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Decarbonisation of heavy-duty diesel engines using hydrogen fuel: a review of the potential impact on NO_x emissions

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As countries seek ways to meet climate change commitments, hydrogen fuel offers a low-carbon alternative for sectors where battery electrification may not be viable. Blending hydrogen with fossil fuels requires only modest technological adaptation, however since combustion is retained, nitrogen oxides (NO_x) emissions remain a potential disbenefit. We review the potential air quality impacts arising from the use of hydrogen–diesel blends in heavy-duty diesel engines, a powertrain which lends itself to hydrogen co-fuelling. Engine load is identified as a key factor influencing NO_x emissions from hydrogen–diesel combustion in heavy-duty engines, although variation in other experimental parameters across studies complicates this relationship. Combining results from peer-reviewed literature allows an estimation to be made of plausible NO_x emissions from hydrogen–diesel combustion, relative to pure-diesel combustion. At 0–30% engine load, which encompasses the average load for mobile engine applications, NO_x emissions changes were in the range −59 to +24% for a fuel blend with 40 e% hydrogen. However, at 50–100% load, which approximately corresponds to stationary engine applications, NO_x emissions changes were in the range −28 to +107%. Exhaust gas recirculation may be able to reduce NO_x emissions at very high and very low loads when hydrogen is blended with diesel, and existing exhaust aftertreatment technologies are also likely to be effective. Recent commercial reporting on the development of hydrogen and hydrogen–diesel dual fuel combustion in large diesel engines are also summarised. There is currently some disconnection between manufacturer reported impacts of hydrogen-fuelling on NO_x emissions (always lower emissions) and the conclusions drawn from the peer reviewed literature (frequently higher emissions).

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Environmental significance

In sectors considering the blending of hydrogen with fossil fuels for decarbonisation, policy and technical decisions should, as a minimum, ensure that NO_x emissions which impact health and ecosystems do not increase. We find that hydrogen–diesel fuel blends, if used in lower load construction machinery and heavy goods vehicles could lead to a reduction in NO_x (and $PM_{2.5}$) emissions compared to pure diesel. However, if used in other sectors with high loads, such as electrical generators (*e.g.* 'diesel farms'), NO_x emissions could be higher than pure diesel, if not additionally abated. End use specific research and testing is required such that the outcome of any hydrogen-blending climate policy also delivers optimal air quality outcomes.

1. Introduction

To limit anthropogenic climate change in line with the 2015 Paris Agreement, many countries have put in place net zero greenhouse gas emissions targets. For example, the UK is now required by law to reach net zero greenhouse gas emissions by 2050.[1] To reach this, a range of low or no-carbon fuels are being considered as replacements for fossil fuels.[2] Renewable electricity is expected to be the primary source of energy in 2050, with projections indicating its generation could increase up to 500% by 2050.[3,4] Battery electric powertrains are not however currently viable for some heavy-duty applications which have weight and volume restrictions, high energy density requirements and/or limits on refuelling times.[5] These applications include heavy goods vehicles (HGVs), non-road mobile machinery (NRMM) and electrical generators, all of which currently rely on diesel as a practical fuel. Decarbonising these sectors requires alternatives that are competitive with diesel *and* reduce net greenhouse gas emissions. The Committee on Climate Change has emphasised that decarbonisation of the country's energy budget must happen quickly and at scale to reach the net zero target,[6] so solutions are required which are deliverable in the short term.

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Hydrogen fuelling is a potential method for decarbonising diesel engines used in heavy-duty applications, offering similar refuelling and versatility characteristics as diesel.[7,8] As an alternative to pure diesel, hydrogen can either be combusted or used in a fuel cell. Hydrogen fuel cells (HFCs) are the most environmentally beneficial option from an end-use emissions perspective since their only by-product is liquid water. HFC passenger vehicles and buses are currently in use in small numbers, but more widespread uptake in buses, rail and HGVs is anticipated by 2030 [9,10] as they become more cost competitive with diesel.[11] Plans for the use of hydrogen to decarbonise NRMM and industrial processes are less developed. Combustion of hydrogen appears a likely short and medium-term end-use, due to simpler technological transformation requirements and lower hydrogen fuel purity requirements.[9,12,13]

Although there are many significant barriers to the development of a hydrogen economy, the UK government has recently doubled its low-carbon hydrogen production pledge to 10GW by 2030.[14] It hopes for widespread use in heavy-duty transport, industry, power and heating sectors by 2050.[9] Challenges such as gas pipeline conversions and the scaling of production are being considered, with investment from government, project developers and companies.[9]

Hydrogen can be blended with diesel for combustion in existing all-diesel engines, requiring minimal structural changes to the powertrain. This allows for cheap and simple initial deployment of hydrogen and offers a low barrier to entry stimulus for the development of a hydrogen economy.[7] Although hydrogen supply will likely be limited during initial years of a (UK) hydrogen economy, the fraction of hydrogen used in a hydrogen–diesel (H2D) fuel blend could be increased as production capacity increases.[9] Passenger vehicles with hydrogen internal combustion engines (H2-ICEs) seem unlikely to become a widespread reality since battery electric vehicles offer a more mature solution with cheaper running costs.[5] However, the straightforward conversion to a dual fuel engine provides a potential low-regret option in the heavy-duty sector on the path to net zero.

