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HYDROGEN-METHANE BLEND FUELLING OF A HEAVY-DUTY, DIRECT-INJECTION ENGINE

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ABSTRACT

Combining hydrogen with natural gas as a fuel for internal combustion engines provides an early opportunity to introduce hydrogen into transportation applications. This study investigates the effects of fuelling a heavy-duty engine with a mixture of hydrogen and natural gas injected directly into the combustion chamber. The combustion system, developed for natural gas fuelling, is not modified for blended hydrogen operation. The results demonstrate that hydrogen can have a significant beneficial effect in reducing emissions without affecting efficiency or requiring significant engine modifications. Combustion stability is enhanced through the higher reactivity of the hydrogen, resulting in reduced emissions of unburned methane. The fuel's lower carbon:energy ratio also reduces CO₂ emissions. These results combine to significantly reduce tailpipe greenhouse gas (GHG) emissions. However, the effect on net GHG's, including both tailpipe and fuel-production emissions, depends on the source of the hydrogen. Cleaner sources, such as electrolysis based on renewables and hydro-electric power, generate a significant net reduction in GHG emissions. Hydrogen generated by steam-methane reforming is essentially GHG neutral, while electrolysis using electricity from fossil-fuel power plants significantly increases net GHG emissions compared to conventional natural gas fuelling.

INTRODUCTION

The ability to provide motive power for transportation poses one of the greatest challenges to the development of a truly sustainable energy system. Heavy-duty applications are particularly difficult, as they typically require high torque, high efficiency, and long range. To date, direct-injection compression-ignition diesel engines have dominated this class; in the near term, these engines will likely remain the motive power source of choice. Fuelling diesel engines with a cleaner-burning fuel, such as natural gas, can reduce the impact of heavy-duty transportation on the environment through lower emissions of both local air pollutants and greenhouse gases

(GHGs). The use of natural gas can also provide energy source diversity benefits, while making use of existing fuel processing and distribution infrastructure. Blending hydrogen into the natural gas offers further advantages, including the application of hydrogen to an in-use transportation application with few requirements for new infrastructure.

To successfully use blends of hydrogen and natural gas in internal combustion engines, the impact of the hydrogen on the combustion performance and emissions of local and global air pollutants need to be evaluated. By including emissions from the fuel production processes, the effects of hydrogen addition to natural gas on the total emissions can be determined. This work investigates the effects of hydrogen-blended natural gas on the tailpipe emissions and performance of a heavy-duty gaseous-fuelled compression-ignition engine. These results are then combined with the fuel-cycle GHG emissions to evaluate the global benefits of adding hydrogen to the natural gas fuel in a heavy-duty direct injection engine.

Natural Gas Fuelling of Heavy-Duty Engines

The use of natural gas in heavy-duty applications has been widely studied, with in-use engines currently being produced by major engine manufacturers including John Deere, MAN, and Cummins-Westport. Most of these engines use a spark to ignite a premixed natural gas-air charge, very similar to current light-duty gasoline technologies. These engines typically achieve significant reductions in ambient air pollutants such as oxides of nitrogen (NO_x) and fine particulate matter (PM). However, these combustion systems typically have lower efficiencies compared to diesel engines and emit higher levels of methane. This results in a smaller reduction in GHG emissions than would be expected based on the fuel's carbon – energy ratio. A more comprehensive review of natural gas fuelling of heavy-duty engines is available elsewhere [1,2].

One technology for natural gas fuelling of heavy-duty engines, developed by Westport Innovations Inc., uses natural gas injected directly into the combustion chamber late in the compression stroke. This technology is particularly aimed at heavy-duty transport truck applications. A small amount of

diesel fuel is injected prior to the natural gas to provide an ignition source for the gaseous fuel. The natural gas then burns as a predominantly non-premixed combustion event. This provides a combustion heat-release rate that is very similar to that for pure diesel fuelling, resulting in engine performance and efficiency equivalent to that of the baseline diesel engine [3]. CO₂ emissions are reduced by the lower carbon – energy ratio of the natural gas, while the fuel's lower adiabatic flame temperature significantly reduces NO_x formation. PM emissions are also lower, due to the lower sooting tendency of natural gas. Based on these effects, test-cycle emissions have been certified at levels below the 2007 standards [4]. Further, as the natural gas is not premixed in the combustion chamber, diesel engine compression ratios and efficiency can be retained, while emissions of unburned fuel (which is primarily methane, a potent GHG) are significantly lower than from many other natural gas fuelling technologies [1].

To reduce emissions sufficiently to meet upcoming standards, engine developers are pursuing various advanced combustion strategies. One of these is the use of exhaust gas recirculation (EGR) as a tool to reduce combustion temperatures and hence limit NO_x formation. This technology has been shown to be effective in reducing emission of nitrogen oxides from both diesel and direct-injection natural gas combustion systems [5,6]. However, at the very high EGR levels required to meet these future regulations, combustion stability is impaired and emissions of CO, PM, and unburned fuel increase substantially [7]. One option which could maximize the potential benefits of EGR is to use a fuel additive to enhance combustion stability. One such additive which has been studied extensively for gaseous-fuelled engines is hydrogen.

Hydrogen Blended Natural Gas in Engines

The concept of using hydrogen as an additive to improve the combustion rate in internal combustion engines was first suggested for conventional gasoline fuelling [8,9]. Several more recent studies have investigated the effects of blending natural gas and hydrogen for use in homogenous charge, spark-ignition engines [10–16]. The results from these studies vary, with the most important influence being enhanced combustion stability [10,11,14]. For a given air-fuel ratio, NO_x emissions are greater with hydrogen addition, due to the higher flame temperature, while CO and HC emissions are reduced [11,14]. The influence of hydrogen becomes more significant at higher air-fuel ratios, where unstable and incomplete combustion leads to high emissions and poor performance. By enhancing combustion stability, hydrogen addition allows operation at higher air-fuel ratios. As the combustion temperature decreases with increasing air-fuel ratio, combining hydrogen addition with higher air-fuel ratios can lead to a net reduction in NO_x emissions [12,14]. Flame stability in the presence of EGR is also improved at all air-fuel ratios [13,15]. Various volumetric hydrogen concentrations have been investigated; values of 15-20% generally achieve substantial improvements without significant negative effects [12,13,17]. Above 30%, substantial reductions in the charge energy density, coupled with a higher potential for harmful pre-ignition, pose substantial handicaps while providing little further benefit in emissions or stability [15,16].

