CAN HYDROGEN ENGINES SUPPORT DECARBONISATION IN THE HEAVY DUTY SECTOR?

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ADVANCED PROPULSION CENTRE UK
TPS THERMAL EFFICIENCY SPOKE

University of Brighton

CMB.TECH LENOIR Hydrogen dual fuel truck

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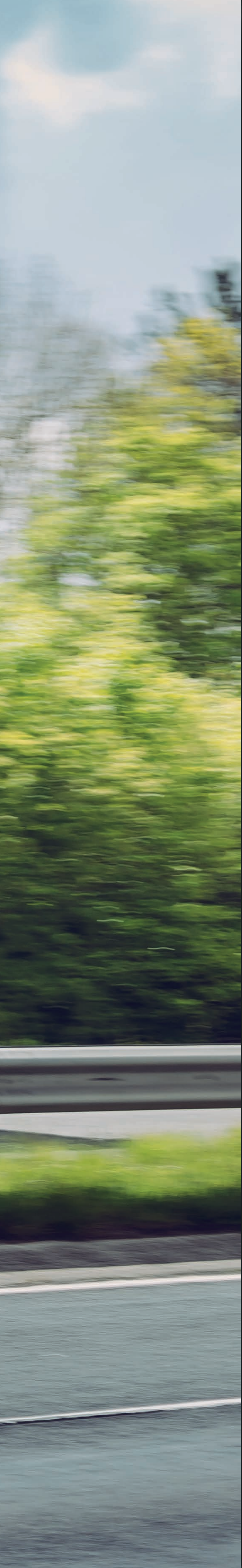

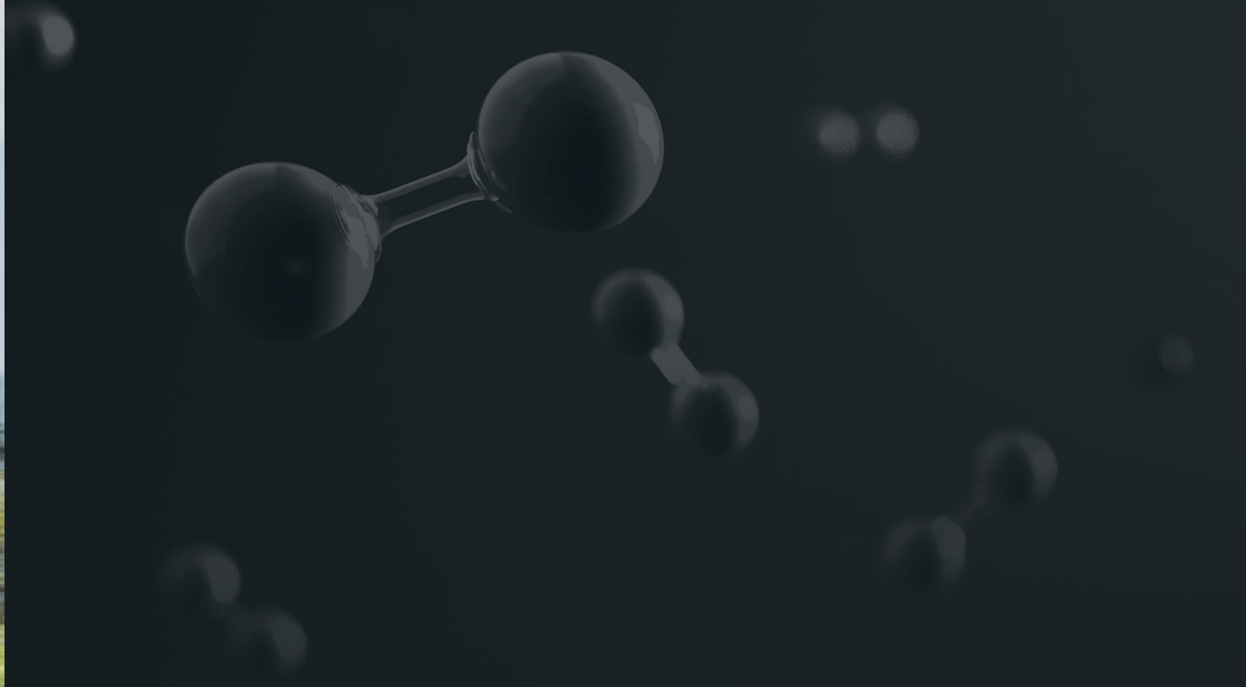

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EXECUTIVE SUMMARY

This report presents evidence on the complementary role of hydrogen internal combustion engines (H2ICE) and hydrogen fuel cells (H2FC) in the hard to decarbonise heavy duty (HD) transport sector. Research to date suggests that H2ICE would have near zero NOx emissions and therefore fulfil the requirements for both carbon and air quality emissions for future transport solutions. Current data also indicates that H2ICE could have lower costs and lifecycle emissions than H2FC. Fuel consumption data for both technologies indicates that they have similar efficiencies, although H2FC is more efficient at lower loads and H2ICE has better efficiency at higher loads. This means that H2ICE could be more favourable for higher power output applications like articulated trucks, while H2FC could be preferable for lower load applications like buses.

Compared to H2FC where significant technical and commercial risk remains for introduction in the HD market, introduction of H2ICE presents a relatively low risk due to the incremental change compared to existing technology and mature supply chain. Therefore, in the short to medium term H2ICE could accelerate decarbonisation in the HD sector, and potentially provide a long-term solution for some applications, depending on longer-term technology performance of both technologies. Additionally, roll out of H2ICE within the UK could accelerate the development of hydrogen infrastructure, build world-leading R&D capability and repurpose the pre-existing ICE supply chain, safeguarding highly-skilled jobs across the UK.

The authors therefore make the following recommendations to support fastest possible decarbonisation in the heavy duty sector:

- **Investigation of real world efficiency of heavy duty freight vehicles powered by both hydrogen engines and hydrogen fuel cells is required.**

  Comparison of efficiency/fuel consumption between hydrogen engines and hydrogen fuel cell vehicles shows that they could have similar efficiency. However, there is a lack of robust data on fuel cell efficiency as part of a vehicle system.

- **Analysis of lifecycle emissions for heavy duty hydrogen engines and hydrogen fuel cells is critical, taking into account higher load duty cycles and more demanding durability requirements.**

  Data in the literature indicates that lifecycle emissions for hydrogen engine passenger cars could be lower than for hydrogen fuel cell vehicles, but data for heavy duty vehicles is not currently available.

- **Funding competitions and incentives for net zero emissions vehicles should be technology neutral to support fastest possible decarbonisation.**

  Further research and development is needed for both hydrogen engines and hydrogen fuel cell systems to meet market and environmental requirements for heavy duty vehicles. To ensure the most competitive zero emissions technology is developed, funding for development and adoption should be based on vehicle performance rather than technology type.

This report presents evidence of the complementary role that hydrogen-fuelled internal combustion engines could play in rapid decarbonisation of heavy duty vehicles, alongside fuel cells.

INTRODUCTION

The expected route to decarbonisation for passenger cars is via battery electric vehicles, with sales of this technology increasing rapidly: the market share of BEV, PHEV and hybrid vehicles doubled between 2019 and 2020, to around 1 in 20 of UK car sales[1]. In the heavy duty sector, rigorous and varied usage patterns combined with high power and energy demands (see Figure 1) mean that there is likely to be a portfolio of technology solutions, with three key powertrain types under development (sustainable engines and electric vehicles powered by batteries or fuel cells).

For heavier, long-range vehicles which make up nearly half of freight emissions[2], battery electrification is challenging due to large battery mass and volume, leading to reduced payload capacity, increased vehicle costs and reduced utility due to long charging times. In the longer term, overhead charging can support electrification of these heavier vehicles although significant infrastructure investment in both catenary systems and power grid would be required to achieve this, with coverage of limited routes.

Hydrogen fuelling is seen as a viable solution for heavy duty vehicles due to higher energy density of hydrogen compared to lithium ion batteries and short refuelling times. Interest in the use of hydrogen as a transport fuel is increasing globally: The European Hydrogen Roadmap[3] provides a vision for hydrogen uptake, providing 24% of EU's energy by 2050 across transport, heat, industrial and power generation sectors. In the UK, the Ten Point Plan aims to reduce UK annual total vehicle CO_2 emissions by three million tonnes in 2030. It includes commitments to increase low carbon hydrogen production capacity to 1 GW by 2025 and 5 GW by 2030[4], with investment in manufacturing methods to reduce production emissions to zero by 2050. The plan also aims to encourage vehicle uptake by improving refuelling infrastructure, targeting 1150 hydrogen refuelling stations by 2030.

Hydrogen fuel cell vehicles (H2FC) are on the global market in limited volumes for passenger cars, for example Hyundai Nexo, Toyota Mirai and Honda Clarity. There have been a range of H2FC bus demonstrators across the UK, with trials of single deck buses in London, Birmingham, Brighton and Aberdeen. Wrightbus, a major supplier of buses across the UK, aims to produce 3000 H2FC buses in the next four years, advocating for a subsidy to enable the buses to reach price parity with diesel models. A range of demonstration programmes of H2FC solutions for heavy goods vehicles are underway. For example, in Europe the roll out of 30 demonstrator trucks is planned for 2021/22 as part of the EU H2Haul project. However, there are significant barriers to the introduction of this technology with extensive research and development needed to meet durability and cost requirements for high energy, heavy duty drive cycles and lifetimes.

Interest in hydrogen internal combustion engines (H2ICE) has therefore been growing across Europe and globally due to its potential to bring zero tailpipe emissions heavy duty vehicles to the market rapidly and cost effectively. For example, JCB are currently developing both H2FC and H2ICE products for the off highway sector, recognising the differing performance characteristics of the two technologies. This paper therefore reviews the potential performance of H2ICE technology for the heavy duty on road sector, comparing it to H2FC, to examine the best applications for each technology.

