Valorization of Stranded Natural Gas

A Major Qualifying Project Report submitted to the faculty of
Worcester Polytechnic Institute, Department of Chemical Engineering.
Sponsored by M2X Energy Inc.

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Abstract

Tight oil extraction has boosted natural gas production (NG), whose main component is methane (CH_4), and it accounted for 11% of the U.S. greenhouse gas (GHG) emissions as of 2020. Companies that do not have a system to use the NG, flare it to maintain safe production, and for regulation purposes. Flaring is only 91% efficient, which wastes energy and causes toxic environmental and health effects. Fuel switching from coal to NG is one of the ways adapted to reduce CH_4 emissions, but leakages during NG transportation to power plants limit its effectiveness. M2X Technology offers a simple, scalable, and modular Gas to Methanol (GTM) unit that converts gas to methanol at the point of extraction. This study aims to analyse the economic and environmental impacts of deploying the technology to all USA flare sites. The methodology involves adapting GTM units to wells of different sizes, analyzing carbon dioxide equivalents (CO_2eq) abatement costs, and the net present value of the investment. Results show that the deployment could reduce U.S. GHG emissions by 3.3% while making profits. The M2X technology's CO_2eq abatement costs outshine other technologies, especially after accounting for the learning rate. The profit margin increases with the size of the well, and the overall NPV would be \$2.8 billion with a 21% error, which is insignificant, considering NPV will still be positive. Computer-coded calculations can be used in future works instead of manual Excel probabilities, to reduce the error.

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1 INTRODUCTION

The growth in tight oil production has led to an exponential increase in greenhouse gas (GHG) emissions, natural gas (NG) is one among them, also known as associated gas. Greenhouse gases have negative effects on the climate, thereby disrupting the ecosystem, as well as the well-being of society. NG is mainly composed of methane, a much more powerful GHG in trapping radiation. It has a global warming potential (GWP) value in the range of 27-29.8. Companies that do not have systems to make use of the NG, flare it to keep up with production. They do so for safety, economic, technical, and regulatory reasons. Besides the justifications flaring is only 91% efficient (Yelvington, Browne, Yik, Merica, & Dean, 2023), which wastes energy, and causes a lot of toxic environmental and health effects. So far there are 6,292 flares in the U.S. burning off 10.65 billion cubic meters of natural gas (The World Bank Group, 2023).

Fuel switching from coal to natural gas in the electricity industry is one of the ways adapted to reduce GHGs emissions. However, it has been limited by leakages that happen when transporting natural gas from the well to power plants, insufficient volumes of NG, as well as the remote locations of most oil reservoirs. This problem is distributed in nature and therefore calls for a distributed solution. M2X technology brings a solution, that captures emitted methane at the point of extraction and converts it to low-carbon methanol. The gas-to-methanol (GTM) unit is modular, scalable, run autonomously, and can operate in different weather conditions. The units can be numbered up or down to adapt to the volume of the flare site, and the size of the wells, and can run in a wide range of gas compositions. This project focuses on adapting the number of GTM units to wells of different sizes, implementing transportation costs to the original base plant TEA model, and analyzing the economic as well as environmental impact of deploying the M2X technology to different flare sites. A sensitivity and learning rate analysis is also performed.

2 BACKGROUND

2.1 Greenhouse Gases (GHGs)

Greenhouse gases (GHGs) trap heat in the atmosphere leading to global warming. When the earth's surface emits infrared radiations, some pass through the atmosphere and some are trapped by GHG, the effect of this is warming the lower atmosphere and the earth's surface. Emissions from human activities have been the main drivers of the global climate crisis since the industrial era. Emissions from human activities have increased worldwide by 43% from the year 1990 to 2015. According to the U.S. Environmental Protection Agency (EPA), in 2020 the U.S. had a total of 5981 million metric tons of CO_2 equivalent emissions. 73% of these emissions were carbon dioxide, 11% methane, 7% nitrous oxide, and 3% fluorinated gases. Historical records demonstrate that the recent global atmospheric concentrations of carbon dioxide are novel even after natural fluctuations have been accounted for. Most of the prevalent GHGs reside in the atmosphere from a decade long up to a century. Their warming effects persist over a long time henceforth affecting both present and future generations (U.S Environmental Protection Agency (EPA), 2022).

Effects of GHG *(Climate change indicators)*

GHG emissions cause a wide range of effects on the earth's climate thereby disrupting the ecosystem, as well as human health. Many places around the world are experiencing intense heat waves, heavier rainfalls, rising sea levels, and unpredictable snowfalls. These changes in weather patterns are attributable to the rising global average temperatures. Scientific results also indicate that such extreme weather events are likely to become more common because of human activities. Intense precipitations can cause population displacements, property damages, as well as the destruction of essential services like energy and water supplies, transportation, and telecommunication. The reduced amount of snowfall means there is less snow cover on the ground thereby reducing the insulating capacity of the ground for specific vegetation and wildlife. For example, 42% of polar bear populations that reside in ice-covered areas, are in danger of extinction because of the negative effects of global warming (Stirling & Derocher, 2012). Frequent wildfires have also caused deterioration of air quality and increased displacement of species. (U.S Environmental Protection Agency (EPA), 2022).

2.2 Natural Gas(NG)

Natural gas is mainly composed of methane (CH_4), a very strong greenhouse gas. Sometimes NG is referred to as "associated gas", it emerges when crude oil is brought to the earth's surface (Elvidge, Zhizhin, Baugh, Hsu, & Ghosh, 2016). The growth in tight oil production in the U.S. has caused an exponential increase in natural gas. The U.S. 48 lower states are comprised of several basin formations that hold great potential for tight oil development. These basins include but are not limited to the Gulf Coast, Permian, Monterey, Williston (Bakken), and Cleveland. The increase in upstream exploration as well as production technologies has increased the production of petroleum and eventually the associated gas (Pederstad, Gallardo, & Saunier, 2015). The U.S. Environmental Protection Agency (EPA) outlines that in 2020, 32% of methane emissions came from natural gas and petroleum systems. Methane plays a huge role in warming the atmosphere thereby contributing to global warming. (U.S Environmental Protection Agency (EPA) , 2022). The global warming potential (GWP) of methane is in the range of 27-29.8 including both fossil and non-fossil sources. GWP refers to a measure of heat absorbed by any greenhouse gas added to the atmosphere over a given timeframe as multiple of the heat that would have been absorbed by the same mass of added CO_2. The lifetime of methane in the atmosphere is insignificant compared to that of carbon dioxide CO_2, however, CH_4 is more powerful in trapping radiation compared to CO_2. Comparing a pound of CH_4 to that of CO_2 released into the atmosphere, CH_4 has a 25 times greater impact compared to CO_2 over a 100years (Team, Pachauri, & Reisinger, 2007) If methane is utilized properly, it can add additional revenues to oil companies while solving a wide range of environmental problems (Pederstad, Gallardo, & Saunier, 2015).

