Stranded Gas Valorization: A Technoeconomic and Environmental Analysis on M2X Energy's Reformer Technology

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Abstract

Greenhouse gasses, normally flared after being harvested alongside oil as associated gas, are fed to a scalable and modular reformer technology by M2X Energy to produce crude methanol primarily for energy production with the goal of reducing carbon emissions from fossil fuel harvesting while increasing profitability. This study aims to economically and environmentally analyze M2X Energy's novel gas-to-methanol reformer when deployed to all flare sites across the United States. This analysis was accomplished by calculating the NPV of several flare sites, completing a sensitivity analysis, and calculating CO_2 abatement costs to determine the continued investment into this technology. An orthodromic distance model was also compared to true transportation distances to measure its accuracy. Results show that most flare sites have a positive net annual profit, and their technology has more affordable abatement costs than several existing technologies for energy production. These results suggest that M2X's reformer technology is profitable as well as affordable in reducing carbon emissions. Future work may include calculating the NPV for all flare sites, and applying this technology to methane-producing landfills.

Acknowledgements

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1.0 BACKGROUND

This chapter focuses on contextual information needed to understand the purpose and application of M2X Energy's gas-to-liquid reformation technology. This includes the tech's impact on the environment, its technical design, and its reception by social groups.

2.1 Greenhouse Gases (GHG) and Its Effects

Greenhouse gasses are gasses that decay slowly in the atmosphere and contribute to the earth's slow trend to warmer climates. They are primarily carbon molecules like carbon dioxide (CO_2) and methane (CH_4); although, there are other molecules like hydrofluorocarbons (HFCs) and nitrous oxide (N_2O). According to a 2022 report from the Intergovernmental Panel for Climate Change (IPCC), "the global net anthropogenic emissions have continued to rise across all major groups of greenhouse gasses" based on data collected since 1990[1] (IPCC W3, 2022). This claim is significant because it highlights that despite international acknowledgement of humanity's large contribution to climate change, not enough measures are being taken to mitigate these summed contributions. As more technology is released commercially, the hope is for industries - the primary contributor to GHG emissions[2] - to adopt these technologies quickly to slow climate change (IPCC W3, 2022).

GHGs are significant to the changes observed in global climates for the past 170 years because of their ability to store energy emitted from the sun and captured in earth's atmosphere. Contrary to popular belief, GHGs are not harmful to the earth's atmosphere; they are naturally occurring gasses that aid in insulating the earth from space's freezing temperatures. The fluctuation of atmospheric concentrations for these gasses have been accurately measured by experts from the Sixth Assessment Report (AR6) originally released in 2021. Their measurements, as illustrated in Figure 1, show that the atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have rose and fell steadily until the industrial revolution in the late 17th century[3] where they

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[1] IPCC 6th Assessment 2022 Report Working Group 3(B.1.2)

[2] IPCC 6th Assessment 2022 Report Working Group 3 (B.2.1). The contribution of the energy supply sector is 34% (20 $GtCO_2$-eq), 24% (14 $GtCO_2$-eq) from industry, 22% (13 $GtCO_2$-eq) from agriculture, forestry, and other land use, 15% (8.7 $GtCO_2$-eq) from transportation, and 6% (3.3 $GtCO_2$-eq) from buildings.

[3] IPCC Sixth Assessment Report Working Group 1. The agencies and organizations responsible for collecting the data on GHG atmospheric concentration for the past 800 thousand years for the IPCC AR6 are AGAGE: Advanced Global Atmospheric Gases Experiment; SIO: Scripps Institution of Oceanography; NOAA: National Oceanic and Atmospheric Administration, Global Monitoring Laboratory; UCI: University of California, Irvine; CSIRO:

rose quickly (IPCC W1, 2022). This quick increase is the reason for the sudden shifts in climate around the world as more GHGs trap more thermal energy from the sun. The warming atmosphere then impacts other sectors of the climate like precipitation and more severe storm systems (NASA, 2019).

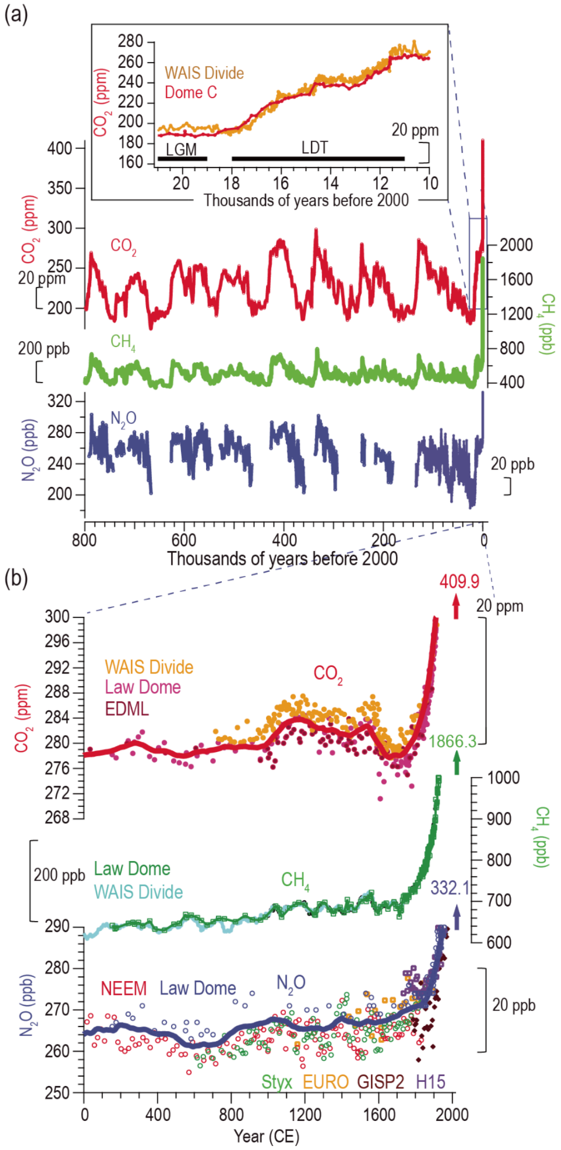

Figure 1. The atmospheric concentrations of the common GHGs carbon dioxide, methane, and nitrous oxide from the IPCC's Sixth Assessment Report (AR6).

Commonwealth Scientific and Industrial Research Organization, Aspendale, Australia; WMO: World Meteorological Organization, Global Atmosphere Watch, CMIP6 (Climate Model Intercomparison Project Phase 6).

The trend that weather has been following over the past few decades are stronger and more violent storm systems. From NASA's Global Climate Change, Alan Buis, who has over 35 years of science communication experience and 17 years at NASA's Jet Propulsion Lab in Media Relations, writes, "one NASA study from late 2018 supports the notion that global warming is causing the number of extreme storms to increase, at least over Earth's tropical oceans" (NASA 2019). These large storms have displaced human populations, damaged property and essential utilities, and upsetted ecosystems as displayed by Hurricane Dorian in 2019 and Hurricane Ian in 2022. On Top of this, other global observations of climate change include unpredictable fluctuations of precipitation, stronger heatwaves, and rising sea levels – all attributed to the warming climate because of increased GHG emissions.

2.2 Natural Gas (NG) and Its Uses

Natural gas is a fossil fuel primarily composed of methane with traces of natural gas liquids (NGLs) and non-hydrocarbon gasses, and is generally harvested from natural gas wells or oil wells (EIA, 2022). When NG is released from oil extraction, it is commonly referred to as *associated gas*. The contiguous United States has many basins that hold promise for tight oil production – petroleum and NG trapped in shale rock – including the Gulf Coast, Permian, Monterey, Williston (Bakken), and Cleveland. These same basins, therefore, hold the majority of flare sites in the lower forty-eight states[4] (EIA Maps).

As a fossil fuel, NG's principal uses revolve around heating spaces, water, cooking, etc. by combustion. The U.S. Energy Information Administration (EIA) organized the national use of NG into these five sectors – residential, commercial, industrial, transportation, and electrical power[5] (EIA, 2023). Electrical power production has seen increased usage of NG as the fuel source instead of other fossil fuels.

