HYDROGEN INTERNAL COMBUSTION ENGINE SUB-GROUP

Powering Growth: The role of hydrogen internal combustion engines in non-road mobile machinery

Prepared for:

The Hydrogen Delivery Council, the Department for Energy Security & Net Zero

This is a report from the Hydrogen Internal Combustion Engine Sub-Group, a task and finish activity of the Off-taker Working Group of the Hydrogen Delivery Council.

This report is provided to the Hydrogen Delivery Council and the Department for Energy Security & Net Zero on the current state of commercial, scientific and technical knowledge related to the performance, emissions and safety characteristics of hydrogen-fuelled internal combustion engines used in non-road mobile machinery (NRMM). The information contained within the report represents a review of understanding and evidence available at the time of writing (2024).

This report represents the views of the Hydrogen Internal Combustion Engine Subgroup and its members and does not represent the views of the Department for Energy Security & Net Zero or the UK Government.

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Executive Summary

This report provides the output of the “Hydrogen Internal Combustion Engine Subgroup” an industry-led “Task and Finish Group” convened by the Department for Energy Security and Net Zero (DESNZ) for the Off-taker Group of the Hydrogen Delivery Council (HDC) who, during the first half of 2024, were charged with the job of considering the latest evidence on the role of hydrogen internal combustion engines (H2ICE) as a decarbonisation option for diesel engines, primarily in non-road mobile machinery (NRMM).

The scope of this industry-led process was to focus on the opportunities and challenges associated with the **application and use of hydrogen in internal combustion engines in the NRMM environment** and make recommendations on how these issues might be addressed. It should be noted that the wider, supply-side considerations such as production, transport and distribution of hydrogen is out of scope, being the responsibility of other HDC sub-groups.

Importantly, the specific examination of H2ICE’s role in the NRMM sector, which is considered one of the hardest to decarbonise, stems from industry’s concern that the generally held assumption within policymakers that decarbonisation technologies are largely electric, either battery or hydrogen fuel cell, and the consequent belief that there is no role for combustion engines in the net zero future, will both risk delivery of targets by 2050 and lead to significant negative economic impacts in the transition, if not addressed.

It is strongly recommended that H2ICE is accepted as an appropriate net zero emissions technology for rapid decarbonisation of the NRMM sector with the co-benefits of significantly improved air quality.

Given the level of reduction in both GHG and regulated emissions available, it is also recommended that H2ICE should be considered a net zero emissions technology for other sectors including on-road applications.

Facilitated by DESNZ and observed by other government department officials, senior representatives from across the sector including original equipment manufacturers (OEMs), key component suppliers, end users, trade bodies, independent experts and academia, assessed the current available evidence on:

- The economic importance of the sector, its stand-alone value and wider impact on whole of the UK economy
- The technical challenges to decarbonisation and delivering Net Zero by 2050, in the sector.
- The specific opportunities that H2ICE can provide in this challenge, particularly in relation to:
    - Addressing the heavy-duty performance and efficiency requirements of equipment used in the sector
    - The extent of its technical ability to deliver GHG reduction and improve air quality

- Finding ways to mitigate the significant inflationary risks of the move to Net Zero
- Ensuring that the sector has access to proven, scaled technology within the timescales for Net Zero
- Mitigating the risk to jobs and the cost of re-skilling in the sector and its supply chain as a result of the transition
- Providing early-stage demand for hydrogen, to accelerate the delivery of the benefit to the wider energy system of the hydrogen economy

H2ICE is considered to be the least inflationary approach to delivering decarbonisation at scale in the NRMM sector and within the timescales of net-zero.

This will also offer a great opportunity to kick-start demand for hydrogen, both within the sector and the hydrogen economy as a whole, in support of the immediate ambition for clean growth in the UK-wide economy.

From an economic perspective, it is estimated by the ONS[1] that the NRMM sector is worth over £17.6B to the UK in 2022, with over 83% of revenue from export and employing around 100,000 people (~31,000 direct and 68,000 indirect). It represents a significant pillar of the UK economy. This significant revenue comes from key global manufacturers with 9 equipment manufacturers including JCB, Volvo Construction Equipment, Caterpillar and Case New Holland together with a range of Tier 1 suppliers (engines, parts and accessories) such as Cummins, Perkins (Caterpillar), Johnson Matthey, BorgWarner and JCB engines.

In this context, it is important to note that NRMM encompasses a wide range of machinery and equipment that is not intended for use on public roadways, including:

- Construction machinery (e.g. excavators, bulldozers, cranes)
- Agricultural machinery (e.g. tractors, combine harvesters)
- Forestry machines (e.g. forest forwarders, chippers)
- Industrial machinery (e.g. forklifts)
- Mining machinery (e.g. shovels, RDTs)
- Access equipment (e.g. AWP, scissor lifts)
- Railway engines
- Generators

With such a vast range of applications and sectors where NRMM is used, these machines are fundamental to the national agenda for growth and infrastructure development, alongside the value and impact the industry has on the UK economy as a whole. Change, particularly that needed to deliver decarbonisation, presents significant risks in terms of jobs and economic capability, so ensuring that the sector continues to function practically through and post the energy transition, is critical for the future.

[1] References are provided in relevant sections of the main body of this report

This equipment operates in hugely varied environments, with very different duty cycles ranging from relatively low energy requirements, operating only a few hours a day, to 24-hour operation at high energy. These duty cycles have a direct influence on the appropriate power system. Many of the low energy, low hours machines (and some medium duty machines) are suitable for electrification, but other propulsion/power systems need to be considered as the load factor increases and environments become more demanding or complicated, such as:

- Machines that are first on site and must operate with no services provided
- Mobile machinery that needs mobile fuel delivery to keep working
- Machines that aren't working due to a refuelling difficulty/breakdown means construction stops
- Machines need to be robust, and not too complicated for the job they do
- Machines that are nomadic – continuously moving onto the next job site (wherever in the world that is) need their fuel to be available wherever they are deployed

These challenges put NRMM applications squarely into the hard to decarbonise box in the Net Zero challenge. The diesel engine is currently almost ubiquitous as the prime mover for NRMM but no "one-size-fits-all" solution for decarbonisation is expected in the future and a balanced portfolio of solutions will be required to effectively decarbonise; in particular making sure that the solutions can deliver scale and robustness, cost-effectiveness, and meet as many as possible of the practical requirements of the applications, in the timescales, without driving inflation or limiting growth.

In this context, the subgroup focused on the evidence showing why internal combustion and hydrogen internal combustion engine machines will more than meet the needs of decarbonised solutions for the applications, specifically focused on:

- Efficiency
- Performance
- Emissions (greenhouse gases and air quality)

In addition, the practical and economic benefits for the transition to hydrogen in these applications are considered. The opportunities identified and conclusions from the evidence are that:

1) H2ICE represents the least inflationary technology for decarbonising NRMM applications. From a business case perspective (hydrogen availability and supply costs aside) H2ICE powered equipment will have a similar capital cost to existing equipment, that is within the scope of "normal" price inflation/improved product development changes, as well as similar maintenance and cost to current equipment. Their durability and robustness will also have a similar depreciation model, and alongside the opportunity for repowering and upcycling, there is significant opportunity to limit the impact on asset replacement programmes and capital investment needs within the net zero transition and therefore represents the most likely solution for zero-emission NRMM technology that will mitigate the inflationary risk of the transition to Net Zero.

2) H2ICE represents the most likely solution that could be deployed in the appropriate applications at scale and in the timescales of Net Zero. All the current decarbonisation technologies are at an early stage in terms of technology readiness and demonstration in NRMM applications. However, the familiarity and the proven match of ICEs to the application performance requirements, coupled with the existing manufacturing capabilities and supply chain at scale means that H2ICE could be the most easily and swiftly deployed at scale.

3) The hydrogen ICE can deliver efficiency and performance on parity with or in excess of that achieved by current hydrocarbon-fuelled internal combustion engines i.e. >40% Brake Thermal Efficiency (BTE) with sufficient power and responsiveness.

4) H2ICE could eliminate CO_2 emissions *and* greatly reduce emissions of NO_x and fine particulate matter (PM) to a level where their contribution to poor air quality could be regarded as insignificant.

5) The public health benefits of the resulting improvement in air quality would be greatest in urban centres, but with broader environmental benefits via reduction in national and transboundary emissions, reduced secondary ozone and PM pollution formation, and reduction in nitrogen deposition and ecosystem impacts.

6) If supported and positively endorsed as a Net Zero solution, H2ICE represents the best opportunity to mitigate the risk of job losses and retention of skills in the transition. By leading and embracing the UK's already globally leading industry with 80% of its revenue today from exports, there is a significant likelihood that first mover advantage will help both to attract talent to fill current skills gaps, and generate disproportionate benefit to UK economic growth, influence and standing from the transition.

7) H2ICE could help accelerate the overall development of the hydrogen economy and the wider energy system benefits that can accrue from implementing hydrogen sooner rather than later. This is due to the high energy demand in the sector and therefore potential volumes of hydrogen that could be used, associated with a technology that is nearer to proven than other technologies.

The group especially noted that it was critically important to recognise that H2ICE should not be considered as a competitor to hydrogen Fuel Cell (H2FC) technology, but rather as a complement to it, exploiting established supply chains and existing production infrastructure, whilst partnering in shared components associated with H_2 fuel delivery. This complementary approach covers a wide range of applications working at different loads. However, some comparisons are inevitably made, and these are supported by data and evidence in the relevant sections where necessary.

When coupled with the UK's leading position on ICE engine research, development and manufacture, H2ICE represents:

- The minimum change option when compared to other technologies; and
- The maximum opportunity to establish the UK as leaders in H2ICE, protect existing jobs in the manufacture and supply chain

- A potential kick-start for the hydrogen economy through leveraging the existing manufacture and supply chain and the proven robustness of ICEs in this demanding application

These impacts, when taken in combination, indicate that the hydrogen ICE represents a major opportunity for NRMM decarbonisation, while delivering immediate improvements in air quality and public health, estimated to deliver savings of £150 m to £505 m per year in environmental and health care costs and as a consequence it is strongly recommended that H2ICE is accepted as an appropriate technology for rapid decarbonisation with the co-benefits of significantly improved air quality, and that:

- H2ICE should be classified and actively promoted as a net zero emission technology for NRMM, recognising that the conclusions from this report are equally applicable to other sectors including on-road applications
    - This will send a clear signal to the industry that investment in this technology is meaningful and will result in new areas of research and development that will further cement the UK's position as leaders in ICE technology
- Further to the above, NRMM using H2ICE to be classified as net zero emission machines
- Ensure emissions regulations and standards are reviewed and updated to ensure "best in class" emissions (GHG and air quality) taking into account any future EU/international regulations
- A voluntary NRMM standard, based on EU Stage V procedures, is established to ensure that all H2ICE achieve the very low NOx and particulate emissions performance detailed in this report
- Establish regulation and new forms of contract in the construction industry in order to recognise and reward low emission solutions, and that construction projects measure and pay for emissions
- Create consistent, harmonised planning regulation/best practice/shared learning on hydrogen safety and on-site requirements
    - Ensure consistency of assessment
- Develop tax breaks and financial incentives specifically for NRMM if the pace of change is to be accelerated
    - Establish security of supply for hydrogen fuel as defined by the low carbon hydrogen standard
    - Establish pricing mechanisms to offset the price differential with diesel

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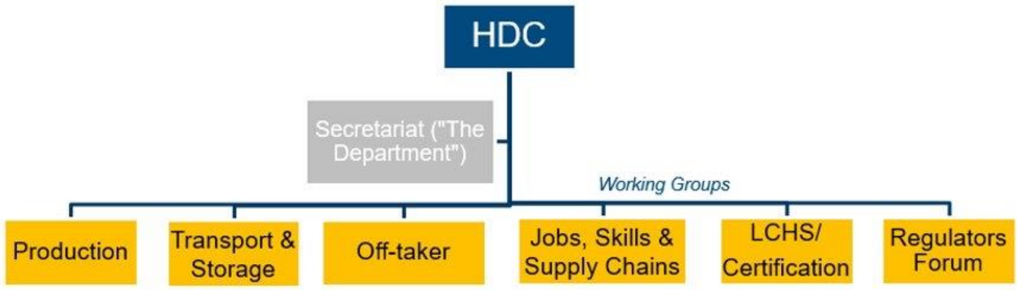
1. Introduction and Background

The Hydrogen Internal Combustion Engine Subgroup is an industry-led task and finish group convened by the Department for Energy Security and Net Zero (DESNZ) reporting to the Off-taker Working Group of the Hydrogen Delivery Council.

The Hydrogen Delivery Council (formerly the Hydrogen Advisory Council) was set up to inform and advance the development of hydrogen as a strategic decarbonised energy carrier for the UK. The Hydrogen Delivery Council (HDC) oversees several Working Groups which reflect key workstreams and are an important forum for official level engagement with representatives of the hydrogen sector.



The HDC Off-taker Working Group's objectives are to:

- Identify barriers to the offtake and end use of low carbon hydrogen across a variety of sectors this decade. In particular:
  - Identify which barriers are primarily for government to address, and which are for industry.
  - Recommend actions for how to address these barriers.
- Provide a forum to share intelligence and best practice amongst prospective end users.
- Ensure the considerations of end users are considered in policy making and strategic planning across the H_2 value chain.

In December 2023, following a request from the former Secretary of State, the Department for Energy Security and Net Zero (DESNZ) convened an industry-led working group to share and consider evidence on the role of hydrogen internal combustion engines (H2ICE) as a decarbonisation option for diesel engines, primarily for non-road mobile machinery (NRMM).

The group was formed as a time-limited task and finish group which, upon completion, would present a report and recommendations to the Hydrogen Delivery Council. The group operated as a subgroup of the Off-taker Working Group within the HDC. Eight meetings were held, from December 2023 through to July 2024.

Though convened by DESNZ, the group was wholly industry-led with senior representation from across the H2ICE sector including original equipment manufacturers (OEMs), key component suppliers, end users, trade bodies, independent experts and academia. Professor Steve Sapsford of Sapsford Consulting Engineers Ltd. and Amanda Lyne of ULEMCo co-chaired the group throughout and agreed the terms of reference, cadence, and outputs with the group members. Administrative and secretariat functions were provided by DESNZ, and meetings were observed by officials from across government. A list and short biographies of authors, contributors and editors involved in the creation of this report are shown in Appendix 3. A full list of the group's members and participants is available in Appendix 4.

The nature of the group's outputs was decided by the membership and, in accordance with HDC Terms of Reference, do not require publication or an official government response. Government welcomes the evidence the group develops and will closely consider all recommendations made, though does so without prejudice to any future policy decisions.

1.1 Scope of Task and Finish Group

As this group was established by DESNZ, the primary focus was on H2ICE in NRMM noting that the Department for Transport (DfT) holds policy responsibility for on-road vehicles. However, as an industry-led group, DESNZ did not seek to limit the scope of discussion and encouraged members to consider evidence and identify barriers related to H2ICE as decarbonisation option for all diesel engines where appropriate. So, while the focus of this report is non-road mobile machinery, it is encouraged that the evidence presented here is considered for on-highway policy.

According to the structure of the HDC, the H2ICE task and finish group's role was to focus on the issues and challenges associated only with the ***application and use*** of hydrogen in internal combustion engines in the NRMM environment. Consequently, no consideration of hydrogen production, transport and distribution has been included here as those are the responsibility of other HDC sub-groups. The focus of this group was the use of hydrogen once delivered to the "site". Consequently, it has been assumed that the hydrogen supplied to the site will conform to the UK Low Carbon Hydrogen Standard[2].

Similarly, although relevant comparisons are made where appropriate in order to provide context for alternative uses of the delivered hydrogen, the conclusions do not encompass a commentary on the specific role of fuel cell electric vehicles/machines in NRMM applications as these were out-of-scope for this group.

[2] UK Low Carbon Hydrogen Standard - GOV.UK (www.gov.uk)

1.2 Non-Road Mobile Machinery – NRMM

NRMM encompasses a wide range of machinery and equipment that is not intended for use on public roadways. A more complete description is included in Section 4 but, in summary, this category includes, but is not limited to:

- Construction machinery (e.g. excavators, bulldozers, cranes)
- Agricultural machinery (e.g. tractors, combine harvesters)
- Forestry machines (e.g. forest forwarders, chippers)
- Industrial machinery (e.g. forklifts)
- Mining machinery (e.g. shovels, rear dump trucks)
- Access equipment (e.g. aerial work platforms, scissor lifts)
- Railway locomotive engines
- Generators

NRMM is subject to specific regulations, particularly concerning emissions and environmental impact. These regulations aim to reduce pollution and enhance air quality by setting limits on the emissions of nitrogen oxides (NO_x), particulate matter (PM), and other pollutants from these machines. These are separate from road-going machines and the current best/lowest levels are prescribed by the European Stage V non-road emission standards. It should be noted that some non-road machines do occasionally drive on the road. These machines do not have to comply with both on- and off-highway regulations. A non-road machine that is driven occasionally on the road (e.g. tractors and backhoe loaders) has to comply with non-road Stage V emissions regulations.

It is estimated that the industry is worth over £17.6B to the UK in 2022 with over 83% exported and employing around 100,000 people (~31,000 direct and 68,000 indirect) and so represents a significant pillar of the UK economy[3] [4].

This significant revenue comes from key global manufacturers with 9 equipment manufacturers including JCB, Volvo Construction Equipment, Caterpillar and Case New Holland together with a range of Tier 1 suppliers (engines, parts and accessories) such as Cummins, Perkins (Caterpillar), Johnson Matthey, BorgWarner and JCB engines.

With such a vast range of applications and sectors where NRMM is used these machines are fundamental to the national agenda for growth and infrastructure development.

[3] Office for National Statistics ABS Approximate GVA
[4] Office for National Statistics SIC 29 Jobs multiplier (2024)

2. Objectives

The objectives of the group were:

- To provide a forum for industry to share and consider evidence on the role of hydrogen combustion as a decarbonisation option for diesel engines.

- To identify barriers to the use of hydrogen combustion as a decarbonisation option for diesel engines and recommend actions to address these barriers.

- To generate a report and accompanying presentation for submission to DESNZ detailing he groups findings, evidence and recommendations.

Although some comparisons with alternative uses of hydrogen in NRMM are inevitably made, this group has been technology agnostic. It is clear that there is no “one-size-fits-all” solution and that a balanced portfolio of solutions will be required to decarbonise this complex sector effectively.

3. Approach

The group held an initial workshop in order to identify the key opportunities and challenges that needed to be addressed and then formed focus sub-groups to gather and summarise data and evidence between meetings and summarise at the next monthly whole-group meeting. The four 4 key areas identified were:

- Performance and efficiency

- Emissions (both greenhouse gas emissions and air quality)

- Practicalities

- Impact

Upon completion, all contributions were compiled together with conclusions, recommendations and policy intervention suggestions into this report and accompanying presentation.

4. The NRMM Sector

The NRMM sector represents a huge variety of machines and applications ranging from construction equipment, agriculture, mining and power generation as described above. The diesel engine is currently almost ubiquitous as the prime mover for NRMM but a brief description of *some* example use cases are given in the following sections in order to provide context regarding the variety of applications.

4.1 Construction Use Cases

Construction vehicles characterised into compact, mid-range, and heavy line machines, range from less than 4 tonnes to greater than 27 tonnes as shown in Figure 1. Compact machines often work in urban locations, with access to existing infrastructure. They support building work and are left on site, operating for around 25% of the working day. Wheeled, mid-range machines typically travel to sites and can work for up to 15 hours per day. These machines drive along roads to frequently moving construction sites and often limited opportunity to refuel on site. Heavy-line machines are the highest utilised equipment. They can run for multiple shifts and are used in large infrastructure construction projects, as well as quarrying operations. In road construction, worksites move rapidly, and these vehicles are trailered to site and refuelled with a fuel bowser.

