# EXTRACTING THE FACTS:

## A Scientific Approach to Proper Evaluation of Hydraulic Fracturing Equipment Emissions

A transparent assesment of emissions from hydraulic fracturing equipment based on actual operating conditions and EPA certified third-party measured data.


### Authors

**William Nieuwenburg**
BJ Energy Solutions, The Woodlands TX, USA

**Dan Fu**
BJ Energy Solutions, The Woodlands TX, USA

**Warren Zemlak**
BJ Energy Solutions, The Woodlands TX, USA

**Tony Yeung**
BJ Energy Solutions, The Woodlands TX, USA

**Caleb Barclay**
BJ Energy Solutions, The Woodlands TX, USA

**Andrew Nix**
Associate Professor in the Department of Mechanical and Aerospace Engineering at West Virginia University, Morgantown WV, USA

# Table of Contents

# Executive Summary

The oil and gas industry has a history of innovation, stewardship and self-regulation. At present, increasing studies linking emissions as one of many contributing factors to climate impact, have increased the urgency for innovation that targets the reduction of fuel combustion and direct emissions.

Oil and Gas producers who rely on hydraulic fracturing technology to responsibly extract hydrocarbon are continually evaluating options to economically reduce overall emissions and the associated carbon footprint. In response to demand for innovation from energy producers, governments, and the public, the adoption of solutions to reduce emissions related to hydraulic fracturing applications has accelerated.

The focus on hydraulic fracturing emissions is largely centered around associated equipment and the corresponding emissions comprised of both greenhouse gases (GHGs) and EPA regulated pollutants. While carbon dioxide ($CO_2$) receives much of the attention for targeted GHG emission reduction, there is a more potent GHG that is highly relevant to hydraulic fracturing operations—methane.

Methane is often ignored when evaluating emissions-reducing technologies available for hydraulic fracturing. Many of the emissions analyses are incomplete, having omitted important factors, such as hydraulic fracturing operating conditions, pressure, injection rates, engine operating time, engine idle time, and other application treatment parameters. In many cases, specific evaluation methods or calculations are used to cast certain technologies in the best light. These incomplete analyses have created a great deal of confusion in the marketplace.

## *Executive Summary (continued)*

At BJ Energy Solutions, we believe the remedy to this confusion is science and transparency. To educate stakeholders in this space, we have conducted a comprehensive, scientific analysis of the emissions profiles and performance of the main types of hydraulic fracturing equipment technologies. For the analysis, Original Equipment Manufacturer (OEM) engine data was used to determine the required number of units, engine load, and fuel consumption for the outlined hydraulic fracturing technologies. The emissions results presented in this paper also include BJ's TITAN natural gas direct-drive turbine technology, which is based on certified third-party test data, following U.S. EPA methods. The testing was conducted under actual operating conditions, and reflects the many engine characteristics and operating parameters that are representative during a full operations cycle.

Our models have been designed and independently validated 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 more. The details of our methodology, including testing assumptions and specific formulas, are contained within.

### *What facts did we extract?*

***Across the Haynesville, Permian, Eagle Ford, and Duvernay/Montney basin scenarios, BJ's TITAN natural gas direct-drive technology demonstrates the lowest GHG emissions.***

***Most importantly, TITAN emits virtually zero methane when under normal operating conditions and has lower EPA regulated carbon monoxide, nitrogen oxide, and particulate matter emissions.***

***The TITAN advantage stems from having one of the highest efficiencies in transferring thermal energy to hydraulic horsepower.***

# Fast Facts

The energy density of natural gas is **22% higher than that of diesel.**

**Methane has 28 times** the global warming **potential of carbon dioxide.**

When generating the same amount of thermal energy, **natural gas emits 27.4% less $CO_2$ than diesel.**

**$CO_2$ is not the** only, nor the **most potent, greenhouse gas.**

**Greenhouse gas emissions are different** from EPA regulated emissions.

A diesel frac fleet may release **154 million pounds of carbon dioxide** into the atmosphere **per year.**

# Introduction

Hydraulic fracturing has been practiced since the 1940s and has played a key role in making North America energy independent. The process itself has traditionally involved vast amounts of equipment powered by industrial diesel reciprocating engines to drive 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.

Hydraulic fracturing operations are typically achieved using a frac fleet consisting upwards of 18 to 24 diesel-powered fracturing pumps 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 (North American Rig Count, Drilling and Frac Spread Count Data, 2021), with each frac fleet consuming upwards of seven million gallons of diesel annually and emitting 154 million pounds of carbon dioxide into the atmosphere. (Chapa, 2019).

To offset diesel consumption and reduce overall greenhouse gases, natural gas is increasingly combined with diesel (example: Tier II and Tier IV 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 the diesel (dual-fuel). There is a misconception that dual-fuel is also a solution to reduce emissions. Our paper will show that the use of blended natural gas and diesel in engines can actually have a detrimental impact on the emissions profile.

Despite the intensifying focus on sustainability, there is still much confusion in the marketplace about which technologies provide the most greenhouse gas reduction while best enhancing economics and operational efficiencies. This confusion is amplified by early conclusions and bias without accounting for factors that are not considered within EPA definitions, using actual field data, or proper validation when comparing next-generation hydraulic fracturing equipment solutions.

This paper drills down into verifiable data to extract the facts: it defines greenhouse gas emissions and provides a detailed scientific analysis of the environmental and operational performance of BJ Energy Solutions' TITAN™ direct-drive natural gas turbine as compared to conventional and other next-generation completion technologies—all based on equivalent comparisons and certified third-party test data.

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

# Getting to know GHG

Greenhouse gas is “any gas that has the property of absorbing infrared radiation (net heat energy) emitted from Earth’s surface and reradiating it back to Earth’s surface, thus contributing to the greenhouse effect." Carbon dioxide, methane, and water vapor are the three most important greenhouse gases (EPA, 2021).

In 2016, more than 190 countries adopted The Paris Agreement, which set the long-term goal of limiting global warming to well below 2.0 degrees Celsius temperature rise and preferably to 1.5, compared to pre-industrial levels. Since 1850-1900, greenhouse gas emissions are believed to be the main cause of global warming, therefore preventing them from being released into the atmosphere is key to achieving this goal. At present, burning fossil fuels for electricity, heat, and transportation is the largest source of greenhouse gas emissions from human activities according to the U.S. Environmental Protection Agency (EPA). Greenhouse gases generally act as a blanket insulating the earth that prevents heat from escaping into space. Each GHG constituent has a different effect on global warming depending on their ability to absorb energy (i.e., radiative efficiency), and how long they stay in the atmosphere (i.e., their

*“According to IPCC, one tonne of emitted methane equals 28 tonnes of emitted $CO_2$.”*

The Intergovernmental Panel on Climate Change (IPCC) has developed a common unit of measure, known as Global Warming Potential (GWP), for understanding how various greenhouse gases contribute to warming the Earth (See Table 1). More specifically, GWP is a measure of how much energy one tonne of an emitted gas will absorb over a given period of time, relative to one tonne of emitted carbon dioxide ($CO_2$). The larger the GWP, the more that a given gas warms the Earth compared to $CO_2$ over a given time period, most often 100 years. According to the EPA, GWP values can change over time due to updated scientific estimates of the energy absorption or lifetime of the gases or to changing atmospheric concentrations of GHGs that alter the energy absorption of one additional tonne of a gas relative to another (EPA Global Warming Potential, 2021).

Although $CO_2$ receives a great deal of attention due to its prevalence, it is not the only, nor the most potent, greenhouse gas. By comparison, fluorinated gases have extremely high global warming potential, but they are not emitted during hydraulic fracturing operations. Methane however, is particularly relevant, since it has high warming potential and it is present in the development of oil and gas production. Using the GWP values from the fifth IPCC report as provided by the Greenhouse Gas Protocol, one tonne of emitted methane equals 28 tonnes of emitted $CO_2$. The sum total emissions from said activities can be expressed as $CO_2e$, where “e” stands for equivalent:

$$CO_2e \text{ (tonne)} = CO_2 \text{ (tonne)} + 28\, CH_4 \text{ (tonne)} + 265\, N_2O \text{ (tonne)}$$

Figure 2 below shows the distribution of emissions from four main GHG gases.

- **Carbon dioxide ($CO_2$):** Carbon dioxide is by far the largest greenhouse gas by volume in the atmosphere as a result of burning fossil fuels, solid waste and biological materials.

- **Methane ($CH_4$):** Thermogenic methane emissions mainly come from the production and transport of coal, natural gas, and oil. Livestock, agricultural practices and decomposition of organic material can also result in biogenic methane emissions.

- **Nitrous oxide ($N_2O$):** Emission of nitrous oxide results from both agricultural and industrial activities, combustion of fossil fuels and solid waste, as well as during treatment of wastewater.

- **Fluorinated gases:** Hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride are the most powerful greenhouse gases from various industrial processes. Although emitted in small quantities, they are highly potent greenhouse gases due to their high Global Warming Potential.

***Figure 2: Greenhouse-gas emission distribution** (EPA, 2021)*

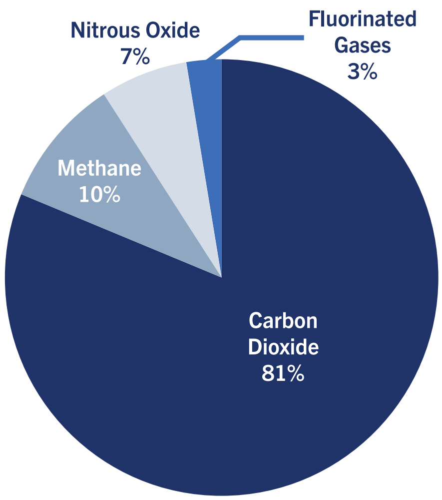



***Table 1: Global Warming Potential Values relative to $CO_2$***
*(Greenhouse Gas Protocol, 2021)*

| 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 | $N_20$ | 310 | 298 | 265 |
| **Substances Controlled by the Montreal Protocal** | | | | |
| CFC-11 | $CCl_3F$ | 3,800 | 4,750 | 4,660 |
| CFC-12 | $CCl_2F_2$ | 8,100 | 10,900 | 10,200 |
| CFC-13 | $CClF_3$ | | 14,400 | 13,900 |
| CFC-113 | $CCl_2FCClF_2$ | 4,800 | 6,130 | 5,820 |
| CFC-114 | $CClF_2CClF_2$ | | 10,000 | 8,590 |
| CFC-115 | $CClF_2CF_3$ | | 7,370 | 7,670 |
| Halon-1301 | $CBrF_3$ | 5,400 | 7,140 | 6,290 |
| Halon-1211 | $CBrClF_2$ | | 1,890 | 1,750 |
| Halon-2402 | $CBrF_2CBrF_2$ | | 1,640 | 1,470 |
| Carbon tetrachloride | $CCl_4$ | 1,400 | 1,400 | 1,730 |
| Methyl bromide | $CH_3Br$ | | 5 | 2 |
| Methyl chloroform | $CH_3CCl_3$ | 100 | 146 | 160 |

# Beyond GHG:

## Engine combustion pollutants regulated by the U.S. EPA Clean Air Act

EPA regulates the following pollutants (Criteria Air Pollutants, 2021) as they relate to equipment utilized in hydraulic fracturing operations:

**Carbon monoxide (CO):** On a global scale, carbon monoxide does not have a significant environmental effect. However, at the source of emissions carbon monoxide can react with other air pollutants to form ground-level ozone ($O_3$). This can be harmful to people in close proximity, often increasing the risk of respiratory diseases such as asthma. Carbon monoxide is also a key component in smog. Carbon monoxide is formed due to incomplete combustion, when the combustion gas does not spend sufficient time at high temperatures to oxidize into $CO_2$.

**Nitrogen Oxides (NOx):** These pollutants include six different chemical components of varying molecular weights. When exposed to light, these chemicals react with volatile organic compounds to create ozone, which is the main component of smog. This directly affects air quality and can cause respiratory and pulmonary illnesses.

The formation of nitrogen oxides occurs by three different mechanisms during combustion:

- Thermal
- Prompt
- Fuel NOx

The vast majority of NOx emissions comes from thermal, with prompt and fuel emissions being negligible. Most thermal NOx is formed in high temperature pockets of the combustion chambers where nitrogen and oxygen react. Maximum thermal NOx is formed at a slight fuel-lean mixture because of the excess oxygen. NOx levels can be reduced by controlling the temperature and stoichiometry of the combustion, although each reduction method has side effects. In reciprocating engines, a common method for decreasing NOx emissions is to lower the combustion chamber reaction temperature, which in turn decreases NOx formation, but this technique increases carbon monoxide production. Humidity also plays a significant impact on overall NOx emissions. The water vapor works to absorb heat from the combustion, which prevents NOx formation; however, this technique increases fuel consumption as the combustion becomes less efficient.