Unlike fuel cells, hydrogen engines are not emissionsfree. Nitrogen oxides (NO_x – sum of NO_2 and NO) form due to the high temperatures of combustion, as described by the Zel'dovich mechanism. The basics around mechanisms of NO_x formation from H_2 combustion, air quality and emissions impacts have been reviewed recently.[13] The adverse health and environmental impacts of NO_2 have an economic cost in the UK of around £5 billion a year.[15,16] Application of emissions abatement and control strategies in energy and transport sectors have led to sustained NO_x emissions reduction over the last 30 years, however international obligations require further NO_x reductions across Europe well into the 2030s.[17] Although NO_x emissions from diesel engines have been under considerable scrutiny following the VW emissions scandal in 2015,[18] NO_x from future hydrogen combustion has received little attention as a consequence of decarbonisation strategies.[10,19] In the research literature it is common for the environmental impacts of hydrogen production to be considered in detail and on an international scale,[20,21] often assuming that hydrogen will be exclusively used in fuel cells.[22] Downstream point-of-use impacts of its combustion, especially on a national or city scale, are however less reported.

There are other lower-carbon alternatives for fuelling heavy-duty engines, such as biodiesel, biogas, compressed natural gas (CNG) and liquid natural gas (LPG). Like hydrogen, these can be integrated relatively easily into existing infrastructure and much of the original powertrain can be retained. Biodiesel can be used directly in diesel engines without any modifications to powertrains or petrol stations. To be truly sustainable and avoid the environmental concerns surrounding land-use change, advanced biodiesel, produced from biogenic waste and residue feedstocks, is required. The extent to which this can contribute to decarbonisation is therefore highly dependent on the amount of waste produced.[23] Since waste may decline in the future due to improved management practices,[24] this energy source may only be able to contribute to decarbonisation in the short to medium term. Similarly, life cycle assessments for use of natural gas in heavy-duty engines sector suggest that deeper decarbonisation methods alongside CNG/LNG would be necessary to meet UK decarbonisation targets for 2030 and beyond.[25] Hence these are only likely to be useful as interim technologies. H2D is a more intuitive option considering the potential to create the hydrogen from renewal energy (green H_2), and as a technology provide a bridge to later 100% hydrogen combustion or fuel-cell end use, necessary for full decarbonisation.

With any internal combustion engine, there are trade-offs between optimising for different air quality and CO_2 emissions, energy efficiency and mechanical or thermal performance.[13] It has frequently been the case that efficiency and mechanical performance are prioritised, leading to some compromise on NO_x emissions. If H2D or pure hydrogen is to be deployed at scale in internal combustion engines, an additional reduction in NO_x emissions alongside gradual decarbonisation would be desirable as a co-benefit. As an absolute minimum the expectation should be that NO_x emissions should not increase if a fuel switch occurs. This is especially desirable in the UK since, with gradual electrification of the passenger vehicle fleet, based on emissions inventory data,[16] non-electrified diesel engines could become the major source of NO_x if no further action is taken. This review presents an evaluation of the possible impacts on NO_x of H2D combustion in heavy-duty diesel engines. Through qualitative and quantitative literature review, we aim to make recommendations, from a NO_x emissions perspective, on the optimal deployment of hydrogen for decarbonisation of NRMM, HGVs and power generators. For completeness, an evaluation of changes in other air quality relevant pollutants are also presented.

2. Literature review

NO_x formation control

In high temperature combustion applications, NO accounts for around 95% of total NO_x emissions at point of exhaust.[26] During the combustion of diesel in Compression Ignition (CI) engines, most NO_x forms through the Zel'dovich mechanism:[27]

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

In a CI engine, this mechanism is elevated by high temperatures, high oxygen concentrations and extended residence time of nitrogen in high temperature regions of the combustion chamber.[28] In theory, adding hydrogen to the combustion process has two opposing effects on NO_x formation. The higher adiabatic flame temperature of hydrogen acts to increase NO_x emissions through the Zel'dovich mechanism. However, the higher flame velocity means the high temperature conditions exist for a shorter period of time, reducing NO formation. If hydrogen is added through the intake air manifold, it can reduce the amount of oxygen entering the chamber, also reducing the yield from the Zel'dovich mechanism. The overall effect of hydrogen addition on NO_x emissions depends on these competing processes. The balance of effects will depend upon many operational factors such as engine load, speed, combustion-system design and fuel injection parameters.[29] 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 are also influenced by relative injection timings of diesel and hydrogen. NO_x is produced in high temperature zones of the combustion chamber, whose existence depends on the heat release rate. NO_x formation can be limited by increasing the ignition delay (the time between start of fuel injection and start of combustion).[31] Further complications therefore arise if the presence of hydrogen affects that ignition delay time.

The emissions of NO_x from diesel combustion can be abated to a degree by internal measures combined with exhaust after-treatment, techniques. Both approaches can also be applied to H2D engines. After-treatment such as selective catalytic reduction (SCR) and lean NO_x traps (LNT) are efficient methods that can reduce NO_x in dual-fuel applications,[13] although they increase cost and complexity of the combustion system and add to overall equipment costs.[32] Internal measures 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;[13] water injection causes elevated CO and unburnt hydrocarbon emissions;[33] and high EGR rate causes elevated emissions of particulate matter (PM).[34]

Hydrogen fuelling in small engines

Initial development of hydrogen combustion engines focused on use in light-duty passenger cars with spark ignition (SI) engines,[35] pioneered particularly in Japan. Although NO_x emissions from small SI engines are lower than their gasoline equivalents, mechanical performance is significantly limited at high loads due to engine knock and autoignition problems.[29,36] These factors make SI engines generically unsuitable for heavy-duty applications, and so our later analysis considers CI engines only. More broadly, smaller SI hydrogen engines lack substantial competitive advantages over battery electric vehicles, which now dominate sales of low-carbon passenger cars.