2.3 Natural Gas Leaks

Usage of Natural gas as a feedstock for other forms of energy like electricity production and liquid fuels is one of the ways used to mitigate the effects of GHG currently. (Browne, 2016). Combustion of natural gas for energy contributes to lower emissions of carbon dioxide (CO_2) and air pollutants than burning petroleum products and coal to produce an equivalent amount of energy. The US Energy Information Administration reports that 117 lb. of CO_2 are produced per million British Thermal Units (MMBtu) equivalent of natural gas in comparison to more than 160 lb. of CO_2 per MMBtu of distillate fuel oil and more than 200 lb, of CO_2 per MMBtu of coal. (US Energy Information Adminstration, 2021).

While fuel switching to natural gas from coal reduces GHG emissions in the electricity production sector, it has been highly limited by NG leakages that happen during transportation from remote locations. It, therefore, brings a question of whether this technology solves the overall GHG emission, especially when compared to current leakage percentage uncertainty. Additionally, NG also has high leakages into the atmosphere from pipelines, NG wells, storage tanks, and processing plants. (Browne, 2016). Companies that have not created a system to make use of this associated gas, burn it (flare) to keep producing oil safely. Which wastes a lot of energy and leads to various environmental effects.

2.4 Natural Gas Flaring

Gas flaring involves the burning of natural gas and other heavier hydrocarbons that comes from oil extraction. The process yields products like carbon dioxide, carbon monoxide, and other by-products of incomplete combustions such as nitrogen oxides and black carbon. The process is only 91% efficient which leads to the release of methane and other harmful pollutants into the atmosphere (Gvakharia, Kort, & Brandt, 2017) . Various methods are used for the global survey of NG flaring. The data used for our analysis is obtained from the National Aeronautics and Space Administration (NASA), using Visible Infrared Imaging Radiometer Suite (VIIRS). From these sources, it was observed that globally, annual gas flares from upstream sources have been consistently over 100 billion cubic meters (BCM). The results have been recorded with an accuracy rate of ±9.5%. The USA is also reported to have the highest number of flare sites in the whole world (Elvidge, Zhizhin, Baugh, Hsu, & Ghosh, 2016).

Figure 1:Flaring from oil production at a remote inaccessible place ((The World Bank Group, 2023): Nico Traut

Though polluting and wasteful, flaring is still widely used as a technique to dispose of gas at processing facilities that do not have the technology to capture and use up the gas. Flaring also happens because of safety, regulatory, economic, and technical reasons. Most oil and gas companies operate processes that involve dealing with exceptionally high and changeable exhaust pressures which could lead to explosions. Operators, therefore, turn to flaring and venting as a relatively safe alternative to depressurize their systems and manage industrial accidents. Further, most oil reservoirs are in remote places *Figure 1,* where it's very hard to transport the associated gas to where it can be processed and utilized. The amounts produced are also of low inconsistent volumes for the operators to make use of them. These reasons make it uneconomic to capture the gas hence flaring is usually done. Sometimes it might be economic and feasible to capture the gas, but government regulations restrict companies from doing so as they do not reserve rights to the associated gas that is produced during oil extraction. Moreover, regulations that are imposed are still ambiguous and they are not effective in diminishing the behavior especially when companies find flaring and paying penalties is more economically viable. Besides the justifications above, flaring is still a massive waste of a treasured natural resource that could be used for meaningful purposes like the production of electricity or even conserved. For example, the amount of natural gas that was flared in 2021 is about 144 BCM, which is estimated to have the capacity of powering the whole of sub-Saharan Africa. Half of that amount was produced by 5 countries as demonstrated in *Figure 2* below, the USA being one among them (The World Bank Group, 2023).

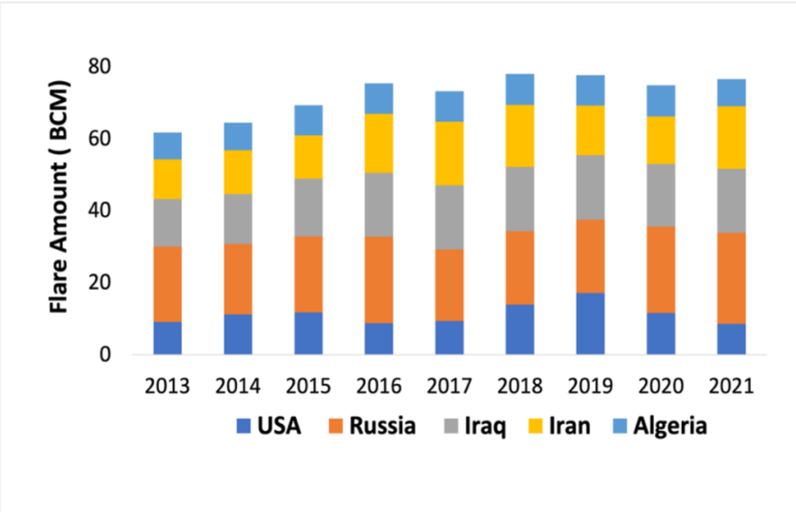

Figure 2: Top 5 countries that contributed to 50% of flares in 2021 worldwide

2.5 *M2X Energy Inc & The M2X Engine Reformer Technology*

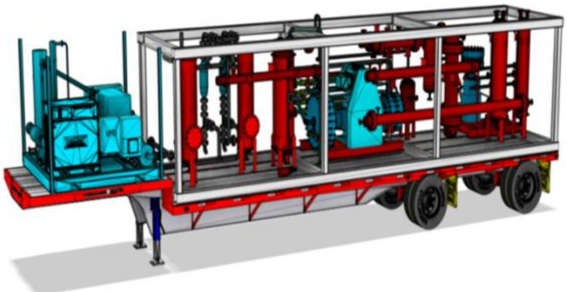

Figure 3:A unit skid of the modular transportable gas to methanol plant ((M2X ENERGY, 2023)

M2X Energy Inc is a climate tech company that was founded to reduce and eventually eliminate the flaring and venting problem outlined earlier as it's an urgent climate task. "Reducing methane emissions from the oil and gas industry is critically important because methane has such a large climate impact in the short-term," says Carmichael Roberts, Breakthrough Energy Ventures. As long as oil and gas are part of the energy industry, it's crucial to reduce their negative impact on the environment (Business Wire, 2023). M2X's technology captures methane emissions and transforms the gas into low-carbon methanol. It has provided a solution to the constraints of gas-to-liquid (GTL) systems that prevented them from being effective in the field. M2X's innovation follows the dissertation work of Joshua Browne, the current chief technology officer (CTO) of M2X, whose techno-economic analysis (TEA) is the main basis for this report. M2X is using an internal combustion engine and modified it to create methanol plants that are modular, scalable, and run autonomously in the field *(Figure 3)*. The units can be numbered up or down to adapt to the volume of the flare site, and the size of the wells, and can run in a wide range of gas compositions. The informally known "plant-on-wheels" units are conversion systems brought at the point of extraction (Browne, 2016).