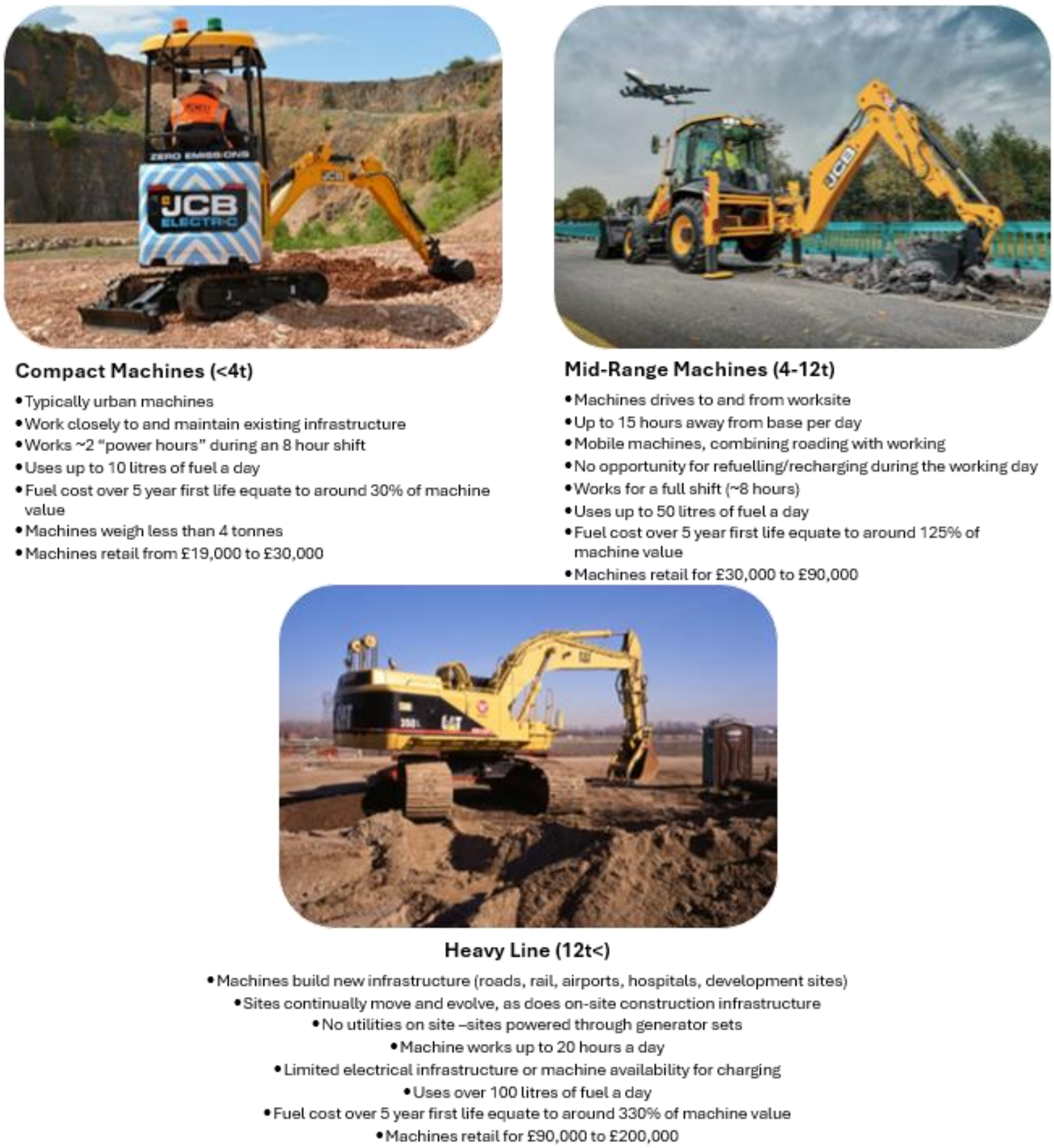


Figure 1: Examples of construction machines and applications in NRMM

4.2 Agricultural Use Cases

There are also a wide range of different mission profiles in the agricultural sector as shown in Figure 2. The type of farm, driven primarily by the location, will determine how equipment is used. Today, diesel is delivered to farms in tankers. Net zero fuel sources in the future will need to allow for the differing user cases and may be farm specific. Many farms are remote with poor electricity grid connections. They may not currently have natural gas connections (a different fuel option) and new infrastructure may be prohibitively costly to install.

Alternative combustion fuels will need good access to feedstock. Cattle farms or vegetable processing plants may have sufficient feedstock for bio-methane production, a potential carbon negative solution, but seasonal variation may mean that that demand exceeds supply at peak times.

Figure 2: Examples of agricultural applications in NRMM

4.3 Power Generation Use Cases

Power generators fall into 3 main categories as follows:

Portable Generators

Portable generators are designed to provide temporary electrical power to power tools, appliances, welfare units and lights at remote sites. They tend to have relatively small power outputs and typically run on fossil fuels, designed for home, small businesses or smaller temporary installations.

Standby generators

Standby generators provide emergency power when the main electrical power system fails, typically in critical environments such as medical installations, critical infrastructure installations, data centres etc. They can sense a drop in power on the grid and rapidly start up to restore power within a few seconds. They often need a locally stored fuel supply to allow then to run for several days. Standby generators can vary significantly in capacity, from small units providing around 7-20 kW for residential use to large industrial units capable of generating several megawatts (MW) of power.

Industrial/mobile gensets

Mobile gensets are used extensively on construction sites. It is often not possible to get a grid supply to the site due to location and, in some cases (e.g. road building), a constantly moving location. Even where the site will eventually have a grid connection some work must be carried out to get this in place and the final connection may not have sufficient power for the construction work. Power is needed for items such as welfare units, communication equipment lighting, electrical equipment such tower cranes and charging small battery powered tools and machines. Being able to generate electricity using an on-site energy store will remain an important need for construction sites for the foreseeable future. There are a number of projects underway to use these assets more efficiently.

Large industrial generators are also used to power manufacturing plants, data centres, remote research stations, drilling rigs, rural communities, and other industrial settings to provide power during routine maintenance or as a primary power source. They are essential in remote locations where access to the electrical grid is limited or non-existent.

4.4 The Challenges of Decarbonisation

NRMM operates in hugely varied environments with very different duty cycles as characterised in Figure 3 and Table 1. These duty cycles range from relatively low energy requirements operating only a few hours a day to 24-hour operation at high energy and have a direct influence on the appropriate power system.

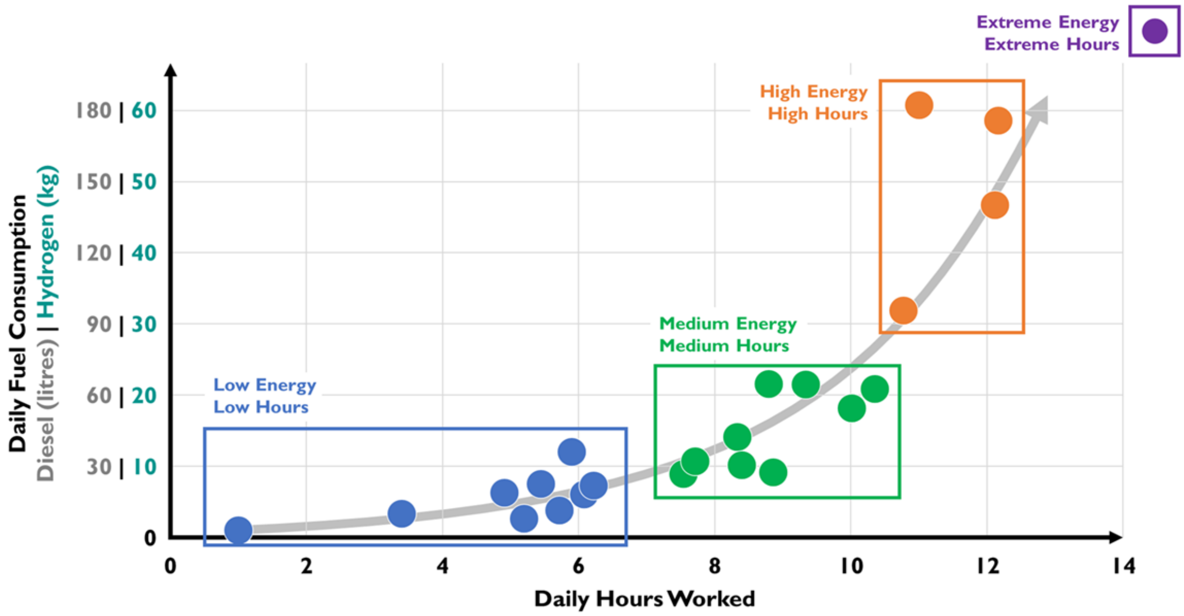


Figure 3: Typical daily hours and energy consumption characteristics for various use cases (Source: JCB). Note vertical scale in litres for Diesel and an equivalent hydrogen mass for comparison.

Use case	**Construction machine description**	**Example construction machine**	**Agricultural machine description**	**Example agricultural machine**
Low energy, low hours	Machines are compact, urban and are transported between sites e.g. a mini excavator		ATV / quadbike or small utility vehicle, fairly easy to refuel or recharge	
Medium energy, medium hours	Machines which are working and on the move all day – they must take everything they need for a day with them e.g. a backhoe loader		General-purpose farmyard tractor or telehandler (e.g. 100 hp)	
High energy, high hours	Machines are large, heavy and perform high power operations, consuming large quantities of fuel over long days, often in remote environments, building new infrastructure e.g.		Heavy duty tractor or specialised sprayer, harvester, etc. (e.g. 300 hp), may be called upon seasonally for 12-14h daily duty cycles several km from home base	

	a tracked excavator			
Extreme energy extreme hours	Power generation provides high power electrical energy, where there is no grid electricity, or the electricity supply is unreliable			

Table 1: Typical use cases for NRMM (construction images sourced from company websites, agricultural images sourced from the NFU)

These are some examples but this list is not exhaustive. Many of the low energy, low hours machines (and some medium duty machines) are suitable for electrification, but other propulsion/power systems need to be considered as the load factor increases and environments become more demanding. For example:

- **Machines may be the first on site, with no services provided**: Users of NRMM repeatedly demand that machines must work in remote locations, ‘off-grid’, from day one of an infrastructure project. When there is absolutely nothing on site, machines must start working. For most sites, tethered electric machines and battery-electric machines will be difficult, unless there is a suitably sized grid connection on, or near site from the start of construction (which must also be installed by a piece of NRMM which is unable to be charged on-site), or a suitably sized ICE-powered generator/large mobile battery pack.

- **Mobile machinery on site needs a mobile fuel delivery to keep working**: While many machines are mobile, it is very rarely appropriate, or possible, for machines to move to refuel/recharge (e.g. tracked machines) – therefore energy must be brought to those machines. Typically, machinery is refuelled using mobile fuel tanks known as “bowsers”, which are brought to site and left in-situ or taken directly to machines. Often the least mobile machines are also the highest consumers of fuel (e.g. large, tracked excavators), which means a large quantity of energy needs to be transported to the machines rather than the machine to the fuel as is customary in the automotive sector (public filling stations or private fuel depots).

- **When machines don’t work construction stops**: Owners and users of NRMM also want machines which are always available to work when needed. Machines must work around required on-site activity, rather than on-site activity fitting around machine availability. This would make battery-electric machines, which rely on planned, coordinated charging time, more difficult to deploy (assuming customers can get sufficient grid-powered megawatt chargers on site, rather than ICE-powered gensets). Machines need to refuel/recharge quickly (in around 10 minutes) and get back to work, or at least be available. Similar demands are placed on agricultural NRMM, which must carry out field operations in a timely and reliable manner.

- **Machines need to be robust, and not too complicated for the job they do**: Machines are work tools. They must be deployed in harsh environments and, importantly, keep working. When a machine stops, work stops, so robust and reliable machines are crucial for the construction industry. When downtime occurs, it is not always straightforward to recover a machine back to an ultra-clean workshop. The ability to repair a machine quickly on-site is also crucial.

- **Machines are nomadic – continuously moving onto the next job site (wherever in the world that is):** While machines may start life in the UK, in time they often end up working abroad. Machines sold in the UK must therefore be reliable in all extremes of temperature, humidity and dust. The combustion engine has been proven, over decades of use, to be resilient, built to withstand even the harshest environments. User concerns about the second-hand export value of alternative-fuelled machinery is also a factor in the agricultural market.

- **Machines are often rented or leased**: Because the needs of a construction company and their projects varies with time, machines are often rented for the duration of the work. This has implications for the adoption of any new technology or fuel, especially if the capital cost is high; while a new (non-fossil) fuel is inevitable, the H2ICE has the advantage of relatively low capital cost increment over Diesel.

In addition, a critically important performance characteristic for NRMM applications is the ability to respond to rapid torque demand (e.g. lifting a heavy load) from the driver. So-called “transient performance” represents the ability of the power source to change load and/or speed rapidly whilst delivering the required performance and simultaneously retaining appropriate control of emissions. Figure 4 below shows the highly transient nature of a typical NRMM application that the propulsion system has to cope with, often in harsh, dusty environments with high levels of vibration and shock loading.

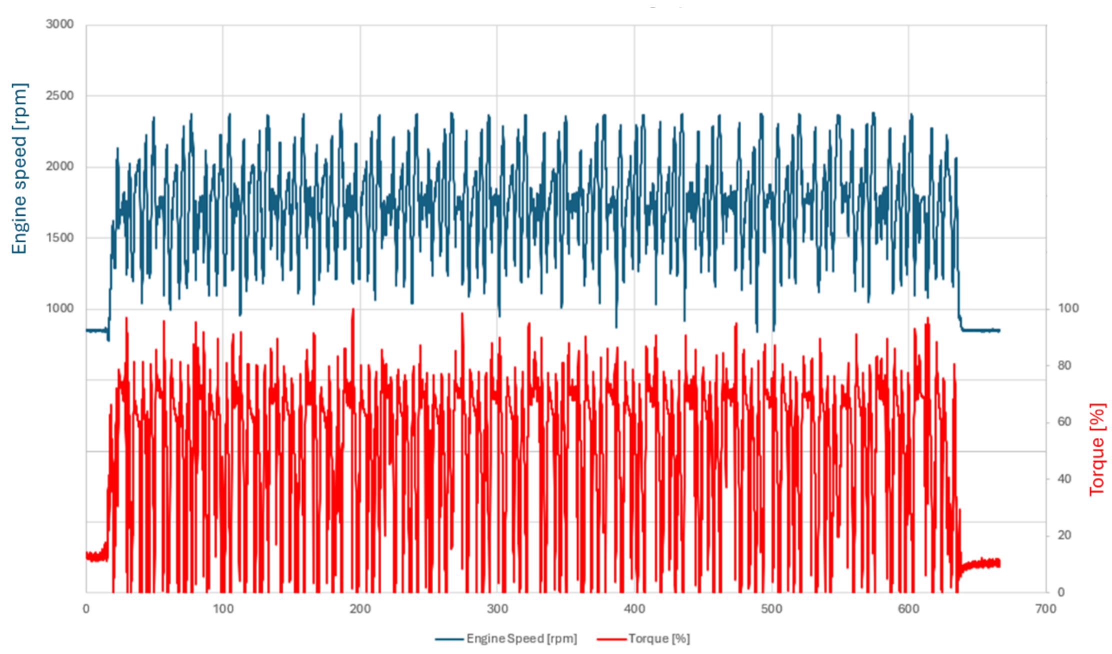


Figure 4: Percentage of maximum torque (red line, right axis) and engine speed (blue line, left axis) demand of a backhoe loader against time (s)

4.5 H2ICE Principles of Operation

Internal combustion engines are hugely successful machines, powering the world's transport, construction, agriculture, shipping and power generation. As a result, an integrated supply chain and infrastructure has developed over the last 130 years to support the design, development, deployment, fuelling and maintenance of these machines. They are able to operate in the harshest environments robustly and reliably with very little supporting infrastructure. Additionally, and particularly for NRMM, they are designed to work with a range of supporting energy transfer systems such as electrical and hydraulic systems.

The hydrogen-fuelled internal combustion engine is essentially the same as one fuelled by liquid or gaseous hydrocarbons such as petrol, Diesel or methane. Fuel is mixed with the air during the intake and/or compression stroke. This mixture is then ignited spontaneously (in the case of Diesel or compression ignition engines) or with a spark (in the case of petrol, methane or hydrogen engines) to release energy that turns the crankshaft to power the vehicle and/or ancillary systems.

Hydrogen has a number of unique properties that make it suitable for combustion, including the following:

- **Wide flammability range**: Hydrogen can be burned in a wide range of fuel-air mixtures. In fact, hydrogen can run on a "lean" mixture, which means the amount of air is more than required for combustion of the fuel. This is important because this results in greater fuel economy and a final combustion temperature that is generally lower, which correspondingly reduces the amount of pollutants emitted via the exhaust. It should be noted that this ability to run very lean represents a new area for research and development and an opportunity for the UK industry to lead the world based on the firm foundations of our existing ICE design and development capabilities, manufacturing base and supporting supply chains.

- **High auto-ignition temperature**: Hydrogen's high auto-ignition temperature enables higher compression ratios compared to a conventional hydrocarbon engine. A higher compression ratio results in greater thermal efficiency, or less energy loss during combustion.

4.6 A Word About Fuel Cells

It is important to consider H2ICE technology with respect to and alongside fuel cell technology. Whilst it should not be considered a competition between H2FC (hydrogen fuel cell) and H2ICE, the comparison of efficiency is often used as a justification for H2ICE not being an appropriate solution.

In reality, both approaches are in relatively early stages in terms of data, development and real-world application. Equally the range and diversity of application requires consideration of the wider system requirements to make the "energy conversion technology" fit for purpose and efficient. Therefore, this simplified dismissal is not helpful in deciding today which is "better" and/or to be ignored.

In Section 5.1 of this report we will highlight that the efficiency of the H2ICE is considerably better than perceived. Furthermore, there are applications, some specific to NRMM, that make H2ICE a preferable solution to fuel cells. Again, the H2ICE should not be considered as a competitor to the hydrogen fuel fell (H2FC), but rather as a complement, in order to exploit established supply chains and existing production infrastructure, and also partner in shared components associated with hydrogen fuel delivery. Some of these characteristics that are known today are highlighted in Table 2.

Hydrogen IC Engine	**Fuel Cell**
• More efficient at high load • Produces mechanical energy directly • Tolerant to air, fuel and coolant contamination • Similar noise to petrol/NG engines • Close to 'zero' emissions at point of use • Durability proven in HD applications	• More efficient at light load • Produce electrical energy (not mechanical) • Require clean air, fuel and coolant • Quiet operation • 'Zero' emissions at point of use • Durability to be proven in HD applications • High heat rejection to coolant (at low temp.)

Table 2: Comparison of H2ICE and fuel cell technology attributes

In NRMM applications the differentiation between fuel cells theoretically high efficiency and that of H2ICE are not clear cut and, in many cases, the H2ICE may be more efficient. This is due primarily to the efficiency of fuel cells being optimal at lower loads (relative to the installed power) whilst NRMM applications tend to be particularly challenging high load and thus high energy consumption applications.

Relatively little public domain data is available for in-use efficiency of H2FC, however, Figure 5 shows a comparison of H2FC and H2ICE efficiency in 2021[5]. As explained in Section 5.1, it is important to compare the *traction* curves (equivalent to brake thermal efficiency) below as these are effectively the power available to do useful work after all the system losses associated with pumps, heat exchangers etc. have been taken into account.

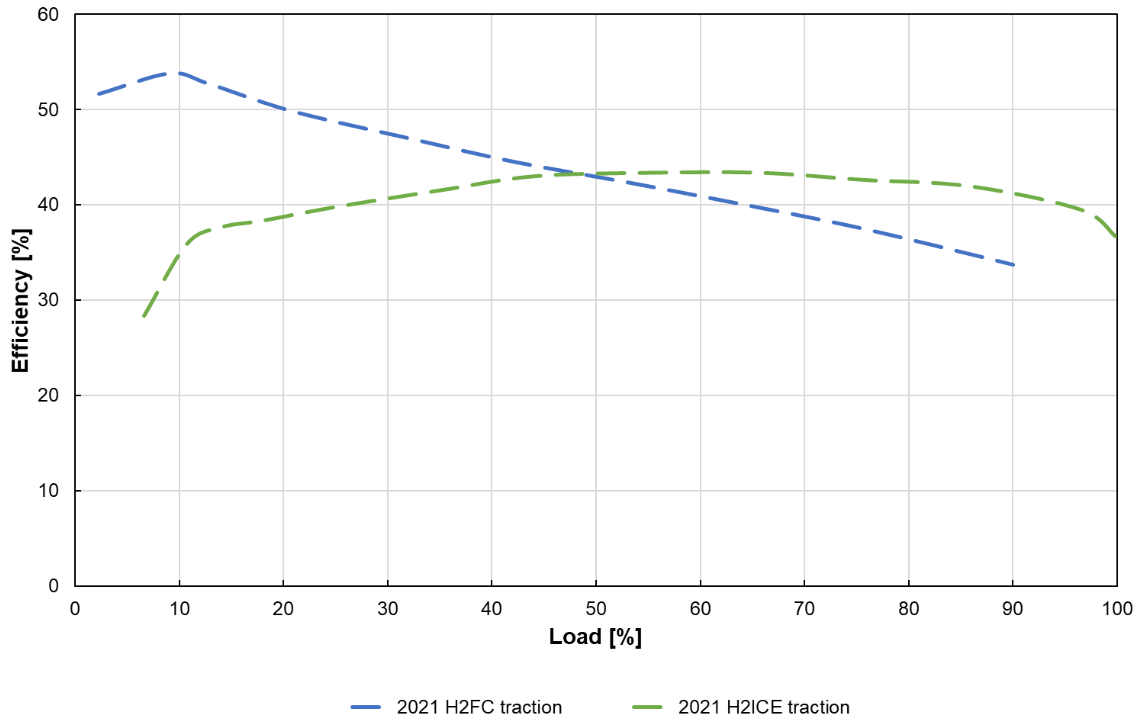


Figure 5: Comparison of H2ICE and H2FC % efficiencies as a function of load.

As mentioned earlier, a critically important performance characteristic for NRMM applications is the ability to respond to rapid torque demand (e.g. lifting a heavy load) from the driver. Fuel cells are not generally able to satisfy these transient requirements on their own and are therefore coupled with a battery system to supplement the fuel cell. The size/capacity of the supporting battery system depends on the frequency and depth of these transient demands and therefore directly affects the cost, weight and the required packaging space on the machine.

PEM fuel cells are also sensitive to the quality of supplied fuel and conditioning of the input air is critical - more challenging to maintain in certain harsh, off-road environments with high levels of dust, vibration and shock loads. Additionally, more work needs to be done on degradation and lifetime of fuel cells, with major refurbishment likely to be required during the lifetime of machines operating in these harsh environments. NRMM is often a tough

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[5] Can hydrogen engines support decarbonisation in the heavy duty sector? 2021 Advanced Propulsion Centre/University of Brighton

application and machines need to be able to operate and be assessed in the real world. ICE has decades of proven and carry-over capability, the only change required to running on hydrogen is the fuel and fuel system.

An additional challenge for large fuel cells (greater than ~50 kW) in NRMM is achieving sufficient cooling, due to the lower operating temperature and limited heat rejection to exhaust of PEM fuel cells compared to ICE. This is further exacerbated in NRMM by the lack of ram air that is available in on-highway applications from the movement of the vehicle through the air. A high-power fan with a corresponding parasitic load can be required for a fuel cell NRMM with a corresponding impact on overall system efficiency.

Development and innovation to address these challenges continues at pace, but it is not yet clear when or how the additional issues of some parts of the NRMM sector will be overcome for widespread fuel cell adoption.