There is however considerable literature on air pollution emissions from small CI engines running on H2D dual fuel, both single-cylinder test-engines and those found in passenger cars. This can provide helpful insight for interpreting possible outcomes from H2D use in larger (CI) engines, for which the literature is noticeably less extensive. Dimitriou and Tsujimura reviewed the performance and emissions of CI engines run on H2D dual fuel up to 2017.[37] Almost all experiments considering NO_x emissions were based on either a low-power single-cylinder engine or a multicylinder passenger car engine. Experiments varied in engine design, load, speed, fuel injection method and hydrogen fraction range. There was general consensus that hydrogen addition beneficially decreased emissions of CO, CO_2, PM and SO_2, however results for NO_x were more mixed. Compared to diesel-only operation, studies could be found that reported decreases in NO_x emissions, increases in emissions or little change. There also appeared to be no clear correlation between EGR rate and NO_x emissions.[34] A similar conclusion was drawn in another review,[38] which suggested the highly variable results were due to substantial differences between test facilities and accuracy of simulation methods.

Engine loading does however appear to be a key factor that in past literature has affected NO_x emissions in single cylinder test-engines. This is likely to translate to larger multicylinder engines due to its basic dependence on combustion chamber temperature. However, whilst some studies report that hydrogen addition caused an increase in NO_x emissions at high loads,[39,40] others found a reduction, even without an anticipated reduction in efficiency.[41] This hints at the complexity of the dual-fuel combustion process. The most common hydrogen injection applied in dual-fuel CI engine studies have been port fuel injection (PFI), manifold injection and direct injection (DI). PFI and manifold injection methods are associated with combustion limitations and reduced volumetric efficiencies.[42] DI is a more recent concept aimed at overcoming these performance limitations. In an SI engine, DI fueling has also been shown to produce lower NO_x emissions when compared to PFI methods under high load conditions.[43] However, the use of DI requires more modifications to the original diesel engine.[44] A recent CI engine simulation suggested that NO_x formation only falls lower than a diesel-only case with a hydrogen energy share above 80%,[45] arising due to improved fuel mixing and the increase in ignition delay caused by hydrogen addition.

Hydrogen fuelling in large engines

Prior to this review there were no assessments of the potential air quality effects of hydrogen-fuelled heavy-duty diesel engines, a key gap in evidence given the current need to develop both policy and regulation in this area for net zero. The available literature reporting NO_x emissions from large diesel engines (typically used in NRMM, HGVs and generators) when run on

Table 1 Summary of test conditions and pollutant emissions from literature investigating hydrogen and diesel dual fuel combustion in heavy-duty compression ignition engines

Authors (reference)	Dataset		Engine	H_2 supply (%)	H_2 injection	Load (%)	Speed (rpm)	EGR	NO_x *vs.* diesel	PM *vs.* diesel	HC *vs.* diesel	CO *vs.* diesel
Dimitriou *et al.* (ref. 46)	1	a	5.4L 4-cylinder	0–98 e	Port	Low	1500	No	Decrease (H_2 fraction-dependent)	Decrease	Negligible	Decrease
		b		0–85 e		Medium			Decrease low H_2/increase high H_2	Decrease	Negligible	Decrease
Hosseini and Ahmadi (ref. 38)	2		Caterpillar 3401 1-cylinder	0–70 e	Direct	100	1600	No	Decrease	Decrease	Slight increase	Increase
Wang *et al.* (ref. 28)	3		10.8L 6-cylinder	0–18 vol	Manifold	70	1800	Yes	Increase low H_2/decrease high H_2	Decrease	N/A	N/A
Liew *et al.* (ref. 52)	4	a	2004 Mack MP7 355E 6-cylinder	0–7 vol	Manifold	10	1200	Yes	Decrease	Decrease	Decrease	Decrease
		b				15			Increase	Decrease	Decrease	Decrease
		c				20			Increase	Decrease	Decrease	Decrease
		d				50			Increase	Negligible	Decrease	Decrease
		e		0–6 vol		70			Decrease low H_2	Negligible	Decrease	Negligible
Liew *et al.* (ref. 53)	5	a	1999 Cummins ISM370 6-cylinder	0–6 vol	Manifold	10	1200	No	Decrease high H_2	Negligible	Increase	Decrease
		b				15			Decrease high H_2	Negligible	Increase	Decrease
		c				20			Negligible	Negligible	Increase	Decrease
		d				30			Increase	Decrease	Negligible	Decrease
		e				50			Increase	Negligible	Negligible	Decrease
		f				70			Increase	Negligible	Negligible	Negligible
Jhang *et al.* (ref. 47)	6	a	Cummins B5.9-160 6-cylinder	0–1.2 vol	Direct	Idle	800	No	Decrease	Decrease	Decrease	Decrease
		b				25	1840		Decrease	N/A	Increase	Decrease
		c				50			Negligible	N/A	Increase	Negligible
		d				75			Increase	N/A	Increase	Negligible
Cernat *et al.* (ref. 54)	7		D2156 MTN8 6-cylinder	0–4.81 e	Manifold	40	1400	Yes	Negligible	Decrease	Decrease	Negligible
Cernat *et al.* (ref. 55)	8		D2156 MTN8 6-cylinder	0–3.85 e	Manifold	55	1450	Yes	Decrease	Decrease	N/A	N/A
Cernat *et al.* (ref. 56)	9		D2156 MTN8 6-cylinder	0–3.15 e	Manifold	70	1450	Yes	Negligible	Decrease	Decrease	Negligible
Aldhaidhawi *et al.* (ref. 57)	10	a	Tractor engine 4-cylinder	0–4.87 e	Manifold	100	1400	No	Increase	Decrease	Decrease	Decrease
		b					2400	No	Negligible	Decrease	Decrease	Decrease
Avadhanula *et al.* (ref. 48)	11		Detroit Diesel series 50 4-cylinder	0–16.2 e	Manifold	45	1200	No	Negligible	N/A	N/A	Decrease
Zhou *et al.* (ref. 49)	12	a	ISUZU 4HF1 4-cylinder	0–40 e	Manifold	10	1800	No	Negligible	Increase	Increase low H_2/decrease high H_2	Decrease
		b				30			Decrease	Decrease	Increase low H_2/decrease high H_2	Decrease
		c				50			Negligible	Decrease	Negligible	Decrease
		d				70			Increase	Decrease	Negligible	Decrease
		e				90			Increase	Decrease	Negligible	Decrease
Köse and Ciniviz (ref. 50)	13	a	Tumosan 185 B 4-cylinder	0–7.5 vol	Manifold	100	1000	No	Decrease high H_2	N/A	Decrease	Increase
		b					1250		Decrease high H_2	N/A	Decrease	Increase
		c					1500		Increase	N/A	Decrease	Increase

