Clearing the air
The truth about diesel, dual-fuel, and electric hydraulic fracturing operations

BY
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www.uswellservices.com
USWS’s state-of-the-art CleanFleet® technology helped Range make progress towards our emissions reduction goals while generating operational cost savings.

In 2019, between the contributions of our team and CleanFleet®, we achieved a 52% reduction in greenhouse gas emissions from combustion sources.

– RANGE RESOURCES

CleanFleet® provides enhanced safety features, smaller physical and environmental footprints, and reduced noise levels at a lower cost relative to traditional completion equipment.

– ANTERO RESOURCES

Deploying [U.S. Well Service’s] electric hydraulic fracturing fleet in the Permian demonstrates our steadfast pursuit to achieving sustainable energy solutions for our business.

– ROYAL DUTCH SHELL
CleanFleet® utilizes field gas rather than diesel fuel to generate power, which saves cost and time. In addition, anytime you can replace a rotating part, such as a diesel engine, with an electric motor, it becomes less of a maintenance problem. And so you end up with lower costs, more efficiencies, better run times — a win-win for everyone.

– EP ENERGY

We have fracked eleven wells on four different pads with CleanFleet®. On a single-well basis, we realized more than $250,000 in diesel savings alone while reducing emissions.

– APACHE CORPORATION

As a result of working with USWS, we have reduced noise pollution, eliminated more than 16 million gallons of diesel from our operations, and reduced emissions by more than 70%. We executed these achievements at efficiency levels exceeding those realized with conventional equipment — demonstrating that environmental performance and financial success can be combined to achieve outstanding results.

– EQT CORPORATION

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Executive summary
As a provider of both traditional diesel and electric hydraulic fracturing technologies, U.S. Well Services (USWS) has the in-field measurements to prove which technology has the smallest environmental footprint and lowest cost profile and — across all these critical metrics — it’s electric.

USWS’s CleanFleet® outperforms diesel and dual-fuel fleets across key environmental, uptime, and operating cost metrics

**SMALLER ENVIRONMENTAL FOOTPRINT**

In third-party testing, CleanFleet® cuts CO₂e emissions by at least

- 42% vs. Tier IV Diesel, or
- 48% vs. Tier II Diesel

CleanFleet® using field gas reduces monthly¹ traffic by

- 110 truckloads² per month¹ vs. Tier II & Tier IV Diesel

In a typical month¹, CleanFleet® cuts total CO₂e greenhouse gas emissions by more than

- 2,200 metric tons vs. Tier IV Diesel

When operators flare the field gas that CleanFleet® uses, CO₂e reductions grow to more than

- 60% vs. Tier II & Tier IV Diesel

CleanFleet® also emits far less smog- and haze-causing particulate matter:

- 76% vs. Tier IV Diesel, or
- 94% vs. Tier II Diesel
Some recently issued “studies” purport one technology or another has the lowest emissions. Those studies rely on manufacturers’ emissions rates at cherry-picked load points that do not represent the full in-field duty cycle; moreover, those reports ignore important maintenance and uptime metrics that directly affect well profitability. This is the first report to directly compare technologies using operating data from in-field equipment.

Our analysis uses a load cycle generated from 45 days’ of in-field measurements collected from USWS’s diesel and electric fleets operating in Texas in late 2019 & early 2020. Using this load cycle as the baseline, we compare in-field measurements and four emissions’ calculation methods recommended by the Intergovernmental Panel on Climate Change (IPCC) and U.S. Environmental Protection Agency (U.S. EPA).

The bottom line? In every analysis, and by every methodology, USWS’s electric CleanFleet® outperforms Tier II and Tier IV diesel and Tier IV dual-fuel fleets.

¹ One month contains 28 operating days
² One truckload contains 5,000 gallons of diesel
³ At $45 per barrel (WTI), expected fuel costs are $2.21 per gallon of diesel and $1.52 field gas netback

**INCREASED UPTIME**

CleanFleet® using U.S. Well Services’s proprietary FracMD+® diagnostics results in

- 64% lower pump damage accumulation rate
- 30% more customer-reported pump hours

**LOWER OPERATING COSTS**

At $45 per barrel (WTI), CleanFleet® using field gas reduces monthly¹ fuel costs by more than $970,000 vs. Tier IV Diesel

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Acknowledgments

The authors wish to recognize many individuals who contributed to the analyses underlying and the development and review of this white paper, particularly Brandon Hinderliter, Alex Christinzio, David Jones, Matthew Moncla, Lacey Poole, Mark Dearing, Mark Golden, Kyle O’Neill, Josh Shapiro, David Treadwell and many more U.S. Well Services team members. The authors also thank Nicole Kaufman Dyess LLC for providing research, analysis, content editing, and formatting assistance.
Frequently asked questions

*Why is this report different?*

In recent years, many oil and gas industry majors began requiring contractors to report on environmental, social, and corporate governance (ESG) factors. As a result, many pressure pumping companies have issued marketing collateral arguing why their technology has the lowest emissions.

First, instead of cherry-picking the emissions calculation methodology that shows our equipment in the best light like many of our competitors, U.S. Well Services (USWS) engaged in an extensive study of the five most widely recognized emissions calculation methods. Second, we calculated emissions over a duty cycle created from data on actual fleet operations rather than comparing equipment emission rates at select load points to produce the most favorable results.

And most importantly, as a provider of both traditional diesel and electric hydraulic fracturing technologies, USWS collected in-field emissions measurements to prove which technology has the smallest environmental footprint — and it’s electric.

The remainder of this FAQ briefly outlines our considerations, methodology, and results in a Q&A format. For additional technical details, please refer to the remainder of this white paper and its appendix.

*FIGURE ES-1*  
As our bright white sand silos and motor control centers demonstrate, an electric CleanFleet® site, with a clean-burning natural gas turbine, emits 76% less equipment-dirtying particulate matter (soot) than diesel & 71% less than dual-fuel fleets.
What pollutants are considered?
USWS is committed to mitigating the environmental impact of hydraulic fracturing operations. Anything introduced into an environment that has a harmful effect is a pollutant. In addition to generating harmful emissions, hydraulic fracturing operations create traffic, produce noise pollution, and release silica dust.

In this analysis, USWS considers emissions from three greenhouse gas (GHG) pollutants — carbon dioxide, \( \text{CO}_2 \); methane, \( \text{CH}_4 \); and dinitrogen oxide, \( \text{N}_2\text{O} \) — and three smog- and acid-rain-causing pollutants regulated by the U.S. Environmental Protection Agency (U.S. EPA) — carbon monoxide, \( \text{CO} \); nitrous oxides, \( \text{NO}_x \); and particulate matter, \( \text{PM} \). Figure ES-2, next page, summarizes why these particular pollutants are so harmful; see Figure 5 (page 20) for additional discussion.

How does one quantify pollutant emissions?
The Intergovernmental Panel on Climate Change (IPCC) and U.S. EPA advise using the most accurate method for which organizations have, or can generate, the data required to determine emissions.

For this analysis, USWS considered the five most commonly used methodologies. From most accurate to least, the methods evaluated in this analysis are:

1. Measuring emissions on-site;
2. Modeling emissions using manufacturers’ (OEM) specifications; and
3. Applying emissions factors published in
   3.2. U.S. Environmental Protection Agency’s “Center for Corporate Climate Leadership” (U.S. EPA Fuel)
   3.3. U.S. Environmental Protection Agency’s “Compilation of Air Pollutant Emissions Factors” (U.S. EPA Equipment)

Figure 6, page 23, describes each method — with pros and cons — in detail.

