Hydrogen as a replacement fuel in diesel engines

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About CS NOW

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that will use the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation ambitions.

CS-N0W aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

List of Acronyms

CI	Compression ignition
DI	Direct injection
EGR	Exhaust gas recirculation
H2D	Hydrogen + diesel fuelled engine
H2-ICE	Hydrogen fuel internal combustion engine
HFC	Hydrogen fuel cell
HGV	Heavy goods vehicle
ICE	Internal combustion engine
NO_x	Nitrogen oxides (the sum of NO_2 and NO)
NO	Nitric oxide
NO_2	Nitrogen dioxide
NRMM	Non-road mobile machinery
PM	Particulate matter
SI	Spark ignition

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1. Executive summary

Decarbonising some transport and energy sectors may require the use of **H**ydrogen as an alternative fuel, potentially blended with **D**iesel fuel in engines (referred to as **H2D**). This approach has recently been commercialised and may support sectors that currently rely on large diesel plant, such agricultural equipment, off-road machinery, and reserve / capacity market power generation (often referred to as diesel farms). Whilst addition of hydrogen can reduce the net carbon emissions from such appliances, it retains the combustion system and exhaust and leads to other emissions that impact air quality. In contrast, the use of hydrogen in electrochemical fuel cells produces no air pollution as a by-product of use.

The most significant impacts to consider from a local air quality perspective are nitrogen oxides (NO_x) and particulate matter (PM). Engine operating conditions, such as load and idling, impact significantly on emissions, so the adoption of H2D as a decarbonisation strategy needs to be well optimised and used in the most appropriate applications. H2D would likely need to still be used in combination with suitable exhaust gas aftertreatment systems.

Adding hydrogen to diesel fuel in compression ignition engines reduces tailpipe emissions of pollutants such as particulate matter (PM) and sulfur dioxide (SO_2), and in this regard could bring worthwhile air quality co-benefits. However, the addition of hydrogen can lead to increased emissions of nitrogen oxides (NO_x) in the exhaust gases under some conditions. The scale of NO_x emissions depends partly on engine load, so the addition of hydrogen appears to be more appropriate in applications with lower loads or extended periods of engine idling (where idling cannot be avoided). Lower average load applications include HGVs, excavators, dumpsters and cranes. In high continuous load applications (e.g. power generation) there is some evidence that addition of hydrogen fuel can increase NO_x emissions, when compared to pure diesel, and so use in these sectors may be less appropriate.

2. Introduction

Biofuels such as biodiesel, hydrotreated vegetable oil and bioethanol have been used to partly decarbonise vehicles and static engines over the last two decades. An alternative approach is to mix hydrogen with diesel (or any equivalence liquid fuel) in dual-fuel internal combustion engines (ICEs). This report examines the potential implications for air quality emissions from using hydrogen in larger diesel engines, and when used in heavy-duty applications such as Non-Road Mobile Machinery (NRMM) and electrical supply installations such as diesel farms.

The UK Government has recognised that hydrogen has the potential to complement electrification, focussing its attention on the development and scaling up of low-carbon hydrogen production methods. The Hydrogen Strategy, published in August 2021, aims to facilitate the deployment of 5 GW of low-carbon hydrogen production capacity by 2030[13]. Plans for how hydrogen could be used to decarbonise NRMM and industrial processes are less developed. Heavy goods vehicles (HGVs), NRMM and generators are heavily reliant on diesel, which has historically been a reliable, cheap and efficient fuel. A £40 million Red Diesel Replacement competition has been funded to support low carbon technologies in this area, with funding expected to begin in April 2022[16].

Hydrogen gas can be blended with diesel in existing ICEs with minimal structural changes to the powertrain. This allows for simple initial deployment of small amounts of hydrogen, something that may be necessary to support a wider business case for investment in hydrogen manufacturing at scale[11]. The amount of hydrogen blended can be varied, depending on the availability of the fuel. This could be useful in the initial years of the UK hydrogen economy, when hydrogen supply is likely to be limited[13]. As supply increases, it would be possible to increase the fraction of hydrogen gas that is injected in a hydrogen-diesel (H2D) fuel blend.

Replacing some diesel or biofuels with hydrogen is very likely to reduce particulate matter (PM) emissions and using 100% hydrogen would also eliminate remaining trace emissions of sulfur dioxide (which derives from sulfur contained in fossil fuels). However, hydrogen combustion is not emissions-free. The major atmospheric emissions of consequence are nitrogen oxides (NO and NO_2, collectively called NO_x). The adverse health and environmental impacts of NO_2 are estimated at around £5bn/year[20,21], where around 30% of emission arise from heavy duty vehicles. Application of emission control strategies in energy and transport sectors has led to sustained NOx emissions reduction over the last 20 years. However, the most recent annual air quality assessment found the UK was non-compliant with annual mean NO_2 standards in 5 zones[22]. Further reduction of 18% in emissions is needed between 2020 and 2030 if the UK is to meet its international obligations under the CLRTAP/Gothenburg Protocol (based on Defra reporting on NECD commitments and attainment [23]). NOx emissions from diesel engines have been under close scrutiny in recent years, following the VW emissions scandal in 2015[24]. Possible NOx emissions from future hydrogen combustion have however received little attention in UK decarbonisation strategies[15,25].

With any internal combustion engine there is a fundamental trade-off between air quality emissions and energy efficiency, since the formation of NOx is linked to combustion temperature and air-fuel mixture used[18]. If H2D combustion in dual fuel engines, or as a pure fuel, is to be deployed at scale, further reduction in NOx emissions alongside decarbonisation would be desirable. This report uses an extensive literature review and meta-analysis to investigate the possible air quality impacts of hydrogen use in those combustion applications where it may be a replacement for existing diesel appliances. These include off road and construction machinery, heavy goods vehicles and capacity market diesel farms. Whilst the end-use applications are diverse, frequently identical engines are used, and hence conclusions on impacts can be broadly extrapolated between end-use sectors.

3. Review of commercial H2D developments

3.1 Summary of recent projects using H2D and H2-ICE

When and how decarbonisation of large diesel engines will be achieved relies on the research and development of new technologies and alternative fuels. The main commercial organisations considering large diesel engine decarbonisation using hydrogen fuel are summarised in Table 2, and each is discussed below. Since these are commercial developments, the new developments are frequently issued via investor or press releases, and rarely are more detailed datasets provided. None of these manufacturers provide data on their emissions in the peer-reviewed literature.

