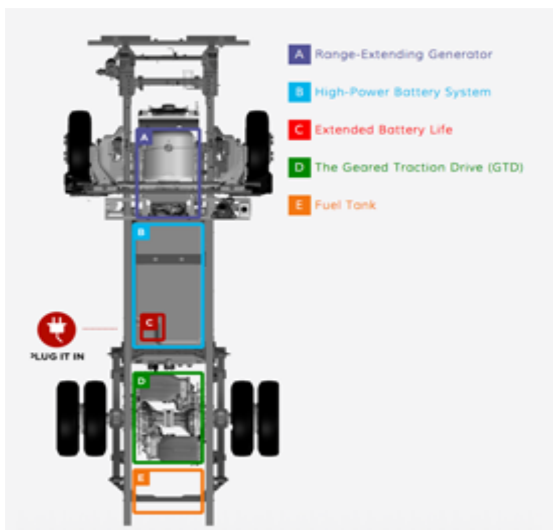
From a sustainability point of view, FedEx is considered an innovator. From their mission statement, "We constantly strive to do more with less, reducing our environmental footprint even as we deepen the ways we connect the global economy." In addition to initiatives such as EarthSmart, FedEx has been searching for alternatives fuels such as CNG, LNG, and electric vehicles. In 2013, Chairman and CEO Federick Smith noted that over the next 10 years, he expects between 5%-30% of US trucking to be fueled by CNG or LNG (Wall Street Journal).

With FedEx already testing multiple CNG and alternative fuel trucks in the field, they are perfectly positioned to take advantage of our unique opportunity. They have partnered with

WrightSpeed, an electric drive train based on CNG, and deployed many pure CNG trucks. On average, CNG trucks cost $50 to fill up each day compared to the $100 required for diesel (BBC).

FedEx Ground is the core of the corporations' business model. Over the most recent fiscal year, FedEx Ground and its subsidiary, Fedex SmartPost, delivered a rough average of 6.7 million packages on a daily basis (FedEx). Consequently, the company accounts for an elaborate distribution supply chain, which ensures effective service for every client across the country.

2.1.2 Wrightspeed

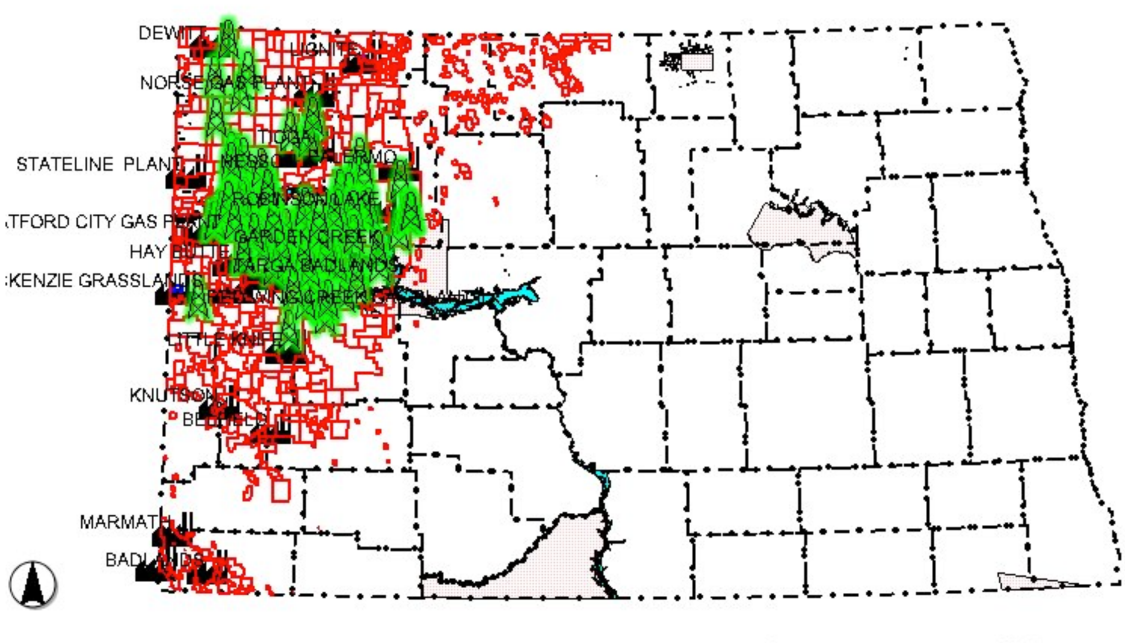


Wrightspeed, an electric vehicle powertrain company, was founded by Tesla co-founder Ian Wright and is headquartered in San Jose, California. Their main product, the Wrightspeed Route, is a plug and play repower kit for commercial vehicles (Wrightspeed). It uses an electric drive powertrain in combination with a power station for efficiency and range. The kit includes a 200kW inverter, electric motors, gear box with clutch-less shifting, battery pack, battery management system, and LCD operation interface (Wrightspeed). Their primary client is FedEx, with the company recently purchasing 25 electric powertrains after testing two initially (BBC).

Their drivetrain is primarily composed of a small gas turbine. This micro turbine can burn diesel, biofuel, or compressed natural gas in order to spin a generator. This generator creates electricity, which is used to charge the batteries. These batteries run the electric motors, which are mounted to four drive wheels. The Route system employs geared-traction drive, comprising a two-speed gearbox with clutch-less shifting that delivers 125 to 250 continuous horsepower and 18,000 pound-feet of total axle torque (Wrightspeed).