Table 1 (*Contd.*)

Authors (reference)	Dataset	Engine	H_2 supply (%)	H_2 injection	Load (%)	Speed (rpm)	EGR	NO_x *vs.* diesel	PM *vs.* diesel	HC *vs.* diesel	CO *vs.* diesel
	d					1750		Increase	N/A	Decrease	Negligible
	e					2000		Increase	N/A	Decrease	Negligible
	f					2250		Increase	N/A	Decrease	Negligible
	g					2500		Increase	N/A	Decrease	Negligible
Kumar *et al.* (ref. 51)	14 a	ISUZU 4HK1 4-cylinder	0–80 e	Manifold	Low	1500	No	Decrease	N/A	N/A	N/A
	b		0–86 e		Medium			Increase high H_2	N/A	N/A	N/A
	c		0–54 e		High			Increase	N/A	N/A	N/A

H2D dual fuels are summarised in Table 1. These works are less numerous than those studying NO_x from passenger car engines, but importantly are often more recent. Most studies involve heavy-duty road vehicles, with very few papers specifically addressing NRMM or industrial engine/prime power. Multiple studies in Table 1 show that it is possible to configure operating conditions to retain or improve combustion performance and efficiency on hydrogen blending.[46–51]

Although NO_x is the primary pollutant of interest in our review, it is important to cnsider other point-of-use emissions arising from H2D. In all cases CO_2 emissions decrease linearly with hydrogen addition by energy share, due to the reduction in the amount of carbon-containing fuel. In most cases, CO decreased for H2D combustion compared to diesel due to increased H/C ratio, improved air-fuel mixing and shorter combustion duration. However, the studies corresponding to datasets 2 and 13 found CO emissions increased on hydrogen addition, due to the increased ignition delay reducing temperatures enough to increase the extent of incomplete combustion.[38,50] Reduced oxygen content also contributed to this through a reduction in CO oxidation.[50] Studying Table 1, this is likely to be due to engines being run at full load, causing increased total fuel consumption.

PM emissions generally decreased for H2D compared to diesel, due to a reduced diesel-to-air equivalence ratio. The reduction was usually most significant at low loads for this same reason. Exceptions were commonly due to decreased soot oxidation rate and incomplete combustion, especially at low loads.[49,52,53]

Results for hydrocarbon emissions are somewhat discordant and appear to be dependent on operational parameters affecting the amount of diesel being burned and the flowrate of diesel. Decreases were observed for studies which were accompanied by increased combustion efficiency, these decreases commonly being largest at high hydrogen energy shares and low loads. An overall increase in HC emissions was observed when the extent of incomplete combustion increased.[38,49,52,53] Experimental variation, including the presence/absence of EGR, is likely to have influenced results here.[46]

Similar to results seen in smaller engines, the relationship between NO_x emissions and hydrogen fraction is very variable in literature reports, likely impacted by experimental factors such as engine model, hydrogen injection method, load, speed and the application of exhaust gas recirculation. Many studies only considered very small hydrogen energy shares.[48,54–57] The observed variation in NO_x emissions from hydrogen addition compared to pure diesel combustion were small, and there was often no clear trend. Other studies have showed that the trend in change in NO_x emissions was only apparent for higher hydrogen fractions.[53]

The effect of engine load on NO_x emissions has been investigated in multiple studies.[45–47,51–53] Most found that when hydrogen is added to diesel, NO_x emissions tend to *decrease* at low loads and *increase* at high loads. However, different experimental conditions mean that the definition of what constitutes 'low' and 'high' load varies between studies, as well as the relative amount by which NO_x emissions change. At low loads, Liew *et al.* observed a delay to the start of combustion on hydrogen addition, possibly explaining the NO_x decrease observed.[53] Zhou *et al.* also found that ignition delay varies with both hydrogen addition and load, affecting NO_x through altering heat release characteristics.[49] An increased ignition delay at low load would result in a narrower heat release peak, resulting in reduced thermal NO_x formation.[58] Kumar *et al.* used supporting temperature, oxygen and unburned hydrogen measurements to explain the load-dependency of the effect of hydrogen on the combustion process.[51] Lower temperatures, reduced oxygen content and increased unburnt hydrogen emissions suggested that at low loads, hydrogen acted as a heat sink due to its higher specific heat capacity. At higher loads, reduced emissions suggested it acted as a heat source to enhance the combustion process. We suggest that at higher load, the effect of load on temperature becomes more important than the effects of hydrogen addition which cause a reduction in temperature, thereby causing an overall increase in thermal NO_x formation.

A similar effect of increased ignition delay was also observed by Hosseini and Ahmadi, who conducted a numerical investigation of DI of hydrogen into a heavy-duty engine.[38] A large and approximately linear decrease in NO_x emissions was observed when hydrogen energy share was varied from 0 to 70% at full load. Similar results were found for both hydrogen addition and hydrogen replacement cases, with larger emissions reduction found in the replacement case due to a larger reduction in temperature. DI was found to increase ignition delay significantly, which may explain the observed decrease in NO_x emissions. Only results from the substitution case are provided in Table 1 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.