Why not just use emissions factors?
Though easy to calculate, emissions factors like those published by the GHG Protocol and the U.S. EPA can be very inaccurate because they fail to consider the condition, load, and efficiency of the prime mover — factors that directly affect its emissions.
For example, if you have two cars that both burn one gallon of gasoline, these methods would estimate these cars produce the same emissions, regardless of the number of miles traveled, the speed at which they traveled that distance, or presence of emissions-reducing technologies.

Or — in the case of frac technologies — regardless the prime mover technology, barrels pumped per minute, pressure at the well head, duration of the stage, or pump utilization rate.

FIGURE ES-2
USWS analyzed emissions of six regulated pollutants commonly emitted by its and its competitors’ equipment in the course of hydraulic fracturing. See Figure 5 (page 20) for additional detail.
How does one compare results across the various methods, data sources and types of equipment?

There are two important considerations when comparing the emissions results from different types of equipment: (1) the pollutants included; and (2) the units of measure of those pollutants.

COMPARING POLLUTANTS

In the case of CO, NO\textsubscript{X}, PM and other U.S. EPA-regulated pollutants, the best way to assess different technologies’ emissions is to compare emissions of each pollutant from each technology as determined by each method. However, one should never compare across methodologies, such as comparing one technology using the GHG Protocol and the other using OEM Specifications, due to the sometimes-considerable differences in results produced by the various methodologies.

To make greenhouse gas emission results more comparable, all protocols recommend calculating emissions from each criterion pollutant separately, and then converting greenhouse gases (GHGs) to CO\textsubscript{2}-equivalents (CO\textsubscript{2}e) by weighting each pollutant by its global warming potential. With the pollutants considered in this analysis, CO\textsubscript{2}e is calculated as

\[
CO_{2e} = CO_2 + (25 \times CH_4) + (298 \times N_2O),
\]

where 25 is the global warming potential of methane and 298 is the global warming potential of N\textsubscript{2}O. For emission-factor methodologies that only estimate CO\textsubscript{2}, CO\textsubscript{2} equals CO\textsubscript{2}e.

This is because some methodologies assume the ratio of CO\textsubscript{2}, CH\textsubscript{4}, N\textsubscript{2}O and other GHGs emitted when a particular fuel is combusted (e.g., GHG Protocol), whereas others estimate those criterion pollutants separately.

COMPARING UNITS OF MEASURE

Emissions are either reported as the total mass emitted over a defined period (e.g., metric tons per year) or as a rate (e.g., pounds per brake-horsepower). However, even emissions reported in the same units, such as grams per kilowatt-hour (g/kWh), may not utilize the same baseline and therefore not be directly comparable.

For example, many manufacturers publish specifications with emissions in g/kWh at different load points. If one plots the OEM’s published emissions rates as in Figure ES-3, next page, it appears that emissions increase at lower load points and drop at higher ones.
Some competitors stop their analysis at this point, arguing to select the technology with the lowest OEM-published emissions rates.

But, as Figure ES-4 demonstrates, once you factor in the number of diesel and dual-fuel engines operating — and the load on these prime movers — the story changes. In reality, there are far more pollutants emitted per hour of operation at higher load points than at lower ones.

In other words, the time spent at each load point matters. And that’s why it’s important to consider cumulative emissions over the entire operating time of a realistic duty cycle [Figure ES-6, next page].

**FIGURE ES-3**
Manufacturer-published per-unit CO$_2$e emissions rates (kg/kWh) over two stages

<table>
<thead>
<tr>
<th>LOAD (× 1,000 kW)</th>
<th>CO$_2$e (kg/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>

**FIGURE ES-4**
Hourly CO$_2$e emissions (Mg/h) at load over two stages (15 pumps operating)

<table>
<thead>
<tr>
<th>LOAD (× 1,000 kW)</th>
<th>CO$_2$e (Mg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

**FIGURE ES-3**
OEM-published emission rates per unit of output (g/kWh) increase at low loads.

**FIGURE ES-4**
After multiplying OEM-published emissions rates by load and number of units operating, emissions per hour (kg/h) shows more pollutants emitted at higher loads.
How does one compare technologies with different duty cycles?

Different technologies require slightly different duty cycles; for example, diesel and dual-fuel engines generally idle at around 10% of their rated load due to parasitic loads (e.g., lube & cooling systems) — or about 250 hhp per pump times up to 16 pumps — while electric turbines can idle as low as 3%, or 540 hhp. Evaluating emissions for diesel and dual-fuel engines with idle-reduction technology (see page 33) adds an additional layer of complexity.

So how do you compare across differing duty cycles?

The preferable option is to normalize total emissions by the duty cycle itself to calculate the weighted average rate of emissions (i.e., grams per kWh). This analysis reports weighted average emissions rates (g/kWh).

It is important not to compare this weighted average to manufacturer specifications; instead, each technology must be modeled over its respective duty cycle first and then normalized to create comparable weighted average emissions rates.

What did we find?

In-field measurements demonstrate that USWS’s OEM-specifications-based model conservatively estimates emissions: our diesel fleets test very close to the model, while our electric turbines consistently test below model estimates [Figure ES-6, next page]. Therefore, USWS’s specifications-based model provides an easily achievable, low estimate of emissions reduced by using our CleanFleet® technology.
FIGURE ES-6 Measured vs. modeled CO$_2$e emissions (g/kWh) by prime mover

- **GHG Protocol**
- **EPA Fuel**
- **EPA Equipment**
- **OEM Specifications**
- **USWS Measured**

Diesel (Tier II)

Diesel (Tier IV)

Dual fuel (Tier IV; 75% NG)

CleanFleet®

FIGURE ES-7 Pump-related plus flared gas CO$_2$e emissions (g/kWh) by prime mover

- **GHG Protocol**
- **EPA Fuel**
- **EPA Equipment**
- **OEM Specifications**

Diesel (Tier II)

Diesel (Tier IV)

Dual fuel (Tier IV; 75% NG)

CleanFleet®
Per this OEM-specifications-based model, CleanFleet® reduces carbon dioxide equivalent (CO₂e) emissions by 28% versus Tier IV diesel and 22% versus Tier IV dual-fuel at a rarely achievable 75% natural gas substitution rate.

OEM-specification-based calculations tend to overestimate emissions produced and therefore underestimate pollution-reduction potential because manufacturers are legally required to meet their specifications. Therefore, USWS also determines our fleets’ emissions by collecting on-site measurements throughout the duty cycle, in accordance with IPCC and U.S. EPA guidance.

And in the field, third-party testing shows USWS’s CleanFleet® reduces CO₂e by 42% versus Tier IV diesel and 48% versus Tier II diesel. (USWS does not operate and therefore did not test any Tier IV dual-fuel units.) Moreover, third-party testing shows that CleanFleet® produces up to 87% fewer CO and 67% fewer NOₓ emissions than expected according to the manufacturer’s specifications — up to 94% less CO than a Tier II diesel, and 12% fewer NOₓ than a Tier IV diesel.

Even greater CO₂e emissions reductions — 60% versus Tier IV diesel and 37% versus dual-fuel — occur when CleanFleet® uses field gas that would otherwise be required to be flared [Figure ES-7, previous page].