3.0 North Dakota

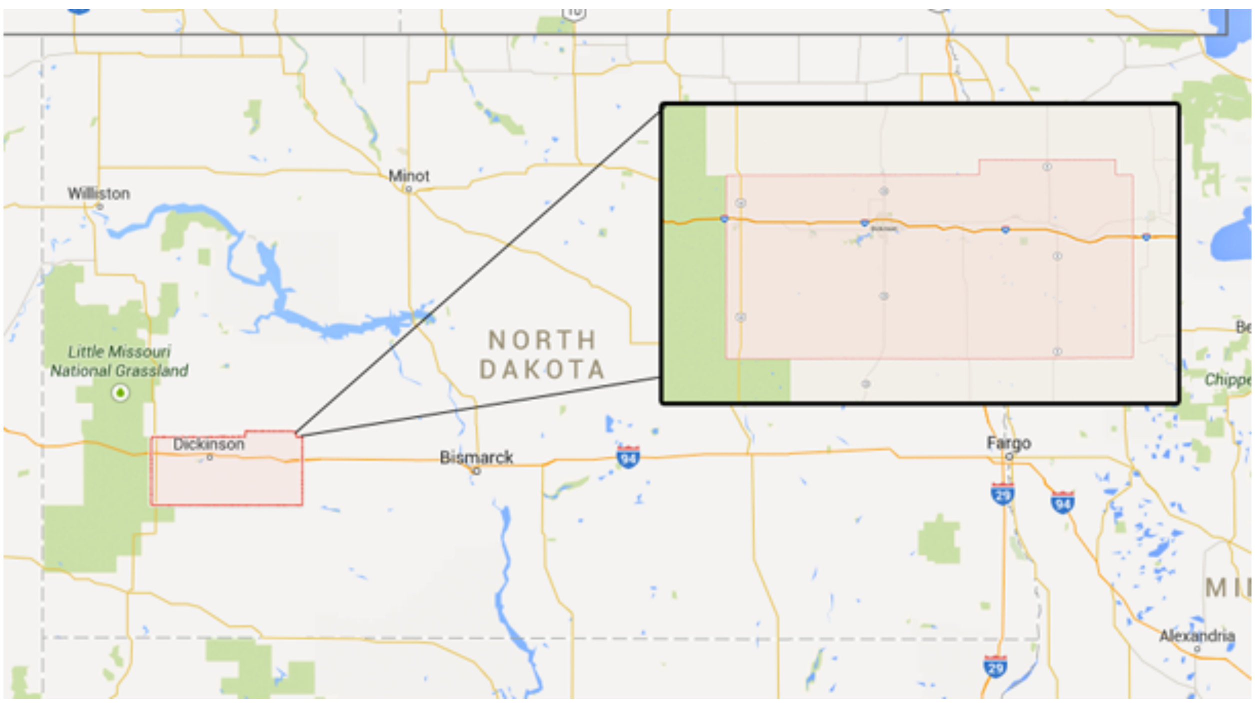
North Dakota, as previously noted, is a state where a majority of the US natural gas flaring takes place. It is important to note that flaring does not occur purely out of necessity (although it does occasionally to maintain flow rates). Natural gas flaring occurs primarily due to lack of infrastructure. That is to say, the transportation pipelines and gas treatment facilities are not available all over the state. The map below shows the network of wells and gas treatment facilities across the state (NDIC).



3.1 Stark County, ND

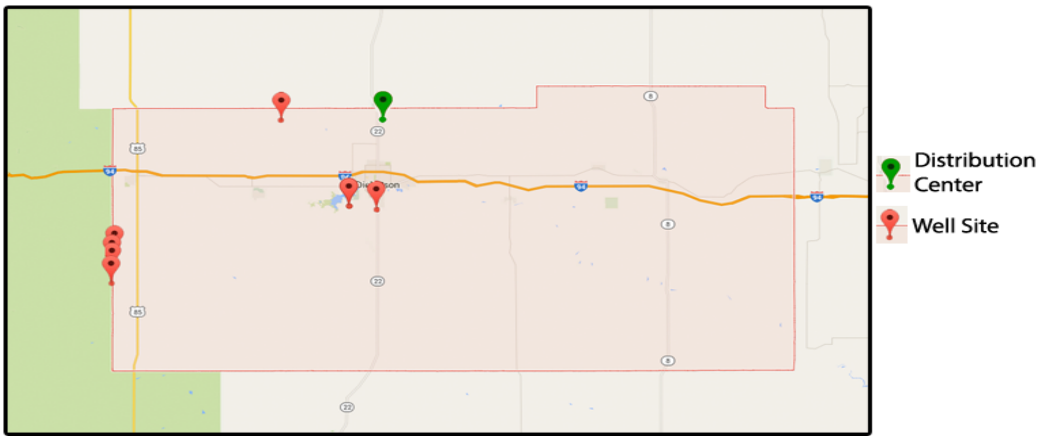
Stark County, ND is located in the southwest part of North Dakota and has approximately 25,000 people as of 2010 (US Census). Its county seat is Dickinson. Since the ND oil boom, Dickinson has become one of the fastest growing cities in the United States. FedEx has daily cargo flight service between the two of the main airports in the state (DIK and GFK).

We have chosen Stark County due to its proximity to many existing well sites. Within approximately 15 miles, there are seven active well sites. By placing a FedEx distribution center within a reasonable distance to both the well sites and Dickinson, we will be able to economically service the surrounding area.



3.2 Oil Well Locations

All of the wells utilized for this analysis are located in Stark County, North Dakota. According to the North Dakota Industrial Commission, Oil and Gas Division, there are 11 active well sites, 7 of which are currently producing and flaring (NDIC).



NDIC File No: 9830 API No: 33-089-00285-00-00 County: STARK CTB No: 109830 Well Type: **OG** Well Status: **A** Status Date: **2/23/2006** Wellbore type: **VERTICAL** Location: SWNE 33-139-96 Footages: 2630 FNL 1500 FEL Latitude: 46.810883 Longitude: -102.795247
NDIC File No: 14141 API No: 33-089-00474-00-00 County: STARK CTB No: 414141 Well Type: **OG** Well Status: **A** Status Date: **11/11/2003** Wellbore type: **DIRECTIONAL** Location: NESE 18-139-96 Footages: 1425 FSL 1050 FEL Latitude: 46.850925 Longitude: -102.835700
NDIC File No: 15043 API No: 33-089-00556-00-00 County: STARK CTB No: 115043 Well Type: **OG** Well Status: **A** Status Date: **1/31/2002** Wellbore type: **HORIZONTAL** Location: SWSW 19-138-99 Footages: 500 FSL 500 FWL Latitude: 46.746994 Longitude: -103.228792
NDIC File No: 15116 API No: 33-089-00558-00-00 County: STARK CTB No: 115116 Well Type: **OG** Well Status: **A** Status Date: **6/13/2001** Wellbore type: **HORIZONTAL** Location: SWSW 7-138-99 Footages: 450 FSL 145 FWL Latitude: 46.776049 Longitude: -103.230204