For premixed combustion, as is found in most spark-ignition engines, the fuel's lower volumetric energy density

tends to reduce the maximum power. This can be overcome with turbocharging [12,14] or injection directly into the combustion chamber. Direct injection of the fuel during the intake stroke typically generates a well premixed charge [18]. However, as the injection is delayed into the compression stroke, the fuel has not fully mixed with air, resulting in a slower combustion event and reduced engine-out power [18]. In a direct injection engine, the effects of hydrogen on the volumetric energy content of the fuel can be overcome by controlling the injection quantity to introduce a constant amount of fuel on an energy basis.

The non-premixed combustion of hydrogen/methane blends, as found in a diesel engine operating on late-cycle direct injected natural gas, has not been as extensively studied as the premixed case. Hydrogen addition to the oxidizer has been shown to increase combustion stability and reduce emissions [19]. For hydrogen addition to the fuel, fundamental studies suggest that non-premixed flame stability is enhanced by the higher flame speeds and improved mixing associated with hydrogen addition [20]. In industrial gas turbines and boilers, hydrogen addition increases NO formation (due mainly to high H and OH radical concentrations) while flame stability is improved [21]. Previous work on a late cycle direct-injection engine (with pilot diesel ignition) revealed that NO_x emissions were increased, while combustion stability was improved and emissions of unburned fuel and PM were reduced [22]. The effects were found to be more significant at conditions where the combustion stability was degraded. However, these tests were conducted only at a single, low-load, high-EGR operating condition; they are not necessarily applicable to more conventional higher load operating conditions.

HYDROGEN

Hydrogen is widely considered to be a potential energy carrier for future transportation applications, based in large part on its suitability for fuelling fuel-cells, but also as a fuel for (near) zero emission internal-combustion engines. However, there is little short-term potential for the development of a hydrogen fuelled motive power source for heavy-duty applications, due to the need for reliable systems with high power densities. Fuel cost and availability, on-board storage and infrastructure are further barriers to be overcome in developing heavy-duty vehicles fuelled with pure hydrogen. Blending hydrogen into natural gas offers a near-term expedient to deploy hydrogen in transportation applications, while also offering reduced ambient air emissions. Most studies reporting the benefits of hydrogen addition to combustion systems generally present their findings on the basis of end-use (tailpipe) emissions, without considering upstream emissions associated with fuel production. To comprehensively assess the GHG benefits of hydrogen blended natural gas fuelling for heavy-duty engines, the impacts on both upstream and end-use emissions need to be considered

Hydrogen Production

Currently, the vast majority of hydrogen (>97%) is produced from steam-methane reforming of natural gas [23]. Hydrogen generation from electricity *via* electrolysis of water offers the potential of greater energy-supply diversity. However, the source of the electricity forms a critical component in the

Table 1: Summary of greenhouse gas emissions from hydrogen generation

Production Source	Refs.	Greenhouse Gases (kg CO _{2,equiv.} /kg H ₂ delivered)	
		Range	Mean (Median)
Steam Methane Reforming	[23,24,25,26*]	10.6-19.2	14 (12.8)
Electrolysis (Average North American electrical generation mix)	[23,25]	34-42	38
Electrolysis (Average California electrical generation mix)	[23,25]	21.7-26.5	24.1
Electrolysis (pulverised coal)	[23,27 [†]]	60-66	63
Electrolysis (Natural Gas fuelled combined cycle gas turbine)	[23,27 [†]]	23.3-32	27.2
Electrolysis (Nuclear)	[23,27 [†] ,28]	1.5-4	2.4 (1.9)
Electrolysis (solar photovoltaic)	[23,26*,27 [†]]	1.2-4.8	2.7 (2.7)
Electrolysis (temperate hydro.)	[29 [†]]	0.9-4.4	2.6 (2)
Electrolysis (tropical hydro.)	[30 [†]]	0.38-127	34 (30)
Electrolysis (wind)	[26*,27 [†]]	0.55-1.24	0.9

Production source: bracketed terms indicate the method of generation of the electricity used to power the electrolyser.

**Reported for distribution as liquid H₂; converted to equivalent for compressed H₂ distribution (liquefaction efficiency 70% [26], compression 85% [23]).*

[†]Calculated based on reported emissions (g CO_{2,equiv.}/kWhr generated), with distribution efficiency assumed to be 92% and electrolysis at 70% [23].

fuel cycle. Results from a number of studies evaluating the fuel-cycle impacts of hydrogen production are summarized in Table 1. Two wide-ranging studies of particular relevance are those of MacLean and Lave [24] and Brinkman *et al.* (in collaboration with GM) [25]. Koroneos *et al.* [26] provide a more detailed analysis of the use of renewably-generated electricity for hydrogen production. Hondo [27] and Wu *et al.* [28] provide detailed analysis of GHG emissions from electricity production, while Gagnon and Vate [29] and Sato *et al.* [30] focus on GHG emissions associated with hydroelectric facilities.

The values cited in Table 1 depend on the boundaries used and assumptions made in the various studies reviewed; these variations contribute to the wide range of GHG emissions reported for some of the production sources. There are also a few effects common to the various hydrogen pathways which need to be mentioned. Specifically, assumptions of the efficiency of the electrolysis process itself varied; most of the studies identify efficiencies on the order of 70-80%. Energy losses for compression, storage, and distribution of the hydrogen as a gas also impose an efficiency penalty. Those studies reported in Table 1 that provided this information indicate that these impose penalties of 5-15% on efficiency [23]. Further variables excluded from the results in the Table include the potential need to liquefy the natural gas feedstock for overseas transportation. This would increase energy usage and CO₂ emissions by approximately 15% above the cited values. The use of localised production can ease distribution problems by making use of existing transmission networks (either electrical or natural gas). However, smaller electrolysers and reformers tend to be slightly less efficient, imposing a 2-3% efficiency penalty compared to centralised production [23].

The electrical generation method profoundly influences the GHG emissions of electrolysis processes. Not surprisingly, fossil-fuel based power stations have high emissions relative to low-emission alternatives such as nuclear, wind or solar. Hydroelectric is generally considered to be ‘low carbon’, and in most temperate climates (and many tropical climates) this is the case, with emissions comparable to solar and nuclear power. High

biogenic methane emissions are sometimes associated with new dams in tropical climates, especially in cases where the reservoir area was not cleared of biological material prior to flooding [29,30]. The wide variability in results for tropical hydro-electric facilities indicates that this is a highly site-specific effect, and that tropical hydro can be as ‘clean’ as other low-GHG emission sources.