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[4] https://www.eia.gov/maps/maps.htm

[5] https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php

2.2.1 The Mishandling of NG and Its Prospective Future

Although NG is being used more as a fuel for electric power production, the transportation and distribution of NG has many leaks. The high number of leaks has prevented NG from replacing conventional fuels like coal and oil as the main fuel used for many processes across multiple sectors. A study done in 2020 estimates methane leakage from pipeline mains in NG local distribution systems in the United States to be 0.69 Tg/year (Weller et al., 2020). The loss of NG is significant because it leads many petroleum mining companies to view NG as a waste byproduct. To safely dispose of this NG, companies commonly practice flaring so the gas cannot combust independently possibly resulting in damages. Another major reason industries flare NG is because the sites that extract petroleum and associated gasses are too far away from processing plants that can utilize the NG to fuel electrical production or transform it into useful chemicals. Regulations also lead to NG flaring from the local, state, and federal levels of legislation. Although NG flaring is not viewed as a major loss to profits, the gas is nevertheless wasted where it can instead be used to create commodities. A company focused on this new way of handling associated gas to be adoptable and profitable by petroleum businesses is M2X Energy Incorporated.

2.3 M2X Energy Inc. and Their Reformer Technology

M2X Energy Inc. is a company founded by Breakthrough Energy Ventures in 2020 to address climate change. They plan to achieve this by reducing GHG emissions from flare sites by converting would-be-flared natural gas to environmentally sustainable, fungible, and economically viable chemical products. Their reformer technology is a small-scale, modular, autonomous gas-to-methanol (GTM) system that is fed methane at flare sites to be converted to methanol. This methanol is then sold to chemical plants for the production of other commodities such as low carbon fuels, engineered lumber, low carbon plastic, and synthetic fibers[6] (M2X Energy).

Their GTM system utilizes a combustion engine to drive the process of producing methanol from methane using carbon monoxide hydrogenation. The engine converts methane to synthesis gas

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[6] M2X Energy Inc. Home Website: https://m2x.energy/.

(syngas) which is primarily made of carbon monoxide and hydrogen, the reactants for methane synthesis. Methane, carbon dioxide, oxygen, water, and nitrogen make up the remaining fractions of the syngas (Yelvington et al., 2023). Dr. Joshua Browne, the chief technical officer (CTO) of M2X Energy, focused his dissertation detailing a TEA on the use of a combustion engine as a micro-reformer for a distributed gas-to-methanol system (Browne, 2016). His paper, written in 2016, forms the basis of the technology used by M2X and the organization's overall business as a climate tech company. The GTM system shows promise in the field because of its lesser constraints compared to the ineffective current gas-to-liquid (GTL) systems available. The GTM system accomplishes this by running autonomously as well as being modular and scalable. Figure 2 displays a full-scale field skid unit that highlights these attributes. The scalability of the modular units enable flare sites to easily increase or reduce the number of units needed to meet a goal. The autonomy of the modular system allows flare sites to keep the system operating without much labor costs.

Figure 2. A full-scale skid unit of M2X's methane reformer technology at a test site in North Dakota (M2X Energy).

The system's autonomous nature consumes, according to M2X's website, 75,000 standard cubic feet (SCF) per day of flare gas which produces 5,000 barrels of methanol per year[7] (M2X Energy). The company, however, conducted field tests for the GTM system over the summer and winter of 2023. Table 1 reports the new consumption and production rates.

Table 1. Reported consumption and production rates of GTM system from 2023 field tests by M2X Energy. The consumed gas includes both feedstock and fuel for onboard processing. KTA is kiloton per annum.

	Consumption of Flare Gas (MSCF/day)	Production of Methanol (KTA)
Generation 1b	125	0.4
Generation 2a	220	0.8

The system utilizes a combustion engine which produces syngas as mentioned earlier. The syngas is then fed through two reactors in series which hydrolyzes the carbon monoxide to synthesize methanol. Dr. Browne provides a simple flowsheet of this process shown as Figure 3, and an Aspen process flow diagram illustrated as Figure 4. The crude methanol produced by M2X's GTM system is approximately 90% pure methanol and 10% water which is then trucked to clients using tankers (Yelvington et al., 2023).

Figure 3. A block flow diagram from Dr. Browne's TEA on the gas-to-liquid (GTL) system utilizing an engine reformer (Browne, 2016).

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[7] M2X Website: https://m2x.energy/.

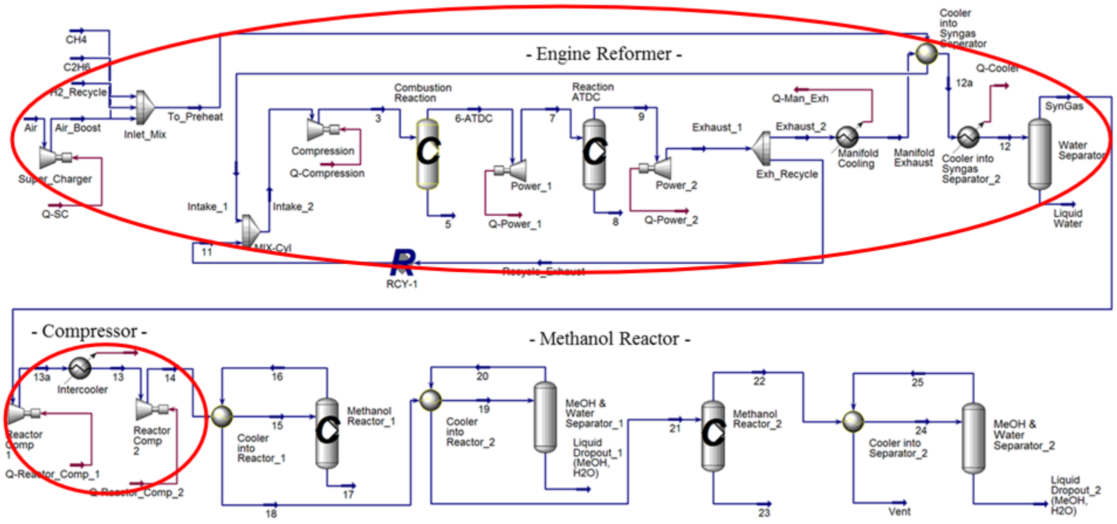

Figure 4. A Process Flow Diagram (PFD) of the GTL system using Aspen (Browne, 2016).

2.3.1 Other Gas-to-Methanol Technologies[8]

Many methods have been developed to convert natural gas to methanol. The first method discovered is the indirect method, also known as the Fischer-Tropsch Synthesis (FTS), in the 1920s. Figure 5 illustrates this process as a process flow diagram. It involves a steam reforming reaction to produce a syngas followed by hydrogenation of the syngas to produce petrochemicals including methanol, light olefins, and others. A few drawbacks to this method, however, is the low methanol yield and the process's selectivity is associated with impurities frequently requiring a purification step.

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[8] Salahudeen et. al Paper. This paper covers multiple technologies, as mentioned in this section, for the conversion of natural gas to methanol as an alternative to gas flaring. The authors also analyzed the reaction conditions in presence of selected catalysts to determine a more viable method. Finally, this paper compared the merits and demerits of unconventional methods to common indirect methods.

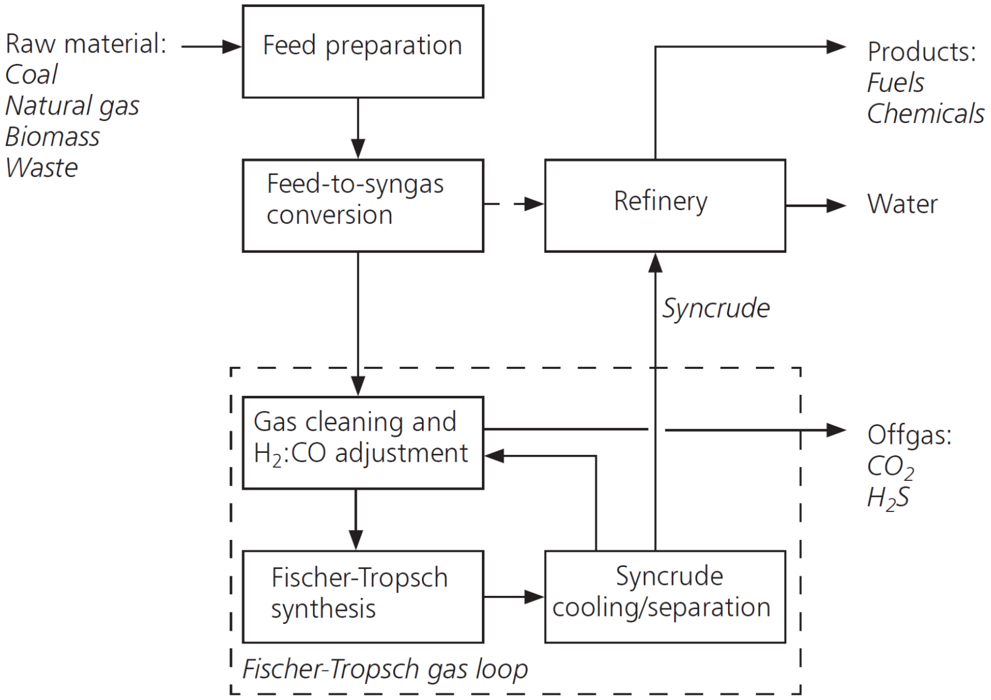

Figure 5. A block flow diagram of a typical Fischer-Tropsch Synthesis (Speight, 2008).