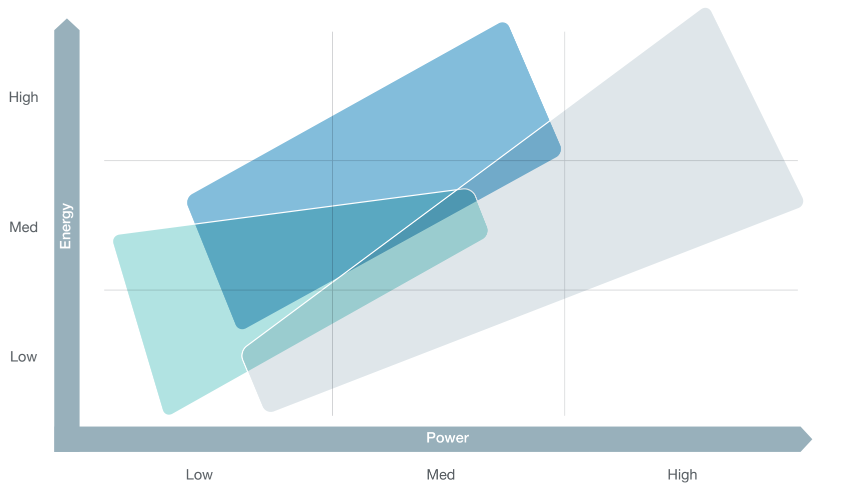
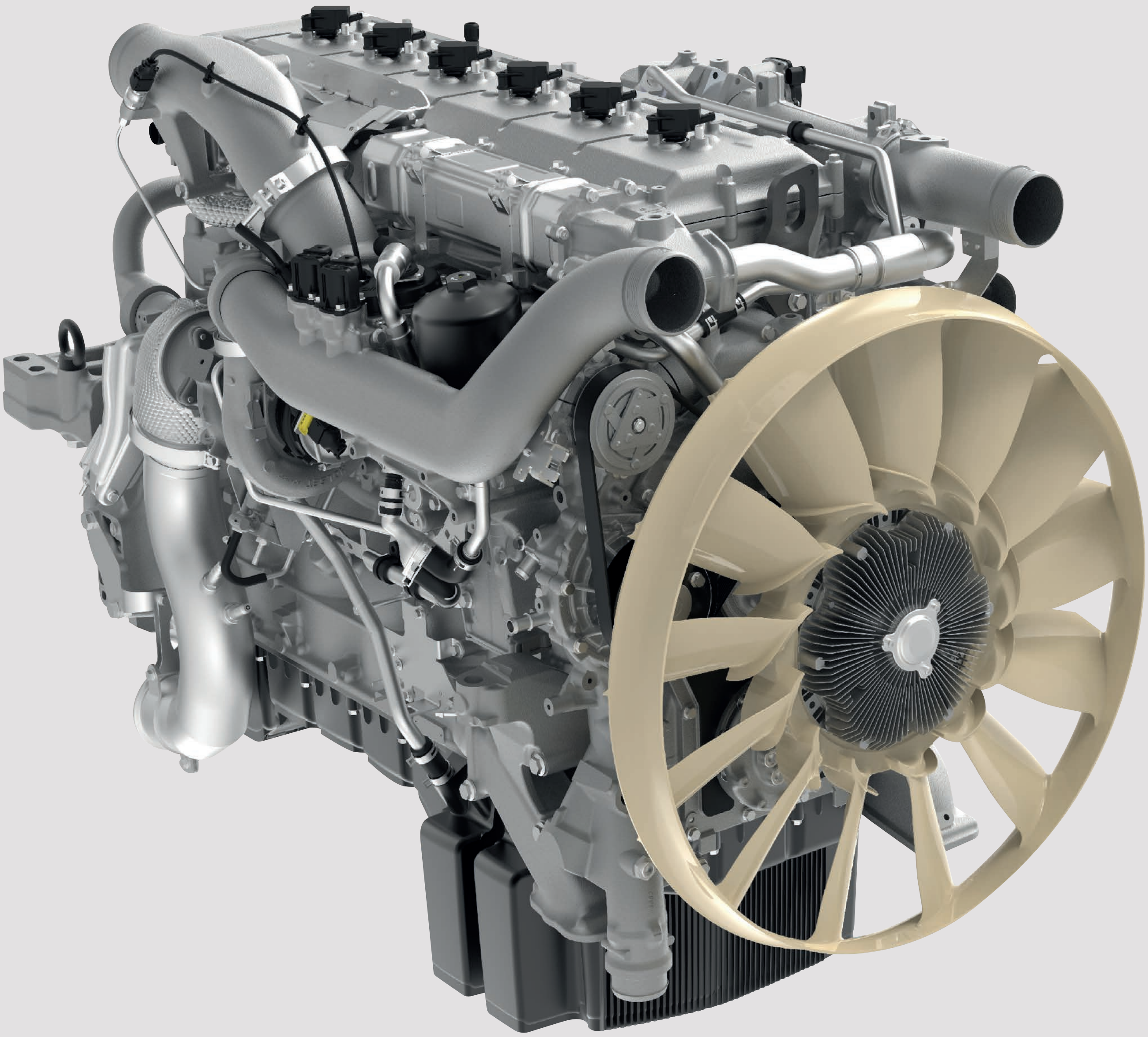


Figure 1: Power and energy requirements for a range of heavy duty vehicles
Source: Advanced Propulsion Centre product roadmaps



MAN hydrogen combustion engine

1 1 SMMT. (2021) *Delivering the Triple Bottom Line: A Blueprint for the Electric Vehicle Revolution*. Available at: https://www.smmt.co.uk/wp-content/uploads/sites/2/SMMT-Electrified-blueprint-FINAL.pdf (Accessed: 15 April 2021)

2 Department for Transport (2017) *Freight Carbon Review 2017, Moving Britain Ahead*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/590922/freight-carbon-review-2017.pdf (Accessed: 15 April 2021)

3 Fuel Cells and Hydrogen Joint Undertaking (2019) *Hydrogen Roadmap Europe, A Sustainable Pathway for the European Energy Transition*. Available at: https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf (Accessed: 22 March 2021)

4 Department for Business, Energy & Industrial Strategy (2020) *The Ten Point Plan for a Green Industrial Revolution*. Available at: https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title (Accessed: 22 March 2021)

TECHNOLOGY BACKGROUND

The EU definition for a zero emission heavy duty vehicle is 'a heavy duty vehicle without an internal combustion engine, or with an internal combustion engine that emits less than 1 g CO_2/kWh … or which emits less than 1 g CO_2/km' so hydrogen engines could offer a route to zero tailpipe emissions vehicles in this sector. The structure and working principles are similar to diesel engines with some modifications for hydrogen fuelling.

Key features are:

Hydrogen fuelling system

Original Equipment Manfacturers (OEMs), companies that supply components to OEMs (Tier 1s) and academic researchers are working on fuelling systems where hydrogen is injected in the intake manifold (port fuel injection, PFI) or directly into the cylinder (direct injection, DI). DI has more complex injector technology and higher fuel supply pressure but reduces the risk of hydrogen ignition in the intake system and can offer improved performance over PFI. Combustion can be stoichiometric (where there is just sufficient air to burn fuel completely) or lean (with additional air).

Ignition system

Recent work on dedicated hydrogen engines uses spark ignition. Diesel pilot ignition is also being investigated, with a similar operating principle to High Pressure Direct Injection (HPDI) CNG engines now offered by several OEMs, because this can form a useful transition technology where hydrogen refuelling infrastructure is in development.

Combustion system

Development of the combustion system for hydrogen fuelling is required, optimising for example, combustion chamber geometry, spark timing, air fuel ratios and valve timing.

Boosting

Turbocharging or supercharging can be used to increase power output; detailed design of these components requires optimisation for air and fuel flow rates across the engine operating range. A hydrogen engine that uses lean burn to control NOx will need very high boost levels to maintain power output.

Emissions reduction

For hydrogen engines, emissions reduction can be carried out using combustion optimisation, ultra lean burn, exhaust gas recirculation (EGR), water injection into the cylinder and/or hydrogen optimised aftertreatment.

Materials and lubricants

Development is needed to ensure compatibility with hydrogen fuelling.

Fuel storage

As for H2FC vehicles, hydrogen can be stored as pressurised gas or a cryogenic liquid.

KEY MODIFICATIONS

Modified combustion system

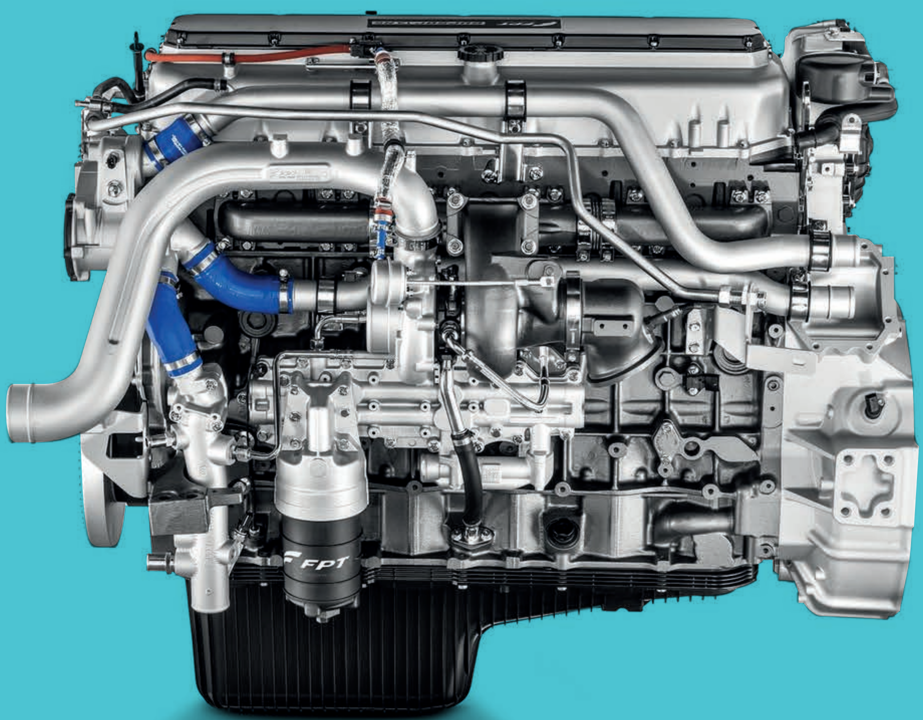
Optimised compression ratio and piston profile, updated piston rings