Comparatively, the overall fuel-cycle efficiency for natural gas (including extraction, purification, distribution and compression) is on the order of 85-90%, while well-to-tank GHG emissions are 0.45-1.1 (median 0.68) kg CO_{2,equiv.}/kg NG (1.2-2.9 kg CO_{2,equiv.} for the same energy content as 1 kg H₂) [24]. This reduction in NG-associated fuel-cycle emissions due to the reduction in natural gas consumption with hydrogen blending is supplemental to reductions in tailpipe emissions. This can offset at least some of the emissions associated with hydrogen production.

Table 1 pertains only to hydrogen generation; the following sections evaluate the use of hydrogen to improve combustion in heavy duty natural gas fuelled engines.

EXPERIMENTAL APPARATUS

The research facility used in this project is based on a Cummins ISX series heavy-duty compression-ignition engine adapted to operate on direct injection of natural gas fuelling. The engine is a production six-cylinder unit modified for single cylinder operation by deactivating the valves and fuel injectors and drilling through the pistons of the five non-firing cylinders. The firing injector, manifold and combustion chamber geometries are unmodified from the multi-cylinder natural gas fuelled engine, resulting in equivalent performance and combustion stability. The engine is mounted on a steady-state motoring dynamometer test bed, which provides precise control of the engine’s speed and allows the single cylinder engine to be operated at conditions equivalent to a multi-cylinder engine. The diesel and natural gas injection processes are controlled electronically using a single multi-fuel injector. Combustion air is supplied by an industrial rotary-screw air compressor fitted with an aftercooler, water separator, and multi-stage oil filtration. The engine is fitted with a high-pressure EGR system which includes a cooler for temperature control and a valve to regulate flow rate. This custom air-exchange system provides a wide range of charge conditions that are controlled independently from changes in fuel composition and engine operating condition. Further details of the engine are given in Table 2; the experimental facility has been described in greater detail previously [31,32].

The engine facility is fully instrumented, with measurements of air and fuel flow (both diesel pilot and natural gas) as well as exhaust concentrations (CO₂, CO, HC, NO_x, PM). The EGR level is determined by comparing measurements of the CO₂ concentration in the intake and exhaust streams. The gaseous fuel flow measurement uses a Coriolis-force mass flow sensor, which provides an actual gaseous mass flow rate, independent of the fuel composition. The combustion process is

TABLE 2: Engine and injector specifications

Engine	Cummins ISX single cylinder 4-stroke, 4-valve
Fuelling	Direct injection; diesel pilot, gaseous main fuel
Displacement (/cylinder)	2.5 L
Compression Ratio	17:1
Bore/Stroke/Connecting Rod Length	137/169/261 mm
Injector	Westport Power Inc. dual-fuel concentric needle
<i>Injection control</i>	Separate diesel and CNG solenoids
<i>Injector holes</i>	7 pilot, 9 gas
<i>Injection angle</i>	18° below fire deck

monitored using a high-speed water-cooled in-cylinder pressure transducer in conjunction with a ½° crank-angle encoder to identify the piston location. The heat-release rate (HRR) can be calculated from this information [33]:

$$\frac{dQ_{net}}{d\theta} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta}, \quad (2)$$

where θ is the crank angle, p is the in-cylinder pressure at a given crank angle, V is the cylinder volume at that point and γ is the specific heat ratio (c_p/c_v – assumed constant). The net heat release rate estimates the rate of energy release from the combustion process, less wall heat transfer and crevice flow losses, assuming a constant cylinder temperature at any given point in the cycle. In this work, the definition of the combustion duration is based on the relative fraction of the total energy released up to a certain crank-angle based on the calculated HRR (the integral of the heat release, IHR). The combustion timing refers to the crank-angle location at which half of the heat has been released (50%IHR), while the burn duration (BD) refers to the total duration of combustion (from 10% IHR to 90% IHR). These results are based on pressure-crank angle data from 45 consecutive cycles collected at each operating condition.

PM emissions are measured using a micro-dilution system, where raw exhaust is diluted (at a volume ratio of 15:1) by clean, dry nitrogen. After being allowed to mix, the total PM mass is measured using a tapered element oscillating microbalance (validated against gravimetric filter measurements [31]). The black-carbon content of the PM is measured using an Aethalometer, where PM is collected on a quartz filter. The attenuation in the intensity of a monochromatic light shone

TABLE 3: Engine operating conditions and fuel blends

Parameter	'Low Load'	'High Load'
Speed (RPM)	800	1200
Indicated Power* (kW) [% load]	10 [25%]	35 [75%]
Ind. Mean Effective Pressure [†] (bar)	6	13.5
Fuel-oxygen equivalence ratio	0.5	0.6
Gaseous Fuel Pressure (MPa)	16	21
EGR (mass %)	40	30
Injection Timings	0.5,10,15° ATDC	0.5,10,15° ATDC
Fuel - %H ₂ by volume	0 : 10 : 23	0 : 15 : 35
- %H ₂ by mass	0 : 1.4 : 3.7	0 : 2.2 : 6.3
- %H ₂ by energy	0 : 3.6 : 9.2	0 : 5.6 : 15.2
Fuel carbon-energy ratio (g C/MJ)	16.7 : 16.1 : 15.3	16.7 : 15.7 : 14.1

*Indicated Power – the power generated by the single firing cylinder, based on the cylinder pressure trace over the compression and power strokes only.

[†]Ind. Mean Effective Pressure – Indicated Power normalized by speed and displacement.

through the sample is measured. This value is then used to calculate the concentration of light-absorbing black carbon on the filter. Further discussion of the Aethalometer operation is provided elsewhere [31].

Engine Test Conditions

The effects of hydrogen addition to the natural gas were evaluated at two baseline operating conditions, as indicated in Table 3. A low-load, low-speed, high-EGR condition was selected to represent a highly unstable operating condition, where hydrogen was anticipated to have the greatest benefit. The details of these experimental results have been presented previously [22]. The second condition involved a higher load at a moderate speed with a moderate level of EGR. This condition is generally representative of a steady-state cruising mode for a heavy-duty engine. The use of EGR maintains relatively low levels of NO_x without degrading the combustion event at this high-load condition. Fuels with three hydrogen concentrations were tested at each operating condition, as shown in Table 3.

Varying the timing of the combustion (controlled by the start-of-injection timing of the diesel; the gaseous fuel injection started a fixed 1.0 ms after the end of the diesel injection) provided a range of combustion conditions while maintaining constant charge composition and overall fuel-air equivalence ratio. The mid-point of the combustion event varied from being at top-dead-centre to 15° after top-dead-center (ATDC), a range typical for heavy-duty engine applications. The later timings corresponded to lower NO_x emissions but reduced efficiency and increased combustion instability. The injection timing was adjusted for the different fuel blends to hold the mid-point of the combustion timing at the specified value. For all conditions, the engine's power output was held constant by varying the mass flow-rate of the gaseous fuel. The pilot diesel quantity was fixed at 5mg/injection, which equates to 5-10% of the total on an energy basis.