FIGURE ES-8
Our normally bright white sand silos visibly demonstrate the increased particulate-matter (soot) emissions from a diesel fleet.
Introduction

U.S. Well Services (USWS) is committed to mitigating the environmental impact of hydraulic fracturing operations. We embrace our role in protecting the environment. Environmental stewardship is not just a mantra; every operational decision considers our three core values:

- **Cleaner communities**: USWS improves the air, land, water, and communities where we live and work.
- **Continuous improvement**: USWS develops products and processes that minimize our environmental footprint.
- **Waste reduction**: USWS uses lean practices to minimize and, where possible, eliminate the creation of waste.

To ensure we achieve our ideals, USWS researches best practices and performs ongoing audits of our processes to guarantee the efficiency, effectiveness, and sustainability of our operations.

In 2013, a goal to reduce the noise and emissions produced by our traditional fleets led to the creation of CleanFleet®. Over the past six years, USWS has completed over 18,000 pumping stages with CleanFleet® — more than any other pressure pumping company utilizing electric frac equipment — and over 57,000 pumping stages with our traditional, diesel-powered fleets.

As a provider of both diesel and electric frac technologies, USWS has the data to prove which technology has the lowest impact. And here’s what the data shows: by utilizing natural-gas-fired turbines and electric motors, electric frac technologies provide completion services with enhanced safety features, a smaller environmental footprint, less maintenance, and reduced noise — at a lower cost — than either traditional diesel or dual-fuel completion equipment.

First, we’ll provide an overview of diesel, dual-fuel, and electric hydraulic fracturing technologies. Then, we’ll quantify the impact of each frac technology by digging into the data — from actual USWS fleets doing real hydraulic fracturing work in Texas in 2019 & 2020.

As a provider of both diesel and electric frac technologies, USWS has the data to prove which technology has the lowest impact.
Hydraulic fracturing technologies

All hydraulic fracturing operations — regardless of technology — use pumps to inject a mix of water, chemicals and sand into the well at high pressures, opening cracks in the hard shale rock and releasing the oil and gas contained in pockets throughout the shale. Each pad may use from 12 to 20 pumps to accomplish this, depending on the pressure and flow requirements of the formation.

Traditional hydraulic fracturing utilizes pumps driven by diesel engines; however, cleaner dual-fuel fleets are gaining ground, and electric-powered pumps are revolutionizing the industry. Here’s how the technologies differ:

**Traditional diesel (Tier II & Tier IV)**

Traditional hydraulic fracturing operations employ pumps driven by diesel engines. Diesel is trucked to the well site, then distributed to each of the pumps. While fuel use depends on the specific pressure and flow requirements of each job, it’s not uncommon for typical high-pressure, high-flow jobs in Texas (e.g., 11,500 psi, 100 bpm) to consume 4,000 gallons of diesel per stage — this means 12 truckloads or more of diesel every day!

U.S. Environmental Protection Agency (U.S. EPA) regulations increased the efficiency required of and reduced the emissions allowed from diesel engines over the past 20 years. Hydraulic fracturing operations generally employ either Tier II or Tier IV diesel engines. Pump units purchased after 2006 and prior to 2015 generally use higher-emitting Tier II diesel engine technology. While Tier IV engines became available as early as 2011, these cleaner engines only became the norm after Tier IV standards became mandatory in 2015.

As shown Figure 1, next page, regulations require Tier IV engines to have significantly lower emissions than Tier II. To achieve these results, Tier IV engines utilize advanced engine designs — such as selective catalytic reactors, exhaust gas recirculation, turbochargers, and high-precision fuel injection systems — to ensure more complete fuel combustion, and thereby, reduce emissions.

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1. Tier III standards did not apply to diesel engines larger than 560 kW, and thus are not common in hydraulic fracturing operations where many pumps rate 2,000 kW or greater.
**Dual fuel (Tier IV)**

Tier IV dual-fuel engines provide a cleaner option than traditional diesel for driving a hydraulic fracturing pump. Similar to a traditional diesel engine, dual fuel requires diesel — and natural gas (CNG/LNG), depending on the quality of site-produced field gas — to be trucked to the well site, then distributed to the pump units. However, because these engines utilize natural gas, they consume less diesel, have lower emissions, and, if using field gas, require fewer truck-loads of fuel than traditional diesel-powered pumps.

Dual-fuel engines work by drawing air, natural gas, and diesel into the engine's combustion chamber so that during the compression stroke, the diesel auto-ignites, igniting the natural gas. Tier IV dual-fuel engines can operate at any substitution rate from 0% (i.e., 100% diesel) up to 75% natural gas — depending on the engine's power and torque requirements. However, as shown in Figure 2, above, the substitution rate falls off considerably at low and high loads. As a result, it’s nearly impossible to maintain peak substitution rates in a typical hydraulic fracturing operation. And, during idle between stages, dual-fuel engines use 100% diesel.

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4 E.g., Cummins’ QS* dual-fuel engines top out at a 70% substitution rate; similarly the CAT 3512E dynamic-gas blended engine peaks at 85% fuel displacement rate (approximately equivalent to a 70% fuel substitution rate).

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**FIGURE 1** Evolution of U.S. EPA emissions standards for non-road diesel engines 900 kW and greater

**FIGURE 2** Natural gas substitution rate for Tier IV dual-fuel engines, per manufacturers literature

**FIGURE 1 LEFT**
U.S. EPA non-road compression ignition engine emission standards for diesel engines above 900 kW evolved greatly since 2000. Versus Tier II, Tier IV’s maximum allowable emissions for non-methane hydrocarbons (NMHC) dropped 85%; nitrous oxides (NOx), 45%; and particulate matter (PM), 80%.

**FIGURE 2 RIGHT**
The natural gas substitution rate for a Tier IV dual-fuel engine peaks at 70-75%, depending on manufacturer; however, the allowed substitution rate falls off considerably at low and high loads.
Dual-fuel engines are also susceptible to the quality of natural gas. While dual fuel engines can make use of field gas, if high, the moisture and sulfur content of field gas can “gum” up the engine, causing reliability issues; hence, dual-fuel fleets using field gas typically require additional pretreatment equipment to “dry” the field gas. More often, dual-fuel fleets opt for CNG or LNG instead because of the narrow band of acceptable field gas quality.

Electric

Electric hydraulic fracturing, such as U.S. Well Services’ CleanFleet®, use electric-motor-driven pumps powered by natural gas generators. The turbine-driven generators make electricity using CNG, LNG, or site-produced field gas that may otherwise be flared.

Unlike dual-fuel engines, these turbines operate at such high temperatures and pressures that they can tolerate a wider range in field gas quality and moisture content; often, the field gas can simply be pressurized and injected. Because power is distributed to individual pump units by electric cables, electricity from the power generation equipment may be located up to several miles away, potentially powering multiple pads at the same time (Figure 3).

**FIGURE 3**

USWS’s PowerPath® solution enables power generation equipment to be located up to several miles from the pad, and potentially to power multiple pads at the same time.
So, instead of the constant rumble of diesel engines and trucks bringing fuel, one hears the steady hum of an electric generator and motors from a CleanFleet® site.

And because electric motors and natural gas turbines have fewer moving parts than diesel or dual fuel engines, there's less maintenance on these units — meaning less downtime and more stages completed per day.