**Particulate Matter (PM):** Composed of very fine particles of soot or silica dust, particulate matter can damage respiratory and pulmonary systems when inhaled. It also contributes to the formation of acid rain and smog. Particulate matter emissions largely result from carryover or residue from noncombustible trace materials in the fuel itself, which means they are generally negligible in natural-gas engines compared to diesel.

# Factors Impacting Emissions

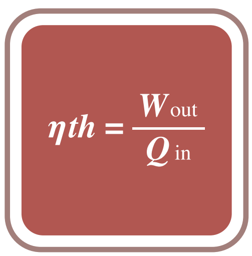
The main focus of hydraulic fracturing is to provide a specific amount of energy downhole to propagate fractures in the targeted rock. This is done by pumping fluids downhole at a rate and pressure governed by available hydraulic horsepower. In order to achieve this objective, a hydraulic fracturing operation relies on specially designed equipment which is able to perform the task of pumping formulated products down the wellbore and into the reservoir at high rates and pressures. The majority of this equipment is made up of hydraulic fracturing pumps which emit the greatest amount of GHGs within a hydraulic fracturing fleet.

Hydraulic fracturing engines driving the pumps work by converting thermal energy into hydraulic horsepower (HHP) which is used to convey the fluid downhole. When sizing a hydraulic fracturing fleet, the main controlling factor is the amount of hydraulic horsepower required. The efficiency with which the system converts thermal energy to hydraulic horsepower determines fuel consumption, which is often used as a proxy for emissions. However, the fuel entering the system is not always combusted fully or cleanly, which further affects a technology's emissions profile.

## Factors Impacting Engine Emissions

There are four main factors that determine an engine's operating emissions. These factors are:

Energy Density of Fuel




Thermal Efficiency

Mechanical Energy to Hydraulic Horsepower Efficiency

Operating Conditions and Equipment Configuration

A common practice of evaluating a hydraulic fracturing fleet emission profile is to focus only on one or two of these factors when comparing different hydraulic fracturing technologies. This practice, however, can lead to a bias or incorrect conclusion. All four of the characteristics significantly impact emissions performance; therefore, they all must be included in any analysis in order to make accurate comparisons.

> *"Thermal efficiency, mechanical energy to hydraulic horsepower efficiency, operating conditions and equipment configuration all play a role on emissions."*

The first three factors are related to converting fuel into useful hydraulic horsepower—a measure that is often used as a basis of comparison. The last factor from the list above, operating conditions and equipment configuration, also plays a significant role in evaluating emissions performance. When the fleet is not actively pumping downhole, emissions are still being produced from other aspects of the operating cycle, such as priming lines, pressure testing, and idling engines while maintenance activities or well swaps are being performed. These low load activities affect some technologies more than others, as do operating conditions, such as temperature, altitude and pressure.

The following section further outlines how each of the four factors impact emissions.

## 1. Energy Density of Fuel

The U.S. Department of Energy delineates energy sources as being primary or secondary. Primary energy sources encompass traditional fuels such as nuclear, coal, natural gas, and oil (including refined products like diesel and gasoline), as well as renewable fuels such as wind, solar, biodiesel, geothermal and hydropower. These primary energy sources are converted to electricity, a secondary energy source, which is transmitted through an electric grid to power homes, businesses, and vehicles.

A hydraulic frac fleet requires a mobile primary energy source since it regularly travels from one remote location to another. This need for mobility essentially excludes using renewables, which are currently developed for stationary applications. Nuclear power and coal are also excluded for practical, safety, and environmental reasons. This leaves diesel and natural gas as the two main options available today.

Energy density, which is defined as the amount of energy stored in a given mass of a material, is one of the main criteria for fuel selection. Here, natural gas has the edge: its energy density is 55 megajoules per kilogram (MJ/kg), which is 22% higher than the energy density of diesel. Utilizing higher density fuel provides greater potential energy for combustion with lower carbon-emissions output as a result. (See Table 2.)

***Table 2: Energy density of different fuels***
*(Hore-Lacy, 2011)*

| Fuel Type | Reaction Type | Energy Density (MJ/kg) | Typical Uses |
|---|---|---|---|
| Wood | Chemical | 16 | Space heating, Cooking |
| Coal | Chemical | 24 | Power plants, Electricity generation |
| Ethanol | Chemical | 26.8 | Gasoline mixture, Alcohol, Chemical products |
| Biodiesel | Chemical | 38 [8] | Automotive engine |
| Crude oil | Chemical | 44 | Refinery, Petroleum products |
| Diesel | Chemical | 45 | Diesel engines |
| Gasoline | Chemical | 46 | Gasoline engines |
| Natural gas | Chemical | 55 | Household heating, Electricity generation |
| Hydrogen gas | Chemical | 142 | Petroleum refining and Fertilizer production |
| Uranium-235 | Nuclear | 3,900,000 | Nuclear reactor, Electricity generation |

*"Among primary fuel sources, natural gas has one of the highest energy densities."*

## *Energy Density of Fuel (continued)*

Both natural gas and diesel convert stored energy into thermal energy through the combustion process, which starts a chemical chain reaction between oxygen and the fuel. Carbon dioxide and water are the products of this reaction. The amount of $CO_2$ and water generated is determined by the stoichiometry detailed below. Because natural gas, consisting predominantly of methane, has a higher hydrogen-to-carbon ratio, it generates 11% less $CO_2$ than diesel. When energy density is factored into the equation, the advantages of natural gas become even greater. In the process of generating the same amount of thermal energy, natural gas emits 27.4% less $CO_2$ than diesel due to its higher energy density and lower carbon content.

**Natural Gas Combustion: $CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$ (2.75 kg $CO_2$/kg Natural gas)**

**Diesel Combustion: $C_{13}H_{28} + 20\ O_2 \rightarrow 13\ CO_2 + 14\ H_2O$ (3.10 kg $CO_2$/kg diesel)**

Recently, the North America oil and gas industry has experienced a rapid increase in the use of natural gas as a fuel source for hydraulic fracturing applications. At present, four types of equipment can be partially or totally powered by natural gas: direct mechanical drive natural gas turbines, Tier II & Tier IV dual-fuel, natural gas turbine generators, and natural gas reciprocating engines for electric fracturing fleets. Although each approach has its own technical and economical justifications, natural gas is gaining ground largely due to its ability to reduce greenhouse gas emissions making it an ideal fuel for the energy transition.

$\eta_{th} = \frac{W_{out}}{Q_{in}}$

## 2. Thermal Efficiency

Thermal efficiency contributes greatly to an engine's emissions profile. Thermal efficiency is the percentage of fuel energy converted to useful work out of the engine, typically measured as shaft horsepower. Efficiency of the engine does not include other external power loss or parasitic loads. Thermal efficiency directly affects emissions, the less efficient an engine is, the more fuel needs to be consumed to achieve the required power output. Each engine type has different engine characteristics that affect the thermal efficiency of that engine. Table 3 lists thermal efficiency of different engine types. (Rentar Fuel Catalyst, 2021)

***Table 3: Thermal efficiency of different engine types in fracturing applications***

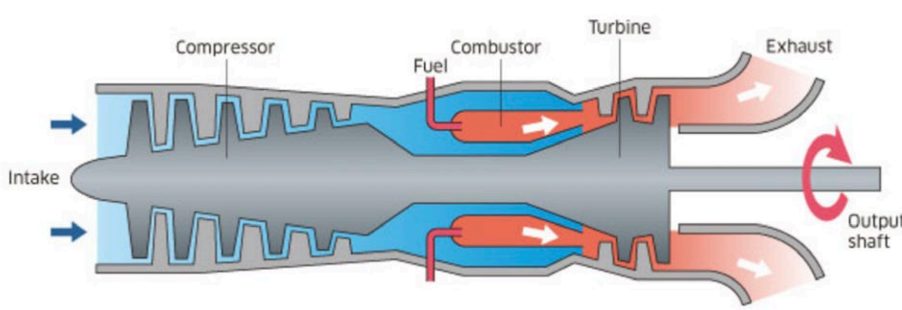
| Engine Description | Engine Thermal Efficiency |
|---|---|
| **TITAN** | 32-34% |
| **Large Natural Gas Turbine** | 32-37% |
| **Natural Gas Reciprocating Generator** | 39-44% |
| **Dual-Fuel Engine** | 35% |

### Natural Gas Turbines (TITAN direct-drive and power generation)

As shown in Figure 3, the basic principle of a gas turbine involves 1) taking air into the compressor, 2) adding natural gas as a continuous fuel into the combustor, 3) the resulting expanded high-pressure, high-temperature gas in the turbine produces power to run the compressor, and 4) output to shaft power to provide mechanical energy to drive pumps, generators, or compressors, etc.

Natural gas turbines operate ideally on the Brayton cycle where thermal efficiency is primarily a function of the compressor pressure ratio and combustion chamber exit temperature within the turbine. The greater the pressure ratio, the greater the power output from the turbine. Increasing this pressure ratio, however, is not easy since it is dependent upon load. Very large gas turbines, which are quite thermally efficient at higher loads, often compete with compression ignition engines (up to 43% efficient). However, at lower loads, their thermal efficiency drops faster than reciprocating engines as pressure ratio decreases. (EPA, 2015)

***Figure 3: Basic principle of gas turbine***
*(Kowasaki, 2021)*



## Thermal Efficiency (continued)

### Diesel Compression Ignition (CI) Engine

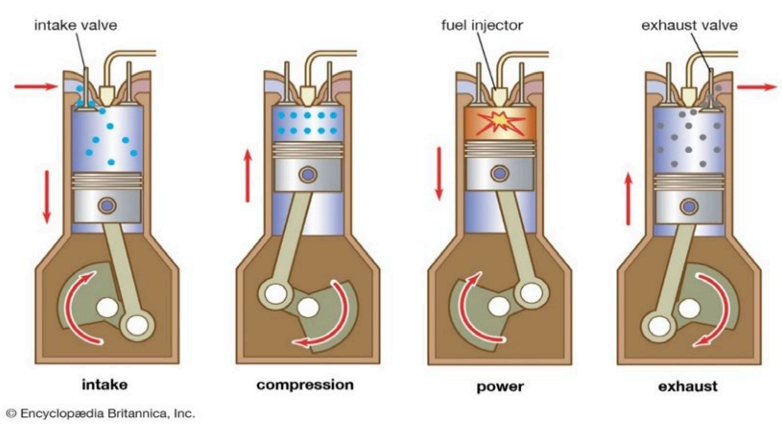
Compression ignition reciprocating engines typically have an advantage over turbines regarding thermal efficiency because they are more flexible in controlling the main parameter affecting the engines' thermal efficiency. Compression ignition engines follow the diesel cycle where thermal efficiency is a function of the compression ratio, which can be increased much more readily. A diesel engine is the highest efficiency simple cycle power generation option on the market. This is due to the high compression ratio that it can achieve.

A diesel engine is an intermittent-combustion, piston-cylinder device. Figure 4 below depicts the operation of a typical four-stroke cycle engine. A diesel engine produces energy by burning fuel that is injected or sprayed into a compressed, hot-air charge within the cylinder. Diesel engines are sometimes called compression-ignition engines because they rely on air heated by compression to auto-ignition temperature of fuel to initiate combustion rather than an electric spark.

### Dual-Fuel Compression Ignition (CI) Engine

A dual-fuel CI engine is an internal combustion engine that uses diesel as a “pilot fuel” to ignite the primary fuel, which is usually natural gas. In dual-fuel CI engines, the primary fuel is mixed more or less homogeneously with the air in the cylinder, as in a spark-ignition engine. Unlike a spark-ignition engine, however, a dual-fuel CI engine uses compression to ignite the air/fuel mixture. A small amount of diesel fuel, or “pilot,” is injected as the piston approaches the top of the compression stroke. The pilot then ignites due to the heat of compression, just as it would in a diesel engine, subsequently igniting the air-fuel mixture in the rest of the cylinder. (SAE International, 2019). As you begin to introduce dual-fuel into the engine, the compression ratio decreases thus decreasing the thermal efficiency.

***Figure 4: Basic principle of diesel engine***
*(Britannica, 2021)*



## Thermal Efficiency (continued)

**Natural Gas Reciprocating Engine**

The essential mechanical components of the Otto-cycle and Diesel-cycle are the same. Both use a cylindrical combustion chamber in which a close-fitting piston travels the length of the cylinder. Natural gas reciprocating engines are nearly identical to diesel compression ignition engines but differ by their combustion method. Natural gas reciprocating engines rely on a spark to ignite the gas in the cylinder.

