The CARBON INTENSITY of NGV C8 TRUCKS

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Abstract

Natural gas combustion emits about three-fourths the tailpipe carbon dioxide of diesel. However, upstream emissions contribute to the carbon intensity of natural gas, such as combustion CO2 from burning fuel for energy used upstream, and fugitive emissions of CH4, that must be incorporated to estimate the true CO2 intensity of natural gas usage. Here I use the Argonne's GREET1 2014 model to calculate the well-to-wheels carbon intensity of Class 8 NGV trucks and compare it to that of incumbent diesel trucks. These calculations incorporate recent findings on fugitive emissions of methane along the US natural gas supply and distribution network, and differences in vehicle engine technologies and in natural gas storage. Simulations reveal that the relative lower engine efficiency of NGVs is the main contributor to the higher carbon intensity of NGVs when compared to diesel, and only the more efficient HPDI natural gas technology is preferable to diesel up to 3% leakage rate. Importantly, CNG storage is more sensitive to leakage than LNG storage: reducing leakage reduces the carbon intensity CNG but has a minimal effect on LNGs. The higher sensitivity of CNG to leakage is due to a supply chain that includes local natural gas distribution networks for distribution to the gas station, where it is compressed, whereas in the case of LNG distribution occurs from centralized liquefaction plants to the stations by trucks. Even when LNG boil-off in the truck is taken into account, the fugitive methane emissions in the LNG supply chain are of a smaller magnitude than in CNG. Although in both cases the single most important factor is the efficiency of the final fuel-to-useful work conversion process (i.e., increase natural gas engine efficiencies) the strategies to reduce the carbon intensity of natural gas as a fuel depend on the fuel storage. Reducing methane leakage is effective in the case of CNG and increasing upstream efficiencies is effective in the case of LNG.

Introduction

The Shale Revolution is providing abundant and cheap domestic natural gas, making it an attractive economic option in transportation in North America. Globally, natural gas is already used as a transportation fuel. There are currently around 17.7 million natural gas vehicles operating worldwide, the vast majority of which are light duty vehicles[1]. Iran and Pakistan represent the largest markets for natural gas vehicles (NGVs) at around 3 million each. Other large markets for light duty NGVs are India, Argentina and Brazil with 1.5 to 2 million each. China has seen rapid development of NGVs, which have increased from 60,000 NGVs in 2000 to more than 1.5 million on the road currently. China currently has 70,000 LNG trucks on the road, and the country's 12th Five Year plan encourages the development of liquefied natural gas (LNG) vehicles[2].

In the United States, there are only 118,000 CNG and 3,400 LNG natural gas vehicles on the road, according to the Energy Information Administration[3]. Although natural gas vehicles have been favored by air quality agencies for the cleaner burning properties of natural gas, only fleets that could manage their own refueling infrastructure, such as taxis, buses and refuse trucks, have been early adopters of natural gas as a fuel. More recently, companies with long-haul truck operations have expressed their interest in embracing this fuel. The 3,400 LNG trucks that are in operation represents only 0.1% of the US current truck fleet, which is estimated in around 2 million trucks[4].

US trucks transport around 9.2 billion tons of freight and drive around 163 billion miles in a year[4] .The majority of these trucks are powered by diesel[4]. Diesel is often the second highest expense for motor carrier after labor and can be as much as 20% of operating costs. In recent years, LNG and CNG fuel has seen a \$1-\$2 discount to diesel on a diesel gallon equivalent basis.[5] Such low prices are creating an incentive for a shift in the long haul truck freight industry, and investment in infrastructure supporting a public natural gas refueling network has emerged.

The heavy duty trucking industry contributes up to 21% of total road transportation greenhouse emissions (5% of total US emissions)[6]. To date, a shift from diesel to natural gas in long haul trucking operations is considered beneficial to carbon (CO_2) emissions, as natural gas trucks emit less tailpipe carbon dioxide[7]. But natural gas production supply chains leak methane, a powerful warming gas, and as more information about the level of this leakage has emerged, scientists have begun to call into question the climate benefit of using natural gas in different types of vehicles. This research seeks to advance the scientific knowledge about the climate effects of

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[1] NGV Europe. Global statistics. http://www.ngvaeurope.eu/worldwide-ngv-statistics
[2] UC Davis China Workshop October 2013
[3] EIA FAQs. How many alternative fuels and hybrid vehicles are there in the US? http://www.eia.gov/tools/faqs/faq.cfm?id=93&t=4
[4] National Transportation Statistics.2014. USDOT. Bureau of Transportation Statistics http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/NTS_Entire_14Q4.pdf
[5] http://www.eia.gov/petroleum/gasdiesel/
[6] http://climate.dot.gov/about/transportations-role/overview.html
[7] How much carbon dioxide is produced when different fuels are burned? http://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11

shifting heavy duty class 8 trucks in the United States to natural gas, and compare them to the life cycle analysis of incumbent fuels.

The well-to-wheels carbon intensity of natural gas as a fuel will be affected by the level of upstream emissions. For example, CO2 can be emitted as a waste byproduct of energy required in upstream processes (combustion CO2) or vented from oil and gas fields (non-combustion CO2). Methane is leaked or vented during natural gas and oil operation (non-combustion methane), but it also results from incomplete combustion during energy generation for upstream processes that use natural gas as a fuel and during flaring operations (combustion methane).

Previous studies have focused on natural gas climate performance in electricity generation[8,9]. A few studies have looked at the carbon intensity of natural gas vehicles, mostly passenger vehicles and transit buses[10], as these applications are the most common transportation applications in the US historically. The cost advantage of natural gas for commercial trucking has received increased attention in recent years[11]. We contribute to this literature by considering the climate performance of a shift to liquefied natural gas (LNG) for heavy duty class 8 trucks.

Several U.S. states, including Oklahoma and Utah, have policies to promote natural gas vehicle use and investment. Commercial forecasts for how much natural gas could replace oil in transportation vary widely, with high end estimates in the millions of barrels per day (mbd)[12]. That’s 5% to 10% of the total available market of about 13 mbd, or more than 25% to 50% of the existing 3.9 mbd market for diesel. At least two firms, Clean Energy Fuels, and ENN have begun building LNG fueling stations in the United States. There are currently 59 public LNG fueling stations and 42 private LNG fueling stations along routes from Los Angeles to Las Vegas, around Houston and around Chicago. The stations currently serve a fleet of 3,400 LNG trucks. California is the state with the largest number of LNG fueling stations, serving over 200,000 gallons a day, with local facilities in Tulare, Lodi, Fontana, Lost Hills, San Diego, Aurora and Ripon, among others. Zeuss Intelligence reports that there are 34 LNG supply plants with trailer loadout capable of producing about 3 million gallons of LNG a day[13]. The United States has over 800 compressed natural gas (CNG) fueling sites of which a little under half are public.[14] Several

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[8] Weber CL, Clavin C (2012) Life Cycle Carbon Footprint of Shale Gas: Review of Evidence and Implications. *Environ Sci Technol* 46:5688–5695.