**Approach**

To ensure equivalency, this analysis normalizes hydraulic fracturing technologies by output, as measured in hydraulic horsepower (hhp). After all, if one hydraulic fracturing technology requires higher pumping power than the other technologies, the results will skew in favor of the technologies operating with the lower output.

For the analyses herein, we assume the following load profile: A representative sample of the assumed load cycle, compared to actual load cycle data from an actual CleanFleet® fleet, is shown in [Figure 4](#), below. This average load profile

**FIGURE 4 Average Texas duty cycle vs. actual CleanFleet® duty cycle**

- Average/assumed load cycle (× 1,000 hhp) [CleanFleet®]
- Average/assumed load cycle (× 1,000 hhp) [Diesel]
- Actual CleanFleet® power generation (MWₑ)

After reviewing 45 days of pump data, USWS fleets operating in Texas in 2019 & 2020 averaged 13 stages per 48 hours, with each stage requiring 18,000 hhp and idle requiring 2,920 hhp for a diesel fleet and 540 hhp for an electric CleanFleet®.
Carbon dioxide (CO₂)
Released through the combustion of fossil fuels, CO₂ accounts for the majority of GHG emissions. CO₂ plays a leading role in climate change because it traps heat, much like the glass panes of a greenhouse. Whereas methane decays in about a decade and N₂O after a century or so, CO₂ emitted today stays in the atmosphere for up to 10,000 years.

Methane (CH₄)
The primary component in natural gas, methane has 25 times the global warming potential of CO₂. Methane is released during the production of oil and gas, by the burning of fossil fuels, and through the decomposition of biological material, such as at landfills and wastewater treatment facilities. Emitted methane stays in the atmosphere for about a decade.

Di-nitrogen oxide (N₂O)
Commonly known as laughing gas, N₂O has a global warming potential that’s 298 times that of CO₂ — and it stays in the atmosphere for more than a century. The combustion of fossil fuels and biofuels, production of nitrogen fertilizers, and widespread cultivation of nitrogen-fixing crops have accelerated N₂O emissions since 2009.

Hydraulic fracturing pollutants regulated by the U.S. EPA Clean Air Act

Carbon monoxide (CO)
Created by burning fossil fuels, carbon monoxide has a weak, indirect effect on climate change. However, it is a key component of smog. In enclosed spaces, breathing air with high concentrations of CO can be fatal. Outdoors, elevated CO levels can exacerbate asthma and trigger angina in those with heart disease.

Nitrous oxides (NOₓ)
NOₓ refers to six highly reactive compounds (NO, N₂O, N₂O₅, NO₂, N₂O₄, & N₂O₅) created primarily through the burning of fossil fuels. When exposed to sunlight, NOₓ react with VOCs in the air to create tropospheric ozone (O₃), the primary component of smog. Together with sulfurous oxides (SOₓ), NOₓ also contribute to the formation of acid rain.

Particulate matter (PM)
Very fine particles (< 10 μm) of soot created by the combustion of fossil fuels and aerated silica dust cause a variety of harmful environmental and health effects. These particles can travel deep inside the lungs, damaging the respiratory and circulatory systems. PM also contributes to the formation of smog and acid rain and reduces visibility by causing haze.
comes from 45 days of on-site data collected on U.S. Well Services (USWS) fleets (both diesel and electric) operating in Texas in 2019 & 2020. On average, our fleets completed 13 stages in a 48-hour period. Based on pump data, completing each stage required 18,013 hhp and took 159 minutes on average; idle time between stages averaged 58 minutes (i.e., 73% pump utilization) and either 2,920 hhp for a diesel fleet and 540 hhp for an electric CleanFleet®.

A diesel fleet requires more power during idle stages than an electric frac fleet like CleanFleet® due to having multiple engines idling versus a single turbine. A CleanFleet® pump idles at zero rpm to provide braking force on the pump, whereas a diesel fleet must keep spinning the engines, despite disengaging the pump, in order to maintain readiness to pump. It is not uncommon for diesel and dual-fuel engines to consume ten gallons of diesel per pump — times up to 20 pumps — per hour of idle time.

**Pollutants**

U.S. Well Services (USWS) seeks to foster environmental stewardship in the oil and gas industry by reducing hydraulic fracturing emissions. We take a holistic view considering both greenhouse gases (GHGs) and pollutants regulated by the U.S. Clean Air Act.

By definition, anything introduced into an environment that has a harmful effect is a pollutant. For example, in addition to generating harmful GHG and other gaseous emissions that may immediately come to mind, hydraulic fracturing operations create traffic, produce noise pollution, and release silica dust.

There are four greenhouse gas (GHG) pollutants of concern: carbon dioxide, CO₂; methane, CH₄; and dinitrogen oxide, N₂O, and fluorinated gases, such as CFCs and PFCs. The first three - CO₂, CH₄, and N₂O - are byproducts of combusting fossil fuels and thus commonly emitted from hydraulic fracturing sites. In addition, the Clean Air Act enables the U.S. EPA to regulate several additional pollutants emitted in hydraulic fracturing, including carbon monoxide, CO; nitrous oxides, NOₓ; particulate matter, PM; sulfurous oxides, SOₓ; and lead. These pollutants cause health- and environment-damaging effects, such as triggering asthma, causing acid rain, and generating smog.

Based on availability of specifications for estimating emissions, this analysis considers emissions from CO₂, CH₄, N₂O, CO, NOₓ, and PM. Figure 5, previous page, describes why these particular pollutants are so harmful.
Methodologies

The Intergovernmental Panel on Climate Change (IPCC) and U.S. EPA advise using the most accurate method for which organizations have, or can generate, the data required to determine emissions.

For this analysis, USWS considered the five most commonly used methodologies. From most accurate to least, the methods evaluated in this analysis are:

1. **Measured Emissions** | Directly measuring CO₂, CH₄, CO and NOₓ emissions throughout the equipment’s load cycle.

2. **OEM Specifications** | Utilizing original equipment manufacturer performance and emissions specifications together with the equipment load profile enables a calculation of CO₂, CH₄, CO and NOₓ emissions — assuming equipment in new condition.


4. **U.S. EPA Fuel** | The U.S. Environmental Protection Agency’s “Center for Corporate Climate Leadership” publishes fuel-specific emissions factors for calculating CO₂ emissions (only).

5. **U.S. EPA Equipment** | The U.S. Environmental Protection Agency’s “Compilation of Air Pollutant Emission Factors” incorporates equipment-specific emission factors — assuming used-condition equipment — in its determination of CO₂, CH₄, CO and NOₓ emissions.

Each method has its pros and cons, as summarized in Figure 6, next page. Measuring emissions and modeling specifications can be very labor-intensive; therefore, many corporations prefer the last three methodologies — the GHG
Protocol and U.S. EPA Fuel and Equipment standards — because they simply multiply fuel receipts by a factor pulled from a table. While these three methods provide a simple estimate of emissions, they fail to consider the condition and thermal efficiency of the prime mover — factors that directly affect its emissions.