A natural gas engine can be designed to either be a lean-burning or rich-burning engine, which is determined by the air to fuel ratio in the chamber. Rich-burn engines are operated near the stoichiometric air/fuel ratio, which means the air and fuel quantities are matched for complete combustion, with little or no excess air. Natural gas reciprocating engines typically have a lower efficiency than diesel engines due to the lower compression ratios however large lean-burning engines can exceed diesel engines. The side effect of having a lean-burning engine is that it results in higher NOx emissions. Natural gas engine efficiencies can range from 28% to 46% depending on their size and air to fuel ratio. Lean-burning engines optimized for maximum efficiency typically have double the amount of NOx emissions of a rich-burning natural gas engine. (EPA, 2015)

# 3. Mechanical Energy to Hydraulic Horsepower Efficiency

The conversion of thermal energy to mechanical energy for driving the fluid pumping system, also known as power train efficiency, is another important factor within the emissions profile. An efficient energy transfer mechanism decreases fossil-fuel consumption, thus lowering GHG emissions. When selecting a power-transfer mechanism, one must consider the number of steps required and the parasitic energy losses which occur in each step.

For hydraulic fracturing, the energy required for a pump to deliver fluid downhole is measured as hydraulic horsepower. Transferring energy from an engine or turbine to a pump often requires many mechanical or electrical devices as shown in Table 4. In an electric fleet, an amount of electricity is lost in the process of power generation, conditioning, distribution, and voltage and frequency conversion.

Although the energy loss in each step is small, the compiling of mechanical and electrical efficiency losses in each component can result in substantial combined losses. Due to these losses, diesel, dual-fuel diesel and direct-drive turbines are generally more efficient. The following examines each more closely.

***Table 4: Power transfer mechanism and efficiency* of various pumping platforms***
**Component efficiency based on OEM data sheets and reported values for typical components used in equipment of this application. Actual efficiency may be lower and will vary depending on load and operation.*

| Engine Description | Engine Thermal Efficiency | Engine Type | Power Train<br>% = Component Efficiency | Total Power Efficiency (SHP to HHP) |
|---|---|---|---|---|
| TITAN | 32-34% | Turbine | Gearbox 97%, Power End 95%, Fluid End 95% | 88% |
| Large Natural Gas Turbine | 32-37% | Turbine | Generator 96%, Power Con'ditiong 95%, Power Distribution 99%, VFD 97%, Elec Motor 95%, Power End 95%, Fluid End 95% | 75% |
| Natural Gas Reciprocating Generator | 39-44% | Recip Engine | Generator 96%, Power Con'ditiong 95%, Power Distribution 99%, VFD 97%, Elec Motor 95%, Power End 95%, Fluid End 95% | 75% |
| Dual-Fuel Engine | 35% | Engine | Transmission 90%, Power End 95%, Fluid End 95% | 81% |

## *Mechanical Energy to Hydraulic Horsepower Efficiency (continued)*

**Direct-Drive Turbine**

The most efficient power transfer from mechanical to hydraulic horsepower is the direct-drive turbine. By removing the need for a transmission, the only losses in the system are the heat from a high-efficiency gearbox and the power end/fluid end component.

**Large Turbine Generator and Natural Gas Reciprocating Engine**

Power generation in the form of a generator at the wellsite requires multiple components each with their own losses. Typically, power generation experiences losses from the engine, through the generator, power conditioning, power distribution, variable frequency drive, electric motor, then the traditional power end/fluid end losses. These losses mean that only approximately 75% of the power from the engine, make their way downhole in the form of useful hydraulic horsepower.

**Diesel and Dual-Fuel Engine**

Conventional fracturing pumps utilize transmissions with torque convertors that result in high amounts of losses from the transmission. The transmission alone is typically 95% efficient. Additionally, a torque converter is required to maintain lockup in the transmission, which produces considerable heat rejection, between 5-15% depending on load and RPM. This means that in total, the transmission is between 81% to 90% efficient. A value of 90% was used in the calculations to be conservative and actual losses would be considerably higher. This results in the power transfer efficiency of a conventional diesel engine or dual-fuel engine as approximately 81%.

Additional power transfer losses that are not shown in the table above are parasitic loads. Parasitic loads are loads that are driven by the main engine but are not converted to useful work in the form of hydraulic horsepower. Certain components on each piece of equipment in a fracturing fleet require cooling or lubrication which places this load on the engine. Examples of these loads are oil pumps, cooling pumps for the engine, power end lubrication, radiators, fans, control system and electrical components etc. Although these loads are not considered losses, they reduce the amount of useful hydraulic horsepower that the engine can output thus increasing emissions.

*"The direct-drive turbine has the highest mechanical energy to hydraulic horsepower efficiency."*

## Parasitic Losses

Parasitic losses raise emissions by increasing the engine load when operating or idling. Examples of parasitic losses include radiator fans, hydraulic pumps, oil pumps, greasers, lube pumps, alternators, and any other piece of equipment that puts load on an engine beyond the main component being driven.

### Turbine Engines

Turbine engines typically do not require as much cooling since most of the heat leaves the turbine in the exhaust gas. Due to the high mass flow rates of air in gas turbines, air extraction from the compressor, and cooling within the combustor and turbine keep the turbine cool without the need for external cooling systems. In addition, the turbine’s material components and oil are typically much more resistant to higher operating temperatures, which further reduces the cooling requirements.

### Diesel and Dual-Fuel

Reciprocating engines often carry greater parasitic loads because they need more intensive cooling systems. Traditional hydraulic fracturing pumps powered by reciprocating engines, along with their lubricants, are sensitive to high temperatures, so they have large liquid-to-air cooling radiators. These radiators require a great deal of energy to achieve the required heat rejection, often placing more than 100 HP of parasitic load on the engine.

### Natural Gas Reciprocating Engines and Turbine Generators

In addition to the losses seen in diesel reciprocating engines, parasitic losses are also significant within electric power trains. Electric motors rely on comprehensive cooling systems, since efficiency and maximum power output rapidly decline as temperatures rise.

## 4. Operating Conditions and Equipment Configuration

### Idling

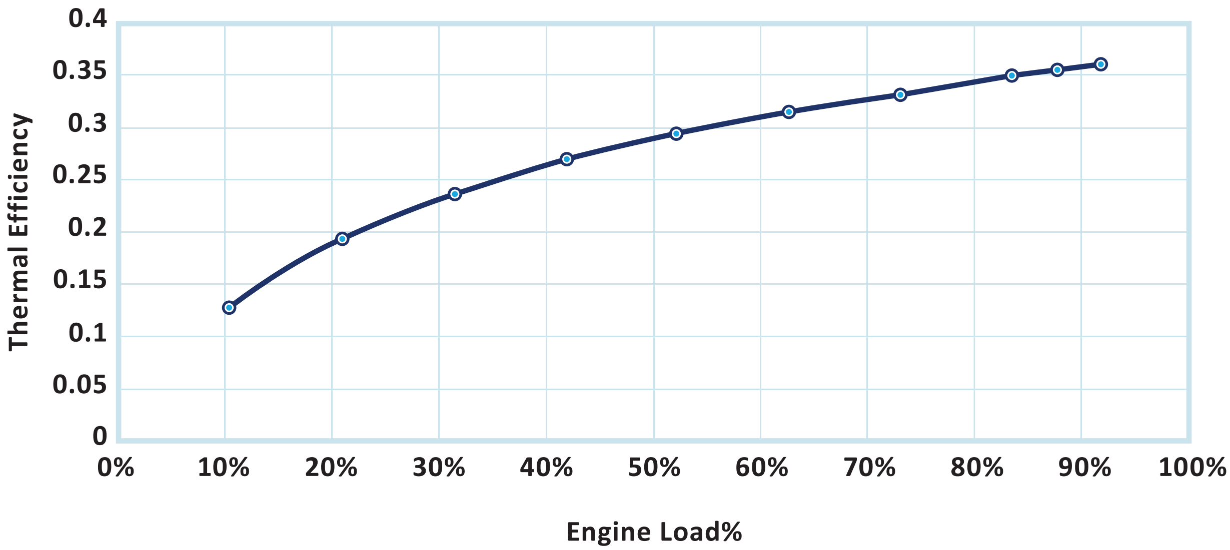
Depending on the fleet type and operating efficiency, idling units can account for 5-15% of total GHG emissions. Currently, diesel or dual-fuel fleets can idle the entire time between stages. Emissions regulatory bodies often use an idle fuel factor to estimate a diesel engine's fuel consumption when idling. This factor is 0.6 liters per hour (L/hr) multiplied by engine displacement volume (Government of Canada, 2021).

### Engine load

All engine technologies operate at their maximum engine fuel efficiency when they are running at near maximum engine load (Figure 5) (McGraw Hill International Editions, 1988). When comparing next-generation fracturing fleets, engine loading is one of the most significant factors affecting the emissions profile. All types of engines perform more efficiently at higher loads, but some have constraints that prevent optimal engine loading (such as engine size, driveline, diesel/natural gas substitution rate). In addition, many next- generation fleets, such as power generation with a large turbine, increase the available power density per unit resulting in less flexibility to optimize distribution of load.

Properly loading large energy output turbines and reciprocating engines can create their own set of challenges. For example, electric fracturing fleets powered by a single large turbine are not as flexible when considering treatment design or operating conditions. If the turbine generator is capable of 34 MW of energy, but the job requirements call for only 20 MW, then the turbine will perform the entirety of the job at 59% of max load. Partial loading on the turbine means it is performing at a lower thermal efficiency which increases fuel consumption and emissions.

***Figure 5: Typical turbine engine efficiency as function of engine load***

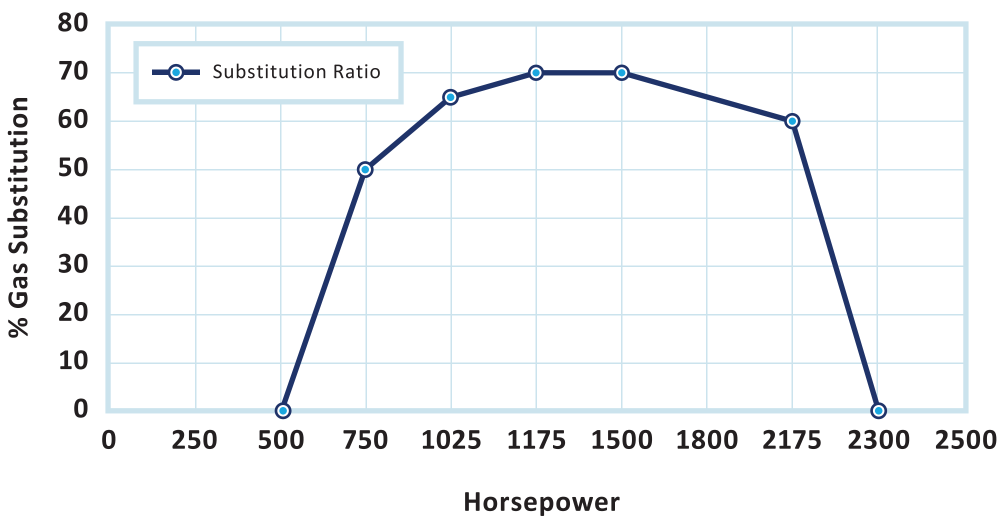


## *Operating Conditions and Equipment Configuration (continued)*

Dual-fuel CI engines also have challenges. Engine loads must be kept lower than those for traditional diesel engines to maintain consistent natural-gas substitution ratios (Figure 6). At both low and high loads, diesel substitution ratios begin to drop off (Yousefi, 2020). Thus, dual-fuel CI engines are restricted: they must operate within a certain range to maintain diesel replacement. Maintaining the necessary load often requires more pumps than usual, which decreases fuel efficiency.

Compared to other options, modulating direct-drive turbines offers greater flexibility to maximize engine load. With a direct-drive natural gas turbine, the number of pumps on location can be adjusted to meet power demand, thus improving fuel efficiency. The power end and fluid end on the unit can also be adjusted based on expected pressures to maximize the engine load.