[9] O'Donoughue PR, Heath GA, Dolan SL (2014) Life Cycle Greenhouse Gas Emissions of Electricity Generated from Conventionally Produced Natural Gas - Journal of Industrial Ecology

[10] Alvarez RA, Pacala SW, Winebrake JJ, Chameides WL, Hamburg SP (2012) Greater focus needed on methane leakage from natural gas infrastructure. *PNAS* vol. 109:6435–6440

[11] Rood Werpy M., Santitni D., Burnham A., and Mintz M., Argonne National Laboratory “White Paper on Natural Gas Vehicle: Status, Barriers, and Opportunities September 2009

[12] In its June 2013 report, “Energy 2020:Trucks, Trains and Automobiles,” Citi Group projects that a shift to liquefied natural gas (LNG) for heavy trucking could eliminate 1.2 to 1.8 mbd of U.S. diesel demand by 2030 and 3.4 mbd globally.

[13] Provided to authors by Zeuss Research consultants

[14] http://www.afdc.energy.gov/fuels/stations_counts.html

national fleets are deploying natural gas trucks, including: Cisco, Pepsi, Walmart, Frito-Lay, HEB, Trimac Transportation, Truck Tire Service Corporation (TTS), Verizon, UPS, AT&T, Food Lion, and Ryder.

Given this interest in LNG and CNG for long distance trucking, we investigate the environmental consequences to a major shift to natural gas fuel specifically to its use in class 8 heavy duty vehicles. We contend that results from the earlier studies on light duty natural gas vehicles and buses should not be generalized to all NGVs without care, as different applications have different engine efficiencies or substitute a different fuel (i.e., diesel rather than gasoline), as we will show, will have an impact on results.

We consider different available technologies for natural gas class 8 engines. For example, natural gas can be used in spark ignition (Si) or compression ignition (Ci) (i.e., Westport's HPDI model) engines, the latter using a diesel ignition pilot. The engine efficiency of Si engines is about 10-15% lower than the HPDI, which greatly impacts the final results. Natural gas can be stored as compressed (CNG) or liquefied (LNG), and this also has implications for emissions.

Life Cycle Analysis models such as Argonne's GREET or California Air Resources Board's (CARB) CA-GREET have been used to do this kind of analysis and can produce a differing range of estimates. How modelers choose to weight methane's warming potential is important to interpreting analysis of natural gas' climate performance. We consider such differences in discussing our analysis. We also find that data limitation is another reason for caution. Upstream methane emissions are typically obtained from the US Environmental Protection Agency's (EPA) Greenhouse Gas Inventory (GHGI)[15], which provide a national average methane leakage during different processes in the pre-production, production and processing, and distribution of fossil fuels. However, data on vehicle and refueling station leakage are absent in the inventory. In addition, several studies have contested EPA's estimates[16,17,18], creating more interest in understanding the differences in various approaches to measuring methane leakage from natural gas operations. We take these discrepancies and uncertainties into account by utilizing scenario analysis to compare the impact of different assumptions about the natural gas supply chain and engine technologies. We focus specifically on comparing break even conditions for natural gas in comparison to existing diesel fuel based operations. Our hope is by doing so, we offer policy makers increased information on which to base their decisions about the environmental role of natural gas in the US freight industry.

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[15] http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html

[16] Petron G et al. (2010) Evidence of emissions from oil and gas drilling operations in northeastern Colorado. *AGU Fall Meeting Abstracts* -1:0272.

[17] Miller SM et al. (2013) Anthropogenic emissions of methane in the United States. *PNAS* 110:20018–20022.

[18] Brandt AR (2008) Converting oil shale to liquid fuels: Energy inputs and greenhouse gas emissions of the Shell in situ conversion process. *Environ Sci Technol*.

Scientists and policy makers have found it useful to estimate the breakeven leakage rate (BLR) for particular fuel applications, that is, the maximum acceptable upstream methane leakage rate at which the combined warming effects of CH4 and CO2 from natural gas balance out the combined effects of CO2 and CH4 of the fuels it substitutes. Such estimates have improved as better understanding of the systems modeled and as new data becomes available but, since new data is always emerging, we believe that understanding the sensitivities of the model is more relevant to policy making than providing a unique distinct value, even when uncertainty bounds are provided. We expand the literature on such break evens to contribute a better understanding of the greenhouse gas consequences for LNG trucking operations.

Methodology

In this paper we investigate the recent literature on emissions and incorporate new data where necessary. We explain the differences between the various estimates by highlighting the different methodological variation and offering comparisons. We then run GREET1 2014 to estimate the carbon intensity of C8 natural gas trucks.

We use the 2014 version of Argonne's GREET1[19], a life cycle analysis model, to compare carbon intensities of both natural gas and diesel long haul combination trucks under different scenarios of methane leakage, engine efficiencies and natural gas storage.

Life cycle analysis (LCA) models take into account materials and energy flows throughout the production and use of a product. For our purposes, LCAs are used to tally the different greenhouse gas emissions and weight them based on their global warming potential (GWP) in order to obtain an estimation of the carbon intensity (CI) of natural gas trucks, measured as carbon dioxide equivalents per mile driven (g CO2e/mi).

We use the 2014 version of Argonne's GREET1. The main advantage of this version is that it incorporates multiple heavy-duty transportation applications, including long-haul combination trucks. In addition, the 2014 GREET1 includes the warming effects of black carbon (BC), but those will have a minimal impact in the time frame of warming in this analysis (100 years).

The functional unit in this analysis is the ***carbon intensity (CI),*** defined here as grams of CO2 equivalent emitted per mile driven **(gCO2e/mi).** In trucking, grams of CO2 per ton carried over a mile (gCO2e/ton.mi) are typically used to account for the potential loss of cargo space when alternative fuel systems are incorporated in the vehicle; however we do use this metric because natural gas systems might not require much cargo space, and because the typical load of a long

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[19] https://greet.es.anl.gov/

haul truck is 80% so even if LNG systems would require additional space that would not exceed the spare 20% in the typical truck.

Since we are evaluating whether NGV trucks provide any climate advantage over diesel vehicles we also estimate the ***carbon intensity spread (CIS)*** between NGV and diesel trucks. The ***breakeven leakage rate (BLR)*** represents the methane leakage that results in neutral changes respect to diesel. Above that number diesel is more favorable, below that number natural gas trucks will be better.

Add some description here about GREET1 2014 – ie describe the basic model and how it works- and discuss if you adjusted any parameters. Then say how you used scenarios for the break evens and what scenarios you performed and why. So that you considered the following different engines at drive cycles of X compared to what specific diesel engine and the following different leakage rates, ie EPA and Brandt.

Based on our results, we discuss how much methane leakage is acceptable for NGV C8 trucks to provide a climate benefit and how that compares to levels of methane leakage surveyed in the recent scientific literature. We also discuss how much of the estimated leakage can be reasonably contained, and to what extend other measures can be implemented for a positive climate footprint of natural gas trucks. We evaluate what parameters dominate the carbon intensity of heavy-duty C8 long-haul trucks to determine what actions can be more effective to reduce overall carbon intensity in this transportation segment.