EFFECT OF HYDROGEN ADDITION ON NATURAL GAS COMBUSTION

The addition of hydrogen to natural gas fuel has a significant impact on engine performance and emissions. In this work, the salient features of hydrogen addition will be identified. Differences between the low and high load cases, and corresponding explanations for the observed differences, will be provided. The main objective of this work is to compare the relative effects at the two different load cases, and then to consider these influences on emissions and efficiency in the context of the entire fuel cycle.

Low Load

The low-load operating condition was selected to investigate whether hydrogen addition could be used to enhance a poor-stability combustion event. This condition suffered from relatively high hydrocarbon emissions (>95% unburned methane), especially at the later timings. Combustion instability and CO emissions were also significantly greater than under a more stable (lower EGR) operating condition. Conversely, NO_x emissions were low. Testing was carried out at two fuel-hydrogen contents, 10% and 23% by volume.

The mean effects of hydrogen addition on the

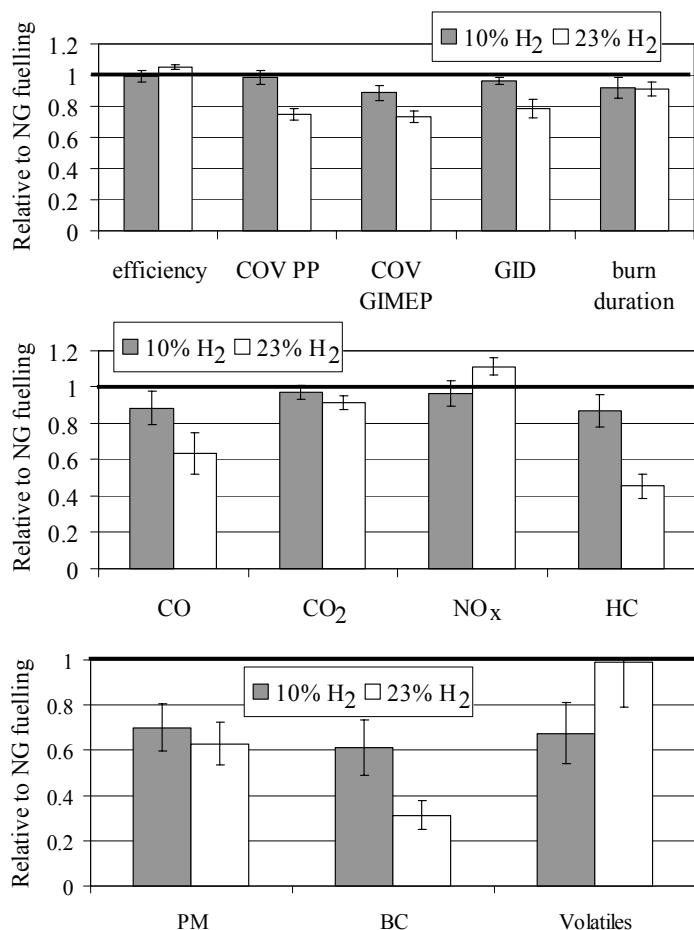


FIGURE 1: Emissions and performance measures, relative to natural gas fuelling, for the low-load high-EGR case. Results are average values for all combustion timings. [COV: coefficient of variation (PP: peak pressure, GIMEP: Gross Indicated Mean Effective Pressure); GID: gaseous fuel ignition delay; BC: black carbon.]

combustion event, gaseous emissions and particulate emissions are shown in Figure 1. The results are represented as ratios relative to the baseline fuelling (natural gas) test case. The ‘error bars’ indicate experimental uncertainty. The high hydrogen content case showed an improvement in efficiency, in part resulting from a reduction in combustion variability demonstrated by the lower coefficient of variation of the peak cylinder pressure (COV PP) and of the overall combustion event (COV GIMEP). The shorter gaseous-fuel ignition delay (GID) indicates that the hydrogen-methane blended fuel is easier to ignite than pure natural gas. Similarly, the reduction in BD (as defined above) suggests that the greater fuel reactivity is influencing the entire combustion event. The fact that there is only a small reduction in BD between the low and high hydrogen concentrations suggests that even a small increase in fuel reactivity may be sufficient to overcome the principal kinetic limitations in the bulk combustion event; this effect is not seen in the ignition process. These results clearly indicate that, at this light-load, high-EGR operating condition, chemical kinetics are controlling both the ignition and progression of the combustion process.

The gaseous emissions results demonstrate that hydrogen addition significantly reduces CO and HC emissions. These findings, combined with the reduction in combustion variability

and improvement in efficiency, indicate that the hydrogen in the fuel is significantly enhancing the overall combustion event. The increased reactivity of the blended fuel tends to offset the slower mixing and combustion rate commonly encountered with high-EGR operation [5]. The lower carbon content of the fuel has a secondary effect on CO and HC; however, it is the principal reason for the reductions in CO₂ emissions. For the high hydrogen concentration fuel, the small increase in NO_x can be attributed to the blended fuel’s higher adiabatic flame temperature. The slight reduction in NO_x (~4%) for the low hydrogen fuelling is most likely an experimental artefact, as it is within experimental uncertainty for the gaseous emissions measurements.

The total mass of the particulate matter emissions is significantly reduced by the hydrogen in the fuel. This is primarily a result of a reduction in the black carbon (soot) being formed in the natural gas combustion. Previous research has indicated that, under moderate and high EGR conditions, more than 80% of the black-carbon PM is generated by the natural gas combustion [34]. However, volatile concentrations are still significant; these are typically attributed to evaporated lubricating oil and diesel pilot fuel which has not burned, but rather condensed in the dilution process. The volatile concentration increases as the BC mass is reduced, resulting in a higher relative contribution of the volatiles.

High Load

The high-load operating condition investigated a higher range of hydrogen in the fuel, at 15% and 35% H₂ by volume. This operating condition was more stable than the low-load case, with lower EGR levels and longer injection duration. The longer injection duration should reduce cycle-to-cycle variability in the injection event. The effects of the hydrogen addition on the combustion performance and emissions are shown in Figure 2.