***Figure 6: Typical gas substitution ratio for dual-fuel engines at varying horsepower loads***



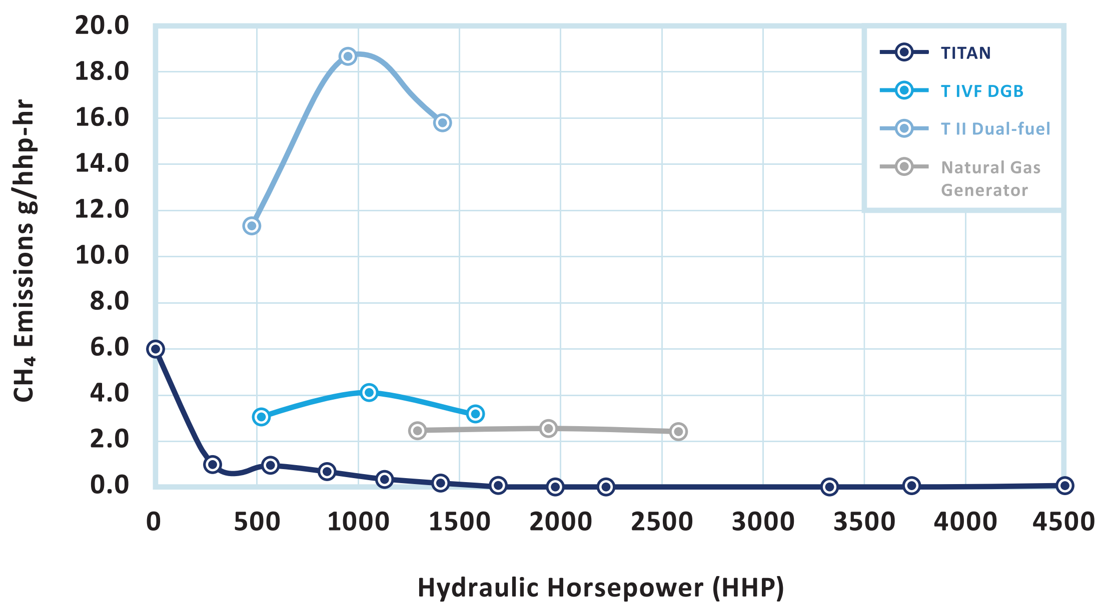
## Methane Emissions

Methane slip is a known challenge of natural gas and dual-fuel reciprocating engines. Methane slip is unburnt or partially burnt natural gas that escapes through an engine. Methane slip occurs in all-natural gas engines to some extent. In natural gas turbines, most of the methane slip occurs at low engine load or at idle. Once the load is increased, methane slip drops to zero or near zero at pumping engine loads. The drop can be attributed to the type of combustion cycle in the turbine. A natural gas turbine burns fuel constantly in the combustion chamber, which prevents methane from escaping unburnt when at load. In contrast, dual-fuel and natural gas reciprocating engines have significant methane slip while at full or partial load. This is due to the cyclical nature of the power stroke of a reciprocating engine. Each valve opening and closing allows some natural gas fuel to escape the cylinder unburnt. Depending on operating conditions, methane slip makes up 10-15% of the total GHG emissions in natural gas reciprocating and dual-fuel engines in the model. However, in actual real-world engines, the methane slip is considerably higher. Manufacturers estimate typical methane slip values to be 5% in a Tier II engine and 1.5-2% in a Tier IVF. However, actual field data on dual-fuel pumps indicates that the values are much higher, in the range of 14-22%. (Johnson, 2018).

*"Methane slip is a known emissions source for any natural gas engine that is more significant in some engines over others."*

Methane slip is so potent that it increases the Tier II and Tier IVF dual-fuel systems emissions profiles dramatically in comparison to their non-dual-fuel counterparts. According to our model, emissions increased by a multiple of 1.2 - 1.4 when switching to dual-fuel for Tier II and by a multiple of 0.95 - 1.05 for Tier IVF. Even these estimates may understate the impact of methane slip. Other research on dual-fuel engines has shown that under actual operating conditions with an engine that has seen years of use, the multiple increases to 1.65 - 2.2. This means that in actual operations, methane slip values are considerably higher than reported by OEMs due to various operating factors. (Johnson, 2017). Figure 7 below highlights the methane emissions from different engines and varying loads.

***Figure 7: Methane emissions from different engines at various horsepower***

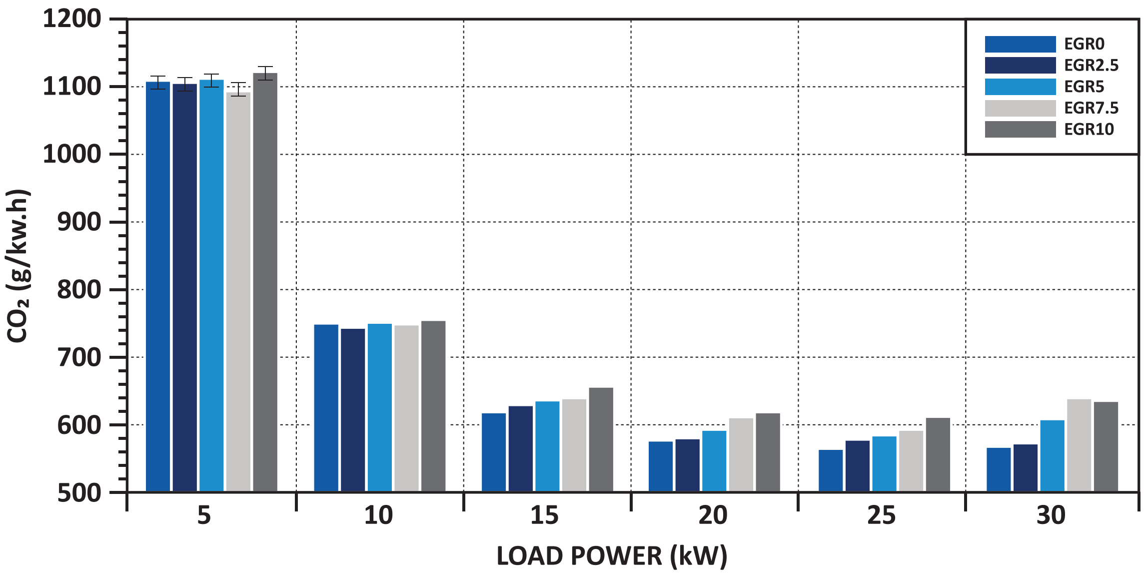


## Tier IV Final Compared to Tier II

A common misconception is that Tier IVF engines release less GHGs than Tier IIs. In reality, Tier IVF engines often have higher emissions due to the technologies used to decrease regulated non-GHGs, such as NOx, CO, and PM. For example, exhaust-gas recirculation (EGR) is commonly recirculated back into the air intake to reduce the combustion temperature, which in turn deters NOx formation.

Since the exhaust gases are mainly nitrogen and inert carbon dioxide, which displaces oxygen, less heat is produced from the same amount of fuel. Although this positively decreases NOx, it negatively increases the amount of fuel consumed to produce the same amount of power. This increase in fuel consumption increases the amount of $CO_2$ emitted. The amount of exhaust gas recirculation was adjusted between 0-10%. At higher EGR percentages, more $CO_2$ was emitted from the engine (See Figure 8).

***Figure 8: $CO_2$ emissions from Tier IV and Tier II engines at various load power***
*(Serio, 2017)*



## Job-Specific Parameters

Reservoir characteristics in different shale basins vary significantly, thus affecting pumping rate and pressures. Environmental factors such as temperature and atmosphere pressure also play a role, since they can negatively impact the performance of certain types of engines such as natural gas turbines. All of these factors must be taken into consideration in assessing the emissions profile of an engine.

In turbine engines, the mass of exhaust gas exerting mechanical force on the turbine blades generates the output power, thus air density significantly impacts turbine engines. The two biggest factors in air density is a function of ambient temperature and altitude. At higher altitudes and ambient temperatures, turbine engines require more fuel to achieve the same horsepower. This impact is relatively linear and basically follows the relationship illustrated in Table 5. The average temperature over the entire year is typically used to estimate a turbine's fuel efficiency in a specific location. Natural gas and reciprocating engines do also face derating power loss, but at much higher altitudes and temperatures typically seen in basins.

***Table 5: Impact of environmental conditions on turbine power loss per turbine manufacturer provided data***

| | Factor | 1% Power loss equals |
|---|---|---|
| 1 | Ambient Temperature | 2˚F (1˚C) Inlet temperature rise |
| 2 | Altitude | 300ft in altitude |
| 3 | Duct Losses | 2.5inch (6cm) $H_2O$ inlet pressure loss<br>6inch (15cm) $H_2O$ exhaust pressure loss |

# Emissions Reporting Practices

Reporting $CO_2e$ in grams per kilowatt hour (g/kw-hr) is perhaps the most common way to report emissions. Although this value does provide a good estimate of the emissions released while pumping, it does not provide a clear picture of total emissions released in an operating day. Daily activities beyond pumping often include swapping wells, priming pumps, pressure testing, idling, and more—all of which contribute to total emissions on a hydraulic fracturing job.

Reporting specific emissions in grams per brake horsepower hour (g/bhp-hr) is another common practice. This method can also heavily skew the results since it does not represent the emissions from a specific amount of hydraulic horsepower required for the fracturing operation.

A more complete picture of emissions can be obtained by reporting total mass of emissions per hydraulic horsepower in a set period of a duty cycle.

# Methodology for Comparing Technologies

There are many factors that affect emissions from a hydraulic fracturing fleet, and they all must be considered in order to ensure an even comparison across the board. BJ Energy developed a methodology for evaluating existing and next-generation hydraulic fracturing technologies in the following manner to ensure a transparent, unbiased and factual comparison.

*"BJ Energy developed a methodology for evaluating existing and next-generation hydraulic fracturing technologies."*

First, a model was developed for calculating the expected emissions released by the main types of hydraulic fracturing technologies used today. This model creates an emissions profile for each technology by considering the amount of fuel consumed, adjusted by the many engine characteristics and operating factors that come into play during a full operating cycle.

Next, comprehensive certified third-party emissions testing was completed on the TITAN direct-drive natural gas turbine under actual operating conditions, following U.S. EPA methods. This testing also factored many engine characteristics and operating conditions that come into play during a full operating cycle.

Lastly, the emissions-testing data was then compared to other hydraulic fracturing technologies in a comprehensive model to generate emissions profiles for each system during a day of operation. Factors within the operating cycle, such as engine idle time, pumping time, pumping pressures and rates, were based on historical data within the various basins of operation.

Historical data was also used for average temperature, barometric pressure and altitude.

# Emissions Calculator Model

The methodology and results presented in this section are detailed in a peer-reviewed technical journal paper in preparation. In the interest of transparency, each component of the model is detailed below. The model begins with the required hydraulic horsepower and arrives at emissions per day through the following process.

1. Modeling Parameters: Converting brake horsepower to hydraulic horsepower
2. Fuel Consumption: Calculating fuel consumption based on engine load at various operating conditions
3. Emissions from Combustion: Computing $CO_2e$ emissions based on fuel consumption
4. Emissions from Engine Characteristics: Adapt $CO_2e$ emissions based on engine characteristics
5. Operating Conditions: Using calculated values to arrive at the expected emissions per day of an operating cycle

Original Equipment Manufacturer (OEM) engine data was used to estimate the required number of units, engine load, and fuel consumption for other hydraulic fracturing technologies. However, 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 take into account any engine performance degradation over time. OEM data uses nominal values with a total tolerance of +/- 2.5%. For the model, equipment was assumed to be new with no degradation to OEM values based on equipment age.

*"For the model inputs, all reciprocating engines were assumed to be new with no degradation to OEM values based on equipment age."*

# Engine Modeling Parameters

Although the BJ's TITAN emissions profile is based on actual operational data, the profiles of other technologies were calculated using the following assumptions, which were based upon widely used values, industry standards, or OEM data. In the interest of transparency, the modeling parameters are detailed below.

## Dual-Fuel Engine

| Engine Description | Engine Size (kW) | Engine Thermal Efficiency | Engine Type | Power Train (% = Component Efficiency) | Total Power Efficiency (SHP to HHP) | Parasitic Loses per Pump | Total Efficiency (Heat input HP to HHP) |
|---|---|---|---|---|---|---|---|
| Dual-Fuel Engine | 1864 kW | 35% | Engine | Transmission 90%; Power End 95%; Fluid End 95% | 81% | Deck Engine Load | 28% |

- Based fuel consumption on OEM data, which is best-case and will increase with longer engine life.
- Estimated BHP to HHP efficiency for a conventional pump to be 84% (i.e., 98% PE, 90% Transmission, and 95% PE), along with 130 HP of parasitic loads from radiators, lube pumps, alternators, and other auxiliary equipment.
- Calculated fuel consumption during idle using 0.6 l/hr*engine displacement.
- This was also done for dual-fuel systems using OEM dual-fuel data. The substitution ratio was estimated based on best-case scenarios under expected loads.
- Comparison included two different industry-leading engine manufacturers for both Tier II and Tier IV engines.