An alternative method to the FTS process is the direct conversion which was initially researched around the 1980s. Unlike the indirect method which requires a substantial quantity of energy, the direct approach utilizes a suitable catalyst to partially oxidize methane to methanol at mild temperatures. Below in Figure 6 is a simple example of this partial oxidation process for the direct conversion of NG to methanol. Unfortunately, the yield of methanol heavily depends on the available oxygen supplied to the reaction. If too much oxygen is used, the methanol produced can further react with the excess oxygen and decompose to carbon dioxide and water.

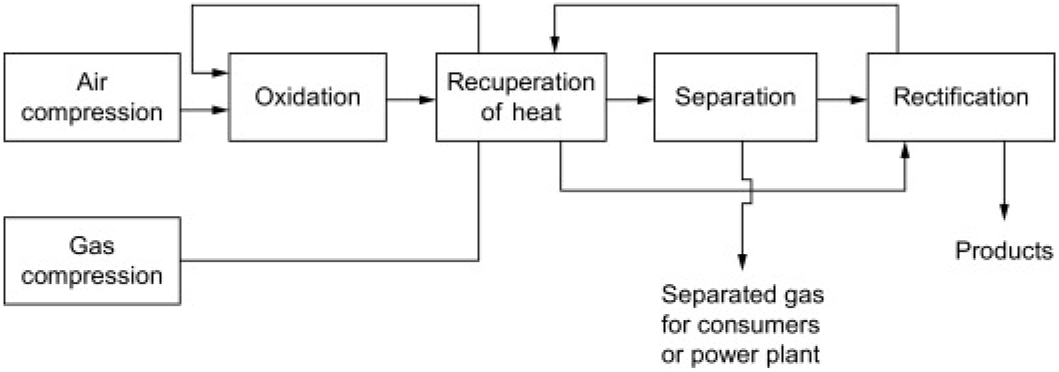

Figure 6. An example of a block flow diagram for the direct conversion of natural gas to methanol (Arutyunov, 2018).

One interesting method for the gas-to-methanol process is biological conversion where a collection of gasses – biogas or natural gas – is fed to microorganisms to be converted into methanol. These specialized microorganisms are usually methanotrophic bacteria with an important enzyme called methane monooxygenase (MMO). This enzyme is responsible for oxidizing the C–H bond in common alkanes, especially methane, to fuel the growth of the bacteria. These methanotrophs are found across the earth in various environments including oceans, wetlands, sewage, and soil. They can, because of their wide prevalence on earth, tolerate a large range in temperature and pressure conditions. They can also utilize methane in low concentrations (~2 ppm). Because of these qualities, lesser care is needed to take advantage of the bacteria's methanol producing capabilities. Many factors limit this method, however, including toxicity of source methane impurities, limitations of gas-liquid mass transfer, accidentally oxidizing methanol, maintaining catalytic activity, and optimizing biotechnological conditions.

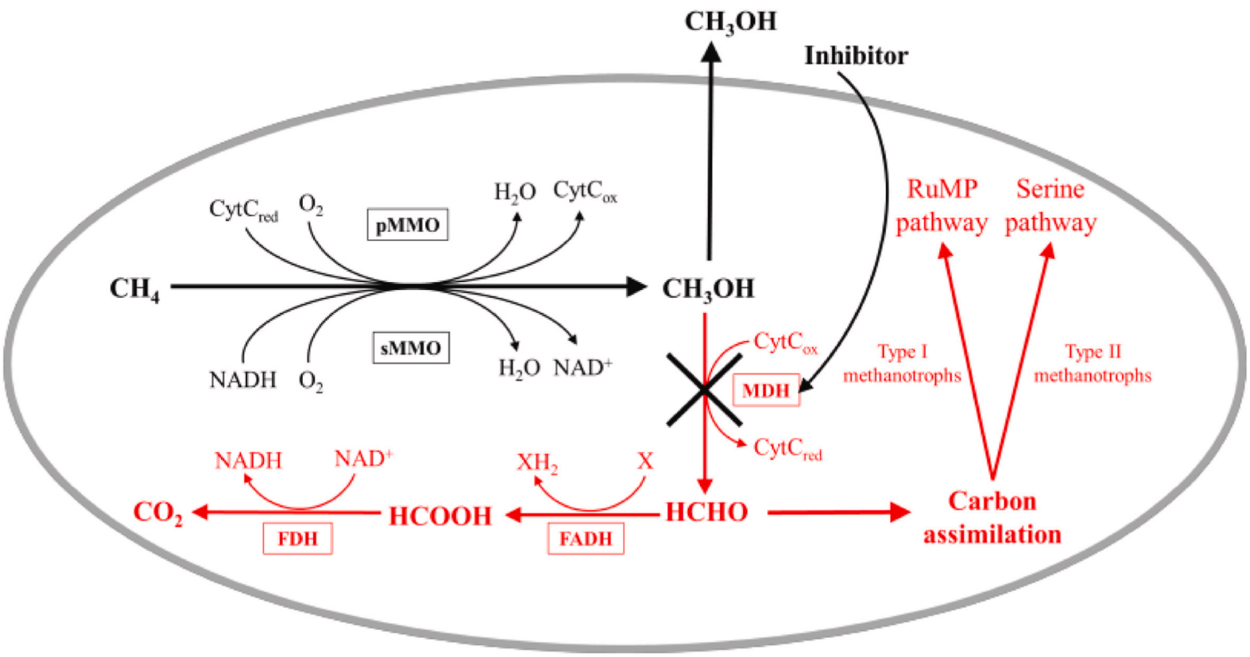

Figure 7. The biological conversion of methane to methanol inside a methanotroph in aerobic conditions highlighting the MDH inhibiting pathway. The sections in red do not occur if 100% of produced methanol is extracted from the bacteria (Saladuheen et. al, 2022).

2.4 The Ethics of M2X's Reformer Technology

Many Americans support an energy shift from fossil fuel dependence to renewable energy sources. A research study from the Pew Research Center surveyed 10,329 U.S. adults in Spring 2023 with the goal to "understand Americans' views of climate, energy, and environmental issues[9]" (Kennedy et al., 2023). A major statistic discovered in this study is that a majority of American adults prioritize the development of alternative energy sources over conventional fossil fuels. However, only 31% of the surveyed population supported a complete removal of fossil fuels as an energy source. Out of the 69% of people who did not want to support a total phase-out of fossil fuels, 35% reported that the U.S. should never phase them out while 32% said the country will eventually (1% reported no answer).

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[9] Kennedy et al., 2023. According to their report, "Everyone who took part in the survey is a member of the Center's American Trends Panel (ATP), an online survey panel that is recruited through national, random sampling of residential addresses. This way, nearly all U.S. adults have a chance of selection. The survey is weighted to be representative of the U.S. adult population by gender, race, ethnicity, partisan affiliation, education and other categories."

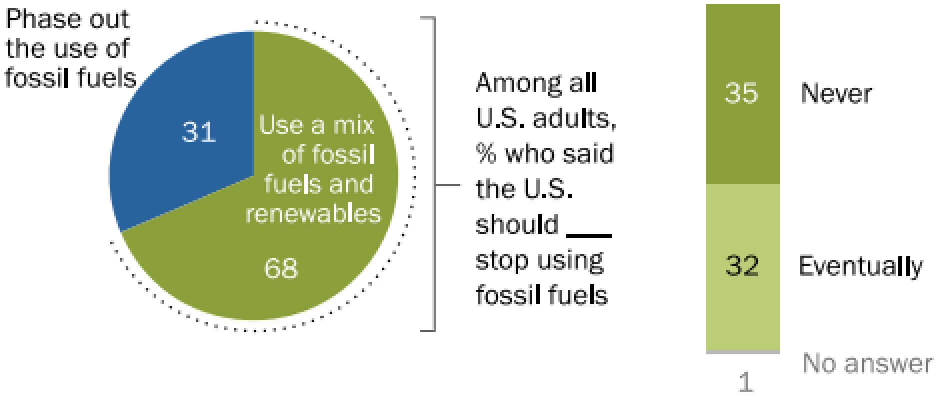

Figure 8. A statistical breakdown of responses by surveyed American adults regarding the shift from fossil fuels to renewable energy sources (Kennedy et al., 2023).

