Energy and Power Engineering, 2023, 15, 1-36
https://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

Analysis of Emissions Profiles of Hydraulic Fracturing Engine Technologies

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How to cite this paper: Nieuwenburg, W., Nix, A.C., Fu, D., Yeung, T., Zemlak, W. and Wells, N. (2023) Analysis of Emissions Profiles of Hydraulic Fracturing Engine Technologies. *Energy and Power Engineering*, **15**, 1-36.
https://doi.org/10.4236/epe.2023.151001

Received: October 14, 2022
Accepted: January 7, 2023
Published: January 10, 2023

Abstract

Today, the oil and gas industry, and in particular hydraulic fracturing operations, have come under increasing pressure from regulators and the public to reduce emissions. As the industry evolves, oil and gas producers are in the position of evaluating alternative technologies which will support their objectives of reducing their overall emissions profile and carbon footprint. As a response, the deployment of technology and solutions to reduce emissions related to hydraulic fracturing applications has recently accelerated, creating various options to address these industry challenges. BJ Energy Solutions and West Virginia University have been working on the application and emissions characterization of various hydraulic fracturing technologies. A study was conducted to evaluate the efficiency and resultant emissions from various technologies, including natural gas reciprocating engines, diesel-natural gas dual-fuel engines, large (>24 MW) gas turbines, and direct drive turbines. The study involved the development of an emissions model with the purpose of estimating total emissions of carbon dioxide (CO_2), nitrous oxide (N_2O) and exhaust methane (CH_4) slip, all Greenhouse Gases (GHGs), and converted to tons of CO_2 equivalent emissions per day of operation. The model inputs are the required Hydraulic Horsepower (HHP) based on pumping rate and pressure for various shale play scenarios. The model calculates emissions from the TITAN, which is a direct-drive turbine model fielded by BJ, using data collected following U.S. Environmental Protection Agency (EPA) testing protocols. The model also calculates and compares other hydraulic fracturing technologies utilizing published Original Equipment Manufacturer (OEM) data. Relevant EPA-regulated criteria emissions of oxides of nitrogen (NO_x), Carbon Monoxide (CO) and Particulate Matter (PM) are also reported. Modeling results demonstrated that in most cases, the TITAN gas turbine system has lower total GHG emissions than conventional diesel and other next-generation technologies, and also has lower criteria emissions. The benefits of the TITAN gas turbine system compared to the other technologies stems from significantly lower methane slip, and the high-power transfer efficiency resulting from directly connecting a turbine to a reciprocating pump, despite the comparatively lower thermal efficiency.

Keywords

Hydraulic Fracturing, Greenhouse Gas Emissions, Gas Turbines, Natural Gas Engines, Engine Efficiency, EPA-Regulated Emissions

1. Introduction

The oil and gas industry has experienced growth in natural gas production over the past decade due to unconventional well development in shale gas basins utilizing hydraulic fracturing to perform well stimulation. The U.S. Energy Information Administration (EIA) has reported that the share of natural gas as an energy source has increased from 17% to 36% of total U.S. energy consumption from 1950-2021 [1]. Hydraulic fracturing processes have enabled oil and gas companies to develop wells that were previously uneconomical to complete. As this relatively new process of oil and gas extraction matures, well-service companies are in a position of opportunity to develop well-stimulation technologies that are both economical and more environmentally friendly. It is estimated that a well that has been completed with hydraulic fracturing emits 22% to 43% more greenhouse gases than other forms of gas extraction [2].

Hydraulic fracturing has been practiced since the 1940s, but has not been heavily utilized until recent history. Hydraulic fracturing has played a key role in making North America energy independent having made the U.S. change from a net importer to a net exporter of 2.73 trillion cubic feet of natural gas in 2020 [3]. The hydraulic fracturing process has traditionally involved vast amounts of equipment powered by Compression Ignition (CI) diesel reciprocating engines to drive positive displacement pumps which inject large volumes of fluid and proppants at high rates and pressures deep underground. This process helps create targeted cracks (fractures) in low-permeability hydrocarbon-bearing reservoirs through which natural gas and oil can flow from. Proppant (such as sand) is deposited in these newly formed fractures to hold them open.

Hydraulic fracturing operations are typically achieved using a frac fleet consisting of upwards of 18 to 24 diesel-powered fracturing pumps rated between 1500 to 2500 hp (1118 to 1864 kW) and five to seven pieces of diesel-powered support equipment (see **Figure 1**). At the sector's peak, there were over 500 frac fleets operating in North America alone [4], with each frac fleet consuming upwards of seven million gallons of diesel annually and emitting 154 million pounds of carbon dioxide into the atmosphere [5].

A conventional hydraulic fracturing fleet utilized Tier 2 (T2) diesel engines. However, in May of 2004, the EPA signed the final rule introducing Tier 4 emissions

Figure 1. Typical hydraulic fracturing fleet with 23 diesel powered fracturing pumps and support equipment.

standards [6]. Tier 4 emissions standards were put in place to reduce criteria pollutants such as oxides of nitrogen (NO_x), Carbon Monoxide (CO) and Particulate Matter (PM). These emissions requirements and the year they go into effect are shown in **Table 1** [7]. While Tier 4 final emissions standards cover several harmful pollutants, it does not cover Greenhouse Gases (GHGs). In fact, there is not currently any federal regulation towards GHG emissions from non-road CI engines. Over the past several years, hydraulic fracturing companies have developed technology to increase hydraulic fracturing economics while attempting to reduce criteria pollutants and greenhouse gases. These fleets in hydraulic fracturing are often referred to as next-generation technology.

One such technology that has seen an increase in usage is dual-fuel engines. To offset diesel consumption and reduce overall greenhouse gases, natural gas is increasingly combined with diesel (for example: Tier 2 and Tier 4 dual-fuel engines). The use of dual-fuel is often sought as a solution to reduce diesel fuel consumption and improve overall economics, utilizing natural gas as the substitute for a portion of diesel (dual-fuel). However, there is a misconception that dual-fuel is also a solution to reduce emissions. Increasingly, studies have found that the use of dual-fuel and dedicated natural gas engines has increased greenhouse gas emissions largely due to increased methane emissions. Some research suggests that natural gas and dual-fuel operations can have greenhouse gas emissions 1.65 and 2.2 times higher than diesel-only respectively [8].

Another innovative technology being utilized in hydraulic fracturing is mobile electrical power generation through natural gas reciprocating engines and/or natural gas turbines. Electric frac fleet usage has risen from 3% to 30% of the U.S. shale market [9]. Typically, these engines generate electrical power on a hydraulic fracturing location, which is then distributed to various fracturing equipment. These technologies benefit from burning only natural gas rather than diesel and a detachment from power generation to load.

Lastly, direct drive turbine technology. These turbines utilize dual shafts directly driving a positive displacement fracturing pump with the power turbine shaft. The dual shaft permits the turbine to run while the output shaft to the pump is stationary, allowing the turbine to run in an idle state while maintaining

Table 1. EPA Tier 4 final emissions standards in g/kWh (g/bhp·hr).

Year	Category	CO	NMHC	NO_x	PM
2011	Generator sets > 900 kW	3.5 (2.6)	0.40 (0.30)	0.67 (0.50)	0.10 (0.075)
	All engines except gensets > 900 kW	3.5 (2.6)	0.40 (0.30)	3.5 (2.6)	0.10 (0.075)
2015	Generator sets	3.5 (2.6)	0.19 (0.14)	0.67 (0.50)	0.03 (0.022)
	All engines except gensets	3.5 (2.6)	0.19 (0.14)	3.5 (2.6)	0.04 (0.03)

air flow. When pumping shaft power is required, the output shaft has immediate access to the power of the turbine to directly drive a positive displacement pump which pumps fracturing fluid systems. Since the turbine is directly mounted to the reciprocating pump, the system transmission losses are theoretically low.

Traditionally, hydraulic fracturing treats a single well at a time, swapping between wells or zones called a fracturing stage. Recently, hydraulic fracturing has moved towards what is called Simulfrac. In Simulfrac operation, two or more wells are stimulated simultaneously using a fracturing fleet. This change has resulted in increased fracturing efficiency reducing completion time by approximately 30% [10].

While oil service companies have invested large amounts of capital and manpower in next-generation technologies, very few scientific studies have been performed to quantify the total emissions from a hydraulic fracturing fleet.

BJ Energy Solutions and West Virginia University have been working on the application and emissions characterization of a direct-drive natural gas turbine technology fielded by BJ called TITAN. The TITAN system consists of a relatively small (4 MW) dual-shaft turbine mounted on a trailer and connected to a reduction gearbox followed by a frac pump. A study was conducted to evaluate the efficiency and resultant emissions from various technologies, including natural gas reciprocating engines, diesel-natural gas dual-fuel engines, large (>24 MW) gas turbines, and the TITAN direct-drive system. The study involved third-party, certified emissions testing of the TITAN system and the development of an emissions model for alternative systems with the purpose of estimating total greenhouse gas emissions reported in carbon dioxide equivalent mass (CO_2e). This model was utilized with the intent of comparing the TITAN system with other existing and next-generation technologies. The model includes emissions of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) summed together using EPA definitions for conversion to total CO_2e. The study also included EPA-regulated emissions to further evaluate the multiple hydraulic fracturing solutions. The model begins with the required hydraulic horsepower (HHP) based on pumping rate and pressure and calculates emissions from each technology. The TITAN system uses data collected following U.S. EPA emissions testing protocols. Published Original Equipment Manufacturer (OEM) data for other engine technologies was utilized for analysis. The model was developed to provide on-site fracking operations with a real-time emissions rate value, and has been built in both Matlab and Excel supported with Visual Basic. The model is also being integrated into existing hydraulic fracturing fleet control systems which will provide real-time emissions data for a fracturing fleet. This functionality is currently in development and is the goal of the model development.

Model test conditions are considered for 3 different shale oil and gas basins with varying ambient conditions, pumping rates and pressures. Since the results are reported based on required HHP, engine efficiency and power transmission losses are also considered. In addition to GHG emissions, relevant EPA-regulated criteria emissions of oxides of nitrogen (NO_x), Carbon Monoxide (CO) and Particulate Matter (PM) are also reported.

Models have been designed to provide a complete picture of total emissions released in an operating day, including all associated activities such as priming pumps, pressure testing, pumping operations, engine idling, and auxiliary systems with the express purpose to evaluate and compare emissions from hydraulic fracturing technologies. The details of the model's methodology, including testing assumptions and specific formulas, are contained within.

