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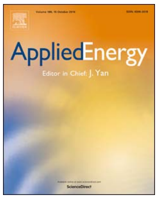

Greenhouse gas emissions and fuel efficiency of in-use high horsepower diesel, dual fuel, and natural gas engines for unconventional well development

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HIGHLIGHTS

- Dual fuel is advertised to reduce diesel consumption by up to 70%.
- When correcting for methane slip, peak substitutions were up to 58%.
- GHG emissions of dual fuel operation were 2.2 and 1.65 times higher than diesel only and natural gas, respectively.
- Dual fuel and dedicated natural gas engines have lower efficiencies than diesel only.
- Even when accounting for methane slip these technologies do offer economic benefits.

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ABSTRACT

We collected data focusing on in-use emissions and efficiency of engines servicing the unconventional well development industry to elucidate real world impacts from current and newly applied engine technologies. The engines examined during the campaigns were diesel only (DO) and dual fuel (DF) diesel/natural gas, compression-ignition (CI) engines and dedicated natural gas, spark-ignition (SI) engines. These included two CI drilling engines outfitted with two different DF kits, two SI drilling engines, and two CI well stimulation engines. Our data were gathered under the load and speed requirements in the field, and the engines were not under our direct control. Greenhouse gas (GHG) emissions were measured from all engines and fueling types and included both exhaust and crankcase emissions. Fuel consumption and engine data were collected to determine fuel efficiency. During steady-state operation, fuel efficiency was 38%, 26%, and 20% for DO, DF, and SI engines, respectively. The loss of efficiency during DF operation was due in part to uncombusted methane (CH_4) slip in the exhaust, which accounted for 18% of the fuel supplied. GHG emissions (carbon dioxide and CH_4) from CI engines were 2.25 times higher during DF compared to DO operation. During DF operation, substitution ratio varied depending on engine load and DF kit, ranging from 9% to 74%. GHG emissions from the SI engines were 1.33 times higher than DO due to lower efficiencies of throttled and rich operation as compared to unthrottled and lean operation for CI engines.

Abbreviations: BSFC, brake-specific fuel consumption; C_2H_6, ethane; C_3H_8, propane; CH_4, methane; CI, compression-ignition; CO, carbon monoxide; CO_2, carbon dioxide; CO_{2eq}, carbon dioxide equivalent; CR, compression ratio; DF, dual fuel; DGB, dynamic gas blending; DLE, diesel liter equivalent; DNG, dedicated natural gas; DO, diesel only; DOC, diesel oxidation catalyst; ECU, engine control unit; EIA, Energy Information Administration; EPA, US Environmental Protection Agency; FG, field gas; g, grams; GHG, greenhouse gases; GREET, greenhouse gases, regulated emissions, and energy use in transportation; GWP, global warming potential; HC, hydrocarbon; kg, kilograms; kW, kilowatts; kW-h, kilowatt-hours; LHV, lower heating value; LNG, liquefied natural gas; LLT, low-load transient (drilling operation); m, meters; m^3, cubic meters; M, million; MJ/SCM, mega-Joules per standard cubic meter; MN, methane number; MW-h, megawatt-hours; N_2, nitrogen; N_2O, nitrous oxide; NG, natural gas; NMHC, non-methane hydrocarbons; NO_x, oxides of nitrogen; rpm, revolutions per minute; SCM, standard cubic meters; SI, spark-ignition; SR, substitution ratio; SS, steady-state (drilling operation); THC, total hydrocarbons; TWC, three-way catalyst; US, United States; WVU, West Virginia University; ZECE, zero emissions conversion efficiency; °C, degrees Celsius; $, US Dollars

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1. Introduction and background

An energy revolution has occurred due to technological advances in directional drilling and hydraulic fracturing. These technologies have increased natural gas (NG) reserves such that they are estimated to last the United States (US) 93 years [1]. One of the key sectors benefitting from an abundance of low cost gas is power generation. Numerous analyses have been conducted examining the conversion of vehicles and/or power plants to use this new resource [2,3]. NG is touted as a low carbon fuel because it has the highest hydrogen to carbon ratio and a higher heating value on a mass basis than fuels such as gasoline. However, when switching to NG, overall system efficiency must be examined along with any NG leaks across the supply chain to assess climate benefits [4]. Alvarez et al. showed that methane (CH_4) leaks across the supply chain must be less than 1.0 and 3.2% to have net benefits for fuel switching for heavy-duty diesel vehicles and power plants, respectively [2]. Others have suggested that benefits occur if the net leakage rates are less than 2.9%, but also noted that losses are typically higher across the supply chain when NG prices are low [3]. To examine the total greenhouse gas (GHG) emissions one must include not only CH_4 leakage but also all carbon dioxide (CO_2) or CO_2 equivalent (CO_{2eq}) emissions across the entire supply chain from development to end use. Such analyses are often called wells to wheels, wells to combustion, or wells to tank [5]. Such studies require collection of an array of data sets from numerous sources and assumptions from across many sectors in order to estimate entire life cycle emissions. A recent study showed that NG from the Marcellus shale could have a GHG footprint of only 53% of coal [6]. They estimated that GHG emissions during stimulation of these new unconventional sources represented about 1.2% of the total life cycle emissions.