Table 1 Summary of current developments in the application of hydrogen combustion for heavy-duty diesel engine decarbonisation

Company	Application	% H_2 addition	Reported NO_x emissions	Other decarbonisation methods	Future decarbonisation targets
JCB	H2-ICE telescopic handler H2-ICE backhoe loader	100%	Lower than pure diesel	HFC BEV for small machines	H2-ICE products on the market by end of 2022 Green hydrogen imports from 2022
Cummins	6.7L medium duty H2-ICE 15L heavy duty H2-ICE	100%	Reduced using after-treatment	HFC BEV for small machines	H2-ICE in Class 8 trucks in 2nd half of 2022 Major role in transport decarbonisation from 2025
Hydra	H2D dual fuel truck retrofits	up to 40 e.%[1]	Comparable to diesel	N/A	50e.% by 2023 100e.% long term goal
HYDI	On-board H_2 production unit for H2D dual fuel	N/A (<100%)	up to 45% less than diesel	N/A	Expanding the applications of the unit Develop model for export
ULEMCo	H2D dual fuel retrofits	30-70 vol.%	50-70% less than diesel	HFC	Design HFC powertrain for

[1] Energy share percentage

Company	Application	% H_2 addition	Reported NO_x emissions	Other decarbonisation methods	Future decarbonisation targets
				H2-ICE	emergency vehicles in UK
HyTech Power	Diesel engine combustion assistance retrofits	N/A (<100%)	50-90% less than diesel reduced using after-treatment	N/A	Zero Emissions Vehicle (100% H_2) Scalable energy storage
New Holland Agriculture	H2D dual fuel retrofit for 140hp tractor	30-60 e.%	Less than diesel	N/A	N/A

In the UK, JCB has been a leading proponent of decarbonisation of construction machinery. In 2021, they established a hydrogen investment fund, aiming to raise £1 billion to aid the growth of a hydrogen economy in the UK[65]. The company invested £100 million at the end of the year to fund the development and production of 'super-efficient' hydrogen engines[66].

Cummins, an American company who manufacture engines and power generation products, announced the beginning of an H2-ICE program in September 2021. This program is developing 6.7L and 15L H2-ICE engines for use in trucks, buses and construction equipment, with some of this work being undertaken in the UK. The company is also experienced in fuel cell production, claiming to have installed over 2,000 HFCs in a range of vehicles across the globe[67].

Both JCB and Cummins produce a range of small electric machines, such as forklifts, dumpsters, mini-excavators and small trucks. JCB's electric products require 1 hour of charging for 8 hours of work time[68,69]. However, both companies report that they consider hydrogen as a solution for NRMM and long-haul trucks, both of which handle with higher loads and long work times. Their H2-ICE approach is to produce new engines to run on

100% hydrogen, rather than converting existing ones for dual fuel combustion. Although this means a completely new engine is required, it utilises existing ICE know-how and production facilities, and many of the powertrain components can be retained[70,71].

Like many other manufacturers[72,73], both JCB and Cummins are exploring hydrogen fuel cells for large vehicles, with prototypes in testing and refinement phases. JCB presented an HFC excavator in 2020 and Cummins an HFC truck in 2019[74,75]. For heavy duty applications, the focus on hydrogen internal combustion engines has been more recent, with manufacturers viewing H2-ICE powertrains as the most appropriate zero-carbon vehicle to bring to market at present. [76,77].

3.2 Dual fuel retrofits

A number of firms are offering diesel engine retrofits for H2D dual fuel operation. Retrofits are generally advertised for heavy-duty road vehicles, but some companies suggest their processes can be applied to other applications[78]. Hydrogen storage tanks are integrated such that space within the vehicle is not overly compromised and the whole retrofit adds of the order 5% to the vehicle weight[78,79].

The world's first commercially available hydrogen powered tractor was announced in 2020 by New Holland, an agricultural machinery manufacturer, and its partners[80]. Hydrogen is introduced to the engine by port injection and the dual fuel composition 30-60 e.% hydrogen, depending on load. The amount of hydrogen added is reduced as engine load increases.

Hydra, a Canadian company, has achieved dual fuel with hydrogen energy share up to 40% in their retrofitted trucks[81]. They use manifold injection of hydrogen, as in most of the literature in Table 1**Error! Reference source not found.**. They claim there is no loss in fuel efficiency, power, torque or goods capacity; whilst tailpipe CO_2 emissions from each vehicle are reduced by up to 40%. To date, one fleet has been converted, with plans to convert 200 fleets[82]. To encourage customers to transition to dual fuel, up to 100,000 CAD per fleet per year is available through government incentives in British Columbia and Hydra are paying 30,000 CAD for early retrofits[83]. Whilst yielding an initial reduction in CO_2, these retrofitted engines cannot support a 100% transition to hydrogen. Hydra aims to increase the amount of hydrogen their retrofits can safely support (see Table 2). The UK could also benefit from a support scheme, but it may be more impactful if directed towards NRMM rather than HGVs: transport contributes a similar percentage of GHG emissions in both countries, but HGVs contribute a much higher fraction of this in Canada (38% in Canada, compared to 27% in UK) since HGV mileage in Canada is much greater than the UK[84,85].

In the UK, ULEMCo undertake similar conversions for up to 70e.% hydrogen dual fuel, with an average hydrogen energy share of 30-40% across completed retrofits to date[78]. One downside to these retrofits are the lead times; it can currently take up to 6 months to complete the conversion due to lack of commercial capacity. This disruption could deter customers as it requires them to find other vehicles for temporary use. If part of a fleet conversion, it is likely one vehicle will be converted at a time to minimise disruption but results in full fleet conversion taking a long time.

Although ULEMCo specialise in HGVs and LGVs, they have recently partnered with Multevo to produce a 75-horsepower dual-fuel hydrogen tractor, demonstrating the versatility of the retrofitting process[86,87]. The ‘Hydrohog’ is currently being trialled for highways maintenance by Telford and Wrekin council[88].

In all cases there was limited information on the impacts of these types of conversion on issues such as original machinery warranties.

3.3 On-board hydrogen production

Both HYDI and HyTech Power use on-board electrolysers supplied with water to produce green hydrogen, which is injected into the air-fuel mixture prior to combustion[89,90]. Energy for the electrolyser is drawn from generators feeding from the combustion powerplant itself. On-board hydrogen production has also been explored in the literature, both by electrolysis and steam-methane reforming[51,91–94]. HYDI began development of the technology in 2013, which has been installed in a range of HGVs. Customer testimonials report an increase in power and improved fuel efficiency[95]. The system takes 4-8 hours to fit and does not require engine modification, since a smaller energy share of hydrogen is used. Although primarily used in heavy-duty trucks, the company aim to expand applications of the unit to generators, rail and shipping[96].

3.4 Exhaust emissions

NO_x and PM emissions are explicitly recognised as important environmental impacts to be managed by most of the organisations considering using hydrogen combustion in engines. Many claim a reduction in emissions compared to pure diesel combustion, from real-world or in-lab tests. It is possible that engineering innovation has overcome some of the compromises between engine performance and tailpipe emissions. However, there is clearly something of a disconnect between manufacturer declared impacts on NO_x emissions (in Table 2) and conclusions that might be drawn from the peer reviewed literature based mostly on laboratory studies.