2. Methodology

The methodology and results presented in this paper were generated using an emission calculator model developed using measured emissions data for the TITAN system, and Original Equipment Manufacturer (OEM) data for all other engine technologies analyzed. Each component of the model is detailed herein. The model input is the required hydraulic horsepower through treatment rate and pressure and the model output is the emissions per day through the process detailed in this paper.

2.1. Emissions Based on Fuel Consumption

The EPA requires mandatory greenhouse gas reporting from large emissions sources. Specifically, for oil and gas companies, this falls under 40 CFR (Code of Federal Regulations) Part 98 Subpart W: mandatory greenhouse gas reporting for petroleum and natural gas systems [11]. For reporting mobile emissions sources, the reporting methodology is outlined in Subpart C, general stationary fuel combustion sources if the fuel is pipeline quality and has a higher heat value of 950 Btu/scf [12]. The calculation outlined in this regulation is primarily dependent on fuel consumption. The model assumed gas is either pipeline gas or is conditioned prior to combustion to pipeline quality. Subpart C calculated emissions based on units of Fuel Consumed (FC) are as follows:

$$E_{CO_2} = \frac{FC * HHV * EF_{CO_2}}{1000} \tag{1}$$

Likewise, the other greenhouse gases are calculated as:

$$E_{N_2O} = \frac{FC * HHV * EF_{N_2O}}{1000} \tag{2}$$

And

$$E_{CH_4} = \frac{FC * HHV * EF_{CH_4}}{1000} \tag{3}$$

where E_{xx} is the emissions rate and EF_{xx} is the emissions factor for CO_2, N_2O and CH_4, respectively, and HHV is the higher heating value of the fuel. The equivalent mass of CO_2e is then the masses of emitted greenhouse gases multiplied by their Global Warming Potential (GWP) factor. The model utilizes the Intergovernmental Panel on Climate Change (IPCC) fifth assessment for global warming potential detailed in **Table 2** [13].

Combining the three GHG emissions rates results in a total CO_2e calculated using Equation (4):

$$CO_{2e} = E_{CO_2} + E_{N_2O} * 265 + E_{CH_4} * 28 \tag{4}$$

where CO_2e is the CO_2 equivalent mass of emissions.

2.2. Required Operational Power

The largest portion of power required in well stimulation by hydraulic fracturing is consumed by the hydraulic fracturing pumps that consist of positive displacement reciprocating pumps. Fracturing treatment designs call for a certain hydraulic horsepower determined by the treatment rate and pressure with the equation below.

$$HHP = \frac{P * Q}{1714} \tag{5}$$

where P is the treatment pressure (in psi) and Q is the fracturing fluid flow rate in GPM. The pump required hydraulic horsepower (HHP_{pump}) is then:

$$HHP_{pump} = \frac{HHP}{\text{Number of Pumps}} \tag{6}$$

The total required Brake Horsepower (BHP) generated by the engines needs to include the hydraulic horsepower being pumped downhole, plus the expected Power Train Efficiency (PTE) and parasitic loads ($HP_{Parasitic}$).

Table 2. Intergovernmental Panel on Climate Change Greenhouse Gases global warming potential factors.

Industrial Designation or Common Name	Chemical Formula	GWP values for 100-year time horizon		
		Second Assessment Report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Carbon Dioxide	CO_2	1	1	1
Methane	CH_4	21	25	28
Nitrous Oxide	N_2O	310	298	265

$$BHP = \frac{HHP}{PTE} + HP_{Parasitic} \tag{7}$$

It is important to note that the $HP_{Parasitic}$ is defined as the parasitic load of the system per pump, not per engine. Parasitic loads in fracturing solutions vary from system to system. For a conventional unit, the hydraulic horsepower in the hydraulic system circuits is a known value of 120.4 HP based on existing BJ conventional pumps. This system runs the coolant pumps, fans, lube oil pumps, and other equipment of a conventional unit. Hydraulic systems pumps are typically 80% - 90% efficient [14]. Assuming best case of 90%, the parasitic load is approximately 133.8 HP. This value was derived from operating conditions on an existing conventional unit (see **Table 3**). However, this value is considered as conservative due to the form factor of the engine from this test set, actual parasitic losses would be higher. This parasitic load does not include loads from other components such as grease pumps, control and instrumentation, alternators, etc. For non-conventional fleets that are utilizing power generation, additional parasitic loads are present. Cooling systems are required for variable frequency drives, electric motors, and other electrical components that lose energy in the form of heat. These components are stored in enclosures that are either forced air cooled, or individual components liquid cooled. Under normal real world operating conditions, these devices efficiency deviate from OEM rated efficiency and if not cooled adequately, will derate [15].

Parasitic loading was assumed the same for all technology solutions except for the TITAN. The TITAN system utilizes a relatively small Tier 4F diesel deck engine that powers the auxiliary equipment such that there are no parasitic loads on the turbine. Fuel consumption and resultant emissions from this deck engine are included in TITAN's emission profile.

Using the engine brake horsepower load, the fuel consumption was determined by interpolating between OEM published datapoints for BHP and fuel consumption.

2.3. Methane Slip

EPA emissions factors assume 99.5% of fuel carbon is converted to CO_2, which is near complete combustion [16]. Complete combustion is when all carbon entrained

Table 3. BJ Energy conventional pump hydraulic parasitic loads.

System	Operating Pressure (psi)	Flow Rate (GPM)	HP
Charge Pump	350	12	2.5
Lube	200	70	8.2
Hydraulic	3550	53	109.8
	Hydraulic Horsepower Required		120.4
	Hydraulic Pump Efficiency		0.9
	Parasitic Load		133.8

in the reactants of the combustion chemical reaction are converted to CO_2. This is not the case in actual natural gas engine operations and methane emissions have been found to be much greater [17]. With natural gas primarily composed of methane, methane slip and crank case emissions are present in natural gas burning engines. Methane slip occurs in engines for two main reasons, dead volume in the form of crevices between cylinder components and incomplete combustion in the form of quenching in the coldest part of the combustion chamber. In natural gas reciprocating engines, methane slip is present during both low and full load conditions due to the dead space and quenching occurring. Quenching occurs when the mixture is too lean or cooled down along the cylinder walls, and is mainly prevalent in low load operations and is present in both turbine and reciprocating engines. Methane slip is particularly harmful as methane is 28 times more potent as a GHG than carbon dioxide.

As a result, even a small amount of methane slip can lead to a large amount of greenhouse gas emitted. Multiple studies involving natural gas engines have found that EPA emissions factors do not properly estimate the increased emissions due to methane slippage. As a result, actual methane emissions should be estimated as:

$$E_{CH_4} = E_{CH_4,\text{Slip}} + E_{CH_4,\text{Crankcase}} \tag{8}$$

where $E_{xxx,\text{Slip}}$ is the emissions rate due to methane slip and $E_{xxx,\text{Crankcase}}$ is the emissions rate through the crankcase for CH_4.

However, OEM data typically do not include methane emissions from the crankcase. Other research on crankcase emissions found that crankcase emissions only account for 0.4% - 0.8% [18] of the total methane emissions. Other research and the EPA suggest crankcase emissions are equal to 2.0% of the exhaust [19]. For estimation purposes, crankcase emissions are not included and therefore methane emissions rate is:

$$E_{CH_4} = E_{CH_4,\text{Slip}} \tag{9}$$

Methane slip in the current model was taken from OEM data for emissions which is derived from air samples in the exhaust stack. With turbines, methane slip is not expected to significantly impact total emissions compared to reciprocating engines if operated above approximately 5% load, which is due to near total combustion of methane when the turbine is at >5% load (see **Figure 2**). However, during very low loads, methane slip in a turbine can occur. This assumption was validated through the TITAN emissions test. For other turbine technologies, methane slip was assumed to be proportional to the methane slip measured in the TITAN turbine.

2.4. Daily Emissions Operating Cycle

A hydraulic fracturing daily operating cycle includes several processes such as pressure pumping, priming pumps, pressure testing, idling, planned maintenance, wells swaps, etc. Many of these processes are performed between fracturing

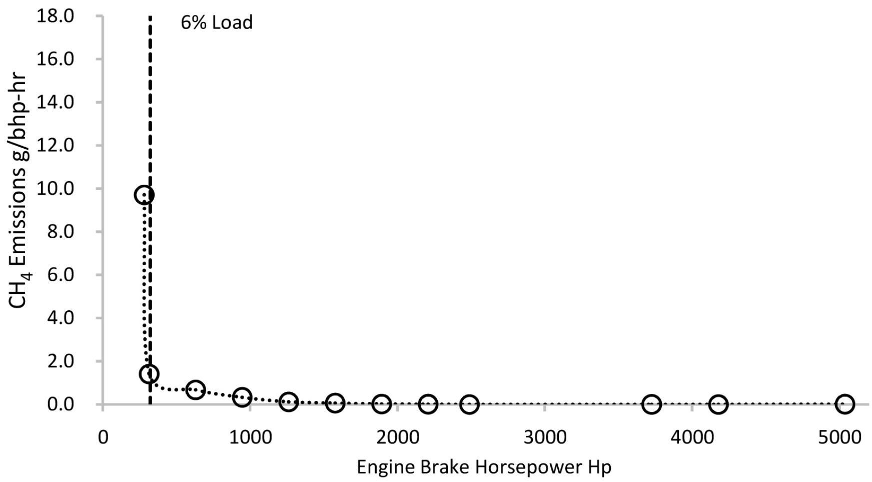

Figure 2. Titan CH_4 emissions test methane slip at various loads.

stages where the engines are at partial loads or shut down completely. To account for the daily processes, the daily CO_2e in metric tons is considered. The calculation for the daily equivalent emissions is:

$$CO_{2e,Daily} = CO_{2e,idle} + CO_{2e,pumping} \tag{10}$$

where $CO_{2e,Daily}$ is the total daily CO_2 equivalent mass of emissions, $CO_{2e,idle}$ is the daily CO_2 equivalent mass of emissions while the units are idling, and $CO_{2e,pumping}$ is the daily CO_2 equivalent mass of emissions while the units are pumping.