Cernat *et al.* conducted multiple tests on a heavy-duty 6-cylinder engine ranging from 40 to 70% load operation, but did not observe the relationship between NO_x emission and load that was found in most other studies.[54–56] The expected increase in NO_x emissions with load was observed at small hydrogen energy shares of up to 2%, but not for higher hydrogen intake. Inferring trends has likely been complicated through application of EGR and the fact that only small hydrogen energy shares of up to 5% were tested. Other studies also found that the application of EGR complicated results. For example, Liew *et al.* compared NO_x emissions from two heavy duty diesel engines, one with and one without EGR.[52,53] For the engine without EGR, NO_x decreased at low loads and increased at high loads as hydrogen intake increased. However, this effect was not observed for the engine with EGR, and unexpected changes in EGR flow rate were observed at times. Hydrogen inclusion changes exhaust gas composition, making it difficult to predict how temperature, and therefore NO_x emissions, are affected by EGR when hydrogen is present.

Only two papers have reported the effect of engine speed on NO_x as hydrogen fraction was added.[50,57] 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 speeds. The authors acknowledged that the impact of hydrogen on NO_x emissions varied depending on engine speed, but did not propose an explanation for this. The complexity of dual fuel combustion is evident and current understanding required for accurate emissions prediction is not complete. Despite this, some important conclusions can be drawn:

NO_x emissions tend to decrease at low loads and increase at high loads when the hydrogen fuel fraction is increased.

The presence and rate of EGR complicates the relationship between hydrogen fraction and NO_x.

If results are to be useful for future policies supporting H2D combustion, experimental conditions need to mimic real-world diesel engine operation. This could 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%.[59] NRMM and heavy-duty road vehicles run at a much wider range of loads, with a lower average load of around 20–30%.[59–61]

3. Quantitative analysis

We conduct a meta-analysis of suitable datasets from Table 1. 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 and meant that most of the literature could be used. Where the unit used in the original paper was vol%, conversions to e% were completed where possible, using a provided calibration curve. Datasets 6 and 13 were excluded on this basis. Up to 40 e% hydrogen addition was considered. Literature suggests this amount of hydrogen can be added safely and easily to an existing diesel engine at a range of loads.[53,62,63] In addition, it is unlikely there would be sufficient industrial hydrogen production capacity in initial years for more than 40 e% hydrogen to be used widely on a national scale. Datasets 7–11 were excluded because they only provide data for small e% well below 40 e%. The literature reports NO_x emissions in a range of different units. In most cases, this was not an issue, since NO_x was converted to a change in emissions *relative* to pure diesel combustion in the same engine. NO_x emissions in dataset 3 required conversion from a ratio of H2D emissions to pure diesel emissions, to a fractional change.

Least squares regression analysis was performed on each dataset to give a simple expression of change in NO_x for different hydrogen fractions. Only 0–40 e% 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 (*e.g.* dataset 5). A linear relationship under these hydrogen fractions, whilst not wholly accurate, is suitable in providing a range of possible 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 the use characteristics found for mobile machinery (0–30) and stationary engine (50–100) end uses. For datasets 1 and 14, where loads were not provided, 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, median and worst-case changes in NO_x emissions were calculated for hydrogen fractions of 10, 20, 30, 40 e%. Best-case is the largest reported literature reduction in NO_x emissions compared to diesel combustion, whilst worst-case refers to the largest increase. Focusing analysis on these three cases reduced the error associated with those few datasets whose regression analyses produced low R^2 values.

4. Results and discussion

Fig. 1a and b show the linearised responses from literature 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 40 e% hydrogen, NO_x relative to diesel combustion varies over the range −59% to +24% for the low load case and −28 to +107% for higher load applications. Fig. 1c and d show best, worst and median scenarios for NO_x emissions for 4 different hydrogen fractions. Whilst this analysis does not provide information on what is the most likely scenario, it does guide the level of risk and potential benefits/dis-benefits, for NO_x emissions that are associated with different H2D applications.

An initial addition of 10 e% hydrogen for low load applications appears to be the lowest-regret option. Fig. 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%.[16] This is a negligible change placed in the wider context of NO_x emissions decreasing by about 3% per year in recent years.[16] Aside from the reality that blending hydrogen initially in small amounts is likely an economic necessity to facilitate a later full transition to hydrogen, a potential upside reduction of NO_x up to 15% makes this a reasonable first step.

Fig. 1d shows the same hydrogen addition for high load applications comes with higher risk in terms of NO_x, with a possible 27% increase in emissions in the worst-case scenario for only a 10 e% fuel share. This is higher than the worst-case