JCB press releases reported a reduction in NO_x emissions and no reduction in performance, including for a pure diesel case when using latest after-treatment technology systems, reducing emissions by 98%[77]. It is not clear therefore how much of the reduction in NO_x was associated with the use of H_2 fuel itself, or a better aftertreatment system. Achieving lower NO_x emissions using after-treatment technologies rather than altering engine design to favour emissions is reported widely[97,98].

HYDI claim their on-board hydrogen unit can reduce NO_x emissions up to 45%, with 6 weeks of testing onboard buses in New Zealand reporting 10-35% emissions reductions[99]. The tests also reported a significant 80% decrease in PM emissions.

For dual fuel engines that run on a range of fuel compositions, the amount of hydrogen can be varied. For example, New Holland dual fuel tractors increase the hydrogen fraction at lower loads. Results indicate that lower loads are more suited to dual fuels with higher hydrogen fractions, from a NO_x emissions perspective. Since technology exists to control the amount of hydrogen injected based on engine load, this could make dual fuel suitable for a range of applications. This may inevitably add cost to the dual fuel combustion retrofit, which would need to be weighed up against the benefits from NO_x emissions reduction.

3.5 Hydrogen production and supply for replacement diesel applications

The DESNZ (formerly BEIS) Impact Assessment of 6th Carbon Budget suggested that hydrogen could make up 20-35% of UK energy consumption in 2050[3,13]. At least a 10-fold increase in hydrogen production would be required if the UK does not rely on imports. In the short term, it is possible that UK hydrogen production will lag behind H2-ICE development. Since H2-ICE and H2D dual fuel engines are only useful if there is sufficient hydrogen available to fuel them, several companies in Table 2 are explicitly considering their own hydrogen supply routes.

In 2021, JCB signed a multi-billion-pound agreement to import 10% of green hydrogen produced by Australian firm, Fortescue Future Industries[100]. By 2030, this deal could provide the UK with just under 50TWh of hydrogen energy annually[38,101]. It therefore has potential to supply the initial increase in hydrogen demand, whilst hydrogen production grows in the UK. Although imported, the production process for this green hydrogen is likely to have lower environmental impact that what is likely to be initially produced by the UK[13].

Cummins produce green hydrogen from electrolysers and were the first to achieve megawatt scale production[102]. Their 20MW PEM electrolyser in Quebec currently produces 3,000 tonnes of hydrogen a year. The company has recently joined with Sinopec to produce green hydrogen in China, with long-term goals of 1GW annual production[103]. They also manufacture electrolysers suitable for a variety of applications, with over 600 electrolysers deployed globally[102]. Hydra have an alternative solution. To ensure access to reliable hydrogen supplies and avoiding risks of running H2D engines on pure diesel, they source waste hydrogen from industrial processes[79]. This is sold to the customer on contract, at a price 5% cheaper than diesel.

Although on-board hydrogen production is one solution, the units from HYDI and HyTech Power can only provide a certain amount of hydrogen to the engine and are limited to much lower hydrogen energy shares than are possible with H2-ICE and dual fuel engines.

4. Scientific background of NO_x production

In most high temperature combustion applications, NO accounts for around 95% of total NO_x emissions at point of exhaust[26]. At the high temperatures of combustion in Compression Ignition (CI) engines it is widely accepted that most NO_x is formed through the Zel'dovich mechanism[27]:

$$N_2 + O \rightarrow NO + N \quad (1)$$

$$N + O_2 \rightarrow NO + O \quad (2)$$

$$N + OH \rightarrow NO + H \quad (3)$$

In a CI engine this mechanism is enhanced by high temperatures, high oxygen concentrations and a longer residence time of atmospheric nitrogen in the high temperature regions of the combustion chamber[28]. In principle, adding hydrogen to the combustion process has two opposing effects on NO_x emissions. The higher adiabatic flame temperature of hydrogen acts to increase NO_x emissions through the Zel'dovich mechanism. However, the higher flame velocity means it is faster burning, hence the high temperatures exist for a shorter period of time. If hydrogen is added through the intake air manifold, it can reduce the amount of oxygen entering the chamber, acting to suppress the Zel'dovich mechanism. The overall effect that hydrogen addition has on NO_x emissions depends on the balance of these competing effects. This in turn will depend upon many operational factors such as engine load, speed, combustion-system design and fuel injection parameters[29]. For example, for pure diesel combustion, NO_x increases with load due to elevated combustion temperatures, but decreases with engine speed due to reduced residence time of combustion gases[30].

NO_x emissions will also be influenced by relative injection timings of diesel and hydrogen. NO_x is produced in high temperature zones of the combustion chamber, whose existence are highly dependent on heat release rate. NO_x formation can be limited by increasing the ignition delay[31], or the time between the start of fuel injection and the start of combustion. Further complications therefore arise if the presence of hydrogen alters the ignition delay.

NO_x from diesel combustion is controlled by both internal measures and exhaust after-treatment, which can all be applied to H2D combustion. Exhaust gas after-treatment such as selective catalytic reduction (SCR) and lean NO_x traps are proven methods to reduce NO_x in dual-fuel applications[18], but they increase cost and complexity of the combustion system[32]. Typical SCR can reduce NO_x by up to 90%, compared to direct exhaust gas recirculation (EGR) engine-out emissions. Cost impacts depend on the size of engine, but for scale, the manufacturer technology costs for meeting Stage V NO_x emission standards for an off-road 2.6L engine are around £1.2K, but with a cost around 2.5 times this value passed to the customer (from International Council on Clean Transportation, 2018 figures). Internal measures to reduce NO_x emission include fuel lean conditions, water injection and exhaust gas recirculation (EGR). Although these methods act to produce a cleaner combustion system, each has its trade-offs. Fuel lean conditions inherently reduce engine efficiency[18]; water injection causes significantly elevated CO and unburnt hydrocarbon emissions[33]; and large amounts of EGR causes elevated particulate matter (PM) emissions[29].

5. Literature Review

5.1 Hydrogen in small engines

Much of initial development of hydrogen combustion focused on spark ignition (SI) engines, for use in light-duty passenger cars[34]. Although NOx emissions from hydrogen fuelled SI engines are low, performance is significantly limited at high loads due to knock and autoignition issues[35,36]. This makes H_2-SI engines unsuitable for heavy-duty applications, which require high torque at low engine speeds. However, there is considerable literature concerning emissions from small CI (internal combustion) engines that run on H2D dual fuel, both single-cylinder test-engines and those found in passenger cars. This can provide helpful insight into emissions from larger engines, for which the literature is less extensive.