$$\begin{aligned} CO_{2e,idle} = T_{Idle} N_{Eng.} \Big(& FC_{Idle} \left(EF_{N_2O} * GWP_{N_2O} + EF_{CO_2} * GWP_{CO_2} \right) \\ & + E_{CH_4,Idle} * GWP_{CH_4} \Big) \end{aligned} \tag{11}$$

The daily equivalent mass of CO_2 emissions while idling ($CO_{2e,idle}$) is equal to the sum of the equivalent CO_2 mass emitted multiplied by the time spent idling (T_{idle}) and the number of engines ($N_{Eng.}$). The equivalent mass of gas emitted for CO_2 and N_2O is equal to the multiplication of the fuel consumption while idling (FC_{Idle}), the emissions factor of of the gas (EF_{xxx}) and the global warming potential factor of the gas (GWP_{xxx}). The mass equivalent of CO_2 emitted for methane is the emission rate of methane through methane slip with an engine load at idle ($E_{xxx,Idle}$) multiplied by the global warming potential of methane (GWP_{CH_4}).

$$\begin{aligned} CO_{2e,pumping} = T_{Pumping} N_{Eng.} \Big(& FC_{Pumping} \Big(EF_{N_2O} * GWP_{N_2O} \\ & + EF_{CO_2} * GWP_{CO_2} \Big) + E_{CH_4,Slip} \Big) \end{aligned} \tag{12}$$

The daily equivalent mass of CO_2 emissions while pumping ($CO_{2e,pumping}$) is equal to the sum of the equivalent CO_2 mass emitted multiplied by the time spent pumping ($T_{pumping}$) and the number of engines ($N_{Eng.}$). The equivalent mass of gas emitted for CO_2 and N_2O is equal to the multiplication of the fuel consumption while pumping ($FC_{Pumping}$), the emissions factor of of the gas (EF_{xxx}) and the global warming potential factor of the gas (GWP_{xxx}). The mass equivalent of CO_2 emitted for methane is the emission rate of methane through methane slip at load ($E_{xxx,Slip}$) multiplied by the global warming potential of methane (GWP_{CH_4}).

3. Emissions Model Source Data

3.1. TITAN System Emissions Measurements

To validate and certify the emissions profile of the BJ Energy Solutions TITAN Technology, a comprehensive, testing protocol was performed following EPA emissions testing methodology (Table 4) described in the Code of Federal Regulations (CFR). In conformance with ASTM D7036 Section 15.3.15 all metering and monitoring equipment meets or exceeds the uncertainty criteria contained in testing method.

To verify and measure TITAN fuel consumption, natural gas samples were taken and sent to certified laboratories. The laboratory results were used to calibrate an orifice-type flow meter that meets or exceeds EPA reference methods for fuel consumption measurements. At various engine loads, fuel consumption and emissions data were collected. These values were selected to replicate anticipated loads in hydraulic fracturing basins. The specific objective was to determine the emissions concentration of NO_x, CO, CH_4, N_2O, PM, and CO_2 from the turbine exhaust. The TITAN utilizes a diesel deck engine to start up and maintain auxiliary systems. The fuel consumption of the diesel engine, which is a CAT C7.1 Tier 4 engine, was included in all emissions profiles based on 40 CFR Subpart C calculation methodologies. This deck engine allows the TITAN turbine to be shut down between stages with minimal idling time, reducing potential methane slip at low turbine load. The TITAN engine used in emission sampling was taken straight from field operations and no cleaning or modification was performed prior to the emissions test other than installing an exhaust stack that complies with EPA Method 1 Sample and Velocity Traverses for Stationary Sources (see Figure 3). Testing procedure for each gas followed the applicable EPA methodology for testing as shown in Table 4 below.

Figure 3. Emissions stack mounted on TITAN.

Table 4. Summary of TITAN emissions sampling methods.

Pollutant or Parameter	Sampling Method	Analysis Method
Sample Point Location	EPA Method	Equal Area Method
Stack Flow Rate	EPA Method 2	S-Type Pitot Tube (PM Isokinetic Calculations)
Oxygen	EPA Method 3A	Paramagnetic Cell
Stack Moisture Content	EPA Method 4	Gravimetric Analysis
Particulate Matter	EPA Method 5	Front Half Filterables
Carbon Monoxide	EPA Method 10	Nondispersive Infrared Analyzer
Stack Flow Rate	EPA Method 19	DRY Oxygen F Factor (Emission Rate Calculations)
NO_x, THC, CH_4, N_2O, CO_2, H_2O	EPA Method 320	Fourier Transform Infrared

The stack was vertically mounted with a transition from rectangular to circular. The exhaust stack and sample port location met EPA requirements outlined in EPA method 1. BJ Energy provided aerial lift for access to the top of the stack. Air Hygiene has fielded verified the measurable dimensions. Air hygiene then performed exhaust gas sampling and measurements. All exhaust samples for gaseous emissions were continuously drawn from the exhaust system at three radial points located at 16.7, 50, and 83.3 percent of the exhaust stack radius. The analytical instrument used for each gas and the instruments sensitivity are outlined in Table 5. For PM testing, an initial velocity traverse was performed across the stack from eight total points. All PM sampling occurred from the same eight points by leaving the probe at each for an equal amount of time.

The results from the emissions tests on the TITAN pumper unit are shown in **Appendix**.

3.2. Emissions Model OEM Engine Source Data

OEM engine data was used to estimate the required number of units, engine load, and fuel consumption for non-turbine hydraulic fracturing technologies. Engine size and specifications were based on typical usage in hydraulic fracturing application. It must be acknowledged that the OEM data is collected under ideal conditions with various parasitic loads such as lubrication pumps, cooling systems, alternator, etc., removed to present maximum efficiency. To adjust these values to real world conditions, the model considered typical efficiencies and parasitic loads in order to arrive at the required hydraulic horsepower, using either industry standard values or documented measurements from manufacturers. It is also important to remember that OEM data is based on brand new equipment and does not consider any engine performance degradation over time. For the model, equipment was assumed to be new with no degradation to OEM values based on equipment age.

Table 5. Analytical instrumentation for TITAN emissions test.

Parameter	Test Device	Range	Sensitivity	Detection Principle
CO	THERMO 48 series	User may select up to 10,000 ppm	0.1 ppm	Infrared absorbtion, gas filter correlation detector, microprocessor-based linearization
NO_x, THC, CH_4, N_2O, CO_2, H_2O	MKS 2030	User may select from multiple ranges	0.1 ppm	Fourier Transform Infrared (FTIR)
O_2	SERVOMEX 1440	0% - 25%	0.10%	Paramagnetic cell, inherently linear

Fuel consumption and emissions values were taken from engine manufacturer published data. OEM engine data can be retrieved from the applicable OEM website for each engine model.

3.3. Model Operating Conditions

The model was developed to examine a wide range of operating conditions. Hydraulic fracturing treatment design is dependent on several variables largely focused on formation geology, location structure. The model utilizes historical basin treatment schedules that have been performed in real world operations, which includes geographical basin, pumping rate and pressure, pumping hours per day, and stage length. The five cases highlighted in **Table 6** were selected to give a wide range of operating conditions and specifically selected due to these conditions' prevalence.

The treatment basin input to the model affects engine performance due to the ambient temperature and altitude (atmospheric pressure). The effect of temperature and altitude of the operating basin is accounted for by derating the turbine performance for TITAN and large turbine systems. Average yearly temperatures for the Permian and Haynesville were based on the 50-year average temperatures of the climate division the basin is located [20]. Yearly average temperature for the Montney/Duvernay were based on the average temperature from 1981-2010 [21]. The altitude used in the model was based on the major city hub the basin largely operates from [22].

While altitude and temperature do have a minor impact natural gas reciprocating, diesel, and dual-fuel engine performance, it was not considered in the model. Natural gas reciprocating, diesel and dual-fuel engines deration occurs at higher altitude and temperatures than natural gas turbines. These values are typically not impactful at average basin ambient conditions. Reciprocating engine efficiency and power are reduced by approximately 4 percent per 1000 feet of altitude above 1000 feet, and about 1 percent for every 10˚F above 77˚F [23]. The historical average ambient temperature and altitude was used shown in **Table 7**.

Table 6. Engine operating condition by test case (basin).

Case	Basin	Pumping Hours	Rate	Pressure	Stage Length Hrs
1	Haynesville	17	80 BPM	12,000 psi	3
2	Permian	17	120 BPM	9000 psi	3
3	Haynesville Simulfrac	17	160 BPM	12,000 psi	3
4	Permian Simulfrac	17	240 BPM	9000 psi	3
5	Montney/Duvernay	17	110 BPM	12,000 psi	3

Table 7. Basin historical average temperature and altitudes utilized in emissions model.

Basins	Average Temperature (°F)	Average Altitude (ft)
Haynesville	64.8	200
Permian	64.1	2900
Montney/Duvernay	36	2133

The effect of altitude on turbine fuel consumption was based on OEM manufacturer values. This value is 3% per 1000 ft of altitude. The affect from temperature was based on the TITAN turbine engine fuel consumption at two different temperatures. A TITAN pumper was operated under load at two different temperatures at the same location to determine the relationship of fuel consumption and temperature change. The results from these test runs are shown in **Table 8**. The change in fuel consumption and the same load was reported as SCF/˚F which had an average value of 74.3 SCF/˚F temperature change. This value is comparable to the OEM reported estimate. OEM reports an estimate of 1% per 1˚C temperature rise. Based on actual data measurements, this value was 0.94% per 1˚C rise.

Treatment rate and pressure for a hydraulic fracturing treatment schedule are dependent on many factors such as well depth, porosity, perforation fracturing pressure and chemical additives. Pressure and rate inputs of the model used are historical values used in well treatment designs.

The pumping hours per day and stage length directly affects the total emissions per day through operating time and down periods. In between stages all technologies run intermittently to a varying degree. This idle time increases fracturing emissions by varying degrees based on model estimates. Between each stage, control systems, heating/cooling and auxiliary equipment all consume power. Operational procedures need to also be performed such as pressure testing, priming, cooldown, and warming up units. The model assumes expected idling performance from each engine technology utilizing current capabilities.

Direct drive turbines idle between stages for cooldown periods and non-fracturing operations such as priming pumps and pressure testing. Due to the quick start up ability, these engines are not idled between stages when operations are not being performed.

Table 8. TITAN turbine temperature change test.