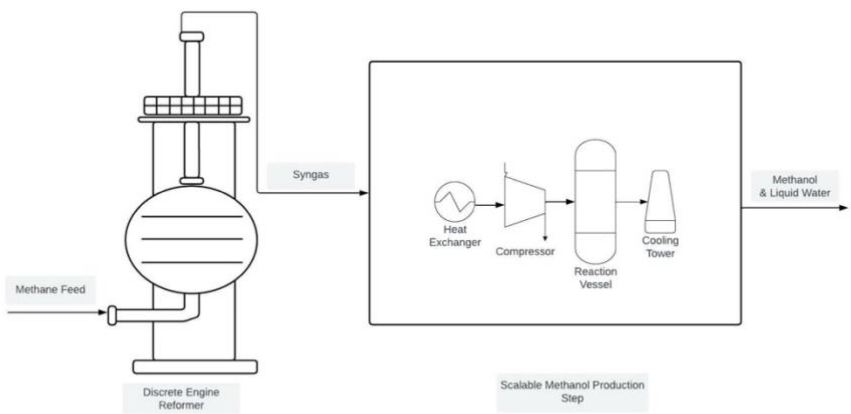

Figure 4: Two Step Process for Production of Methanol from Methane. Adapted from Browne's dissertation Flowsheets (Browne, 2016)

The units convert the gas that would otherwise be flared on-site to methanol which is then transported to end users through tanker trucks (Salmon, 2023).

The system is composed of a discrete engine reformer component as well as a scalable methanol production step as shown in *Figure 4.* The engine reformer takes in methane and converts it to syngas which is mainly composed of carbon monoxide and hydrogen. Other remaining components include methane, carbon dioxide, oxygen, water, and nitrogen. The syngas is then converted to methanol through a series of reactors. For this report, I will be using values of 75,000scf/day (75 Mscf/day) of flare gas for unit intake capacity, and 7gal crude methanol per Mscf of methane fed for methanol yield, as quoted by Paul Yelvington the chief science officer (CSO) of M2X. For the methanol yield, 90% of the product is pure methanol and 10% is liquid water. It should be noted these values have changed per M2X's field demonstration done in the first quarter of 2023. Technology advancements have resulted in a unit intake capacity of approximately 85,000scf/day producing 5000 barrels of methanol per year. Results of the field demonstration will be available in the summer, thereafter they will start to plan for deployment of the units to flare sites within the United States (Business Wire, 2023). Therefore, the impact analysis of deploying the GTM units to different flare sites around the U.S. conducted in this report is invaluable.

3 METHODOLOGY, RESULTS & DISCUSSION

3.1 Adapting GTM units to wells of different sizes.

This analysis was done to understand the distribution of GTM units required at individual flare sites and select the best approach for rounding up the number of units. The analysis was performed using Visible Infrared Imaging Radiometer (VIIRS) flare data that was obtained from the Earth Observation Group (Earth Observation Group, 2021). The flare data was given in units of BCM, which was converted to mscfd using appropriate unit conversions. Additionally, the original data set outlined flare sites in terms of longitudes and latitudes, which are hard to interpret and visualize. Therefore, the different location IDs' longitudes and latitudes were mapped to the associated states and counties using the spatial analysis data tool on ArcGIS. The analysis focused on two main components: the required number of GTM units at each flare site, as well as the associated methanol yield.

To calculate the number of units *Equation 1* below was used, and the associated sample calculation is outlined under *Appendix A.*

$$Number\ of\ Unit\ skids = \frac{Methane\ flared\ (Well\ \ volume)\ \left(\frac{mscf}{day}\right)}{GTM\ unit\ intake\ capacity\left(\frac{mscf}{day}\right)}$$

Equation 1: Number of Unit Skids Required

The values obtained from this calculation contained decimal places. However, we can't manufacture a fraction of a GTM unit. We, therefore, needed to select an effective way of rounding the decimals to whole numbers. To perform the investigation, we studied two approaches. Approach 1 is referred to as the minimal number of units, and the second one is zero methane. For approach one, we rounded up anything with > 0.5 decimal and turned several units to partial capacity. For example, for a flare site located in Lea New Mexico, with a volume of 4561mscf/day, 60.82 units were required. This value was rounded to 61, and the additional unit would only be running at 82% of its total capacity. Anything with < 0.5 decimal was rounded down and the rest of the methane was flared. The amount of methane allowed to flare was obtained from the difference between the net methane converted and the volume of the well. Hence, this approach is referred to as the minimal number of units. For approach 2, we treated units as a system of reactors and rounded up everything, then turned down multiple reactors to run at partial capacity. For example, for our highest volume flare site in McKenzie North Dakota, with a volume of 5581.1mscfd, 74.42 units were required. This value was rounded to 75 units, and two of the units would only be running at 71% of their total capacities. No methane would be allowed to flare in this case;

hence, this approach is referred to as zero methane. Therefore, for approach 2 the methane converted was equal to the volume of the well.

The methanol (CH_3OH) yield was calculated using *Equation 2* below, for methane (CH_4) converted in each of the approaches. The sample calculation is also demonstrated in *(Appendix B)*. Similarly, the calculations were repeated for each site using Excel and presented together for each state.

$$CH_3OH\ yield = CH_4\ converted\left(\frac{CH_3OHyield}{Mscf\ of\ CH_4\ converted}\right)$$

Equation 2: Methanol Yield

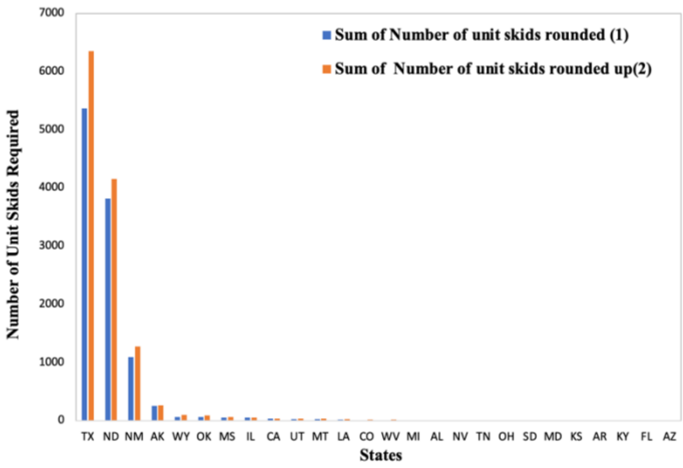

Figure 5: Number of Unit Skids required over different states

Both studies gave insightful results, as demonstrated in *Figure 5* and *Figure 6* below. From *Figure 5* it is observed that approach 2 required more units compared to approach 1 by 87%. *Figure 6* demonstrates that approach 2 would yield more methanol compared to approach 1.

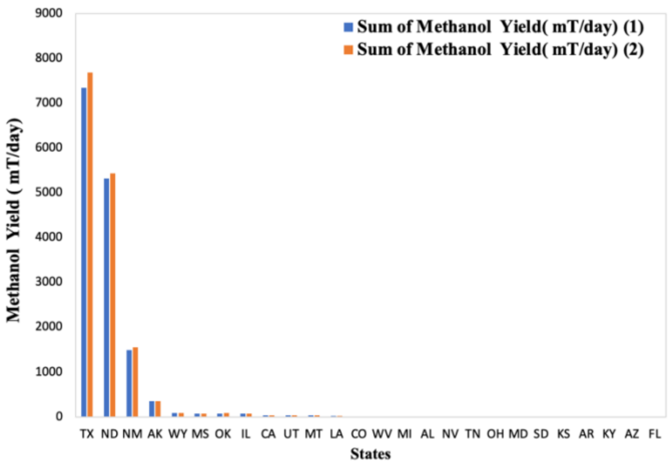

Figure 6: Anticipated Methanol yield across different states

Additionally, approach 2 allowed zero methane to be flared, while approach 1 would flare approximately 29000mscfd. Approach 2 will be used for further economic and environmental impact analysis of our study, as our main goal is to reduce flares. It should be noted that this choice might not be necessarily the most profitable. The higher number of units ensures no methane is flared but results in higher capital expenditures, and some of the units would not be used to full capacity. Therefore, further modeling could be done in the future to find the optimum point between the associated capital expenditures, methanol yield, and methane allowed to flare.