Material compatibility

Upgrades to seals, hoses, valves, valve seats, lubricants

Fuelling system

Injectors for manifold injection (PFI) or injection directly into the cylinder (DI or HPDI), spark plugs



Safety

Crank case ventilation, knock control

Air path

Upgraded boosting, e.g. turbocharger modification

Emissions control

Options include water injection, ultra lean burn, exhaust gas recirculation, hydrogen optimised aftertreatment

Control

Upgraded control system

Hydrogen engine history

Hydrogen engines have been developed and manufactured in small volumes in the past. For example, around 100 hydrogen-powered 7 series vehicles were manufactured by BMW in 2005-2007 with a 6L V12 engine and liquid hydrogen storage. The naturally aspirated engine, with mixed lean burn and stoichiometric operation and a three-way catalyst, had marginally better fuel consumption than the gasoline equivalent vehicle over the US highway cycle, and for the FTP-75 cycle average NOx emissions were 0.0008g/mi and CO levels of 0.003 g/mi; 3.9% and 0.3% of the US SULEV[5] emissions limit in force at the time respectively[6]. With a modern boosted engine using diesel engine architecture as a baseline, the thermal efficiency of an H2ICE can be substantially improved over this concept.

Hydrogen-powered BMW 7 series

5 Delphi Technologies (2018/2019) *Worldwide Emissions Standards On and Off-Highway Commercial Vehicles 2018/2019*. Available at: https://www.delphi.com/sites/default/files/inline-files/booklet%20emission%20heavy%20duty.pdf (Accessed: 15 April 2021)

6 Wallner, T., Lohse-Busch, H., Gurski, S., Duoba, M., Thiel, W., Martin, D. and Korn, T. (2008) 'Fuel economy and emissions evaluation of BMW Hydrogen 7 Mono-Fuel demonstration vehicles', *International Journal of Hydrogen Energy* 33(2008) pp.7607–7618

Hydrogen-powered BMW 7 series engine

PERFORMANCE

Acceptability of H2ICE depends on ability of the technology to provide a route to reach net zero greenhouse gas (GHG) emissions by 2050, and the capacity to provide zero impact air quality emissions. For operators, cost of ownership and logistics efficiency are key so powertrain efficiency, alongside acceptable power output are important characteristics. This section summarises evidence of H2ICE performance from recent academic literature and recent industrial publications.

Efficiency and fuel consumption

Engine efficiency can be assessed in a range of ways. Different measures of efficiency are stated in publications, so it is therefore important to clarify their meaning:

- Theoretical efficiency
  The second law of thermodynamics governs the maximum proportion of fuel energy that can be converted to useful power output for a particular engine cycle, e.g. otto (gasoline) and diesel cycles.
- Indicated thermal efficiency
  Gross and net indicated efficiency represent the theoretical efficiency adjusted to take into account heat losses (gross indicated thermal efficiency) and combined heat and air path losses (net indicated efficiency).
- Brake thermal efficiency
  Efficiency of conversion of fuel energy to useful torque output, taking into account thermodynamic, pumping, friction and ancillary losses (e.g. energy to drive air conditioning system pumps and fuel pumps).
- Traction efficiency
  Brake thermal efficiency adjusted for losses in the driveline, e.g. friction losses in the gearbox.

Internal combustion engine efficiency varies depending on operating speed and load. A typical engine efficiency map for a heavy duty diesel engine is shown in Figure 2, based on benchmark testing of current engines. The plot shows efficiency plotted against engine speed and percentage load, with lighter colours representing higher efficiencies. The figure shows that there is an area of higher efficiency which is typically at higher speeds and loads. The shape of the efficiency map, combined with gear ratios, will dictate how the engine will perform over a given vehicle duty cycle. It is clear from this map that the efficiency of an engine over a drive cycle will generally be lower than the peak brake thermal efficiency. Heavy duty vehicles, particularly large freight trucks, typically operate at higher loads where engines are more efficient with a typical efficiency drop of 4–6% between drive cycle efficiency and peak brake thermal efficiency.

For hydrogen engines, brake thermal efficiencies up to 45% and indicated thermal efficiencies up to 50% are reported in the academic literature, reflecting the range of engine types, operating conditions and optimisation activities carried out by the researchers. Recent work from AVL and Westport suggest indicated thermal efficiencies for compression ignition hydrogen with diesel pilot could be over 48%[7]. Data from Keyou published in 2018[8] showed brake thermal efficiencies up to 44.5% with an efficiency map shown in Figure 3.

Developments in novel engine thermodynamic cycles, such as the Recuperated Split Cycle Engine being developed by Dolphin N2, and Double Compression and Expansion engines are expected to increase engine brake thermal efficiency. A recent Advanced Propulsion Centre (APC) roadmap[9] presents targets of 55% in 2025 and 60% in 2035 for heavy duty engines. It would be expected that these efficiency improvements would also apply to hydrogen engines, for example, work to develop the Recuperated Split Cycle Engine for hydrogen fuelling is currently underway supported by the APC Advanced Route to Market Demonstrator programme in a project called RE-ARMD.

7 Munshi, S., Garner, G., (Westport Fuel Systems) Theissl, H, Hofer, F and Raser, B. (AVL List GmbH) (2021) *Total Cost of Ownership (TCO) Analysis for Heavy Duty Hydrogen Fueled Powertrains*. Available at: https://wfsinc.com/file_library/files/wpt-wfsinc/20201225_Westport_AVL_Whitepaper_Hydrogen_HPDI_final.pdf (Accessed: 22 March 2021)

8 Keyou GMBH (2018) 'Highly Efficient Hydrogen combustion engines as an alternative to fuel cells and electric drives in the commercial vehicle sector', 27th *Aachen Colloquium Automobile and Engine Technology*. Aachen, Germany, 8-10 October.

9 Advanced Propulsion Centre UK (2020) *Technology Roadmaps*. Available at: https://www.apcuk.co.uk/technology-roadmaps/. (Accessed: 22 March 2021)

Figure 2: Typical heavy duty diesel engine efficiency map
Source: Ricardo

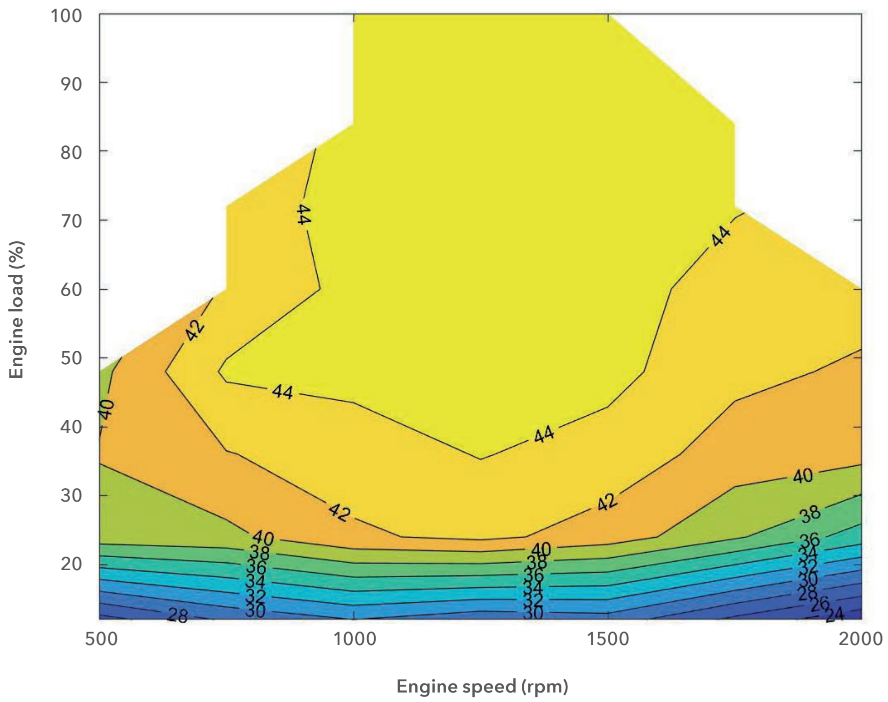
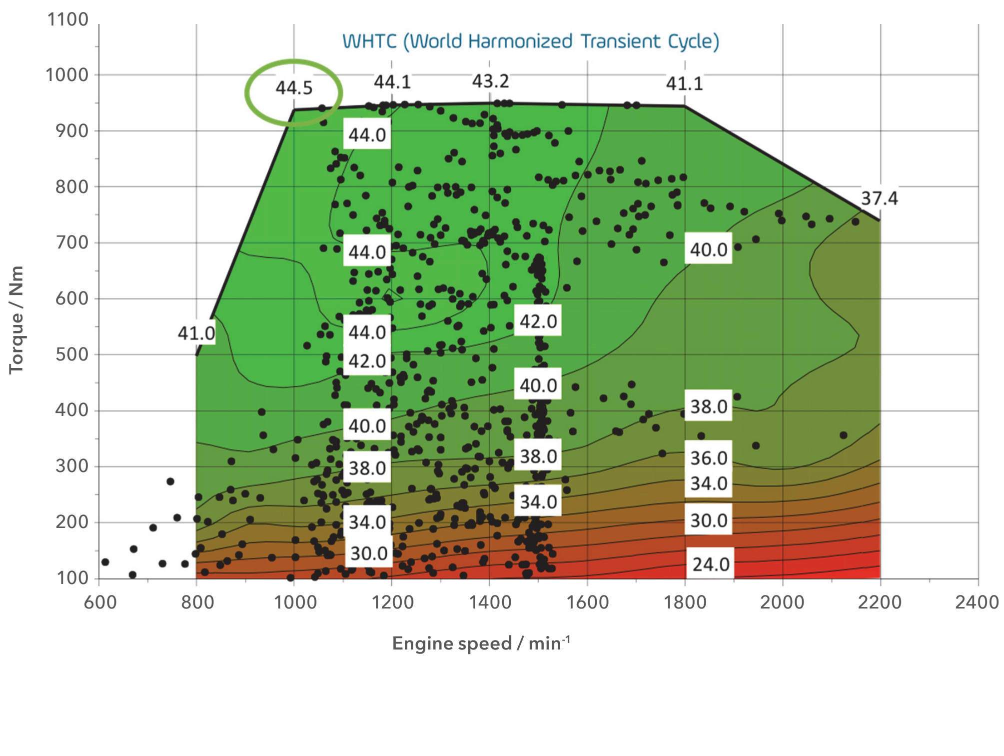