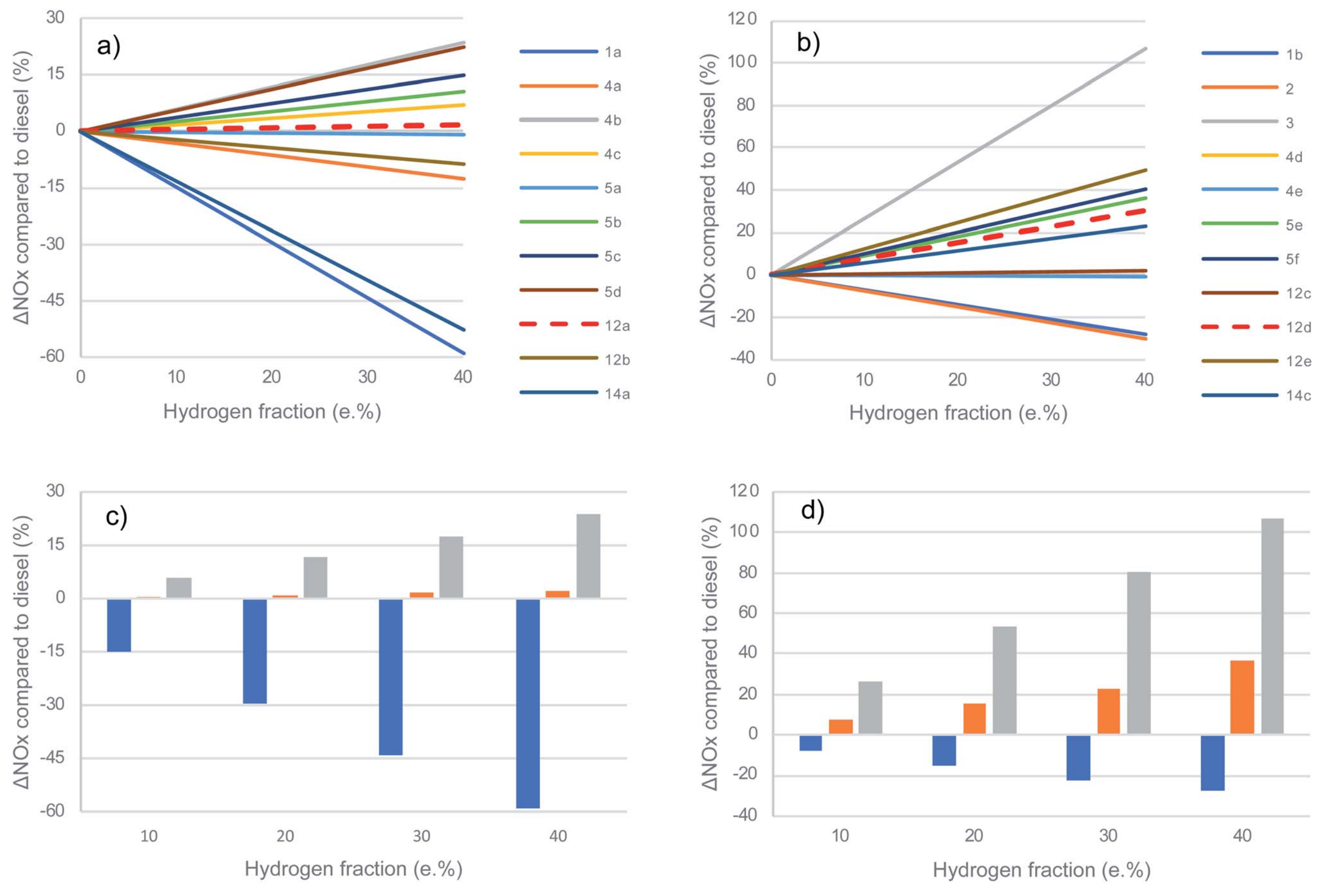

Fig. 1 Meta-analysis of effect on NO_x emissions for H2D combustion in large diesel engines for different H2D fuel compositions. (a) 0–30% low load case (b) 50–100% high load case. Numbers in the legend correspond to datasets in Table 1. The median dataset is presented as a red dashed line. (c) Worst (grey), median (orange) and best-case (blue) NO_x scenarios for 0–30% load (d) worst (grey), mean (orange) and best-case (blue) scenarios for 50–100% load.

scenario of 40 e% hydrogen at low load. The potential reward in emissions reduction is also much smaller, at just 7.5%. This analysis suggests that H2D combustion in large diesel engines would be best used in applications which have lower average loading. This would include a range of NRMM typically used on construction sites, such as excavators and dumpers. Hydrogen energy shares should be low at first, until NO_x emission factors could be evaluated in the practice in the field. Using H2D in electrical generators, which operate at higher loads for longer periods of time, appears more likely to lead to increase in NO_x when compared to current pure diesel engine emissions.

Whilst there is a clear difference in results for high and low load cases, the limited database should be kept in mind. Additionally, we have linked load to application by reported average engine load. In reality, especially for mobile engine applications, the engine will run at a wide range of loads depending on driving conditions/power demands.

The effect of age/era of the test engine as a contributing factor to the wide range of NO_x emissions reported has been considered. Newer engines are designed to be compliant with more stringent NO_x regulations, hence older engines in the analysis are likely to have produced more NO_x because of their design. Although the above meta-analysis uses *relative* NO_x emissions, it is likely the effects of hydrogen fraction change depending on engine era due to different engine designs. Since production year is not available for most of the engines in the literature, it is not clear how important this consideration is. 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.

Hydrogen fuel and engine idling

Engine idling is often characterised by elevated exhaust emissions, including for NO_x.[47,59,62] Dataset 6 (Table 1) is the only study to explicitly consider 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 was based on a marine diesel engine, with a similar effect reported.[63] Results from a two-year study of NRMM in real-world operating conditions on a construction site suggested that, on average, 45% of plant time is spent idling.[60] This is much higher than for road transport and a lack of regulations to reduce idling of NRMM make air quality emissions a serious consideration in cities.[64] Desouza *et al.* found exhaust treatment technology ineffective during idling[60] since exhaust systems often rely on heat from the engine to maintain catalyst temperature. The data from Jhang *et al.* suggested adding 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 would increase idle emissions. This potential reduction in idling NO_x emissions from hydrogen addition further supports the case for H2D use targeted at low average load applications.

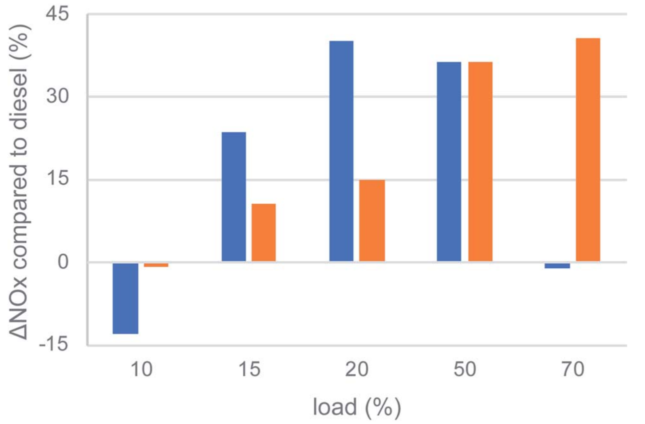

Fig. 2 NO_x emissions from combustion of H2D dual fuel of composition 40 e% hydrogen, for engine loads 10–40%. Raw data for the engine with EGR (blue) is taken from dataset 4 (see Table 1). Raw data for the engine without EGR (orange) is taken from dataset 5 (see Table 1).