In summary, this indicates that H2ICE is a particularly viable technology for heavy duty applications requiring ruggedised solutions and those that may be susceptible to contamination risks such as heavy-duty trucks, off road machinery, heavy agricultural machines and larger gensets.

5. Perceived Challenges for H2ICE

The perceived arguments against the internal combustion engine and the hydrogen internal combustion engine specifically are focused on:

- Efficiency
- Performance
- Emissions (greenhouse gases and air quality)

The following sections will show that these arguments are not founded on up-to-date, real-world data and evidence, particularly as it relates to NRMM and other heavy-duty applications. In fact, the H2ICE in NRMM is shown to be efficient, powerful and clean.

5.1 Performance and Efficiency

This section will illustrate that modern hydrogen internal combustion engines have efficiencies and performance that are similar to or better than equivalent diesel fuelled engines and, therefore, pose no challenges regarding fulfilling operational requirements.

5.1.1 Base Engine Architectures and Adaptations

Typically, hydrogen engines are currently being derived from existing base engines and are therefore modified from either spark ignition (SI, or petrol), compression ignition (CI, or diesel) or in some case natural gas (NG) derivatives. Research and development are either undertaken on the full multi-cylinder engine as used in the vehicle or machine, or on single cylinder research engines (SCREs) which comprise just one of the multiple identical cylinders, and are an easier tool for laboratory-based research. Future designs of H2ICE will be able to adopt best practice from these research and demonstration programmes to develop hydrogen specific combustion systems. In general, the base engine architectures discussed above have the following characteristics:

- Spark ignition (SI) or gasoline/natural gas engine derived, typically smaller displacement (up to 0.5 L/cylinder) with an angled/pent roof, high tumble engine architecture - normally adopted from automotive application due to the existence of spark plug and ignition system required for hydrogen combustion. However, some HD engine manufacturers have existing natural gas engine variants; These engines have cylinder heads already featuring spark plug integration and normally a gas optimised combustion system. Direct injection (DI) engines can be adapted for hydrogen direct injection relatively easily, by replacing the gasoline DI injector with a suitable hydrogen DI injector.

- Compression ignition (CI) i.e. Diesel engine derived, typically a high swirl diffusive burn combustion chamber design with a piston bowl and tend to have a higher cylinder capacity and run to a lower operation speed. These engines need to be modified to accept a spark plug and/or DI injector. The pistons can be readily adapted to different compression ratios and chamber shapes for better H2 combustion.

5.1.2 Injection Technology

Early derivatives of H2ICE typically utilise port fuel injection (PFI) due to its easy integration into existing engines, low injection pressure requirement and availability of parts. PFI typically leads to reductions in volumetric efficiency due to the displacement of inlet air with hydrogen, which leads to reduced power density. This can be compensated for with a powerful boosting system increasing the volumetric efficiency of the engine and hence how much hydrogen can be burned [9.4, 9.5][6].

Hydrogen direct Injection (H2DI) can provide higher specific power output, improved efficiency and offer better transient response compared to PFI due to the reduced pumping work and lower demands on the boosting system [9.6, 9.7], however the injector technology is still in development and requires engineering to package appropriately.

Despite a relatively short fuel-air mixture preparation window (i.e. ~4-20 ms at engine speeds between 1000-5000rpm), DI presents opportunities for further optimisation of engine control, efficiency, and emissions relative to PFI [9.8-9.10]. In 2009, BMW successfully demonstrated an indicated thermal efficiency of 45% with a 200-bar fuel injection system using DI operation [9.11] strongly outperforming the company's previous PFI approach.

The wide flammability limits and fast burning velocity of hydrogen [9.6] make it an attractive fuel particularly when operated in a lean combustion regime, which allows for a higher compression ratio piston to enable greater thermal efficiency.

Table 3 highlights the available injector technologies, their working ranges, advantages, and challenges. Note specific powers quoted are for heavy duty NRMM applications where engine speed is limited. Higher specific powers can be achieved in high-speed engines i.e. motorsport applications and automotive-derived concepts.

Fuel Injection Technology	**Low Pressure PFI**	**Low Pressure DI**	**Mid Pressure DI**	**High Pressure DI**
Typical Injection pressure (bar)	5~10	15~30	40~60	~300
Typical Specific power for HD Engine (kW/L)	<25	>25	>25	>30
Peak BMEP (bar)	<20	>20	>20	>25

[6] Numbers in square parentheses indicate technical references contained in sections 9 (for performance and efficiency) and 10 (for emissions)

Advantages	• Easy to integrate on existing engines. • Availability of injector hardware	• Power density • Transient response	• Power density • Transient response • Smaller package • Improved mixing	• Could enable CI combustion and higher efficiencies
Challenges	• Reduced power density • Boosting system required • Backfire-mitigation. • Relatively poor transient response	• Injector packaging • Mixture homogeneity	• Injector packaging	• Injector packaging • Source of high-pressure hydrogen
Technology Readiness	Available	Nearing SOP	In development SOP ~2025	In development

Table 3: Fuel Injector Technology attributes for H2ICE

5.1.3 Hydrogen Combustion Approaches

As a fuel hydrogen has a number of unique characteristics compared to the diesel and gasoline that it may replace, these include:

- High gravimetric energy density of ~120 MJ kg^{-1}, which is nearly 3 times that of diesel and gasoline (approximately 42-44 MJ kg^{-1})
- Hydrogen exhibits a very wide flammability range from λ = 0.14 - 10 versus 0.26 - 1.51 for iso-octane, a typical gasoline surrogate [9.6]
- A very low ignition energy requirement of 0.02 mJ compared to 0.28 for iso-octane
- A high stoichiometric air fuel ratio of 34:1 (by mass) relative to ~14 for hydrocarbon fuels
- A very small quenching distance of 0.64mm relative to 3.5mm for Iso-octane.

Most of the above attributes can be advantageous to the combustion process or require minor changes to the engine design to optimise hydrogen combustion relative to hydro-carbon fuel combustion. Table 4 highlights the main approaches for hydrogen combustion concepts that have been studied in research.

Combustion Concept	**Operational impacts**
Pure Lean combustion	Engine is operated with excess air to fuel. Typically λ>2.0 for low engine out NO_x High boost pressure requirement High efficiency achieved

Lean & Exhaust Gas Recirculation (EGR)	Lower boost pressure requirement EGR can help lower engine out NO_x Complexity of EGR system and risk of condensate formation
Stoichiometric combustion	Similar operation to standard gasoline engine Can work with appropriate Catalyst design to minimise tail pipe NO_x High engine out NO_x Higher specific power output Efficiency likely to be lower
Stoichiometric with Combustion moderator	Typically employs water injection For high power applications i.e. motorsport. [9.12]

Table 4: Potential H_2 combustion engine concepts

For NRMM applications discussed in this report it is assumed that the combustion approach adopted would be either pure lean combustion or lean with EGR due to the need to achieve higher thermal efficiencies, minimal engine out NO_x with a lesser need for high power density. The other concepts are however reviewed in some of the literature identified within this chapter.

5.1.4 Engine Efficiency

As with any propulsion/power system, the efficiency of H2ICE is of considerable importance. It impacts the range/operating time of the vehicle due to the technical challenges around volumetric storage of hydrogen as a gas. Currently hydrogen fuel is costly and as such maximising the efficiency is critical to the total cost of ownership (TCO) and the H2ICE value proposition.

JCB have demonstrated their 448, 4-cylinder, 4.8 litre 55 kW engine (a similar base architecture to the current production Diesel Direct injection engine) equipped with a PFI H_2 combustion system. The torque curve for the engine has been matched and the peak efficiency and overall area of high efficiency has been improved on the H_2 converted engine with relatively little engineering effort.

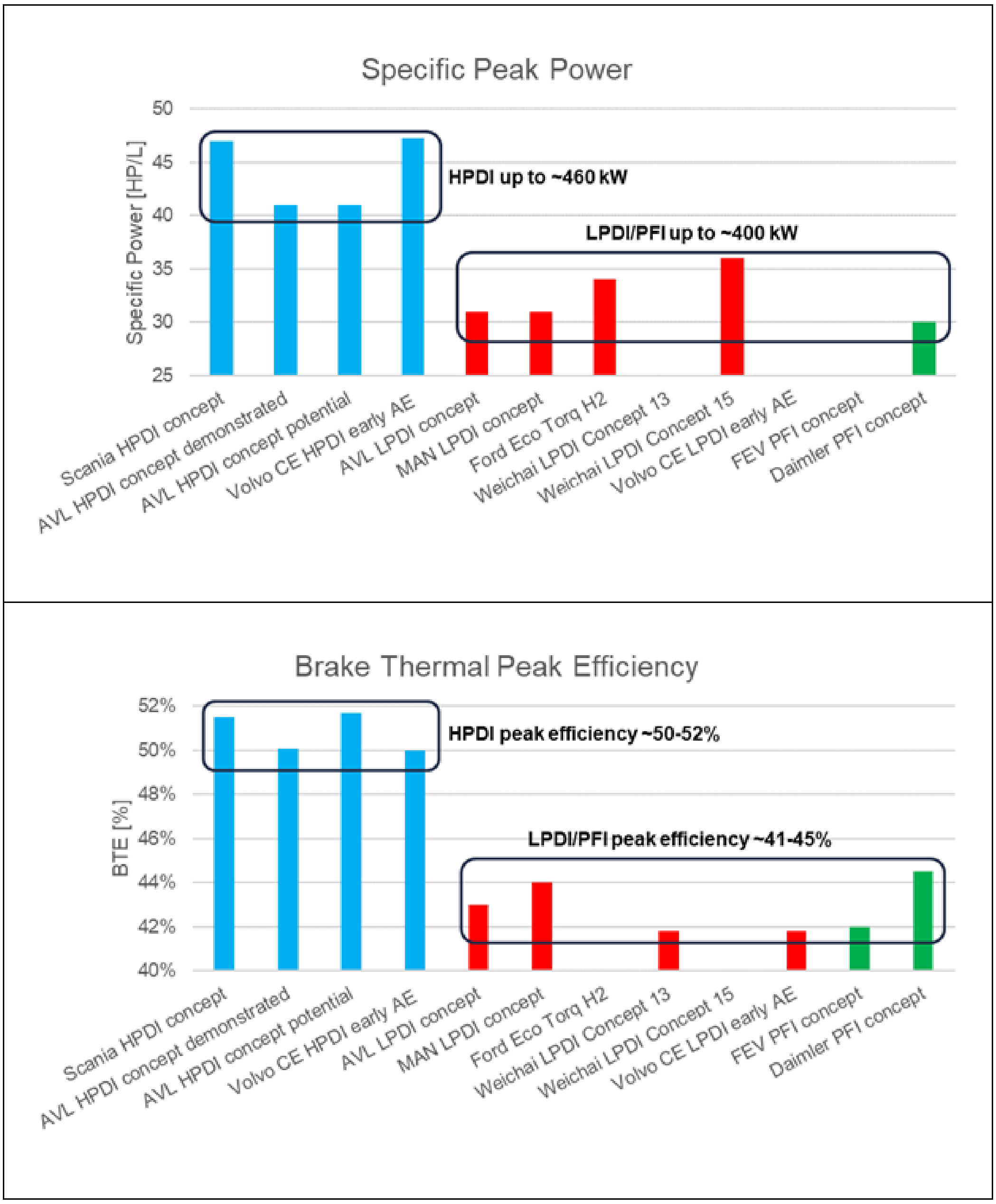

Figure 6: Example power and efficiency data for various engine types provided by Volvo CE

Figure 6 shows example data shared by Volvo Construction Equipment (CE) as part of this review. It highlights the performance difference both in specific power and brake thermal efficiency (BTE, see sidebar) for both high pressure direct injection (HPDI) and low-pressure direct injection (LPDI) and PFI engines. The PFI and LPDI engines have peak efficiencies between ~41-45% whilst HPDI offers a technology pathway to >50%BTE.

Similar data with respect to power density and applied injector technology is presented in Figure 7 for both on road and NRMM applications courtesy of FEV [9.13]. The grey symbols represent DI applications of H2 combustion and the red the PFI applications. It can be noted that on-road (triangles) are typically small displacement 2 L engines (automotive) or a number of on road heavy duty applications. The automotive applications have typically adopted DI, to achieve high power densities, whilst the NRMM are a range of PFI and DI applications.

The **brake thermal efficiency** (BTE) is the ratio of the brake power (calculated from measured torque and speed) at the engine output to the power generated by the combustion of the fuel, calculated from the measured fuel mass flow rate and the calorific value (lower heating value) of the fuel. BTE *includes* the effects of mechanical parasitic losses in the engine such as bearing friction, and ancillary components including the water pump, oil pump, fuel pump and electrical loads. Consequently, the BTE is a more accurate measure of the whole engine system efficiency and is akin to including the "balance-of-plant" in a fuel cell system as opposed to just the fuel cell stack efficiency. For a fuel cell this balance of plant includes the losses associated with components such as pumps, heat exchangers, compressors, recirculation blowers and/or humidifiers needed to condition the intake air and fuel supply to the fuel cell stack. These should be taken into account when comparing efficiencies between the technologies.

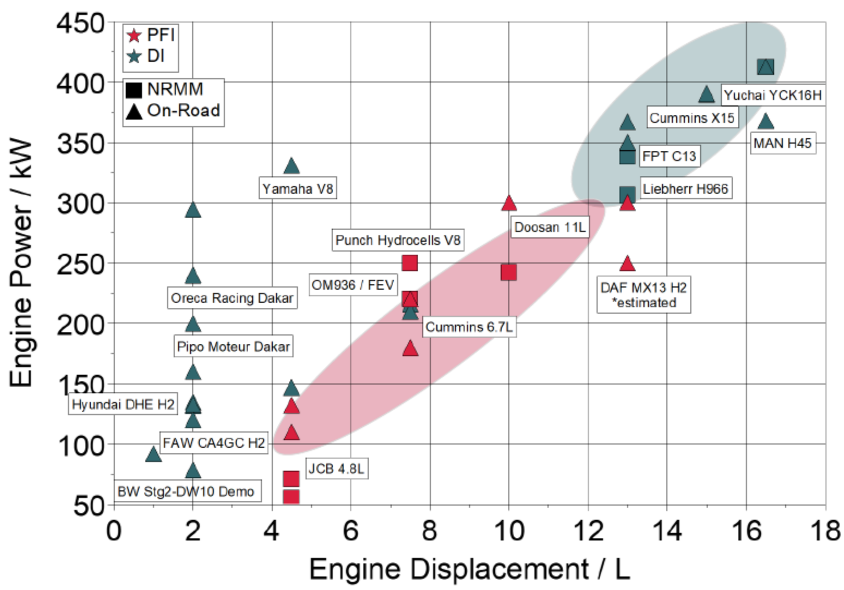

Figure 7: Example H_2 engine development projects as a function of power and engine displacement [9.13]

Figure 8 shows data presented by Achates Power of their novel opposed piston concept engine running on hydrogen fuel for a 13 L heavy duty application [9.14]. This shows brake thermal efficiencies of up to 49% and above 40% for nearly all of the operating map.

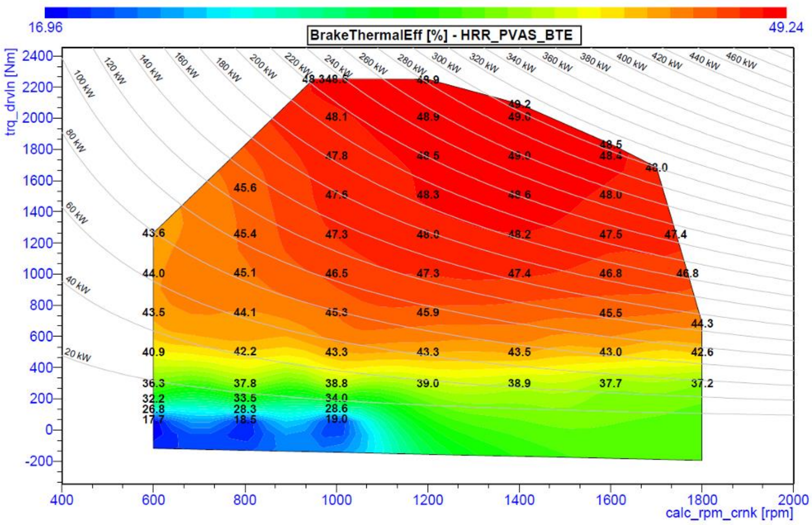

Figure 8: Example brake thermal efficiency data of Achates Power Opposed Piston Engine Concept for a 13 L Heavy Duty Engine Application [9.14]

5.1.5 Engine Performance

The criteria to achieve high thermal efficiency, sufficient power, low NO_x emissions, high combustion efficiency (i.e. all H_2 is burned and little to zero H_2 slips into the exhaust stream), and combustion stability with no abnormal combustion determine the requirements for mixture preparation and consequently the combustion process. Qualitative trade-off characteristics between these requirements for well-mixed H_2-air mixtures are shown in Figure 9. NO_x emissions increase rapidly at $\lambda < 2$ and peak around λ = ~1.3 [9.6]. Lean combustion with $\lambda > 2$ has the potential to decrease NO_x emissions by keeping the combustion temperature below the threshold of thermal NO formation (i.e., 1800K [9.16]). Ultra-lean operation with λ > ~3.3 is undesirable from an engine efficiency and very high boost pressure perspective due to reduced flame speed and delayed heat release rate, which negatively impacts the combustion phasing and hence combustion efficiency.

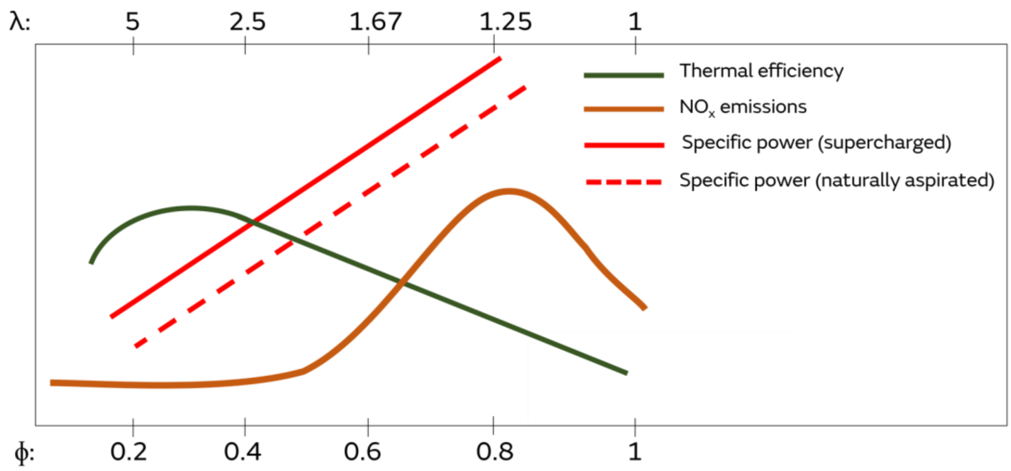

Figure 9: The qualitative trade-off characteristics of H2-ICE performance for homogenous mixtures at different global mixtures ϕ. [9.15]

Stoichiometric operation can be favourable from the highest power output, torque, and moderate boost pressure perspective even though it increases NO_x emissions and the chances of abnormal combustion. To address these issues, Kapus et al. [9.12] recently demonstrated that stoichiometric operation coupled with a combustion moderator such as water injection and/or EGR (to handle irregular combustion) has the potential to achieve full load conditions. It was further highlighted in the same study that stable combustion with reasonable combustion speed and similar efficiency levels can be achieved with λ = 1 coupled with EGR addition rather than lean operation. This further permits the use of NO_x reduction catalysts, similar to three-way catalysts (TWC). In addition, diluting air with an optimal EGR amount can lead to high specific power output, high efficiency and low NO_x emissions [9.16, 9.18]. However, these combustion characteristics are less relevant to the application of NRMM.

For stable lean combustion with homogenous mixture distribution, numerous studies reported high thermal efficiency of up to 45% at various speed-load mapped conditions (see Appendix 2) due to the high laminar flame speed, wide flammability limit, and high diffusivity of hydrogen [9.1]. Engine displacement, injection timings, fuel injection pressure, λ and peak thermal efficiency from these studies are summarised in Appendix 2.

For heavy duty applications AVL have demonstrated a 24 bar BMEP, 300 kW application with a brake thermal efficiency of 43% with matched transient performance of the baseline engine [9.19].

Appendix 2 shows the range of H2ICE engines in public domain literature sampled. In total 29 engine concepts are presented with 16 developed from SI base engine technology, 9 on CI base engine and 3 derived from natural gas engines. Pre-2021 research publications were removed from the analysis such that an up-to-date assessment could be made on the status of H2ICE performance and efficiency. The SI base concepts are typically derived from automotive engines or undertaken on single cylinder research engines such that the cylinder displacements range from 0.33 L to 0.66 L. The CI based concepts are typically based on heavy duty engine designs with displacements ranging from 0.5-2.8 L/cylinder. The 3 NG concepts are all heavy-duty base engines with 1.28-2.17 L/cylinder capacity. The efficiencies of the engines are presented either as indicated thermal efficiencies (ITE, see sidebar) or brake

Unlike BTE, **indicated thermal efficiency** (ITE) only captures the efficiency of converting the chemical energy of the fuel in to indicated performance directly from the cylinder, typically calculated from in-cylinder pressure/volume measurements to measure the “indicated” work of the engine and is used on single cylinder research engines (SCREs) where the true mechanical efficiency of the engine is not well represented due to unrealistic friction characteristics of SCREs and additional external supply systems for coolant and oil. Brake thermal efficiency is a direct measurement of the efficiency of converting the chemical energy of the fuel into usable (or “brake”) performance, i.e. producing mechanical power at the output of the engine. Due to these different measurement methods, there would be some reduction in ITE to BTE due to additional losses not incurred on an SCRE, but these have not been accounted for in this meta-analysis as the exact measurement approaches used on each published SCRE, the approach to calculation of ITE may be different, but the difference is highlighted here for completeness.

thermal efficiencies, depending on whether they are SCREs or multicylinder engines, respectively.