Figure 3: Brake thermal efficiency contour plot for a hydrogen engine
Source: Keyou GMBH, Aachener Colloquium 2018



AIR QUALITY EMISSIONS

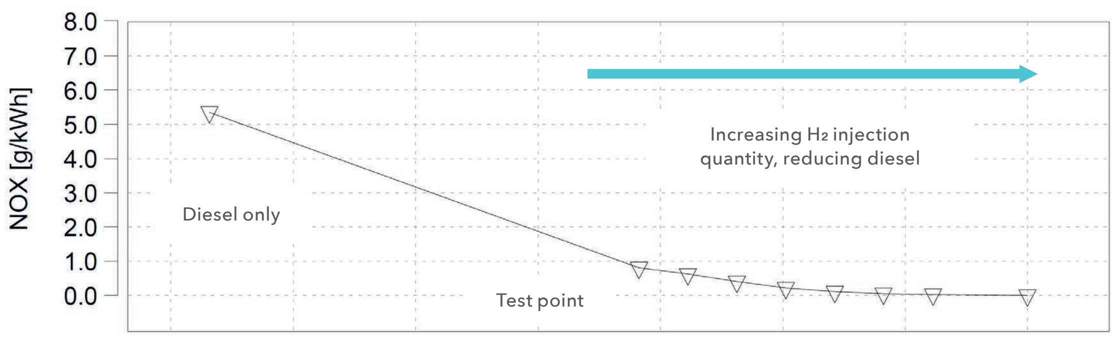
The products of hydrogen combustion are water and NOx, with levels of NOx emissions strongly related to combustion temperature. The wide flammability limit of hydrogen means that the engine can be run with a higher proportion of air, lean combustion, which reduces the combustion temperature thereby reducing NOx emissions. Further reduction of NOx emissions can also be achieved by:

- Exhaust gas recirculation (EGR) – reducing the oxygen content in the combustion chamber, reducing the temperature and therefore NOx emissions
- Water injection – water is injected into the combustion chamber to reduce combustion temperatures
- Aftertreatment – may be necessary for cold start or transient conditions.

Results presented in the academic literature show near zero tailpipe NOx levels can be achieved with stoichiometric combustion, in combination with high EGR rates and a three-way catalytic converter, but with reduced engine power and combustion stability. The focus of much research has therefore been on lean combustion, where very low, near zero, NOx can be achieved through engine optimisation alone (DI injector design and ignition timing), water injection, EGR and/or aftertreatment. Recent work[10] has demonstrated single digit parts per million (ppm) engine out NOx emissions for DI lean combustion.

Industrial researchers have also demonstrated engines with very low NOx emissions. Work from CMB.TECH[11] presented in Figure 4 shows near zero NOx for diesel pilot hydrogen combustion in a 12.7L engine. In this figure the data point on the left is a production calibration point for the engine out emissions on diesel fuel only for the EURO VI truck engine as a reference point. The set of data points on the right are where the engine is operating with 98% of the fuel energy derived

Figure 4: NOx measurements for diesel pilot hydrogen combustion, (1200 rpm, 400 Nm) with varying diesel injection and injection timing
Source: CMB.TECH



from hydrogen, with varying injection timing for the diesel pilot injection. The advanced injection reduces NOx to virtually zero by creating a multi point ignition behaviour similar to homogenous charge compression ignition engines.

Keyou state in a recent paper[12] that the combination of lean combustion with EGR resulted in engine out NOx emissions which were ~10 times smaller than current Euro VI NOx limit. With hydrogen optimised aftertreatment, tailpipe NOx emissions were unmeasurable with current emissions measuring instrumentation.

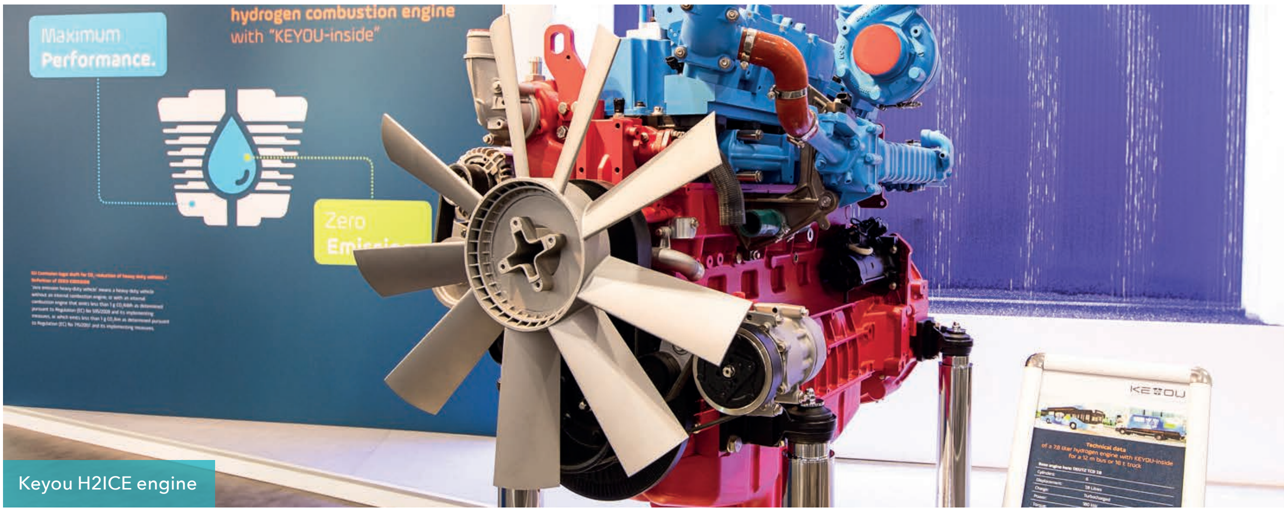
Small quantities of hydrocarbon emissions and particulates may be present in the exhaust due to lubricant burning in the combustion chamber, particularly during start up and idle. As has been shown with modern diesel engines, hydrocarbon emission levels can be reduced with further development, for example, through optimisation of the ignition timing, air fuel ratio, piston ring geometry and cylinder liner surface finish, and by the use of aftertreatment[13].

Power output

Power output from hydrogen engines tends to show a trade off with lean conditions required for low NOx, sometimes requiring power reduction to avoid adverse combustion conditions such as knock. Recent studies have shown potential for increased power output at lean conditions for an optimised direct injection system, using boosting technology such as supercharging or electric turbochargers. Further electrification of the powertrain, hybridisation, could also be used to meet peak torque requirements.

Research and development needs

Based on review of the published literature and results from industrial organisations, H2ICE are capable of near zero emissions operation with efficiencies comparable to a diesel engine. However, much of the recent research has been performed for light duty engines. Therefore, a key R&D challenge is to develop engines which can meet the more stringent durability requirements of a heavy duty engine, and ensure performance over typical duty cycles, particularly at cold start and transient operating conditions.



Keyou H2ICE engine

10 Takagi, Y., Oikawa, M., Sato, R., Kojiya, Y. and Mihara, Y, (2019) 'Near-zero emissions with high thermal efficiency realized by optimizing jet plume location relative to combustion chamber wall, jet geometry and injection timing in a direct-injection hydrogen engine', *International Journal of Hydrogen Energy* 44 (18). Available at: https://doi.org/10.1016/j.ijhydene.2019.02.058 (Accessed: 3 March 2021)

11 CMB.tech (2021) 'Hydrogen combustion and the use of seeded hydrocarbon fuel for seeded ignition', 3 March 2021

12 Keyou GMBH (2018) 'Highly Efficient Hydrogen combustion engines as an alternative to fuel cells and electric drives in the commercial vehicle sector', 27th *Aachen Colloquium Automobile and Engine Technology*. Aachen, Germany, 8-10 October.