The effect of hydrogen addition to the fuel at high load differs significantly from the influences observed at low load. There is no detectable change in efficiency, due to a smaller fraction of the total fuel being lost as unburned fuel emissions for the zero hydrogen case (~0.5%, compared to ~1.5% for the low-load case). As a result, the fact that the hydrogen addition reduces these emissions has no discernable impact on the overall fuel conversion efficiency. The gaseous fuel ignition delay is reduced, indicating that the hydrogen in the fuel enhances the gaseous fuel ignition, most likely due to the wider flammability range of the hydrogen. The lower coefficient of variation of the peak pressure (COV PP) reinforces this, as the peak pressure typically occurs early in the combustion process, which is most sensitive to the stability of the ignition event. The fact that the overall combustion stability, as represented by the COV GIMEP, is only slightly improved with hydrogen addition further indicates that the principal effect at this load condition is on enhancing the initial combustion stages. The fact that the hydrogen does not significantly reduce the burn duration at high load reinforces the assessment that the overall combustion event is less sensitive to the enhanced reactivity of the fuel. This rate depends primarily on the rate at which the fuel and air are mixing, independent of the hydrogen content of the fuel.

The effects of the hydrogen on the emissions are generally similar to the low-load case. CO and HC emissions are reduced,

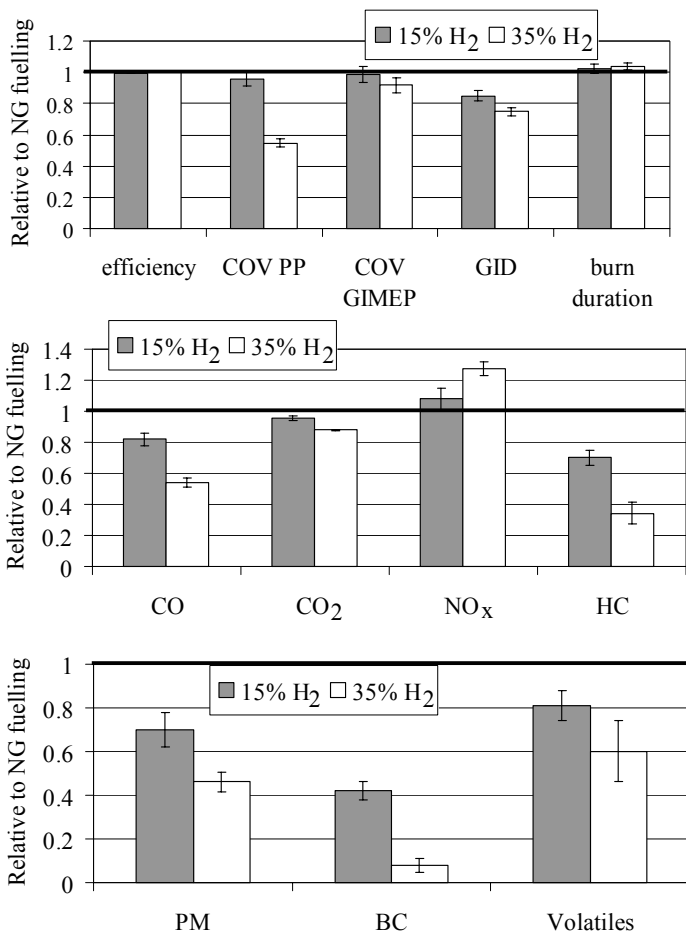


FIGURE 2: Emissions and performance measures, relative to natural gas fuelling, for the high-load moderate-EGR case. Results are average values for all combustion timings. [COV: coefficient of variation (PP: peak pressure, GIMEP: Gross Indicated Mean Effective Pressure); GID: gaseous fuel ignition delay; BC: black carbon.]

in part due to the reduction in carbon content of the fuel. This effect would have a magnitude similar to the reduction in CO₂ emissions, which is less than 20% of the actual reductions in emissions of these species. The majority of the reductions are most likely due to enhanced kinetics in the vicinity of the reaction zone and during the early-combustion period. In particular, the concentrations of reactive radicals such as OH and H have been shown in previous work to be substantially increased with hydrogen addition to the fuel [21]. NO_x emissions are increased; this may be attributed to the hydrogen-blended fuel's higher flame temperature. CO₂ emissions are reduced because of the fuel's lower carbon-energy ratio. Particulate matter emissions are also significantly reduced, with virtually no black-carbon PM being detected with the high hydrogen concentration. The oxidation of PM precursors (which typically lead to black carbon) in the reaction zone will be enhanced by the higher concentrations of radicals, resulting in less PM formation and hence lower emissions.

Net Engine Emission Effects

The experimental results indicate that the addition of hydrogen to natural gas can result in significant improvements in combustion stability, while reducing emissions of most local

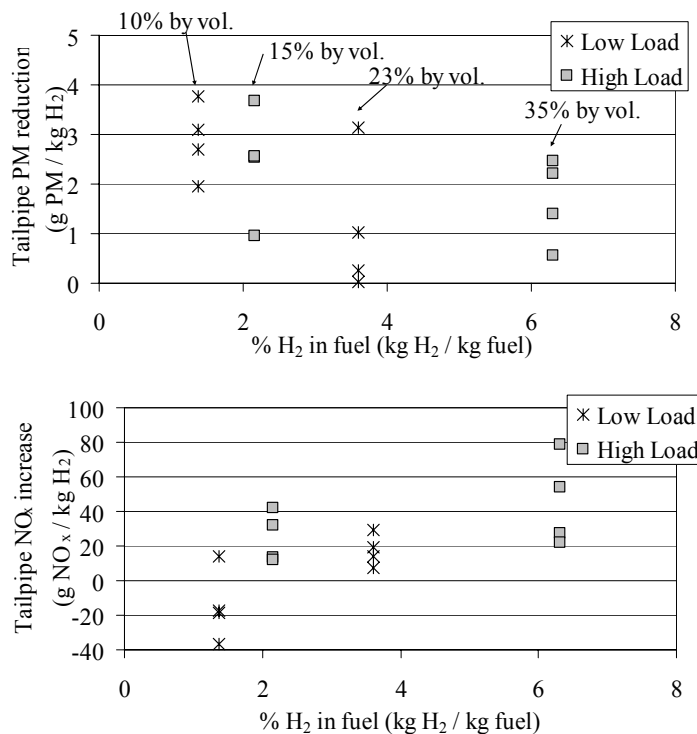


FIGURE 3: Effect of hydrogen addition on change in measured emissions of PM and NO_x, as a function of hydrogen content, relative to pure natural gas. Top: reduction in PM mass emissions per kilogram of H₂ added to the fuel. Bottom: increase in NO_x mass emissions per kilogram of H₂ added to the fuel. The individual points at each H₂ concentration are for four timings. Both low-load and high-load cases are shown.

and global air pollutants. The effects on PM and NO_x emissions, at all the operating conditions, are shown in Figure 3 on the basis of change in the emitted mass of pollutant as a function of the mass of hydrogen consumed. The individual points represent the various timings used in the tests. For both sets, the combustion timing was varied from 0 to 15°ATDC in 5°CA steps. In agreement with previous work [5,6], the PM increases with later timing while NO_x emissions are reduced. In Figure 3, for each fuelling condition the higher PM values relate to the later combustion timings, while higher NO_x levels are generated at the earlier timings.