Assumptions

Vehicle efficiency

As our results demonstrate, energy conversion efficiencies play a major role in LCA results. In natural gas vehicles, spark ignited (Si) or compression ignited (Ci) engines can be used, which are assumed 15 and 7% less efficient than diesel respectively in this analysis. Wesport-Cummins offers the HPDI model, which features a Ci engine with a diesel pilot ignition system that provides efficiency levels similar to traditional diesel vehicles.

Fuel economy is given in miles per diesel equivalent gallon (mpdeg). The absolute efficiency of an engine or drivetrain is unknown since it could vary with vehicles load or duty cycle. We consulted with engineers from truck engine manufacturer Westport to estimate comparable drivetrain and drive cycle fuel efficiencies for trucks running on natural gas or diesel. EPA GHG regulations suggest a thermal efficiency of around 40% in order to meet the CO_2 per bhp/hr limit. We assume transient applications, that SI engines will not exhibit any efficiency differences from using CNG or LNG, and that the HPDI model (a CI natural gas model with diesel pilot ignition) will give diesel equivalent fuel economies (minus a penalty for LNG fuel injection systems).

This results in a fuel economy of 5.39 mpdge for the HPDI, 4.80 for the SI trucks, and 5.6 for diesel trucks.

Methane slip (tailpipe methane)(vehicle combustion methane)

Methane slip is typically higher in NGVs than in diesel, but the more efficient engines of the HPDI model also provide the additional benefit of lower tailpipe emissions of methane. Methane slip values are given in grams of methane per mile driven (g/mile). The Cummins 15L ISX diesel engine certifies to 0.02 g/bhp-hr, which corresponds to 0.07 CH4 g/mile. The ISX 12G certifies to 1.7 g/bhp-hr and the Westport HD 15L achieved around 1.0 g/bhp-hr over the equivalent engine test cycle. Assuming the same relative efficiency of 11% for SI and parity for HPDI, this corresponds to tailpipe CH_4 figures of 6.3 and 3.6 g/mile respectively (SI and HPDI)

Boil-off

Boil-off refers to the vaporization of gas from liquefied natural gas tanks. This occurs both in on-board vehicle storage and on site storage in liquefaction facilities and refueling facilities. We use the GREET1 default value of a 1% boil-off with an 80% recovery rate.

GWP

The global warming potential (GWP) assigns climate weights to the different greenhouse gases and translates them to carbon dioxide equivalents (CO2e). GWPs are dynamic. The climate weights decrease over the lifetime of a greenhouse gas as it disappears, so a time horizon must be chosen for the comparison, which typically is 20 or 100 years. The 20-year GWP of methane, for example, is 86 while the 100-y GWP of methane is 30, meaning in 20 years, one gram of methane emitted today would have created the equivalent warming of 86 grams of CO2 emitted today but in 100 years it will have the effect of only 30 grams of CO2 emitted today. Although IPCC recommends using the 100yGWP and this is what most analysts use, some use the 20yGWP (REF HOWARTH) thus give methane a higher warming weight. In addition GWP values for any given period are corrected as new science arises, with a new value of 35 for the 100yGWP of methane being suggested lately. We use the default GREET GWPs which are based on the most recent values sanctioned by IPCC, which is 30 for methane in the 100y range.

Natural gas storage

Natural gas is stored as compressed natural gas (CNG) or liquefied natural gas (LNG). The difference is relevant because they imply different supply chain configurations. Natural gas is delivered to industrial liquefaction plants via transmission lines, liquefied and distributed as LNG to stations by truck. In the case of CNG, natural gas is delivered for compression to the stations using the transmission and the local distribution systems. While LNG procurement might require higher energy inputs, which incur in emissions, CNG procurement makes a larger use of leaky distribution systems.

Upstream emissions: Combustion and non-combustion methane and carbon dioxide.

Upstream greenhouse gas emissions in oil and gas are dominated by carbon dioxide (CO2) and methane (CH4). Methane emissions include fugitive methane leaks, methane venting, and unburned methane from combustion and flaring processes. CO2 emissions result from combustion processes, flaring of methane, and vented CO2. The only non-combustion specie GREET1 incorporates is methane in the form of leakage from natural gas systems (wells, processing and distribution). GREET1 also incorporates combustion CO2, and combustion methane.

1. Combustion carbon dioxide and methane from upstream energy processes.

Significant amounts of methane and carbon dioxide emissions result for incomplete combustion of fuels that provide energy in upstream processes. These emissions are incorporated in GREET1.

2. Combustion carbon dioxide and methane from flaring.

Flaring of natural gas produces both carbon dioxide and methane. In oil operations, flaring is practiced as a remediation technology when co-produced associated gas is stranded (i.e., not sold to markets). In natural gas operations, flaring only occurs during the pre-production operations (i.e., drilling and fracking)

The scale of gas flared in natural gas operations is significantly smaller than the sale of associated gas flaring during oil production. One caveat with GREET1 is that it does not incorporate the tight oil from North Dakota, which currently flares a large proportion of the associated gas. Therefore GREET1 is biased towards oil fuels such as diesel.

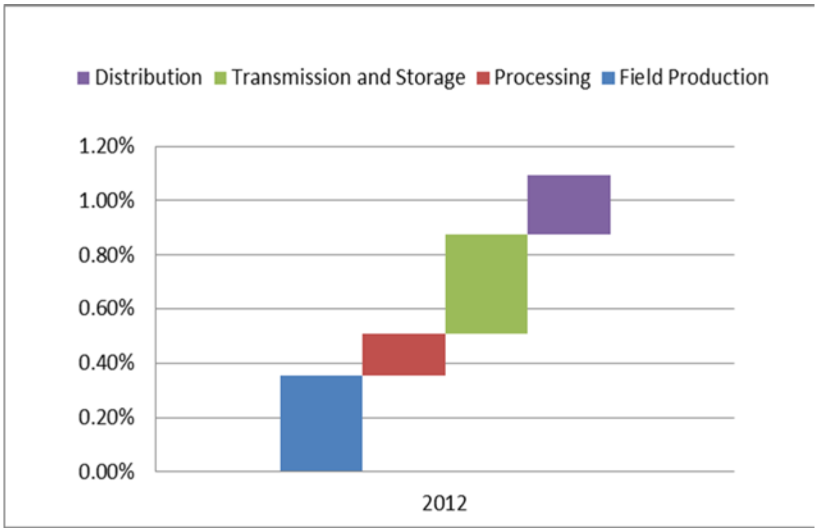
3. Non-combustion carbon dioxide in natural gas and oil

GREET does not incorporate emissions of geologic CO2 in either natural gas or oil pathways.

4. Non-combustion methane in natural gas: Methane leakage

According to EPA’s 2014 Greenhouse Gas Inventory (2014 GHGI) natural gas systems leaked about 6,186 Gg of methane (129.9 Tg CO2e) in 2012 (each year the inventory reports data corresponding to two years before). This corresponds to about 1.12% leakage system-wide (national average), from which 0.2% results from pre-production (i.e., drilling and fracking), 0.4% result from production, 0.2% from processing of gas, and 0.7% from transmission and distribution (figure 4). The EPA inventory does not include potential leaks from refueling stations or vehicles.