## Natural Gas Reciprocating Engine

| Engine Description | Engine Size (kW) | Engine Thermal Efficiency | Engine Type | Power Train (% = Component Efficiency) | Total Power Efficiency (SHP to HHP) | Parasitic Loses per Pump | Total Efficiency (Heat input HP to HHP) |
|---|---|---|---|---|---|---|---|
| Natural Gas Reciprocating Generator | 2,500 kW | 39-44% | Recip Engine | Generator 96%; Power Con'ditiong 95%; Power Distribution 99%; VFD 97%; Elec Motor 95%; Power End 95%; Fluid End 95% | 75% | 130 | 31% |

- Based fuel consumption 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 75% (i.e., 95% PE, 95% FE, 95% Electric Motor, 97% VFD, 99% Power Distribution, 95% Power Conditioning, and 96% Generator), along with a highly conservative estimate of 130 HP of parasitic loads from radiators, lube pumps, alternators, cooling systems and other auxiliary equipment. (These loads can be as a high 180HP.)
- Acknowledged that gas generators would run periodically between stages at a partial load to maintain power supply. Estimated idle time by assuming generators would run for five minutes after each stage and 10 minutes before to allow for proper cooldown, start up, pressure testing, and priming pumps. In actual operation, this time may be considerably longer. Estimated partial load to be 25% of maximum load based on fluctuating horsepower demand between stages.
- Based on these collective assumptions, the reciprocating engine was assumed to run 15 minutes between stages at 25% engine load to complete pressure test, priming and other operating functions.

## Large Natural Gas Turbine (>24MW)

| Engine Description | Engine Size (kW) | Engine Thermal Efficiency | Engine Type | Power Train (% = Component Efficiency) | | | | | | | Total Power Efficiency (SHP to HHP) | Parasitic Loses per Pump | Total Efficiency (Heat input HP to HHP) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Generator | Power Con'ditiong | Power Distribution | VFD | Elec Motor | Power End | Fluid End | | | |
| Large Natural Gas Turbine | 31,000 kW | 35% | Turbine | 96% | 95% | 99% | 97% | 95% | 95% | 95% | 75% | 130 | 25-30% |

- 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 3% load, producing $CO_2$e emissions at idle of approximately 2.5 MT/hr. This is a conservative estimate as emissions during idle can be considerably higher due to methane slip.
- Fuel consumption is based on OEM data, which is best-case and will increase with longer engine life.
- Estimated BHP to HHP efficiency for large natural gas turbine to be 75% (i.e., 95% PE, 95% FE, 95% Electric Motor, 97% VFD, 99% Power Distribution, 95% Power Conditioning, and 96% Generator), along with a highly conservative estimate of 130 HP of parasitic loads from radiators, lube pumps, alternators, cooling systems and other auxiliary equipment. (These loads can be as a high 180HP.)
- Large turbines are not shutdown (and must idle) between stages.

## TITAN Modeling Parameters.

### Direct-Drive Natural Gas Turbine (4.2MW)

- 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.
- Third party emissions 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.
- The total TITAN emissions include the TITAN Pump deck engine running for the entire duration of the stage pump time, as well as 10 minutes prior to (start-up) and 5 minutes post stage (cooldown). This makes up 6% of the total daily diesel consumption.
- Turbine idle time is approximately 10 mins before and 5 mins after each stage to account for cooldown, start up, and priming pumps.
- Temperature and atmosphere pressure are based on the individual Basin historical averages.

# TITAN Emissions Testing Protocol

To validate and confirm the emissions profile of the BJ Energy Solutions TITAN Technology, a comprehensive, scientific emissions testing protocol was followed. All emissions testing on the TITAN was performed using U.S. EPA methods (Table 6) described in the Code of Federal Regulations. 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 measure TITAN fuel consumption, natural gas samples were taken and sent to certified laboratories. The samples were then used to calibrate an orifice-type flow meter that meets or exceeds EPA requirements (Method 19) 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 NOx, CO, $CH_4$, $N_2O$, PM, and $CO_2$ from the unit's exhaust. The TITAN utilizes a diesel deck engine to start up and maintain auxiliary systems. The fuel consumption of the diesel engine was included in all emissions profiles. This deck engine allows the TITAN turbine to be shut down between stages with minimal idling time. The calculations considered 10 minutes of idling time for starting up and priming the pumps, and five minutes for turbine cooldown. These values were based on historical data from field operations.

*Table 6: Summary of 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) |
| NOx, THC, $CH_4$, $N_20$, $CO_2$, $H_20$ | EPA Method 320 | Fourier Transform Infrared |

## *TITAN Emissions Testing Protocol (continued)*

In April 2021, BJ Energy Solutions engaged Air Hygiene, a certified third-party emission testing company, to complete the testing program in Granbury, Texas. A commercial TITAN unit was taken directly from the operations without any maintenance and modifications being conducted. Below is the overview of the testing program.

| | |
|---|---|
| **Participating Organizations** | BJ Energy Solutions, LLC<br>Air Hygiene |
| **Location** | Granbury, Texas |
| **Testing Commencement Date** | April 10th, 2021 |
| **Emission Parameters Measured** | NOx, CO, THC, $N_2O$, $CH_4$, PM, $H_2O$, $CO_2$, $O_2$ |
| **Equipment Tested** | Direct Drive Turbine Frac Pumper (TF50F w DLE) |
| **Sampling Location** | • From exhaust of Direct Drive Turbine Frac Pumper<br>• For all gases, three sample points in the exhaust stack from the Frac Pump Turbine, at 16.7, 50.0, and 83.3 percent of the diameter<br>• For all PM testing, 8 sampling points in the exhaust stack from the Frac Pump Turbine |
| **Federal and State Certifications** | • "Stack Testing Accreditation Council AETB Certificate No. 3796.02"<br>• "International Standard ISO/IEC 17025:2005 Certificate No. 3796.01"<br>• "Texas NELAP Accreditation No. T104704523; Mobile Lab No. 1M10470452" |

To capture the emissions profile and turbine efficiency under various load conditions, the TITAN direct drive unit was run at four different shaft horsepower settings. The results are summarized in Table 7 below.

***Table 7: TITAN emission testing results***

| Parameter | Run NG-1 | Run NG-2 | Run NG-3 | Run NG-4 |
|---|---|---|---|---|
| Load Designator | NG-Idle | NG-8000 | NG-12000 | NG-13250 |
| Stack Flow (RM19) (SCFH) | 465,338 | 987.594 | 1,049.396 | 1,141.426 |
| Shaft Horsepower (SHP) | 300.0 | 2,488.0 | 3,725.9 | 4,179.1 |
| Hydraulic Horsepower (HHP) | 268.0 | 2,223.0 | 3,329.0 | 3,733.0 |
| Shaft Power (skW) | 223.7 | 1,855.4 | 2,778.5 | 3,115.6 |
| NOx (ppmvd) | 12.23 | 36.84 | 55.49 | 60.40 |
| NOx (ppm@15%$O_2$) | 31.20 | 47.84 | 61.14 | 63.57 |
| NOx (g/shp*hr) | 1.03 | 0.79 | 0.85 | 0.89 |
| NOx (g/hhp*hr) | 1.15 | 0.89 | 0.95 | 1.00 |
| NOx (g/skW*hr) | 1.38 | 1.06 | 1.14 | 1.20 |
| CO (ppmvd) | 531.75 | 20.27 | 7.58 | 9.36 |
| CO (ppm@15%$O_2$) | 1,356.48 | 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 |
| 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) | 1,247 | 535 | 444 | 449 |
| $CO_2$ (g/hhp•hr) | 1,396 | 599 | 497 | 503 |
| $CO_2$ (g/skW•hr) | 1,672 | 718 | 596 | 603 |

*“Emissions tests were completed on a commercial TITAN pump, taken directly from the field to the testing site with no modifications made to the unit, other than adding the EPA compliant exhaust stack to achieve accurate measurement.”*

# Calculating Emissions from Combustion

Based on the fuel consumption of each technology, the model calculated greenhouse gas emissions using EPA methodology, specifically 40 Code of Federal Regulation Part 98 Subpart W: Mandatory Greenhouse Gas Reporting for natural gas and petroleum systems. The calculation method is outlined specifically in 40 CFR 98.233 paragraph Z (Cornell Law School, 2021).

This methodology multiplies the amount of fuel consumed by the high heat value (HHV) of the fuel. It then multiplies this value by the fuel-specific emissions factor for a particular greenhouse gas. The high heat value was normalized to 1,004 HHV for natural gas within the model, since this is the value that engine manufacturers use to conduct their engine tests. This value was also used to conduct the TITAN emissions testing.

$$CO_2 = 1\text{x}10^{-3} * \textit{Volume of Fuel} * \textit{HHV} * \textit{EF} \quad \text{(Eq. C-1)}$$

where:

$CO_2$ = Annual $CO_2$ mass emissions for the specific fuel type (metric tons).

Fuel = Mass or volume of fuel combusted per year, from company records as defined in § 98.6 (express mass in short tons for solid fuel, volume in standard cubic feet for gaseous fuel, and volume in gallons for liquid fuel).

HHV = Default high heat value of the fuel, from Table C-1 of this subpart (mmBtu per mass or mmBtu per volume, as applicable).

EF = Fuel-specific default $CO_2$ emission factor, from Table C-1 of this subpart (kg $CO_2$/mmBtu).

$1 \times 10^{-3}$ = Conversion factor from kilograms to metric tons.

The values used in Table C-1 (Cornell Law School, 2021) in the emissions calculation are defined in Table 8. These values are specified and defined by the EPA. The first three columns are the fuel-specific emissions factors for $CO_2$, $N_2O$ and $CH_4$. The last column is the high heat value of fuel.

***Table 8: Fuel Values for natural gas and diesel***

| EPA Default Values | | | | |
|---|---|---|---|---|
| **Natural Gas** | **EF $CO_2$ kg/mmBTU**<br>53.06 | **EF $N_2O$kg/mmBTU**<br>0.0001 | **EF $CH_4$ kg/mmBTU**<br>0.001 | **HHV BTU/scf**<br>**1,004** |
| **Diesel** | **EF $CO_2$ kg/mmBTU**<br>73.96 | **EF $N_2O$kg/mmBTU**<br>0.0006 | **EF $CH_4$ kg/mmBTU**<br>0.003 | **HHV BTU/gal**<br>**0.138** |

These values were then multiplied by their global warming potential. The $CO_2e$ emissions for the day would then be the sum of mass for each emission multiplied by the global warming potential.

# Emissions Due to Engine Characteristics

The major shortcoming of the EPA method of calculating emissions is that it does not consider engine characteristics. It does not take into account the age of the engine, air-to-fuel ratio, and most importantly methane emissions, including methane slip and potential fugitive crank case emissions. With natural gas and dual-fuel engines, crank case emissions would also be present. Crankcase emissions are methane that escapes the engines through the lubrication or crankcase ventilation system. These emissions are substantial--however, they are engine dependent and not easily estimated. Crankcase emissions are not present in turbine engines due to the lack of crank cases. The EPA method is particularly inaccurate when calculating the methane emissions from large, natural gas engines, since it does not consider the decrease in engine performance at lower loads. This drop in engine performance leads to greater amounts of harmful pollutants and emissions. Thus, it is not valid to assume that the same amount of emissions will be released for each unit of fuel consumed. The type and amount of emissions released is heavily dependent on factors such as engine load, fuel-to-air ratio, engine condition, and combustion temperature. Accordingly, our model takes these factors into account by using OEM-measured emissions and fuel-consumption data.

## Operating Conditions

Our model creates a specific operating profile for each type of technology based on regional historical data for operating rates and pressures as well as yearly average historical temperatures and altitudes for each basin. This profile is used to estimate total emissions per day for a hydraulic fracturing fleet across a full operating cycle, including pumping, engine idling, pressure testing, and priming pumps. Treatment parameters for each basin are listed in Table 9.