3.2 Implementing transportation costs to the original base plant TEA Model

This analysis was done to study the feasibility of the project after accounting for transportation costs that were ignored in Browne's original base plant Techno-Economic Analysis (TEA) model (Browne, 2016). To calculate the transportation costs, we needed to calculate a transportation distance from a reference point using the *distance equation,* outlined under *Appendix C*. Odessa TX, was chosen as a reference point, located at Latitude and longitude coordinates 31.8456, and -102.3676 respectively (LatLong Net , 2023). Odessa TX was chosen because it is located within a 100-mile radius of most of the wells of interest. Additionally, its pre-existing infrastructures and market characteristics are very developed which makes it reliable for trucking. The methanol produced would be aggregated at a hub and then transported to end users in larger quantities. For example, flares located around the Permian Basin or Eagle Ford regions in Texas could be aggregated near the Gulf Coast, which could then be exported overseas. All the factors mentioned here make TX a great pinpoint for starting the deployment. It should be noted that this reference point might not be a feasible aggregate location for methanol produced in areas like the Bakken Formation Wells in the Williston Basin - North Dakota (Yelvington, Browne, Yik, Merica, & Dean, 2023). Therefore, we might need to rethink the final product for the corn belt region and consider higher-value products. For example, producing ammonia and urea through the Harbor Bosch Process instead of methanol. To analyse the feasibility of the project while accounting for transportation costs we considered two parameters: the annual net profit as well as the net present value (NPV).

The net annual profit for year 1 of the project was calculated using the formula outlined in *Equation 3*. The expenses included: operations and management (OM) cost as well as natural gas costs. A case with and without transportation costs was also considered. Revenue was a function of the methanol produced, and the current methanol price was based on Methanex (Methanex Corporation, 2022). A sample calculation involving the step-by-step procedure for obtaining the net annual profit is also outlined under *Appendix C*, adapted from Josh's TEA analysis (Browne, 2016). It should be noted the plant gets refurbished every after two years, hence refurbishment costs will be accounted for biannually.

$$Net\ Annual\ Profit = Revenue - Expenses$$

Equation 3: Net Annual Profit

Following the net annual profit analysis, a further study was done to see the impact of transportation costs on the NPV of the project. Josh's original base plant model was scaled down from a volume of a well of 0.333 mmscfd to 0.075029 mmscfd for a sample flare site located in Reeves, Texas. The NPV was calculated using, *Equation 4* below. An equivalent Excel input was used for the repetitive calculations as outlined in *Appendix D.* NPV is a function of annualized discounted cashflows, including capital costs. The discounting was done using an internal rate of return (IRR) of 10%, a corporate income tax rate of 35%, and assumed plant life of 20 years. The total plant capital cost for the module plant was scaled down from the base plant's total capital cost using the "six-tenths" factor rule power law (Yelvington, Browne, Yik, Merica, & Dean, 2023). Accounting for scaling economics of small unit operations (Weber, Jalal , & Barclay, 2020). The empirical relationship between scale and cost from the power rule is used to obtain the total plant cost for the module plant as demonstrated in *Appendix D.*

$$NPV = \sum_{N=0}^{N\,final} ACFN(\,1 + i)^{\,-N}$$

Equation 4 : Net Present Value

From this study, it was found that the investment is economically feasible since we obtain a positive net annual profit in all sites as seen in *Figure 7*. We also found that there is a slightly lower net annual profit when accounting for transportation costs. Besides the conclusions, the study brought a question of whether transport costs would be significant enough to impact the NPV. An NPV analysis was done for the same 0.075029 mmscfd volume sample flare site located in Reeves, Texas. By considering a transportation distance of 82 miles, to Odessa TX, the project was found to have a NPV of 0.32M$. Additionally, using a goal-seek analysis shown under *Appendix E* as well as a graphical approach presented in *Figure 8* below, the breakeven transportation distance for the Reeves flare site was found to be 1165.35 miles. This means that we can afford to transport the methanol produced at this site up to 1165.35 miles without having a negative NPV, given a plant life cycle of 20 years. Further, a net present value can be calculated for a specified distance using the relationship equation outlined in *Figure 8*. A similar analysis can be done for every single flare site. In the future, this model could be automated by advanced computer-coded calculation techniques. For example, a code could be written to generate a maximum allowable transportation distance for methanol produced in site X, given the size of the flare and specific methanol yield. One could also consider different hubs as reference points of collection, and account for more accurate transportation distances. This code would be a more accurate estimation as opposed to the distance formula which accounted only for the shortest diagonal distance between two points. Sometimes existing infrastructures between

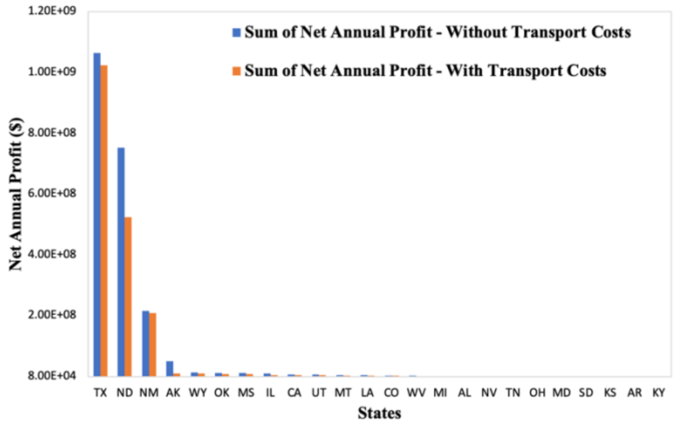

Figure 7: Net Annual Profit across different states

remote areas might require trucks to travel around in loops as opposed to diagonally. A sensitivity study is also done under *Section 3.5* to demonstrate how sensitive the NPV is to transportation costs.