Exhaust gas recirculation

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.[65] It has the potential to reduce NO_x from H2D combustion to facilitate its use in high load applications such as generators. The studies by Liew *et al.* on NO_x from H2D provide the best quantitative comparison of diesel engines with and without EGR, since other experimental conditions are consistent across studies. Fig. 2 presents analysis of datasets 4 and 5, of relative NO_x from H2D containing 40 e% hydrogen compared to pure diesel combustion. There appears to be no clear, predictable trend for how relative NO_x is influenced by EGR at different loads. Relative NO_x is considerably lower when EGR is present at 10 and 70% loads, but this is not the case for intermediate loads. At 15 and 20% loads, relative NO_x emission more than doubled and EGR had no effect on relative NO_x at 50% load. Both the presence of hydrogen and engine load alter exhaust gas composition, which is likely to be a factor.

Whilst the data at 70% load suggest EGR could reduce NO_x, and thus support a case for H2D use in high load applications, two studies is a very limited evidence base. In addition, studies have found that for engines running on H2D, EGR reduces engine efficiency and increases PM emissions.[37,46] H2D in low average load applications is still recommended as the low-regret option of hydrogen combustion in large diesel engines. Fig. 2 suggests that EGR may not be necessary in these cases and may in fact significantly increase NO_x emissions. Again, the limited data available means this is not definitive.

5. Commercial review

When and how decarbonisation of large diesel engines will be achieved relies largely on industry research and development of new technologies and alternative fuels. The main commercial organisations considering large diesel engine decarbonisation

Table 2 Summary of current developments in the application of hydrogen combustion for heavy-duty diesel engine decarbonisation

Company	H_2 combustion products	Current progress	H_2 addition	NO_x	Other decarbonisation methods	Hydrogen production solutions	Future decarbonisation targets
JCB[66–72]	H2-ICE telescopic handler	Prototypes in testing and refinement phases	100%	Less than diesel	HFC	Imports from Australian company, Fortescue Future Industries	H2-ICE products on the market by end of 2022
	H2-ICE backhoe loader				BEV for small machines		Green hydrogen imports from 2022
Cummins[73–80]	6.7L medium duty H2-ICE	Prototypes in testing and refinement phases	100%	Reduced using after-treatment	HFC	Megawatt scale electrolysers	H2-ICE in Class 8 trucks in 2nd half of 2022
	15L heavy duty H2-ICE				BEV for small machines	Goals for Gigawatt scale electrolysers in China	Major role in transport decarbonisation from 2025
Hydra[81–83]	H2D dual fuel truck retrofits	One fleet converted	Up to 40 e%	Comparable to diesel	N/A	Waste hydrogen sourced from industrial processes, sold to customers at a price 5% lower than diesel	Plans to convert 200 fleets 50 e% by 2023 100 e% long term goal
HYDI[84–87]	On-board H_2 production unit for H2D dual fuel	Installed in a range of HGVs	N/A (<100%)	Up to 45% less than diesel	N/A	On-board H_2 production	Expanding the applications of the unit Develop model for export
ULEMCo[88–91]	H2D dual fuel retrofits	A number of HGVs in real-world operation 'Hydrohog' being trialled for highways maintenance	30–70 vol%	50–70% less than diesel	HFC H2-ICE	N/A	Design HFC powertrain for emergency vehicles in UK
HyTech Power[92,93]	Diesel engine combustion assistance retrofits	Available for purchase	N/A (<100%)	50–90% less than diesel Reduced using after-treatment	N/A	On-board H_2 production	Zero emissions vehicle (100% H_2) Scalable energy storage
New Holland Agriculture[94]	H2D dual fuel retrofit for 140hp tractor	Available for purchase	30–60 e%	Less than diesel	N/A	N/A	N/A

using hydrogen fuel at (time of writing) are summarised in Table 2. Since these are business developments, the basic commercial intentions are generally issued *via* investor announcements or press releases, but rarely are any detailed datasets provided. None of the manufacturers in Table 2 has provided data on emissions in open-source formats, or *via* the peer-reviewed literature.

JCB and Cummins

In the UK, JCB has been a leading proponent of decarbonisation of construction machinery. Cummins, an American engine manufacturer, have been developing heavy-duty H2-ICEs since 2021. Both companies produce a range of small electric machines, such as forklifts, dumpsters, and small trucks.[66,78] However, they identify hydrogen as the solution for larger NRMM and long-haul trucks, which require higher loads and long work times. Their H2-ICE approach is to produce new engines to run on 100% hydrogen, rather than converting current engines for dual fuel use. Whilst this means a completely new engine is required, it utilises existing engine know-how and production facilities, and many of the powertrain components can be retained.[72,74] Like other manufacturers,[95,96] both companies report exploring HFCs for large vehicles.[67,75] For heavy-duty applications, the focus on H2-ICEs has been more recent, with manufacturers identifying it as the most cost-effective method for heavy-duty engine decarbonisation.[70,73]

Dual fuel combustion

Several companies are now offering diesel engine retrofits for H2D dual fuel operation. Retrofits are generally advertised for heavy-duty road vehicles, but some companies suggest the technology can be applied to other applications.[88] Hydrogen storage tanks are integrated such that space within the vehicle is generally not reduced and the whole retrofit adds modestly to the vehicle weight.[82,88] Whilst yielding an initial reduction in CO_2, these retrofitted engines cannot support a final 100% transition to hydrogen. However, companies are aiming to increase the amount of hydrogen their retrofits can support.[82,92] A downside to these retrofits are the lead times, with one company suggesting retrofits to a new engine can take up to 6 months.[88]