Turbine HHP	Turbine Gas Fuel Consumption (SCF/hr) @61°F	Turbine Gas Fuel Consumption (SCF/hr) @48°F	ΔSCF/hr per Δ°F
500	14,676	14,345	25.46
1000	18,278	17,727	42.38
1500	21,965	21,147	62.92
2000	25,344	24,286	81.38
2500	28,775	27,719	81.23
3000	32,143	30,790	104.08
3500	35,425	33,990	110.38
4000	38,255	37,132	86.38

Natural gas reciprocating engines have rated minimum loads proscribed from the engine manufacturer. Natural gas reciprocating engines do not perform optimally at low loads and are unstable [24]. To avoid this effect, a battery bank is used to supply power between stages at low loads. In the event the engine needs to be run, the generator will run above the minimum stable load to charge the battery then shut down. OEM recommendation is to stay at a minimum load greater than 50% [25]. The model assumes the natural gas engines run at idle at 50% load for the same duration as the TITAN engines

Large single turbines have a long cooldown and startup period. Due to this often the large turbine is left running between the stages. However, unlike the natural gas reciprocating engines, the turbine can idle at very low loads, in the case of the TITAN down to 3% engine load. However, while turbines can idle at low engine loads, methane slip becomes exponentially worse at these lower loads.

Conventional and dual-fuel internal combustion engines in past and current fracturing operations have been left to idle the duration between stages. While there are no-idle technologies for these systems, they are not widely utilized.

Methane Slip

Resulting from the TITAN emissions test, the methane slip as a function of engine load was plotted. This function is plotted vs to OEM reported methane slip data for other compression ignition engine types. **Figure 4** shows a drastic decrease in methane slip once the load on the TITAN turbine goes from idle to partial loading. Under normal operating conditions methane slip for the TITAN turbine is near zero. This differs from compression ignition engines as they continue to have substantive methane slip rate at expected operating loads.

4. Engine Modeling Parameters

The modeling parameters for each engine type required assumptions of engine size (power in kW), thermal efficiency range, powertrain losses and parasitic loads.

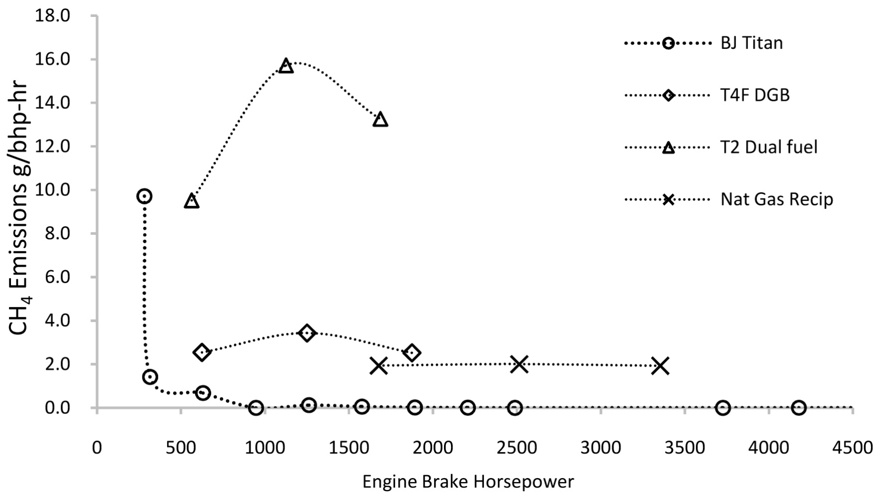

Figure 4. Methane slip from emissions test on TITAN turbine at increasing load compared to OEM reported methane slip data.

Data is provided for dual-fuel, natural gas reciprocating, large natural gas turbine and the TITAN engines in **Appendix**.

4.1. Conventional Diesel Engine

Modeling parameters and assumptions for the diesel engines analyzed in this study are presented below, following presentation of modeling parameters and assumptions for all engine types.

- Engine models for the calculation used were Cummins QSK 50 Tier 4F FR6740, QSK 50 FR 6890 Tier 2, CAT 3512 C HD Tier 2, CAT 3512 E Tier 4.
- Fuel consumption is based on OEM data from two different industry-leading engine manufacturers for both Tier 2 and Tier 4F engines.
- CO_2, CH_4, and N_2O emissions rate based on EPA combustion calculations.
- Estimated PTE efficiency for a conventional pump is 81% (*i.e.* 95% Fluid End and 95% Power end (QWS 2500 XL) [26], 90% Transmission (CAT TH48-E80 transmission) [27], along with 133.8 HP of parasitic loads.
- Number of engines required is based on a max engine load of 82%. This value was selected as a general estimate based on historical performance of conventional diesel fracturing operations performed by BJ Energy. 100% engine load is not used to account for operational redundancy, increased reliability, and account for transmission gear gaps. In operations, spare pumps are required in the event of a failure on one of the other pumps. Typically, 1 - 2 pumps are operating more than what is required at 100% load. Figure 5 shows results from a hydraulic fracturing pump test performed by BJ Energy. Due to transmission gearing and maximum rod load of the power end, conventional systems have a maximum operating pressure at each gear. For example, at 10,500 psi, the pumping units' highest achievable gear for operation would be 3rd. While operating under these conditions, the engine load would be 78.9%.

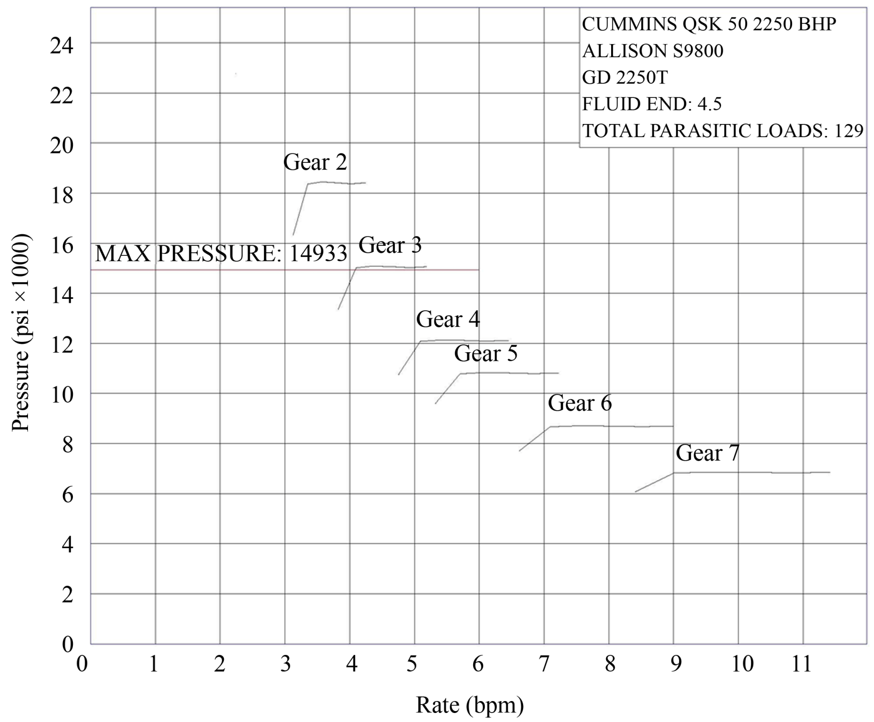

Figure 5. Conventional fracturing pump curve at 100% engine load varying engine RPM.

- Assumed conventional engines idled between fracturing stages.
- Estimated fuel consumption during idle using 0.6 L/hr * engine displacement [28].

The conventional modelling parameters are illustrated graphically in **Figure 6** at the end of this section.

4.2. Dual-Fuel Engine

Modeling parameters and assumptions for the dual-fuel engines analyzed in this study are presented below and illustrated graphically in **Figure 7**.

- Engine models for the calculation used were Cummins QSK 50 Tier 4F FR6740, QSK 50 FR 6890 Tier 2, CAT 3512 C HD, and CAT 3512E Tier 4F DGB.
- Fuel consumption based on OEM data from two different industry-leading engine manufacturers for both Tier 2 and Tier 4F engines.
- CO_2 and N_2O emissions rate based on EPA combustion calculations. CH_4 emissions based on OEM methane slip data.
- Estimated PTE efficiency for a conventional pump to be 81% (*i.e.* 95% Fluid End and 95% Power end (QWS 2500 XL) [26], 90% Transmission (CAT TH48-E80 transmission) [27], along with 133.8 HP of parasitic loads.
- Assumed conventional dual-fuel engines idled between fracturing stages.
- Calculated fuel consumption during idle using 0.6 L/hr*engine displacement.
- Number of engines required based on a max engine load of 75%. This value was selected to maximize the substitution ratio. Based on engine OEM data, substitution ratio decreases as load increases above 75% - 80%.

Engine Description	Engine Type	Rated Power (kW)	Power Train Component Efficiency - %	Total Power Efficiency (BHP to HHP)	Parasitic Loses per Pump (hp)
Diesel Only	Cat 3512 and Cummins QSK 50	1,864	Transmission 90%; Power End 95%; Fluid End 95%	81.2%	134

Figure 6. Diesel only engine modeling parameters.

Engine Description	Engine Type	Rated Power (kW)	Power Train Component Efficiency - %	Total Power Efficiency (BHP to HHP)	Parasitic Loses per Pump (hp)
Dual Fuel Engine	Cat 3512 T4F DGB and CAT 3512C HD T2	1,864	Transmission 90%; Power End 95%; Fluid End 95%	81.2%	134

Figure 7. Dual-fuel engine modeling parameters.

4.3. Natural Gas Reciprocating Engine

Modeling parameters and assumptions for the natural gas reciprocating engines analyzed in this study are presented below and illustrated graphically in Figure 8. Powertrain efficiencies for the variable frequency drive and electric motor are based on OEM reported efficiencies for a component typical in hydraulic fracturing size and rating.

Actual operating conditions are non-ideal, component efficiencies would be affected by power quality, loading type, and power generation form factor. Depending on the generator and the electric motor, a transformer may be required. Typically, transformer efficiencies are defined by Department Of Energy (DOE) 2016 standards however these efficiency ratings have a few flaws. The DOE 2016 standard rates the transformer efficiency under linear loads at 35% total load [29]. Increasing the load on the transformer and nonlinear loads would increase total expected losses. Increasing the load on the transformer increases coil loses due to increasing temperature. Non-linear loads increase the stray load losses in an electrical system. Some estimates state that these factors can lead to 3.1 - 7.2 times higher losses than DOE standards [30]. Other research suggests that introducing nonlinear loads can increase losses by 6 times [31].