As discussed in earlier sections, hydrogen addition to the fuel significantly reduces PM emissions at all operating conditions. The greatest effects are observed at the latest combustion timings, where PM emissions are highest. On a per unit of hydrogen basis, the greatest reductions in PM emissions are achieved at the lower hydrogen concentrations. This indicates that even relatively small concentrations of H₂ can have a substantial positive impact on reducing PM emissions.

NO_x emissions are also shown in Figure 3. The results demonstrate that higher hydrogen concentrations substantially increase NO_x emissions on a per-unit hydrogen basis. This is due to the highly nonlinear relation between NO formation *via* the thermal kinetic mechanism and the combustion temperature. The one exception to this is the low-load case with the low hydrogen concentration, where NO_x emissions are slightly lower than for the natural gas fuelling. This is most likely a result of experimental variability, as the measured difference is

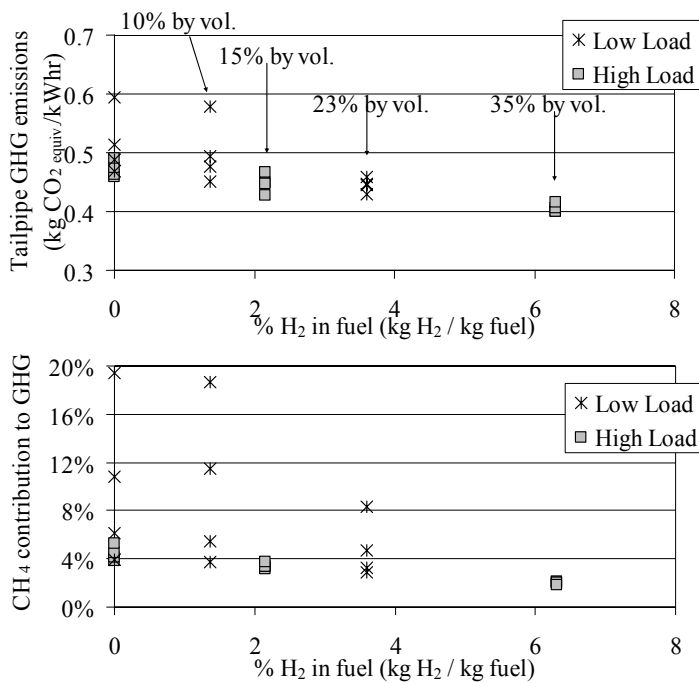


FIGURE 4: Effect of hydrogen addition on tailpipe GHG emissions, as a function of hydrogen content in the fuel. Top: GHG emissions normalized by power. Bottom: Contribution of CH₄ to net GHG emissions. The individual points at each H₂ concentration are for four timings. Both low-load and high-load cases are shown.

smaller than the experimental uncertainty of the NO_x measurement. To offset the increase in NO_x emissions observed with most of the hydrogen fuelling conditions, the engine could be operated at higher EGR levels. The improved combustion stability and lower by-product emissions associated with hydrogen addition would counteract the negative effects of increasing the EGR fraction. The net result of combining hydrogen addition to the fuel with higher EGR rates would be to maintain or even reduce engine-out NO_x while simultaneously reducing PM, HC, CO and GHG emissions.

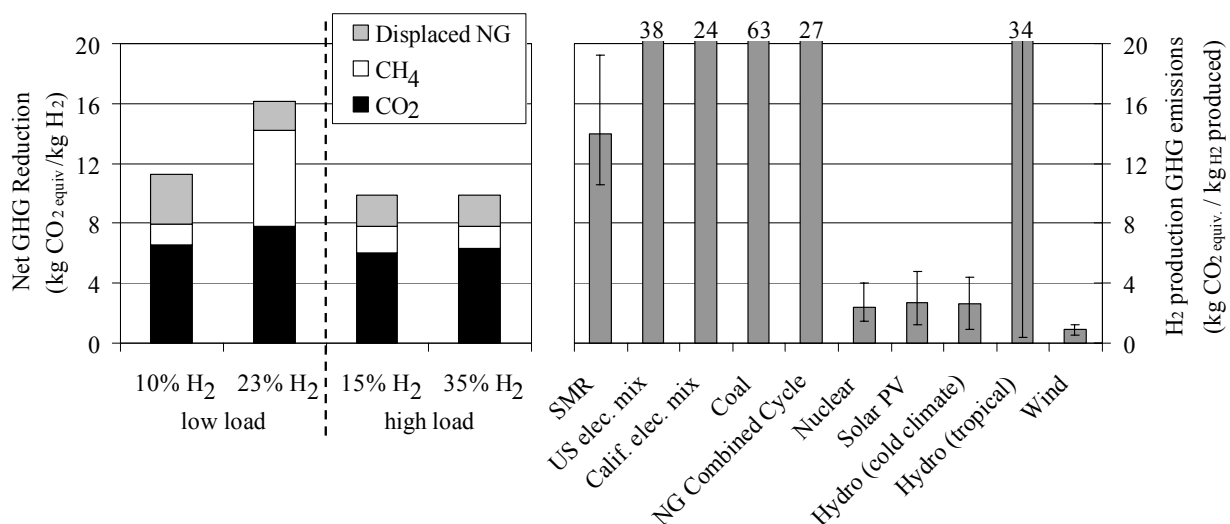


FIGURE 5: Effect of hydrogen addition on measured greenhouse gas emissions, as a function of hydrogen content in the fuel. Results for both low-load and high-load cases are shown. The plot on the right shows the equivalent GHG emitted during the production of hydrogen for various generation strategies; error bars indicate the range of reported values for each strategy. SMR: Steam Methane Reforming. PV: Photovoltaic.