This report is significant because it illustrates that a majority – 63% – of Americans are expecting a shift from fossil fuels to more renewable energy sources. New technology that increases the longevity of fossil fuel industries, however, continues to be developed. The GTM module from M2X Energy is one such example. This tech enables the fossil fuel industry to increase profits from oil drilling and fracking by selling the produced methanol versus flaring it as a waste gas. The question is then asked: where does this GTM tech from M2X stand concerning the shift from fossil fuels to renewable energy?

To answer bluntly, the introduction of this GTM technology contributes little to the aforementioned fuel shift and instead more towards the environmental impact oil collection has. Elitumaini Swai, a WPI alumna, authored a paper in 2023 which is the foundation for this project. A major conclusion from Swai is that the profit margins of oil and gas companies would increase and "the overall NPV for all sites would be $2.8 billion with a 21% error" (Swai, 2023). Compared to a sum annual profit estimate of $37 trillion across the top fifteen gas and oil companies[10], it is clear that M2X's GTM tech's contribution of $2.8 billion is minimal (Artis, 2023). In other words, it would only increase Big Oil's annual profits by around 0.000076%.

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[10] Artis, 2023. An expert blog from the National Resource Defense Council (NRDC) reporting an expansion of fossil fuel industries in the second quarter of 2023.

This GTM technology, however, will significantly lower U.S. greenhouse gas emissions by 3.3 percent (Swai, 2023).

2.0 METHODOLOGY

This chapter focuses on defining a techno-economic analysis (TEA) and designing an analysis model specific to M2X's gas-to-liquid (GTL) reformation technology to determine its feasibility in the market compared to other competitive technologies.

3.1 Techno-economic Analysis of M2X Energy's Technology

A useful tool in determining the feasibility of M2X Energy's GTM technology when deployed to all flare sites in the United States is a techno-economic analysis (TEA). These analyses are designed to evaluate the economic performance of a new technology. This is accomplished by a manufacturing cost assessment that compares the capital expenses plus operating expenses of both the new technology and a benchmark technology already competitive in the market. An example of this benchmarking is illustrated in Figure 9.

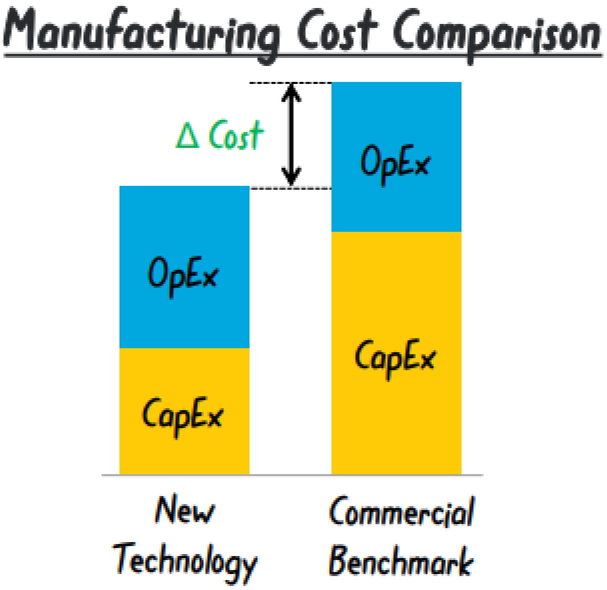

Figure 9. Cost benchmarking of two competing technologies for a techno-economic analysis (TEA). This example shows the new technology as more cost effective because of a lower capital expense (Energy.gov).

Capital expenses are one-time costs that are amortized over the assets' useful lifetime to relate the capital expense (CapEx) to a specific production volume. Operating expenses (OpEx) are recurring costs that can be either variable or fixed. Examples of fixed costs are labor, rent, and utilities which are not tied to production volume. Materials and transportation charges, however, are examples of variable costs because they are dependent on the production volume. Below in Table 2 the capital and operating expenses are tabulated into contributing costs.

Table 2. Contributing costs to the manufacturing expenses of M2X Energy's GTM technology.

Capital Expenses	**Operating Expenses**
Cost of GTM Skid	Utilities to Power Skid
	Transportation

The modular and autonomous design of M2X's tech eliminates major labor costs to operate and maintain the fielded skids at the flare sites. At the same time, the design utilizes a combustion engine to drive the reaction which only adds gasoline as a utility for operating expenses. Finally, the cost of these GTM skids is categorized as a capital cost. The cost for each flare site is dependent on the required number of skids which is determined by either one of two approaches first mentioned by Swai's paper (Swai, 2023). These approaches are needed because Equation 1, which is used to find the required number of skids, outputs fractional numbers which need to be rounded to a whole number.

$$Number\ of\ Skid\ Units\ =\ \frac{Well\ Volume}{GTM\ Unit\ Intake\ Capacity}$$

Equation 1. To Determine the Number of GTM Units Required per Flare Site.

Approach 1, also known as the minimal number of units, either rounds up the required number of skids calculated and assumes partial capacity for the GTM reactors, or rounds down and flares the remaining methane not reacted. This ensures that the minimal number of skids are used which reduces manufacturing costs. Environmentally, however, methane would be flared; so, an acceptable quantity of flared methane must be defined when using this approach. Approach 2 models all skids at a flare site as a system of reactors when rounded up, resulting in multiple units running at partial capacity. This approach prohibits any methane from being flared which is the best option environmentally; however, since some units will be running at partial capacity – and therefore a lesser efficiency – the operating cost for this approach will be higher. Optimally, a combination of both approaches should be used across all national flare sites to minimize manufacturing costs for this TEA.

3.1.1 Transportation

A major contributor to the manufacturing costs of most businesses is transportation costs which are categorized as operating costs. Swai designed a transportation model to expand Dr. Browne's TEA analysis. Firstly, reference points need to be determined to establish points for the distance equation defined below as Equation 2. These reference points serve as general assumptions to where the processed methanol will be delivered to be further processed or used as feedstock for another chemical process. This distance formula takes into account the curvature of the Earth and is known as the great-circle, or orthodromic, distance.

$$Distance = cos^{-1}(sin(x_1) * sin(x_2) + cos(x_1) * cos(x_2) * cos(y_2 - y_1)) * 3963$$

Equation 2. To determine the distance (in nautical miles) between a flare site and a reference point. x_1 and y_1 are the latitude and longitude of the reference point. x_2 and y_2 are the latitude and longitude of each flare site. All coordinates are in radians derived from decimal degrees.

A public list of flare sites was found from the Earth Observatory Group. This organization used the Virtual Infrared Imaging Radiometer Suite onboard the NASA/NOAA Suomi National Polar-orbiting Partnership and NOAA-20 satellites to map all flare sites around the world. They were able to do this because flare sites emit an abundance of infrared from the fire which is measured and recorded by the VIIRS. For the purposes of this study, only flare sites in the United States will be used.

An accurate transportation model for this analysis was then designed that utilized all oil/gas processing facilities in the United States, as reference points, by determining which facility is closest to each flare site. This is a superior method because it minimizes the transportation distance for methanol between the flare site and a processing plant. The assumption, however, is that M2X will have an agreement with the processing facility to purchase their crude methanol.

The software used for this analysis was Microsoft’s Excel because of its approachability and ease of use when working with tabulated data. Another tool used to simplify this process was ChatGPT. This artificial intelligence chatbot, when given well designed instructions, can output functional code quickly as well as define preset functions. The spreadsheet was designed to allow for future analyses, using net annual profit, on this technology using alternative assumptions or added data.

The distance between a flare site and each reference point was calculated and stored in an array for each flare site. These distances for each flare site were then compared to find the shortest length. A new array is then created to show the closest reference point for each flare site and its calculated distance. This distance was used to find the transportation cost for that flare site. Finally, all expenses for that flare site, including the crucial transportation cost, attributes to the Net Present Value (NPV) of that flare site. The assumption made here is that the distance is a straight line and does not account for the added distance from roads and other transportation infrastructure like railways and canals.

This model can be further refined to consider the added distance from roads and other infrastructure. Traditionally, a GIS system would be used to find these routes which would then be inputted into the model as the distance between flare sites and processing plants. For this project, because of time constraints, a couple dozen cases are selected to find the true distance to be used in the analysis using Google Maps. The NPV of these “true distance” cases are then compared to their "straight distance” counterparts to get a correction factor. This was accomplished by finding the correction factor for each of the select flare sites using Excel’s Solver function. These correction factors were then averaged and used to find the corrected distance. This correction factor is designed to determine the transportation distance from the straight line method for more accurate NPV calculations.