In hydraulic fracturing, the load on the fluid end and the use of variable frequency drives would ensure that the load is nonlinear, and harmonics would be seen [32]. These harmonic and nonlinearity increase the losses in variable frequency drives by an average of 16.9% [33], bringing down the VFD efficiency by approximately 0.5%. Some research suggests that this value would be higher, largely due to the need for additional power required for a cooling system. This research found that a VFD driven system was 8% less efficient than an across the line starter motor system. 3% attributed to losses in the VFD and 5% to the additional cooling requirements [34].

Power distribution on location introduces some loses in the power cables in the form of heat. This results in a voltage dropped defined by the equations below for either single phase.

Engine Description	Engine Type	Rated Power (kW)	Power Train Component Efficiency - %							Total Power Efficiency (BHP to HHP)	Parasitic Loses per Pump (hp)
			Generator	Power Con'ditiong	Power Distribution	VFD	Elec Motor	Power End	Fluid End		
Natural Gas Reciprocating	CAT 3520H	2,469	96%	95%	100%	97%	96%	95%	95%	76.6%	134

Figure 8. Natural gas reciprocating engine modeling parameters.

$$\Delta V = \frac{1.73\Omega * I * L}{1000} \tag{13}$$

By selecting cables typical to the voltage, and power requirements of a natural gas-powered fracturing fleet, the expected drop would be approximately 0.04% This calculation is based on copper 500 kcmil 3 phase cable @ 90˚C assuming on length of 100 ft. These losses can increase as harmonics are introduced [35].

Furthermore, electric motor efficiencies typically peak at 75% to 80% load, and as such most motors are operated in this range [36]. However, electric motor efficiency drastically begins to decrease at 50 percent load due to linearity decreasing [37]. This means that if the fracturing treatment conditions cannot optimally load the electric motors, the overall system efficiency will decrease. Lastly, the rated efficiency is based upon a power factor reported by the OEM. However, as non-linearity increases, power factor decreases. As the power factor decreases system efficiency will decrease as well. Other components such as reactors, rectifiers, switchgears, breakers will have a relatively small number of losses in the form of heat as well [38].

Taking into consideration all of the above stated system losses and efficiencies, a power quality/conditioning factor was included and estimated as 95%.

- Engine model for the calculation used was CAT G3520H.
- Fuel consumption based on OEM data, which is best-case and will increase with longer engine life.
- Estimated BHP to HHP efficiency for natural gas reciprocating engine to be 76.6% (*i.e.* 95% PE, 95% FE, 96% Electric Motor [39], 97% VFD [40], 95% Power Conditioning, and 96% Generator [41]), along with an estimate of 133.8 HP of parasitic loads.
- Assumed 100% engine load achievable, engines would load share between the numbers of engines required.
- Acknowledged that gas generators would run periodically between stages at a partial load to maintain power supply to control systems, auxiliary equipment, and operating processes. Estimated idle time between stages was the same amount of time the TITAN turbines idled which is based on two months of field data.
- Engine load at idle was assumed minimum stable load of 50%.

4.4. Large Natural Gas Turbine (>24 MW)

Modeling parameters and assumptions for the large natural gas turbine analyzed in this study are presented below and illustrated graphically in **Figure 9**.

Engine Description	Engine Type	Rated Power (kW)	Power Train Component Efficiency - %							Total Power Efficiency (BHP to HHP)	Parasitic Loses per Pump (hp)
			Generator	Power Con'ditiong	Power Distribution	VFD	Elec Motor	Power End	Fluid End		
Large Turbine	Pratt & Whitney FT8	30,941	N/A	95%	100%	97%	96%	95%	95%	79.8%	134

Figure 9. Large natural gas turbine (>24 MW) modeling parameters.

Electrical component efficiency assumed the same as the natural gas electrical components except for the generator efficiency. Presently, engine data alone is not available, so efficiency for the engine that was considered was the generator holistically, meaning the engine and alternator.

- Engine models for the calculation used were SWIFTPAC 30 FT8.
- Large turbines are not shutdown (and must idle) between stages.
- At the time of publishing this paper, no methane slip data was available from the large turbine providers. For the model, we have estimated idling at 2.3% load which is the same load as the TITAN turbine idle load. Scaling the emissions rate of the TITAN at idle to the size of the large turbine results in producing CO_2e emissions at idle of approximately 3.59 MT/hr. The scaling factor used was 7.73 which was based on the two turbines max horsepower.
- Fuel consumption is based on OEM data. Only fuel consumption and efficiency data at full load available for large turbine. TITAN thermal efficiency vs load curve was scaled to match the 100% load condition of the OEM published data and provide estimate fuel consumption fuel range.
- Estimated BHP to HHP efficiency for large natural gas turbine to be 79.8% (*i.e.* 95% PE, 95% FE, 96% Electric Motor, 97% VFD, 95% Power Conditioning), along with a highly conservative estimate of 130 HP of parasitic loads.
- Assumed 100% engine load achievable, engines would load share between the numbers of engines required.

4.5. TITAN Direct-Drive Natural Gas Turbine (4.2 MW)

Modeling parameters and assumptions for the large natural gas turbine analyzed in this study are presented below and illustrated graphically in **Figure 10**. Since the turbine is directly mounted to the power end through a gearbox and the turbine shaft has a maximum speed, the maximum pumping rate of the unit is based on the gear ratio, stroke length, and plunger diameter of the gear and positive displacement pump. This means that unlike other technologies, the TITAN direct drive turbine is rate limited, rather than power limited for commercially available pumps. This means that under normal operating conditions with the positive displacement pump at its maximum rpm, the engine load is less than 100%. For modeling purposes, the maximum rate of the pump was selected based on the expected power end that would be utilized in the pressure ranges (see **Table 9**).

Engine Description	Engine Type	Rated Power (kW)	Power Train Component Efficiency - %	Total Power Efficiency (BHP to HHP)	Parasitic Loses per Pump (hp)
BJ Titan	TITAN	4,000	Planatary Gearbox 97%; Power End 95%; Fluid End 95%	87.5%	Deck Engine running at load

*Actual Fuel consumption and Emissions were used for BJ Titan

Figure 10. Direct-drive natural gas turbine (4.0 MW) modeling parameters.

Table 9. TITAN pump maximum rate based on hydraulic fracturing treatment pressure.

Treatment Pressure Range (PSI)	Max Rate (BPM)
0 - 10,000	16.0
10,001 - 12,499	14.0
12,500+	12.0

- TITAN emissions model was based on third party verified emissions testing data. This test recorded the fuel consumption and exhaust stack emissions of the TITAN turbine at varying loads.
- Engine load and flow rate based on actual flow rates achievable with existing power end fluid end combination.
- Third party emission testing was completed on a commercialized TITAN pump pulled directly from field operations with no modifications.
- Negligible methane slip was verified by independent emissions testing data however was still included in modeling.
- Titan turbine and deck engine idle time estimated to be 1.01 hours per day, which is based on 2 months of operating data.
- Temperature and atmospheric pressure are based on the individual Basin historical averages.
- The calculations considered the average idling time between stages based on two months of field operations data.

5. Results and Discussion

To compare different hydraulic fracturing technologies emissions footprint, the model was run in five different test cases. These cases are to summarize typical hydraulic fracturing treatment jobs on a daily operating cycle. Each technology was also compared in the first case on a strictly pumping time basis to compare emissions only while pumping. Lastly, criteria pollutants were looked at for each technology for the first case. The error bars and uncertainty for the TITAN emissions test represent a 95% confidence level of measurement. Each measurement device was calibrated and certified to be within allowable uncertainty proscribed by the applicable EPA method testing requirements and ASTM D7036 section 15.3.11 and 13. Uncertainty value was selected based on the maximum allowable error for each gas component measurement. Error and uncertainty for the other engine technologies was based on OEM reported uncertainty for provided data.

5.1. Emissions Model Results

In each of the five cases presented in the results, total CO_2e is presented in MT/day based on the model assumptions for a daily operating cycle. The graphs produced by the model stack the three greenhouse gases emitted during combustion. These results show that N_2O makes up a negligible amount of the daily GHG emissions, with the largest portion being CO_2. Methane emissions results varied greatly depending on the engine type.

Case 1: Haynesville—17 pumping hours, 80 BPM and 12,000 psi

The results for Case 1, shown in Figure 11, suggest the TITAN offers a 5.9% - 43.4% CO_2e emissions reduction compared to current and next-generation technologies with an average reduction of 24.8%. Table 10 shows the distribution of each GHG component that makes up the total daily GHG emissions. While the natural gas reciprocating engine had lower CO_2 emissions than the TITAN in this scenario, it emitted 57.8 times the amount of methane, which is 28 times more potent than CO_2 in terms of global warming potential. This is largely due to the amount of methane slip seen in natural gas reciprocating engines at high loads. The TITAN direct-drive turbine performs optimally in operating environments which demand high HHP. This is largely because engine load can readily be increased, which improves fuel efficiency. The model expected fuel consumed per day of operation is outlined in Table 11. Natural gas reciprocating engines show 4.4% less fuel consumed, however have 5.9% higher GHG emissions. The TITAN displaces approximately 96.8% of diesel consumption when compared to Tier 2 and Tier 4F engines. The TITAN consumes 12.8% less natural gas than the large turbine, this result is likely a result of increased thermal efficiency of the TITAN compared to the large turbine from higher engine loads. While TITAN does consume some diesel, the overall BTUs consumed per operating day by the TITAN is 8.4% less than the large turbine.

Table 10. Emissions model tabulated results for Case 1 Haynesville basin.