**FIGURE 6** Comparison of most common emissions quantification methodologies

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Shortcomings</th>
</tr>
</thead>
</table>
| USWS’s measured-in-field emissions | The best means of evaluating emissions performance, taking measurements in-field throughout the duty cycle enables quantification of real-world emissions performance for all criterion pollutants | - To generate comparable data, measurements must be taken on all types of equipment in similar operating conditions (ambient temperature, elevation, etc.)  
- USWS does not own any dual-fuel equipment |
| OEM specifications-based model  | A computer model created by USWS that uses specifications published by original equipment manufacturers (OEMs) to determine the maximum expected emissions over a set of operating conditions | - Limited to whatever pollutants for which the OEM publishes emissions specifications  
- Since failing to meet published specifications may trigger a warranty claim, OEMs publish maximum — instead of expected — emissions at each load point |
| Greenhouse Gas (GHG) Protocol | Emissions factors published by the World Business Council for Sustainable Development and the World Resources Institute, that uses the carbon content of the fuel to estimate of CO₂ emissions | - Only estimates CO₂ and ignores all other pollutants  
- Based solely on quantity of fuel burned; agnostic to how equipment type and operating environment affect fuel efficiency, emissions produced |
| U.S. EPA Fuel                  | Emissions factors published by the U.S. EPA’s Center for Corporate Leadership that uses the carbon content of the fuel to estimate of CO₂ emissions | - Only estimates CO₂ and ignores all other pollutants  
- Based solely on quantity of fuel burned; agnostic to how equipment type and operating environment affect fuel efficiency, emissions produced |
| U.S. EPA Equipment             | Equipment-specific emissions factors from the U.S. EPA’s “Compilation of Air Pollutant Emissions Factors” (AP-42) that assume used-condition equipment to estimate CO₂, CH₄, CO and NOₓ emissions | - Based solely on quantity of fuel burned; agnostic to operating environment, duty cycle, and recent advances in engine technology that improve fuel efficiency & reduce criterion pollutant emissions |
For example, consider two traditional diesel engines delivering the same output: one with a Tier II rating; the other, Tier IV. Both engines use the same quantity of diesel, despite Tier IV regulations requiring substantially lower emissions compared to Tier II. To achieve these results, Tier IV engines utilize advanced engine designs — often relying on higher-pressure fuel systems with precise, electronic fuel injection controls; larger piston displacements; crank-case cooling; exhaust gas recirculation; and catalytic filters — to ensure more complete combustion, thereby lowering emissions. In other words, they are substantially different engines.

Despite these differences, the last three methodologies — the GHG Protocol and the U.S. EPA Fuel and Equipment standards — result in Tier II and Tier IV engines having near-identical emissions when operating on the previously


FIGURE 7 Pump-related CO₂e emissions (100 yr/kWh) over the 48-hour average duty cycle per the three emissions-factor based methodologies evaluated

<table>
<thead>
<tr>
<th>Tier II</th>
<th>Tier IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG Protocol</td>
<td>8.08</td>
</tr>
<tr>
<td>U.S. EPA Fuel</td>
<td>8.17</td>
</tr>
<tr>
<td>U.S. EPA Equipment</td>
<td>7.79</td>
</tr>
</tbody>
</table>

FIGURE 8 Manufacturer's specifications for Tier II vs. Tier IV diesel engine fuel economy & emissions

<table>
<thead>
<tr>
<th></th>
<th>Fuel economy (gal/hr)</th>
<th>CO₂ emissions (g/kWh)</th>
<th>Hydrocarbon emissions (g/kWh)</th>
<th>CO emissions (g/kWh)</th>
<th>NO₂ emissions (g/kWh)</th>
<th>PM emissions (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT 3512C [Tier II]</td>
<td>104.60</td>
<td>699</td>
<td>0.21</td>
<td>0.97</td>
<td>8.81</td>
<td>0.13</td>
</tr>
<tr>
<td>CAT 3512E [Tier IV]</td>
<td>128.40</td>
<td>707</td>
<td>0.07</td>
<td>0.21</td>
<td>4.36</td>
<td>0.05</td>
</tr>
</tbody>
</table>
described load cycle, as shown in Figure 7, previous page. That’s the flaw in these emissions-factor based methodologies.

The deficiency of these methodologies is even more pronounced when one considers manufacturer-published fuel efficiencies and emissions, which often show Tier IV engines consuming more fuel yet producing considerably lower emissions Figure 8, previous page.

That’s why the IPCC and the U.S. EPA advise organizations use the most accurate and lowest uncertainty method for which they have or can generate the data. Both hierarchies recommend the use of direct measurements first, then of emissions simulations models, and of generic emissions factors last.\textsuperscript{12,13}

\textit{Comparing technologies}

There are two important considerations when comparing the emissions results from different types of equipment: (1) the pollutants included; and (2) the units of measure of those pollutants.

\textbf{COMPARING GHGS}

To make greenhouse gas emission results more comparable, IPCC protocol recommend calculating emissions from each criterion pollutant separately, and then converting GHGs to CO\textsubscript{2}-equivalents (CO\textsubscript{2}e) by weighting each pollutant by its global warming potential.\textsuperscript{14} With the pollutants considered in this analysis, CO\textsubscript{2}e is calculated as

\[\text{CO}_2\text{e} = \text{CO}_2 + (25 \times \text{CH}_4) + (298 \times \text{N}_2\text{O}),\]

where 25 is the global warming potential of methane and 298 is the global warming potential of N\textsubscript{2}O.

For emission-factor methodologies that only estimate CO\textsubscript{2}, CO\textsubscript{2} equals CO\textsubscript{2}e. This is because some methodologies assume the ratio of CO\textsubscript{2}, CH\textsubscript{4}, N\textsubscript{2}O and other GHGs emitted when a particular fuel is combusted (e.g., GHG Protocol), whereas other estimate those criterion pollutants separately.


FIGURE 9 OPPOSITE TOP
OEM-published emission rates per unit of output (g/kWh) increase at low loads.

FIGURE 10 OPPOSITE MIDDLE
After multiplying OEM-published emissions rates by load and the number of units operating, emissions per hour (Mg/h) shows more pollutants emitted at higher loads.

FIGURE 11 OPPOSITE BOTTOM
Totaling emissions over an identical duty cycle as shown is the best way to compare emissions by different technologies.

COMPARING OTHER REGULATED POLLUTANTS
In the case of CO, NOₓ, PM and other U.S. EPA-regulated pollutants, the best way to assess different technologies’ emissions is to compare emissions of each pollutant from each technology as determined by the same method. One should never compare across methodologies due to the sometimes-considerable variation in results produced by different methods.

COMPARING UNITS OF MEASURE
Emissions are either reported as the total mass emitted over a defined period (e.g., metric tons per year; grams per hour) or as a rate (e.g., pounds per brake-horsepower; kilograms per kilowatt-hour). However, even emissions reported in the same units, such as grams per kilowatt-hour (g/kWh), may not be directly comparable.

For example, many manufacturers publish specifications with emissions in g/kWh at different load points. If one plots the OEM’s published emissions rates as in Figure 9, next page, it appears that emissions increase at lower load points and drop at higher ones. Some competitors stop their analysis at this point, arguing to select the technology with the lowest OEM-published emissions rates.

But, as Figure 10 demonstrates, once you factor in the load the story changes. In reality, there are far more pollutants emitted per hour of operation at higher load points than at lower ones. Hence, the time spent at each load point is important. And that’s why it’s important to consider total emissions over the entirety of a realistic duty cycle [Figure 11].