NDIC File No: 15283 API No: 33-089-00561-00-00 County: STARK CTB No: 115283 Well Type: **OG** Well Status: **A** Status Date: **7/4/2002** Wellbore type: **HORIZONTAL** Location: SESW 6-138-99 Footages: 180 FSL 1440 FWL Latitude: 46.789722 Longitude: -103.224845
NDIC File No: 15305 API No: 33-089-00562-00-00 County: STARK CTB No: 115305 Well Type: **OG** Well Status: **IA** Status Date: **7/20/2002** Wellbore type: **HORIZONTAL** Location: NWSW 18-138-99 Footages: 1890 FSL 145 FWL Latitude: 46.765471 Longitude: -103.230348
NDIC File No: 15609 API No: 33-089-00569-00-00 County: STARK CTB No: 115609 Well Type: **OG** Well Status: **A** Status Date: **10/28/2004** Wellbore type: **HORIZONTAL** Location: SWSW 5-140-97 Footages: 415 FSL 160 FWL Latitude: 46.964406 Longitude: -102.956574

3.2.1 Oil Well Data

The data for the flaring amounts over the last five years of each well site were averaged in order to come up with approximately 10 MCF per site per day (NDIC). Although there are currently only seven sites actively flaring, we have extrapolated the data to allow for 10 sites. This will produce approximately 100 MCF per day, enough to power approximately 35 FedEx vehicles. *See gas demand per vehicle and calculations in section 7.0 Economics.*

4.0 Site Equipment

In order to be able to properly utilize the flare gas, a certain amount of infrastructure must be established. The gas must first be captured, then compressed, stored, and transported. It must then be stored again before being used to power the fleet vehicles. A compressor and storage tank is required for every well site, trucks are needed for transport, and a final storage tank at the distribution center is necessary.

4.1 Compressor

Similar to the EOR team, we will utilize the ArielCorp Throw JGA/6 at each of our ten sites. Although we do not have the same flow rate and capacity requirements as the EOR team (our flow rates and gas capture amounts are significantly less), we plan to utilize this larger compressor in order to account for varying flow rates. The natural gas will be compressed to 2.5MPa and stored in onsite storage tanks.

4.2 Storage Tanks

Industrial sized storage tanks (~10 MCF) will be utilized to store the newly compressed gas. The project requires a total of 13 storage tanks. This includes a storage tank for every site (10), one for every delivery truck (2), as well as a larger (~200 MCF) at the distribution center (1).

4.3 Transport

After purchasing the trucks, we will need to hire drivers in order to transport the gas. Each driver will make one trip per day to five sites. This means that we will need to hire two (2) drivers in order to accommodate the ten well sites. On average, each site is approximately 15 miles from the distribution center, with clusters of sites. The daily trip for each driver will be ~90 miles.

5.0 Distribution Center

FedEx Ground accounts for network of more than 500 distribution hubs and local pickup-and-delivery terminals located throughout the United States and Canada (FedEx). Accordingly, real estate is a large consideration for FedEx, with substantial exposure to rental expenses in addition to the firm's sensitivity to fuel expense. Thus, our investment thesis for the distribution center is advantageous to FedEx by limiting both their risk to rental and fuel expenses.

The investment approach consisted of the acquisition of an existing property rather than developing the property ourselves. In order to determine the ideal location for the distribution center, two key factors were considered. In order to ensure lower proprietary transport cost and more timely fuel distribution to the respective tenant, proximity to well sites is an essential factor. In addition, it is important the facility's location is in proximity to relatively urban areas with considerable demand amongst the population.

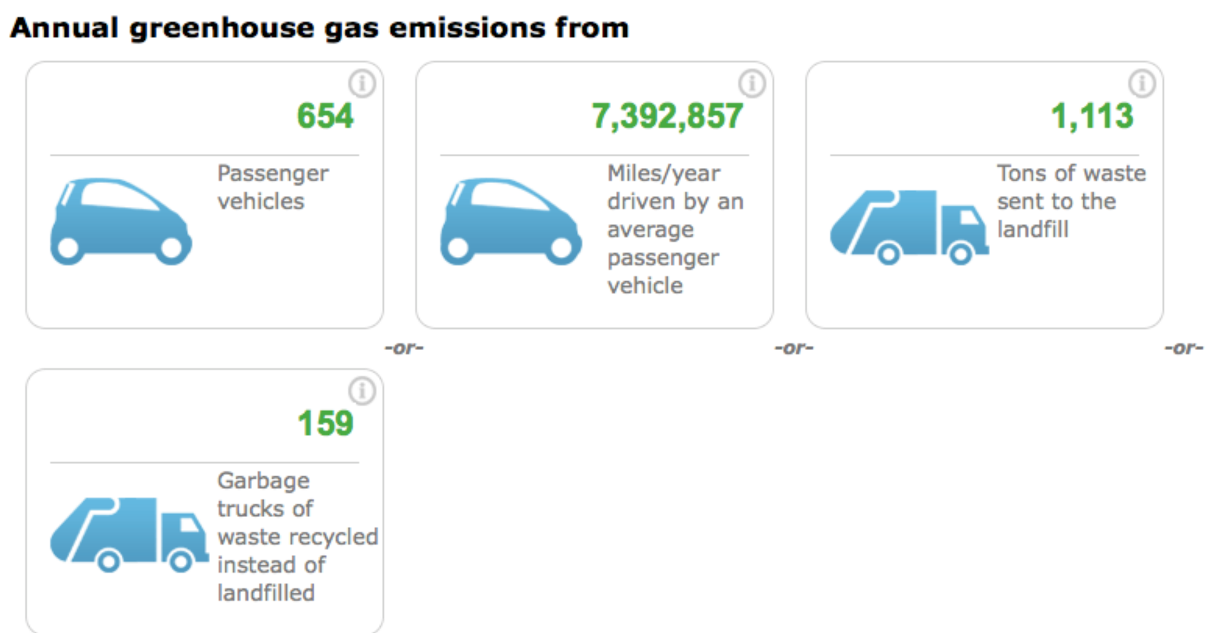
We identified the following property: The Distribution warehouse, Located on Hwy 22 & 31st St SW, Dickinson, ND 58601 (LoopNet). This location fit our criteria for the project requirements.

Located at an average distance of 15 miles away from our well sites, travel costs can be minimized in addition to providing efficient delivery service to FedEx. The property accounts for 6 acres of land, and a warehouse size of 23,750 square feet. Price at $20 dollars on a square foot basis, the property was valued at a substantial discount relative to its respective market (LoopNet). In addition to the investing in acquisition of the current property, 25% of the property value in renovation expenses was factored into the initial investment, in order to satisfy FedEx's needs. Overall, the projected upfront investment for the property came out to be $593,750.