Concentrating specifically on the research carried out since 2021, the analysis selected 25 published papers, analysed shown in Table 5. The lowest ITE and BTE presented were 34% and 35% respectively and the highest ITE and BTE were 48.3% and 51.5% respectively. The average ITE and BTE of the samples were found to be 43.9% and 41.8%. In general, the efficiencies of the SI derived concepts are lower, in part due to their typically smaller cylinder size leading to higher thermal losses. Whilst only 3 NG derived engines are featured in the table, such that the statistical representation is small, Table 5 does indicate that they offer the highest average BTE and are potentially an excellent starting point for refining H_2 combustion system performance.

	All	**ITEs for SCRE**				**BTEs for multi-cylinder engines**			
		All	**CI**	**NG**	**SI**	**All**	**CI**	**NG**	**SI**
Samples	25	6	4	1	1	19	6	2	11
average	42.3	43.9	46.6	42	35	41.8	41.3	46.8	41.2
max	51.5	48.3	48.3	42	35	51.5	47	51.5	45
min	34	35	44	42	35	34	34	42	36

Table 5: Analysis of published ITE and BTE performance of H_2 development engines.

5.1.5.1 Transient Performance of Hydrogen ICEs

Transient performance represents an engine's ability to change load and/or speed dynamically whilst retaining appropriate control of emissions. The ability to respond to rapid torque demand from the driver is a critically important performance characteristic for NRMM applications. For an H2ICE this is a function of the fuel injection technology and the airpath system of the engine. Whilst H2ICE for NRMM are expected to run lean for NO_x emission abatement this has a few technical implications. These include higher demand on the engine boosting system due to increased air flow requirement for lean operation. The effect of transient loading on emissions is discussed in Section 5.2, but from an engine performance perspective these requirements can be met through existing engine boosting technologies such as 2-stage boosting systems; variable geometry turbocharging (VGT) and electrically assisted boost systems. Figure 10 shows the normalised torque and speed profiles for an engine undergoing the NRTC (non-road transient cycle). During the 1200 second cycle the engine speed and load are exercised dynamically over 100% of the speed and torque range of the engine, making robust transient performance critical.

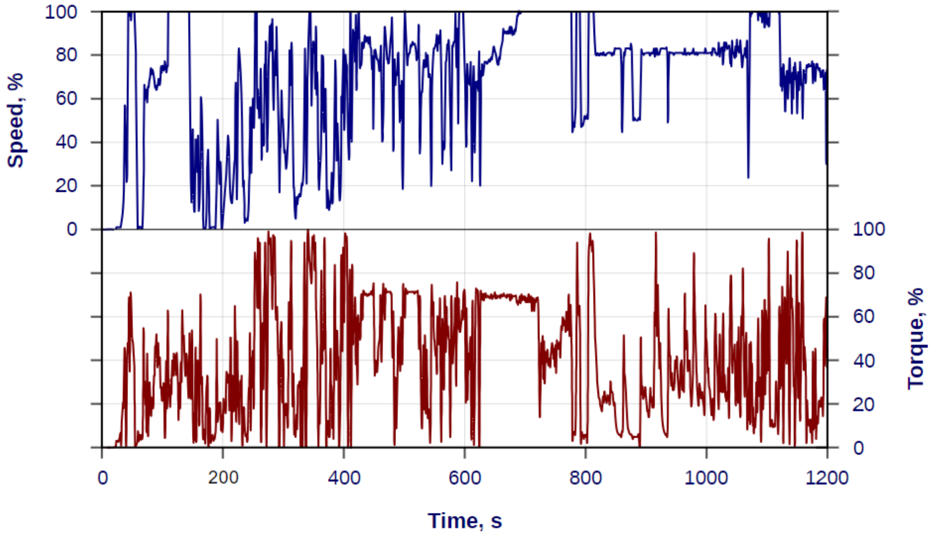

Figure 10: Normalized speed and torque over the Non-Road Transient Cycle (NRTC)

A more specific transient response case is applied to generators, another NRMM application, which is based on the measurement of block load acceptance to an ISO standard 8528 [9.51]. Within this standard there are various classes, typically in the genset rental industry G2 class is the benchmark standard. This describes a minimum performance requirement when a block load is applied, in respect to frequency and voltage. Thus, one can quantify how much load the unit will accept, as a percentage of its maximum steady-state capacity, whilst still maintaining a G2 class of performance.

For a 60 kVA Stage V Diesel JCB Genset, running at 50Hz, JCB are able to achieve a G2 rating of 50%, so the unit will accept a block load of 30 kVA (50% of its maximum output). For their equivalent H_2 fuelled IC Engine JCB were able to achieve a G2 rating of 70% (42 kVA), a 40% improvement over the 30 kVA performance of the G60StV Diesel fuelled equivalent genset as summarised in Table 6. This clearly shows that hydrogen fuelled engines can exceed the transient performance ability of their diesel fuelled equivalent.

	50 Hz (kVA)/ %	60 Hz (kVA)	Max Steady state rating (kVA)
G60 Diesel	30 kVA/50%	45 kVA/75%	60
G60 Hydrogen	42kVA/70%	60 kVA/100%	60

Table 6: Summary of JCB Generator performance to ISO 8528 block load testing

5.1.6 Other opportunities, Future Enhancements and improvements in H2ICE

The ability to improve H2ICE efficiency even further is well understood. These include adopting technologies proposed in traditional engine technology "walks" such as:

- Advanced thermodynamic cycles e.g. adoption of Miller cycle or over-expansion concepts
- Optimisation of the gas exchange process for both engine breathing and charge motion
- Reduction of engine friction
- Optimised compression ratio for the properties of hydrogen and engine application
- Implementation of exhaust energy recovery
- Advanced control of combustion such as pre-chamber combustion systems [9.49]

Improvement of the power density of hydrogen engines typically falls into 2 categories- motor sport/high performance applications, which are less relevant to the NRMM sector and the more relevant approach of increasing the torque (BMEP) of heavy-duty hydrogen combustion systems, both are highlighted below.

5.1.6.1 High Performance/Race Engine Technology

AVL Racetech have demonstrated H2ICE technology on a two-litre turbocharged engine achieving 301.7 kW power output at 6,500 rev/min (>150 kW/L) peak torque of 500 Nm equates to 32 bar BMEP which is similar to that achieved by the highest performance petrol road car engines. To achieve this level of performance the engine implemented PFI water injection to avoid pre-ignition and ran at stoichiometric operating conditions [9.50].

5.1.6.2 Heavy Duty Engine Technology

Primarily the torque (BMEP) of heavy-duty engines can be enhanced through the mitigation of abnormal combustion events such as pre-ignition. Some of the potential approaches are highlighted below.

- Hot spot induced pre-ignition
  - Update engine design to create well distributed temperature level on cylinder head and piston
  - Use optimized spark plug designs for H_2 combustion with appropriate heat rating and electrode materials that are compatible with hydrogen
- Lubrication oil induced pre-ignition

    - Update piston ring design and lubrication composition, reduce top land hight due to smaller quenching distance of hydrogen

- Ignition system
    - Optimise around low ignition energy requirement of hydrogen.
        - Use optimized spark plug design
        - Optimise supplied ignition energy
- Improved mixture homogeneity through higher pressures and optimised injection strategies
    - Increased (leaner) air fuel ratio through adoption of advanced boosting technologies.

5.2 Emissions (greenhouse gas and air quality)

Emissions from the exhaust of an internal combustion engine fall into two main categories:

1. Their impact on **air quality** (AQ), which has effects ranging from the local in the vicinity of the machine or vehicle [10.1] through to regional and global. Nitrogen oxides from exhaust have effects mainly close to point of emissions whilst particulate matter (e.g. $PM_{2.5}$), can spread over large distance scales. Ambient air quality is regulated nationally, typically as a maximum hourly, daily and annual average concentrations, and there are also public health guidelines for pollutants, issued by the World Health Organisation [10.2]. These exhaust air pollutants also have negative effects on ecosystems, which are protected also via regulation, and limits set on permissible critical emissions.
2. Their impact on **greenhouse gas** (GHG) emissions, including carbon dioxide (CO_2) and other long-lived gases which may be present in smaller quantities but have a higher Global Warming Potential (GWP); this is a global phenomenon, meaning that a given quantity of GHG has essentially the same impact upon the UK wherever in the world it is emitted, although the UK along with many other nations has national targets for reduction of its locally-emitted GHGs [10.3,10.4,10.5,10.6].

Historically, fossil-fuelled ICEs have been a major source of both NO_x and $PM_{2.5}$ pollution in many cities. Per-vehicle emissions of NO_x and PM from ICEs peaked in the late 1980s and early 1990s and have fallen ever since [10.1]. State-of-the-art in emission control has substantially reduced the contribution of the modern ICE to air quality, but it remains an area of active interventions.

Hydrogen is a carbon-free fuel, meaning that a hydrogen ICE operates with essentially no fuel-related carbon emissions, fully addressing environmental concerns linked to GHGs. Whilst hydrogen combustion has the potential to create both NO_x and $PM_{2.5}$ in exhaust gases, along with the greenhouse gases CO_2 and N_2O, this is not inevitable and all can be close to eliminated using modern engine designs and technology (including emissions control/after-treatment technologies where appropriate). This section looks in more detail at both these topics using state-of-the-art data from contributing stakeholders JCB, Cummins and Volvo Construction Equipment, supported by other information that is already published.

Sections on air quality and greenhouse gases are both structured as follows:

- An introduction to how they arise and the standards that must be achieved: “What does good look like?”
- Evidence from stakeholders and the public domain: “What has been measured?”
- Analysis and commentary on that evidence relative to society’s needs: “What does this mean?”

Data presented is centred on three current hydrogen ICE research, development and production-approved projects being delivered by stakeholders who supported the production of this report:

- JCB are promoting the hydrogen ICE as their power unit of choice for many machines and provided previously un-published data from their ongoing development program [10.7]. It should be noted that this engine has now been independently certified for production (see Appendix 6 for test certificates and air quality impact assessment).
- Cummins are developing two hydrogen ICE sizes, 6.7 and 15 litres, with a UK collaborative research project called BRUNEL funded by the Advanced Propulsion Centre [10.8]. The 6.7 litre unit is the more relevant of the pair, by virtue of being a relevant size for most NRMM, and specifically tested to NRMM standards; the 15 litre unit is aimed at large trucks but is included here for comparison.
- Volvo Construction Equipment (Volvo CE) are developing a hydrogen ICE for on & off highway use through a European collaborative project, CORAM PL-H2 [10.9]

All these engines differ in terms of technology detail and engine R&D maturity which leads to some spread in data. The JCB engine is the most mature in terms of development, having exited the research stage, entered product development and now been certified; it is dedicated to off-highway use, and uses Port Fuel Injection (PFI) technology. The Cummins units use Direct Injection (DI) of the fuel into the cylinder for higher power output. The Volvo CE unit retains PFI but uses other features like twin turbochargers to improve power output.

In addition, data from the public domain is cited in the following sections and was compiled by the University of Bath and the Advanced Propulsion Centre. This data tends to refer to older technologies and reports, so it is given less emphasis, however it is used to support the stakeholder data and to illustrate recent improvements. It is referenced in the sections where it is cited.

5.2.1 Air quality

5.2.1.1 How air quality emissions arise

The combustion of a hydrocarbon fuel (such as diesel, petrol or their renewable equivalents) in air should be a simple oxidation process, producing water, and carbon dioxide only. However, in practice this is difficult to achieve, and a number of other by-products are present in exhaust.

- The intent of combusting a fuel in air is to use the oxygen in the air to release the stored energy in the fuel. The other constituents of air should not take part in this reaction, remaining inert. However, if sufficient energy is available (characterised by high peak, local temperature) nitrogen can also be oxidised producing NO and NO_2, collectively referred to as NO_x, and small quantities of N_2O.

- Modern diesel ICEs are highly efficient at combusting the fuel they use, however very small quantities of hydrocarbon fuel may not be fully oxidised resulting in emissions of hydrocarbons, carbon monoxide (CO) and soot but these emissions are regulated to very low levels. Hydrogen contains no carbon, so there are no air quality-relevant partial combustion products produced. Emissions of unburned hydrogen is possible and will be discussed in the GHG section, but it is not considered as an air quality emission.

- Particulates (PM) are airborne suspended solids and liquids, and in exhaust gases these are mostly carbon-based arising from partially combusted components from the hydrocarbon fuel. As hydrogen does not contain carbon its combustion does not produce particulates. Reciprocating piston ICEs use hydrocarbon-based lubricating oil to reduce friction and prevent wear of the piston/piston rings to cylinder interface. This results in *very* small quantities of oil being combusted. This is the only source of particulates from the hydrogen ICE itself.

5.2.1.2 Exhaust emission regulations

Emission of air pollution gases from ICEs and industrial equipment has been regulated for many decades, with ever lower limits being introduced at intervals of 5-10 years for both road vehicles and non-road mobile machinery (NRMM) [10.1]. The regulation stipulates an allowable mass of substance per kilowatt-hour of engine output. Figure 11 shows how these EU & UK regulations have become increasingly stringent. This has resulted in substantial reductions in emissions and consequential improvements in UK air quality from the mid-1990s to the present day [10.1], although ambient concentrations of NO_2 are in some cities still higher than UK national annual average limit values, and in many locations are higher than recommended annual average concentrations in the World Health Organisation air quality guidelines [10.1, 10.2].

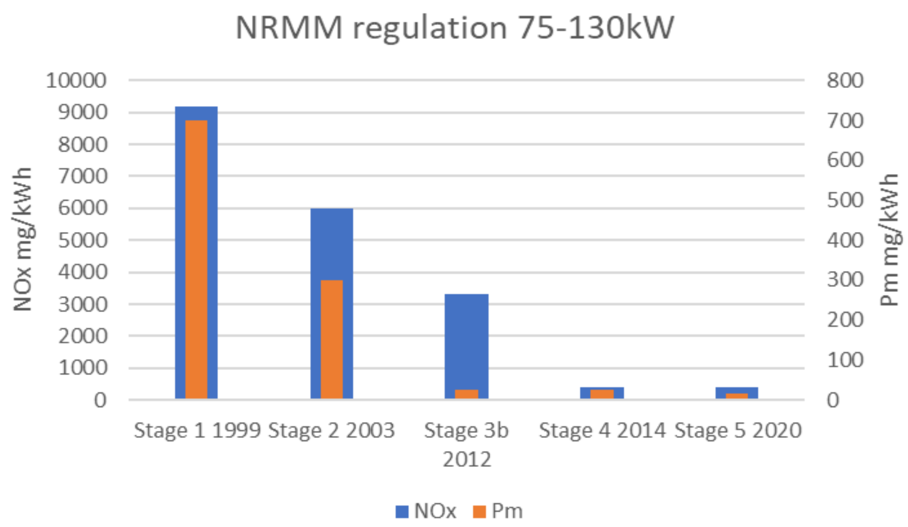

Figure 11: Evolution of EU NRMM emission regulations (note, from Stage 3b, these regulations covered power range 56-130 kW)

A key factor to consider in the context of next generation NRMM is that new vehicles enter the fleet generally displacing some of the oldest vehicles, which have very high emissions by today's standards. Local planning and permitting requirements for construction may well mandate only newer types of vehicles can be used. The best-known example of this is London's Ultra Low Emission Zone (ULEZ) for road vehicles; but in urban construction it is commonplace to mandate equipment complying with more recent "Stage IV" (for date of manufacture 2015-2018) or "Stage V" (2019 onwards) legislation [10.11].

The UK has retained use of the European (EU) exhaust emission regulations. These are increasingly harmonised with the equivalent US regulation. A summary of current and likely future regulations is given in Table 7; EU Stage V is the regulation relevant to NRMM and includes a measure of fine particle number, since these are believed to be most harmful to health and can bypass filtration devices including those in the human body [10.1]. Hence, PM are measured and regulated both by total mass produced (PM) and by number of particles at a certain size (PN).

	EU Euro VI	EU Euro 7	**EU Stage V**	CARB Tier 5
Type	Regulation	Regulation	**Regulation**	Proposal 2034
Applies To	On Highway HDV (truck, bus)		**Off Highway (NRMM)** 56-560kW	
Date Applicable	2013 onward	2027 onward	**2019 onward**	All ratings 2034 onward (some interim)
Test Cycle	WHTC	WHTC	**NRTC**	NRTC
NO_x (mg kWh^{-1})	460	200	**400**	40

PM (mg kWh^{-1})	10	8	**15**	5
PN (size, number kWh^{-1})	23nm, $6x10^{11}$	10nm, $6x10^{11}$	**23nm, $1x10^{12}$**	Proposal in development

Table 7: Emission regulations present and proposed future. Note that Stage V includes further test cycles RMC and NRSC in addition to the NRTC.

Emissions are assessed by testing the engine in a laboratory over a “test cycle”, which operates the engine at a mix of speeds and loads representing the way it is used in the real world; in the case of on-highway engines, there is an added requirement for real-world compliance. The off-highway test is the Non-Road Transient Cycle (NRTC) (Figure 12), which represents typical operation for a range of construction machines, farm equipment, generator sets and other NRMM.

It is very important to note that the NRTC is a highly transient cycle covering the full engine operating map. It should also be noted that in-service emissions are actively quantified via an In-Service Monitoring (ISM) regime as part of the Stage V regulation. This ISM of machines in-use has shown that real world emissions are close to NRTC certification levels (see Appendix 3), demonstrating that machines perform with good in-service compliance in the field as well as on the testbed.

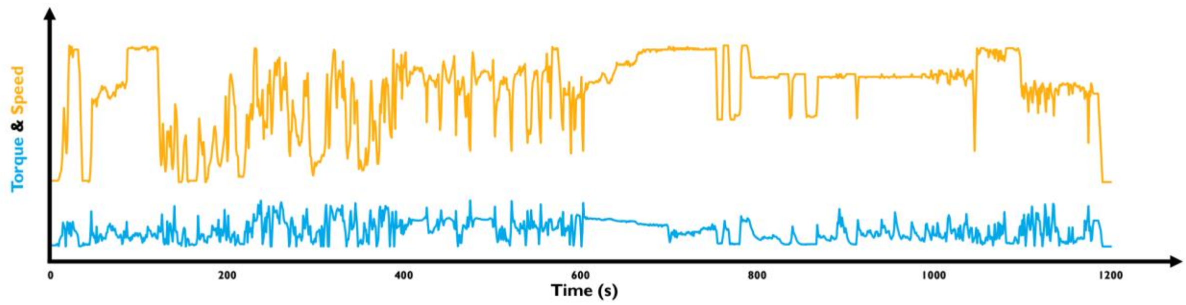

Figure 12: Non-Road Test Cycle as a function of torque and speed (image courtesy of JCB)

Historically, emission regulations for NRMM have been more lenient than those for on-highway, recognising that road vehicles are found in large numbers close to pedestrians, homes and workplaces, whereas safety considerations prevent bystanders being close to an excavator or tractor at work, and they are usually working in smaller numbers. However, as Table 7 shows, Stage V and Euro VI are now set at similar levels for NO_x and PM. The proposed US (CARB) Tier 5 regulation (for NRMM), which could be phased in between 2029 and 2034, is in fact lower than European Euro 7 (on-highway). While it is not relevant to the UK, the US Tier 5 working proposal is included as a useful reference for the most stringent potential future global standards.

5.2.1.3 Air quality emissions data from H2ICE

5.2.1.3.1 NO_x emissions

As described above, the formation of NO_x requires sufficient energy to be available locally (as in lightning – the largest natural source of atmospheric NO_x). In an engine, this is the result of high peak, local combustion temperatures. Hydrogen engine design has to ensure these conditions do not occur [10.4].

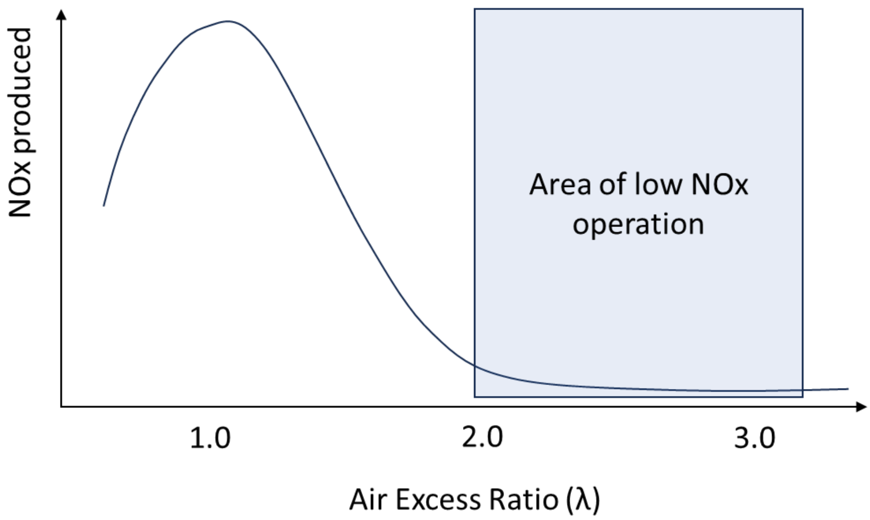

Figure 13: NO_x formation response to excess air in internal combustion engines

The hydrogen engines being developed by the stakeholders employ the same basic combustion strategy to achieve this – lean, homogenous charge premixed combustion. This means the hydrogen and air are mixed to form a homogenous charge, avoiding rich pockets or zones before ignition, with the charge containing an *excess* of air to reduce rate of combustion and consequently reduce peak temperatures (Figure 13). Under these conditions, NO_x is not produced in any significant quantity, if at all: JCB data shows circa 0.001 g per kWh under steady state conditions. The challenge for engine development is to ensure these conditions are maintained under all operating modes, fast transient changes (a sudden request for power) being the most challenging because of the time needed for the turbocharger to start delivering more air – this can require the air surplus to be consumed to burn more fuel while it does. This is the source of the small amounts of NO_x produced when running NRTC type cycles. However, this can be reduced by well-established SCR (selective catalytic reduction) type aftertreatment systems. These use urea (known as AdBlue) to react with the NOx, producing nitrogen and water; the principle is already very well proven on diesel HGVs and NRMM.