U.S. Well Service’s OEM-specifications-based model — using specifications manufacturers are legally to held to achieve — errs on the conservative side by overestimating electric turbine emissions and still demonstrates the considerable emissions savings available with CleanFleet®.
FIGURE 9 Manufacturer-published per-unit CO$_2$e emissions rates (kg/kWh) over two stages

FIGURE 10 Hourly CO$_2$e emissions (Mg/h) at load over two stages (15 pumps operating)

FIGURE 11 Cumulative emissions (metric tons) over two stages (15 pumps operating)
However, different technologies require slightly different duty cycles — such as engines with idle reduction technology (discussed further on page 33). So how do you compare across differing duty cycles?

One option is to look at the intensity of emissions per unit of output; however, the preferred method is to normalize total emissions by the duty cycle itself to calculate the weighted average rate of emissions (e.g., grams per kilowatt-hour). **This analysis reports in terms of weighted average emissions rates in grams per kilowatt-hour (g/kWh).**

Though both measures use the same units, it is important not to compare this weighted average to manufacturers’ specifications. Instead, each technology must be modeled over its respective duty cycle first and then normalized to create comparable weighted average emissions rates.

So, for this analysis, we applied each of these methods to generate total emissions over our average 48-hour load cycle, such as in **Figure 12**, below, which shows the pump-related emissions as calculated by USWS’s specifications-based model. [Note scaling difference between CO\textsubscript{2}e (100×) versus NO\textsubscript{2}, CO and PM.] Then, we subsequently normalized emissions to grams per kilowatt-hour (g/kWh) and plotted the data by both technology and emissions calculation methodology. **Figure 13**, next page, shows normalized, or weighted average, CO\textsubscript{2}e emissions by technology for all methodologies. [Similar plots for other pollutants analyzed are available in the appendix.]

**FIGURE 12** Pump-related emissions for various prime mover technologies over the assumed 48-hour load cycle as calculated using USWS’s manufacturer (OEM) specifications-based model.

**FIGURE 12** Weighted average of pump-related CO\textsubscript{2}e emissions (g/kWh) over the 48-hour average duty cycle per U.S. Well Services’s manufacturer (OEM) specifications-based model.
Results
As shown in Figure 13, below, the GHG Protocol estimates the smallest emissions reductions of all methods: the difference between Tier II/IV diesel and CleanFleet® is only 9%. However, as discussed previously, this protocol cannot distinguish between, e.g., Tier II versus Tier IV diesels, nor does it give you a full picture of the emissions because it only calculates direct greenhouse gas emissions (CO\(_2\) and CH\(_4\)). Hence, the GHG Protocol can be considered the most conservative estimate of savings available through electric hydraulic fracturing.

On the other hand, using the EPA’s fuel-based “Center for Climate Leadership” standard shows the widest spread: using this protocol, CleanFleet® saves an unrealistic 91% on CO\(_2\)e emissions versus diesel! But this EPA Fuel method suffers many of the same drawbacks as the GHG Protocol: it calculates only direct greenhouse gas emissions and fails to distinguish different generations of prime mover technologies, impeding our ability to differentiate Tier II and Tier IV diesel engines or electric turbines with and without water injection.

As always, the truth is somewhere between the extremes. The U.S. EPA’s Equipment-based AP-42 standard, the first of the emission-factor-based methods to consider indirect GHGs, shows CleanFleet® produces a 62% emissions reduction versus Tier IV diesel. However, this standard again fails to consider

FIGURE 13
Comparing normalized pump-related CO\(_2\)e emissions (g/kWh) by emissions calculation methodology

*Figure 13: Comparison of pump-related CO\(_2\)e emissions (g/kWh) by emissions calculation methodology.*
the nuances between later, higher efficiency generations of technologies (e.g., Tier II versus Tier IV diesel and higher substitution rates in dual fuel engines).

As expected, our OEM-specifications model consistently came in with higher emissions than the other methods; after all, manufacturers are legally held to achieving no higher than their published specifications. Yet, our OEM-based model strikes a balance on the conservative side: underestimating diesel emissions and overestimating turbine emissions.

Using this model, a dry CleanFleet® reduces CO₂e emissions by 29% versus Tier IV diesel and 22% versus dual-fuel operating at a highly optimistic 75% natural gas substitution rate.

Additionally, compared to traditional Tier IV diesel, the specifications-based model projects that CleanFleet® reduces pump-related NOₓ by 28%. Similarly, a water-injected CleanFleet® cuts pump-related CO₂e by 21% and NO₂ by 86% compared to a fleet using Tier IV dual-fuel engine with a 75% substitution rate.

The only indirect emission that the specifications-based model shows CleanFleet® does not reduce is carbon monoxide (CO). CleanFleet® turbines provide more-complete combustion than internal-combustion engines, reducing CO₂, CH₄, NOₓ, and particulate matter (PM) emissions.¹⁵ However, USWS continues to seek technologies to lower all emissions.

And these modeled pump-related emissions reductions likely underestimate the true impact of using CleanFleet®. Whereas traditional operations use additional diesel or dual-fuel generators to power ancillary loads, USWS powers its blenders, field-gas conditioning, sand equipment, control van, and lights using the reserve capacity of the on-site generator(s).


**USWS’s state-of-the-art CleanFleet® technology helped Range make progress towards our emissions reduction goals while generating operational cost savings. In 2019, between the contributions of our team and CleanFleet®, we achieved a 52% reduction in greenhouse gas emissions from combustion sources.**

— RANGE RESOURCES
Case study: In-field emissions measurements

Per IPCC guidelines, U.S. Well Services (USWS) seeks the most accurate emissions data we can get. So, in addition to modeling the emissions of its fleets, we perform emissions testing on our fleets throughout the duty cycle, using TCEQ- & NELAP-certified third-party contractors using 40 CFR 60 & 40 CFR 63 approved methodologies.

After normalizing on-site emissions measurements collected from February to July 2020 from our Tier II and Tier IV diesel fleets and CleanFleet® fleets with and without water injection by power output (Hp-hr), we applied these measured rates to our assumed 48-hour duty cycle (Figure 14). USWS does not operate any dual fuel fleets, and therefore does not have on-site emissions measurements for this technology.

These measured results show some variations compared to our manufacturer-based models. As expected, Tier II diesel CO₂ e was higher than our specifications-based model as a result of testing older equipment versus models that assume like-new specifications; however, newer Tier IV diesel engines and CleanFleet® fleets with and without water injection tested below manufacturers’ specifications.

All technologies’ NO₂ emissions tested at least 50% below the manufacturer’s specifications. Tier II diesel fleets produced slightly more CO than modeled,

FIGURE 14 Field-measured pump-related emissions (g/kWh) over the 48-hour duty cycle

<table>
<thead>
<tr>
<th>Technology</th>
<th>CO₂ e (g/kWh)</th>
<th>NO₂ (g/kWh)</th>
<th>CO (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel (Tier II)</td>
<td>10.19</td>
<td>0.64</td>
<td>1.80</td>
</tr>
<tr>
<td>Diesel (Tier IV)</td>
<td>9.32</td>
<td>0.40</td>
<td>0.05</td>
</tr>
<tr>
<td>Dual Fuel (Tier IV; 0% NG)</td>
<td>Not measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual Fuel (Tier IV; 75% NG)</td>
<td>Not measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CleanFleet® (dry)</td>
<td>5.26</td>
<td>1.24</td>
<td>0.09</td>
</tr>
<tr>
<td>CleanFleet® (wet)</td>
<td>5.40</td>
<td>0.35</td>
<td>0.32</td>
</tr>
</tbody>
</table>

FIGURE 14 Onsite testing of USWS’s Tier II diesel, Tier IV diesel and electric fleets confirms that CleanFleet® produces considerably lower emissions than diesel. Most notably, NO₂ and CO emissions tested far below levels expected based on the manufacturer’s specifications.
while CleanFleet® fleets with and without water injection reduced CO emissions by 87% and 65%, respectively, compared to our specification-based model.