3.1.2 Economic Impact Using Net Present Value (NPV)

The NPV is a superior value than net annual profit when gauging the worth of a project since NPV takes into account the project's lifetime and discounts annual cash flows to the present. A reasonable assumption for the lifetime of one of these GTM units is 20 years because most industry plants have similar lifetimes. Another industry standard used in calculating NPVs for this analysis is an initial rate of return (IRR) of 10 percent.

Before finding the NPV of a flare site project, the expenses and revenues must be calculated for each year the GTM units are in operation. The expenses include operating and maintenance costs with and without overhaul, transportation costs, and natural gas costs. The revenue is calculated from the volume of methanol sold to the market based on volume of methanol manufactured, the market price for crude methanol, and days the GTM skid operates per year. The assumptions used for these calculations are listed in Table 3 below.

Table 3. Assumptions for expenses and revenue calculations

Methanol Transportation Cost	0.0004	$/(gal*mile)
Operation and Maintenance	6.04	$/bbl
Plant Availability	292	days per year
Overhaul Costs	1000	$
Engine Operating Hours	7008	hours per year
Engine Time Between Overhauls	14016	hours

Reaction Efficiency	90	%
Methanol:Methane	7	gal/mscf
Unit Skid Intake Capacity	75	mscf per day
Initial Rate of Return (IRR)	10	%
Corporate Income Tax Rate	35	%
Lifetime of Skid Unit	20	years
Factor Rule Power Law	0.6	
Base Skid Capacity	0.333	mmscfd
Base Skid Capital Cost	1.43×10^6	$
Natural Gas Cost	1	$/mscf
Crude Methanol Market Price	575	$/mT

Microsoft’s Excel software has a preset function to calculate the NPV with the inputs of an interest rate, an investment, and the cash flows of each year of the project’s lifetime. The investment for each flare site project is the capital cost using either the minimum units method or the zero methane flared method. The capital costs are scaled down from a base skid capital cost using the one-sixth rule and a base skid capacity (Yelvington et. al, 2023).

$$Plant\ Capital\ Cost\ =\ Base\ Skid\ CapCost\ *\ \left(\frac{Flare\ Site\ Volume}{Base\ Skid\ Capacity}\right)^{0.6}$$

Equation 3. To calculate the capital cost of a flare site project based on the capacity of a base skid unit and the one-sixth rule.

Realistically, the NPV for every flare site would then be calculated. Excel, however, has a challenging time to find the NPV of multiple cases without creating a large file which would be too sluggish to work with. For this project, therefore, the NPV of multiple representative cases will be considered instead. This was accomplished by randomly choosing 20 flare sites with similar well volumes which all have the Targa Midstream Services - Lowry processing plant as their closest oil/gas facility.

3.1.3 Measuring Responsiveness

A sensitivity analysis is a tool that looks at how responsive a technology's value is – in this case its NPV – to changes in contributing costs to aid in decisions on technology deployment to the market. As mentioned previously, the contributing factors to the NPV for this analysis are the initial rate of return, cost of natural gas, and the distance between flare sites and the closest gas processing facility. To determine the sensitivity of this deployed technology, the NPVs will be compared by varying these contributing factors. These comparisons will highlight how sensitive these variables are to the profitability of this technology when deployed. This was accomplished by focusing on several flare sites and varying transportation distance.

3.2 Avoiding Carbon Emissions

The environmental impact from the reformation technology by M2X was assessed by comparing its carbon dioxide abatement ($CO2_{eq}$) to technologies already being used, as well as calculating the national reduction of GHG emissions. The carbon dioxide abated from flaring was calculated with the assumption that the flaring is 91% efficient. Abated carbon dioxide from M2X's reformer technology was assumed to have an efficiency of 99.9% with 30% of the methanol yield used as fuel and the rest being used downstream for chemical synthesis (Yelvington et al., 2023).

To be more specific, this project compared the $CO2_{eq}$ costs of M2X's technology with existing methods including corn starch ethanol, solar thermal, offshore wind, new coal with carbon capture and storage (CCS), retrofit coal with CCS, NG combined cycle, and solar photovoltaic technologies. This was accomplished by first calculating the CO_2 averted by M2X's technology.

This is a sum of $CO2_{eq}$ emitted from methane released, CO_2 from methanol combustion, and CO_2 from methanol transportation.

$$CO_2\ averted = CO_2\ produced\ by\ M2X\ tech\ -\ CO_2\ produced\ by\ flaring$$

$$CO_2\ produced\ by\ M2X\ tech\ =\ CO2_{eq}\ for\ CH_4\ released + CO_2\ from\ MeOH\ combustion + CO_2\ from\ transportation$$

Equation 4. The CO_2 averted from using M2X technology versus only flaring carbon dioxide. A positive value shows more CO_2 produced by M2X technology. Calculation samples of this equation can be found in Appendix A.

After finding the $CO2_{eq}$ averted, the levelized cost of energy (LCOE) for M2X's technology needs to be calculated. The LCOE is the present value of the total cost (capital and operating costs) of the project divided by the energy generated by the project[11] (Department of Energy, 2017). This value allows multiple technologies with differing lifespans, project size, capital costs, and capacities to be compared so informed decisions can be made on which projects should be invested. Assuming the LCOE for flaring is zero, $(LCOE)_{ref} = 0$, Equation 5 provides the CO_2 avoidance cost for each flare site (Roussanaly, 2019).

$$CO_2\ avoidance\ cost\ = \frac{(LCOE)_{CCS} - (LCOE)_{ref}}{(t_{CO2}\,/\,MWh)_{ref} - (t_{CO2}\,/\,MWh)_{CCS}}$$

Equation 5. To find the cost of abating $CO2_{eq}$ using M2X's reform technology in \$/mT. The denominator is the difference of the CO_2 emission intensity of energy from the reformer technology in tons of CO_2 per unit of energy generated in MWh.

The average avoidance cost of select flare sites subjected to M2X's reformation technology was then compared to the avoidance costs of the conventional technologies listed earlier.

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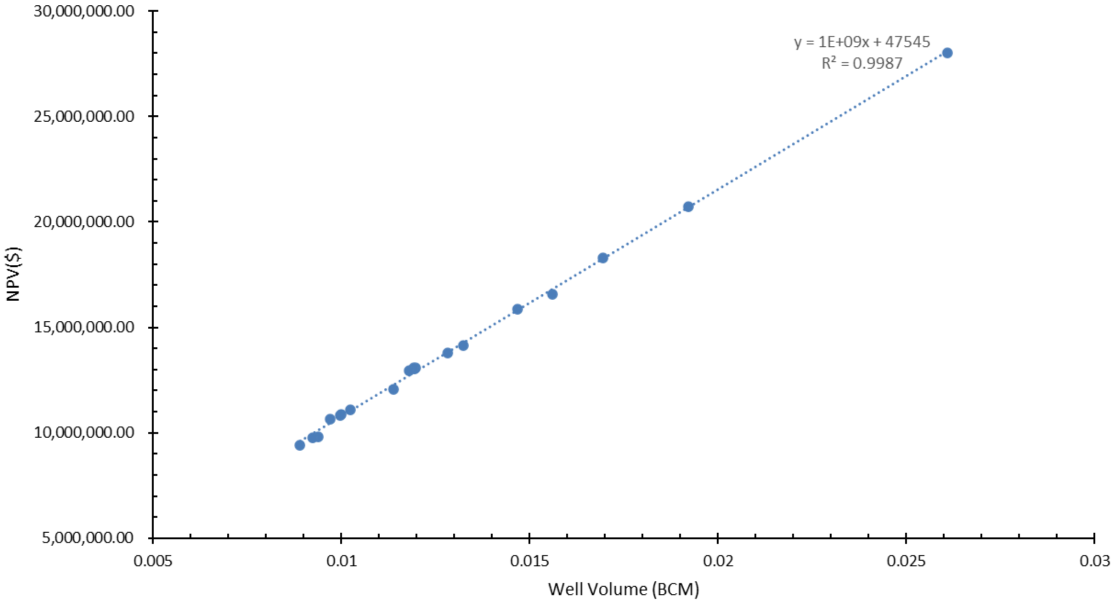
[11] Department of Energy, 2017: https://www.energy.gov/eere/iedo/life-cycle-assessment-and-techno-economic-analysis-training.

3.0 RESULTS AND DISCUSSION

This chapter focuses on analyzing the results of the calculations, as well as discussing the importance and application of the figures from the technoeconomic and environmental analyses.

4.1 Economic Impact Upon Deployment

From the 20 randomly chosen flare sites that have Targa Midstream Services - Lowry Gas as their closest processing facility, I plotted the well volume of each flare site to their respective NPV for both the minimum unit approach and the zero flare approach. Both plots return high linear correlations suggesting the well volume of a flare site is responsible for that flare site's profitability. This is sensible because the well's volume dictates the maximum volume of methanol produced: the only source of revenue for this technoeconomic analysis. Another observation is that both approaches – minimum unit and zero flare – show practically the same plot because the only difference between them is the addition of one skid unit.