After discussing potential rental rates with knowledgeable commercial and industrial property brokers in the surrounding area (Everett Real Estate Inc.) we concluded that the optimal range for annualized rents ranged from $15-$25 per square foot. After factoring in a rent premium, consequent of the free fuel that will be provided, we projected an efficient rental rate of $17 dollar a square foot for a 15 year contract.

6.0 Environmental Analysis

Across the 10 well sites used for this model, approximately 36.5 MMCF would be captured over a year. This equates to 1,080 metric tons of natural gas repurposed instead of flared. From the chemistry analysis done for the EOR team, each ton of gas combusted in the presence of air produces 2.876 tons of CO_2, 12.55 tons of N_2, 2.202 tons of H_2O, and 38kg of SO_2. This means that over 3,105 tons of CO_2 would be avoided. CO_2 equivalents are below (EPA):



7.0 Economics

Property Acquisition & Renovation Costs	$593,750.00
Compressor Costs (10 units)	$850,000.00
Storage Tank Cost (13 units)	$140,000.00
Total Truck Cost (2 units)	$160,000.00
Total Investment Costs	$1,743,750.00
Yearly Operating and Maintenance Costs	$74,727.27
Yearly Fuel Costs	$30,660.00
Equity Share	35%

Loan Rate	8%
Loan Term	10 years
Yearly Minimum Debt Payment	$216,183.00
Yearly Variable Costs	$301,343.00
Contract Period	15 Years
Daily Gas Demand per Vehicle (MSCF)	2,533.40
# of Vehicles at Facility	35
Average Gas Flared per well site (MSCF)	9
Well Sites Utilized	10
Size of Distribution Center (Sq. Ft.)	23,750
Annual Rent (Sq. Ft.)	**$17.00**
Annual Rent Revenue	$403,750.00
Depreciation Period	20 Years
Effective Tax Rate	28%
EBITDA	**$298,362.73**
IRR	**13.27%**

8.0 Conclusion

By combining capture, compression, transport, and rent, we were able to create a midstream gas company infrastructure. This allowed for an economically feasible business plan to combat natural gas flaring in Stark County, North Dakota. Roughly $2.02MM of investment is required to fund this project. These funds will be obtained in the private markets. On a 15-year investment horizon projections show the potential of ~13% return for investors. In addition, the project is expected to breakeven after 7 years.

There are also abundant benefits for the surrounding area that will result from the project. If the gas is utilized rather than flaring, the environmental and health effects are mitigated. In addition, the use of flare gas reduces our dependence on gasoline for transport. The project can also contribute to the long-term job creation in the community, potentially contributing to the urbanization of the area as well. An added benefit may come in the form of tax credits, due to increased regulation on flaring. Overall, the environmental and economic benefits of this project make it an attractive investment opportunity.

Project #3

Utilizing Methane-Oxidizing Bacteria to Produce Animal Feed

Paul Burgess | Max Orenstein | Ilhan Savut

1.0 Introduction

This section of the report explores the economic feasibility and environmental impact of industrially cultivating aerobic methanotrophic bacteria on natural gas to create an animal feed supplement. The environmental impact of both mitigating carbon dioxide emissions by growing the bacteria and the benefits of replacing conventional animal feeds with a bacterial meal are discussed in length. Finally, we present an in-depth economic analysis of a centralized bioreactor and processing factory in the Bakken oil fields in North Dakota that uses trucks to transport compressed natural gas from well heads.

2.0 A Biological Solution

Methane (CH_4) is the simplest alkane and its most oxidized form in the presence of oxygen is carbon dioxide (CO_2). Combustion of methane gas during flaring produces carbon dioxide, but the energy stored in the organic bonds of this hydrocarbon is lost in the form of heat (Energy-

Harvesting Pathways). However, there are certain prokaryotic microorganisms, known as methylotrophs, which are capable of growing on carbon compounds that lack carbon-carbon bonds (Madigan). Methanotrophs are a specific subgroup of methylotrophs that can strictly oxidize methane and use it as their energy source in catabolic[1] processes or as their carbon source in anabolic[2] processes.

This section explores the basic pathways for methane oxidation and the type of aerobic bacteria that is best for methane consumption. Additionally, this section looks at four different products that can be made using methanotrophic bacteria and outlines the benefits and limitations of each.

2.1 Types of Methane Oxidation

In terms of the carbon cycle, there are two main sinks of methane: aerobic oxidation by methanotrophs, as introduced above, and anaerobic oxidation by Archaea. Nonetheless, growing the latter group poses the inherent problem of maintaining an anoxic environment under atmospheric conditions, which is both costly and difficult. In addition, unlike aerobic forms, the metabolism of anaerobic methane oxidation has not been extensively researched and is not well understood (Chistoserdova). For example, a pure culture of an anaerobic methane-oxidizer had not been isolated by 2013 and extensive research of literature did not yield any evidence that such undertaking has been successful since then (Vigneron). Therefore, the focus of this report is aerobic methanotrophs.

Aerobic methanotrophs are further classified into numerous subgroups based on structural and biochemical properties but tend to have the enzyme methane monooxygenase (MMO) in common, albeit in different forms. For the purposes of this report, *Methylococcus capsulatus*

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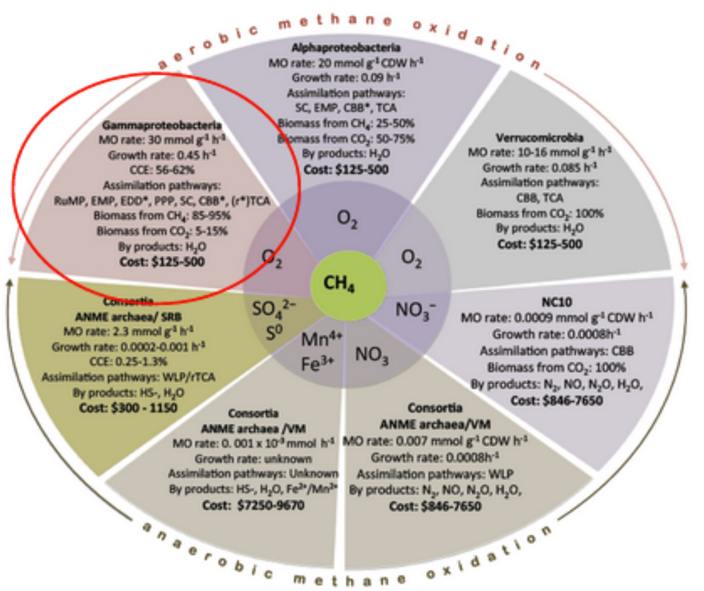
[1] Catabolism: breakdown of organic compounds to release energy

[2] Anabolism: synthesis of complex molecules for cellular use (for example, ATP)

was determined to be the most appropriate species for three reasons (Bothe). First, it is a species that is genetically and biochemically understood. Second, it belongs to the gamma-proteobacteria class of bacteria, which show robust and efficient growth in the presence of high methane concentration. Third, it is a Type X gamma-proteobacteria, which have both types of the methane monooxygenase enzyme (pMMO and sMMO), making them versatile and capable of growing in a variety of conditions.