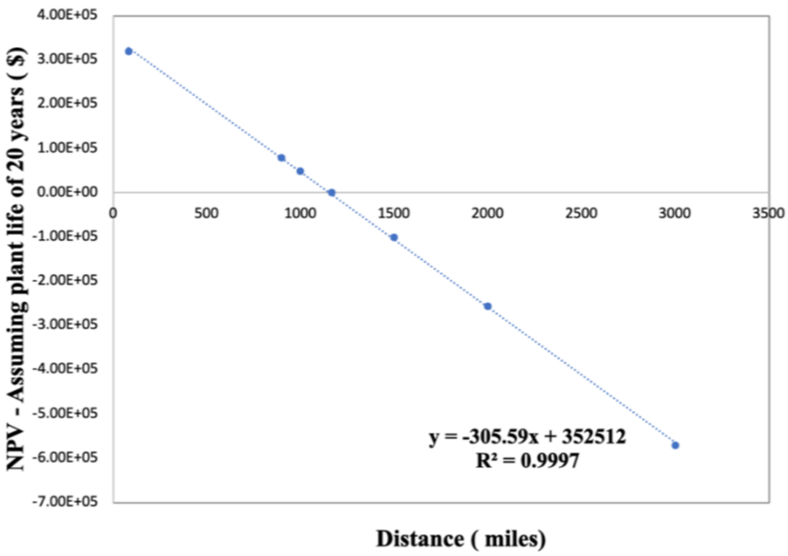

Figure 8: NPV as a function of transportation distance

3.3 *The economic impact of deploying the M2X Energy Technology*

Afterward, we evaluated the net present value (NPV) for deploying the 75mscf unit to the different upstream flare sites in the USA to determine the overall economic impact of the technology. To perform the analysis, we needed to use representative flare sites for all 2858 sites. A histogram was generated to understand the distribution of the wells of different sizes. The histogram was generated using Excel with a bin width of 0.2, and an overflowing bin was set to 1mmscfd, as represented in *Figure 9*. This overflow bin was selected based on interview results with Browne, the CTO, at M2X Energy. Browne outlined that; upon deployment, we would start with flare sites under hundreds of mscfd.

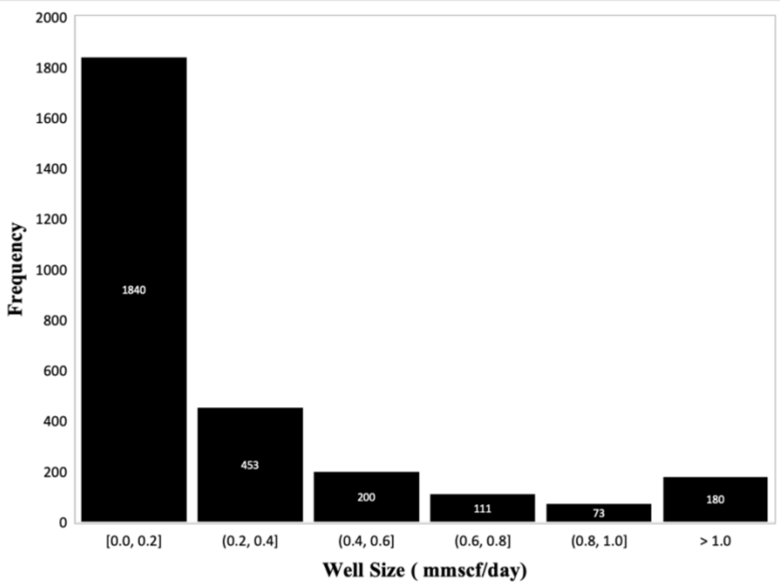

Figure 9 :Well sizes distribution

Browne's comments were also backed up by what the data demonstrates. It is seen in *Figure 9*, 93% of all the flare sites considered have a well volume <1mmscfd. Hence, the selection of representative flare sites between sizes of 75 mscfd to 900mscfd for our analysis. The individual sites were selected at random in the ratios of 4:2:2:1:1 from the first five bins shown in *Figure 9*. We also selected sites that were within less than a 100-mile radius from our aggregate reference point in Odessa TX. It must be noted that this categorization was done solely on the assumptions outlined in the discussion here, and they would differ based on the set of assumptions considered.

An economic impact analysis was performed on the selected flare sites by computing the associated NPV of each site. The NPV was calculated using *Equation 5 below*, which is multiples of the base plant NPV, assuming the same IRR, corporate income tax rate, and plant life indicated in *Section 3.2*. The total NPV for all wells was calculated by multiplying the NPVs for the representative well with the respective number of wells of that specific size.

$$NPV\ of\ Well\ X = \left(\frac{Well\ Size}{Module\ Plant\ Capacity}\right) NPV\ of\ Module\ Plant$$

Equation 5 : Net Present Value

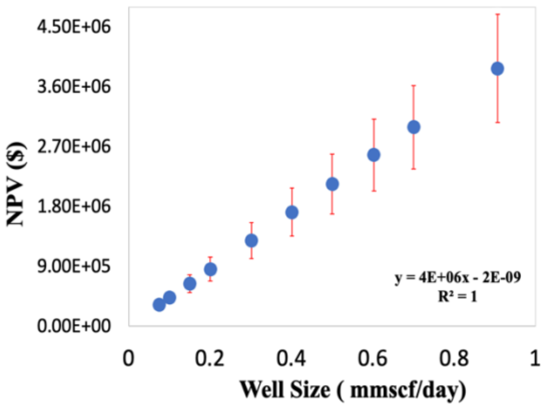

Figure 10 : NPV as a function of Size of Wells

As seen in *Figure 10*, it was found that the NPV increases linearly with the associated well size for the representative flare sites. Upon calculating the total NPV for all sites it was found to be 2799M$ with a 21% percent error, which is insignificant considering it still yields a positive NPV. The error can be attributed to the varying well volumes as well as the actual transportation distances. The NPV value for a specific flare site can also be obtained using the linear equation outlined in *Figure 10*. It should be noted that all the sites selected are in Texas within a 100-miles radius, which is why this formula of multiples works. If we were to select sites that were further away from the aggregate point, this formula wouldn't hold, and we would need to compute each NPV separately while accounting for the associated transportation distance. For a future analysis, advanced computer-coded calculations can be used, for example, one can consider writing specific code that can prompt to enter an aggregate point, well size then compute the exact associated NPV.

3.4 Environmental impact of deploying the M2X Energy Technology

The M2X technology's environmental impact was assessed by comparing its carbon dioxide abatement costs (dollars per ton of carbon dioxide avoided) to other technologies, as well as calculating the overall reduction in GHG emissions. The difference between carbon dioxide equivalents (CO_2eqs) of total emissions from flaring and those from deploying the M2X technology provided the net amount of CO_2 abated. The CO_2eqs from flaring were calculated assuming a flare efficiency of 91%. CO_2eqs from M2X technology were calculated under the assumption that the technology is 99.9% efficient, 30% of the methanol yield is used as fuel, and 70% is used for downstream chemical synthesis. (Yelvington, Browne, Yik, Merica, & Dean, 2023). As demonstrated by the International Energy Agency, (IEA) the levelized cost of energy generation is the present value of the sum of discounted costs divided by total production adjusted for its economic time value (IEA, 2010). It's technically the price that must be charged per unit to cover all expenses plus the desired rate of return (Rubin, 2013). Hence, the levelized cost for M2X technology was obtained by performing a goal-seek analysis on methanol price to obtain an NPV of zero. The levelized cost of flaring was assumed to be zero for this analysis. The differences between the levelized costs and the CO_2eqs were then used to calculate the ($/mT of CO_2 abated) ratio as well as the abatement elasticity which is the inverse parameter (mT of CO_2 abated/$) ratio as demonstrated in *Appendix F*.

The value obtained was compared with other technologies based on current estimates of marginal costs as presented by the work of Kenneth Gillingham (Gillingham, 2018). The author's estimates were based on Energy Information Administration in 2018, for facilities that came online in 2022.