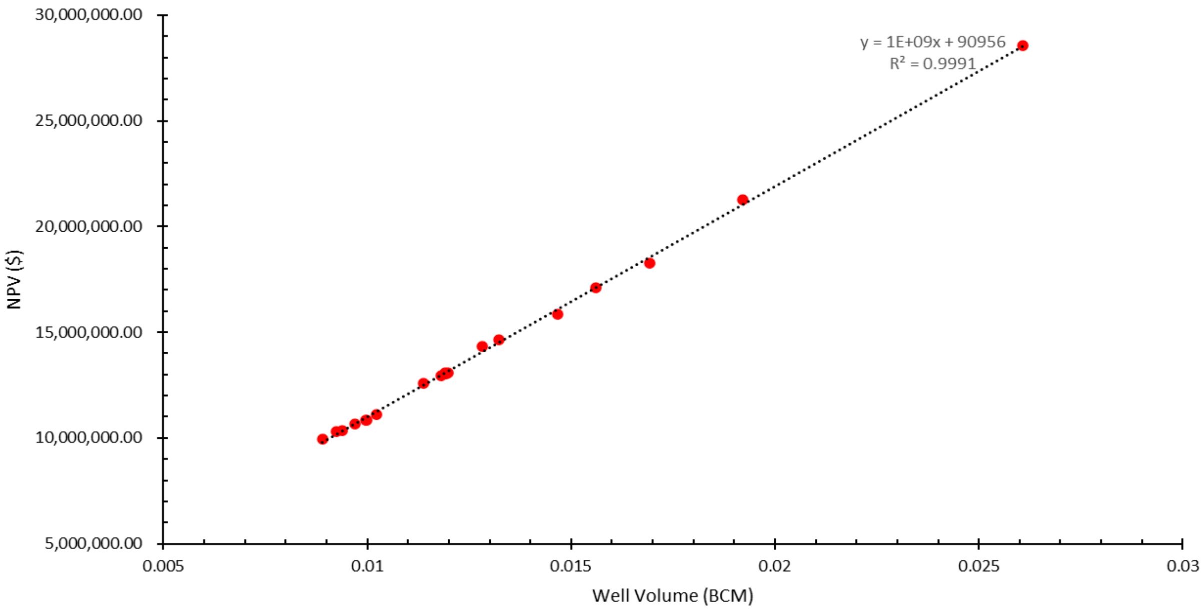


Figure 10. Two plots relating NPVs and well volumes of selected flare sites. (Top) Minimum units approach. The equation of the line is y = $(1\text{x}10^9)$x + 47545 with $R^2 = 0.9987$. (Bottom) Zero methane flared approach. The equation of the line is y = $(1\text{x}10^9)$x + 90956 with $R^2 = 0.9991$.

More interestingly, the true distance and orthodromic distance for each selected flare site were used to find a correction factor for the model which uses trigonometry instead of existing infrastructure. Looking at Figure 11, the averaged correction factor of 1.138 outputs corrected distances with low error. The two exemptions to this are numbers 11 and 16 in the plot. This highlights the fact that some flare sites have longer transportation distances despite neighboring each other and utilizing the same oil/gas processing facility. This correction factor, however, was determined using only a handful of flare sites and may not translate well to other flare sites utilizing other processing plants. The small sample size would also output an inaccurate correction factor leading to the error observed below.

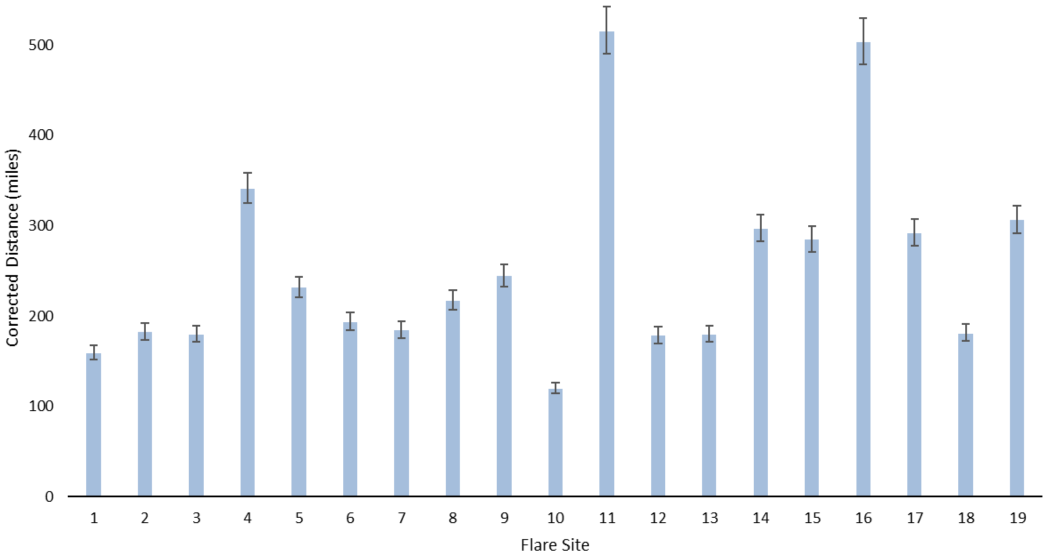
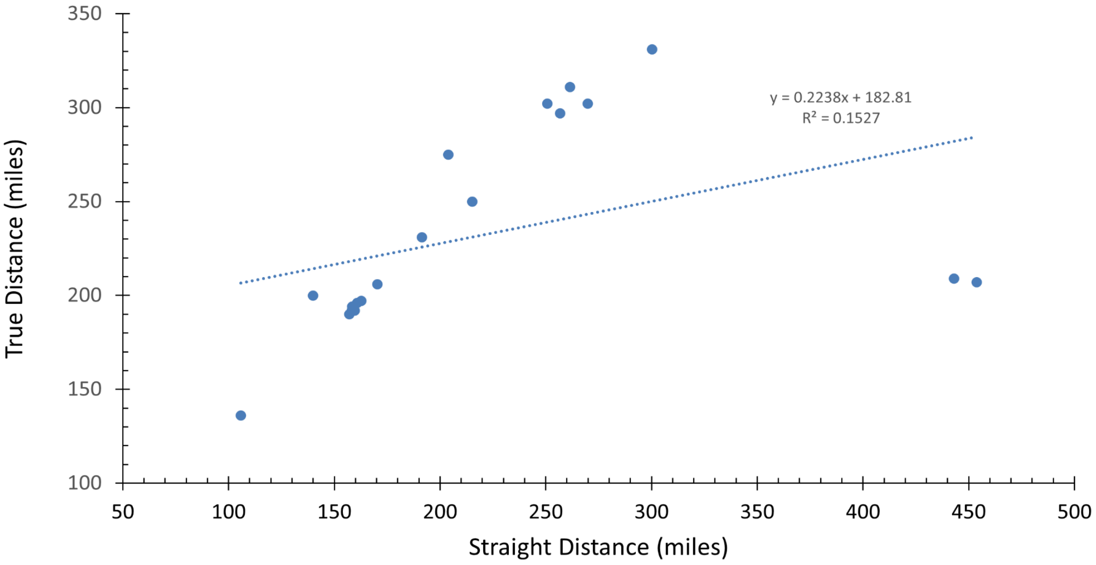


Figure 11. The corrected distance, in miles, for the selected flare sites using a correction factor of 1.138. The error bars compare the corrected distance to the true distance.

Next, the distances for the straight "crow" model and the determined true distance were plotted against each other to discover a trend, if any existed. The results are illustrated below as Figure 12.