Figure 4. Breakdown of methane leakage in natural gas systems.



Several independent studies have suggested estimates that range from 0 to 8%. The discrepancy with EPA has been attributed to methodological issues to a high extent. Brandt et al. conclude the actual leakage rate might be between 1.9- 2.6%. Often times, the difference in estimations can be explained by methodological approaches and assumptions used in the different studies.

In terms of methodology, a major distinction can be made between top-down and bottom-up approaches. EPA produces bottom-up estimates, which are device and inventory based and reflect specific activity. Top-down analyses, however, sample the atmosphere and estimate ambient methane concentrations. Top-down approaches systematically produce higher values than bottom-up. A challenge with top-down estimates is attributing methane emissions to the appropriate source. For example, NOAA's Petron top-down approach estimated on 2012 that 3.8% of the gross natural gas produced leaks based on top-down measurements in the Colorado Weld County and attributes them to "A mix of venting emissions of raw natural gas and flashing emissions from condensate storage tanks". However, the county in particular had 850 tight gas and 1583 oil/condensates, as points out Michael Levi in his paper "Climate Consequences of Natural Gas as a Bridge Fuel"[20], so it can hardly be attributed to shale gas production (or gas

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[20] Levi M., "Climate consequences of natural gas as a bridge fuel" Climatic Change

production in general), without further inquiry on whether the methane came from oil wells or gas wells. Karion[21] estimates a 6.2-11.7% of Uintah County natural gas production in Utah leaks, but this was based on one air measurement in one specific day, and also attributed all methane detected to natural gas production activity, whereas other sources might have contributed. Miller[22] combined results from about 7,000 aircraft samples and 5,000 stationary samples across five US shale plays during the years 2007 and 2008. Emissions were allocated to the possible sources and compared to the EDGAR inventory, which is a spatial proxy for EPA's aggregated data. According to Miller the combined oil and gas emissions measured in the US are 2.84 times larger than in EDGAR's (and thus EPA). According to the study, EPA's underestimations are particularly significant in Texas and Oklahoma, both major oil and gas producing states, but also in the Northern half of California, which has little oil and gas production other than the gas fields around the Sacramento area, which is in the edge of the affected area. No underestimations are detected in North Dakota either, the second (but only since recently) oil producing state in the nation, or over the Northeast regions where the Marcellus and Utica basins are producing large amounts of natural gas from conventional and unconventional wells. Indeed, according to Miller results, EPA seems to could even be over-representing emissions in the Northeast of the country and in the oil producing regions of Southern California. There is significant uncertainty associated with these results and further inquiry is required before they can be used to contest EPA data.

Besides measuring methodologies, assumptions used in the calculation also exert an important effect on results. Clark's[23] paper shows that assumptions about methane content in natural gas, productivity of individual wells (i.e., the Estimated Ultimate Recovery, or EUR), allocation to co-products (i.e., how much of the methane leaked is due to oil, gas or natural gas liquids production), as well as how much of the surfacing gas is vented versus captured or flared can dominate results in leakage calculations. Ingraffea[24], for example, assumes that all the natural gas that surfaces during flowback (i.e., when fracking fluids return) is vented, but a MIT study by O'Sullivan, finds that on average, only 15% is vented (another 15% is flared, and 70% is

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June 2013, Volume 118, Issue 3-4, pp 609-623

[21] Karion A et al. (2013) Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophys Res Lett* 40:4393–4397.

[22] Miller SM et al. (2013) Anthropogenic emissions of methane in the United States. *PNAS* 110:20018–20022.

[23] Clark C.E., Han J., Burnham A., Dunn J.B., Wang M."Life-Cycle Analysis of Shale Gas and Natural Gas" December 2011. Center for Transportation Research. Energy Systems Division, Argonne National Laboratory.

[24] Ingraffea A, Phillips N, Townsend-Small A (2012) Methane emissions from natural gas systems. *Background Paper Prepared for the National Climate Assessment*.

captured)[25]. Allen actually finds leakage of oil and gas production is smaller than EPA suggests[26].

The variability in methodology and assumptions questions the validity of comparing the results among different studies, but in 2013, Brandt[27] settled the question based on a meta- analysis of 20 years of published literature. They concluded that EPA is likely underestimating actual leakage by about 30 to 40%. In other words, actual leakage might be 25 to 75% higher than what EPA reported in 2013[28], therefore the actual leakage rate could be 1.85 -2.95 % rather than EPA's current 1.12%.

Brandt suggests EPA's method is missing a small group of operators that contribute to the majority of emissions. EPA calculates potential emissions by multiplying emissions factors from the 1990s by activity data. Then to from these potential emissions subtracts the theoretical reductions induced by air quality regulation (NESHAP) and by the EPA's voluntary Natural Gas STAR (GasSTAR) program throughout the supply chain. But the NESHAP reductions of methane emissions could be overestimated, if states fail to monitor and enforce the regulations. EPA estimates could also be biased towards "good" operators as EPA is incorporating data from the GasSTAR voluntary program, in which companies with good business practices are more likely to participate, according to research by EDF[29][30].

Besides "bad" operators, EPA is missing another potentially important source: leaking abandoned wells. In her Ph.D. dissertation, Princeton's Mary Kang determined that 16% of the abandoned oil and gas wells in Pennsylvania are high emitters (≥1 kg/day/well), which would as a group be leaking the equivalent of 0.3 to 0.5% of gross gas withdrawal in that state in 2010[31].

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[25] O'Sullivan F, Paltsev S (2012) Shale gas production: potential versus actual greenhouse gas emissions. *Environ Res Lett* 7:044030.

[26] Allen DT et al. (2013) Measurements of methane emissions at natural gas production sites in the United States. *PNAS* 110:17768–17773.

[27] Brandt AR et al. (2014) Methane Leaks from North American Natural Gas Systems. *Science* 343.

[28] Brandt et al describe EPA leakage rate at 1.5%, but that was according to the 2013 inventory, which used a different estimation methodology. Standardizing the methodology to the one used in the 2014 inventory would result in a leakage rate of 1.13% for that year.

[29] ICF "Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries." March 2014 http://www.edf.org/sites/default/files/methane_cost_curve_report.pdf

[30] EDF. Harnessing the Potential of Natural Gas: Addressing Methane Emissionshttp://csis.org/multimedia/video-harnessing-potential-natural-gas-addressing-methane-emissions

[31] Kang M, Nanno C., Reid M.C., Zhang X., Mauzeralla D.L., Celia M.A., Chen Y., Onstott T.C. "Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania." PNAS | December 23, 2014 | vol. 111 | no. 51 | 18173–18177

Taking into account that there are about 3 million abandoned oil and gas wells in the United States, the exclusion of those in the EPA inventory can introduce a significant biase.

To what extent can methane leakage be reduced?