Figure 2.1.1: Types of Methane Oxidation



Despite methanotrophic versatility, it is unrealistic to expect a completely sterile growth environment at an industrial scale. Thus, further research on the topic suggested that the growth media would have to consist of a "bacterial consortium" (Bothe). *M. capsulatus* exhibited higher growth rates in the presence of non-toxic species from two other genera of bacteria, namely *Bacilli* and *Ralstonia*. The impact of these symbionts was twofold. To begin with, they removed longer hydrocarbons found in flare gas (i.e. ethane, propane, and butane) and protein waste, which are toxic to *M. capsulatus* at high concentrations (Bothe). Moreover, the removal of these hydrocarbons prevented invading bacteria from contaminating the culture, since the medium was free of organic carbon that is essential for their growth. The specific growth and treatment conditions are outlined in Section 3.

2.2 Alternative Products: Why Animal Feed?

Three other alternatives were examined before being deemed impractical and abandoned in favor of animal feed. These are discussed below.

2.2.1 Formaldehyde production

Formaldehyde is an intermediary of the RuMP and serine cycles employed by methane oxidizing gamma and alpha-proteobacteria (Madigan). Formaldehyde is a chemical product of considerable value and has a large market due to its numerous uses. Nonetheless, it would be hard to isolate because it is an intermediary and because of its location (formaldehyde is not excreted but instead remains in the cell). This would greatly limit its production.

2.2.2 Biofuel

The dried biomass of the bacteria could be made into pellets and used as a fuel source. Yet, this would require the active dehydration of the bacteria cultures (passive dehydration is insufficient for the pellets to be combusted). This process is theoretically limited since the energy stored in the biomass cannot offset the energy required for dehydration.

2.2.3 Bioplastic production

Alpha-proteobacteria can produce polyhydroxybutyrate (PHB), a high quality polymer that can be made into plastic products. However, currently PHB cannot be produced at appreciable levels and has a very narrow range of conditions under which it can be properly isolated. This option should be pursued in the future, when appropriate catalysts become available, since theoretically it can be cheaper than oil-based plastics and is also biodegradable.

3.0 Methods

The conditions, infrastructure, and processes necessary for growing *Methylococcus Capsulatus* and the heterotrophic strains are discussed below as well as the processes of turning the biomass into a bacterial meal.

3.1 Growth Conditions

Despite *Methylococcus Capsulatus'* robust consumption of methane, it cannot survive alone in a pure natural gas environment due to a number of toxic contaminants (Overland). Thus three additional non-toxic species from the bacteria genera *Bacilli* and *Ralstonia* are employed to consume the longer hydrocarbon contaminants (Bothe). The four strains of bacteria are grown in a fermenter with different percentages: *Methylococcus Capsulatus* makes up the majority of the culture at 80%, while the other three are DB3 19%, DB4 0.3%, DB5 0.5%, respectively (Bothe). The heterotrophic bacteria are not only important for eliminating natural gas contaminants and reducing the solution's toxicity, but their presence is also quite significant at 20%. These strains will ultimately be filtered out during the production of animal feed.

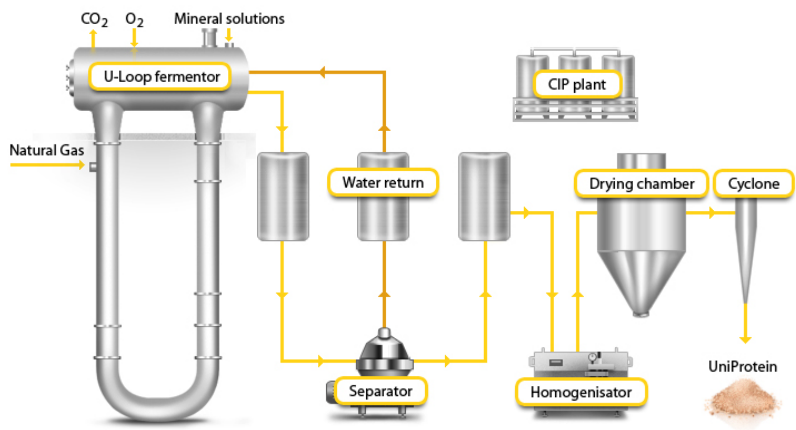
The bacteria are first grown in a loop fermenter where natural gas is added in addition to ammonia, oxygen, and a mineral solution (Overland). By nature of the fermenter, the methane from the natural gas has a long residence time in order to achieve maximum consumption. Equation 3.1 shows the chemical equation with inputs and outputs for the production of biomass (UniBio):

$$CH_4 + 1.454\ O_2 + 0.105\ NH_3 \rightarrow$$
$$0.520\ (\text{biomass}) + 0.480\ CO_2 + 1.69\ H_2O \qquad \textbf{(Eq. 3.1.1)}$$

Because the loop fermenter allows for high methane consumption, the biomass yield is impressive: 2 cubic meters of methane produces 1 kilogram of dry biomass (Overland). This yield was a critical assumption in our economic analysis and a sensitivity test was explored to observe the change in the internal rate of return due to potential uncertainty in the yield.

A significant amount of water is actually produced during this process - an important environmental benefit when compared to the water intensive production methods of conventional animal feed. CO2 is also produced, but in lower quantities when compared to flare gas. These benefits are discussed in length in **Section 4**.