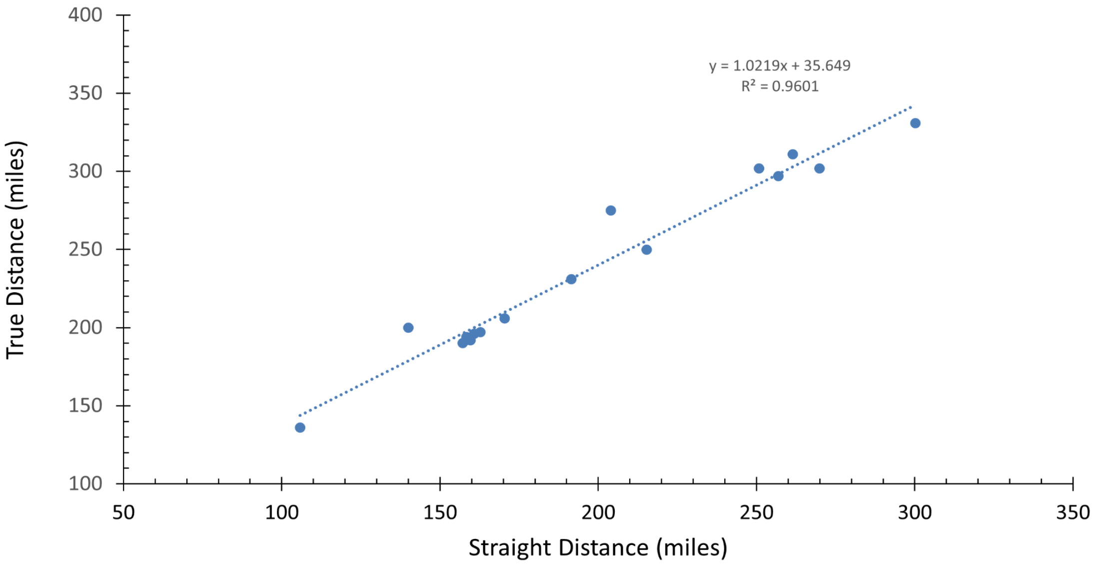


Figure 12. Two plots comparing the straight "crow" distance calculated versus the true distance determined from existing infrastructure. The top plot utilized all selected flare sites. The bottom plot removed a pair of data points.

The two data points in the top plot of Figure 12, while looking like outliers, are not in fact statistically outliers when using an alpha value of 0.05. The justification for removing these data to produce the bottom plot is that the orthodromic distance calculated using the straight "crow" model is not accurate, or is inaccurate for small distances. After removing these points, there is a strong trend relating these two distances suggesting that the crow model accurately estimates a realistic transportation distance.

4.2 Sensitivity Analysis

As mentioned in the methodology, the sensitivity of this technology was determined by varying the initial rate of return, cost of natural gas, and the transportation distance to see their effects on a flare site's NPV. One way to display this is through a bar graph as illustrated in Figure 13 below. This chart shows the lower and upper bounds of the impact by the select variables.

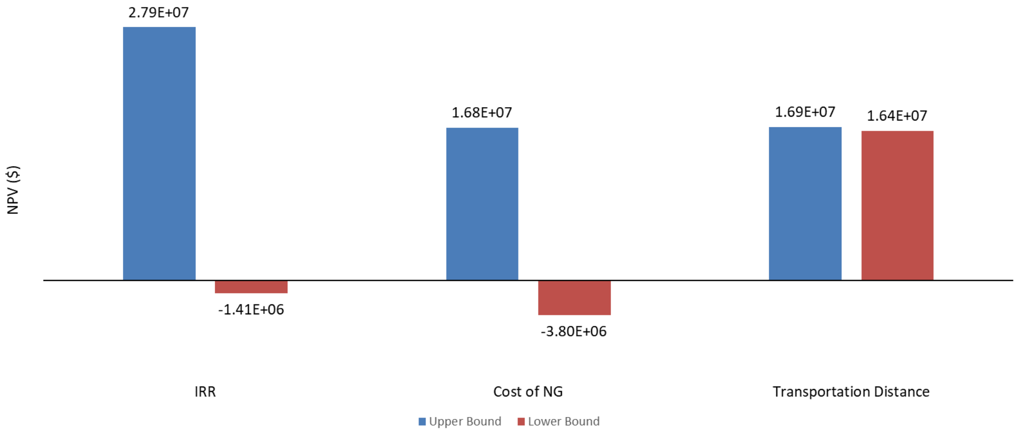


Figure 13. A sensitivity chart that highlights the upper and lower bounds for each measured metric contributing toward a flare site's NPV.

Looking at this sensitivity chart, the initial rate of return has the largest range while transportation distance has the smallest range in regards to NPV. This suggests that transportation distance has little impact on the NPV of a flare site. The opposite is true for IRR which has the most impact according to this analysis. This makes sense because the IRR is used to discount annual cash flows for NPV calculations. A major takeaway from this analysis is to focus more on what the given IRR is rather than the transportation distance which is relatively affordable.

4.3 Environmental Impact from Carbon Emissions

A major motivation for M2X Energy's deployment of their remediation technology is to lower carbon emissions from oil/gas well harvesting. Sample calculations, as found in Appendix A, estimate that the CO_2 avoidance cost of this technology is $64 per mT of carbon dioxide averted. In other words, when using this technology it will cost $64 to prevent one tonne of CO_2 being emitted into the atmosphere. A study by Kenneth Gillingham and James H. Stock compares abatement costs for several common technologies which are shown in Figure 14 below alongside the abatement cost of this technology (Gillingham, 2018).

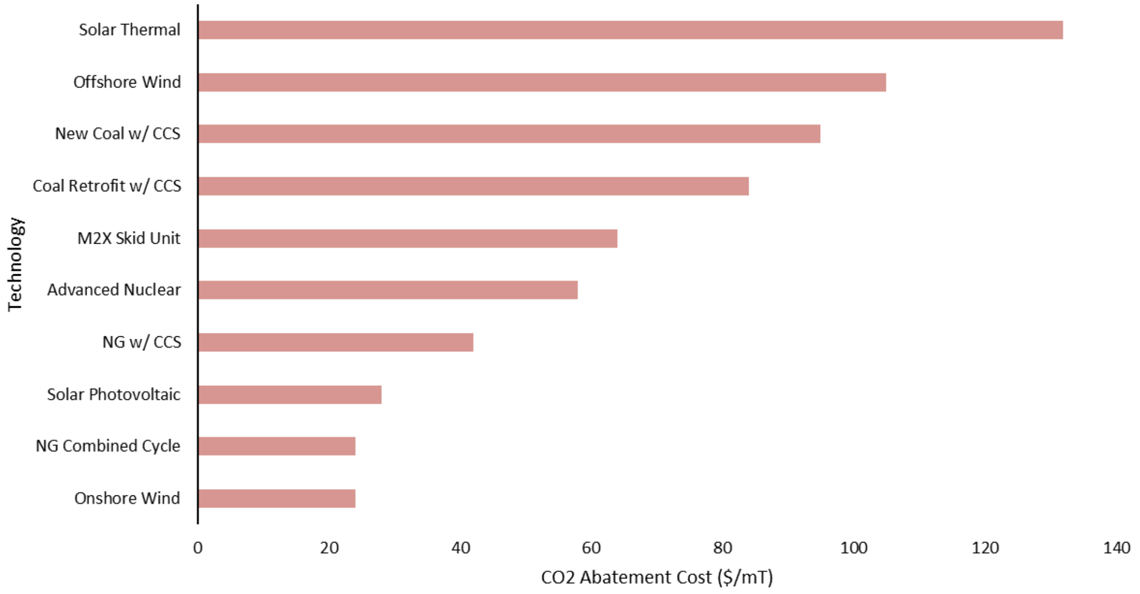


Figure 14. Comparing $CO2_{eq}$ abatement costs across several common technologies used in energy generation.

The abatement cost of M2X's technology is lower than the non-fossil fuel technologies solar thermal and offshore wind, as well as new coal and coal retrofit which both have carbon capture and storage capabilities. Although the M2X unit has a higher abatement cost than the other select technologies, it should be noted that M2X's unit is not limited to energy generation. The methanol produced has many uses including low-carbon plastics, a hydrogen carrier, and synthetic fibers. Carbon capture and storage technologies, as well as advanced nuclear, are usually capital intensive and would impose a great upfront risk to M2X Energy. This, alongside the moderate abatement cost of M2X's GTM technology, suggest justification for continued support and investment.

4.0 CONCLUSIONS AND RECOMMENDATIONS

After economically and environmentally analyzing the reformer technology from M2X Energy on converting associated gas to crude methanol, there is justification for continued investment. Net annual profits were calculated for all flare sites where these gas-to-methanol units can be deployed. Most reasonable sites have profits suggesting this technology will do well when deployed. This analysis does not, however, account for monetary agreements between M2X and oil harvesting sites – such as lease contracts – which would add additional expenses eliminating some flare sites as profitable sites for deployment. Despite this, this model does an acceptable job giving a rough estimate. Another economic factor for continued support is the carbon dioxide abatement cost of M2X's reformer technology. Although M2X runs in the middle when compared to existing technologies, the methanol produced by their reformer technology has a wider range of utilization while the technology in comparison is only for energy production. Plus, their GTM technology has better abatement costs than some carbon capture and storage options as well as offshore wind and solar thermal. M2X's abatement cost, therefore, points toward continued investment when viewed environmentally.