Dimitriou and Tsujimura reviewed works on the performance and emissions of CI engines run on H2D dual fuel, up to 2017. Of the 36 experiments which considered NO_x emissions, all bar two were conducted with either a low power single cylinder engine or a multicylinder light-duty passenger car engine. Experiments varied in many factors, including engine type, load, speed, fuel injection timing, range of hydrogen additions, and emissions reduction technologies. As a result, whilst there was good agreement between experiments that hydrogen addition decreased CO, CO_2, PM and SO_2 emissions, results for NO_x were more mixed. Compared to diesel-only operation, just over half the studies recorded a decrease in NO_x emissions, with the remainder finding an increase or negligible change. There also appeared to be no clear correlation between EGR supply and NO_x emissions[37]. A similar conclusion was drawn in another review[38], which suggested the scattered results are due to variations in test facilities and accuracies of simulation methods.

Engine loading appears to be a key factor affecting NO_x emissions in single cylinder test-engines, and this is likely to translate to larger engines due to its effect on combustion temperature. However, whilst some studies find hydrogen addition caused an increase in NO_x emissions at high loads[39,40], others found a reduction in NO_x emissions[41]. This hints at the complexity of the dual fuel combustion process, where engine load may change the effects of hydrogen addition on NO_x emissions[42].

The most common hydrogen injection applied in dual-fuel CI engine studies are port fuel injection (PFI), manifold injection and direct injection (DI). Adaptation of these conventional engines for PFI and manifold injection strategies are simple, but the injection methods are associated with combustion issues and reduced volumetric efficiencies[43]. The DI method is a more recent concept, aimed to overcome performance limitations associated with PFI. Spark ignition engines, have also been shown to produce lower NO_x emissions than PFI methods under high load conditions[44]. However, DI requires more modifications to the original engine[45], and a recent CI engine simulation suggested that NO_x only drops below the diesel-only case with hydrogen energy shares above 80% [46]. This was due to improved fuel mixing and the increase in ignition delay caused by hydrogen addition.

5.2 Hydrogen in large engines

A literature review of NO_x emissions from heavy-duty and large diesel engines (typically used in NRMM, HGVs and generators) run on hydrogen is summarised in Table 1**Error! Reference source not found.**. Academic papers on this topic are generally more recent than for small engines, with the first covered here published in 2009[47]. These papers rarely place their findings in the specific context of heavy-duty diesel engine decarbonisation, suggesting this is an issue that has not yet received much attention. As for smaller engines, there is general consensus that other minor air pollution emissions such as SO_2 and PM, decrease with increasing hydrogen fuel fraction.

Avadhanula et al. studied hydrogen addition of up to 16% hydrogen energy share, on a mid-size stationary engine generator[47]. NO_x emissions decreased at low hydrogen additions compared to diesel and increased at higher hydrogen additions. The variation of NOx was small, within +/- 2.5% of diesel NO_x emissions. In-cylinder temperatures were calculated to support variations in the Zel'dovich mechanism being responsible for these small changes.

Wang et al. numerically investigated NO formation in a heavy-duty 6-cylinder diesel engine with EGR, at 70% load[28]. A large increase in NO was observed when hydrogen energy share was increased to 16%, correlating to peak heat release rates. A dramatic drop in NO was observed for hydrogen 16-18% blends, with authors suggesting this is a result of temperatures dropping below 1900K, below which the effect of the Zel'dovich mechanism is significantly reduced. This was a result of incomplete ignition of the H2D mixture and reduced combustion.

Cernat et al. conducted multiple tests on a heavy-duty 6-cylinder engine ranging from 40-70% load[48–50]. For all loads, no clear trends in NO_x emissions were observed when hydrogen intake increased. The expected increase in NO_x emissions with load was observed at small hydrogen energy shares of up to 2%, but this cannot be said for higher hydrogen intake. Inferring trends has been complicated through application of EGR and the fact that only small hydrogen energy shares of up to 5% were tested. As a result, no clear conclusions about NO_x and hydrogen intake can be drawn.

Jhang et al. also studied NO_x emissions from a heavy-duty 6-cylinder engine, without EGR and through DI of hydrogen, which replaced a fraction of diesel fuel[51]. NO_x increased with load, except for at idle conditions, where NO_x emissions are 20 times higher, likely due to the lower engine speed. Increasing the volume of hydrogen in air from 0-1.2% decreased NO_x emissions for idle conditions and increased NO_x emissions at 25% load. NO_x increase was negligible at higher loads.

Hosseini and Ahmadi also used DI of hydrogen without EGR in a numerical investigation[38]. However, they found contradicting results of a large and approximately linear decrease in NO_x emissions as hydrogen energy share was varied from 0-70% at full load. The authors examined both hydrogen addition and hydrogen replacement and found similar results for both, with larger emissions reduction found in the replacement case, due to a larger reduction in temperature. The reason for contradicting results to Jhang et al. is unclear, but it is likely due to a difference in experimental parameters. DI was also found to increase ignition delay, which may partly explain the observed decrease in NOx emissions. Only results from the substitution case are provided in Table 1**Error! Reference source not found.** because addition of hydrogen does not result in decreased diesel usage, something with no benefits for reducing carbon emissions, and hence outside a net zero scope.

A study investigating hydrogen addition by port injection at low and medium loading of a heavy-duty diesel engine without EGR, found similar results to Jhang et al.[52]. They found general trends of a decrease in NO_x at low load and an increase at medium load with hydrogen addition. Of the multiple studies which varied engine load, this is the most useful dataset, since it includes a large range of hydrogen energy share ratios from 0-85%, with the engine operating smoothly. Comparison to results from the same engine running on pure diesel with 24.6-24.8% EGR, revealed that in most cases, NO_x emissions are significantly higher in the dual fuel case. Only at low loading, above 80% hydrogen energy share, does NO_x fall below the ‘diesel with EGR’ case.

Liew et al. compared NO_x emissions from two heavy duty diesel engines, one with and one without EGR[42,53]. They conducted experiments at different speeds and loads and took a weighted average of these conditions according to the European Stationary Cycle (ESC) emissions test. Hydrogen was increased to 0-4 vol.% in intake air. The ESC results showed the presence of EGR slowed the rate of NO_x increase compared to pure diesel combustion, and reduced NO_x for any fixed amount of hydrogen. The authors concluded that EGR with small amounts of hydrogen addition is beneficial in reducing NO_x emissions. Additional experiments at different loads and 1200rpm constant speed were carried out. For the engine without EGR, NO_x decreased at low loads and increased at high loads as hydrogen intake increased. The decrease at low loads is partly explained by a measured delay to the start of combustion on hydrogen addition. However, this trend is less apparent for the engine with EGR, and unexpected changes in EGR flow rate were observed at times. This suggests the combination of H2D dual fuel and EGR has a complex effect on chamber temperature and exhaust gas emission composition.