***Table 9: Emissions model case parameters***

| Case | Basin | Pumping Hours | Rate | Pressure | Stage Length Hours |
|---|---|---|---|---|---|
| **1** | Haynesville | 17 | 80 BPM | 12,000 PSI | 3 |
| **2** | Permian | 17 | 120 BPM | 9,000 PSI | 3 |
| **3** | Haynesville Simulfrac | 17 | 160 BPM | 12,000 PSI | 3 |
| **4** | Permian Simulfrac | 17 | 240 BPM | 9,000 PSI | 3 |
| **5** | Montney/Duvernay | 17 | 110 BPM | 12,000 PSI | 3 |

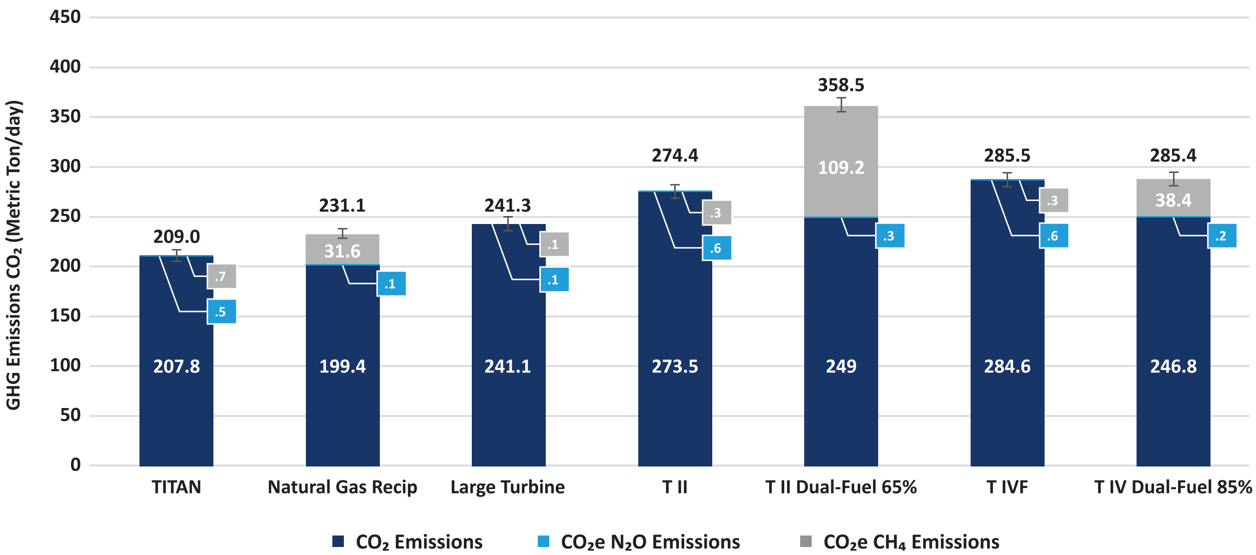
***"Natural gas turbine engines are derated when operating in high ambient temperature environments or at higher altitudes such as the Permian; however the analysis demonstrates that the selected turbine for the TITAN still outperforms other low emission alternatives."***

# Emissions Model Results

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

*Note: $N_2O$ does not appear in the figures as it is significantly smaller than $CO_2$ and $CH_4$ Emissions.*

***Figure 9: $CO_2e$ emissions for different frac fleets in Haynesville***




For the job scenario case 1 described above, the TITAN offers a 10%-42% $CO_2e$ emissions reduction compared to current and next gen technologies. While the natural gas reciprocating engine had lower $CO_2$ emissions than the TITAN in this scenario, it emitted 50 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 total emissions reduction of the TITAN under this scenario is outlined in Table 10.

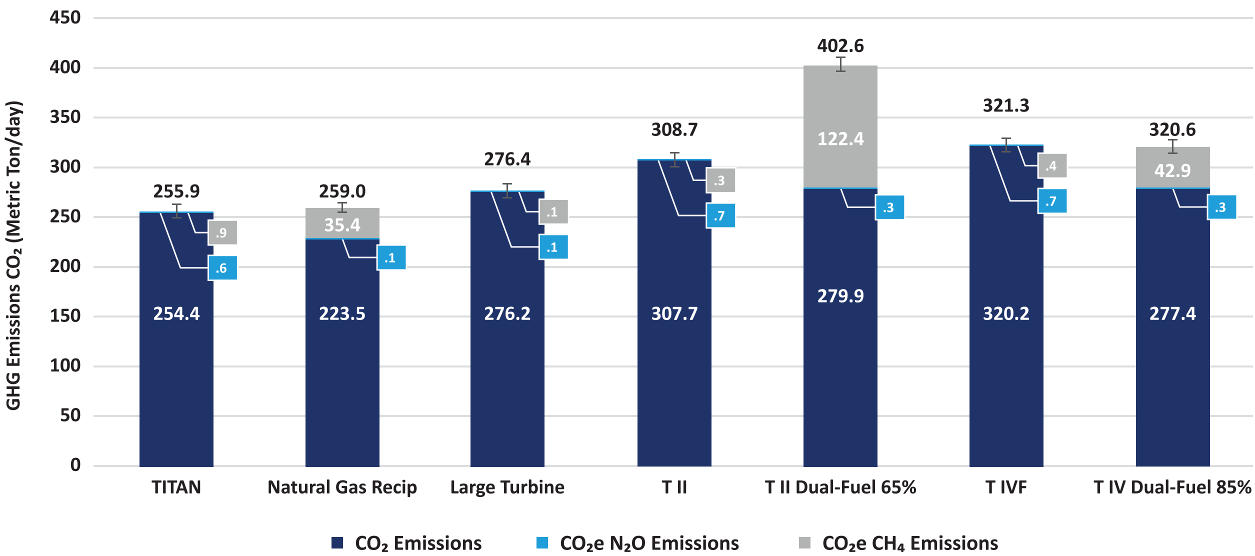
***Table 10: Emissions Compared to TITAN in Haynesville***

| | $CO_2e$ (Metric Ton/Day) | % Reduction of TITAN compared to other engine systems | Annual $CO_2e$ reduction of TITAN compared to other engine systems (Metric Ton/Yr)* |
|---|---|---|---|
| TITAN | 209.0 | | |
| Natural Gas Recip | 231.1 | 10% | 6,914 |
| Large Turbine | 241.3 | 13% | 10,098 |
| Tier II | 274.4 | 24% | 20,409 |
| Tier II Dual-Fuel 65% | 358.5 | 42% | 46,639 |
| Tier IVF | 285.5 | 27% | 23,880 |
| Tier IV Dual-Fuel 85% | 285.4 | 27% | 23,834 |

**Annual $CO_2e$ increase based on 26 operating days per month*

## Case 2: Permian - 17 pumping hours, 120 BPM and 9,000 psi

*Figure 10: $CO_2e$ emissions for different frac fleets in the Permian*




In this scenario, the difference between the TITAN and other solutions tightens to an emissions reduction of 1%-36% $CO_2e$. In this scenario the natural gas recip and the TITAN are within a margin of uncertainty and therefore it cannot be concluded which has lower $CO_2e$ emissions. The TITAN's fuel efficiency decreases due to the higher temperatures and higher altitude within the Permian, along with lower loads being placed on the turbine. TITAN still outperforms the other technologies in emissions reductions as detailed in Table 11.

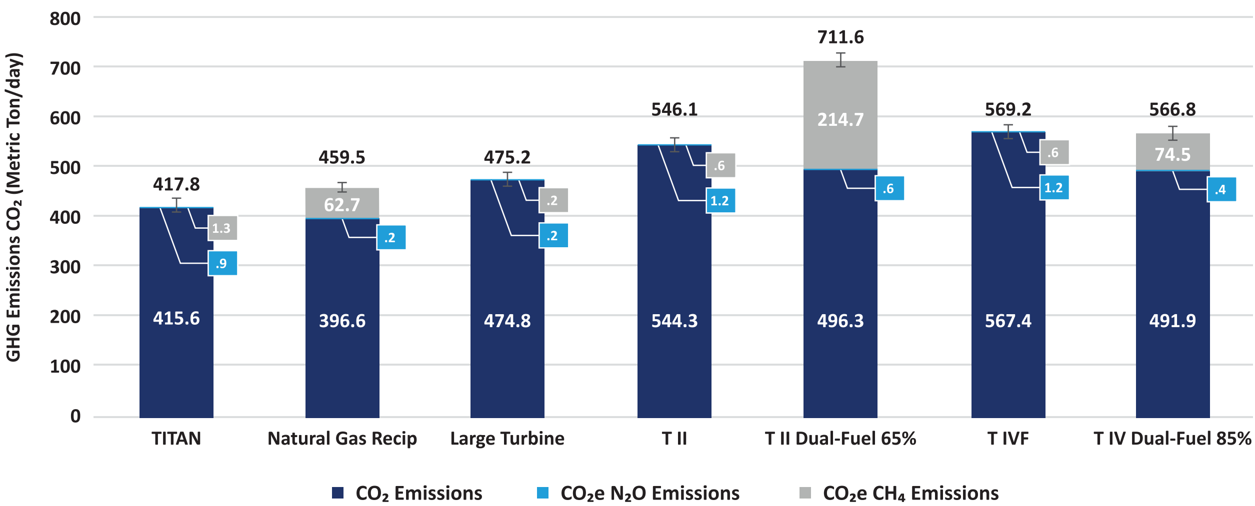
*Table 11: Emissions Compared to TITAN in the Permian*

| | $CO_2e$ (Metric Ton/Day) | % Reduction of TITAN compared to other engine systems | Annual $CO_2e$ reduction of TITAN compared to other engine systems (Metric Ton/Yr)* |
|---|---|---|---|
| TITAN | 255.9 | | |
| Natural Gas Recip | 259.0 | 1% | 960 |
| Large Turbine | 276.4 | 7% | 6,394 |
| Tier II | 308.7 | 17% | 16,462 |
| Tier II Dual-Fuel 65% | 402.6 | 36% | 45,766 |
| Tier IVF | 321.3 | 20% | 20,367 |
| Tier IV Dual-Fuel 85% | 320.6 | 20% | 20,163 |

**Annual $CO_2e$ increase based on 26 operating days per month*

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

***Figure 11: $CO_2$e Emissions Simulfrac operations in Haynesville***




In this scenario, the TITAN performs better than all other technologies between 9%-41% (Table 12) for $CO_2$e emissions. Of note, the emissions from the large natural gas turbine increase dramatically in this scenario because the hydraulic horsepower requirement is greater than the power that a single turbine can provide. This means that a second turbine is needed and the two will operate with lower thermal efficiency. Dense power production from a single, large turbine often does not give the operator sufficient flexibility to make adjustments to the available power on location, which decreases the engine's thermal efficiency in some scenarios.

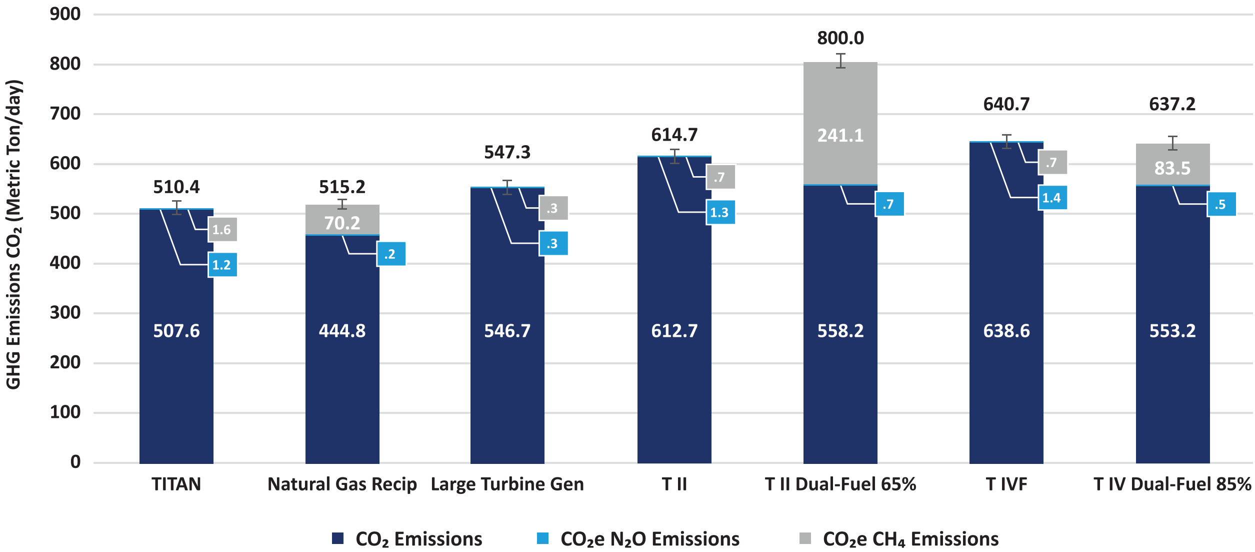
***Table 12: Emissions Compared to TITAN for Simulfrac in Haynesville***

| | $CO_2$e (Metric Ton/Day) | % Reduction of TITAN compared to other engine systems | Annual $CO_2$e reduction of TITAN compared to other engine systems (Metric Ton/Yr)* |
|---|---|---|---|
| TITAN | 417.8 | | |
| Natural Gas Recip | 459.5 | 9% | 12,974 |
| Large Turbine | 475.2 | 12% | 17,864 |
| Tier II | 546.1 | 23% | 39,978 |
| Tier II Dual-Fuel 65% | 711.6 | 41% | 91,626 |
| Tier IVF | 569.2 | 27% | 47,196 |
| Tier IV Dual-Fuel 85% | 566.8 | 26% | 46,439 |

**Annual $CO_2$e increase based on 26 operating days per month*

# Case 4: Permian Simulfrac - 17 pumping hours, 240 BPM and 9,000 psi

*Figure 12: $CO_2$e Emissions for Simulfrac operations in the Permian*




In this scenario, the TITAN performs better than all other technologies between 1%-36% reduction. However, the natural gas reciprocating engine is within the model uncertainty and therefore cannot be concluded as having higher or lower $CO_2$e emissions than the TITAN in this scenario (Table 13).