This subsector includes the energy consumption and GHG emissions from the development of new unconventional gas wells. On-site execution of these new extractive technologies require significant energy and are often powered by onsite compression-ignition (CI) diesel engines. On average at a site, drilling rigs consist of 2.15 engines, with an average size of 1030 kilowatts (kW). These engines operate 62.6 h per 305 meters (m) drilled, at an estimated average load of 48.5% [7]. With continued advances in technology, the length and depth of these new unconventional wells continue to increase [8]. In 2016, Halliburton completed the longest well with a lateral length of 5639 m and total length of 8244 m [9]. The well included 124 "frack" stages. High-horsepower diesel engines also power hydraulic fracturing pumps and the longest US well utilized dual fuel (DF) stimulation engines to reduce fuel consumption by 40%. Total engine capacities for fracturing spreads may be 14,914 kW or more as each site requires anywhere from eight to nearly two dozen stimulation pumps. Typically, a diesel engine rated between 1119 and 1864 kW [10] powers each pump. We reviewed recent literature and found that average fuel consumption per well for vertical drilling, horizontal drilling, and hydraulic fracturing was 50,876, 232,553, and 79,494 l, respectively [11]. Fuel consumption increases with length of the well and number of fractured stages. As such, unconventional well development is also expensive – average horizontal well costs range from $1.8 M to $2.6 M while well completion ranges from $2.9 M to $5.6 M [12]. Note $ is US Dollars.

Recently, researchers at Stanford developed "*GHGfrack*", an open source model aimed at estimating GHG emissions from drilling and stimulation of unconventional wells [13]. Their model uses CO_2 emissions factors for diesel fuel of 0.269 kg (CO_{2eq}) per kilowatt-hour (kW-h) of lower heating value (LHV) as does the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) Model [13,14]. *GHGfrack* requires additional information regarding details such as drill rates and flow rates to estimate the total CO_{2eq} emissions. Their results showed that, in all four analyzed cases, hydraulic fracturing yielded the highest fuel consumption and highest GHG emissions as compared to drilling. This paper will examine the CO_{2eq} emissions compared to those emission factors used in literature [13,14]. It is also noted that other studies have tried to indirectly quantify GHG emissions from well sites during the development stages [15] but such methods cannot relate GHG emissions to the prime-movers since measurement results represent the entire site. Since little in-use data are available and rely on older emissions factors, we present these in-use results to represent new emissions rates not only for prime-movers using conventional diesel fuel but also newly applied technologies that include dedicated and DF engines which are seeing additional market penetration. These data can be used by industry, regulators, and researchers to understand the current strengths and weaknesses from application of these technologies. In addition, this analysis produces the first in-use evaluation and emissions factors from these technologies. Industry is likely to continue to invest in these new technologies to reduce energy consumption and their associated costs, but such investments must include a broad understanding of the implications on GHG emissions and efficiency of new cost saving measures [16]. Accurate and direct baseline quantification of GHGs is crucial to reducing uncertainty and establishing mitigation targets [17].

One method to reduce operating costs is to reduce diesel fuel consumption by replacing it with NG. For example, a fracturing fleet of 14,914 kW could consume 3785 l of fuel per day, which is nearly $50,000 per day. Diesel fuel prices are typically more volatile than NG, which typically retains a three to one price advantage [18]. DF conversion kits allow for substitution of NG into the engine intake, providing energy for combustion thus decreasing diesel fuel demand. In addition to current cost reductions, the demand for diesel fuel is expected to grow faster than other fuels through 2040 [19]. Researchers have suggested that such an increase could disrupt the energy production sector, as the distribution of energy demand would be unbalanced [20]. The same study highlighted that DF or DNG engines and other alternative fuels could help offset this imbalance but that any analysis must include any CH_4 emissions, which could offset GHG reductions [20]. Others have also suggested that increasing the use of DF engines could offer future balance and they provide an extensive review of DF combustion and emissions [21]. DF systems are subject to the emissions standards of their respective diesel engines, but off-road engines are not subject to GHG or fuel efficiency standards.

An alternative to partial reduction in diesel fuel consumption is to use only NG as fuel. Currently this requires use of spark-ignition (SI) engines such as the Waukesha L7044GSI. Both fueling methods are also capable of using field gas depending on quality, which eliminates refining, processing, and transmission (by pipeline or truck) costs and the respective GHG emissions. For reference, the average price of diesel fuel for 2016 was $0.61/l [22]. The 2016 average Henry Hub price for NG was $8.60 per megawatt-hour (MW-h) [23]. Approximately 0.76 kilograms (kg) or 1.04 standard cubic meters (SCM) of NG yields the energy in a diesel liter equivalent (DLE) [24]. Based on the Henry Hub price, this yields a NG cost of around $0.09/DLE.

Diesel engines are typically favored for their efficiency and durability. Modern on-road diesel engines typically have efficiencies around 43–44% [25]. The most efficient four-stroke CI engine is above 50% [26]. Diesel engines are also inherently more efficient than SI engines that are impacted by compression ratio (CR) limitations, throttling, low volumetric efficiency (especially for gaseous fuels), and lean operation [27].

1.1. Dual fuel combustion

Current DF conversion kits utilize NG fumigation, which introduces NG prior to the intake air compressor. The added NG reduces the diesel fuel required to meet a target engine power. Systems are calibrated over the entire load range and utilize engine parameters to determine the substitution ratio of NG. However, the fuel substitution map is limited on the lower end due to misfire or incomplete combustion of the dilute fuel gas, and on the upper end due to knocking [28]. In some cases, increased NG substitution has been shown to decrease brake-specific