For future work on this analysis, I recommend using some coding language to calculate the NPV for all flare sites. This way, we can confirm the above results and conclusions apply to all flare sites across the United States. The biggest interest, however, is how accurately the orthodromic model estimates the true distance between a flare site and its closest processing facility. From the nineteen flare sites selected to further study this, both distance models closely followed a trend with an R-squared value of 0.9601 suggesting the orthodromic model accurately models true distances using existing infrastructure.

An additional note is that M2X is planning to pivot their business to apply their reformer technology to landfills rather than flare sites. Therefore, a future analysis can look at how this technology will work when deployed to landfills, and how this compares to flare site deployment and a combination of both deployment plans.

5.0 APPENDICES

Appendix A: CO_2 Avoidance Costs

According to IPCC's report from 2021, one tonne of methane is assumed to be equivalent to 30 tonnes of carbon dioxide based on the 100-year global warming potential (GWP). The EPA has a well detailed website about global warming potential which is found through this link. In summary, it is an index used to compare how different gasses contribute to global warming using CO_2 as the baseline (GWP = 1).

Assuming a 99% efficiency of methanol synthesis,

$CO2_{eq}$ for CH_4 released =

$$0.001 * (CO2_{eq}:CH4) * Well\,Volume * Operating\,Time$$

$$0.001 * \frac{30\, mT\, CO2_{eq}}{mT\, CH_4\, released} * \frac{921.28\, mscf}{day} * \frac{0.0279\, mT}{mscf} * \frac{292\, days}{year} = \frac{225.2\, mT\, CO2_{eq}}{year}$$

CO_2 from CH_4 combustion =

$$0.3(0.999 * MeOH\ Produced * Operating\ Time * Combustion\ Ratio)$$

$$= 0.3(0.999 * \frac{18.52\, mT\, MeOH}{day} * \frac{292\, days}{year} * \frac{0.001375\, mT\, CO_2}{0.001\, mT\, MeOH} = \frac{2228.5\, mT\, CO_2}{year}$$

According to the Environmental Defence Fund (EDF), which is this link, the GHG emissions from trucking is the product between the transportation distance, the weight or quantity of the shipment, and the emission factor of the transportation mode. For a standard American freight truck, its emission factor is 161.8 g CO_2 per ton-mile.

CO_2 from MeOH Transportation $= (Ton - miles) * (Emission\ Factor)$

$$= (0.999 * MeOH\,Yield * Distance) * (EF) * (\frac{1\,mT\,CO_2}{1000000\,g\,CO_2})$$

$$= (0.999 * 18.52\,mT\,MeOH * \frac{1.01\,tonnes}{mT} * 162\,miles) * (\frac{161.8\,g\,CO_2}{ton-mile)}) * (\frac{1\,mT\,CO_2}{1000000\,g\,CO_2})$$

$$= 0.49\,mT\,CO_2\,per\,truckload$$

Assuming 1 truckload per operating day,

$$= \frac{0.490\,mT\,CO_2}{day} * \frac{292\,days}{year} = \frac{143.02\,mT\,CO_2}{operating\,year}$$

CO_2 released by Flaring =

Assuming flaring is 91% efficient at combusting NG,

$$= 0.91 * Well\,Volume * Operating\,Time * (CO2_{eq}: CH_4\,flared)$$

$$+ 0.09 * Well\,Volume * Operating\,Time * (CO2_{eq}: CH_4\,released)$$

$$= 0.91 * \frac{921.28\,mscf}{day} * \frac{0.0279\,mT}{mscf} * \frac{292\,days}{year} * \frac{0.00275\,mT\,CO2_{eq}}{0.001\,mT\,CH_4\,flared}$$

$$+ 0.09 * \frac{921.28\,mscf}{day} * \frac{0.0279\,mT}{mscf} * \frac{292\,days}{year} * \frac{30\,mT\,CO_2}{mT\,CH_4\,released}$$

$$= \frac{18782.5\,mT\,CO_2}{operating\,year} + \frac{20264.8\,mT\,CO_2}{operating\,year} = \frac{39047.3\,mT\,CO_2}{operating\,year}$$

$CO2_{eq}$ Produced by M2X Technology

$$= 225.2 + 2228.5 + 143.02 = 2596.7\,mT\frac{2596.7\,mT\,CO2_{eq}}{operating\,year}$$

Averted $CO2_{eq}$ $= (CO_2\,released\,by\,Flaring) - (CO2_{eq}\,Produced\,by\,M2X\,Tech)$

$$= 39047.3 - 2596.7 = 36450.6\,mT\,CO2_{eq}\,per\,operating\,year$$

Avoidance Cost: Assuming a well volume of 921.28 mscf, M2X's Generation 2a skid producing 0.8 KTA of MeOH, and the lower heating value of methanol according to the DoE's website is 57,250 Btu/gal,

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ energy\ generated\ over\ lifetime} = \frac{\$581804.47}{975\ MWh} = \$597/MWh$$

CO_2 Avoidance Cost

$$= \frac{597 - 0}{2.34\ mT\ CO_2\ averted/MWh} = \$255.13/mT\ CO_2\ averted$$

For 1 skid unit, it will then be

$$\$255.13/4 = \$63.78/mT\ CO_2\ averted$$

Appendix B: Microsoft's Excel Workbook

The spreadsheet used for this techno-economic and environmental analysis can be found with this link.

Appendix C: Calculating a Flare Site's NPV

$$Daily\ MeOH\ Yield = Well\ Volume * Rxn\ Efficiency * MeOH{:}\ CH4 * \frac{1\ bbl}{42\ gal} * \frac{1}{7.46}$$

$$Daily\ MeOH\ Yield = 3622.01\ mscf * 0.9 * 7gal{:}\ mscf * \frac{1\ bbl}{42\ gal} * \frac{1\ mT}{7.46\ mscf} = 72.83\ mT/day$$

$$Theoretical\ \#\ of\ Units\ =\ Well\,Volume/Skid\ Intake\ Capacity$$

$$Theoretical\ \#\ of\ Units\ =\ 3622.01\ /75\ \ =\ \ 48.29$$

$$Capital\ Cost\ =\ Base\ Skid\ Capital\ Cost\ *\ (\frac{Unit\,Skid\,Intake\,Capacity/1000}{Base\,Skid\,Capacity})^{Power\ Law}\ *\ \#\ of\ Skids$$

$$Capital\ Cost\ =\ 1.43\ *\ 10^{6}\ *\ (\frac{75/1000}{0.333})^{0.6}\ *\ 48$$

$$Transportation\,Cost\ =\ MeOH\,Transport\,Cost\ *\ MeOH\,Yield\ *\ Plant\,Availability\ *\ Distance$$

$$Transportation\ Cost\ =\frac{\$0.4}{gal*1000\,miles}*\frac{333\,gal}{mT}*\frac{1.4\,mT}{day}*\frac{292\,days}{operating\,year}*73\,miles\ =\ \$3,965.17$$

$$NG\ Cost\ =\ Well\,Volume\ *\ NG\ Cost\ *\ Plant\ Availability$$

$$NG\ Cost\ =\ 3622.01\,mscf\ *\frac{\$1}{mscf}*\frac{292\,days}{operating\,year}\ \ =\ \$1,057,626.71$$

$$OM\ w/o\ Overhaul\ =\ Op.\ and\ Maintainance\ *\ MeOH\,Yield\ *\ Plant\ Availability\ +\ \frac{Overhaul\,Cost*Engine\,Op.\,Hours}{Engine\,Time\,Between\,Overhauls}$$

$$OM\ w/o\ Overhaul\ =\frac{\$6.04}{bbl}*\frac{72.83\,mT}{day}*\frac{292\,days}{operating\,year}+\frac{0*7008\,hrs}{14016\,hrs}\ \ =\ \$128,446.35$$

$$Expenses\ =\ OM\ Cost\ +\ Transportation\,Cost\ +\ NG\ Cost$$

$$Expenses\ =\ \$128,446.35\ +\ \$3,965.17\ +\ \$1,057,626.71\ =\ \$1,190,038.23$$

$$Revenue\ =\ MeOH\,Yield\ *\ Plant\ Availability\ *\ MeOH\ Market\ Price$$

$$Revenue\ =\frac{72.83\,mT}{day}*\frac{292\,days}{operating\,year}*\frac{\$575}{mT}\ \ =\ \$12,227,922.81$$

Assuming an interest rate of 10% and a skid unit’s life is 20 years, and using Excel’s NPV function,

$$NPV\ =\ (0.10,\ Capital\ Cost,\ Revenue\ per\ year)\ =\ \$61,324,599.97$$

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