The JCB, Cummins and Volvo CE R&D projects [10.8, 10.9, 10.10] supplied their latest NO_x emissions data, some incorporated into this report within only a few days or weeks of coming out of the laboratory, hence capturing the very latest state of development. Table 8 and Figure 14 present NO_x emission data compared to the current (Stage V) NRMM exhaust emission standards previously described. This data very much represents the state of the art, with updates from both JCB and Cummins incorporated during the drafting of this report.

For JCB, the data arises from development and validation testing of a future NRMM product and can be considered the most mature. For the Cummins/Brunel project, engine testing was being undertaken during the period of formation of this report, with only initial results available. It is important to note that, during this period, the target for the 15 L engine was to achieve EURO 7 *on-highway* tailpipe emissions limits for certification cycle and real driving testing, with the simplest aftertreatment system design and using available (developed for diesel) components. The initial results meet these targets with significant margin, and further enhancement of base engine and aftertreatment system is underway. Following on from the EURO 7 work, optimisation of the engines is being carried out, and an initial result for the 6.7l engine on the off-highway NRTC test is shown here. Engine calibration and aftertreatment system architecture may well be different with NRMM specific, yet to be fully defined, design targets, potentially matching the JCB figure. Unfortunately, full results will not be available until after the publication of this report.

Stakeholder Project	**Engine Specification**	**After Treatment**	**Test Cycle**	**Observed NO_x g kWh^{-1} Tailpipe**
JCB [10.8]	Off Highway, PFI Turbo	SCR	NRTC	0.020
Cummins 6.7 L (10.9)	Off Highway, DI Turbo	SCR	NRTC	0.025
Volvo CE [10.10]	On Highway, PFI 2 Turbo	Estimated	NRTC	0.029
Stage V Regulation	Current UK standard		NRTC	0.400
Cummins 15 L [10.8]	*On Highway, DI Turbo*	*SCR*	*WHTC*	*0.035*

Table 8: Stakeholder R&D data for NO_x at tailpipe. For JCB & Cummins, an SCR (AdBlue) system is fitted; for Volvo CE, the raw engine-out value of 0.58 g kWh^{-1} was multiplied by an assumed 95% SCR conversion efficiency

Figure 14 shows that all three stakeholders' NRTC-tested engines deliver a 93-95% reduction in tailpipe NO_x compared to the current Stage V limit for diesel engines. In fact, all three would also meet the US Tier 5 Final proposal for 2034.

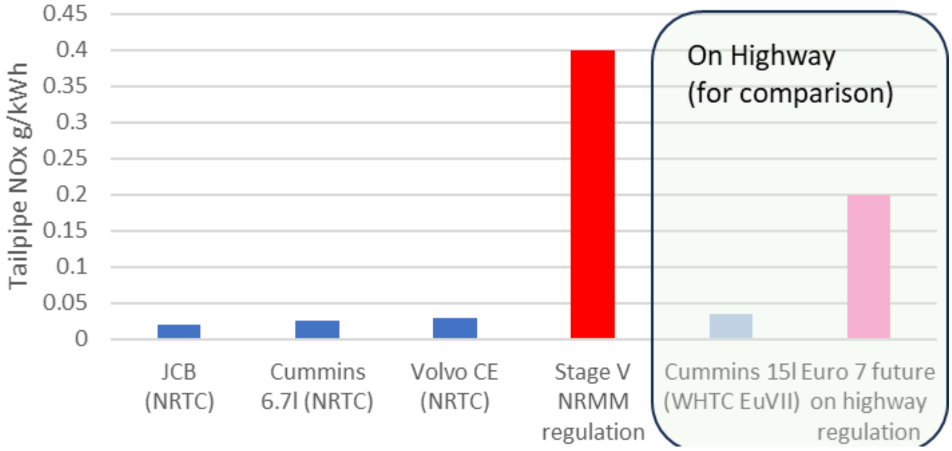

Figure 14: Stakeholder NO_x emission data, tailpipe. Note 1: Volvo CE data assumes a 95% NOx conversion applied to engine-out data. Note 2: The Cummins 15 L engine was tested on the on-highway WHTC, which was found to give slightly higher NOx than the more valid NRTC test

In addition to NO_x emissions data supplied by the three manufacturers (Figure 14) other publicly available research data was surveyed by University of Bath and the APC, capturing four further projects by organisations AVL, Bosch, FEV and the University of Graz (marked as D, E, F and G; references 10.12 to 10.15 on Figure 15), in addition to a wider literature survey where minimum and maximum values are presented. Data included here was published mostly in the last 5-10 years, however with this now being a fast-moving R&D field seeing considerable investment, it would be expected that older data may show higher emissions than the 2024 state of the art. Some of the data is also related to on-highway applications and test cycles, which are similar but not perfectly comparable.

Figure 4.5 shows that the latest state-of-the-art stakeholder data shows significantly lower NO_x than historical published data, although even here all are well within current regulation and therefore, significantly lower than a current diesel product.

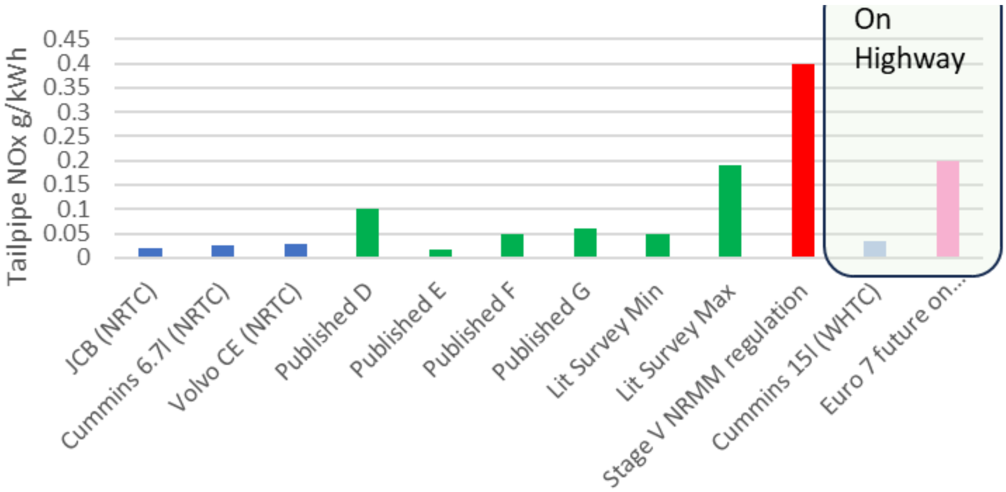

Figure 15: Comparison of tailpipe NO_x emissions from various engine types against literature review and regulation

5.2.1.3.2 Particulate emissions

Hydrogen itself cannot produce particulates and hence there have been fewer laboratory studies than for NO_x; the only potential source of particulates from the engine itself is the combustion of tiny quantities of lubricating oil, and these can be captured using a Particulate Filter, technology again already proven on diesel HGVs and NRMM. However, data from JCB and Cummins research programmes is shown in Table 9 and plotted alongside one public domain data set in Figure 16. As with NO_x, the Cummins 15 L data comes from an on-highway project but is included here for comparison.

Stakeholder Project	Engine Specification	After Treatment	Test Cycle	Observed PM		
				Eng Out mg kWh^{-1}	Tailpipe mg kWh^{-1}	Tailpipe PN
JCB	Off Highway, PFI Turbo	PF	NRTC	0.7	0.03	0.02×10^{12} 23nm
Cummins 6.7 L	On Highway, DI Turbo	SCR +PF	WHTC			0.324×10^{12} 10nm
Stage V Regulation	Current UK standard		NRTC		15	1×10^{12} 23nm
Cummins 15 L	*On Highway, DI Turbo*	*SCR + PF*	*WHTC*	*4.0*		*0.1×10^{12} 10nm*

Table 9: Particulate emissions data provided from stakeholders

Raw engine-out particulate mass from JCB and Cummins engines are well within the Stage V regulation at the tailpipe, meaning that particle filter aftertreatment is not strictly necessary to comply but it is considered best practice.

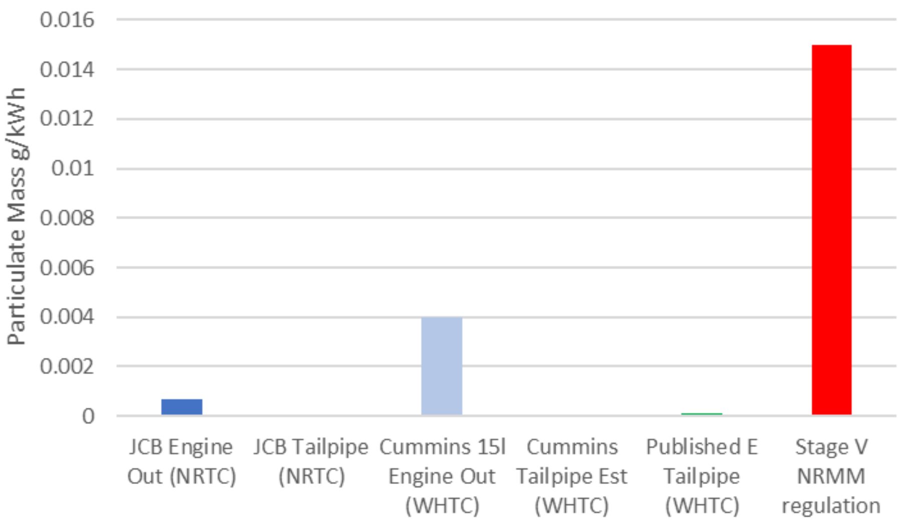

Figure 16: Tailpipe particulate emissions by mass for various H_2 engines and Stage V diesel. The tailpipe estimate for Cummins assumes the same filtration efficiency as JCB, as a filter was not fitted for the tests

JCB report a tailpipe particle number count of ~2% of the Stage V limit and a mass at 0.2% of Stage V limits. The Cummins engines use a different particle size of 10 nanometres (as their research is aimed at Euro 7 on-highway) which cannot be compared to Stage V NRMM but is within the proposed Euro 7 requirements for 2027 onward. Cummins did not provide engine out mass data for the 6.7 L engine, and the final after-treatment architecture of the Cummins engines for on-highway or NRMM is not determined yet, hence an estimate is shown if filtration were used.

5.2.1.4 Air quality analysis and discussion

5.2.1.4.1 Relationship to ambient air concentration

Laboratory test data on engines, vehicles or machinery delivers a measurement of the quantity of pollutant at the tailpipe; human health and the environment are impacted by the resulting concentration in the “ambient” air. There is a significant degree of dilution from tailpipe to ambient, but the science of this relationship can be modelled.

One of three stakeholder projects (JCB) used air quality measurements near a machine in operation, and ambient data from London, to infer the impact of NRMM on air quality with the support of Ricardo Energy & Environment [10.25], a consultant specialising in air quality data analysis. The baseline for this data is an air quality monitoring site at Malet Street, in central London (WC1E), where concentrations of NO_x are historically high. The mean annual NO_x concentration at this location was 73.5 µg m^{-3}, which exceeded the England and Wales limit value of 40 µg m^{-3}. (Note the proposed EU limit is 20 µg m^{-3}, and the WHO guideline is 10 µg m^{-3} [10.2]). NRMM (which will be mainly construction equipment) was estimated to contribute ~8% of the ambient NO_x in Malet Street, or 5.8 µg m^{-3}. The breakdown of estimated NO_x sources is shown in Figure 17.

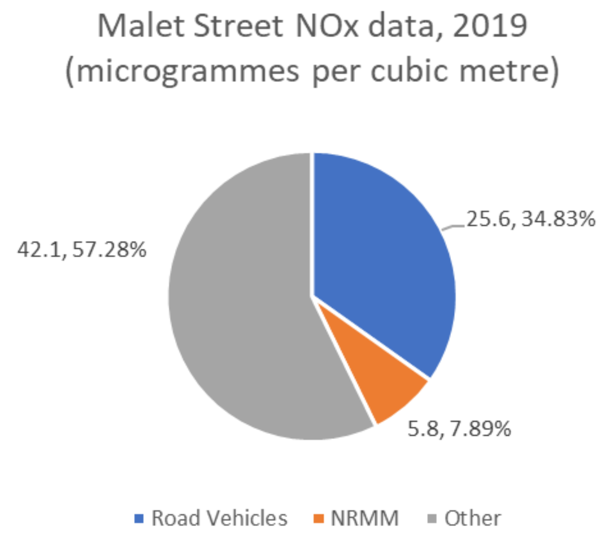

Figure 17: Inventory estimated contributory emission sources of NO_x at a Malet Street in central London

Adopting the latest Stage V (diesel) NRMM equipment in this location would reduce the atmospheric contribution of construction equipment to ambient NO_x from 5.8 µg m^{-3} to 3.9 µg m^{-3} (a reduction of 33%[7]). However, adoption of the hydrogen ICE NRMM (based on JCB emissions data) would reduce NO_x much further, from 5.8 µg m^{-3} to only 0.019 µg m^{-3}, or a reduction in the NO_x attributable to NRMM of 99.7%, when compared to present-day emissions (Figure 18).

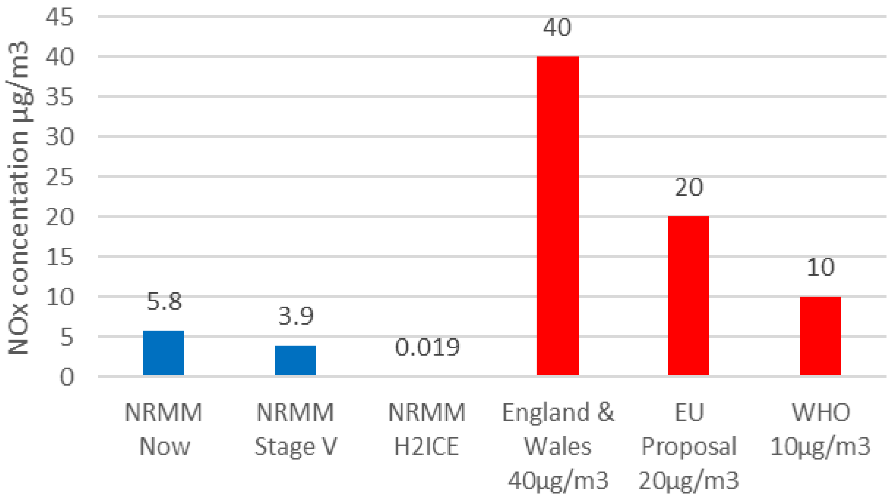

Figure 18: Contributions to a case study urban NO_x concentration from existing NRMM and counterfactual JCB Hydrogen ICE emissions.

The local effects on ambient $PM_{2.5}$ concentrations from adoption of hydrogen ICE for NRMM have not been quantitatively evaluated and are more complex since $PM_{2.5}$ is a longer-lived

[7] Stage V does not reduce NO_x over Stage IV, hence smaller reduction

pollutant that also has secondary production in the atmosphere. Nonetheless, the direct reductions in emissions that are reported for hydrogen ICE compared to Stage V diesel shown in Table 9 would feed through to local benefits, but with wider beneficial impacts since PM is transported over longer distance scales.

5.2.1.4.2 Fiscal measure of health impacts

An estimate has been made of the cost savings arising from avoided damage to the environment, human health and productivity, using the current Stage V diesel standard as a baseline, compared to widespread adoption of the hydrogen ICE. The estimate used DEFRA 2023 air quality appraisal damage cost guidance (March 2023 version) [10.23], and NAEI 2022 sectoral annual emissions [10.24]. For simplicity, it was assumed that 100% of the construction and agricultural fleet would adopt hydrogen ICE technology. This estimate indicates damage costs avoided of £150 M/yr (central estimate) to £505 M/yr (high sensitivity upper bound).

5.2.2 Greenhouse gas emissions

5.2.2.1 How greenhouse gas emissions arise

The “greenhouse effect” arises when gases increase the retention of heat in the atmosphere arising from infrared radiative interactions with absorbing molecules. The most abundant and well-known greenhouse gas is carbon dioxide (CO_2), but others include methane (CH_4) and nitrous oxide (N_2O), alongside some halogenated refrigerants. Exchange of greenhouse gases with the biosphere occurs, for example plant life absorbing CO_2 emitted by the breathing of animals, fires and volcanic activity. However, in recent centuries the extraction and combustion of fossil fuels has produced more CO_2 than nature can absorb.

The predominant GHG emission from a fossil-fuel burning ICE such as a diesel engine is CO_2. This comes from the carbon in the fuel, a hydrocarbon whose combination with oxygen produces CO_2 and water (plus, the air quality pollutants discussed in the previous section). Hydrogen fuel produces only water when it burns, however, there are potential non-fuel related GHG emissions such as:

1. Combustion of very small quantities of lubricating oil to produce CO_2.
2. Formation of nitrous oxide, N_2O, from combustion, and/or as an unintended reaction in aftertreatment systems.
3. Escape of hydrogen by failure to combust fully (leakage from the fuel system and refuelling before it reaches the engine is also a factor, although this is also true of hydrogen fuel cells and is not specific to a hydrogen ICE).

Because a GHG emission has the same impact wherever it is emitted, it is important to consider GHGs on a “life cycle” basis, which includes not just emissions from the vehicle or machine, but also from the production or distribution of fuel, and manufacture and disposal of the vehicle or machine. For this reason, the concept of a “zero emitting vehicle”, which is useful for tailpipe air quality, can be misleading for GHGs.

However, life-cycle considerations are not considered here, for two reasons:

- The manufacturing carbon footprint of an ICE is low compared to the use phase (when using fossil fuels). It is also low compared to BEV and H2FC powertrains [10.15]
- In this context, hydrogen fuel would either be green (made from renewables via electrolysis for example) or, as a transition step, blue (made from fossil fuel with capture and sequestration of the carbon). If those conditions are met (and hydrogen production was out of scope for this group), then GHG emissions from the fuel supply chain are small.

5.2.2.2 Greenhouse gas regulations

Greenhouse gas emissions are regulated globally by the Paris Agreement, which obliges signatory nations to regulate and report their emissions. At UK level this is achieved through Carbon Budgets and the Climate Change Act [10.3 to 10.6]. Since each gas has a different absorption characteristic, each is allocated a “Global Warming Potential” (GWP). Because different gases have different loss or sink processes, and hence lifetimes in the atmosphere, the GWP is stated as an average effect of a time integral, typically over 20 years (GWP_{20}) or 100 years (GWP_{100}). The 100-year potential is the one used in the Paris Agreement. Table 10 shows GWP of the gases considered [10.17].

Gas	**GWP100**
Carbon Dioxide, CO_2	1
Hydrogen, H_2	11
Nitrous Oxide, N_2O	273

Table 10: Global warming potentials of various gases

Carbon dioxide and nitrous oxide are reportable under the Paris Agreement, but hydrogen is not. However, as hydrogen is the fuel (therefore used in large quantities) the effects of unburned fuel escaping merits discussion.

At a more machine-specific level, there is not yet any regulation of CO_2 emission or GHGs for NRMM, as there is for on-highway vehicles. Because they use the same engines as NRMM it is worthy of note that the European Union has recently adopted a “zero GHG emitting” standard for heavy duty on-highway vehicles, requiring that they (a) meet the Euro 7 emission standard, regardless of power source and (b) emit no more than 1 g CO_2 kWh^{-1} (or 1 g per passenger-km or 3 g per ton-km using the VECTO drive cycle simulation) [10.18].

Finally, for the NRMM owner or operator, a major driver for adopting a low or zero carbon machine is regulation, at a business level, of their emissions, for example Environmental, Social & Governance (ESG), or Corporate Social Responsibility (CSR) commitments.

5.2.2.3 Greenhouse gas emissions data for H2ICE

5.2.2.3.1 Carbon dioxide emissions

As previously described, the most effective method of control for CO_2 is to use a fuel that is both zero-emitting at the point of use, and net-zero over the lifecycle. Some fuels such as biodiesel may be net zero over the fuel production and use cycle but lead to immediate CO_2 emissions at point of use. Sustainable hydrogen however achieves both, since no CO_2 is released on use, and the lifecycle can be made net zero. In NRMM equipped with a hydrogen ICE, the only emissions of CO_2 are from very small quantities of combusted lubricating oil, and from the breath of the human operator.

Source	Stage V Diesel	Ambient Air Pass-through	NRMM Operator	H2ICE JCB (NRTC)	H2ICE Cummins 15l (WHTC)	H2ICE Cummins 6.7l (NRTC)
CO_2 (g/kWh)	800	3.94	2.567	0.43	0.2	<1 (preliminary data)

Table 11: CO_2 emissions comparison for various engine types / sizes

Table 11 and Figure 19 show test data from JCB and Cummins, compared to some relevant benchmarks; in this data, the ambient CO_2 concentration (420 ppm) has been subtracted, to show only the added emission, but this ambient CO_2 does pass through the engine in addition. Both stakeholder engines were within the 1g kWh^{-1} definition threshold used in the proposed EU on-highway regulation and show a greenhouse gas reduction of at least 99.9% on the current Stage V diesel unit.