Zhou et al. studied the effect of a hydrogen energy share up to 40% on NO_x emissions from a diesel engine used in trucks[54]. As hydrogen fraction was increased, a very small decrease in NO_x at low loads and a large increase at high load were observed. They also found that ignition delay varies with both hydrogen addition and load, likely affecting NO_x through altering heat release characteristics.

The same engine was used by Kumar et al. in developing a NO_x model for diesel engines, which was validated with experimental diesel and H2D combustion measurements[55]. H2D measurements showed that NO_x emissions decreased at low loads and increased at high loads. Supporting temperature, oxygen and unburned hydrogen measurements revealed the load-dependency of the effect of hydrogen on the combustion process. Lower temperatures, reduced oxygen content and increased unburnt hydrogen emissions suggest that at low loads, hydrogen acts as a heat sink due to its higher specific heat capacity. At higher loads, reduced hydrogen emissions suggest it acts as a heat source and enhances the combustion process. NO_x variation with EGR for H2D combustion is briefly considered in this study. The difficulty in modelling exhaust gas was noted, due to the presence of hydrogen influencing the already complex combustion process.

Only two papers were found to investigate the effect of engine speed on NO_x as hydrogen fraction was added[56,57]. Engines were operated at full load in both studies. NO_x emissions were higher at the lower engine speed, as expected. Increasing hydrogen intake slightly reduced NO_x at low engine speeds, whilst dramatic increases in NO_x emissions were observed at high engine speeds. In contrast to other studies[42,54], hydrogen addition did not have a significant effect on ignition delay[56]. Authors acknowledged that the impact of hydrogen on NO_x emissions varies depending on engine speed but did not propose any explanation for this.

Table 2 Summary of test conditions and NOx emissions from literature investigating hydrogen and diesel dual fuel combustion in heavy-duty compression ignition engines

Authors (reference)	Dataset		Engine	Data location	H2 supply (%)	H2 injection	load (%)	speed (rpm)	EGR	NOx emissions vs diesel
Dimitriou et al. (52)	1	a	5.4L 4-cylinder	fig. 5	0-98 e.	port	low	1500	no	decrease (H2 fraction-dependent)
		b		fig. 8	0-85 e.		medium			decrease low H2/increase high H2
Hosseini and Ahmadi (38)	2		Caterpillar 3401 1-cylinder	fig. 14 (substitution)	0-70 e.	direct	100	1600	no	decrease
Wang et al. (28)	3		10.8L 6-cylinder	fig. 6	0-18 vol.	manifold	70	1800	yes	increase low H_2/ decrease high H_2

Liew et al. (42)	4	a	2004 Mack MP7 355E 6-cylinder	fig. 9	0-7 vol.	manifold	10	1200	yes	decrease
		b		fig. 10			15			increase
		c		fig. 11			20			increase
		d		fig. 13			50			increase
		e		fig. 15	0-6 vol.		70			decrease low H_2
Liew et al. (53)	5	a	1999 Cummins ISM370 6-cylinder	fig. 12	0-6 vol.	manifold	10	1200	no	decrease high H_2
		b		fig. 12			15			decrease high H_2
		c		fig. 12			20			negligible
		d		fig. 7			30			increase
		e		fig. 7			50			increase
		f		fig. 7			70			increase
Jhang et al. (51)	6	a	Cummins B5.9-160 6-cylinder	fig. 8	0-1.2 vol.	direct	idle	800	no	decrease
		b					25	1840		decrease
		c					50			negligible
		d					75			increase
Cernat et al. (48)	7		D2156 MTN8 6-cylinder	fig. 7	0-4.81 e.	manifold	40	1400	yes	negligible
Cernat et al. (50)	8		D2156 MTN8 6-cylinder	fig. 2b	0-3.85 e.	manifold	55	1450	yes	decrease
Cerant et al. (49)	9		D2156 MTN8 6-cylinder	fig. 8	0-3.15 e.	manifold	70	1450	yes	negligible
Aldhaidhawi et al. (56)	10	a	Tractor engine 4-cylinder	fig. 14 (red bars)	0-4.87 e.	manifold	100	1400	no	increase
		b		fig. 15 (red bars)				2400	no	negligible
Avadhanula et al. (47)	11		Detroit Diesel series 50 4-cylinder	fig. 8	0-16.2 e.	manifold	45	1200	no	negligible
Zhou et al. (54)	12	a	ISUZU 4HF1 4-cylinder	fig. 7	0-40 e.	manifold	10	1800	no	negligible
		b					30			decrease
		c					50			negligible

		d					70			increase
		e					90			increase
Kose and Ciniviz (57)	13	a	Tumosan 185 B 4-cylinder	fig. 12	0-7.5 vol.	manifold	100	1000	no	decrease high H_2
		b						1250		decrease high H_2
		c						1500		increase
		d						1750		increase
		e						2000		increase
		f						2250		increase
		g						2500		increase
Kumar et al. (55)	14	a	ISUZU 4HK1 4-cylinder	fig. 10	0-80 e.	manifold	low	1500	no	decrease
		b		fig. 11	0-86 e.		medium			increase high H_2
		c		fig. 12	0-54 e.		high			increase

5.3 Summary of literature

The review reveals that relatively few publications have investigated NO_x emissions from large diesel engines run on H2D dual fuel. Of the literature that does exist, most studies concern heavy-duty road vehicles, with very few papers targeted at NRMM or industrial engine decarbonisation. Similar to results from smaller engines, the relationship between NO_x emissions and hydrogen fraction remains unclear. Discrepancies between the studies arise for many reasons, with different engine designs and experimental conditions reducing the comparability of results. Injection parameters vary across experiments and the effect that hydrogen has on these, and therefore on NO_x emissions, is not considered in detail. Although the two studies that use DI of hydrogen see a decrease in NO_x emissions relative to the diesel-only case, the trends in NO_x as hydrogen fraction increases are contradicting. Reductions in NO_x emissions may partly be explained by increased ignition delay, but it is unclear whether the presence of hydrogen is the cause. In addition, many studies only consider very small hydrogen energy shares.

Despite the uncertainty, some general conclusions can be drawn:

- NO_x from H2D combustion is largely controlled by temperature, as it is predominantly formed through the Zel'dovich mechanism.
- NO_x emissions tend to decrease at low loads and increase at high loads when the hydrogen fuel fraction is increased. However, different experimental conditions mean the dividing line between what constitutes low and high load varies between studies, as well as the relative amount by which NO_x emissions change.
- The presence and rate of EGR complicates the relationship between hydrogen fraction and NO_x emissions. Hydrogen affects exhaust gas composition, making it difficult to predict how temperature and therefore NO_x emissions are affected by EGR when hydrogen is present. It is likely to be dependent on other operational conditions.