Figure 3.1.1: UniProtein® Growth and Treatment Diagram



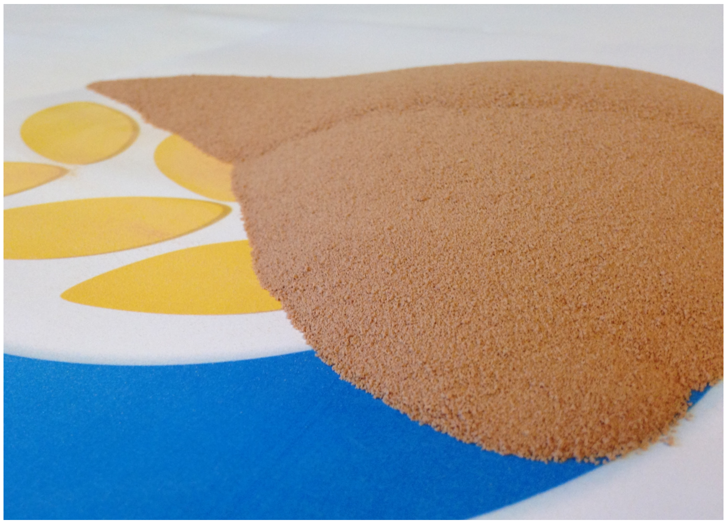
3.2 Treatment Process

Bacteria are continuously harvested from the loop fermenter and go through a number of treatments before it is sold as animal feed. It is first transported from the loop fermenter to a separator where water is removed and recycled. Bacteria are then centrifuged and ultra filtered to remove the heterotrophic stains. The bacteria are then finely blended, heat inactivated, and dried to produce the final product (Overland).

3.3 Animal Feed Characteristics

The particles are about 200 micrometers in diameter, dust free, and can be added directly into an animal feed mix as a dietary supplement. The bacterial meal is 71% protein, and has comparable protein per unit weight to soybean meal and fishmeal (UniBio). Similar protein content was an important factor for our economic analysis because by setting the price of the bacterial meal equal to its competitors, we are assuming that the customer is getting the same quantity of protein per dollar regardless of the type of animal meal they purchase.

Figure 3.3.1: Example UniProtein® Bacterial Feed



4.0 Environmental Analysis

This section outlines the various environmental benefits of creating animal feed from methanotrophic bacteria. On the one hand the growth of bacteria on methane in lieu of flaring results in a significant reduction in carbon dioxide emissions. On the other, using this green technology to produce a comparable animal feed supplement is important not only for future food scarcity issues, but water and land security as well. Finally, this section discusses the impact of feeding varying quantities of the bacterial meal to different animals - the results are quite favorable.

4.1 Emissions Comparison

Natural gas is flared because the global warming potential of methane is much higher than that of carbon dioxide. By growing methanotrophic bacteria on surplus natural gas rather than flaring it, the carbon dioxide emissions are greatly reduced. The following equation shows the basic balanced chemical equation for flare gas (UniBio):

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2H_2O \qquad \textbf{(Eq. 4.1.1)}$$

one mole of methane produces one mole of carbon dioxide. In comparison, growing methane-oxidizing bacteria on natural gas results in a 52% reduction in CO_2 emissions (UniBio). The balanced chemical equation for the growth of biomass is presented in **Eq. 3.1.1**. Yet the equivalent CO_2 emissions due to the transport of CNG to a centralized facility as well as the construction and operation of the plant must be considered in a carbon offset analysis. Nonetheless, growing the bacteria in order to create a value-added good in the form of animal feed has important environmental consequences that are discussed in the following section.

4.2 Benefits of Feed Replacement

The environmental benefits of bacteria-based animal feed production are multiplied through the replacement of existing feed options: soybean meal (SBM) and fishmeal (FM).

Soybean meal has been an attractive source of animal feed due to its high protein content and digestibility. Price controls and the use of soybean as a source of biofuel has led experts to estimate that demand for soybean will increase by 66 percent in the next five years (Clay). However, there are numerous environmental concerns associated with soybean cultivation. To begin with, runoff from soybean meals can potentially lead to groundwater contamination due to high levels of agrochemical and pesticide use (Francois). The extensive land area required for planting soybean has led to deforestation and soil erosion. Similarly, despite advances in irrigation methods, industrial scale farming of soybean remains a water-intensive activity. Lastly, using soybean meal as animal feed poses a threat to food security (Clay). High demand from cattle farmers endangers the food supply in regions where it constitutes part of the human diet – primarily Asia where it is consumed as tofu.

Fishmeal refers to fish-based products that are often fed to poultry and pigs; the rise in aqua farming has made this an affordable and convenient option (UK Department for Environment). Nonetheless, fishmeal has detrimental effects on the environment, similar to those of soybean meal. Aqua farms are a source of seawater contamination due to discharge of chemicals and fish waste of high organic content (Food and Agriculture Organization). Moreover, the building of these aqua farms can lead to partial or complete destruction of coastal regions and the seabed. It also disturbs aquatic ecosystems by introducing new diseases and by causing overfishing of small ocean fish, which are fed to the farmed fish. The processing of fish into fishmeal is energy intensive due to need for drying and grinding (Food and Agriculture Organization). Lastly, fish cannot be stored for extensive periods of time since fish stocks are vulnerable to contamination by food-borne bacteria like *Salmonella* (Food and Agriculture Organization). This makes the supply of raw fish volatile, since populations can vary from one year to the next. Therefore, using fishmeal to feed poultry and cattle also indirectly threatens food security since its stable supply cannot be ensured.

Bacteria-based animal feed does not suffer from these issues, or at least not to the same extent as fishmeal and soybean meal do. Overall, replacing these options with bacteria meal would not only decrease flare gas emissions but also would have secondary environmental benefits.

4.2 Dietary Impacts

A number of studies have been conducted where animal feed produced from methanotrophic bacteria has been feed to a variety of animals to observe the consequences. In particular, percentages of conventional feed for broiler chickens, pigs, blue foxes, carnivorous minks, Atlantic salmon, rainbow trout, and Atlantic halibut were replaced with bacterial meal. Each type of animal had different responses to the new type of feed, some benefiting more than others. For example, broiler chickens experienced improved amino-acid digestibility, increased lean-fat ratio, and increased weight gain, while other animals saw reduced feed intake as they adjusted to the new type of the feed (Overland). Other benefits include bacterial meal's long shelf life and the improved storage quality (odor) of the meat of animals whose diet was supplemented with bacterial meal (Overland).