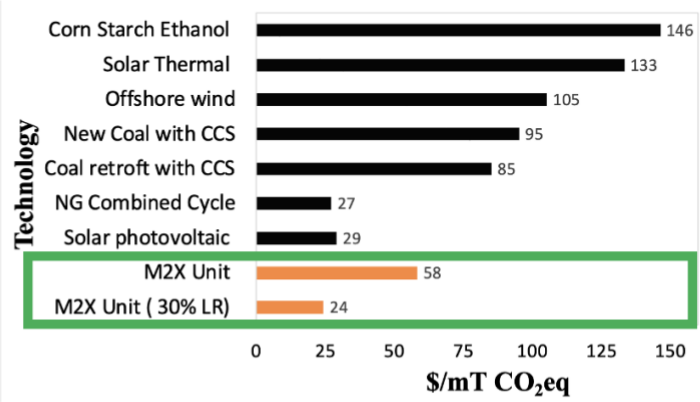

Figure 11: $/mT of Carbon dioxide equivalents avoided for different technologies

As demonstrated in *Figure 11* the carbon dioxide abatement cost for the M2X engine reformer technology is found to be 59$/ mT of CO_2. The value is lower than that of several technologies such as solar thermal, offshore wind, new coal, and coal retrofit with carbon capture and storage. Even though M2X technology is more expensive than NG combined cycle, and utility-scale solar photovoltaic, it still outshines them when accounting for the learning rate (See *section 3.5 below)*. It should also be noted that the estimates presented for contrast, compare the cost per ton of CO_2 abated by replacing electricity generated by an existing coal-fired power plant with electricity generated by a cleaner alternative. In our report, these values are solely used to compare the CO_2eq emissions from the different technologies and not necessarily the exact end products of each technology. Another performance metric considered was the “inverse abatement cost” which is also the measure of abatement elasticity. This value was found to be 0.017 mT of CO_2 /$, which indicates that for any additional capital cost spent on M2X technology, about 0.017 mT of is CO_2 averted. This metric is a great justification for continued investment in M2X Technology.

Further, it was found that deploying the M2X Technology to all flare sites in the USA will result in a 3.3% reduction in GHG emissions. This value was estimated based on the percentage of carbon dioxide emission avoided by using M2X Technology instead of flaring, which was on average 94%. As indicated in the introduction *section 2.2* flares contribute only to 32% of methane emissions, and methane emissions contribute only to 11% of total USA GHG emissions. Hence, the multiples of these three percentages results in the estimated reduction in US GHG emissions.

3.5 Sensitivity Analysis & Learning Rate

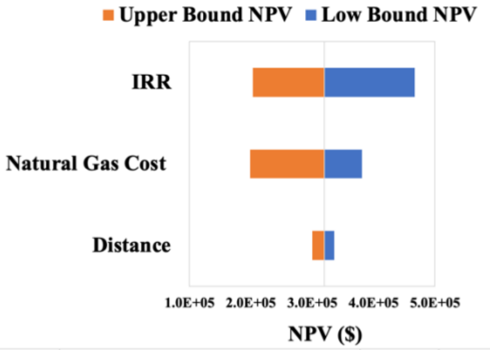

Figure 12: Sensitivity Chart Analysis on NPV

A sensitivity analysis was done to understand how the NPV for the M2X Technology would change with a change in the IRR, natural gas cost, and transportation distance. The analysis was done by performing NPV calculations for the representative site in Reeves TX with high bound parameters as well as low bound parameters as demonstrated in *Figure 12* below. Empirical analyses such as NPV calculations, get impacted by a slight change in some of their contributing factors. Hence, the sensitivity chart is a significant tool in aiding decisions for deploying the technology. For example, from our findings, it is evident that the NPV is much more sensitive to the IRR in comparison to the natural gas costs, and least sensitive to the transportation costs. Therefore, upon deployment, the team might want to put more focus on the required rate of returns as opposed to the transportation distance.

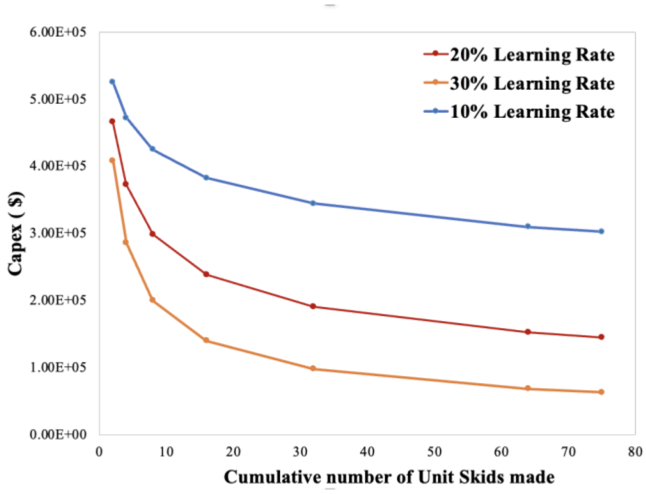

Figure 13: Learning rate

Further, small-scale plants, need to leverage economies of mass production in the absence of economies of scale, just like other energy technologies such as solar and wind. Mass-produced items have demonstrated a cost reduction by a common factor from the continuous improvements made as new products are made. This factor is referred to as the learning rate as demonstrated by Wright's Law (Yelvington, Browne, Yik, Merica, & Dean, 2023). Wright's law provides a reliable framework for forecasting cost declines as a function of cumulative production and specifically outlines that cost will fall by a constant percentage for every cumulative doubling of units produced (Wright, 1968) (Korus, 2019). Robert's work provides a power law correlation for accounting for the cost diminution in technologies (Weber & Snowden-Swan, 2019). The Power Law states that Cost n^{th}/Cost1 α E^a where: a= complexity of the process, E =number of units mass manufactured. Typically, learning rates have varied between 10-30% during the first 30 years of the introduction of technologies like photovoltaics, ethanol plant, and wind turbines. Hence, the analysis was done with learning rates of 10%, 20%, and 30% respectively to see the effect on the Capex with increasing number of unit skids. The results of the analysis are demonstrated in *Figure 13 below*. The Capex cost for the 75^{th} skid would increase by 240,000$ considering a learning rate of 30% in comparison to that of 10%. These findings are also coherent with Dahlgren et al's work which has shown that economies of mass production are very similar to economies of scale when scaled in number rather than in volume (Dahlgren, Göçmen, Lackner, & Ryzin, 2013).

This work also demonstrates the full potential of small unit scale as our analysis focused on the increased number of GTM units produced for higher volume flare sites.

4 CONCLUSION

Therefore, if we were to deploy this technology to all flare sites in the US, we would reduce US GHG emissions by 3.3% while making profits. As demonstrated, the M2X Technology is better than many others in terms of CO_2e abatement costs. Its cost is lower than new coal with carbon capture storage (CCS) as well as solar and offshore wind. Even though expensive when compared to NG combined cycle and solar photovoltaic utility, it still outshines the rest when accounting for the learning rate, with its abatement costs of 24$/ mT CO_2. Additionally, the profit margin increases with an increase in the size of the wells, and the overall NPV for all sites would be $2.8 billion with a 21% error, which is insignificant, considering that NPV will still be positive. Computer-coded calculations can be used in future works as opposed to manual Excel probabilities, to reduce the error.