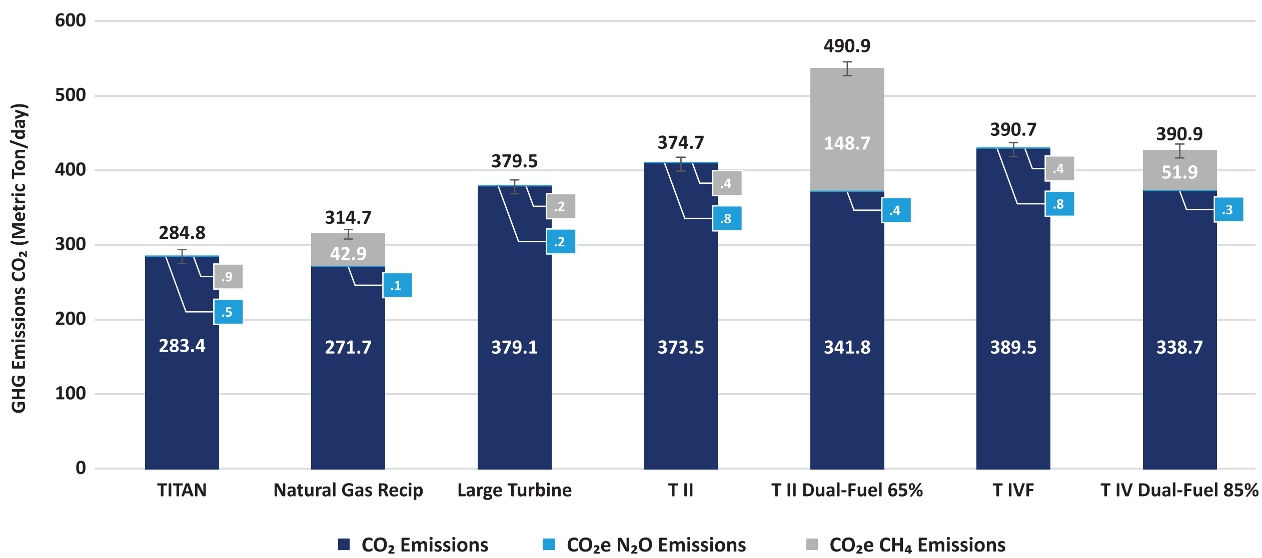
*Table 13: Emissions Compared to TITAN for Simulfrac in the Permian*

| | $CO_2$e (Metric Ton/Day) | % Reduction of TITAN compared to other engine systems | Annual $CO_2$e reduction of TITAN compared to other engine systems (Metric Ton/Yr)* |
|---|---|---|---|
| TITAN | 510.4 | | |
| Natural Gas Recip | 515.2 | 1% | 1,527 |
| Large Turbine | 547.3 | 7% | 11,509 |
| Tier II | 614.7 | 17% | 32,542 |
| Tier II Dual-Fuel 65% | 800.0 | 36% | 90,340 |
| Tier IVF | 640.7 | 20% | 40,636 |
| Tier IV Dual-Fuel 85% | 637.2 | 20% | 39,558 |

**Annual $CO_2$e increase based on 26 operating days per month*

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

***Figure 13: $CO_2$e Emissions for different fleets in Montney/Duvernay***




For the job scenario described above, the TITAN offers 10%-42% $CO_2$e (Table 14) emissions reduction compared to current and next-generation technologies. Although this basin is located at high altitude, the low average ambient temperature present in this Basin has a greater influence on the turbine power efficiency.

***Table 14: Emissions Compared to TITAN in Montney/Duvernay***

| | $CO_2$e (Metric Ton/Day) | % Reduction of TITAN compared to other engine systems | Annual $CO_2$e reduction of TITAN compared to other engine systems (Metric Ton/Yr)* |
|---|---|---|---|
| TITAN | 284.8 | | |
| Natural Gas Recip | 314.7 | 10% | 9,348 |
| Large Turbine | 379.5 | 25% | 29,543 |
| Tier II | 374.7 | 24% | 28,050 |
| Tier II Dual-Fuel 65% | 490.9 | 42% | 64,320 |
| Tier IVF | 390.7 | 27% | 33,077 |
| Tier IV Dual-Fuel 85% | 390.9 | 27% | 33,120 |

**Annual $CO_2$e increase based on 26 operating days per month*

## Basin Conditions

Despite the negative impacts of higher temperatures and altitudes, the TITAN still performs better than other technologies in all basins under the same operating parameters. As shown in Figure 14 below, the TITAN offers best-in-market $CO_2e$ emissions regardless of basin. Table 15 shows TITAN performance in the four selected basins. While the changes in altitude and average temperature affect the total GHG emissions of the TITAN, its performance is still better than the other technologies. The average reduction in emission ranges from 7.9% to 39.8%.

***Figure 14: Impact of different basin environment on TITAN and other engine's $CO_2e$ emissions***

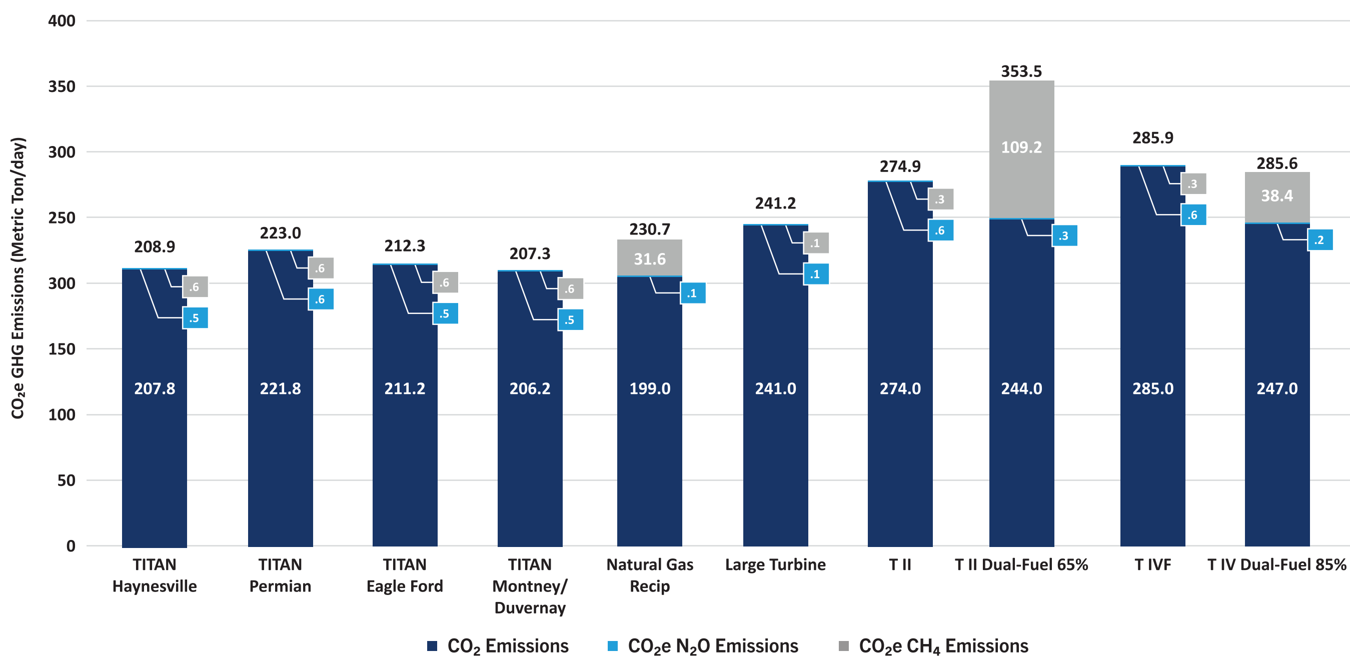



***Table 15: Emissions Compared to TITAN in four different basins***

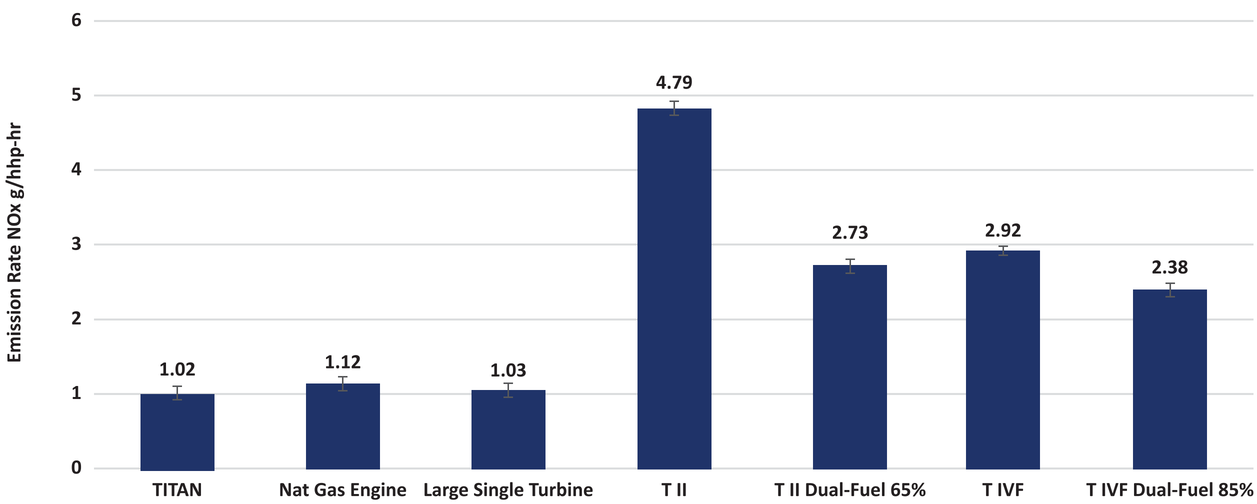
| $CO_2e$ Emissions (MT/Day) | TITAN Haynesville | TITAN Permian | TITAN Eagle Ford | TITAN Montney/Duvernay | Average Reduction |
|---|---|---|---|---|---|
| | 208.9 | 223.0 | 212.3 | 207.3 | |
| Greenhouse Gas Emissions Redution % | | | | | |
| Natural Gas Recip | 9.6% | 3.6% | 8.1% | 10.3% | 7.9% |
| Large Turbine | 13.5% | 7.6% | 12.0% | 14.1% | 11.8% |
| Tier II | 23.9% | 18.8% | 22.6% | 24.5% | 22.4% |
| Tier II Dual-Fuel | 41.7% | 37.8% | 40.8% | 42.2% | 40.6% |
| Tier IVF | 26.8% | 21.9% | 25.6% | 27.4% | 25.5% |
| Tier IV Dual-Fuel | 26.8% | 21.9% | 25.6% | 27.4% | 25.4% |

## Model Results of Emissions Regulated by EPA

Natural gas engines offer considerable improvement in NOx emissions over diesel engines due to the lower combustion temperature where NOx formation is less common. As shown in Figure 15, natural gas turbine engines offer approximately a 9% improvement (1.12 vs 1.02 g/hhp-hr) over natural gas reciprocating engines.