In all cases, however, the bacterial meal could not replace 100% of the conventional animal feed. Certain percentages of each animals' respective feed could be replaced with bacterial meal before negative consequences such as reduced weight gain, feed intake, etc. began to occur. **Table 4.1.1** summarizes the percentages of dietary protein (soybean meal and fishmeal) that can be replaced by bacterial meal without impairing animal growth performance (Overland):

Table 4.1.1: % Feed Replacement	
Chickens (15%)	Pig (41%)
Rainbow Trout (38%)*	Mink (20%)*

Atlantic Halibut (13%)*	Blue Fox (30%)*
Atlantic Salmon (52%)*	*=Carnivorous

Nevertheless, these percentages are quite impressive, considering the low water and land requirements of methanotrophic bacteria and the use of an otherwise wasted natural resource. It is important to note that many of the tested animals are carnivorous, yet species such as the Atlantic salmon could receive up to 52% of their dietary protein from a non-meat product. The use of small quantities of bacterial meal was approved for use in animal feed in the European Union in 1995, while no parallel regulations currently exist in the United States (UniBio).

5.0 Case Study for Economic Analysis

In order to test the economic feasibility of producing animal feed from methanotrophic bacteria, we generated a hypothetical situation where trucks are used to transport compressed natural gas from well heads in the Bakken oil fields in North Dakota to a centralized bioreactor and processing plant. A number of assumptions were made to determine the internal rate of return for the operations of such a plant, and a sensitivity analysis for a number of variables was performed to observe the change in IRR.

Figure 5.0.1: UniProtein® Facility Diagram

5.1 Assumptions

The assumptions for the economic model are outlined in **Tables 5.1.1-5.1.3**:

Table 5.1.1: Field Assumptions	
Average Cubic Feet of Methane Flared /year /well	3.65 million
Average Distance of Well Head from Centralized Plant (miles)	40
Number of Gas Sites	100
Percent of Methane in Natural Gas	95%

The average volume of methane flared per well per year was calculated using data from the North Dakota Industrial Commission (NDIC Oil and Gas Server). The average distance of the well heads from a hypothetical centralized plant was approximated using maps on the NDIC server. The number of gas sites was set at 100 to account for the majority of well sites in the region.

Table 5.1.2: Trucking Assumptions	
Cost of One Truck (USD)	80,000
CNG Truck Capacity (cubic feet)	100,120
Cost of Diesel (USD/gallon)	2.68

Labor Cost (USD/hour)	25
MPG	15
Average Speed (MPH)	55

The price of a CNG truck was approximated based on prices of trucks with similar purpose, while the cost of diesel comes from average price of diesel in North Dakota.

Table 5.1.3: Plant Assumptions	
Cubic Feet of Methane / Kilogram Bacterial Feed	70.62
Contract period (years)	15
Annual Operation Costs (USD)	1 million
Annual O&M	100,000
Plant Cost (USD)	30 million

One very important assumption is the ratio of cubic feet of methane to 1 kilogram of bacterial feed. This is based on the assumption presented in **Section 3.1** that 2 cubic meters of the methane produced 1 kilogram of dry biomass (Overland). The plant cost was approximated based on the following assumption: that an 88 million dollar plant can produce a minimum of 25,000 metric tons of feed per year (UniBio). Using our economic model, 25,000 metric tons of feed would require about 500 well sites. Thus assuming a non-linear relationship between well sites and plant cost (economies of scale), we predict that 100 well sites would require a 30 million dollar plant.

Lastly the price of fishmeal and soybean meal are take to be 1689$ and 459$ per metric ton, respectively (World Bank). Our economic model assumes that the bacterial meal is sold to customers at the price as either fishmeal or soybean meal (two separate analyses). Since the protein content for bacterial meal is comparable to that of fishmeal and soybean meal, we can ensure that the customer is getting the same quantity of protein per dollar regardless of the type of animal meal they purchase.

5.2 Sensitivity Analysis

In order to account for uncertainty in different variables and to explore variable options that produce positive IRRs, we performed a sensitivity analysis on the internal rate of return by altering one variable at a time. Similar procedures were performed for both soybean meal and fishmeal prices. The same "base case" variable values were used for both types of analysis. These values remain constant as each of the low, base, and high input values are altered for each variable for each iteration of the sensitivity analysis, resulting in three different IRR values for each variable. Positive IRR's signify positive return equity over the course of the contract period.

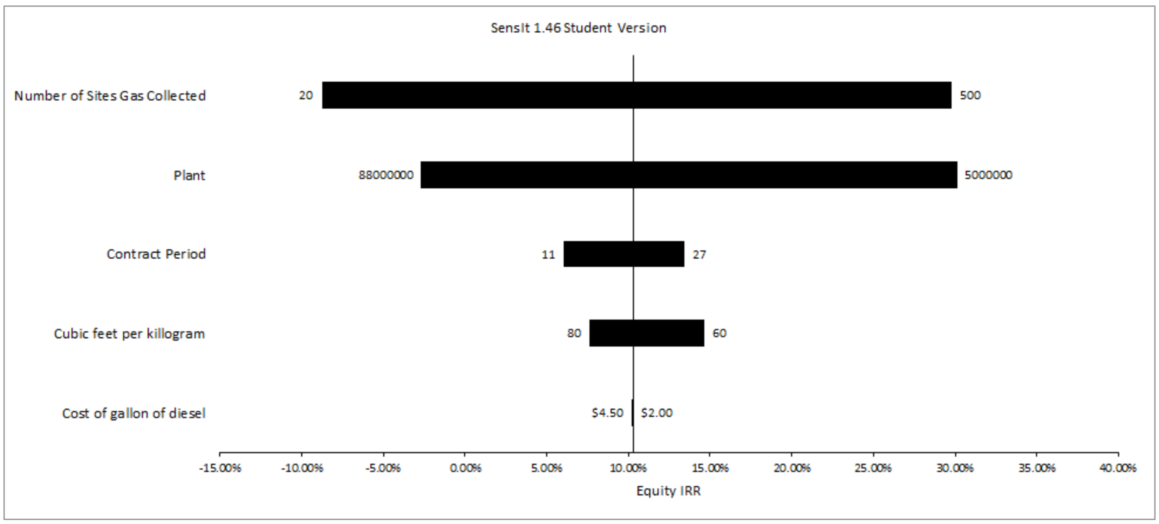
5.2.1 Fishmeal Sensitivity Analysis

Table 5.2.1: Equity Internal Rate of Return for the Replacement of Fishmeal

	Input Value			Output Value		
Input Variable	Low	Base Case	High	Low	Base	High
Number of Sites Gas Collected	20	100	500	-8.78%	10.29%	29.78%
Plant	88000000	30000000	5000000	-2.73%	10.29%	30.16%