5 NOMENCLATURE

BCM - billion cubic meters
CO_2eqs - carbon dioxide equivalents
EPA - Environmental Protection Agency
GHGs -greenhouse gases
GTL - gas to liquid
GTM -gas-to-methanol
GWP- global warming potential
IEA - International Energy Agency,
IRR - internal rate of return
mmscfd – million square cubic feet per day
mscfd – thousand square cubic feet per day
MMBtu -million British Thermal Units
mT – Metric Tones
NASA- National Aeronautics and Space Administration,
NG - natural gas
NPV - net present value
OM - operations and management
Scfd- square cubic foot per day
TEA - techno-economic analysis
VIIRS - Visible Infrared Imaging Radiometer Suite

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7 APPENDIX

7.1 Appendix A – GTM Units Sample Calculations

**This sample calculation was done for the Highest volume flare site * Note that the majority of flare sites that would be considered for first deployment are within a range of (75-500 mscfd). This flare site is on the extreme range and it's only used to demonstrate the required number of unit skids. The same case goes with the methanol yield sample calculation

$$Number\ of GTM\ units = \frac{Well\ \ volume\ \left(\frac{mscf}{day}\right)}{Unit\ skid\ intake\ capacity\left(\frac{mscf}{day}\right)}$$

$$Number\ of\ Unit\ skids = \frac{5581.17\ \ \left(\frac{mscf}{day}\right)}{75\left(\frac{mscf}{day}\right)} = 74.42$$

7.2 Appendix B – Methanol Yield Sample Calculations

**This sample calculation was done for the Highest volume flare site

$$CH_3OH\ yield = CH_4\ converted * \ CH_3OH \frac{yield}{Mscf\ of CH_4\ converted}$$

$$CH_3OH\ yield = 5581.17\left(\frac{mscf}{day}\right) * \frac{0.9 * \ 7gal\ CH_3OH}{Mscf\ of CH_4\ converted} * \frac{1bbl}{42gal} * \frac{1mT}{333gal} = 105.59\frac{mT}{day}$$

7.3 Appendix C: Net Annual Profit Calculations

**This sample calculation was done for a flare site located in Reeves Texas which has a well gas volume of 75.029 mscfd, similar to the capacity of our unit skid (75 mscfd)

$$Net\ Annual\ Profit = Expenses - Revenue$$

Case 1: Without transportation Costs- Original base plant model:

$$Expenses = OM\ costs\ + Natural\ Gas\ costs$$

$$OM\ costs\ \ = (Operations\ and\ Maintainance * CH_3OH\ Production * Plant\ Availabilty) + \left(\frac{Overhaul\ costs * Engine\ Operating\ hours\ per\ year}{Engine\ time\ between\ Overhaul}\right)$$

$$OM\ costs\ \ = \left(\frac{6.04\$}{bbl} * \frac{11.25bbl}{day} * \frac{292days}{year}\right) + \left(\frac{0\ * 7008\ hrs}{14016\ hrs}\right) = 1.98 * 10^4\$$$

*Overhaul costs set to zero, replace after two years

$$Natural\ Gas\ costs = Well\ gas\ flow * natural\ gas\ cost * plant\ availability$$

$$Natural\ Gas\ costs = 0.075029\ mmscfd * 1000 * \frac{1\$}{mscfd} * \frac{292days}{year} = 2.19 * 10^4$$

$$Expenses = 1.98 * 10^4\ + \ 2.19 * 10^4\ = 4.18 * 10^4\$$$

$$Revenue = CH_3OH\ yield * Plant\ Availability * CH_3OH\ Price$$

$$Revenue = 1.42 \frac{mT}{day} * \frac{292\ days}{year} * \frac{575\$}{mT} = 2.83 * 10^5\$$$

$$Net\ Annual\ Profit = 2.83 * 10^5 - 4.18 * 10^4\$ = \ 1.97 * 10^5\$$$

Case 2: With transportation Costs:

** This is like case 1, except we now account for transportation costs in expenses. Distance Equation (ExcelDemy.com , 2022)

$$Distance = \text{ACOS(COS(RADIANS(90} - \text{C5))} * \text{COS(RADIANS(90} - \text{C6))} + \text{SIN(RADIANS(90} - \text{C5))} * \text{SIN(RADIANS(90} - \text{C6))} * \text{COS(RADIANS(D5} - \text{D6)))} * 3959$$

$$\text{Where C5 and D5 are the Latitude and Longitude of the reference point in Odessa TX, while C6 and D6 are the Latitude and Longitude at each flare site.}$$

The function N: $(\text{COS(RADIANS(90} - \text{C5))} * \text{COS(RADIANS(90} - \text{C6))} + \text{SIN(RADIANS(90} - \text{C5))} * \text{SIN(RADIANS(90} - \text{C6))} * \text{COS(RADIANS(D5} - \text{D6)}, Provides\ the\ value\ using\ trigonometry\ operators$

$$\text{ACOS(Function N)}, returns\ inverse\ cosine\ value$$

$$3959\ , multiplication\ converts\ the\ value\ into\ miles$$

$Excel\ Input, results\ into\ a\ distance\ of\ 82.017\ miles, from\ Odessa\ Texas\ to\ this\ flare\ site\ located\ in\ Reeves\ Texas,$

$$Transportation\ costs = CH_3OH\ transport\ cost * CH_3OH\ Production * Plant\ Availability * \ distance$$

$$Transportation\ cost = \frac{0.4\$}{gal * 1000\ miles} * \frac{333gal}{1mT} * \frac{1.4mT}{day} * \frac{292days}{year} * 82.017\ miles = 4.53 * 10^3\$$$

$$Expenses = OM\ costs\ + Natural\ Gas\ costs + Transportation\ costs$$

$$Expenses = 1.98 * 10^4\ +\ 2.19 * 10^4 + 4.53 * 10^3 = 4.63 * 10^4\$$$

$$Net\ Annual\ Profit = 2.83 * 10^5 - 4.63\ * 10^4\$ = \ 1.92 * 10^5\$$$

7.4 Appendix D Net Present Value Calculations

$$NNPV = \sum_{N=0}^{N\ final} ACFN(\ 1 + i)^{\ -N}$$

Excel Input Equivalent used:

$$NPV = (NPV\ (\ IRR, yr1cashflow : OFFSET(yr1cashflow, plant\ life - 1{,}0)) - Plant\ Capital\ Cost$$