A recent analysis by the World Resources Institute suggests that 40-60% of leaks can be preventable profitably with current technology. Natural gas can be captured during pre-production with what is called "Green Completions" or "Reduced Emissions Completions" (RECs), which can be defined as the use of portable equipment (depicted below) to process gas and condensate, and separate the natural gas that can be contained and sold or flared. This approach contrasts with conventional methods in which the flowback and debris from well completion are disposed into an open pit or tank and where methane and other volatile compounds are vented to the atmosphere. At present, green completions are voluntary, but as of January 1, 2015, operators must use RECs and a completion combustion device (e.g., flaring the gas). Green completions used in field pre-production can reduce emissions during such operations, but this is likely to have a limited impact. First, pre-production emissions represent only a small share of the supply chain leaks. Additionally, many operators already implement these technologies in field operations, but it is likely that adoption by the few super-emitter operators is necessary in order to completely eliminate emissions in that stage. Other technologies, as suggested by EPA's Natural Gas Star program can be implemented at the different stages cost effectively and with short payback periods[32].

Results

The Carbon Intensity of NGVs

Figure 1 shows the difference between the carbon intensity of NGV trucks and the baseline diesel truck according to simulations using Argonne's 2014 version of the GREET1 life cycle assessment model and assuming EPA current estimate of 1.12% leakage. The effect of fuel storage choice is also shown. Si engines are currently available and in use in the United States with either LNG or CNG storage. HPDI engines with natural gas stored as LNG are another potential technology, although not currently being sold via mass production manufacturing.

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[32] EPA Natural Gas Star Program Recommended Technologies
http://www.epa.gov/gasstar/tools/recommended.html

Scenarios used consider long-term and near term climate effects of natural gas evaluated by using 100 or 20 year global warming potentials (GWP).

Our simulations with the 1.12% methane leakage assumptions (current EPA official methane leakage estimate for natural gas) suggest that when high efficiency HPDI model is used in C8 natural gas trucks, a wells-to-wheels 1% *reduction* in carbon emissions over equivalent diesel trucks is realized. However, when less efficient spark ignition engines running on LNG or CNG are operated, they are 9 and 10% *more* carbon intensive, respectively, than diesel trucks (figure 1, panel 2).

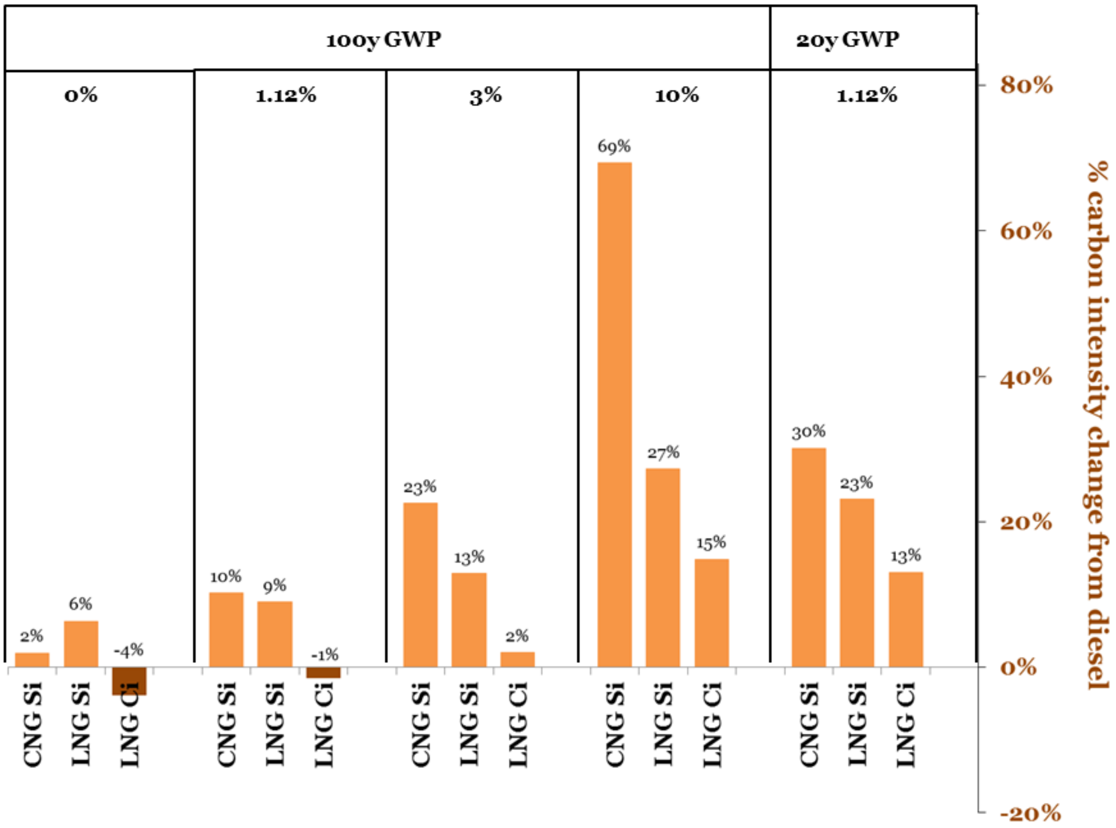
If methane leaks were completely eliminated (i.e., 0% leakage), HPDI trucks would be 4% *less* carbon intensive than diesel trucks, but if a Si engine is used, NGVSs still would produce a 2% and 6% increase respect to diesel if storing as CNG and LNG respectively (figure 1, panel 2).

In a scenario of 3% methane leakage, about what has been suggested as likely (Brandt et al, 2013) an HPDI natural gas engine would produce 2% *more* carbon emissions than a diesel truck, an Si engine would produce 13% more if running on LNG, and 23% more when running on CNG (figure 1, panel 3).

In a unlikely scenario of 10% methane leakage nationally, an HPDI natural gas engine would produce 15% more carbon emissions than a diesel truck, an Si engine would produce 27% more if using LNG and 38% more if running on CNG (figure 1, panel 4).

The final panel shows results for a 1.12% leakage rate using a 20-year GWP to evaluate methane's short term impact on climate. If a 20y global warming potential is used natural gas trucks become clearly disadvantageous with respect to diesel trucks (Figure 1, panel 5). In this case, we see none of the natural gas engines or storage options provide any advantage over diesel. This approach penalizes natural gas vehicles because methane is a short lived climate pollutant, and its effects are felt stronger in the near term, whereas the longer-term effects of its lower cumulative CO2 emissions over time are disregarded.

Figure 1. Difference (%) in carbon intensity between NGVs and Diesel vehicles under different leakage assumptions.


100y GWP
20y GWP
0%
1.12%
3%
10%
1.12%
2%
6%
-4%
10%
9%
-1%
23%
13%
2%
69%
27%
15%
30%
23%
13%
CNG Si
LNG Si
LNG Ci
80%
60%
40%
20%
0%
-20%
% carbon intensity change from diesel

In summary, natural gas can achieve lower carbon intensity than diesel under current leakage assumptions of 1.12% only through the use of the high efficiency engines such as the HPDI but not with less efficient Si engines. Indeed, even if the leaks would be completely eliminated, natural gas Si engines would still deliver more grams of carbon per mile than diesel. A leakage rate of 3% or higher would make all types of current natural gas engines undesirable. Our finds show that CNG is also clearly more sensitive to leakage. This finding is consistent with relatively higher methane leakage rates along the natural gas pipeline distribution network than in upstream drilling operations because the delivery of natural gas for CNG is more heavily dependent on pipeline shipments compared to diesel pipeline to truck shipments and also compared to LNG which is distributed by truck from LNG plants to stations.