	CO_2e of N_2O Emissions (MT) per Day	CO_2e of CH_4 Emissions (MT) per Day	Total CO_2e Emissions (MT) per Day	% Reduction of Titan Compared to Other Engines
TITAN	0.4	0.5	208.7	
Nat Gas Recip	0.1	31.1	221.8	5.9%
Large Turbine	0.1	0.1	247.3	15.6%
T4F Dual Fuel	0.2	38.3	294.0	29.0%
T2	0.6	0.3	280.7	25.6%
T4F	0.6	0.3	295.6	29.4%
T2 Dual Fuel	0.3	111.0	369.0	43.4%

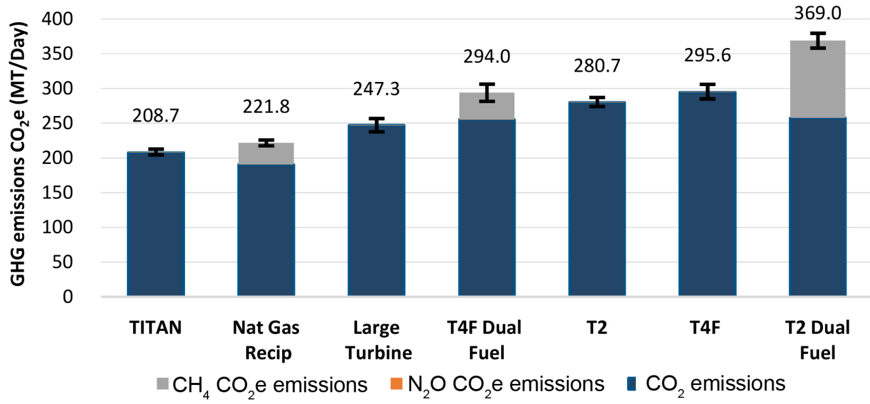

Figure 11. Case 1 CO_2e emissions for different frac fleet technologies in Haynesville basin.

Table 11. Fuel consumption results for various engines in Case 1 Haynesville basin.

	Natural Gas (MCF/Day)	Diesel Fuel (Gal/Day)
TITAN	3738	893
T4F	0	28,946
T2	0	27,487
Dual Fuel 70% - 85% Substitution	3683	5736
Natural Gas Recip	3572	0
Large Turbine	4217	0
T2 Dual Fuel	2748	10,908

Case 2: Permian—17 pumping hours, 120 BPM and 9000 psi

The results from the model for Case 2, shown in Figure 12 and Table 12 suggest the TITAN offers an emission reduction compared to other technologies except for natural gas reciprocating engines. While Titan emits on average 22.9% less than other technologies, the model results in the TITAN having 2.4% more GHG emissions than the natural gas reciprocating engine. This change between Cases 1 and 2 are driven by two factors. The first is the increased altitude between the Permian and Haynesville basin. The altitude based on the model assumptions would result in an increase of fuel consumption of 8.1%. The other factor, which contributes less to the difference between Case 1 and Case 2 is the engine load. The engine load affects the thermal efficiency of the engine to a varying degree. The engine load for the TITAN from Case 1 and Case 2 was 81.2% and 68.5% respectively. This change in engine load results in a decrease of thermal efficiency of 2% - 3%, based on TITAN emissions test data results. This points to issues with the TITAN being rate limited rather than power limited, which is especially shown in low pressure basins such as the Permian. Table 13 summarizes the fuel consumption that was used by the model and shows similar trends to Case 1.

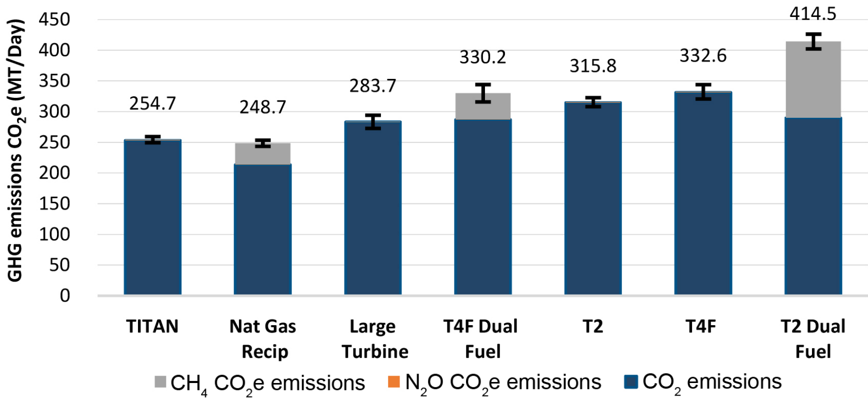

Figure 12. Case 2 CO_2e emissions for different frac fleet technologies in Permian basin.

Table 12. Emissions model tabulated results for Case 2 Permian basin.

	CO_2e of N_2O Emissions (MT) per Day	CO_2e of CH_4 Emissions (MT) per Day	Total CO_2e Emissions (MT) per Day	% Reduction of Titan Compared to Other Engines
TITAN	0.7	0.6	254.7	
Nat Gas Recip	0.1	34.7	248.7	−2.4%
Large Turbine	0.1	0.1	283.7	10.2%
T4F Dual Fuel	0.3	42.8	330.2	22.9%
T2	0.7	0.4	315.8	19.4%
T4F	0.7	0.4	332.6	23.4%
T2 Dual Fuel	0.4	124.4	414.5	38.6%

Table 13. Fuel consumption results for various engines in Case 2 Permian basin.

	Natural Gas (MCF/Day)	Diesel Fuel (Gal/Day)
TITAN	4513	1190
T4F	0	32,565
T2	0	30,922
T4F Dual Fuel	4141	6451
Natural Gas Recip	4006	0
Large Turbine	4908	0
T2 Dual Fuel	3090	12,258

Case 3: Haynesville Simulfrac—17 pumping hours, 160 BPM and 12,000 psi

The higher overall horsepower demand of a Simulfrac shows similar trends to Case 1. Overall, the results shown in Figure 13 and Table 14 show an emissions reduction of TITAN between 5.4% and 42.8% with an average of 24%. The average decreases between Case 1 and Case 3 largely by the increased performance of the single turbine. With the higher overall horsepower demand, the job requirements increase engine load which in turn, will increase thermal efficiency, decreasing specific fuel consumption per horsepower of the large turbine (see Table 15 for model fuel consumption for Case 3).

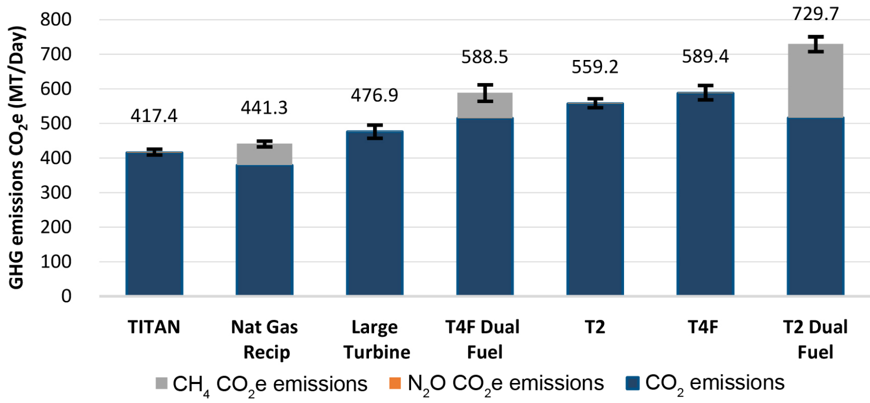

Figure 13. Case 3 CO_2e emissions for different frac fleet technologies in Haynesville performing a Simulfrac.

Table 14. Emissions model tabulated results for Case 3 Haynesville basin performing a Simulfrac.

	CO_2e of N_2O Emissions (MT) per Day	CO_2e of CH_4 Emissions (MT) per Day	Total CO_2e Emissions (MT) per Day	% Reduction of Titan Compared to Other Engines
TITAN	0.8	1.1	417.4	
Nat Gas Recip	0.2	61.6	441.3	5.4%
Large Turbine	0.2	0.2	476.9	12.5%
T4F Dual Fuel	0.5	72.8	588.5	29.1%
T2	1.2	0.6	559.2	25.4%
T4F	1.2	0.7	589.4	29.2%
T2 Dual Fuel	0.6	212.7	729.7	42.8%

Table 15. Fuel consumption results for various engines in Case 3 Haynesville basin performing a Simulfrac.

	Natural Gas (MCF/Day)	Diesel Fuel (Gal/Day)
TITAN	7475	1785
T4F	0	57,707
T2	0	54,756
T4F Dual Fuel	7053	13,528
Natural Gas Recip	7110	0
Large Turbine	8576	0
T2 Dual Fuel	5262	23,119

Case 4: Permian Simulfrac—17 pumping hours, 240 BPM and 9000 psi

Case 4 shows the continued trend similar to Case 2 of better performance by the natural gas reciprocating engine compared to TITAN in the Permian basin. When excluding the natural gas reciprocating engine, the TITAN results show 7.7% to 37.8% GHG emissions reduction. Figure 14 and Table 16 matches previous trends in other cases by show an increasingly worse performance overall performance in the Permian. This case is where single large turbines perform most optimally as the engine load increases to approximately 86%. Fuel consumption from the emissions model is shown in Table 17.

Case 5: Montney/Duvernay—17 Pumping hours, 110 BPM and 12,000 psi

The last case is the Montney and Duvernay basin. This basin differs from the other two basins as it has an average annual temperature that is considerably lower. While it is expected to perform significantly better than the Haynesville cases, the actual results are similar. This is due to the altitude difference counteracting the lower ambient temperature. Figure 15 and Table 18 show the results from the model for this environmental extreme case. The fuel consumption utilized by the model is in Table 19. In all five cases, diesel only and dual-fuel engines

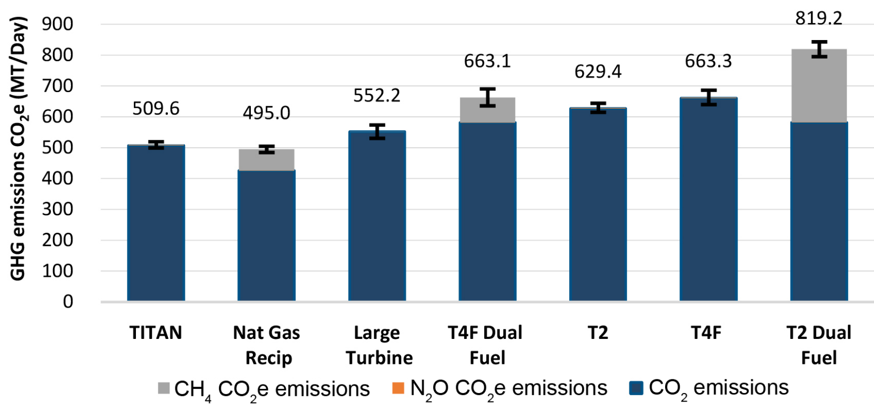

Figure 14. Case 4 CO_2e emissions for different frac fleet technologies in Permian performing a Simulfrac.