13 Xu, P., Ji, C., Wang, S., Bai, X., Cong, X, Su, T. and Shi, L. (2019) 'Realizing low emissions on a hydrogen-fueled spark ignition engine at the cold start period under rich combustion through ignition timing control', *International Journal of Hydrogen Energy* 44 (16) pp. 8650-8658. Available at: https://doi.org/10.1016/j.ijhydene.2019.01.275 (Accessed: 22 March 2021)

Xu, P., Ji, C., Wang, S., Bai, X., Cong, X, Su, T. and Shi, L. (2018) 'Realizing low NOx emissions on a hydrogen-fuel spark ignition engine at the cold start period through excess air ratios control', *International Journal of Hydrogen Energy* 43 (46) pp. 21617-21626. Available at: https://doi.org/10.1016/j.ijhydene.2018.09.136 (Accessed: 3 March 2021)

Ji, C and Wang, S (2013) 'Combustion and emissions performance of a hydrogen engine at idle and lean conditions', *International Journal of Energy Research* 37(5) pp. 468-474. Available at: https://doi.org/10.1002/er.3020 (Accessed: 3 March 2021)

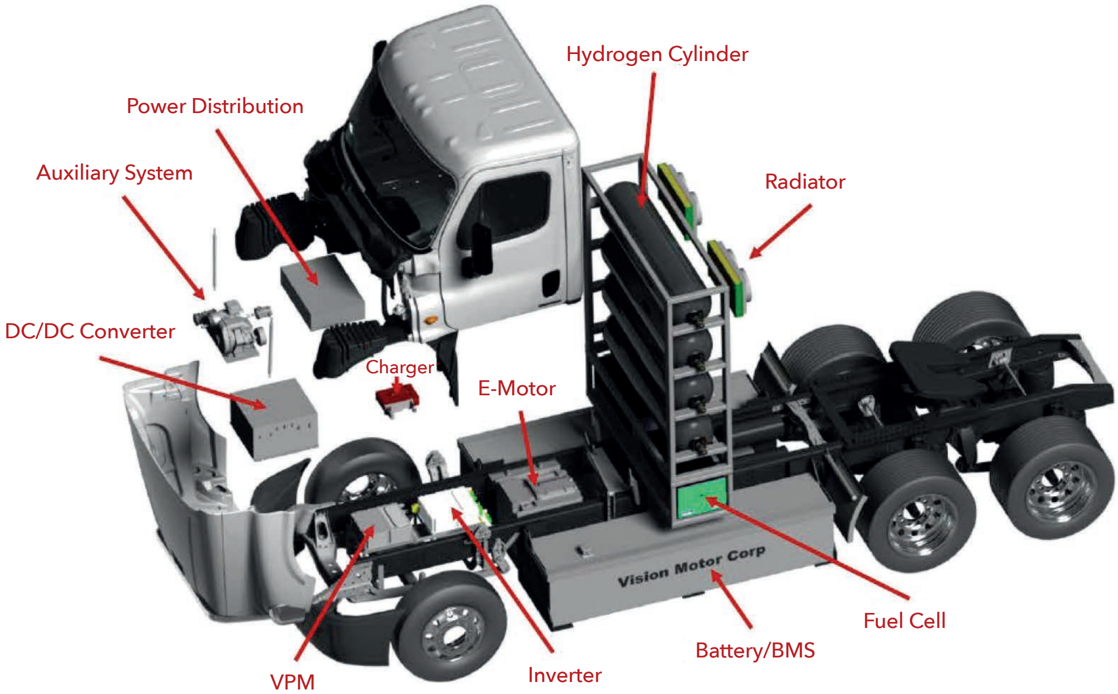
HYDROGEN ENGINES COULD OFFER SIMILAR PERFORMANCE TO FUEL CELLS

An appreciation of how attributes might vary between H2FC and H2ICE is key to understanding which application each technology might be most suitable for. This section therefore compares the performance of H2ICE and H2FC systems for cost, efficiency, tailpipe air quality emissions and lifecycle emissions.

Cost

There are key differences in costs between H2FC and H2ICE vehicles due to differences in powertrain cost and the hybrid system necessary for H2FC vehicle operation. The cost of H2ICE will increase compared to a diesel equivalent due to the hydrogen storage tanks. For the H2FC vehicle, the ICE is replaced by a PEM fuel cell, its supporting balance of plant, an electric drive system and the traction battery. (Figure 5).

Figure 5: H2FC truck layout showing key components
Source: fc_tech_report.pdf (ca.gov))



A comparison of estimated H2FC and H2ICE powertrain costs in 2025 and 2035 is shown in Table 1, based on a range of evidence including APC roadmaps and recent product announcements. The analysis makes the following assumptions:

- Fuel cell stack, hydrogen storage and battery costs are assumed to be APC roadmap target values
- The cost of the fuel cell hybrid system is not included (electric machine and power electronics) as it is expected to be a relatively small cost compared to other fuel cell vehicle components
- H2ICE engine costs are based on current diesel engine costs, including aftertreatment, with hydrogen-optimised fuelling and boosting systems
- Both H2ICE and H2FC costs are quoted at mass market volumes
- Exchange rate $1.4 = £1

This analysis shows that while H2ICE vehicles would have a cost premium compared to diesel ICE due to additional hydrogen fuel tanks, in the short term the technology would be significantly less expensive than a fuel cell system due to the high cost of the fuel cell stack and hybrid system battery that is necessary to manage transient operation. If fuel cell stack and battery costs fall in line with APC targets, this cost differential may reduce with time. The level of confidence in H2ICE costs is relatively high as they are based on the current diesel engine cost profile. However, fuel cell stack target costs in 2035 are based on aggressive reductions between 2025 and 2035, so there is a risk that these targets might not be met, for example if expected sales volumes are not achieved. In this case the cost differential between H2FC and H2ICE could remain large. Traditionally, it is argued that the fuel cell justifies this cost by being more efficient; therefore, a logical next step is to examine whether this is still the case.

Table 1: Cost estimates for H2FC and H2ICE powertrains in 2020 and 2035

System/cost	2025		2035	
	H2ICE	H2FC	H2ICE	H2FC
Engine/fuel cell system	41[b] $/kW @350kW[d]	195 $/kW[a] @190 kW[e]	42[b] $/kW @350kW[d]	80 $/kW[a] @190 kW[e]
	$14.4k	$37.1k	$14.4k	$15.2k
Fuel tanks	365 $/kg[a] @70kg[c]	365 $/kg[a] @70kg[c]	200 $/kg[a] @70kg[c]	200 $/kg[a] @70kg[c]
	$25.5k	$25.5k	$14k	$14k
Battery	N/A	97 $/kWh[a] @ 73 kWh[e]	N/A	63 $/kWh[a] @ 73 kWh[e]
	-	$7.1k	-	$4.5k
Total	**$39.9k**	**$69.4k**	**$28.35k**	**$33.7k**

Table 1 – Cost estimates for H2FC and H2ICE powertrains in 2025 and 2035. Cost estimates are based on the following references:
a. Advanced Propulsion Centre roadmaps 2020
b. Ricardo analysis
c. 2020_06_TE_comparison_hydrogen_battery_electric_trucks_methodology.pdf (transportenvironment.org)
d. Volvo FH Powertrain Specifications | Volvo Trucks
e. Hyundai Xcient specification (Hyundai Motor's Delivery of XCIENT Fuel Cell Trucks in Europe Heralds Its Commercial Truck Expansion to Global Markets – Hyundai Hydrogen Mobility (hyundai-hm.com))

Efficiency and fuel consumption

A range of data is published on fuel cell efficiency:

- PEM fuel cell stack efficiency – PEM fuel cell stack efficiency is related to the voltage output of the cell at a range of current densities (equivalent to engine load).
- PEM fuel cell system efficiency – fuel cell system efficiency takes into account the energy use of the fuel cell stack and the balance of plant, for example pumps and heat exchangers. Data shown in Figure 6 presents fuel cell stack and system efficiency for the Toyota Mirai published by Argonne National Laboratory[14]. The graph shows clearly that efficiency reduces with fuel cell power output, and the efficiency reduction between the output of the fuel cell stack and the fuel cell system.
- Traction efficiency – includes losses in the series hybrid system, for example, due to battery charging/discharging and in the electric machine and power electronics.

Relatively little public domain data is available for on the road efficiency of H2FC, however Figure 7 shows a comparison of H2FC and H2ICE efficiency in 2021 and 2035 based on current data and APC roadmap targets for H2FC and ICE efficiency. Fuel cell system efficiency curves for 2021 are based on Mirai fuel consumption data from fueleconomy.gov[15], with estimates for traction efficiency losses. H2ICE efficiency in 2021 is derived from data published by Keyou. 2035 traction efficiency curves are then generated for both technologies from APC 2035 efficiency targets, using the same efficiency vs load characteristics as 2021 data and taking into account drivetrain losses. The data shows that the most efficient system depends on the load, with H2FC more efficient at lighter load, and H2ICE more efficient at higher loads. Which system gives the best efficiency over a vehicle drive cycle will therefore depend on the load conditions, it might be expected that over a relatively higher load heavy duty drive cycle (such as an articulated truck) the H2ICE may give better efficiency whereas over lighter load duty cycles (such as a city bus) H2FC may have better efficiency.

Figure 6: Toyota Mirai fuel cell stack and system efficiency (source Argonne National Laboratory)

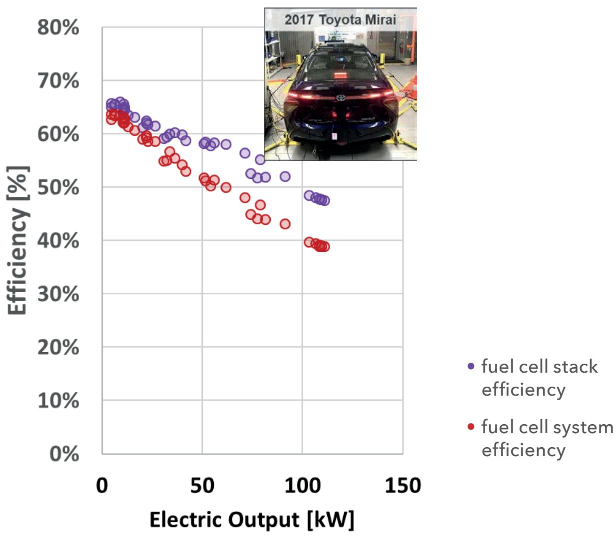
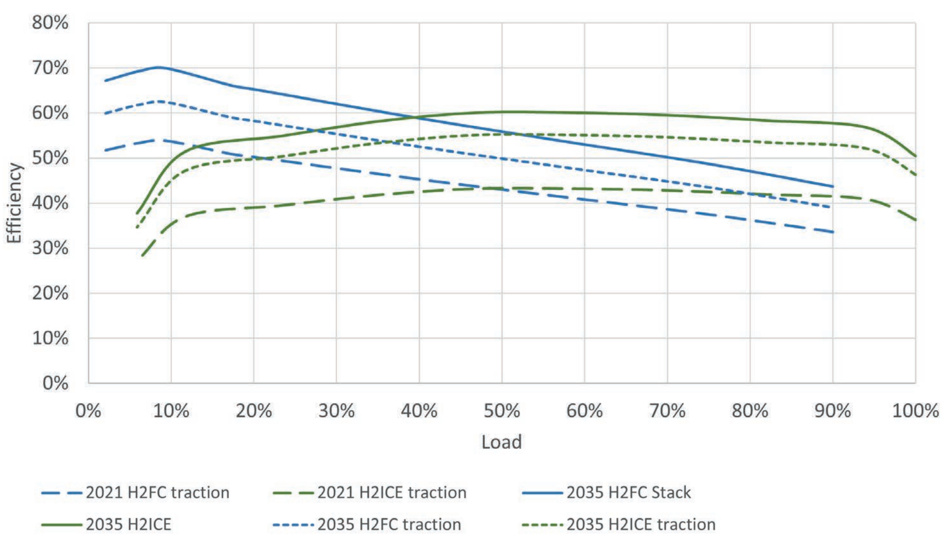