$$NPV = (NPV\ (\ 10\%\ , 0.05 * 10^6 : OFFSET(0.05 * 10^6, 20 - 1{,}0)) - 583{,}751 = 3.2 * 10^5\$$$

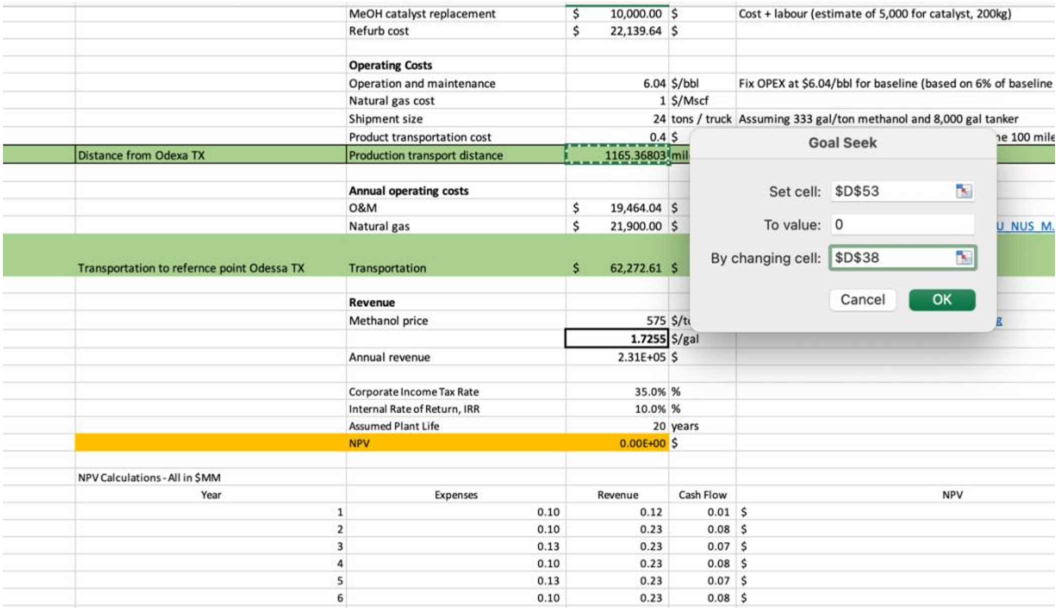
Calculating Module Plant's total capital cost

$$Module\ plant\ Capex = Base\ plant\ Capex\ * \left(\frac{Module\ plant\ \ Capacity}{Base\ plant\ Capacity}\right)^{\propto}$$

$$Module\ plant\ Capex = 1.427 * 10^{6} * \left(\frac{0.075mmscfd}{0.333mmscfd}\right)^{0.6} = 583{,}751\$$$

Note: Economy of scale means that the ratio of (capex/capacity) for a plant decreases with increasing capacity and this is true when the exponent alpha is less than one as in the above expression.

7.5 Appendix E: Goal Seek method for obtaining the breakeven distance.



	MeOH catalyst replacement	$ 10,000.00	$	Cost + labour (estimate of 5,000 for catalyst, 200kg)
	Refurb cost	$ 22,139.64	$	
	Operating Costs			
	Operation and maintenance	6.04	$/bbl	Fix OPEX at $6.04/bbl for baseline (based on 6% of baseline
	Natural gas cost	1	$/Mscf	
	Shipment size	24	tons / truck	Assuming 333 gal/ton methanol and 8,000 gal tanker
	Product transportation cost	0.4	$	
Distance from Odexa TX	Production transport distance	1165.36803	mil	
	Annual operating costs			
	O&M	$ 19,464.04	$	
	Natural gas	$ 21,900.00	$	
Transportation to refernce point Odessa TX	Transportation	$ 62,272.61	$	
	Revenue			
	Methanol price	575	$/t	
		1.7255	$/gal	
	Annual revenue	2.31E+05	$	
	Corporate Income Tax Rate	35.0%	%	
	Internal Rate of Return, IRR	10.0%	%	
	Assumed Plant Life	20	years	
	NPV	0.00E+00	$	

NPV Calculations - All in $MM

Year	Expenses	Revenue	Cash Flow	NPV
1	0.10	0.12	0.01	$
2	0.10	0.23	0.08	$
3	0.13	0.23	0.07	$
4	0.10	0.23	0.08	$
5	0.13	0.23	0.07	$
6	0.10	0.23	0.08	$

7.6 Appendix F CO_2eq abatement cost calculations

$$CO_2\ Averted = CO_2\ produced\ by\ using\ M2X\ technology - CO_2\ produced\ by\ flaring$$

$$CO_2\ produced\ by\ using\ M2X\ technology = (CO_2\ eq)\ for\ CH_4\ released + CO_2\ from\ methanol\ combustion + CO_2\ from\ methanol\ transportation$$

Assuming an efficiency of 0.999 – quoted by Josh

One tonne of methane is assumed to be equivalent to 30 tonnes of CO_2 based on the 100-year global warming potential (IPCC, 2021). (https://www.iea.org/reports/flaring-emissions) , https://www.epa.gov/ghgemissions/understanding-global-warming-potentials , https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

$$(CO_2\ e)for\ CH4\ released = 0.001 * \frac{75.02\ mscf}{day} * \frac{0.0279mT}{mscf} * \frac{0.0021Mt}{day} * \frac{(30\ CO_2e)mT}{mTCH_4\ released} * \frac{292days}{yr} = \frac{18.34mT}{yr}$$

Emissions from combustion: http://static.berkeleyearth.org/memos/fugitive-methane-and-greenhouse-warming.pdf

$$CO_2 from\ CH_3OH\ combustion = 0.3(0.999 * \frac{1.42mTCH_3OH}{day} * \frac{292day}{yr} * \frac{0.001375\ mT\ CO_2}{0.001mT\ CH_3OH} = \frac{170.80mT}{yr}$$

Transportation emissions formula: https://business.edf.org/insights/green-freight-math-how-to-calculate-emissions-for-a-truck-move/ -
Emission factor from EDF: https://storage.googleapis.com/scsc/Green%20Freight/EDF-Green-Freight-Handbook.pdf -

$$CO_2\ from\ CH_3OH\ transportation = 0.999(82.01miles)\left(\frac{1.42mTCH_3OH}{day}\right)\left(\frac{1750gCO_2}{mile}\right)\left(\frac{292days}{yr}\right)\left(\frac{1truck}{24mT}\right)(\frac{1.102 * 10^6mT}{1g} = \frac{6.05mT}{yr}$$

$$CO_2\ produced\ by\ using\ M2X\ technology = \frac{195.20mT}{yr}$$

$$CO_2\ produced\ by\ flaring = (0.91)\left(\frac{75.02\ mscf}{day}\right)\left(\frac{0.0279mT}{mscf}\right)\left(\frac{292days}{yr}\right)\left(\frac{0.00275(CO_2e)mT}{0.001mTCH_4\ flared}\right) + \left(\frac{0.188\ mTCH_4\ released}{day} * \frac{(30\ CO_2e)mT}{mTCH_4\ released} * \frac{292days}{yr}\right) = \frac{3180.01mT}{yr}$$

$$CO_2\ Averted = \frac{3180.01mT}{yr} - \frac{195.20mT}{yr} = 2984.81\frac{mT}{yr}$$

$$Levelized\ cost = Methanol\ Price\ at\ NPV = 0, = \frac{422.56\$}{mTCH_3OH}$$

$$\frac{Revenue}{yr} = (0.999)\left(\frac{1.42mTCH_3OH}{day}\right)\left(\frac{292days}{yr}\right)\left(\frac{422.56\$}{mTCH_3OH}\right) = \frac{1.73E10^5\$}{yr}$$

$$\frac{\$}{mT\ CO_2\ averted} = \frac{(1.73 * 10^5\$ - 0\$)}{2984.81mT} = \frac{58.09\$}{mT}$$

$$\frac{mT\ CO_2\ averted}{\$} = \frac{2984.81mT}{(1.73 * 10^5\$ - 0\$)} = \frac{0.0172\ mT\ CO_2\ averted}{\$}$$