If results are to be useful for future policy regarding H2D combustion, experimental conditions need to mimic real-world diesel engine operation. This would give insight into the most suitable areas for H2D diesel engine combustion from a NO_x emissions perspective, since the load at which a large diesel engine will run depends on its end-use application. For example, electrical generators and other stationary machinery tend to run at relatively constant, higher loads, typically above 50% [58]. NRMM and heavy-duty road vehicles run at a much wider range of loads, with a lower average load of around 20-30% [58–60].

6. Meta-analysis

In this section, we conduct a meta-analysis using suitable literature datasets. The analysis is based on the key conclusions from the literature review in Section 5, assessing the influences of both load and EGR on the effect that hydrogen has on NO_x emissions.

6.1 Methodology

Two criteria for hydrogen addition were devised such that only relevant and comparable data from different studies were then used in our later analysis:

- The amount of hydrogen added is expressed in the literature either as an energy share percentage (e.%) or as a fractional volume in air (vol.%). Hydrogen e.% was chosen as the common axis, as it takes into account the difference in energy densities of hydrogen and diesel which meant that most of the literature could be used. For datasets 3, 5 and 6, where the unit used in the original paper was vol.%, conversions to e.% were carried out where possible using a provided calibration curve. Datasets 6 and 13 did not provide enough information to convert data to e.%, hence were excluded.

- Up to 40 e.% was considered useful for two reasons. Firstly, it is likely that with limited hydrogen supply in initial years, hydrogen will be added to fuel combustion incrementally. Secondly, literature suggests this amount of hydrogen can be added safely and easily to a diesel engine at a range of loads[46,54,55]. Combustion issues such as autoignition and knocking are not observed at these quantities and only minimal changes to the engine technology would be needed[46,54]. Datasets 7-11 were excluded because they only provide results for small e.% well below 40e.%.

The literature quotes NO_x emissions in a range of units. In most cases, this was not an issue, since NO_x was converted to a percentage change in emissions compared to pure diesel combustion in the same engine. NO_x emissions in dataset 3 were quoted as a ratio (x) of emissions from H2D to emissions from pure diesel. This was converted to a fractional change (y) through the following manipulation:

$$x = \frac{NO_{df}}{NO_d}; \quad y = \frac{NO_{df} - NO_d}{NO_d} = \frac{NO_{df}}{NO_d} - 1 = x - 1$$

where NO_{df} is the H2D dual fuel emissions from H2D dual fuel and NO_d is the diesel emissions. Note NO is assumed to represent NO_x emissions.

Once hydrogen fraction and NO_x emissions were converted into appropriate units, least squares regression analysis was performed on each dataset to give a simple expression of change in NO_x for different hydrogen fractions. Only 0-40e.% points were included in the regression analysis because the literature review revealed that the effect of hydrogen addition on NO_x emissions can change at very high loads (see for example, dataset 5). A linear relationship under these hydrogen fractions, whilst not entirely accurate, is suitable in providing a range of outcomes for NO_x, especially when combining multiple datasets. The data was split into 0-30% load and 50-100% load, to approximately correspond to mobile machinery and stationary engine applications, respectively.

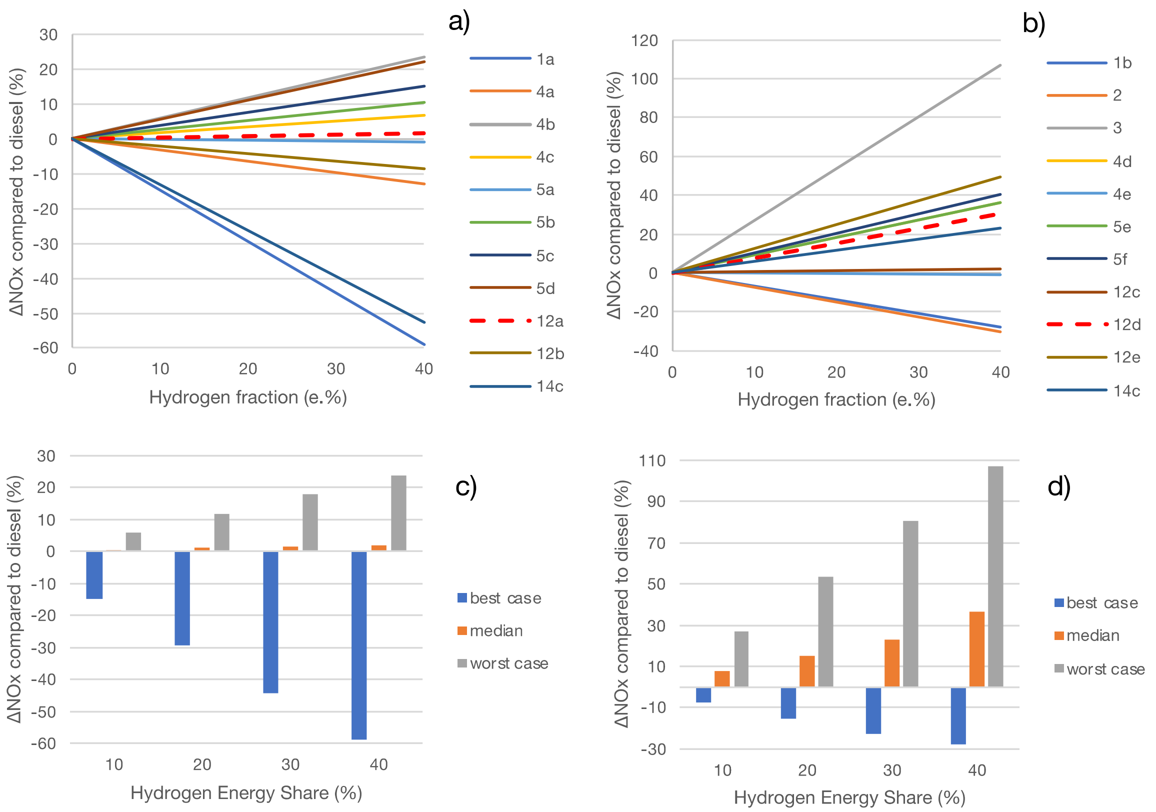
Load factors were not provided for datasets 1 and 14. For these datasets, the low load cases were assumed to be within the 0-30% range and the high load cases in the 50-100% range. This assumption was considered preferable to excluding the data, due to the limited number of datasets. Dataset 14b was a medium load case and therefore excluded from the analysis.

Best-case, average and worst-case changes in NO_x emissions were calculated for hydrogen fractions of 10, 20, 30, 40 e.%. Best-case is the largest reduction in NO_x emissions compared to diesel-only combustion, whilst Worst-Case refers to the largest increase. The Median was chosen to represent a plausible central outcome. Focusing analysis on these three cases reduced the error associated with those few datasets whose regression analyses produced low R2 values.