Figure 7: Comparison of H2FC and H2ICE efficiency



Air quality emissions

PEM fuel cells emit only water from the tailpipe, except for start-up and shut-down phases where small amounts of hydrogen may be emitted. The H2ICE, unlike its hydrocarbon-fuelled relatives, does not emit any carbon monoxide or unburned hydrocarbons; particulates can only arise from combustion of stray lubricating oil, which forms a minor part of total particulates in a Diesel engine. Both this and unburned hydrogen can be addressed by conventional aftertreatment. Research detailed in this report shows that NOx emissions for H2ICE can be reduced to levels that are unmeasurable with current emissions measuring equipment; significantly below the SULEV level which is below the lowest proposal for Euro VII. Although these small quantities of emissions cannot be described as "absolutely zero", they are lower than ambient air concentrations in many western cities today.

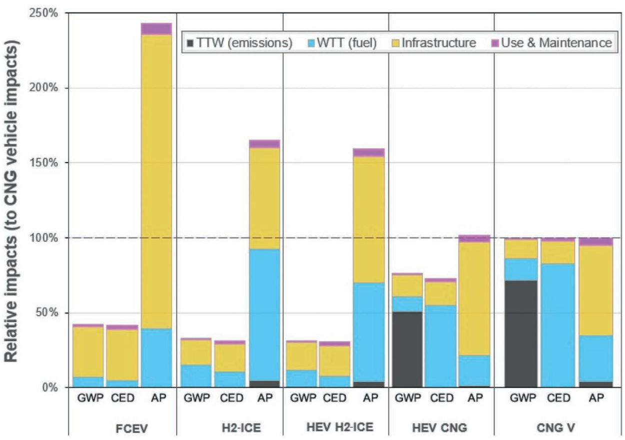
Life cycle emissions

There are few publications comparing lifecycle emissions for H2ICE and H2FC vehicles. Researchers[17] have compared Well to Wheels emissions for passenger cars for a range of hydrogen production pathways, based on GREET model data for H2ICE fuel consumption and emissions. Based on fuel consumptions of 38.2 mi/gal (7.4 L/100 km), 50.2 mi/gal (5.6L/100 km), and 65.3 mi/gal (4.3 L/100 km), respectively for H2ICE, H2ICE hybrid, and H2FC, the analysis shows an increase in overall Well to Wheels greenhouse gas (GHG) emissions for H2ICE compared to H2FC.

Lifecycle emissions have been evaluated by researchers[18] for H2ICE and H2FC passenger cars, again based on GREET model data, assuming fuel consumption for H2FC was 131.58 km/kg and H2ICE was 59.24 km/kg. Despite this increased fuel consumption, the H2ICE vehicle was found to outperform the H2FC vehicle for global warming emissions, energy consumption and acidification emissions due to the shorter life of the H2FC vehicle (Figure 8).

The authors are not aware of any references comparing lifecycle emissions for H2FC and H2ICE powered heavy duty vehicles, for example, a recent study for EC DGCLIMA examining a range of heavy duty vehicle types does not include analysis for a H2ICE[19]. However, the analysis presented in this report shows that for heavy duty vehicles, the fuel consumption of H2FC and H2ICE could be similar, which would have a significant impact on relative lifecycle emissions potentially leading to further reductions in H2ICE emissions compared to H2FC. It is therefore recommended that lifecycle analysis is carried out comparing H2FC and H2ICE heavy duty vehicles taking into account their relatively high load duty cycles and more stringent durability requirements.

Figure 8: Comparison of lifecycle impacts of fuel cell (FCEV), H2ICE, hybrid H2ICE and CNG vehicles, in terms of global warming potential (GWP), energy consumption (CED) and acidification emissions (AP) Source: https://doi.org/10.1016/j.ijhydene.2021.01.034



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15 Fuel Economy (2021) *Compare Fuel Cell Vehicles*. Available at: https://fueleconomy.gov/feg/fcv_sbs.shtml (Accessed:19 April 2021)

16 Keyou GMBH (2018) 'Highly Efficient Hydrogen combustion engines as an alternative to fuel cells and electric drives in the commercial vehicle sector', 27th *Aachen Colloquium Automobile and Engine Technology*. Aachen, Germany, 8-10 October.

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19 Ricardo Energy & Environment, E4Tech and Institute for Energy and Environmental Research Heidelberg (2020) *Determining the Environmental Impacts of Conventional and Alternatively Fueled Vehicle Through LCA, Final Report for The European Commission, DG Climate Action*. Available at: https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1 (Accessed: 19 April 2021)

HYDROGEN ENGINES COULD ACCELERATE DECARBONISATION IN THE HEAVY DUTY SECTOR

A range of H2FC truck demonstration programmes are ongoing, for example as part of the H2Haul programme, 30 fuel cell truck demonstrator vehicles are expected to be on the road in 2021/22[20]. However, recent roadmaps indicate that H2FC may not be mainstream technology for heavy duty vehicles until 2040.

Recent APC[21] and CENEX[22] roadmaps for heavy duty vehicles (Figures 9 and 10) show the scale of development needed before H2FC implementation in the mass market is feasible, with APC analysis concluding that H2FC vehicles may not reach mass market adoption until around 2040 for urban or long range, heavy duty vehicles.

Evidence from public domain industrial press releases, such as those from MAN[23] and Westport[24], show that R&D for H2ICE is underway with MAN expecting to demonstrate prototype H2ICE vehicles on the road in 2021. Additionally, the ability to utilise existing supply chains for H2ICE vehicles could support faster ramp up of production volumes, so H2ICE technology could reach mass market in the 2025–2030 timeframe. H2ICE could therefore provide a route to rapid decarbonisation in the heavy duty sector, encouraging the uptake of hydrogen fuelling while H2FC technology (or indeed, more efficient H2ICE types) technology matures. Technology suitability depends on duty cycle due to efficiency / load profiles, so H2FC may be more suitable for lower load applications like buses, with H2ICE giving better performance for higher load applications like heavy duty freight. Any roll out of hydrogen mobility depends on the supply chain for hydrogen specific components like fuel tanks, a workable hydrogen supply and operator confidence in the technology. However, there is a risk that if H2ICE technology is not rolled out, and the volume of low carbon drop in fuels remains relatively low, decarbonisation in the heavy duty truck sector could make slow progress until alternatives, such as H2FC, are on the market.

20 Fuel Cells and Hydrogen Joint Undertaking. *Truck Study. Fuel Cell Hydrogen Trucks*. Available at: https://www.fch.europa.eu/sites/default/files/Truck%20study.%20Fuel%20Cell%20Hydrogen%20Trucks.pdf (Accessed: 19 April 2021)

21 Advanced Propulsion Centre UK (2020) *Technology Roadmaps*. Available at: https://www.apcuk.co.uk/technology-roadmaps/. (Accessed: 22 March 2021)

22 CENEX (2021) 'CENEX hydrogen technology roadmap', *The Future of Hydrogen in Aberdeen*. Aberdeen, 17 March.

23 Green Car Congress (2020) *MAN Presents Hydrogen Roadmap; Use in Fuel Cells and Combustion Engines*. Available at: https://www.greencarcongress.com/2020/10/20201020-man.html (Accessed: 22 March 2021)

24 Westport Fuel Systems (2021) *Westport Fuel Systems and AVL Joint Paper Assesses Total Cost of Ownership for Hydrogen Internal Combustion Engines*. Available at: https://investors.wfsinc.com/news/news-details/2021/Westport-Fuel-Systems-and-AVL-Joint-Paper-Assesses-Total-Cost-of-Ownership-for-Hydrogen-Internal-Combustion-Engines/default.aspx (Accessed: 22 March 2021)

Westport Fuel Systems (2021) *Westport Fuel Systems to Cooperate with Truck and Bus Manufacturer Scania on a Direct Injected Hydrogen Engine Research Project*. Available at: https://investors.wfsinc.com/news/news-details/2021/Westport-Fuel-Systems-to-Cooperate-with-Truck-and-Bus-Manufacturer-Scania-on-a-Direct-Injected-Hydrogen-Engine-Research-Project/default.aspx (Accessed: 19 April 2021)

Figure 9: Advanced Propulsion Centre 2020 Technology roadmaps for heavy duty on and off road vehicles
Source: Advanced Propulsion Centre technology roadmaps