Table 16. Emissions model tabulated results for Case 4 Permian basin performing a Simulfrac.

	CO_2e of N_2O Emissions (MT) per Day	CO_2e of CH4 Emissions (MT) per Day	Total CO_2e Emissions (MT) per Day	% Reduction of Titan Compared to Other Engines
TITAN	1.2	1.3	509.6	
Nat Gas Recip	0.2	68.9	495.0	−3.0%
Large Turbine	0.3	0.3	552.2	7.7%
T4F Dual Fuel	0.6	81.1	663.1	23.1%
T2	1.3	0.7	629.4	19.0%
T4F	1.4	0.7	663.3	23.2%
T2 Dual Fuel	0.7	236.9	819.2	37.8%

Table 17. Fuel consumption results for various engines in Case 4 Permian basin performing a Simulfrac.

	Natural Gas (MCF/Day)	Diesel Fuel (Gal/Day)
TITAN	9082	2231
T4F	0	64,944
T2	0	61,628
T4F Dual Fuel	7831	15,963
Natural Gas Recip	7979	0
Large Turbine	10,007	0
T2 Dual Fuel	5842	26,482

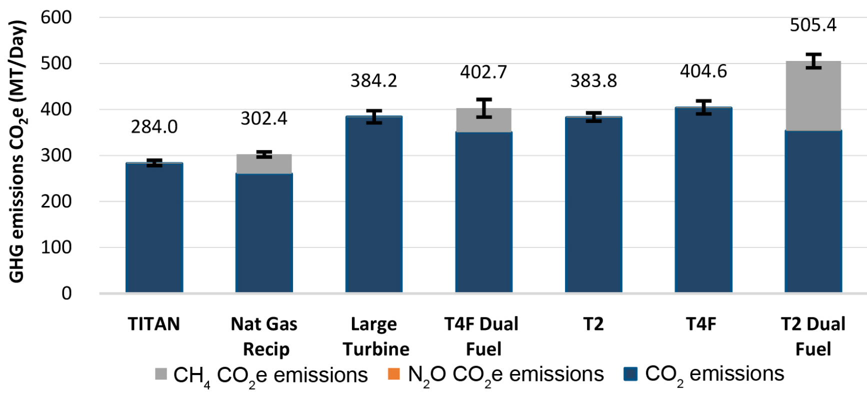

Figure 15. Case 5 CO_2e emissions for different frac fleet technologies in Montney/Duvernay basin.

Table 18. Case 5 CO_2e emissions for different frac fleet technologies in Montney/Duvernay basin.

	CO_2e of N_2O Emissions (MT) per day	CO_2e of CH_4 Emissions (MT) per day	Total CO_2e Emissions (MT) per day	% Reduction of Titan Compared to other engines
TITAN	0.5	0.7	284.0	
Nat Gas Recip	0.1	42.1	302.4	6.1%
Large Turbine	0.2	0.2	384.2	26.1%
T4F Dual Fuel	0.3	51.8	402.7	29.5%
T2	0.8	0.4	383.8	26.0%
T4F	0.9	0.5	404.6	29.8%
T2 Dual Fuel	0.4	151.2	505.4	43.8%

have similar GHG emissions apart from Tier 2 dual fuel. While dual-fuel engines decrease the CO_2 emissions, they drastically increase the methane emissions. This affect is even more impactful for Tier 2 dual-fuel engines as they have the

Table 19. Fuel consumption results for various engines in Case 5 Montney/Duvernay basin.

	Natural Gas (MCF/Day)	Diesel Fuel (Gal/Day)
TITAN	5122	1190
T4F	0	39,616
T2	0	37,577
T4F Dual Fuel	5058	7814
Natural Gas Recip	4874	0
Large Turbine	6816	0
T2 Dual Fuel	3774	14,959

highest methane slip. Tier 2 dual-fuel values in Case 5 were 2.92 times higher than Tier 4F methane emissions and 216 times higher than TITAN methane emissions.

5.2. Pumping Comparison

To compare engine technology baseline while pumping, all idling was removed from the model with the results shown in Figure 16. The emissions from idling and their percentage of total GHG emissions are shown in Table 20. The overall trend of the best performing technologies continuous even while idling is removed. The diesel and dual-fuel options idling emissions per day range between 3.08% - 3.87% of their total GHG emissions. This means that even if conventional fleets implement zero idle technology, next-generation engine technologies still offer significant emissions reduction while pumping. Natural gas reciprocating and TITAN emit very little between stages as they can only idle when power is demanded by operations. The large turbine is most significantly impacted by emissions while idling making up 10.16% of the total CO_2e daily emissions. With idling removed, the large turbine only emits 7.9% more emissions than the TITAN compared to 15.6% when including idling.

5.3. TITAN Power Limiting

As mentioned, the TITAN rate is limited due to the commercially available positive displacement pumps for hydraulic fracturing. The TITAN is not able to operate at its maximum thermal efficiency like other engine technologies that separate hydraulic power from power generation. With the assumption that the TITAN is power limited with the development of new commercial pumps, the TITAN can be modelled under the ideal condition. Under this assumption, the model was rerun the model using the TITANS worse performing operating conditions, Case 4. The results for the ideal TITAN is compared to the model results for the TITAN and natural gas reciprocating engine in Figure 17. In Case 4, daily CO_2e emissions for the TITAN went from 509.61 MT/day to 490.28 MT/day, a 3.8% reduction. This increase in performance puts the ideal TITAN in this scenario 0.2% better than the natural gas engine.

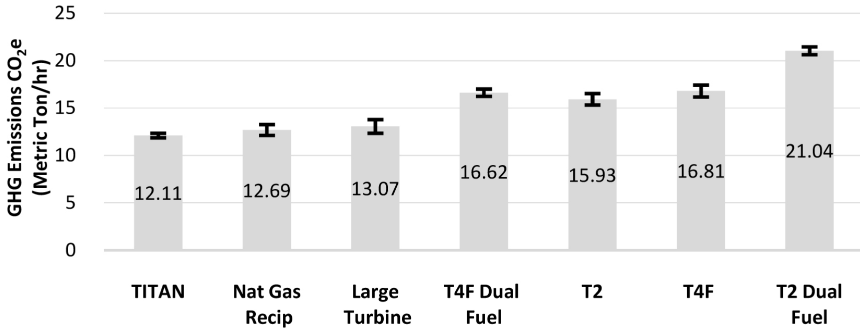

Figure 16. Emissions rate per pumping hour of various fracturing fleet technologies based on emissions modelling.

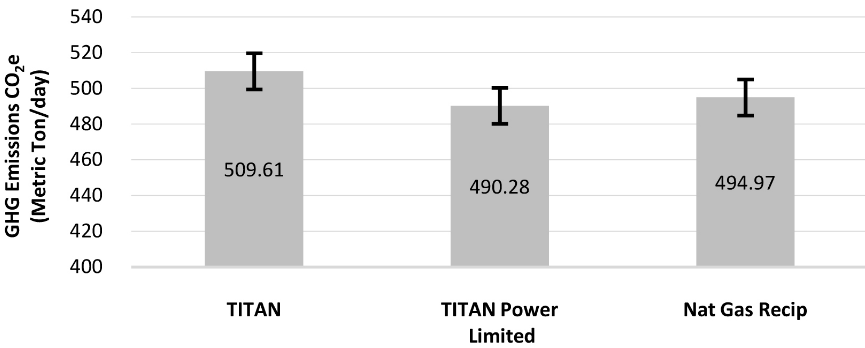

Figure 17. Emission rate of ideal TITAN engine compared to leading GHG emissions engine technologies.

Table 20. Emissions modeling idle CO_2e emissions comparison between engine technologies.

	CO_2e Emissions (MT) While Pumping per Day	CO_2e Emissions (MT) While idle per Day	Percentage of Emissions from Idle
TITAN	205.86	2.86	1.37%
Nat Gas Recip	215.76	6.04	2.72%
Large Turbine	222.16	25.13	10.16%
T4F Dual Fuel	282.60	11.38	3.87%
T2	270.75	9.93	3.54%
T4F	285.70	9.91	3.35%
T2 Dual Fuel	357.66	11.38	3.08%

5.4. EPA-Regulated Emissions Results

Criteria pollutants measured from the TITAN emissions test were compared to OEM reported emissions. These values were taken with the engine loads in Case 1, these values do vary slightly between each case, but the overall trend remains constant. NO_x emissions rate and CO are compared in **Figure 18**, and PM compared in **Figure 19**. The overall results are tabulated in **Table 21** for each value.

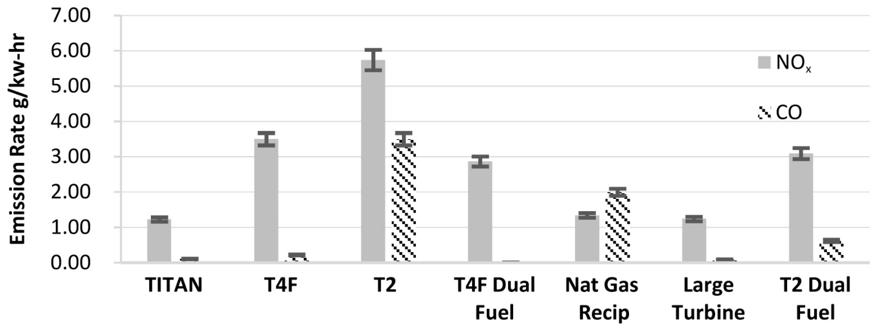

Figure 18. Emissions rate of NO_x and CO by various frac fleet engine technologies on Case 1 engine loading.

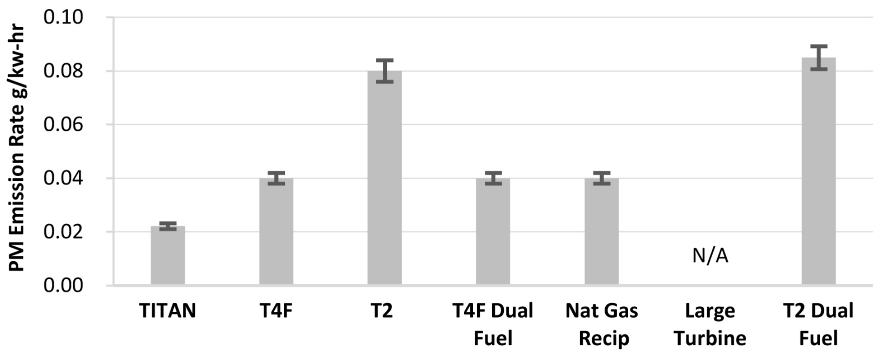

Figure 19. Emissions rate of Particulate Matter (PM) by various frac fleet engine technologies on Case 1 engine loading.