Despite these variations from the model, these third-party-collected, field-based measurements correlate better to USWS’s specifications-based model than any of the other emissions methodologies evaluated and fall well within the range of results expected. Figure 15, below, switches Figure 14’s categorical axis to show the spread of emissions results by prime-mover technology.

From this view, it is clear that USWS CleanFleet® fleets — with and without water injection — outperform both diesel and dual fuel fleets: at its worst, CleanFleet® still reduces emissions compared to a dual-fuel engine hitting a rarely attainable 75% natural gas substitution rate operating at its best.

Overall, on a technology-versus-technology basis, these measurements prove CleanFleet® is the clear winner: versus a comparable Tier IV diesel fleet, a water-injected CleanFleet® cuts CO₂e emissions by 42% and NOx emissions by 12%. Similarly, a CleanFleet® without water injection cuts CO₂e by 44%.

**FIGURE 15**
On-site testing of USWS’s Tier II diesel, Tier IV diesel and electric fleets confirms that CleanFleet® produces considerably lower emissions than diesel. Most notably, NOx and CO emissions tested far below levels expected based on the manufacturer’s specifications.

**FIGURE 15** Measured vs. modeled pump-related CO₂e emissions (g/kWh) by prime mover

- Diesel (Tier II)
- Diesel (Tier IV)
- Dual fuel (Tier IV; 0% NG)
- Dual fuel (Tier IV; 75% NG)
- CleanFleet® (dry)
- CleanFleet® (wet)
Today, no diesel or dual-fuel idle-reduction technology completely eliminates idling because of diesel engines’ warm-up and cool-down requirements. However, to test the sensitivity of our results to the future evolution of idle-reduction technologies for diesel and dual-fuel systems, USWS re-ran calculations assuming no fuel use during idle for diesel and dual-fuel technologies — the equivalent of the best possible idle-reduction technology.

Without the emissions incurred at idle, dual-fuel becomes more competitive with electric; after all, dual-fuel relies on 100% diesel during idle. As shown in Figure 16, above eliminating idle on a Tier IV dual-fuel engine narrows CleanFleet® CO₂e emissions reduction to 18% according to our specifications-based model. However, with the assumed 73% pump utilization, the impact is minor for Tier IV diesel (26% for a Tier IV diesel using the best-possible idle technology versus 29% without idle-reduction technology).

**FLARING UNUSED FIELD GAS**

CleanFleet® produces additional emissions reductions when using field gas that would otherwise be required to be flared.

While jurisdictional regulations and operators’ commitments to reducing their carbon footprints make flaring less common, certain situations still require field gas be flared. Electric hydraulic fracturing and, to a lesser extent, dual-fuel technologies enable an alternate use for field gas.

**FIGURE 16** Pump-related CO₂e emissions (g/kWh) by prime mover, excluding idle for diesel & dual fuel

<table>
<thead>
<tr>
<th>Diesel (Tier II)</th>
<th>Diesel (Tier IV)</th>
<th>Dual fuel (Tier IV, 0% NG)</th>
<th>Dual fuel (Tier IV, 75% NG)</th>
<th>CleanFleet® (dry)</th>
<th>CleanFleet® (wet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
<td>400</td>
<td>600</td>
<td>800</td>
<td>1000</td>
</tr>
<tr>
<td>GHG Protocol</td>
<td>EPA Fuel</td>
<td>EPA Equipment</td>
<td>OEM specifications</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**USING BEST POSSIBLE IDLE-REDUCTION TECHNOLOGY**

Eliminating idle emissions makes dual fuel more competitive with CleanFleet®.
We have fracked eleven wells on four different pads with CleanFleet®. On a single-well basis, we realized more than $250,000 in diesel savings alone while reducing emissions.

— APACHE CORPORATION

Assuming a traditional diesel operation would flare the same quantity of natural gas as the CleanFleet® site consumed and a 98% flare efficiency, a CleanFleet® reduces CO₂e emissions by more than 60%, as shown in Figure 17, below. Similarly, CleanFleet® still cuts CO₂e emissions by more than 37% compared to a Tier IV dual-fuel engine with a 75% substitution rate that flares the remaining field gas.

**Economics**

Cutting greenhouse gas emissions, reducing noise, improving operational efficiencies, and increasing safety are great — so long as they’re cost-effective: it all comes down to the bottom line. And, here again, CleanFleet® comes out ahead.

While capital cost of an electric hydraulic fracturing fleet exceeds the capital cost of a similarly rated diesel or dual-fuel fleet, the extended lifetime of the equipment enables U.S. Well Services (USWS) to offer its electric frac fleets at a rate competitive with diesel & dual-fuel fleets. But operating a CleanFleet® is

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**FIGURE 17**

Using field gas that would otherwise be flared is one key benefit of CleanFleet® that greatly decreases its environmental impact versus diesel and dual-fuel technologies.

---

**FIGURE 17** Pump-related plus flared field gas CO₂e emissions (g/kWh) by prime mover and emissions calculation methodology
more cost-effective for two reasons: (1) the fuel cost savings by eliminating diesel; and (2) the revenue generated by pumping more hours each day.

**Fuel cost savings**

Using on-site field gas that would otherwise be flared has the potential to reduce fuel costs by more than 85% versus Tier IV diesel. Even when you evaluate your operating costs on a horsepower-by-horsepower basis considering a wide range of oil prices and its effect on commodity prices, on-site field gas always provides the lowest-cost and least cost-volatile solution, as shown in Figure 18, above.

Even after taking into account the additional fees associated with leasing gas conditioning equipment to ensure the heat content and consistent pressurization required to fire the dual fuel engine or natural-gas turbine, CleanFleet® using CNG saves more than $250,000 — or 23% — per month versus Tier IV diesel at $45 per barrel, as shown in Figure 19, next page.

---

**FIGURE 18** Fuel cost (USD) per stage for 18,013 hhp, 159-minute stage duty cycle at varying WTI prices

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>WTI ($/barrel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel (Tier IV)</td>
<td>$3,000</td>
</tr>
<tr>
<td>Dual fuel (Tier IV; 75% CNG)</td>
<td>$6,000</td>
</tr>
<tr>
<td>Diesel (Tier II)</td>
<td>$9,000</td>
</tr>
<tr>
<td>Dual fuel (Tier IV; 75% field gas)</td>
<td>$12,000</td>
</tr>
<tr>
<td>CleanFleet® (CNG)</td>
<td>$15,000</td>
</tr>
<tr>
<td>CleanFleet® (field gas)</td>
<td>$18,000</td>
</tr>
</tbody>
</table>

**FIGURE 18**

CleanFleet® provides the lowest cost per stage and least cost-volatile solution for our assumed duty cycle at a variety of WTI prices ($/barrel). See Figure 19 (page 36), table for additional scenario assumptions.

---

Need fuel cost savings & emission reduction estimates for a different duty cycle? Email info@uswellservices.com for your custom calculation.