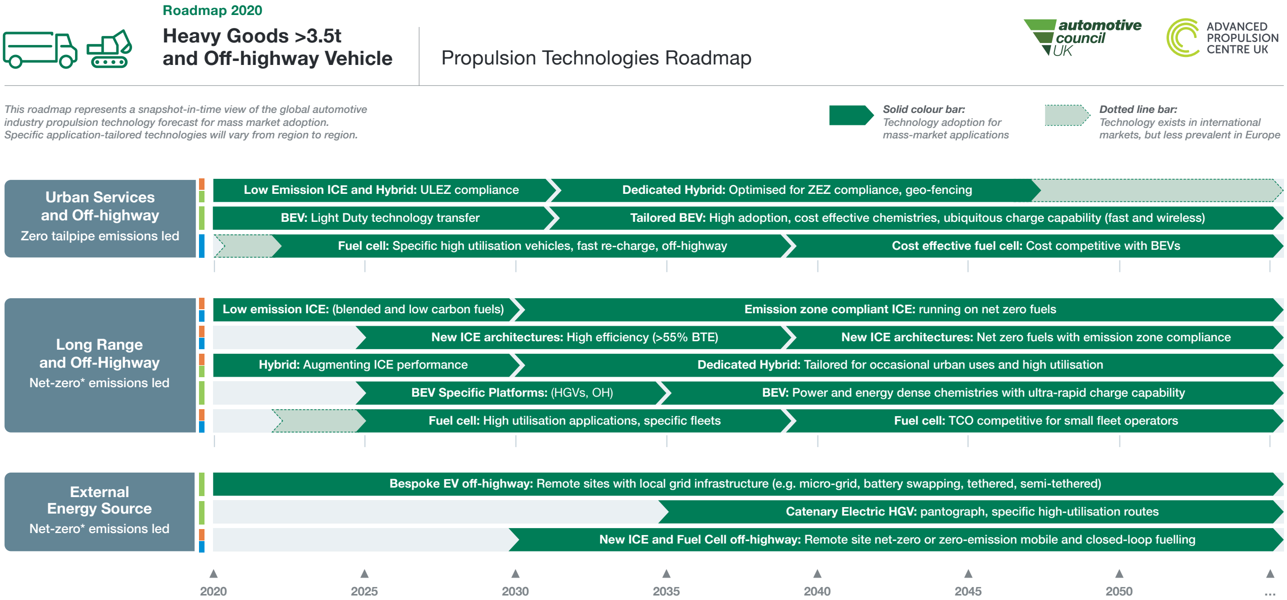
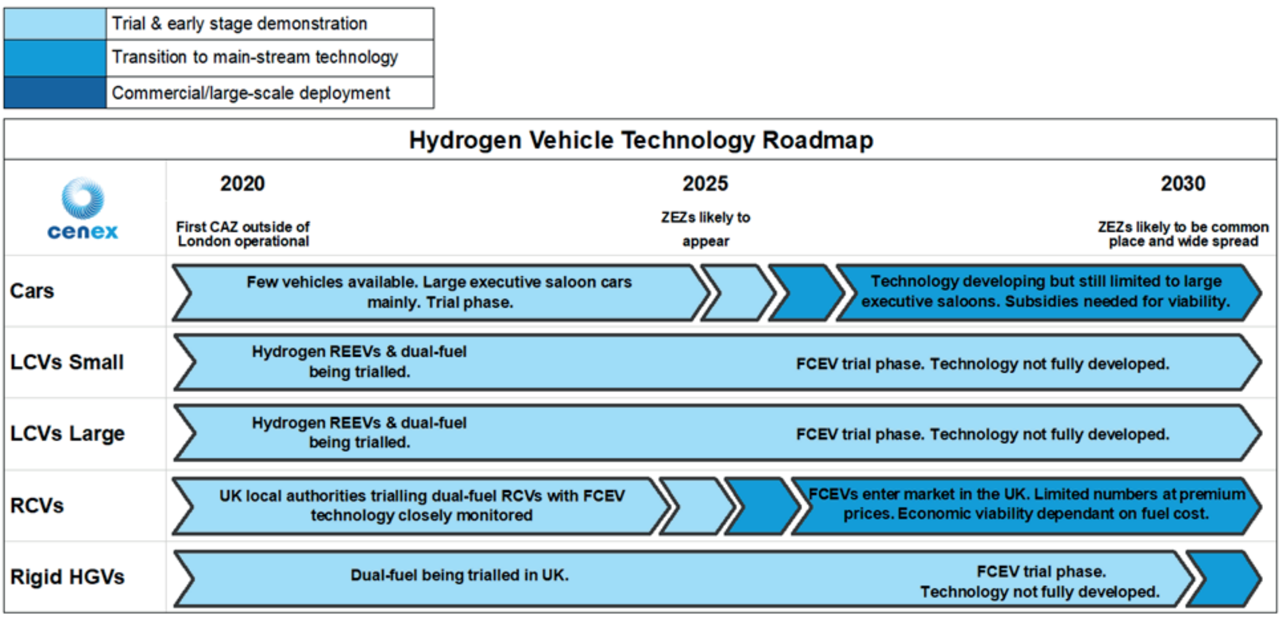


Figure 10: Cenex roadmaps for hydrogen on road vehicles
Source: CENEX



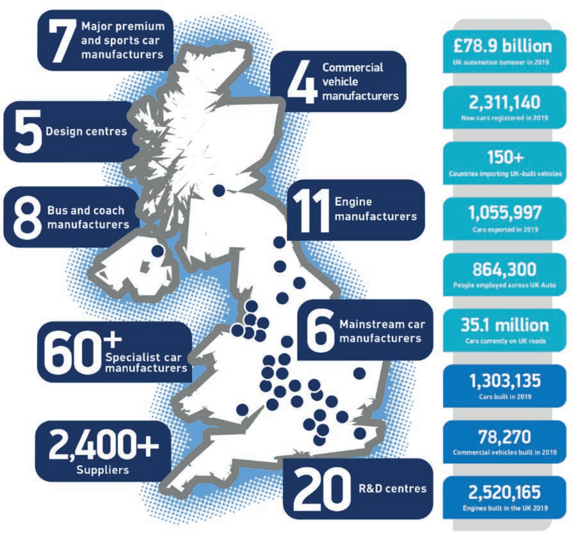
THE UK COULD BUILD A COMPETITIVE ADVANTAGE IN THIS TECHNOLOGY AREA

The automotive industry plays a significant role in UK prosperity and employment; in 2019 the industry had a turnover of £78.9 bn and employed more than 800k people across the UK.

Data from SMMT shows that there are 11 engine manufacturers across the UK, who produced more than two million engines in 2019 (see Figure 11). Repurposing the engine supply chain from conventional fuels to sustainable fuels such as low carbon hydrogen would therefore offer the potential to safeguard high quality manufacturing and R&D jobs.

Analysis of recent academic activity shows that research into hydrogen combustion is being conducted worldwide, with the vast majority of journal papers being produced in China (see Figure 12). China is the world's largest producer of hydrogen, accounting for one third of global production and has many government-backed projects aiming to diversify fuels for transport.

Figure 11: Analysis of the impact of the automotive industry in the UK
Source: SMMT



It is difficult to be certain about the extent of industrial activity in H2ICE technology as R&D activities are frequently confidential. Patents can be used to gauge industrial interest, albeit with a time delay due to time taken during filing. Figure 13 shows an analysis of patents which relate directly to H2ICE technology and related components. Data shows a peak in activity around 2005-10 with Toyota, BMW and Ford key players. There has been a recent resurgence in activity, with patents in between 2017 and 2020 from MAN, ULEMCO and Keyou.

There has also been an increasing number of conferences and seminars on the subject of H2ICE with participation from European technology developers. For example, at the International Engine Congress 2021, a session was dedicated to H2ICE with presentations from AVL, FEV, IAV, Bosch, Keyou, Mahle Powertrain and Liebherr Machines. OEM and Tier 1 activity is also demonstrated in recent press releases, for example both MAN and JCB have announced plans to develop prototype vehicles with both H2ICE and H2FC technology, and recently a partnership was announced between Westport and Scania to develop the HPDI system for hydrogen fuelling[25]. This evidence leads to an overall picture of growing international interest in this technology area. There is potential for the UK to build world-leading capability in this area of traditional R&D strength. However, while significant progress is being made globally, development in the UK is restricted by a lack of funding for R&D in this area.

25 Green Car Congress (2021) *Westport Fuel Systems & Scania Partner on Direct-injected Hydrogen Engine Research Project*. Available at: https://www.greencarcongress.com/2021/01/20210122-westport.html (Accessed: 15 April 2021)

Figure 12: Geographical distribution of research papers published between 2015 and 2021

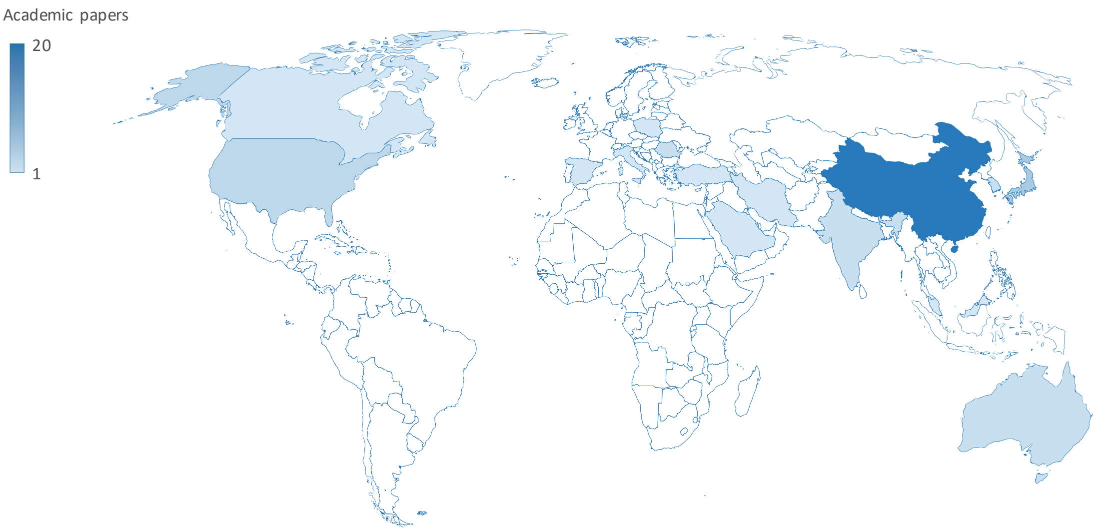
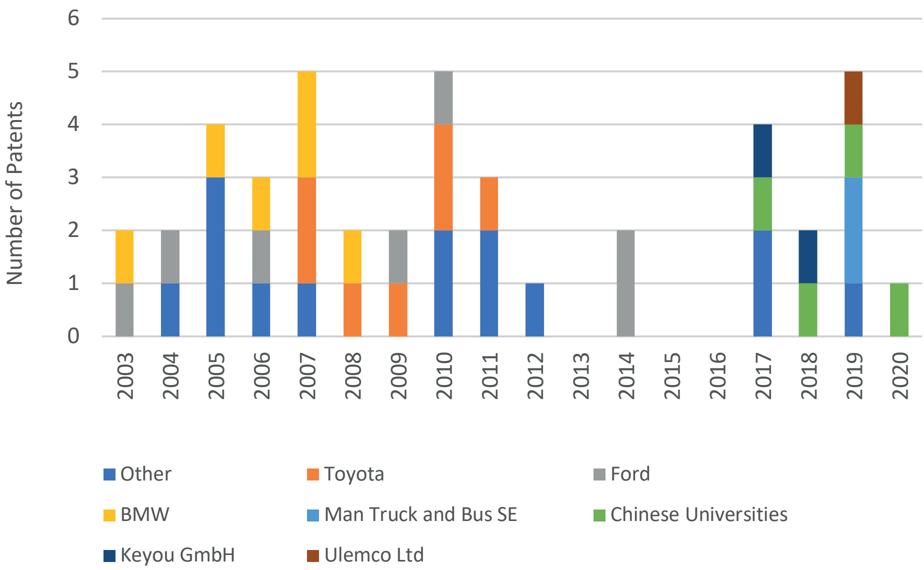