Break evens for natural gas in heavy-duty transport

We next consider the “maximum acceptable” upstream methane leakage rate at which the combined warming effects of CH4 and CO2 from natural gas as a transport fuel are equal to the combined effects of CO2 and CH4 of the fuels it substitutes, that is diesel. We refer to this comparison as the breakeven leakage rate (BLR).

Figure 2 shows the carbon intensities of the different NGVs and that of diesel at different leakage rates for the various natural gas technologies available in trucks. BLRs are determined by the crossing of any natural gas technology with diesel. Our results indicate that, in the 100y time frame, leakage rate below 2.8% justifies a switch to NGVs heavy-duty trucks that use HPDI technology and LNG storage but should be limited to 0% if NGV trucks use spark ignition engine technology and LNG storage. Our results also show that Si CNG vehicles provide benefits only at near zero leakage levels, but Si engines combined with LNG storage are undesirable even if methane leaks are completely eliminated.

Figure 2. Carbon Intensity (gCO2e/mi) of diesel and NGVs under different methane leakage assumptions. The crossing of NGV lines with diesel line indicates breakeven leakage rates.

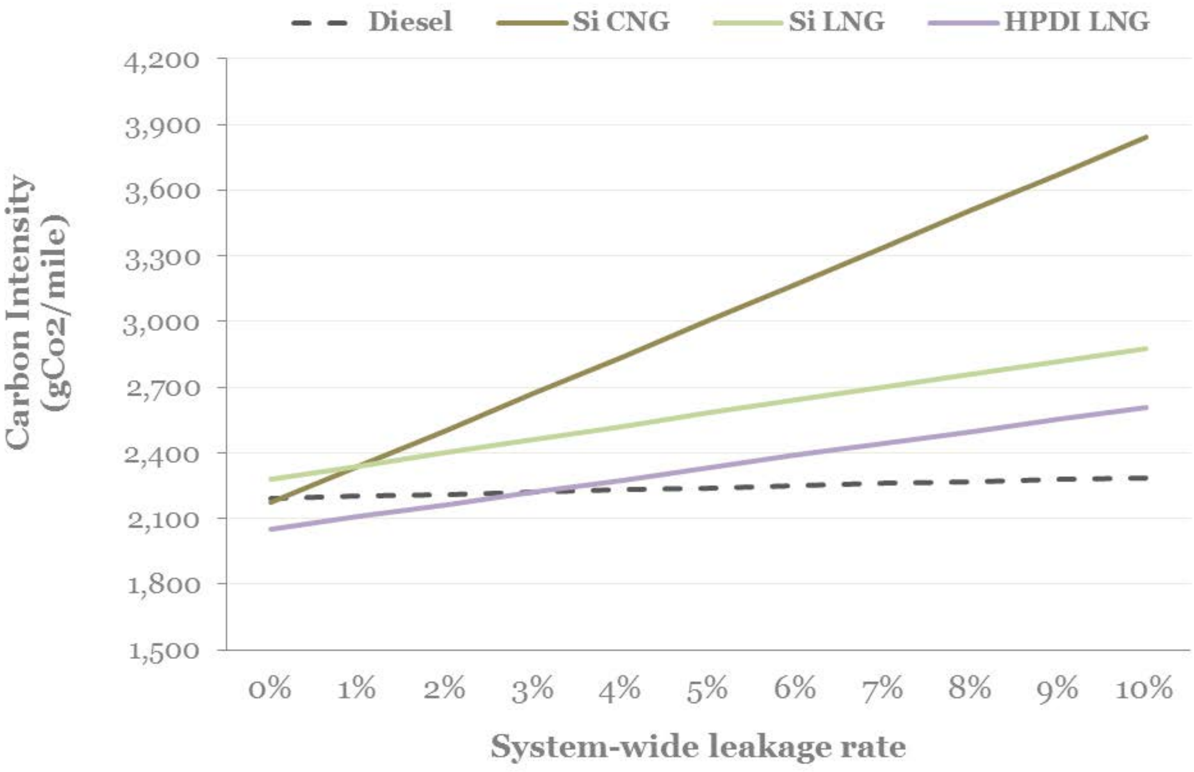
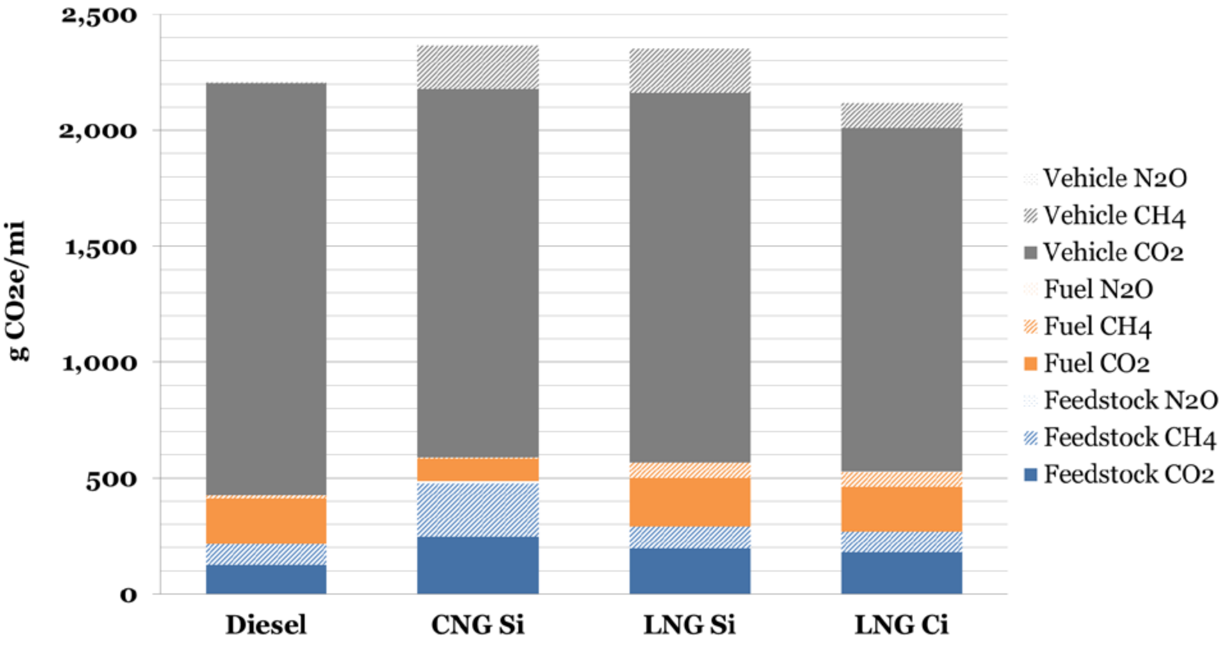


Figure 1 shows that diesel's carbon intensity estimates are only slightly sensitive to leakage. For every 1% increase in methane leakage, diesel trucks incur in 9 additional grams of CO2 equivalents per mi (+0.4%). Natural gas trucks are more sensitive to leakage but there are more so if they use CNG. Every 1% increase in leakage adds 56 gCO2e/mi to HPDI LNG trucks (+2%), 60 gCO2e/mi to Si LNG trucks (+2%), and 167 gCO2e/mi to Si CNG trucks (+6%). When comparing the more efficient HPDI and Si engines (both running on LNG) under different leakage rates, the HPDI maintains an advantage over the Si.