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17 Diesel = State & federal tariffs (assumed = $0.44/gal) + Transport fee (assumed = $0.50/gal) + [WTI ($/barrel) ÷ 42 gal/barrel]

18 Relationship between WTI, mean seasonal natural gas prices, and seasonal variations as described by P. Hartley, K. B. Medlock III, & J. Rosthal, "The Relationship between Crude Oil and Natural Gas Prices," The James A. Baker III Institute for Public Policy at Rice University (November 2007).

Maintenance

Greater pump hours and higher utilizations mean more production and higher-revenue wells.

Natural gas turbines and electric motors do not require transmission or radiator repairs, oil changes, and other routine maintenance that traditional diesel and dual fuel engines do. Hence, USWS’s CleanFleet®, utilizing USWS’s proprietary FracMD® diagnostics, reduces the pumps’ damage accumulation rate by up to 64% — thereby increasing pump hours by up to 30%.

EP Energy found that, with CleanFleet®, “The company increased average pumping hours per day by 30% in its first three pads.” Similarly, Shell reported, “Maintenance-related downtime was so remarkably low, we were able to achieve a rhythm in our operations that’s difficult to obtain over an extended time with a traditional fleet.”

FIGURE 19
Monthly (28 days) fuel cost estimate for our 18,013 hhp, 159-minute stage time, 72% pump utilization duty cycle by prime mover at varying commodity prices, including $350 per day CNG conditioning equipment rental costs and $1,250 per day fuel delivery fee for CNG & diesel. Excludes the cost of fuel consumed during idle for diesel and dual-fuel units.

<table>
<thead>
<tr>
<th>West Texas Intermediary ($US/barrel)</th>
<th>$10</th>
<th>$45</th>
<th>$80</th>
<th>$115</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel price ($/gal)</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>CNG ($/mcf)</td>
<td>6.53</td>
<td>11.58</td>
<td>15.97</td>
<td>20.07</td>
</tr>
<tr>
<td>Field gas netback ($/mcf)</td>
<td>0.15</td>
<td>1.52</td>
<td>2.72</td>
<td>3.84</td>
</tr>
<tr>
<td>Diesel (Tier IV)</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>Diesel (Tier II)</td>
<td>595,125</td>
<td>932,012</td>
<td>1,268,900</td>
<td>1,609,845</td>
</tr>
<tr>
<td>Dual fuel (75% CNG)</td>
<td>531,657</td>
<td>887,657</td>
<td>1,209,975</td>
<td>1,518,678</td>
</tr>
<tr>
<td>CleanFleet® (CNG)</td>
<td>472,842</td>
<td>830,937</td>
<td>1,142,232</td>
<td>1,432,962</td>
</tr>
<tr>
<td>Dual fuel (75% field gas)</td>
<td>206,067</td>
<td>374,266</td>
<td>533,790</td>
<td>690,415</td>
</tr>
<tr>
<td>CleanFleet® (field gas)</td>
<td>10,636</td>
<td>107,783</td>
<td>192,875</td>
<td>272,294</td>
</tr>
</tbody>
</table>
Conclusion
As a provider of both traditional diesel and electric frac technologies, U.S. Well Service (USWS) knows which technology has the smallest environmental footprint — and it’s electric.

This analysis reviewed data from more than 45 days of diesel and electric hydraulic fracturing to establish an average 48-hour duty cycle for hydraulic fracturing in Texas. Per IPCC and U.S. EPA recommendations, USWS relied on the most accurate emissions methodologies available to it — both collecting on-site data and modeling emissions using manufacturer specifications.

On-site testing demonstrated slight variations versus our model, as expected; after all, the specifications-based emissions model assumes like-new equipment. Yet, in all cases, CleanFleet® comes away the clear winner: in testing, a water-injected CleanFleet® cuts CO₂e emissions by at least 42% and NO₂ emissions by at least 12% compared to a Tier IV diesel fleet; versus a Tier IV dual fuel fleet achieving a 75% substitution rate, our models show a water-injected CleanFleet® cutting CO₂e by at least 20% and NO₂ by at least 86%.

Additionally, when utilizing site-produced field gas, CleanFleet® can save more than 85% on fuel costs compared to traditional diesel, and more than 60% compared to dual-fuel systems. On top of that, CleanFleet® can unlock additional efficiencies by reducing breakdowns, increasing pump hours, and thereby completing wells faster — and generating revenue sooner.

The bottom line? USWS’s CleanFleet® shows that electric hydraulic fracturing is cleaner, more productive, and lower cost than diesel and dual-fuel systems.

As a result of working with USWS, we have reduced noise pollution, eliminated more than 16 million gallons of diesel from our operations, and reduced emissions by more than 70%. We executed these achievements at efficiency levels exceeding those realized with conventional equipment — demonstrating that environmental performance and financial success can be combined to achieve outstanding results.

— EQT CORPORATION
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CHIEF TECHNOLOGY OFFICER
Lon Robinson, the Chief Technology Officer at U.S. Well Services, has extensive knowledge in engineering equipment design and leadership of design processes. Robinson’s career in oil & gas includes many design and management positions, including Senior Technology Manager at Halliburton, where he led a department of over 100 engineers, designers, and technicians; Chief Global Technical Advisor at Halliburton; and engineering management roles at Superior Well Services and the Keane Group. Robinson earned his degree in mechanical engineering from Texas Tech University. He is a member of the Academy of Mechanical Engineers at Texas Tech, is a registered professional engineer, and holds a project management professional certification. Lon holds multiple patents related to hydraulic fracturing and other heavy equipment.

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NATURAL GAS PROCESS ENGINEER
Vanessa M. Hordijk is a senior chemical engineer with 23 years of experience in the oil & gas industry, where her experience ranges from development to commercial delivery, including R&D, equipment design, process and project engineering, field operations, and technical service. Hordijk received her bachelor’s in chemical engineering from Tuskegee University. Currently, she serves as a Natural Gas Process Engineer for U.S. Well Services. In this role, Hordijk provides technical support for all gas-processing engineering and related issues pertaining to CleanFleet®, including fueling sources, air emissions, and operations of the gas turbines.
About USWS
U.S. Well Services LLC (USWS) provides high-pressure, hydraulic fracturing services in unconventional oil and natural gas basins. Our clients benefit from the performance and reliability of our equipment and personnel. All of our fleets operate on a 24-hour basis — enabling the high utilization rates that result in more efficient operations.

We’re powering oilfield innovation
With 34 patents granted and 104 more pending, USWS is committed to mitigating the environmental impact of hydraulic fracturing, and we continue to innovate new technologies as we push towards this goal.

In 2013, a goal to reduce the noise and emissions produced by our diesel fleets led to the creation of our CleanFleet®, the industry’s first fully electric mobile hydraulic fracturing fleet. Over the past seven years, we’ve completed over 18,000 pumping stages with CleanFleet® — more than any other pressure pumping company with electric frac equipment. In addition to being cleaner and more economical than diesel and dual-fuel systems, CleanFleet® lowers window-rattling dBₐ by up to 95% and reduces average sound pressure by 69% — enabling operators to frac closer to residences and opening up new siting possibilities. And we’re continuing to lead the way with our industry-leading predictive maintenance analytics; our high-voltage, long-distance microgrid solution; our innovative gas conditioning and pressurizing system; our revolutionary slickwater, linear gel, and crosslink replacement product; and more.

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