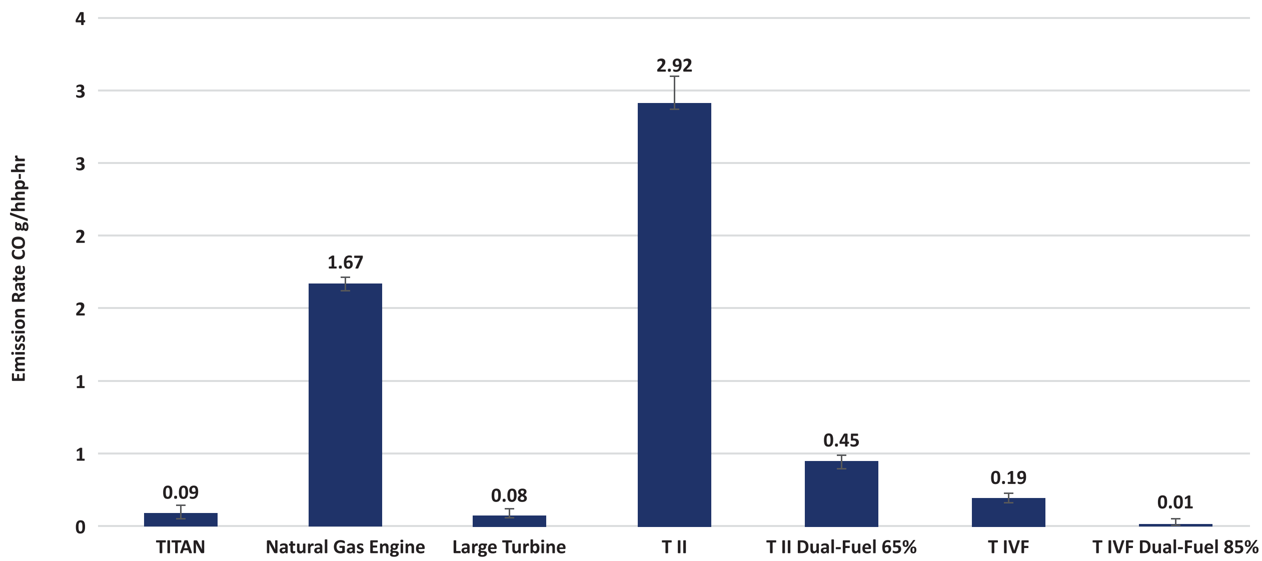
Today, modern gas turbines normally deploy Dry Low Emission (DLE) technology to reduce NOx emissions from the exhaust. The amount of NOx produced is temperature-dependent, with lower combustion temperatures producing less NOx. The traditional method of reducing NOx is Wet Low Emission (WLE) technology, where water or steam is used to cool the combustion chamber. This method makes combustion less efficient and increases fuel consumption. Also, WLE requires large amounts of clean water. Gas turbines with DLE combustors were developed to reduce NOx emissions without these undesirable side effects.

*Figure 15: NOx emissions from different engines*



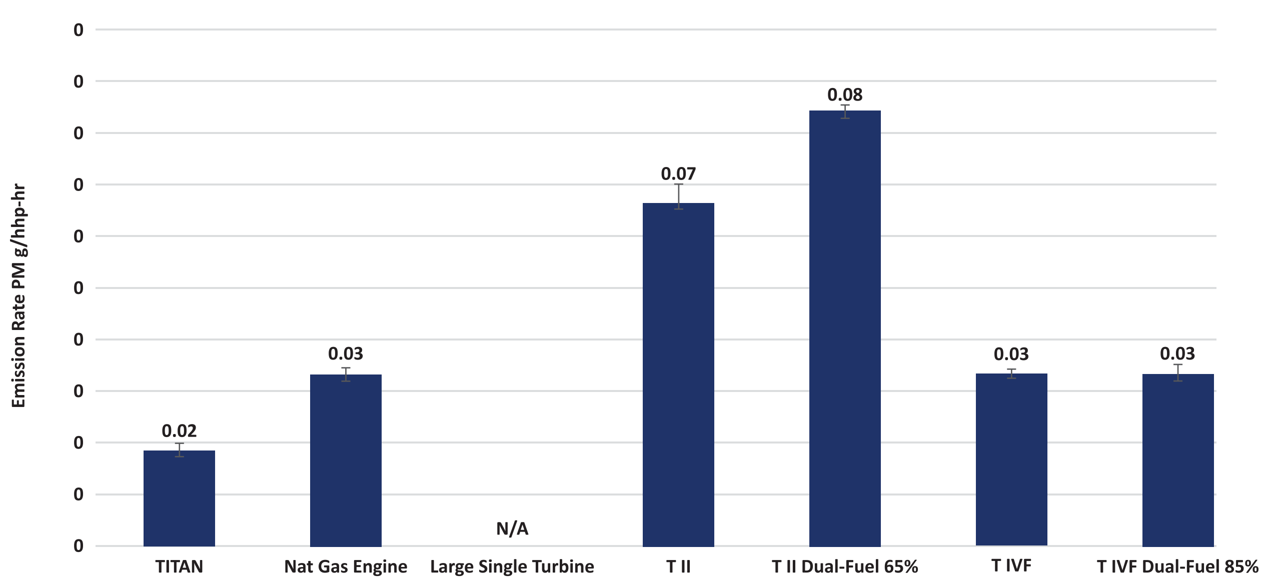
Carbon monoxide emissions are dependent on maintaining a proper air-to-fuel mixture ratio to ensure complete combustion. TITAN carbon monoxide emissions are well below the T IVF (due to exhaust gas recirculation) and offer lower CO emissions than natural gas engines (see Figure 16).

***Figure 16: CO emissions from different engines***




Particulate matter emissions from the TITAN offers market-best performance as shown in Figure 17 below.

***Figure 17: Particulate matter emissions from different engines***




***"TITAN has the lowest EPA regulated emissions."***

## Other Considerations Impacting Emissions Profile

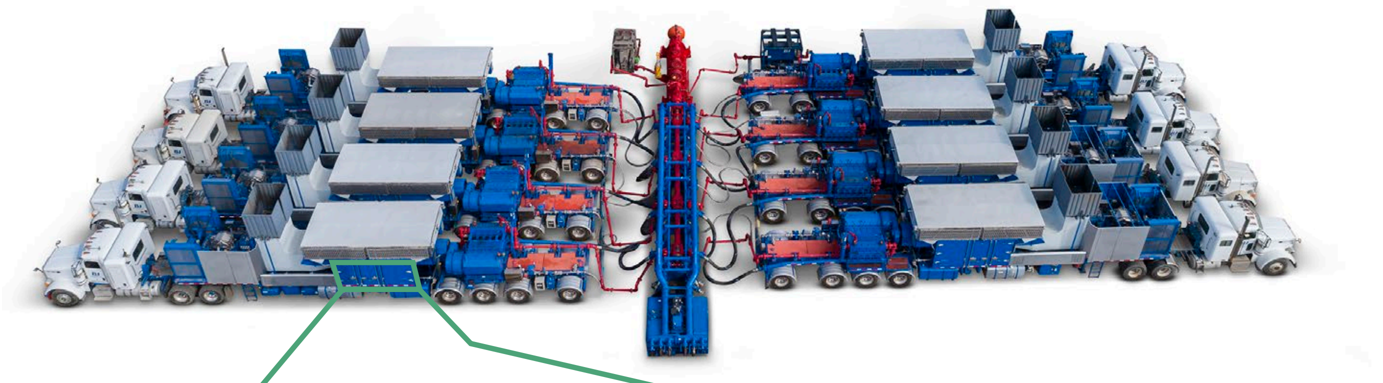
Some considerations could not be included in the model due to operational variablility. These factors include:

**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 particular 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's 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.

***First 40,000HHP commercial fleet of TITAN hydraulic fracturing pumps powered by 8 natural gas direct drive turbines.***



***Providing the highest power density available - the 5,000 HHP turbine mounted on a TITAN unit.***

# Conclusion

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 the Equipment Configuration. Our findings 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.

The TITAN's competitive advantage stems from the efficient transfer of power created by the natural gas powered turbine, through a direct mechanical drive line to the pump. 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. In ALL cases, the TITAN demonstrated lower GHG emissions than conventional diesel and other next-generation technologies. Testing also validated that the TITAN had the lowest EPA regulated NOx, CO, and PM emissions.

Natural gas powered direct drive turbine mechanical systems provide the highest power transfer efficiency. As compared to diesel or dual-fuel based mechanical drive systems, TITAN has the highest power density and eliminates methane slip under load. 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. This 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 findings include:**

- Engine thermal efficiency should not be the single measure used to evaluate actual HHP delivery. The entire system must be considered as it relates to engine SHP to HHP energy transfer onsite.
- 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 and excludes parasitic losses stemming from required components such as cooling radiators, lubrication systems, hydraulics etc. To accurately test reciprocating engines, actual testing should be performed to include all parasitic losses and engine degradation.
- As one of the most potent GHG gases, methane should be considered when evaluating GHG emissions in natural gas and dual-fuel reciprocating engines.
- The higher the load on the turbine driving the TITAN pumping units, the better the fuel economy and the lower the emissions.
- Use of Tier IV diesel powered hydraulic fracturing equipment does not always provide lower GHG emissions as compared to Tier II diesel engines.
- The paper excludes the evaluation of electric powered hydraulic fracturing equipment which is connected to a utility electrical grid. To properly evaluate the emissions impact of an electric fracturing fleet powered by an electrical grid, other factors must be considered such as the source of the power and its related emissions – both of which represent a very small portion of the industry's current equipment set.

Beyond emissions, there are many other characteristics which should be considered in evaluating current and future hydraulic fracturing equipment technologies. The intent of this paper is to provide clarity on hydraulic fracturing equipment emissions, the most pressing issue related to sustainability and the environment.

# 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.

# References


Britannica diesel engine. (2021, October 1st). Retrieved from Britannica.com: https://www.britannica.com/technology/diesel-engine

Britannica. (2021, February 21st). Retrieved from www.britannica.com: https://www.britannica.com/technology/diesel-engine/Fuel-injection-technology

Canada Energy Regulator. (2017, September). Retrieved from www.cer-rec.gc.ca: https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/crude-oil-petroleum-products/report/2017-duvernay/2017dvrn-eng.pdf

(2017). Catalog of CHP Technologies. CHP &EPA.

Chapa, S. (2019, April 30th ). Baker Hughes chooses Permian Basin to debut 'electric frack' technology. Retrieved from Houstonchronicle.com: https://www.houstonchronicle.com/business/energy/article/Baker-Hughes-chooses-Permian-Basin-to-debut-13808592.php

Climate.gov. (2021, October 4th). Retrieved from Climate.gov: https://www.climate.gov/maps-data/dataset/past-weather-zip-code-data-table

Cornell Law School. (2021, June 5th). Retrieved from www.law.cornell.edu: https://www.law.cornell.edu/cfr/text/40/98.233

Criteria Air Pollutants. (2021, October 1st). Retrieved from EPA: https://www.epa.gov/criteria-air-pollutants

EPA. (2015, March). Retrieved from www.epa.gov: https://www.epa.gov/sites/default/files/2015-07/documents/catalog_of_chp_technologies_section_3._technology_characterization_-_combustion_turbines.pdf

EPA. (2021, October 1st). Retrieved from www.epa.gov: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

EPA Global Warming Potential. (2021, October 1st). Retrieved from EPA: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

Government of Canada. (2021, October 4th). Retrieved from www.nrcan.gc.ca: https://www.nrcan.gc.ca/energy/efficiency/communities-infrastructure/transportation/idling/4457

Greenhouse Gas Protocol. (2021, October 1st). Retrieved from ghgprotocol.org: https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

Hore-Lacy, I. (2011). Nuclear Energy in the 21st Century. In I. Hore-Lacy, Nuclear Energy in the 21st Century (pp. chapter 1, section 6, page 9). London: Academic Press.

Johnson, D.R., Heltzel, R, Nix, A., Darzi, M., Dakota, O., Greenhouse gas emissions and fuel efficiency of in-use high horsepower diesel, dual fuel, and natural gas engines for unconventional well development, https://www.sciencedi rect.com/science/article/abs/pii/S0306261917312679, November 17, 2017.

Johnson, D.R., Heltzel, R.*, Nix, A.C. and Darzi, M.*, 2018, "Estimated Emissions from the Prime-Movers of Unconventional Natural Gas Well Development Using Recently Collected In-Use Data in the United States," Environmental Science and Technology, 2018, 52, 5499-5508. https://doi.org/10.1021/acs.est.7b06694."

Kawasaki . (2021, October 1st). Retrieved from Global.kawasaki.com: https://global.kawasaki.com/en/energy/equipment/gas_turbines/outline.html

North American Rig Count, Drilling and Frac Spread Count Data. (2021, October 1st). Retrieved from OILPRICE.COM: https://oilprice.com/rig-count

Rentar Fuel Catalyst. (2021, October 4th). Retrieved from Rentar.com: https://rentar.com/efficient-engines-thermodynamics-combustion-efficiency/

Review of Emerging Resources: U.S Shale Gas and Shale Oil Plays. (2011, July 8th). Retrieved from EIA: https://www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf

SAE International. (2019, November 21st). Retrieved from www.sae.org: https://www.sae.org/publications/technical-papers/content/2019-28-2390/

Serio, D. D. (2017). Effects of EGR rate on performance and emissions of a diesel power generator fueled by B7. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 39, 1919-1927.

Heywood, J. B. Internal Combustion Engine Fundamentals. Singapore: McGraw Hill International Editions, 1988.

Yousefi, A. (2020). On the Variation of the Effect of Natural Gas Fraction on Dual-Fuel Combustion of Diesel Engine Under Low-to-High Load Conditions. Mechnical Engineering, 17.

**BJ Energy Solutions, LLC**
2001 Timberloch Place, Suite 350
The Woodlands, TX, USA 77380
1-346-867-8900
bjenergy.com