The net engine-out GHG emissions, shown in Figure 4, are significantly reduced by the addition of hydrogen to the fuel. This value includes both CH₄ and CO₂ emissions, combined on the basis of global warming potential [35] (see the Appendix for the equations used in calculating net GHG emission rates). The principal cause of the observed reduction in tailpipe GHG is the lower carbon-energy ratio of the fuel (Table 3). This results in lower CO₂ emissions per unit of power produced, an effect that is relatively insensitive to load or combustion timing. At the lower load condition, the reduction in net GHG emissions does vary substantially with injection timing; this is a result of high unburned fuel (CH₄) emissions at late timings. At low load and late timing, the CH₄ contributes ~20% of the net engine-out GHG emissions without hydrogen in the fuel, as shown in Figure 4. At low hydrogen content, only a small reduction in this fraction is observed; however, the high-hydrogen content fuel generates a much larger reduction. The variability in GHG emissions at high load is much smaller, because of the improved combustion stability at this condition and the correspondingly smaller contribution of methane to the GHG emissions.

OVERALL GREENHOUSE GAS EMISSIONS

The experimental results demonstrate that replacing natural gas with hydrogen in the fuel significantly reduces CO₂ and CH₄ emissions, resulting in a reduction in engine-out GHG emissions. The hydrogen in the fuel also displaces some natural gas, reducing the GHG emissions associated with natural gas extraction and delivery. *However, the global effect of hydrogen blending in natural gas depends on the emissions associated with the production and distribution of the hydrogen.*

Figure 5 shows the reduction in GHG emissions achieved by hydrogen addition to the fuel per unit of hydrogen consumed, including both the emissions reductions (CO₂ and CH₄) as well as the GHG emissions savings associated with the reduction in natural gas consumption. The addition of hydrogen to the fuel results in a greater net reduction in GHG emissions at lower loads, because of the reduction in CH₄ emissions discussed earlier. At high load, there is relatively little

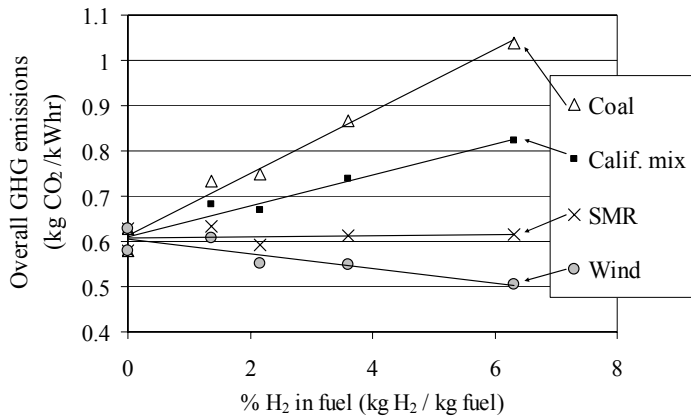


FIGURE 6: Overall (engine and fuel cycle) GHG emissions for four H₂ generation pathways (conventional pulverized coal power plant; average California electrical generation mix; steam-methane reforming with domestic natural gas; wind turbine generation). Low and high load conditions shown.

variability in the results, as demonstrated previously in Figure 4. Of particular note in Figure 5 is that the addition of hydrogen reduces net GHG emissions by on average 10 kg CO_{2,equiv.}/ kg H₂. Even greater reductions are achieved at those conditions where the hydrogen is producing the largest improvement in the combustion process.

These results provide a benchmark for comparison against the fuel-cycle GHG emissions associated with hydrogen production, also shown in Figure 5 (based on the results presented in Table 1). The use of electricity generated from fossil-fuel power plants can result in a net increase in GHG emissions at most conditions. A similar conclusion applies for conventional electricity generation ‘mixes’ such as US average (~50% coal) and California (~20% coal, ~30% natural gas) [23]. Lower GHG electricity sources, such as wind, solar, nuclear, and hydro (in appropriate locations) offer a substantial net benefit. Other techniques, such as sequestering carbon emissions from conventional power plants or using H₂ generated as a by-product of industrial processes (such as Sodium Chlorate production), could also lead to low-GHG hydrogen production. Combined with natural gas vehicle fuels, these sources of hydrogen have the potential to provide a significant net improvement in GHG emissions.

To provide a more quantitative analysis of the effects of H₂ addition to a natural-gas fuelled engine, the engine-out (tailpipe) and fuel-cycle emissions have been combined in Figure 6 for four of the hydrogen production routes. The analysis includes both the GHG emissions from fuel production and the tailpipe emissions (the method is shown in more detail in the Appendix). The results indicate that the use of hydrogen generated from steam-methane reforming has a generally neutral influence on total GHG emissions. This is a result of the fact that, while overall GHG emissions increase at high load with SMR, they are lower at low load due to the significant reduction in CH₄ emissions. Using electrolysis, with the electrical supply generated from a ‘clean’ source (wind is shown; similar results can be achieved using hydro-electric, nuclear, and solar-PV, as suggested by Table 1 and Figure 5) can achieve significant real benefits in terms of lower GHG emissions, as well as significantly reducing emissions of ambient air pollutants such as PM and hydrocarbons.

DISCUSSION

Combining Hydrogen generated from low-GHG sources such as wind, solar and hydro sources with natural gas offers the potential to substantially reduce the GHG emissions of gaseous fuelled transportation applications. The deployment of blended natural-gas/hydrogen fuel in vehicles would have impacts on the fuelling infrastructure and the on-vehicle equipment. Provision of hydrogen generation equipment at the filling station would minimize the need to transport and distribute the hydrogen. However, depending on the generation method selected, this could impose a 1-3% efficiency penalty on the production process [26]. On-vehicle storage of the hydrogen/natural gas blends could use the same carbon-fibre wrapped storage containers as are available for pure high-pressure natural gas or hydrogen storage. A larger volume of tank would be required to maintain the vehicle’s range, depending on the hydrogen content of the fuel. For the 35% (by volume) H₂ fuel case, this would result in an approximately 50% increase in the required volume to store an equal quantity of fuel (on an energy basis). For lower hydrogen concentrations, the needed increase in volume (or reduction in range) would be correspondingly less. If on-board compression were required to reach the desired injection pressures, the maximum compressor work (with the storage tank at its lowest pressure) would increase on the order of 50% with 35%H₂; however, this would still only be around 1-2% of the total energy contained in the fuel [31].

The near-term introduction of hydrogen to a heavy-duty on road application has other benefits which are more difficult to quantify. Such usage will facilitate the early deployment of hydrogen in transportation applications, while requiring relatively minor modifications to the engine or delivery system. The current tests show that by modifying the commanded injection parameters, the engine’s performance can be maintained while emissions are reduced. Coupling the engine’s on-board control computer with a method for measuring the concentration of hydrogen in the fuel would permit the development of an engine system which can operate on a range of hydrogen-natural gas blend fuels. This could include running on pure natural gas in cases where no hydrogen is available. The injection timing and EGR level could be modified based on the fuel content to optimize the combustion performance, minimizing local and global pollutant emissions while maximizing efficiency.