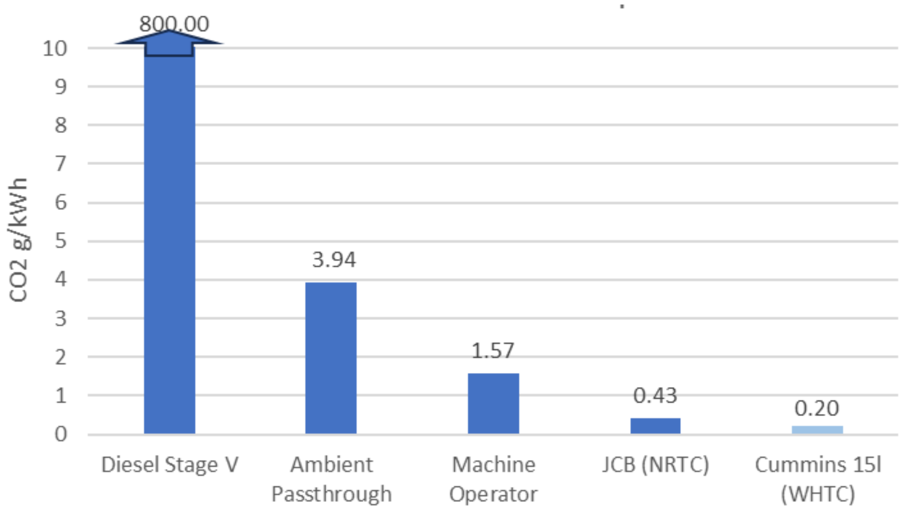

Figure 19: Carbon dioxide emissions comparisons between Diesel Stage V and H2ICE

Two other comparisons are worthy of note. First, the CO_2 added to the air in the exhaust is a fraction of that already there (which is dependent on the engine's excess air ratio, taken here to be 2.5). Secondly, JCB conducted an estimate of the CO_2 emitted by an excavator's operator (through breathing) in comparison to the engine; the operator's emissions are ~4 times those of the engine.

5.2.2.3.2 Nitrous oxide

Nitrous oxide (N_2O) is formed by the heat of combustion, in the same way as NO_x, but is a greenhouse gas and, by removing 99.9% of the CO_2 when switching from diesel to a hydrogen ICE, the N_2O impact, although still very low, becomes more noticeable. NO_x emissions are abated using an SCR aftertreatment system, but under some conditions an SCR system may produce small amounts of N_2O by incomplete reduction of NO_x. This has been evident in some on-road HD diesel applications, and regulation has already been put in place to control this from an air quality perspective (US HD truck and Euro 7). H2ICE specific SCR systems can avoid this characteristic as is shown by the JCB test results below. JCB testing shows that the percentage of N_2O in the oxides of nitrogen is very low, at 1% of the total.

JCB presented N_2O data with a tailpipe emission of 0.00073 g kWh^{-1} made up of 0.0005 g kWh^{-1} from combustion and 0.000273 g kWh^{-1} from the aftertreatment system. Multiplying this by the GWP100 of 273, (Table 10) the CO_2-equivalent is shown in Figure 20, alongside the CO_2 data from the previous section. It can be seen that, while N_2O adds to the total greenhouse gas effect, the combined effects of CO_2 and N_2O emitted still represents a 99.9% reduction compared to a Stage V diesel.

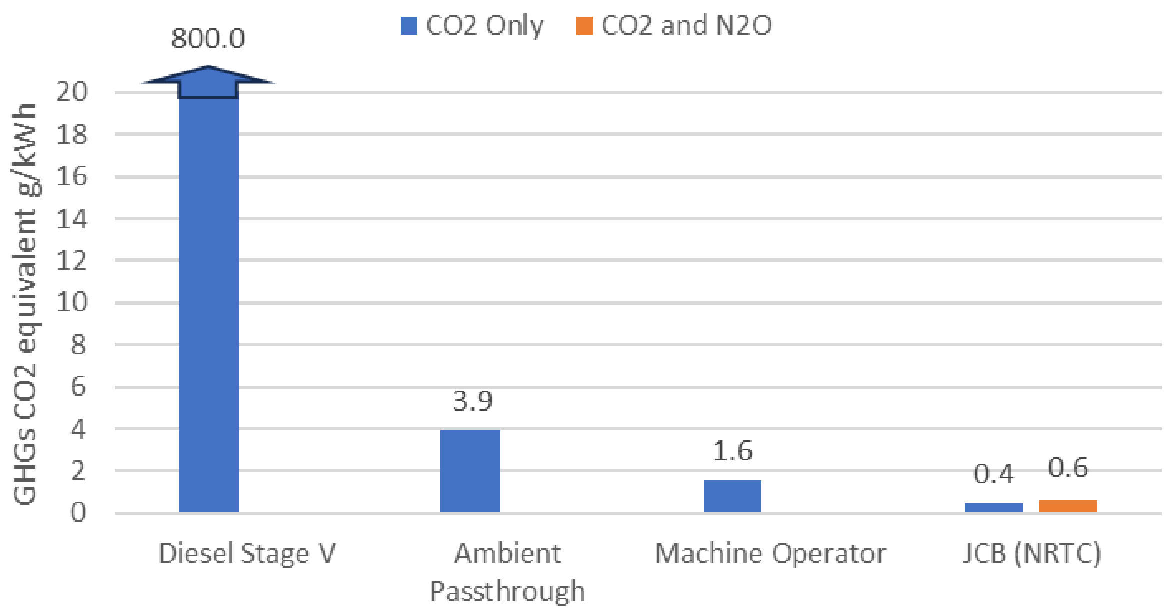

Figure 20: Impact of N_2O on overall H2ICE GHG emissions, expressed as CO_2 equivalent

5.2.2.3.3 Hydrogen

Hydrogen is not a reported greenhouse gas under the Paris Agreement but has been shown to have a Global Warming Potential [10.17]. As it is the fuel for both the hydrogen ICE and the fuel cell (as well as, potentially, aviation and industrial furnaces), its greenhouse-gas impact merits review.

Hydrogen is a very reactive fuel, meaning that large quantities should not escape unburned into the exhaust in a lean-burn engine where there is always a surplus of air to combust it. The addition of an oxidation catalyst to the exhaust after-treatment system (which is a part of the standard package for diesel after-treatment, along with the SCR and PF systems described) should reduce any remaining "hydrogen slip" to near zero.

JCB have reported hydrogen slip of 0.023 g kWh^{-1} post oxidation catalyst. This has a CO_2 equivalency of 0.25 g kWh^{-1}. Figure 21 shows the effect of hydrogen slip added to the CO_2 and N_2O emissions shown previously, on a CO_2-equivalent GWP basis.

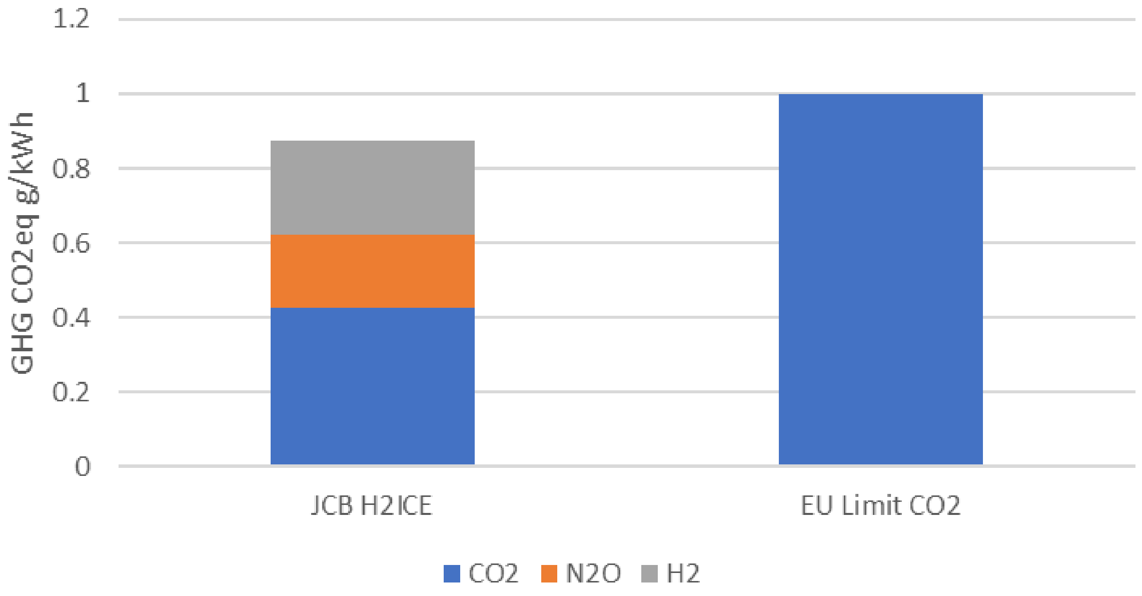

Figure 21: Cumulative greenhouse gases from a JCB H2ICE engine expressed as $CO_{2\,eq}$. Note that the EU limit value refers to CO_2 only and is an on-highway standard (not NRMM)

This shows that, at these very low levels of GHG emissions all these potential sources need to be considered. It also shows that the total from all these sources still represents a reduction of ~99.9% from using diesel fuel and meets the EU definition of an on-highway zero emissions vehicle (HD truck) [10.18].

5.3 Practicalities, Safety and Operational Experience

During the course of the meetings, the subgroup assessed the experience of the practicality and safety of hydrogen in relation to current NRMM applications by analysing case studies from the limited trials of hydrogen use, in real world applications in the UK and further afield.

The group discussed a range of comments and experiences that highlighted the practical and safety issues associated with using hydrogen as an alternative fuel/energy source such as access to low carbon hydrogen supplies, transporting hydrogen and refuelling infrastructure requirements. It should be noted that these apply to both fuel cell and H2ICE applications.

In this report, therefore, the NRMM aspects of using hydrogen in the applications generally are highlighted, and any specific differences for ICE noted separately.

5.3.1 Engineering and materials practicalities for H2ICE

The engineering practicalities of H2ICE in NRMM are largely related to applying gas systems to equipment and the impact this has on packaging onboard storage at a machine level.

Ensuring materials compatibility is a generic process for engineering and understanding of the compatibility issues for all hydrogen systems, is a well-researched area of study. Assessment and research take account of specific issues around concern for embrittlement, the risk of leaks, the impact of hydrogen on other materials in the engine systems such as lubricants, and the overall lifetime and durability of the engine, the machine, its maintenance and its performance.

Hydrogen is not a drop-in replacement fuel when used as a mono-fuel in conventional engines and machines. Using the transfer of knowledge and innovation behind lean burn and other state of the art combustion technologies/approaches to deliver ultra-low emission and performance requirements means that hydrogen engines have been and will be designed to be fit for purpose with hydrogen, and as result will be developed using compatible materials. Engine, machine developers and academia have many years of experience and know-how in combustion engine engineering and materials that can be directly transferred to development of hydrogen engines, as well as setting goals, targets and expectations for research for future improvement.

At the machine level, as with the road transport experience, there are engineering challenges behind finding enough space onboard conventionally-designed equipment for the hydrogen storage. This challenge is inherent when considering gaseous fuels as opposed to volumetrically energy dense liquid fuels. To address the challenge, an understanding of real-world energy use, refuelling strategies and possible design changes are needed, which are all within the normal experience of technology developers.

The NRMM engine and machine developers are, however, generally not familiar with the issues involved in using high pressure hydrogen onboard equipment (usually 350 bar – 700bar), experience that can be transferred from wider transport sector. Hydrogen storage and pipework requirements are set by the international standards (e.g. R134 in automotive applications) which take account of the material compatibility issues, and other engineering design requirements for safety.

The use of these high-pressure tanks and related components will add some cost at a machine level when compared to today's "simple" fuel tank systems; in the automotive sector there is already a relatively small cost differential for compressed natural gas vehicles for the use of 200-220 bar gas systems, and therefore there is expectation that hydrogen systems will be marginally more expensive than CNG when at scale, due to the higher pressures involved. The supply chain for high-pressure hydrogen components is at an early stage, and not at scale today. Given the components will largely be the same for both transport and NRMM applications and for fuel cell and H2ICE, by sharing common standards, components and suppliers, the trajectory for costs coming down will be accelerated by creating the shared demand and therefore benefit all (see Section 5.3.5).

As discussed in Section 5.1, the efficiency of H2ICE in application matches or improves upon diesel fuel use (with lean burn technology and potentially without the need for after-treatment etc.) meaning there is benefit from using H2ICE.

The subgroup therefore confirmed that compatible material options exist today from scaled supply chains for engine manufacture, and therefore do not present concerns from an engineering perspective, and that at a material level, the group concluded that engines themselves will largely "cost the same as existing engines". At a machine level, although there are packaging challenges related to using a pressurised gas and a lack of direct experience of the safety requirements specifically to using hydrogen, the knowledge and experience of this is directly transferable from wider transport applications.

5.3.2 Hydrogen Quality

Whilst the production, distribution and supply of hydrogen is outside the scope of this group, it is worth discussing the impact of hydrogen quality on the cost of hydrogen as a fuel.

The supply chain for hydrogen today is mostly serving its conventional uses. The hydrogen that is made from fossil natural gas, using energy (steam reforming or otherwise) to release it from the carbon in the hydrocarbon source, is usually supplied as "industrial grade hydrogen" at 99.99% purity. The assumption the H2ICE subgroup made in this task was that the Hydrogen Delivery Council is focused on resolving the actions needed to ensure that hydrogen for energy use, will be supplied as "decarbonised" to give a lower carbon footprint from a GHG perspective than diesel, as defined by the DESNZ Low Carbon Hydrogen Standard[8].

However, it recognised that there are a range of sources and approaches that can be used to produce decarbonised hydrogen which help to deliver energy resilience and security within the system, and that some of these routes to produce hydrogen particularly from waste gas streams, from gas with carbon capture and storage have the potential to produce

[8] UK Low Carbon Hydrogen Standard, 2023 (Department of Energy Security & Net Zero)

“fuel grade” hydrogen, which would further enhance the resilience and options for decarbonised supply, as long as they can meet the detailed specification requirements for fuel.

Today’s standard for hydrogen fuel quality (SAE J2719 and/or ISO 14687:2019 Type 1 Grade D) is, however, set to meet the needs of fuel cell technology at the high purity level of min 99.97% hydrogen. This is required to assure the long-term durability of the catalysts in the fuel cells of today, and the associated manufacturer warrantees. In practice to meet this standard, the hydrogen needs to be manufactured through electrolysis (which electrochemically splits water (H_2O) using electricity) or requires additional energy and capitally intensive processing steps to achieve the purity, and then supplied logistically through dedicated distribution supply chains. Having a less tight specification for hydrogen as a fuel widens the production routes, reduces the energy and capital needed to make it and makes pipeline supply easier.

As the combustion process is less sensitive to impurities, a potential benefit of H2ICE is therefore that hydrogen used in engines can be used at a technically lower specification than that needed for H2FC, assuming that the possible impacts of any impurities on tailpipe emission standards and engine performance can be assured. Combustion can today easily use standard industrial grade 99.99% pure hydrogen and in the future might provide opportunity to widen the specification further, ultimately reducing the cost of hydrogen fuel supply.

5.3.3 On site operational experience and safety implications

The operational and safety issues identified within the group were overwhelmingly related to general use of hydrogen on-site, and therefore similar for both H2ICE and H2FC. One of the most significant operational changes is the need to assess the safety and risk implications for using the hydrogen-powered machines and any on-site hydrogen storage and supply infrastructure at the location of use.

Using hydrogen as a fuel/energy vector is a “new” experience for all applications involved in the hydrogen economy, albeit that using hydrogen in industrial processes such as the chemical industry, has a wealth of knowledge and experience that can be brought to bear on these new applications. In road transport, where hydrogen fuel has been more widely trialled and deployed, many of the safety standards and risk assessments for use have been defined and resolved. Sharing knowledge on these are needed to support the application of hydrogen in general in NRMM, which given the diversity of application and use scenarios, will need to be actively managed and facilitated for some time to enable wide scale deployment.

Aside from the overall safety and risk assessment needs of the move to using hydrogen fuel in the NRMM machines, the second most significant consideration operationally is how and where will the equipment be refuelled.

The filling process for a hydrogen machine is similar to filling diesel machines, in the sense that fuel is supplied to the equipment via a refuelling nozzle (or in the case of stationary gensets via a direct connection to the hydrogen storage supply). However instead of using liquid pumps to deliver the diesel from the storage tank to the machine, filling at pressure (350 or 700 bar), requires various levels of compression in the supply chain, to deliver full tank loads. As a consequence, compressed gaseous filling is somewhat slower than filling a diesel machine. Improving or optimising the time to transfer the fuel from storage to machine also requires additional compressed gas solutions such as cascade filling techniques (where the hydrogen is stored at different pressures) and even cooling during the filling process. This process and the solutions behind these technologies are proven for other gaseous fuels and in other sectors, albeit that for hydrogen the fuel supply industry is still working on the optimal configurations and requirements for the different applications such as public infrastructure, back-to-base applications, different use cases etc.

These considerations are, however, very unfamiliar for the NRMM sector and, because of the additional need in some types of equipment for the fuel to come to the machine rather than the machine go to the fuel (e.g. tracked vehicles, harvesters), there is a need for specific solutions that will work practically for the sector, particularly construction, mining and off-grid locations. Some early-stage examples of solutions for this additional complexity in NRMM (over other applications) including prototype options have been developed by JCB, ULEMCo and Fuel Cell Systems, and need to have elements of high-pressure onboard storage, all terrain off road capability, fast filling and direct refuelling connection (see Figure 22).

Figure 22: Example photographs of three hydrogen refuelling solutions

The frequency of refuelling (probably more often than is currently required for diesel) will also necessitate further operational considerations on site, along with the need to develop plans for scheduling this carefully within shifts and work patterns to ensure machine high-utilisation and uptime.

Aside from these generic issues the following examples of the NRMM application specific experiences give insight into how these hydrogen fuel limitations and differences impact the practical operational experiences of hydrogen in NRMM applications.

5.3.3.1 Construction Site Case Study

As mentioned previously, a key difference in construction equipment is the need for distribution of fuel to some machines rather than the machine going to the refuelling facility. In many cases this is needed for tracked machines such as excavators, which on a large infrastructure project may be working kilometres away from the filling station. For such cases the mobile fuel trucks described above may be needed and, depending on site conditions, this may require the construction of a suitable haul road, unless a full “off road and autonomous” solution can be developed.

Planning ahead on how and for what the hydrogen equipment will be used, and to what extent the hydrogen refuelling process impacts/disrupts site operations, will become an essential part of a contractor’s role going forward. These considerations will vary depending on the specific site:

A. On small sites it is expected that hydrogen will need to be delivered to site, probably daily. Deliveries can be made by mobile refuelling trucks which combine hydrogen storage with the filling equipment and possibly even onboard compression, or in high-pressure tube trailers (hydrogen fuel delivery vehicles), connected directly to the machines via pressure regulators and a filling nozzle. Machines would either need to travel to the refuelling truck to be refuelled (possible with tyred machines such as wheel loaders) or the refuelling truck would need to travel to the machines, a likely scenario for tracked machines such as excavators.

B. On larger sites it is likely that hydrogen will need to be stored on site. Storing hydrogen on site will follow precedent from guidelines developed for road transport applications, like the those issued by the BGCA, which define safe distances and hazard requirements dependent on the volumes being stored. Ensuring that the volumes stored will be below COMAH levels will be a key factor in determining the optimum levels to have on site. Depending on the individual site risk assessment process, it is likely that dedicated storage areas, hard standing, protection barriers and such like could be needed. These facilities will take up more space than equivalent diesel storage. Some form of electrical power for the facility would be needed. The hydrogen itself may be stored in multi-cylinder packs (MCPs) in racks or in tanks; and then other equipment such as specialized compressors, cooling systems, lightening protection systems and fire protection systems, are all needed to safely manage and deliver the hydrogen to the machine.

C. For major infrastructure projects and sites operational over significant timescales, the volumes of hydrogen needed may warrant, or lend themselves to, onsite production (or at least a localised dedicated supply) which could provide a legacy in the local area for wider economic development. The example for this is the Lower Thames Crossing project which, with the Highways agency, will procure the hydrogen supply through the lifetime of the construction project. The winning supplier would then have hydrogen supply and refuelling infrastructure in the area as a legacy.

Hydrogen use on construction sites has been demonstrated in a number of projects and locations in the UK, particularly within HS2 sites, and the recent DESNZ-sponsored Red Diesel Replacement demonstration projects.

From a business case perspective all of the above will currently add significant cost to the projects; the extra time and resource for the planning; the purchase or hire of the specialised equipment; the allocation of extra space and the differential cost of hydrogen supply over diesel. The differential cost of the actual H2ICE powered equipment that will likely be hired into the projects through plant hire companies, is proportionally minor in comparison to other technologies. This therefore stands as a good example of how H2ICE in NRMM could be used to accelerate the wider hydrogen demand and economy.

5.3.3.2 Agricultural and forestry case study

There is a huge diversity and range of equipment used in agriculture (farms, forestry etc) which is currently almost exclusively powered by un-taxed “red” diesel, in what are, by definition, rural locations. A key challenge for decarbonisation, in this use case, aside from this diversity and remote operational environment, is the very long-life span of the assets, often owned for more than 15 years.

The energy requirements of large farm vehicles and mobile forestry machines make the use of battery electric technology unlikely in the near term as they would require large, expensive and heavy batteries, regular high-power charging (which impacts battery life) or battery swapping – all of which are impractical in a rural farm setting. These machines will therefore need an alternative fuel.