Hydra, a Canadian company, introduced hydrogen to the engine by manifold injection,[82] similar to most of the research literature in Table 1. They claim there is no loss in engine performance, whilst tailpipe CO_2 emissions from each vehicle are reduced by up to 40%. Both the Canadian government and Hydra have put in place incentives to encourage users to transition to dual fuel.[82,97] Whether government incentives are best targeted at HGVs or NRMM may depend in part on the relative contribution each sector makes to emissions: HGVs contribute a higher fraction of GHG emissions from transport in Canada (38% in Canada, compared to 27% in UK) due to greater mileage.[98,99]

Both HYDI and HyTech Power use on-board electrolysers supplied with water to produce hydrogen which is injected into the air-fuel mixture prior to combustion.[85,92] On-board hydrogen production has also been explored in the research literature, both by electrolysis and steam-methane reforming.[47,100–102] HYDI have reported an increase in power and improved fuel efficiency.[84] The system takes 4–8 hours to fit and does not require engine modification, since only a small energy share of hydrogen is used.[86]

Exhaust emissions

Performance for NO_x and PM emissions are commonly recognised as key issues by manufacturers considering hydrogen fuelling. Many claim a reduction in emissions compared to pure diesel combustion, from either real-world or in-lab tests.[87] Achieving lower NO_x emissions using after-treatment technologies rather than altering engine design, is reported widely.[80,93] JCB reported a 98% reduction in engine-out NO_x emissions and no reduction in performance for hydrogen fuel, as compared against a pure diesel comparison with after-treatment technology system.[70] It is therefore possible that latest engineering innovation has overcome some of the compromises between engine performance and tailpipe emissions. However, there is clearly a disconnection between this level of manufacturer proposed reductions of NO_x emissions (in Table 2) and the conclusions that would be drawn from the peer reviewed literature (earlier figures).

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.[94] Results from the meta-analysis in this paper indicated that, when considering NO_x emissions, lower loads are indeed more suited to dual fuels and higher hydrogen fractions. Since technology exists to control the amount of hydrogen added based on engine load, and this could make dual fuel suitable for a range of applications. This may inevitably add cost however to combustion retrofits, which would need to be weighed up against the benefits from NO_x emissions reduction.

6. Conclusions and recommendations

Hydrogen and H2D dual fuel combustion are potential solutions for reducing greenhouse gases from diesel engines when used in heavy-duty diesel applications. H2D dual fuel may become an important short-term decarbonisation method as part of a longer-term transition to pure hydrogen technologies. Such an approach offers a relatively cost-effective way to reduce fossil fuel reliance as it can largely be used in current diesel engines, with minimal modification. Particular attention in this review is paid to NO_x from H2D combustion in large CI engines, an air quality impact which does not arise from alternative powertrains such as fuel cells and batteries.

Peer-reviewed studies of large CI engines run on H2D are limited. The relationship between NO_x emissions and hydrogen fraction can difficult to discern due to experimental variation across studies. It was clear, however, that engine load and the application of EGR were key factors in affecting results. A range of possible outcomes for NO_x were found, resulting from H2D combustion of up to 40 e% hydrogen in large CI engines. A meta-analysis was used to quantify the range of possible NO_x emissions resulting from H2D combustion, of up to 40 e% 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 10 e% hydrogen under high load was worse than 40 e% 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. Without additional abatement/aftertreatment technologies, H2D would be best used in lower average load applications such as excavators, dumpsters and cranes. It should be noted that this conclusion is based on a relatively limited database, hence we suggest that more research and testing should be conducted to confirm this result.

EGR may be effective for reducing NO_x at both very high and very low loads when H_2 is added, but there is not enough data to have high confidence in this conclusion. The impact of EGR is likely to vary depending on the engine application, hence choices around the use of H2D in a hydrogen economy should be matched to specific end-uses. Similarly, the use of higher hydrogen fuel fractions at idle may help reduce NO_x from construction machinery, a notable benefit given these often occur in urban areas.

More data is needed on the effects of other aspects of engine operation on NO_x emissions, such as engine speed and hydrogen injection method. This may help to separate individual NO_x contributions to gain a better understanding of the relationship between engine operation, fuel composition and NO_x emissions. Additionally, confirmation through experiment is needed to establish that engine load is the dominant factor controlling NO_x emissions from H2D combustion in CI engines.

A follow on from this review would be the creation NO_x emission scenarios from the meta-analysis with studies weighted according to the different engine designs likely to be used in the UK (or any country looking to use H2D in heavy duty engines). This could support the development of a refined 'most likely' outcome for NO_x emissions, which alongside real-world testing, may help to determine whether hydrogen-specific NO_x standards and therefore additional aftertreatment technologies are required.[103–105] A larger range of studies would be needed for this analysis if uncertainties in projections were to be narrowed.

Both H2-ICE and H2D dual fuel retrofits are being demonstrated commercially, many of whom are also developing green hydrogen production and supply routes. NO_x emissions are explicitly considered by manufacturers and are claimed to be reduced either by internal or external measures. For example, one dual fuel manufacturer used adaptive technology to reduce hydrogen fraction as engine load increased. It was not clear from public information sources whether this was to specifically limit NO_x emissions, however it may well have had this beneficial effect. This showed that if the cost is reasonable, additional technology could be applied to actively control hydrogen fraction based on engine load, and to minimise NO_x emissions.

Taking the evidence in this review the following five recommendations for policy consideration emerge:

1. 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.

2. 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.

3. 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.

4. 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.

5. The long-term trajectory for the 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 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.

Conflicts of interest

There are no conflicts of interest to declare.

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