Figure 3 shows the contribution to the well-to-wheel carbon intensity of diesel and NGV trucks by each greenhouse gas and by each life cycle stages of fuel (i.e., feedstock procurement, fuel production, and in vehicle use). Three-quarters to two-thirds of the total well-to-wheels emissions are produced during vehicle use (grey), whereas upstream emissions (blue for feedstock procurement and orange for fuel production) are a relatively smaller part.

Figure 3. Contribution of the different gases and segments of life cycle to well-to-wheels Carbon Intensity of Diesel and different configuration of natural gas C8 trucks under 1.12% leakage.



Carbon dioxide emissions (solid) dominate vehicle emissions, and significantly contribute to feedstock and fuel cycle processes in all cases. Methane emissions (stripped) are significant during vehicle operations in all cases, but more so for the less efficient Si engine than for the HPDI. This indicates that increased engine efficiencies can be effective at reducing the overall carbon intensity.

Total upstream methane emissions are similar in diesel, CNG, and LNG, but breaking them down shows they originate from different processes. In diesel, emissions are originated during feedstock procurement (i.e., oil production). In the case of CNG, methane emissions are larger during feedstock procurement than during fuel production, contrary to what happens in the LNG case. This is explained by the fact that, in the CNG pathway, natural gas is transported via both long distance pipelines and local distribution to refueling stations where it is compressed to become a fuel. In the LNG pathway, we assume natural gas is transported via pipeline to centralized liquefaction plants. It is then converted to LNG fuel and is transported to refueling stations using trucks. The feedstock pathway of LNG incurs in lower emissions and sensitivity to leakage as it bypasses the local natural gas pipeline distribution system. In addition, some of this upstream methane results from power operations rather than leakage per se; this explains why LNG, with is higher energy inputs, has higher methane emissions than CNG during fuel production. Increased efficiencies in these operations are likely to have a significant impact in the overall carbon estimate.

Other than in the CNG feedstock part, where methane leakage is a major contributor, it is remarkable that upstream emissions are typically dominated by carbon dioxide emissions from burning fuel, and thus correlated to energy use and process efficiencies, rather than methane leakage. In the CNG pathway, most of the energy is used in the feedstock cycle (e.g., due to energy to power compressors), whereas in the LNG pathway more energy is required in the fuel cycle (e.g., higher power requirements in liquefaction). Also, as noted earlier, methane is also a combustion product when energy is produced for upstream processes. This suggests that increased efficiencies at all levels could be beneficial for the reduction of the carbon footprint of fuels

Discussion

The use of natural gas in transportation has been found to produce a limited, if any, reduction in carbon emissions with respect to diesel use once upstream emissions are taken into account. Likewise, given national data on leakage, we find that current methane leakage of 1.12% has a limited effect on the climate performance of NGVs. Indeed, there are other factors, such as engine efficiency and power-related upstream emissions that significantly affect the results.

Our results highlight the relevance of both engine type and storage type.

Under currently assumed leakage levels of 1.12%, the majority of the carbon intensity of NGVs is contributed by emissions from vehicle use rather than from upstream natural gas processes. NGVs typically have higher methane slip (i.e., methane in the exhaust gas), but less so with the more efficient Ci engines than in the Si. For these two reasons, the vehicle efficiency is material to understanding the contribution natural gas can make as a low carbon fuel in transportation. In heavy-duty trucking, both spark ignition (Si) and compression ignition (Ci) natural gas engines are available and Ci engines are about 10-15% more efficient than Si. However, the Ci models at this juncture are more expensive and production by a joint venture between Cummins and Westport is currently suspended due to lack of customer interest and the high cost to officially certify environmental compliance. It is expected that storage costs and other inputs to advanced technologies will fall in the coming years as new entrants come to market from China or elsewhere. Since a significant share of carbon comes from oil and gas upstream power requirements, -typically met by a combination of oil, gas and electricity sources- increased system efficiencies could also significantly reduce the carbon intensity of related transportation fuels.

Upstream methane leakage could be reduced by about 0.4-0.6% cost effectively[33]. Technologies such as green completions, and low bleed pneumatic devices can be effective if implemented at field operators during drilling, fracking and liquids unloadings. The 2012 New Source Performance Standards (NSPS) for Oil and Gas operations aimed at reducing smog pollutants have produced the co-benefit of reduced methane emissions at drilling sites. However, methane specific regulations announced in early 2015, and likely to come in line in 2016, by the Obama administration have the potential to include other segments, such as gas transmission and distribution pipelines, which contribute to about half the total well-to-wheels methane emissions. However, even if leakage is reduced completely, Si engines (4.8 mpdge) are still more carbon intensive than Ci technology.

Choice of storage is also a factor to consider. The LNG pathway is dominated by emissions combustion processes rather than by leakage. And the opposite is true for the CNG pathway. This is for two reasons. In CNG pathway, natural gas uses both the natural gas transmission system and the local distribution system before the natural gas is compressed after being delivered to a refueling station, where it is compressed onsite. The energy use for compression is smaller than the energy required in liquefaction. The LNG pathway simulated in this study does not involve distribution in natural gas local pipelines; therefore the leaks along this segment of the natural gas supply chain do not influence LNG's carbon performance. However, the high energy inputs of liquefaction imply a higher generation of carbon dioxide (and combustion methane) during energy generation combustion processes. These two factors make CNG more sensitive to leakage, and LNG more sensitive to upstream energy efficiencies so in order to reduce the carbon intensity of natural gas in transportation, different strategies are required for the different fuels.

If CNG is used, then controlling leakage is crucial. If LNG is used, then reducing upstream energy uses is more effective. This is not to say methane leakage should be neglected. It contributes to short term global warming and thereby needs to be eliminated. In the long run, methane leakage from upstream also make up an important share of CNG carbon intensity but in the case of LNG reducing upstream energy uses may prove more effective. We recommend policies pursuing the optimization of both natural gas engine and upstream power processes.

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[33] Bradbury J, Obeiter M., Draucker L, Wang W., and Stevens A. "Clearing the Air: Reducing Upstream Greenhouse Gas Emissions from U.S. Natural Gas System. A Summary for Policymakers. WRI March 2013.

Discussion of Variations and Uncertainties

Caution must be used when using these results in making policy decisions. Models are never completely error free and results are very sensitive to assumptions and methodological approaches.