Contract Period	11	15	27	6.05%	10.29%	13.42%
Cubic feet per kilogram	80	71	60	7.62%	10.29%	14.64%
Cost of gallon of diesel	$4.50	$2.68	$2.00	10.20%	10.29%	10.33%

Figure 5.2.1: Fishmeal Sensitivity Analysis

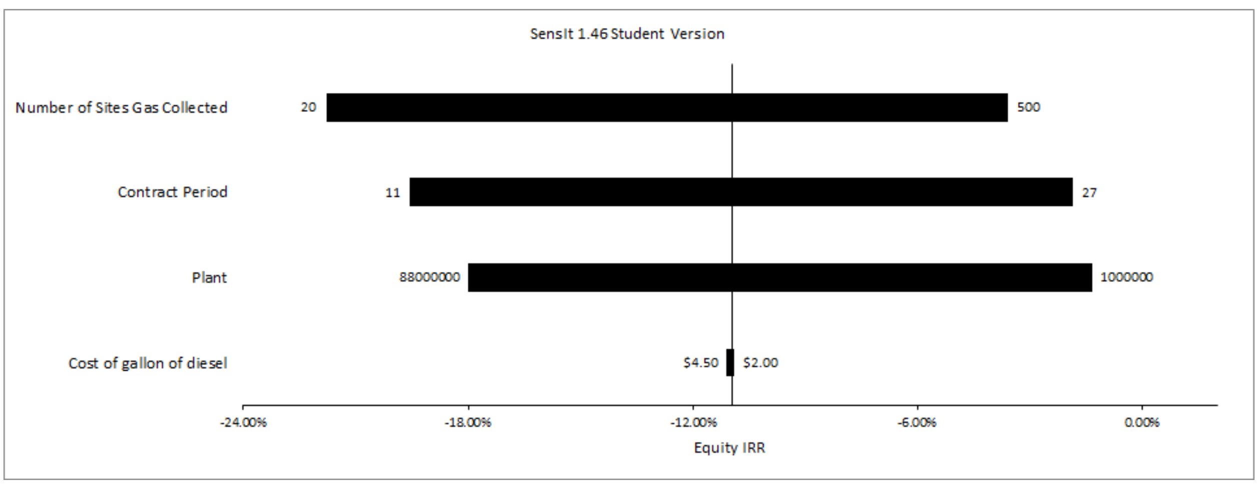


Notable results for the fishmeal sensitivity analysis observed in **Table and Figure 5.2.1** are as follows. Changing the number gas sites from 20 to 500 results in an increase in the IRR from -9% to 30%. Similarly, changing the construction cost of the plant from 88 million dollars to 5 million dollars increases the IRR from -3% to 31%. The contract period shifted the IRR by 7%. Depending on the accuracy of the ratio of cubic meters of methane per kilogram of biomass, small uncertainty (+ - 10 cubic meters per kilogram biomass) the IRR can change by 7%. Finally, the price of diesel surprisingly had little effect on the IRR. Thus, it is quite possible to achieve positive IRR depending on the accuracy of our assumptions and the economic model.

5.2.2 Soybean Meal Sensitivity Analysis

Table 5.2.2: Equity Internal Rate of Return for the Replacement of Soybean Meal						
	Input Value			Output Value		
Input Variable	Low Output	Base Case	High Output	Low	Base	High
Number of Sites Gas Collected	20	100	500	-21.79%	-10.96%	-3.59%
Contract Period	11	15	27	-19.54%	-10.96%	-1.84%
Plant	88000000	30000000	1000000	-17.99%	-10.96%	-1.34%
Cost of gallon of diesel	$4.50	$2.68	$2.00	-11.10%	-10.96%	-10.9%

Figure 5.2.2: Soybean Meal Sensitivity Analysis



Notable results for the soybean meal sensitivity analysis observed in **Table and Figure 5.2.2** are as follows. Changing the number gas sites from 20 to 500 results in an increase in the IRR from -22% to -4%. Similarly, changing the construction cost of the plant from 88 million dollars to 5 million dollars increases the IRR from -18% to -2%. The contract period shifted the IRR by -18%. Finally, the price of diesel once again had little effect on the IRR. Setting the price of our bacterial meal equal to that of the current soybean meal price always results in a negative IRR. Thus, our animal feed is not currently competitive with soybean meal without help from regulatory policies.

6.0 Conclusion

When examining the biological methods that can be used to mitigate the flaring of natural gas, utilizing aerobic methanotrophs to produce animal feed is not only the most effective technological alternative, but it is also economically viable. The bacterial meal is nutritionally adequate to replace significant percentages of specific animals' dietary protein and provides important environmental benefits with regards to carbon emission and feed replacement. Growing methanotrophs on natural gas reduces carbon dioxide emissions by 52% and using bacterial meal in lieu of soybean meal and fishmeal reduces groundwater contaminants and pollutants and saves water, land, and food that could otherwise be fed directly to humans. Future research in production efficiency, improved nutritional quality, and alterations for specific animal preferences can decrease the price of bacterial meal and make it a more desirable product for farm animals, humans, and the environment alike (Bothe).

Report Summary:

The flaring of natural gas is a worldwide problem that not only is harming the environment, but also wasting a valuable resource. Over the last year, our team has been searching for ways to capture part of that value while reducing the harmful effects of flaring. Ultimately, we presented three alternate pathways, each with different capital requirements, equipment needs, process flows, and mitigation effects. The Enhanced Oil Recovery pathway allows gas to avoid flaring while providing increased oil extraction. Although the costs associated with these technologies make this option uneconomic, if oil prices were to rise above $75 that could change. Similarly, by allowing FedEx to use the natural gas for transport instead of flaring it, significant value is captured. Creating a midstream company to locally transport compressed natural gas in order to fuel FedEx fleet vehicles at a distribution center, proved to be both economic and environmentally friendly. Lastly, having bacteria consume the natural gas and produce animal feed curbs flaring while economically helping the food chain. Overall, the three distinct pathways provide an in-depth look into potential solutions to this worldwide problem. While there are several assumptions that were made in the process of making this report, we believe that our report provides an accurate insight into viable solutions. Further research and increased conversations with commercial partners would be required before implementing these pathways.

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