Table 21. Tabulated emissions modeling results for EPA criteria pollutants for various engine technologies in Case 1.

	NO_x g/kw-hr	CO g/kw-hr	PM g/kw-hr
BJ Titan	1.22	0.11	0.02
T4F	3.50	0.22	0.04
T2	5.74	3.50	0.08
T4F Dual Fuel	2.86	0.01	0.04
Natural Gas Engine	1.34	2.01	0.04
Large Single Turbine	1.24	0.09	N/A
T2 Dual Fuel	3.13	0.60	0.09

The table follows expected results for the engine type and fuel consumed. Natural gas engines typically result in lower NO_x and PM emissions. NO_x emissions are expected to be higher in diesel and/or reciprocating engines due to the higher engine temperature. CO emissions are more dependent on engine tuning rather than fuel and engine type. CO is resultant from the incomplete combustion in an engine with the combusted gas not spending sufficient time at high temperatures. Overall, the emissions test resulted in lower criteria emissions than data reported by OEM manufacturers engines compared to the TITAN.

5.5. Other Considerations Impacting Emissions Profile

Some considerations could not be included in the model due to operational variability.

- Dual-fuel systems failing to reach OEM-reported substitution rates: Another drawback to dual-fuel systems is that the substitution ratio between diesel and natural gas decreases at high engine loads. In the event a pump is lost, or pressures increase, the substitution ratio can drop off. Often, more equipment than necessary is sent to a location to mitigate this situation, which can result in increased emissions from idling and under-loading the engines.
- Transmission power gap: With conventional and dual-fuel equipment, engine power cannot be utilized to its full potential in some operating conditions, due to the characteristics of the transmission. While the engine may be rated for a specified load, more equipment may be needed on location to achieve the required rate if the engines do not have sufficient torque for the selected transmission gear ratio. Needing more equipment than necessary causes the pumps to run at less efficient loads.
- Engine degradation: Engine performance degrades with increased operating hours. This can increase GHG emissions, along with potential methane slip. Over time an engine will wear, decreasing performance and fuel-to-air ratio will fall out of tuned values, which can lead to incomplete combustion. Thus, OEM emission values tend to be low. This effect usually impacts reciprocating engines to a greater degree than turbine engines. Excluding the actual TITAN tests, all other engines evaluated were based on OEM data under ideal conditions. OEM-provided emissions data is based on new, bare-engine testing.

6. Conclusions

When assessing and comparing different hydraulic fracturing technologies, it is critical to consider the various factors impacting engine operating emissions, including the Energy Density of Fuel, Thermal Efficiency, Mechanical Energy to Hydraulic Horsepower Efficiency, Operating Conditions, and Equipment Configuration. The results conclude that the TITAN technology stands out as the leading emissions solution for hydraulic fracturing operations. This is supported by a hydraulic fracturing emissions model which is based on actual third-party emissions test data.

In most cases, the model shows that the utilization of TITAN resulted in lower GHG emissions than conventional and next-generation technologies. This largely stems from the high-power transfer efficiency power created by the natural gas-powered turbine, through a direct mechanical drive line to the pump. Another key factor to the model results is the higher loading that is achieved on the TITAN turbine in various cases compared to a single large turbine. The turbine selected for the TITAN platform allows for modularity to properly load the engines efficiently depending on the operational requirements and environment to minimize emissions. The one case where natural gas reciprocating engines out-performed the TITAN turbine was in the Permian basin. This is driven by higher engine thermal efficiency and the high altitude and temperatures in the basin. Testing also validated that the TITAN had the lowest EPA-regulated NO_x, CO, and PM emissions. In all cases, next-generation technologies resulted in lower GHG emissions than conventional diesel, and dual-fuel engines.

Natural gas-powered direct drive turbine mechanical systems provide the highest power transfer efficiency. As compared to electric-powered hydraulic fracturing equipment, the power transfer from the turbine to the pump on the TITAN platform is mechanical and direct. Direct drive eliminates energy loss from the required electricity generation, electricity conditioning, distribution, voltage and frequency conversion for hydraulic fracturing equipment that relies on the generation and transfer of electricity. Other conclusions drawn from these results are:

- As one of the most potent GHG gases, methane should be considered when evaluating GHG emissions in natural gas and dual-fuel reciprocating engines. Methane slip increased engine GHG emissions rate greatly over EPA calculated emissions which underestimates the effects of methane slip.
- The higher the load on the turbine driving the TITAN pumping units, the better the fuel economy and the lower the emissions. To maximize turbine efficiency, thus minimizing GHG emissions, the focus of improving direct drive turbine technology should focus on improving the maximum power output of the utilized positive displacement pumps.
- The use of Tier 4F diesel-powered hydraulic fracturing equipment does not always provide lower GHG emissions as compared to Tier 2 diesel engines. This result is due to engine technologies that are utilized to reduce NO_x emissions, but decrease thermal efficiency.
- The industry in the past has utilized dual-fuel engines to decrease operating costs by displacing diesel fuel with natural gas. In the past, there was also the incorrect assumption that this decreases GHG emissions. In all Cases 1 - 5, GHG emissions between Tier 4F dual-fuel and diesel only were nearly identical. Tier 2 on the other hand, has substantially higher GHG emissions due to the extreme amount of methane slip. In fact, in all cases, Tier 2 dual fuel had considerably higher GHG emissions than the next closest technology.

Acknowledgements

BJ Energy Solutions and the authors would like to thank Aethon Energy for their support in providing access to equipment dedicated to their operations. The scheduled emissions testing could not have been completed in a timely manner without their accommodations. BJ Energy would also like to thank Air Hygiene for providing technical support and completing the TITAN emissions testing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix: TITAN Emissions Test Data

Table A1. TITAN emissions test results.

Parameter	Run NG-1	Run NG-2	Run NG-3	Run NG-4
Load Designator	NG-Idle	NG-8000	NG-12,000	NG-13,250
Stack Flow (RM19) (SCFH)	465,338	987,594	1,049,396	1,141,426
Shaft Horsepower (SHP)	300.0	2,488.0	3725.9	4179.1
Hydraulic Horsepower (HHP)	268.0	2,223.0	3329.0	3733.0
Shaft Power (skW)	223.7	1,855.4	2778.5	3115.6
NO_x (ppmvd)	12.23	36.84	55.49	60.40
NO_x (ppm@15% O_2)	31.20	47.84	61.14	63.57
NO_x (g/shp*hr)	1.03	0.79	0.85	0.89
NO_x (g/hhp*hr)	1.15	0.89	0.95	1.00
NO_x (g/skW*hr)	1.38	1.06	1.14	1.20
CO (ppmvd)	531.75	20.27	7.58	9.36
CO (ppm@15% O_2)	1356.48	26.32	8.35	9.85
CO (g/shp*hr)	27.19	0.27	0.07	0.08
CO (g/hhp*hr)	30.44	0.30	0.08	0.09
CO (g/skW*hr)	36.47	0.36	0.09	0.11
THC (as C3) (ppmvd)	131.28	4.37	5.37	5.71
THC (as C3) (ppm@15% O_2)	334.88	5.67	5.91	6.00
THC (as C3) (g/shp*hr)	10.55	0.09	0.08	0.08
THC (as C3) (g/hhp*hr)	11.81	0.10	0.09	0.09
THC (as C3) (g/skW*hr)	14.15	0.12	0.11	0.11
CH_4 (as C1) (ppmvd)	311.50	0.51	0.00	1.07
CH_4 (as C1) (ppm@15% O_2)	794.62	0.66	0.00	1.13
CH_4 (as C1) (g/shp*hr)	9.10	0.004	0.00	0.01
CH_4 (as C1) (g/hhp*hr)	10.19	0.004	0.00	0.01
CH_4 (as C1) (g/skW*hr)	12.21	0.005	0.00	0.01
N_2O (ppmvd)	2.05	0.88	0.32	0.26
N_2O (ppm@15% O_2)	5.24	1.14	0.35	0.27
N_2O (g/shp*hr)	0.16	0.02	0.00	0.00
N_2O (g/hhp*hr)	0.18	0.02	0.01	0.00
N_2O (g/skW*hr)	0.22	0.02	0.01	0.00
Filterable PM (mg)	7.67	4.34	3.39	2.00
Filterable PM (gr/dscf)	1.30E−02	3.19E−03	2.06E−03	1.12E−03

Continued

Filterable PM (g/shp*hr)	1.39	0.09	0.05	0.02
Filterable PM (g/hhp*hr)	1.56	0.10	0.05	0.03
Filterable PM (g/skW*hr)	1.87	0.12	0.06	0.03
CO_2 (%vd)	1.55	2.60	3.04	3.17
CO_2 (g/shp*hr)	1247	535	444	449
CO_2 (g/hhp*hr)	1396	599	497	503
CO_2 (g/skW*hr)	1672	718	596	603

Nomenclature

BBL	Barrel
BPM	Barrels Per Minute
CO_2e	Equivalent Mass of CO_2
E_{CO_2}	Emitted CO_2 in Metric tons/hr
EF_{CO_2}	Emissions Factor for CO_2
E_{N_2O}	Emitted CO_2 in Metric tons/hr
EF_{N_2O}	Emissions Factor for CO_2
E_{CH_4}	Emitted CH_4 in Metric tons/hr
$E_{CH_4,Slip}$	Emitted CH_4 Including Slip in Metric tons/hr
EF_{CH_4}	Emissions Factor for CH_4
FC	Fuel Consumption gal/hr
V_{engine}	Engine Displacement Volume
GWP	Global Warming Potential
HP	Horsepower
HHP	Hydraulic Horsepower
$HP_{Parasitic}$	Parasitic HP Load on Engine
HHP_{Pump}	Hydraulic Horsepower Per Pump
HHV	Higher Heating Value BTU/unit volume
MT	Metric Ton
OEM	Original Equipment Manufacturer
P	Treatment Pressure in psi
PTE	Power Transfer Efficiency
Q	Flow Rate in Gallons Per Minute
T2	Tier 2
T4F	Tier 4 Final