Like other NRMM applications, machines and equipment used on farms are long-life assets with working lives of 15-20 years. To meet net zero targets, this suggests limited opportunity to get capital investment decisions made soon (in the next decade) to deliver by 2050. The capital depreciation and ROI of these investments can, however, be amortised over these longer periods, which can help the business case for investment in both the alternative fuel and additional machine/equipment cost. However, a level of certainty regarding the performance of the technologies, the practicalities in use and operational cost would need to be determined within the next few years. Since it is also “unlikely that the UK farm sector will be able to go through multiple transitions from fossil fuel ICE"[9]. The sector needs leadership and vision on where they should be focused. It is worth noting that this sector has already embraced alternative fuels in the form of biomethane, and products/machines are available that run on this fuel. The basic architecture of methane and hydrogen engines, and some gaseous fuel handling parts, are similar to those used for hydrogen, and are therefore complementary from the economies of scale perspective.

With the long asset life for farm vehicles and the low volumes, (e.g. under 15,000 tractors are sold each year in the UK; for specialised equipment like a combine harvester, numbers are even lower), these are a "prime" candidate for upgrading and repowering with combustion engines powered by alternative fuels like biomethane/bio-CNG and hydrogen. This upcycling opportunity, plus the need for robust equipment to deal with the "dirty" conditions (dust, slurry, mud etc.), favours the role for H2ICE over fuel cell technology in this application (which like other NRMM application needs significant R&D development to ensure that it can meet viable for the duty cycle and conditions).

Similar to the other sectors, however, the main challenge will be supply/sourcing of the alternative fuel to the rural location in a cost-effective manner. Onsite production of some of the fuel choices, including hydrogen, is theoretically more feasible than in other sectors (due to access to space and local renewable resources), however the business case for these investments is heavily linked to scale, which will likely only be applicable in the largest sites. It is therefore likely that a suitable mobile refuelling solution will be needed that can accommodate both mobile machines and those that will be out in the "field".

Addressing the safety standards and considerations of using hydrogen NRMM and fuel supply will also be slightly different for these agricultural applications, as the fragmented nature of the industry will warrant specific training and best practice advice.

5.3.3.3 Quarries case study

Interviews with representatives from two of the UK's major aggregates/quarrying companies were completed to explore both the inherent issues in their businesses to decarbonise and specifically on their NRMM.

Quarries use equipment that are largely "big dump trucks" with minimum 30 tonne payload in 40/50 tonnes machines as well as mid-range "shovels" at 25 tonnes. The challenge for decarbonisation of these very heaviest machines is most significant for them. The machines cost upwards of £500 k each, are kept for between 3 and 5 years and are subjected very aggressive use e.g. carrying full loads (80 tonnes) down or up steep gradients of the quarry at full load for the engines. Other examples include medium articulated dump trucks (25-30 tonnes) that are owned and operated for 10-12 years, meaning on this kind of life cycle, the next year's capital replacement budget will procure machines that will be used at least until 2036. Consequently, this means they are less than 5 years away from needing alternative fuelled, zero emission solutions to meet 2040 net-zero targets; in a world in which the solution is not clear. If H2ICE can be developed and deployed cost effectively at scale the

9 Farm of the Future, 2021 Royal Agricultural Society of England

targets seem much more achievable, at least from an equipment and technology perspective.

As part of the sector's thoughts to improve capital utilisation and TCO models, some are moving to a lease model in the future as well as looking at "rebuild", (and repower, upcycling etc.).

A typical machine will use 40 million litres of fossil derived fuel ranging from small sites using equivalent of 50 kW/hour to big sites using a million plus litres a year.

Most have explored HVO and biodiesel but, given the volumes that they need to procure, the current cost differential to diesel and concerns over security of supply from certified sources are currently barriers to the wide deployment of these drop-in fuels.

There is some belief that battery electric machines (BEM) could potentially do 50% of the mid-range equipment (up to 25 tonne machines), however this has yet to be proven in real-world demonstration. Larger than this, batteries are too heavy and/or will need supercharging to mitigate downtime. Either way, grid connectivity is the sector's major concern both from a cost and availability of supply for their sites. Although most quarries have mains connections, the power they use is for other processes (such as asphalt production) and so will need increased grid connectivity and capacity for NRMM charging.

Some locations might be suitable for off grid solar type approaches, but this is highly complicated and capitally intensive, and therefore fleetwide deployment of BEM is considered to be very challenging.

Other hydrogen specific practicalities noted:

- The challenge of hydrogen energy density was noted in terms of the implications of space on equipment for sufficient daily use/range. One source anecdotally suggested this is "5 times greater volume needed than liquid fuels" for the same use cycle. As noted in the engineering challenge area, this may lead to the need for machines to use 700 bar to address this, which is more expensive (in comparison to 350 bar) both for onboard storage and within the supply infrastructure. In the longer term, liquid hydrogen may be needed if these volumes are required across a whole site.

- There is some awareness of the opportunity for H2ICE, however the sector buys machines not engines, and the timescales to availability from new of the full range of equipment will need to be addressed to help meet 2040/50 net zero targets for assets that are owned for upwards of 12 years.

- Like construction, key concerns exist about practicality in general such as how much hydrogen will be needed on a site (particularly given the volumes). Based on a top end use at a large site they could be fuelling six 100 tonne trucks working double shifts (16 hrs), taking the equivalent of 1.5 MW of power/energy demand each. Security of supply of the hydrogen will be a significant factor at these volumes, giving both opportunity for onsite generation, and the wider use for such hydrogen in the process production for fuel switching, however realities (particularly in terms of volumes, see below) of these need to be explored beyond the theory if this are to be investable business cases.

- The above particularly invokes practical concerns around issues with storing H_2 on site (DSEAR, COMAH or otherwise) and on a mixed-use site, alongside asphalt production etc.

- In respect of the mobile machines, use outside the quarry (on the road) needs to be allowed for.

The last two points infer that in any event, agreed standards for use need be established before being able to implement solutions.

5.3.3.4 Power Generation Examples

Small scale mobile generators, used on construction sites demonstrated by JCB and others, mobile vehicle charging solutions such as the example show this summer by Commercial Fuels at the Belgian Grand Prix and/or at public events from companies like Plus Zero at the Edinburgh Fringe etc, have very similar practical challenges as noted earlier i.e. ensuring hydrogen supply to the equipment at the site and addressing any safety assessment requirements, although these generators do not require the compressed gas volumes (they will directly connect at low pressure (<10bar) to the storage vessel or tube trailer, mitigating some of the refuelling cost requirements). It should be noted that these examples shown in Figure 23 and 24 are all H2ICE rather than fuel cell deployments.

Figure 23: Example photograph of a H2ICE electrical genset

Figure 24: Example photograph of H2ICE genset

Having sufficient hydrogen connected to the generator, in these cases mostly with “multi-cylinder packs” (MCP) for the length of the run for the generator will take up space which has both adds cost and limitations at space constrained locations. The usual site safety assessments are also required, however the ongoing very public demonstrations of hydrogen use with both H2FC and H2ICE generators, such as those where H2FC were used, like the Goodwood Festival of Speed (Toyota), Latitude 2024 (Geopura, Figure 25)) and in the wider hydrogen use industry are helping to provide learning and precedent for safe deployment.

Figure 25: Example photograph of H2FC power source

The most significant practical challenge for larger scale fixed generators for grid scale back up power etc. is the volume of hydrogen that will be needed. Unless pipeline supplied, the volumes stored on site would need to be kept below COMAH levels, and therefore as with other examples need regular “tube trailer” replenishment.

H2FC technology has some advantage from quieter operation for urban and event applications, however, feedback confirms that H2ICE is quieter than diesel, and the overall piece of equipment can be insulated to minimise external noise output.

5.3.4 Education and training

General training is needed for use of “new” equipment, however, being based on familiar combustion powertrains, this is expected to be minimal for the H2ICE itself (as opposed to the fuel handling system). This is not necessarily the case for FC and other electric solutions.

Risk assessment and site safety certification will be needed because of the different hazards from using hydrogen, however, this is true for both H2ICE and H2FC.

The most significant difference is in relation to maintenance. Service technicians within the NRMM industry are well versed in handling existing machine fleet technology. They have developed a deep understanding of these systems through years of experience and training. Hydrogen combustion engine technology is therefore familiar to any technician who has serviced and maintained a diesel engine powered machine. As such, minimal training (e.g. gas safety awareness and spark plug replacement) will be required to support this technology compared to others.

5.3.5 Economic and business case implications

Alternatively-powered and fuelled machines tend to be more expensive than current diesel equipment when considered on a total cost of ownership basis due to:

- Operational cost differences given the current availabilities and costs of alternative fuels
- Capital cost differences of new technologies, that are not at scale and with themselves inherent supply chain cost differences
- Different depreciation structures, known or otherwise
- The unknown implications of maintenance over the life of the machine.

NRMM is a highly competitive sector with operational cost being one of the single biggest differentiating factors between OEM machines (they have worked hard for years to improve fuel use efficiency by “a few % at a time”), followed by reliability (to mitigate life-time maintenance costs and maximise uptime) and then robustness (providing machines that can cope with harsh use and duty cycles). In the UK, the market is also heavily influenced by financial cost models, due to its significant reliance on lease and hire of plant and equipment such that depreciated value of machines is also crucial to creating a strong business model within the NRMM industry.

As an example of this tight competition, at the machine level, the least expensive change to reduce GHG emissions, in comparison to diesel is to use sustainable “drop in” fuels, like HVO. In 2022, the price differential between HVO and standard B7 pump diesel was of the order of 15 pence per litre[10] and this is still true today. In discussing Net Zero strategies with operators, even the implications of the higher costs of these fuels (and lack of security of supply in the volumes needed) are current barriers for delivering decarbonisation.

Another contributor to the overall cost of these machine are the critical raw materials embedded within them. Electrification of NRMM is highly likely to be limited by raw material availability, given the size of batteries that would be required by such equipment. Electrification in road vehicles is already projected by the International Energy Agency[11] to lead to shortfalls in global supply of lithium and copper, while the markets for nickel and cobalt will be tight. Prices will need to rise to bring on additional supply, with a likely knock-on impact on battery costs. Additional demand from the non-road sector would exacerbate this situation. Storing energy on board as hydrogen used on H2ICE or H2FC machines instead of in batteries, significantly reduces this raw material intensity, with H2ICE also saving on the materials and precious metals, needed for motors, and other related electrical/stack system components.

Given the wide ranging economic implications of the applications for NRMM, such as the overall cost of construction projects (actual build plus the quarrying of the materials used), in food production, and back-up power energy generation, the NUMBER ONE opportunity for assessing the role of H2ICE in support of delivering Net Zero in NRMM is therefore the extent which equipment powered by hydrogen combustion, can mitigate the inflationary implications of the net zero transition for users of the equipment.

That said, given the very early stage of the range of technologies and approaches to decarbonisation in the sector (almost no real-world in use data exists to date), it is not possible with any certainty to provide direct cost comparisons between the mature application of diesel machines with these new solutions, however the factors to be considered are:

1) On an operating expense basis, the efficiency of the use of the fuel in the specific duty cycle is the key parameter for comparison. Given the performance assessment of H2ICE (similar if not better than diesel), if the price of hydrogen (delivered to the machine) is also similar to diesel on an energy basis, then there is very good prospect that machines with these engines will be no more expensive to operate, than the current solutions. NB: it was not the scope of the subgroup to comment on the potential cost of scaled H2 price, although as the planned Hydrogen Production Business Model (HPBM) benchmarks the production price to natural gas, currently anticipated to be cheaper than diesel, so this should go a long way to supporting this market need, as far as the molecule price is concerned. As noted however, distributing and storing gaseous hydrogen onsite will at least in the early stages, require greater investment in planning and site infrastructure than is currently needed today with diesel, as well as the increased capital cost comparison for the equipment for distribution (tube trailers etc) and refuelling (compression, and high-pressure storage). Although some of these cost differences can be considered by contractors when estimating and tendering, there remains a significant “gap” post-implementation

[10] Decarbonising Heavy Duty Vehicles and Machinery (zemo.org.uk)
[11] Global Critical Minerals Outlook 2024 – International Energy Authority

of the HPBM, to address the full differential between diesel and current hydrogen supply costs. They will apply to fuel cell or H2ICE.

2) The maintenance costs of machines with H2ICE are not expected to be any more expensive than their diesel equivalents. The current expectations on lifetime are within the parameters of conventionally fuelled engines, and as consequence are more likely than new technologies which are yet unproven in the application to give a similar depreciation value. OEM warranties are likely to be the same.

3) The main TCO difference for the business case is therefore in relation to capital cost comparison. Capital cost relates to manufacturing scale, supply chain and inherent material costs in the production process. This is explored in more detail below, as a key expectation is that the capital cost of H2ICE will be significantly lower than other net zero-emission technologies, and therefore it's key differentiator for mitigating the cost of Net zero for the NRMM sector.

What makes hydrogen combustion stand out, as "the lowest capital cost" option for net zero-emission NRMM equipment?

Importantly, to deliver the high power, highly transient performance demanded by the NRMM industry, specific technology is required. As such technologies developed in applications like light-duty automotive, are not directly transferable, which in turn limits the potential leverage volume, as is the case today for existing diesel engines and machines. There is some cross-over with HGV, particularly in the medium-sized equipment, but minimal from the mass market, passenger car sector.

Data shows that the capital cost per kW of a conventional engine technology is £80/kW[12]. This is based on mature production volumes, developed over decades, within a well-structured and costed supply chain. (based on using diesel, HVO or similar drop in fuels). Current expectations for hydrogen engines produced in small volumes may cost around 25% more, based on the need for spark-plugs, coils, some tooling costs and initial R&D returns. As production volume increases, with scale, costs are expected to match conventional engine costs.

Otherwise, capital cost comparisons between diesel equipment and hydrogen ICE, at machine level relate to the additional cost for onboard hydrogen storage and related high-pressure components. This is currently estimated at low volume to be around £30/kW and for volume production at £9/kW based on the following:

- Hydrogen tanks generally cost £1,000 per kg currently (including tank and on-tank valves – which typically include a regulator, shutoff solenoid and temperature relief valves), however production is currently at a relatively low scale.

- With 33.3 kWh of energy per kg of hydrogen, this equates to £30/kWh.

[12] Closed DESNZ call for evidence: Non-road mobile machinery: decarbonisation options 2023.

- Faurecia, who are global leaders in their investment and strategy for hydrogen tanks, is targeting to reduce H_2 storage system costs by 75% by 2030, to €315 per kilogram of H_2 stored (at 700 bar)[13],[14].

- These figures are in-line with the 2030 US Department of Energy target cost for storage tanks of $9/kWh ($300/kg H_2), at 100,000 tanks per year annual production volume[15], and is supported by the Clean Hydrogen Strategy and Roadmap 2024 to 2028 target to reduce the unit price of carbon fibre by 50% vs 2020[16].

- Mass production volume pricing of hydrogen tanks can be estimated to be ~£9/kWh.

Publicly available comparisons[5] of cost trajectories for both H2ICE and H2FC are set out in Table 12 and show cost-down for H2ICE based on well understood experience-based assumptions of the impact of maturity and scale; those for H2FC are less certain based on learning curve expectations and forecasts given the unproven nature of the technology.

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 12: Cost estimates for H2FC and H2ICE powertrains in 2020 and 2035

Furthermore, the predicted cost evolution for scaled production of technology like batteries, and electric motors are not easily applied to the sector and, in any event, would need to be developed specifically for these applications. This is due to need for specific transient responses, efficiency at high and low temperatures and acceptance of impurities in the air such as dust and fumes, resilience of the technology in harsh environments and being easy to operate, service and repair.

This principle is illustrated in an internal study by JCB when comparing today's fuel cell technology (developed for road applications) with hydrogen ICE (see Figure 26). JCB

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13 Faurecia Hydrogen Strategy, 2020, Faurecia
14 Hydrogen is poised to fuel cell composites growth, Part 2, 2021, Composites World
15 A review on the cost analysis of hydrogen gas storage tanks for fuel cell vehicles, 2023, Energies Journal
16 US National Clean Energy Strategy and Roadmap, 2023, US Department of Energy

examined the powertrain up to and including the rotating mechanical output (the flywheel for engines and motor output for fuel cells) for a 20-tonne excavator (which typically uses a 129 kW engine) and compared the costs as follows:

- For the **diesel** and **hydrogen engine**, costs are based on JCB's data for a 55 to 129 kW engine (including ancillaries and cooling fan) (minimal difference between power ratings when levelized for kW).

- For the fuel cell, this is based on data from the JCB fuel cell powered excavator prototype (actual supplier quotations) which included:

    - **Hydrogen Fuel Cell:** 70 kW fuel cell (£1,410 per kW) – note lower than engine peak power due to ability to provide average power requirement rather than peak transient demand. The peak transient demand was fulfilled by the supporting battery pack.

    - **Additional System Components:** DCDC converter, power electronics, Lithium-Titanate high power battery pack, electrically driven cooling fan, four separate radiators (for coolant and electric motors – all levelized to the 70kW output).

JCB contend that until the operational application issues are resolved, the fuel cell technology for the equivalent machine, is 20-40x more capitally expensive than hydrogen combustion.

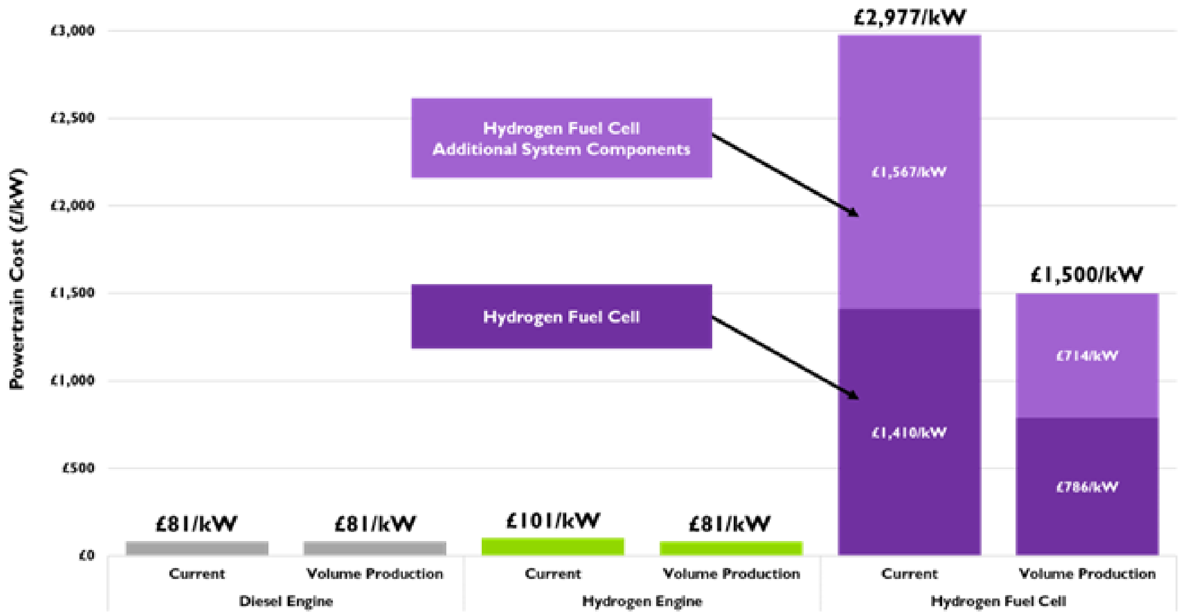


Figure 26: Cost comparison for alternative propulsion systems (source: JCB)

At a machine level, engines may be hybridised, with electric/hydraulic drive architectures, in the various configurations from series to range extension and parallel drives. This will be developed on a machine-by-machine basis, depending on the different duty cycles, power demand etc. and, of course, TCO considerations. Having an engine with similar costs to a conventional engine with effectively zero-emissions allows for energy use optimisation and benefits from use of "right-sized" electric motors, inverters and battery storage.

A specific business case benefit of H2ICE technology Is the potential to retrofit into existing equipment when more hydrogen engines are commercially available. Extending the life of equipment through repowering and upcycling avoids the embedded carbon of new vehicle manufacture and, as long as the refurbishment can be done at lower cost than purchase from new, it will also allow for a significant improvement in TCO.

Replacing diesel engines with hydrogen engines is likely to be an easier (and therefore cheaper) process to complete than is possible with other zero-carbon technology based on electrified drivetrains (fuel cell or battery electric). In the case of these new technologies, it is very challenging to match the power output and the other ancillary equipment such as hydraulics, thermal management systems etc. of the original diesel machine with the electric system, without effectively completing a full, bespoke redesign; whereas replacing one engine with another (albeit needing hydrogen storage) is something that is a well-established and a routine process today. Once hydrogen engines are available in various sizes and performance ratings, this approach could significantly accelerate the timescales for decarbonisation across the sector.

From a business case perspective, based on the above, H2ICE powered systems, are expected to:

- Have a similar capital cost at the engine level. At a machine level the capital cost will be slightly higher due to the differential cost of onboard hydrogen storage, but this is expected to be within the scope of “normal” price inflation/improved product development changes. Equally the machines and engines will likely require similar maintenance regime and cost to current equipment.

- Demonstrate life-time durability and robustness that matches existing equipment and therefore will have a similar depreciation model to that used in the industry today

- Have the opportunity for repowering and upcycling more easily and cost-effectively than other zero-emission solutions and therefore offers significant opportunity to limit the impact on asset replacement programmes and capital investment needs within Net Zero transition

H2ICE therefore represents the most likely solution for net zero-emission NRMM technology that will mitigate the inflationary risk of the transition to Net Zero.

5.4 UK Economic Impact

The NRMM sector i.e. UK manufactured machines, engines and key elements of the supply chain for off-highway and non-mobile powered equipment, was worth at least £17.6 Billion to the UK economy in 2022 with over 80% of that revenue coming from export /foreign income. That same year, almost 100,000 jobs were supported in the sector directly and indirectly of which around 56% were involved in engine production[17].

Equally, given the breadth of applications and industry uses of these types of equipment, including of construction, agriculture and stationary energy generation, the widespread value of the sector to the whole of the UK economy is fundamental. For more market detail, please refer to Appendix 1.