6.2 Results and discussion

Figures 1a and 1b show the linearized responses of NO_x emissions from H2D combustion in large diesel engines for low (0-30%) and high (50-100%) load, respectively. There is considerable variation in both figures, which increases with hydrogen energy share, due to differences in experimental factors across studies. For 40e.% hydrogen, NO_x relative to diesel combustion is -59 to +24% for the low load case and -28 to +107% for higher load applications.

Figure 1 Meta-analysis of effect on NO_x emissions for H2D combustion in large diesel engines for different H2D fuel compositions. a) 0-30% Low Load case b) 50-100% High Load case. Numbers in the legend correspond to datasets in Table 1. The median dataset is presented as a red dashed line. c) Worst, Median and Best-case NOx scenarios for 0-30% load d) Worst, Mean and Best-case scenarios for 50-100% load.



Figures 1c and 1d show best, worst and median scenarios for NO_x emissions for 4 different hydrogen fractions. Whilst this analysis does not provide information on the most likely scenario, it does guide the level of risk, and potential benefits, for NO_x emissions that are associated with different H2D applications.

An initial addition of 10e.% hydrogen for low load applications is the lowest-regret option. Figure 1c suggests NO_x emissions would only increase by 6% in the worst-case scenario. If only initially deployed in industrial NRMM, this would increase total UK NO_x emissions from fuel combustion activities by ~0.2%[21]. This is a negligible change placed in the wider context of NO_x emissions decreasing by about 3% per year in recent years[21]. Aside from the reality that blending hydrogen initially in small amounts is likely an economic necessity to facilitate a later full transition to hydrogen, the potential modest reduction of NO_x up to 15% makes this a reasonable first step.

Figure 1d shows the same hydrogen addition for high load applications comes with higher risk in terms of NO_x, with a 27% increase in emissions in the worst-case scenario. This is higher than the worst-case scenario of 40e.% hydrogen at low load. The potential reward in emissions reduction is also much smaller, at just 7.5%.

This analysis suggests that, from a NO_x emissions perspective, H2D combustion in large diesel engines would be best used in applications which have lower average loading. This would include a range of NRMM that would typically be used on construction sites, such as excavators and dumpers. Hydrogen energy shares should be low at first, to minimize the risk of increased NO_x. Using H2D in electrical generators, which operate at higher loads for longer periods of time, is more likely to lead to increases in NO_x compared to current diesel-only emissions.

The effect of engine age as a contributing factor to the wide NO_x emissions reported has been considered. Newer engines are designed to be more efficient and compliant with more stringent NOx regulations, hence older engines in the analysis will have produced more NO_x by design. Although the above meta-analysis uses relative NO_x emissions, it is likely the effects of hydrogen fraction will vary depending on engine age and designs. Since production year is not available for most of the engines in the literature, it is not clear how important this consideration is. But all literature used has been published in the last 13 years. NRMM tend to have long working lifetimes, so it is plausible that some older engines might be retrofitted to accommodate hydrogen, particularly large stationary installations such as diesel farms.

6.3 Idling

Engine idling is often characterised by high exhaust emissions, including NO_x[51,59,61]. Dataset 6 is the only study to explicitly considered NO_x emissions with hydrogen addition under idling conditions. A 7% decrease in NO_x emissions was reported as hydrogen fraction was increased to 1.2 vol.%. The only other literature with idling data was based on a marine diesel engine, and this showed a similar effect[62]. Results from a two-year study of NRMM in real-world operating conditions on a construction site suggested that, on average, 45% of machine's time is spent idling[59]. This is much higher than for road traffic in the UK and the lack of regulations to reduce idling of NRMM make these emissions an issue[63]. Descouza et al. suggest that construction site workers need to alter their behaviour to reduce idling, as they found exhaust treatment technology ineffective under these conditions[59]. Although the reasons were not explicitly addressed, it is potentially due to exhaust system cooling under low engine outputs, since such systems can rely on heat from the exhaust to maintain catalyst temperature. The data from Jhang et al. suggests hydrogen could be an alternative method to reducing NO_x emissions under idling conditions. Whilst more data at higher hydrogen fractions and from different engines would be necessary to confirm this, there is no evidence suggesting hydrogen addition will increase idle emissions.

This potential reduction in idle emissions from hydrogen addition further supports the case for prioritising H2D in low average load applications. It may be the case however that alterative anti-idling strategies, either technical or operational, in nature might achieve the same NOx reduction effect as adoption of hydrogen as a fuel. These should not be discounted as alternatives. In contrast electrical generators spend most of their operational time working at high and relatively constant loads, hence idle emissions are not significant.

6.4 Exhaust gas recirculation

An analysis similar to that described earlier, but by further separating studies by engines with and without EGR, was attempted. The results were not particularly informative, due to the spread of results across studies as well as the dominating effect of load on controlling NO_x. EGR is a method commonly used in modern diesel engines to reduce NO_x emissions by reducing combustion temperatures and the oxygen content of intake air[64]. It has the potential to reduce NO_x from H2D combustion to facilitate its use in high load applications such as generators.

Results from the studies by Liew et al. (datasets 4 and 5) on NO_x from H2D provide the best quantitative comparison of diesel engines with and without EGR, since experimental conditions are kept as consistent as possible across studies. Meta-analysis results for datasets 4 and 5 are presented in Figure 2, of relative NO_x from H2D containing 40 e.% hydrogen compared to pure diesel combustion.

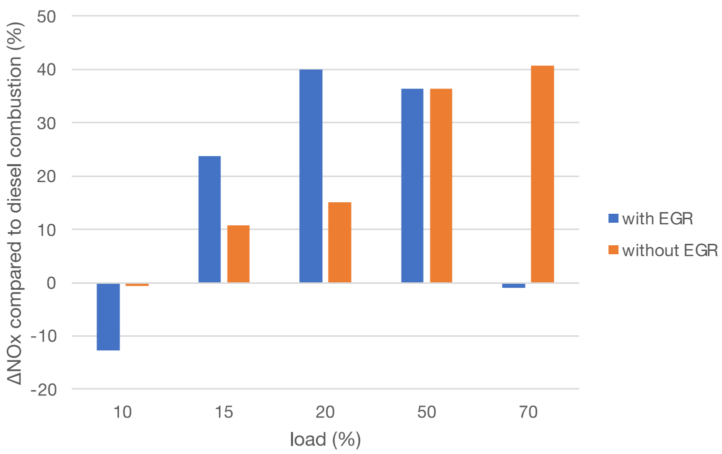


Figure 2 NO_x emissions from combustion of H2D dual fuel of composition 40e.% hydrogen, for engine loads 10-40%. Raw data for the engine with EGR (blue) is taken from dataset 4 (see Table 1). Raw data for the engine without EGR (orange) is taken from dataset 5 (see Table 1).