The results presented in this report are originated with the 2014 version of GREET1 (Argonne National Lab). Assumptions about leakage, and distances traveled and energy efficiencies reflect national averages rather than actual environmental performance for natural gas in a particular state. Thus, our results differ from analysis performed specifically for the state of California using CA-GREET. Also, results from 2014 GREET1 differ significantly from the 2013 national version. Among the differences between the two national model vintages, the inclusion of transmission for LNG and the addition of heavy-duty pathways in the 2014 version are relevant

When comparing the oil and natural gas pathways, GREET1 seems to be biased towards oil. This is due to the fact that GREET1 still does not incorporate shale oil pathways which can also be methane and CO2 intensive and thus the domestic oil production, with increased shale development, is not accurately represented. Since large parts of associated gas from shale oil development in North Dakota are flared, incorporation of this pathway and allocation of those emissions to oil rather than natural gas fuels would tilt the balance in favor of natural gas. Since current estimates of natural gas flared in North Dakota are in the 109 bcf per year[34], equivalent to about one third of what it is believed to leak, this can be a significant bias. GREET1 does account for flaring of associated natural gas in conventional oil production, but it is possible that these emissions are incorrectly applied to natural gas. For these reasons, the carbon intensity of natural gas in GREET1 is *overestimated* compared to oil pathways while the carbon intensity of diesel is underestimated. Our research suggests that on an apples to apples basis, a proper application of upstream methane leakage and CO2 flaring to tight oil production in the United States would likely result in highlighting that greater advantages are possible from a shift to natural gas fuel away from diesel than calculated now with existing model assumptions.

Contrary to the results presented here, calculations using CA-GREET for the low carbon fuel standard (LCFS) provide that natural gas fuels perform about 20% better than incumbents.

The main difference LCFS and the results presented here is the choice of functional unit. The LCFS is addressed to fuel producers who control fuels, thus LCFS lookup tables show the carbon intensities of fuels expressed as grams of carbon dioxide equivalent per Mega Joule (gCO2e/MJ). In this study, we show the carbon intensity of NGVs expressed as grams of carbon dioxide equivalents per mile driven (gCO2e/ mile) thus incorporating the vehicle efficiency to our

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[34] Energy Information Administration
http://www.eia.gov/todayinenergy/detail.cfm?id=18451

metric. When the LCFS values are translated to gCO2e/mile, the values are closer to the values presented in this study.

There are other aspects that drive the differences. The LCFS results are based on a study commissioned to TIAX Consulting in 2007[35]. The consultants used the CA-GREET1.7 version of 2007, which has many differences to the GREET1 2014.

Several changes have been incorporated in more recent versions of both national[36] and California[37] GREETs. Methane leakage in natural gas pathways was only incorporated in the 2013 version of CA GREET, as concern over leakage has arisen after the recent escalation of shale development over the past few years. The accepted 100-year GWP for methane in 2007 was 23; nowadays it is 30, and it is possible that in the future it will be changed to 35. The result of such changes will be an analysis that shows a poorer climate performance of natural gas, which is more affected by methane leakage than oil pathways.

Even when updated revisions of the CA-GREET are used, there are some parameters that are different in California. This is the case for upstream combustion emissions in both oil and gas pathways. Because California air quality regulation is more stringent also for stationary sources, and because regulation is often met with improved efficiencies, upstream oil and gas production and refining use less energy and thus incur in lower emissions in California than the US national average. This will have an important effect on final carbon intensity results for California specific natural gas applications. Also, eventually California will receive more natural gas from Canada and Colorado, which have their own set of leakage rules and regulations.[38] The particularities of these supplies will have to be taken into consideration.

Until last year, both GREET1 and CA-GREET were designed exclusively for light duty vehicles. So far, only the 2014 version of GREET1 includes heavy-duty vehicle pathways. Prior to this version the well-to-wheel analysis of heavy-duty trucks required considerable manipulation by the modeler and different assumptions about vehicle efficiency, for instance, could produce great variations in results.

Summary and Final Remarks

Natural gas can achieve lower carbon intensity than diesel under current leakage assumptions of 1.12% only through the use of the high efficiency engines such as the HPDI but not with less

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[35] TIAX LLC. Full Fuel Cycle Assessment: Well-to-Wheels Energy Inputs, Emissions, and Water Impacts. State Plan to Increase the Use of Non-Petroleum Transportation Fuels AB 1007. June 2007 CEC-600-2007-004-F

[36] Argonne National Laboratory "Summary of Expansions and Updates in GREETTM1_2014 and GREETTM2_2014 Models" October 2013. Argonne National Laboratory. Energy Systems Division. Systems Assessment Section

[37] California GREET supporting documentation. http://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet2.0_supdoc-121614.pdf

[38] Medlock, Kenneth, Baker Institute CES Rice World Gas Trade Model and Working Paper January 2015

efficient Si engines. When using HPDI engines, natural gas will be beneficial as long as leakage rate remains under 3%.

Until HPDI technology can be widely adopted, natural gas production and distribution methane leakage needs must be completely eliminated for today's fleet of Si NGV trucks to have lower carbon intensity than standard diesel trucks. Methane leakage could be reduced to 0.4-0.6% cost effectively. Our environmental study has found that there are a plethora of technologies with payback periods between one half to three years that could achieve significant reductions at different stages of the natural gas supply chain. Technologies such as green completions, and low bleed pneumatic devices can be effective if implemented at field operators during drilling, fracking and liquids unloadings. Many of these reductions are being realized by operators under the EPA Natural Gas STAR program. However, enrollment is voluntary and some segments in the supply chain, such as transmission operators, may not enjoy the economic. There is also the possibility that the minority of operators contribute to the majority of emissions do not join the program, as they might lack the awareness of the program. Therefore, we suggest regulations rather than voluntary programs to ensure all operators implement best available technology to reduce methane leakage emissions.

In addition, regulations typically target new and modified sources, whereas existing sources such as abandoned wells could be major contributors. A special program, a sort of Superfund for methane, that addresses the abandoned sources could be significant in reducing leakage.

An important conclusion of our study, nonetheless, is that we have shown that leakage is only part of the problem. Even if leakage is reduced completely, current Si engines running on CNG are more carbon intense than diesel. Only efficient engines, such as the HPDI, can produce 7% reduction in carbon emissions over diesel trucks under optimum (fuel economy of 5.36 mpdge, no leakage, central LNG facilities). Therefore, a focus in improving vehicle efficiency performance can potentially have a major impact in reducing the carbon intensity of NGVs for long distance trucking.

Finally, we have shown that emissions upstream combustion processes have a similar or larger contribution than methane leakage, and a focus on increasing efficiencies in these processes is relevant.

Our research shows that solely focusing on methane leakage will not sufficiently address the poorer carbon performance of natural gas in heavy duty freight transportation applications. While methane leakage should be eliminated because leaks represent an unnecessary release of greenhouse gases in the atmosphere, our study indicates that a combination of approaches, including aiming for higher efficiency vehicles and higher efficiencies in upstream processes, is necessary to reduce the carbon intensity of natural gas in transportation.

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