Figure 13: Analysis of patent filings for hydrogen combustion engines and associated components




H2

CONCLUSIONS AND RECOMMENDATIONS

Recent technology roadmaps indicate that heavy duty hydrogen fuel cells may not reach mass market until 2040. Combined with low penetration of battery electric vehicles in this sector and a slow increase in production volumes of sustainable replacements for fossil fuels, there is a real risk that no significant progress will be made to decarbonise the heavy duty vehicle sector until after 2040.

Research to date suggests that H2ICE would have near zero NOx emissions and therefore fulfil the requirements for both carbon and air quality emissions for future transport solutions. Current data also indicates that H2ICE could have lower costs and lifecycle emissions than H2FC. Fuel consumption data for both technologies indicates that they have similar efficiencies, although H2FC is more efficient at lower loads and H2ICE has better efficiency at higher loads. This means that H2ICE could be more favourable for higher power output applications like articulated trucks, while H2FC could be preferable for lower load applications like buses.

Compared to H2FC where significant technical and commercial risk remains for introduction in the HD market, introduction of H2ICE presents a relatively low risk due to the incremental change compared to existing technology and mature supply chain. Therefore, in the short to medium term H2ICE could accelerate decarbonisation in the HD sector, and potentially provide a long-term solution for some applications, depending on longer-term technology performance of both technologies. Additionally, development of H2ICE within the UK could accelerate the roll out of hydrogen infrastructure, build world-leading R&D capability and repurpose the pre-existing ICE supply chain, safeguarding highly-skilled jobs across the UK.

The authors therefore make the following recommendations to support fastest possible decarbonisation in the heavy duty sector:

- **Investigation of real world efficiency of heavy duty freight vehicles for both H2FC and H2ICE is required.**

  Comparison of efficiency/fuel consumption between H2FC and H2ICE vehicles shows that they could have similar efficiency. However, there is a lack of robust data on fuel cell efficiency as part of a vehicle system.

- **Analysis of lifecycle emissions for heavy duty H2ICE and H2FC is required, taking into account higher load duty cycles and more demanding durability requirements of heavy duty applications.**

  Data in the literature indicates that lifecycle emissions for H2ICE passenger cars could be lower than for H2FC vehicles, but data for heavy duty vehicles is not present.

- **Funding competitions and incentives for net zero emissions vehicles should be technology neutral.**

  Further R&D is needed for both H2ICE and H2FC systems to meet market and environmental requirements for heavy duty vehicles. To ensure the most competitive zero emissions technology is developed, funding for development and adoption should be based on vehicle performance rather than technology type.

APPENDIX

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University of Brighton Advanced Engineering Centre (AEC) is an internationally-recognised centre of research excellence with an established track record of pioneering research in applied thermofluids, including automotive engineering, heat transfer, sprays and two-phase flows. We work alongside global academics, industry leaders and policymakers to significantly impact the transportation, aerospace and medical sectors. Our automotive research is focused on efficient, zero emission sustainable propulsion and sustainable fuels across different sectors. www.brighton.ac.uk/aec

The group was selected to host the Advanced Propulsion Centre Spoke for Thermal Propulsion Systems Thermal Efficiency in 2015, which works to support the thermal propulsion system community bringing together specialist academic, technological and commercial expertise to share best practice for the development of low emission propulsion technologies.

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Glossary

Air path
The route air takes through an internal combustion engine, intake – cylinder – exhaust

CO
Carbon monoxide

Homogenous charge compression ignition
A form of internal combustion engine where well-mixed fuel and air are compressed until auto ignition

HDPI CNG engines
High Pressure Direct Injection: engines with high pressure injection of fuel directly into the cylinder

Knock
Engine noise and vibration caused by adverse combustion phenomena

Lean combustion
Combustion with excess air compared to stoichiometric combustion

Lifecycle emissions
Emissions assessed over the complete vehicle lifecycle, including vehicle production, operation and end of life

NOx
Nitrogen oxide emissions, including both nitric oxide (NO) and nitrogen dioxide (NO2)

OEMs
Original Equipment Manufacturers (e.g. vehicle manufacturers)

PEM fuel cells
Polymer Electrolyte Membrane fuel cells, developed mainly for transport applications with hydrogen fuel. The discussion in the report refers only to PEM fuel cells

Pumping losses
Energy required to move air in and out of the combustion chamber

Stoichiometric combustion
Combustion where there is just sufficient air to burn fuel completely

Tier 1s
Companies that supply components to OEMs


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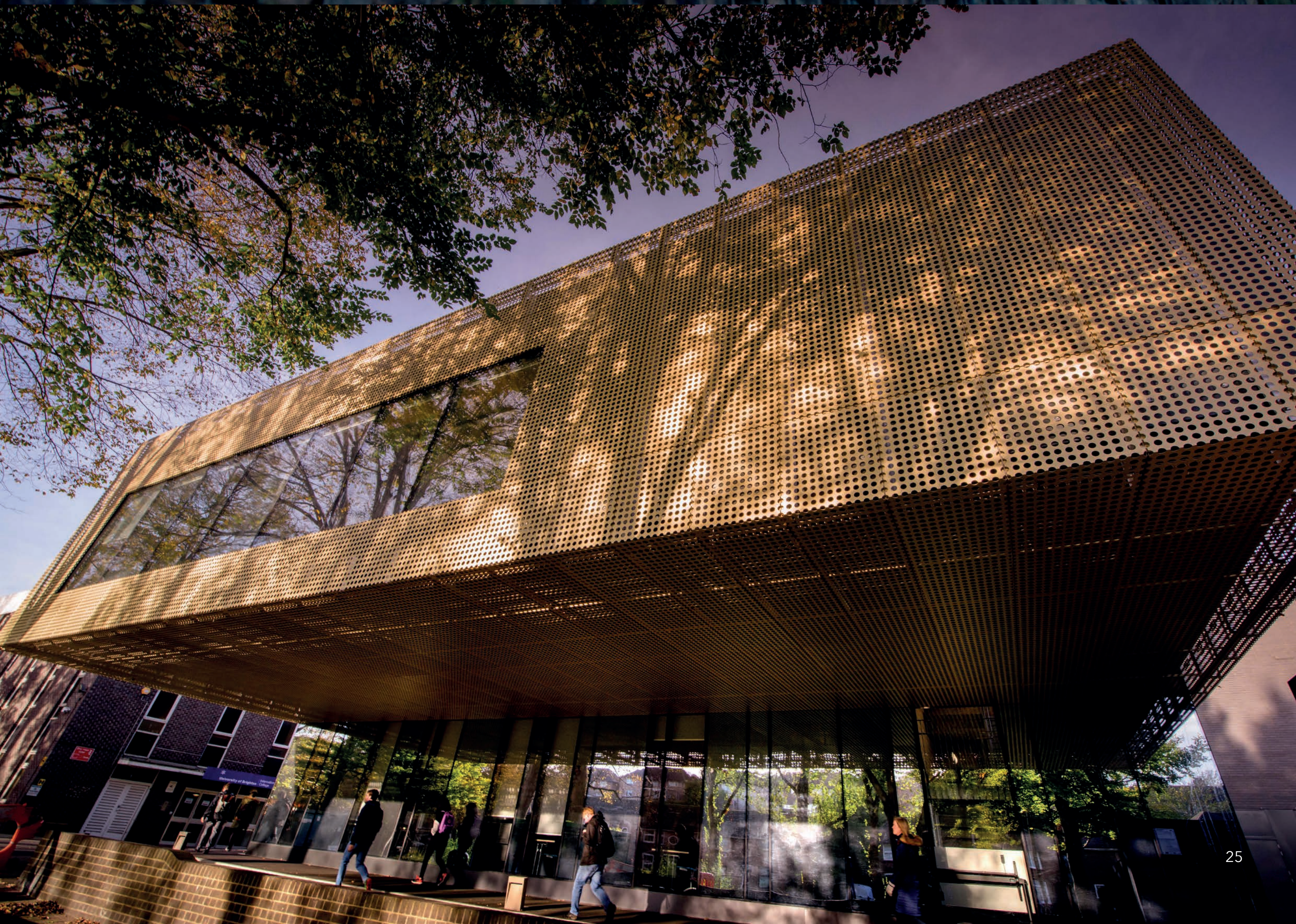
OF BRIGHTON
Advanced Engineering



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