Although absolute NO_x emissions are lower at all loads for the engine with EGR, relative NO_x emissions are important when considering the introduction of hydrogen into existing diesel engines. Relative NO_x is considerably lower when EGR is present at 10 and 70% loads, but this is not the case for intermediate loads. Relative NO_x is more than doubled at 15 and 20% loads and EGR has no effect on relative NO_x at 50% load. Both the presence of hydrogen and the engine load alter exhaust gas composition, which is likely to be the main cause.

There seems to be no clear, predictable trend for how relative NO_x is influenced by EGR at different loads. Whilst the results at 70% load suggest EGR could reduce NO_x to support a case for H2D use in high load applications, two studies are a very limited evidence base. In addition, studies on smaller engines running on H2D have found that EGR reduces engine efficiency and increases PM emissions[52].

7. The implications of using 100% hydrogen in ICE or fuel cell vehicles

In the longer term, using H2D hydrogen-diesel blends in heavy duty combustion appliances such as capacity market provision, construction and agricultural machinery, is unlikely to be consistent with the move to net zero. There are three longer term options under consideration:

1. Battery electric powertrains are expected to be widely used in road transport and do not produce any tailpipe emissions that impact on air quality. However, there are certain heavy-duty applications for which the current energy density requirements, weight and volume restrictions and refuelling times mean current battery technology is generally not suitable[5]. These include shipping, aviation, heavy goods vehicles (HGVs), non-road mobile machinery (NRMM) and some large-scale combustion processes. John Deere has developed an electric autonomous tractor with maximum power output 500 kW[8] although with several hours charging times. In contrast, hydrogen possibly offers fast refuelling for similar mechanical output performance[11,12].
2. Hydrogen could power fuel cell electric powertrains in heavy-duty road transport. The only by-product is water, and no NO_x emissions would be produced. Fuel cell passenger vehicles and buses are currently in use in small numbers and could become cost competitive with diesel by as early as 2030[14]. The government hopes to see the widespread use of hydrogen fuel cells (HFCs) in buses, rail and HGVs in 2030[13,15]. Fuel cells offer a efficiency decoupled from Carnot cycle limits in ICEs and would potentially reduce hydrogen consumption. However, the technology is less developed, particularly for niches such as off-road vehicles, and they require highly pure hydrogen.
3. Combustion of hydrogen in ICEs is more likely in the short-term due to simpler vehicle transformation requirements and lower hydrogen fuel purity requirements[13,17,18]. Reducing the purity processes in hydrogen production and delivery reduces the cost of hydrogen[17]. In the medium-term, ICE vehicles could be designed to run using 100% hydrogen. Combusting pure hydrogen in an ICE leads to the emissions of NO_x, although this does also result in lower emissions of other pollutants such as particulate matter and sulfur dioxide. Whether pure H2-ICE engines would have lower and higher NO_x emissions than present day diesel equivalents are likely to depend on the regulatory standards that are required, and the extent of exhaust gas aftertreatment that is applied. In principle lower NO_x should be achievable, however this may require some trade-off with performance and cost.

8. Conclusions

This report focuses on decarbonisation of heavy-duty diesel engines through H2D dual fuel combustion and longer-term pure hydrogen (H2-ICE). Applications of these engines potentially include NRMM, HGVs and electrical generators; these are among the most challenging machines to decarbonise due to long periods needed between refuelling, and high power demands. H2D dual fuel may become an important short-term decarbonisation method before a transition to pure hydrogen combustion and/or fuel cell technologies. H2D offers a relatively cost-effective way to reduce fossil fuel reliance as it can largely be used in current diesel engines with minimal modification. NO_x emissions from H2D combustion in large CI engines is a potential air quality disbenefit which does not arise from alternative powertrains such as fuel cells and batteries. H2D and pure hydrogen combustion does however bring air quality benefits through reducing SO_2 and PM emissions.

An analysis identified that peer-reviewed studies of large engines run on H2D are limited in number, but are more recent, when compared to the literature on smaller engines for passenger vehicles. The exact relationship between NO_x emissions and hydrogen fraction was heavily influenced by experimental and engine designs across studies, however generally as hydrogen fraction in H2D was increased, NO_x emissions tended to decrease at low loads and increase at high loads. As hydrogen fraction is varied, NO_x emissions are also dependent on whether EGR is applied, due to the effect of the changing fuel composition feeding back on exhaust gas composition.

A meta-analysis was used to quantify the range of possible NO_x emissions resulting from H2D combustion, of up to 40e.% hydrogen, in large CI engines. A range of possible outcomes for NO_x were found, from a small decrease to a large increase. The median increase in NO_x emissions from H2D (compared to diesel) was smaller for low loads than high loads. Considering the highest reported NO_x emissions, H2D of 10e.% hydrogen under high load was worse than 40e.% hydrogen under low load. A quantitative comparison of similar engines with and without EGR revealed no clear trend for NO_x under different loads. It is possible that EGR can reduce NO_x at both very high and very low loads, but there is not enough data to confirm this. Hydrogen has the potential to reduce the elevated NO_x emissions that can result from engine idling in NRMM and HGVs.

Recommendations for decarbonisation of heavy-duty engines using hydrogen combustion from a NO_x emissions perspective are presented here, based on results from the meta-analysis and commercial review:

- H2D as a technology would be best used in lower average load applications such as excavators, dumpsters and cranes if avoidance of NO_x emissions was a major consideration. The scale of NO_x benefits is difficult to judge and would depend on the sophistication of the aftertreatment system supplied. Replacement of diesel with H2D would however likely provide more universal reductions in emissions of SO_2 and PM including in high load applications.
- Technology could be applied to actively vary the hydrogen fraction used based on engine load, such that NO_x emissions were minimised. Use of higher H_2 fuel fractions during periods of idle may help reduce NO_x emissions, particularly in construction applications. This would be a notable benefit given these engines are often used in urban areas. Alternative anti-idling strategies may also be equally or more effective, however.
- There is uncertainty about the impacts of EGR regimes and their application in H2D dual fuel combustion engines. The impact of EGR is likely to vary depending on the engine application, and research is needed to understand how best to match EGR with each end-use.
- Similarly, more evidence is needed to determine whether hydrogen addition to diesel would benefit NO_x emissions under idle conditions for a wider range of engine applications (beyond the construction sector) and if used in combination with abatement / aftertreatment approaches. The performance of engines specifically designed for hydrogen and specific applications may well improve upon the emissions performance of retrofits.
- The long-term trajectory for the end-use of hydrogen as a fuel may be influenced by an early adoption of H2D dual fuel in sectors such as capacity market power generation, construction and agricultural sectors. Moving later from H2D to H2-ICE, rather than fuel cell power trains, would be an incremental progression that would allow manufacturers to continue to exploit past manufacturing investments in ICE

production facilities and existing technological know-how. Policy support for early adoption of H2D may set a pathway that retains combustion appliances for the longer-term, along with the need to manage their possible NO_x air quality impacts.

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