CONCLUSIONS

1. The addition of hydrogen to the natural gas in a direct-injection compression-ignition engine offers the potential of reduced local air pollutant emissions. HC and CO emissions are reduced by 15%-20% for every 10% increment in H₂ concentration in the fuel, primarily from improved combustion stability. PM emissions are reduced by 10% for the same increment, primarily due to reductions in the black-carbon content of the PM. Sufficiently high concentrations of hydrogen in the fuel can virtually eliminate emissions of black carbon particulate. These benefits are achieved independent of the source of the hydrogen.
2. Engine-out greenhouse gas emissions are significantly reduced with hydrogen addition. The CO₂ emissions are reduced by the fuel’s lower carbon-energy ratio, while CH₄

is reduced by improved combustion stability. At high load, a 10% increase in hydrogen in the fuel reduces GHG by 3.5%. Even more significant GHG reductions, of 5% per 10% increment of hydrogen in the fuel, are achieved at low load where CH₄ composes a greater fraction of the net GHG emissions.

3. NO_x emissions are increased by 10% for each 10% increment in hydrogen in the fuel. With hydrogen in the fuel, operating at higher EGR fractions could offset these increases while maintaining combustion stability and low levels of HC, CO, and PM emissions.
4. Hydrogen addition to the fuel can enhance the combustion event, especially at low-load and high-EGR conditions. At these conditions, the higher reactivity of the fuel helps to reduce the combustion event's kinetic limitations.
5. At high load, the ignitability of the gaseous fuel and the early-cycle stability are enhanced by hydrogen addition. The overall combustion rate is not significantly affected, suggesting that while the ignition event is kinetically limited, the overall combustion process is primarily mixing-controlled.
6. By generating hydrogen from electrolysis fuelled by hydropower, photovoltaic cells, wind turbines, or nuclear generating stations, net reductions in GHG of between 6 kg and 10 kg CO_{2,equiv.} can be achieved per kilogram of H₂ consumed at all operating conditions. Even greater reductions are achieved at less stable operating conditions. Simultaneously, fossil natural gas is replaced by a locally-generated, renewable alternative which can be used as an additive in existing fuel systems with minor modifications to the engines or distribution systems.

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NOMENCLATURE

ATDC	-	After Top-Dead-Center
BC	-	Black Carbon
BD	-	Burn Duration (10%-90% IHR)
CH ₄	-	Methane
CO	-	Carbon Monoxide
CO ₂	-	Carbon Dioxide
CO _{2,equiv}	-	Mass of CO ₂ to Generate an Equivalent Global Warming Potential
COV	-	Coefficient of Variation
EGR	-	Exhaust Gas Recirculation
GHG	-	Greenhouse Gases
GID	-	Gaseous Fuel Ignition Delay
GIMEP	-	Gross Indicated Mean Effective Pressure
H ₂	-	Molecular Hydrogen
HC	-	Hydrocarbons
HRR	-	Heat Release Rate
IHR	-	Integrated Heat Release Rate
NO _x	-	Oxides of Nitrogen (NO, NO ₂)

NG	-	Natural Gas
PM	-	Fine Particulate Matter
PP	-	Peak Pressure
PV	-	Photovoltaic
SMR	-	Steam Methane Reforming

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APPENDIX

The method and constants used in calculating the net GHG emissions are shown below:

Fuel Cycle:

For most of the studies cited in Table 1, the fuel cycle GHG emissions were reported in the form of kg CO_{2, equiv.} / kg H₂ produced, including hydrogen production, delivery to the filling station in a gaseous state, and compression for vehicle filling. Most of the studies included the GHG emissions associated with the fabrication of the components of the fuel production pathway; only Brinkmann *et al.* explicitly excluded these [25]. Several of the cited studies reported GHG emissions associated with electrical production, rather than H₂ production. For these cases, the fuel-cycle (FC) emissions were calculated from:

$$FC_{H_2}(\text{gCO}_{2,\text{equiv}} / \text{kg}_{H_2}) = \frac{mGHG_{\text{elec}}(\text{gCO}_{2,\text{equiv}} / \text{kWhr}_{\text{electricity}})}{\eta_{\text{electrolysis}} * \eta_{\text{distribution}} * \eta_{\text{compression}}} * LHV_{H_2}(\text{kWhr} / \text{kg}_{H_2})$$

For this analysis, the efficiency values used were: $\eta_{\text{electrolysis}} = 70\%$; $\eta_{\text{distribution}} = 92\%$; $\eta_{\text{compression}} = 85\%$. An LHV_{H_2} of 142 MJ/kg_{H2} (39.4 kWhr/kg_{H2}) was used [33].

Engine Out:

Engine out GHG emissions were calculated using:

$$mGHG_{\text{engine}}(\text{gCO}_{2,\text{equiv}} / \text{kWhr}) = mCO_2(\text{gCO}_2 / \text{kWhr}) + mCH_4(\text{gCH}_4 / \text{kWhr}) * GWP_{CH_4}(\text{gCO}_2 / \text{gCH}_4)$$

where $mGHG_{\text{engine}}$ represents the power-specific GHG emissions rate in terms of an equivalent mass of CO₂, mCO_2 is the measured power specific engine-out emissions of CO₂ and mCH_4 is the measured power specific engine-out emissions of methane. GWP is the global warming potential (on a mass basis for a 100 year time horizon) of methane relative to CO₂; a value of 23 was used based on the IPCC published values [35].

Overall:

The overall emissions of greenhouse gases include both fuel cycle and engine-out values. They were combined using:

$$mGHG_{\text{net}}(\text{gCO}_{2,\text{equiv}} / \text{kWhr}) = mGHG_{\text{engine}} + m_{NG}(\text{kg}_{NG} / \text{kWhr}) * FC_{NG}(\text{gCO}_{2,\text{equiv}} / \text{kg}_{NG}) + m_{H_2}(\text{kg}_{H_2} / \text{kWhr}) * FC_{NG}(\text{gCO}_{2,\text{equiv}} / \text{kg}_{H_2})$$

where the mass flow rate of fuel (m_{NG} and m_{H_2}) are calculated based on the mass ratio of hydrogen in the fuel and the measured mass flow rate of gaseous fuel. Median values from Table 1 were used for the fuel cycle emissions of H₂; FC_{NG} used was 0.68 kg CO₂ / kg NG, based on [24].