For instance (all data sourced from ONS[18]):

- The value of new construction work (in current prices) in Great Britain in 2022 increased 15.8% to a record high of £132,989 million; this was driven by growth in both private sector work of £14,093 million and in the public sector of £4,068 million.

- Construction new orders rose 11.4% in 2022 to £80,837 million, driven by private infrastructure, private commercial and other public non-housing; the only sector that decreased was private industrial.

- In the Quarter 3 (July to Sept) 2022, 374,332 Value Added Tax (VAT) and Pay As You Earn (PAYE) registered construction firms were operating in the construction industry across Great Britain, which is a 5.9% growth compared with 2021.

- The number of construction-related employees (excluding self-employment) in Great Britain increased 3.3% in 2022 compared with 2021, totalling at 1.4 million workers; the biggest contributor to the growth in 2022 was England with a growth of 3.5%, Wales and Scotland both increased by 2.0%.

- The construction industry saw a 59.4% annual increase in the number of recorded company insolvencies in 2022.

- The all-work construction Output Price Index saw strong annual price growth of 8.8% in December 2022.

[17] Companies House, ONS ABS Approximate GVA, and ONS SIC 29 Jobs multiplier (2024)

[18] Construction statistics, Great Britain - Office for National Statistics

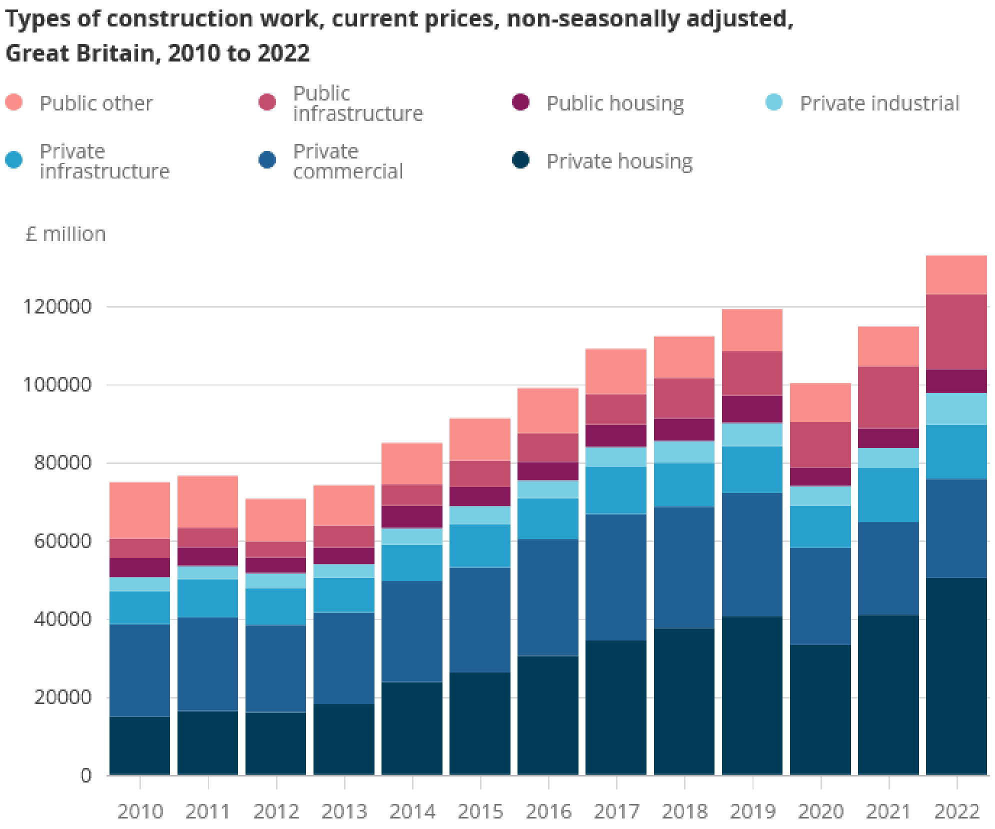


Figure 27: Total new work construction output increased 15.8% in 2022, reaching a record high value of £132,989 million (source: Construction statistics, Great Britain from the Office for National Statistics)

The use of NRMM on the overall economy has significant impact on cost and delivery of huge swathes of public-funded activities, from construction to the subsidised farming sector.

Having this equipment productive, decarbonised, cost effectively will underpin many of the clean growth ambitions going forward, and value for money delivered from investments in infrastructure, as well as reducing the overall embedded carbon that is included in our publicly procured development projects. Smart Investment to support the sectors where NRMM is used in the process to Net Zero will have significant multiplying effect on the UK economy as a whole, as well for the sector itself.

5.4.1 NRMM contribution to GVA in the UK Economy

The key UK manufacturers and suppliers and examples of their equipment are illustrated in Figure 28 below:

Manufacturer	Example Models (not full range, concepts included)
JCB	
Caterpillar	
Case New Holland	
Terex	
Komatsu	
McCloskey	
Volvo Construction Equipment	
Mecalac	
Thwaites	

Manufacturer	Example Models (not full range, concepts included)
Cummins	
Perkins (Caterpillar)	
BorgWarner	
JCB Engines	

Figure 28: Example products and services from key UK manufacturers and suppliers

Figure 29 below shows the companies house revenue breakdown and growth from these listed key players and shows that, in 2021, NRMM contributed £2.6 billion of GVA to the UK economy.

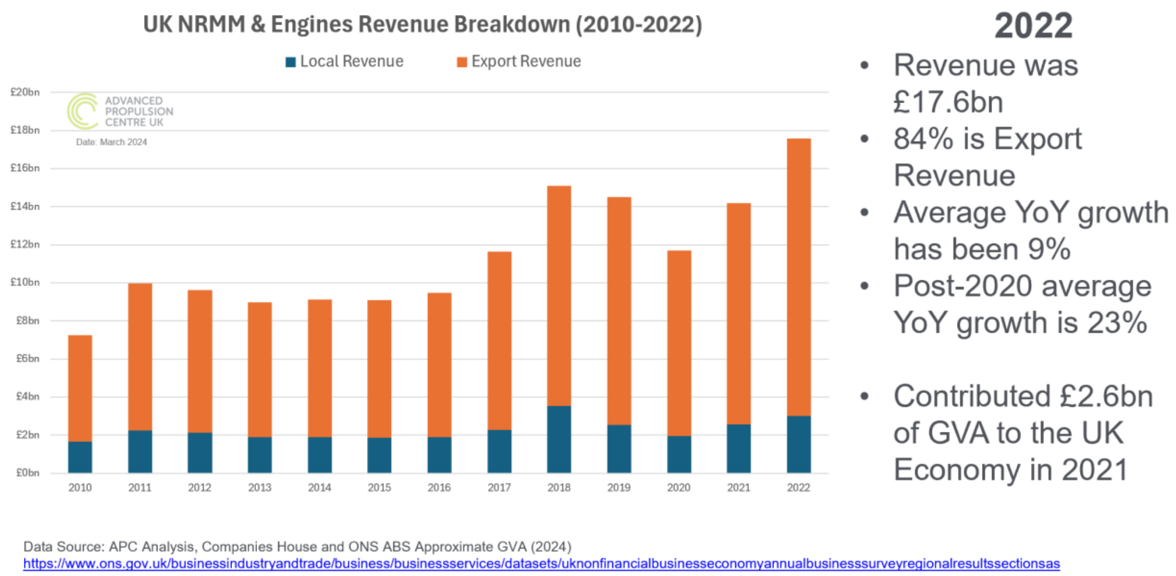


Figure 29: Heavy duty industry revenue analysis based on Companies House data for the defined list of companies

The NRMM industry makes up over 80% of the UK's heavy-duty industry (systems and vehicles above 3.5t), showing the strategic importance of the sector. Across the whole UK automotive and NRMM industry, companies such as JCB, Caterpillar, Perkins, Case New Holland and a proportion of Cummins serve the NRMM sector specifically (Figure 30).

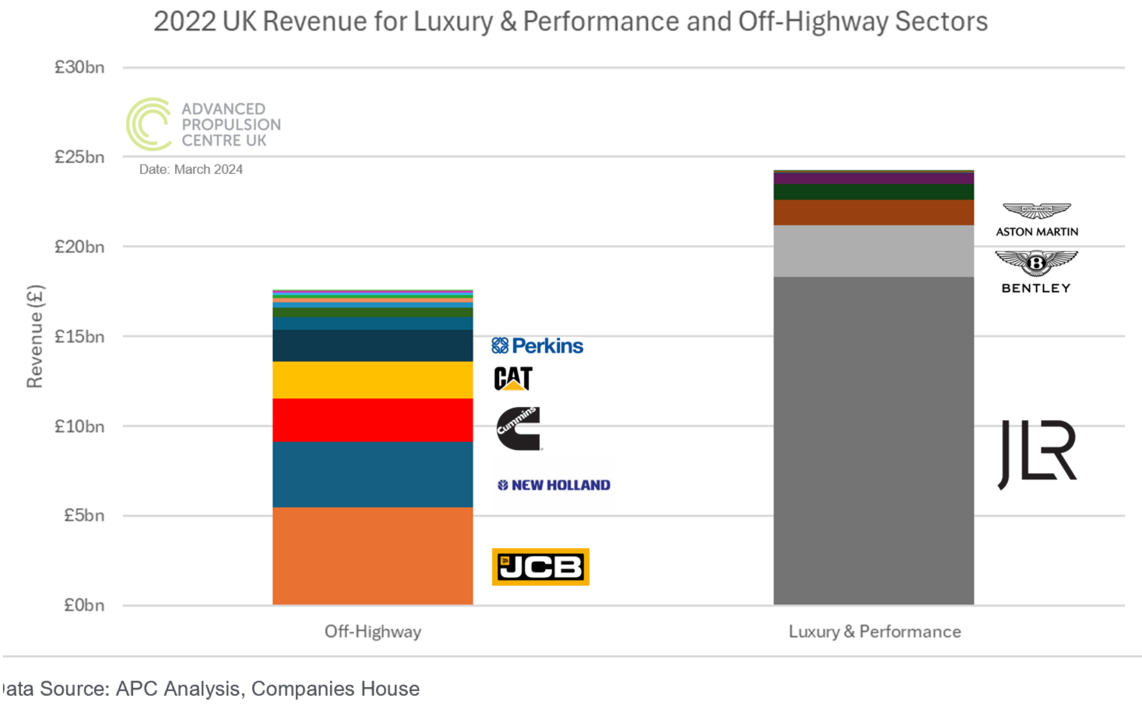
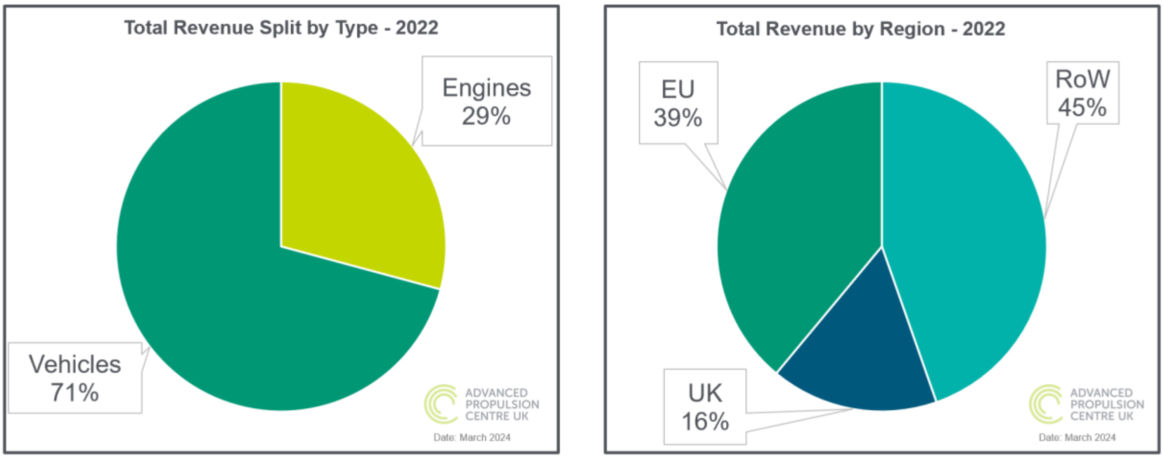


Figure 30: NRMM vs on-highway UK company revenue 2022. From the Advanced Propulsion Centre.

NRMM revenue is comprised of 71% from whole vehicles and 29% from engines. 84% of the UK manufactured vehicles and engines are exported to Europe and the rest-of-world (Figure

30). Due to this high proportion of export, it important that the UK maintains alignment with its key export markets to continue to grow the industry. It is therefore important to note that the EU currently has the same air quality targets as the UK. If the UK takes a different approach to regulation than our nearest trading bloc, UK companies could be put at a disadvantage.



Data Source: APC analysis, Companies House (Regional data excludes Thwaites)

Figure 31: Breakdown of heavy-duty industry revenue (source: Companies House)

Global manufacturing volumes of hydrogen engines will initially be low, before ramping up as more widespread adoption takes place. For engine manufacturing costs to fall, the demand globally would need to increase dramatically. This will require widespread adoption of H2ICE across many markets. High demand from the UK market alone may not be enough to impact manufacturing costs.

5.4.2 Growth from innovation

The UK has recently held a world leading position in ICE production and innovation; within the last ten years, the UK contributed 25% of all Europe’s engine manufacture. However, the arrival of electrification in the light duty sector, supported by targeted policies that promoted research into battery-electric systems and manufacturing, has not been matched by such major support for the H2ICE or hydrogen as a fuel. While there is an opportunity now, there is also a risk of losing the UK’s strong position.

The development of lean burn and hydrogen engines represents an opportunity to directly benefit from the existing knowledge base into addressing the innovation needs of decarbonisation and delivering clean growth whilst establishing the UK as a leader in H2ICE engine technology and supply.

Innovating on how to apply and use hydrogen technologies ahead of other markets gives us both leadership benefit in our own economy and provides a springboard for new growth outside the UK. Getting ahead by supporting the more easily adopted and more readily available H2ICE innovations will give the UK opportunity for fuel cell innovation in the future.

5.4.3 Jobs created/protected (OEM and supply chain)

There are a significant number of people currently employed in the NRMM and engines sector. In 2022, almost 100,000 jobs are supported either directly or indirectly (Figure 32), of which around 56% are involved in engine production (Figure 31). This shows both the importance of the sector and the foundation on which to build future clean engine supply chains. A transition to electro-mobility will likely result in a 28% job loss[19] in traditional automotive manufacturing industry. Safeguarding the skills and supply chains set up already in the UK is a robust strategy to secure the UK as a key leader in the transition to net zero and retain the benefits that this sector brings to the economy. Across the automotive and NRMM manufacturing sector, there is an expectation that there will be a global overcapacity of engines by 2030. With engine makers likely to rationalise their engine manufacturing footprint over the coming decades, having a supportive home market through appropriate policy and regulation will make retaining UK manufacturing and supporting jobs a more attractive prospect.

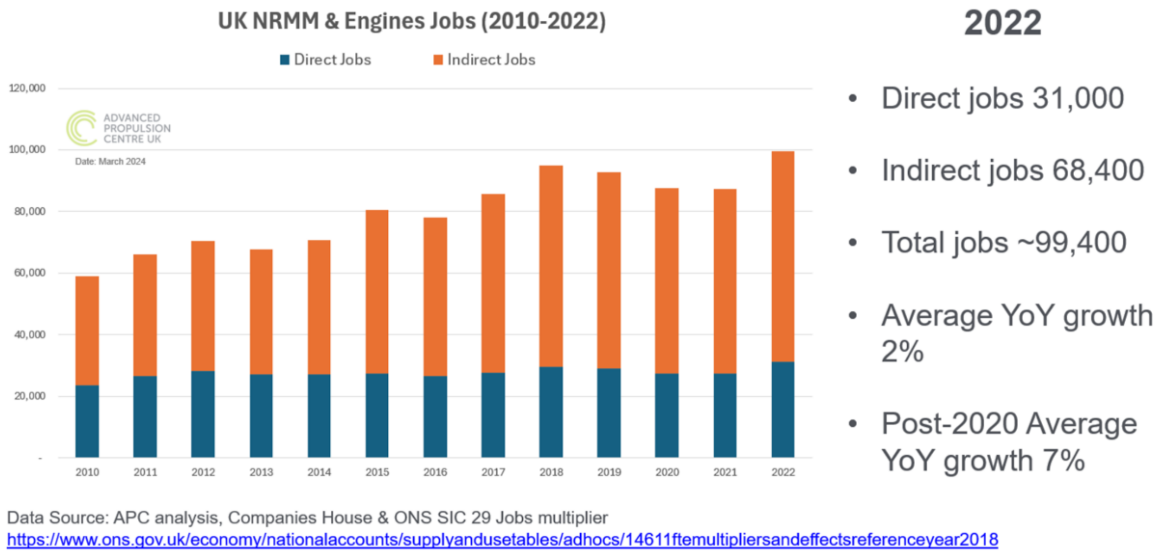


Figure 32: Direct and indirect jobs in UK NRMM sector

Particularly important is the fact that hydrogen combustion engine technology is familiar to any technician who has serviced and maintained a diesel engine powered machine. As such, minimal training (e.g. gas safety awareness and spark plug replacement) will be required to support this technology, therefore protect these jobs in the transition.

A Transport and Environment study in 2017[20] discussed the effect of the transition away from ICE to BEV in automotive applications concluding that:

“The shift in sales away from the ICEs towards BEVs results in important changes in the automotive value chain and the required skills. It will also result in some loss of jobs in the automotive sector – although there will be net gains economy wise. **Some automotive job losses are likely since the manufacturing process for a conventionally fuelled car**

[19] https://www.transportenvironment.org/articles/dramatic-job-creation-finding-e-vehicles-study
[20] How will electric vehicle transition impact EU jobs

differs significantly from the one of an electric vehicle.” Most significantly the report notes that this change in manufacturing from ICE to battery production is largely overseas.

When considering the wider supply chain, the study also notes that, with the whole scale transition, massive transformation and business change is needed across industry into alternative products, manufacturing processes and even different sectors if the net effect of the job impacts is to be at least safeguarded. They argued, 7 years ago for the automotive sector, that to do this “engineers and skilled workers will have to be trained to match the automotive sector’s evolving needs” and that “with increased integration of the energy, telecommunication, and transport sectors, the impact of electric vehicles on job creation will need to be decoupled from its mere consequences on OEMs and their traditional tier 1 suppliers” illustrated in Figure 33 below:

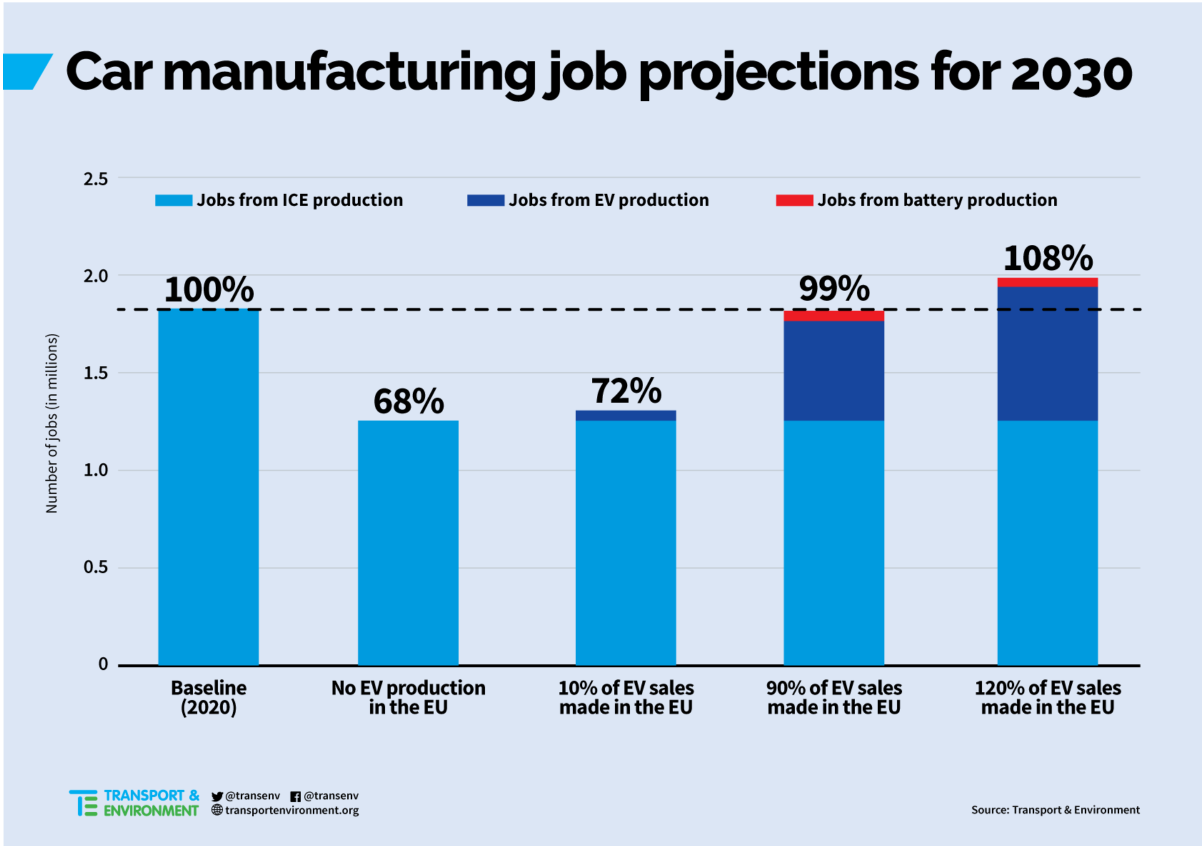


Figure 33: T&E study on impact of transition to passenger car manufacturing

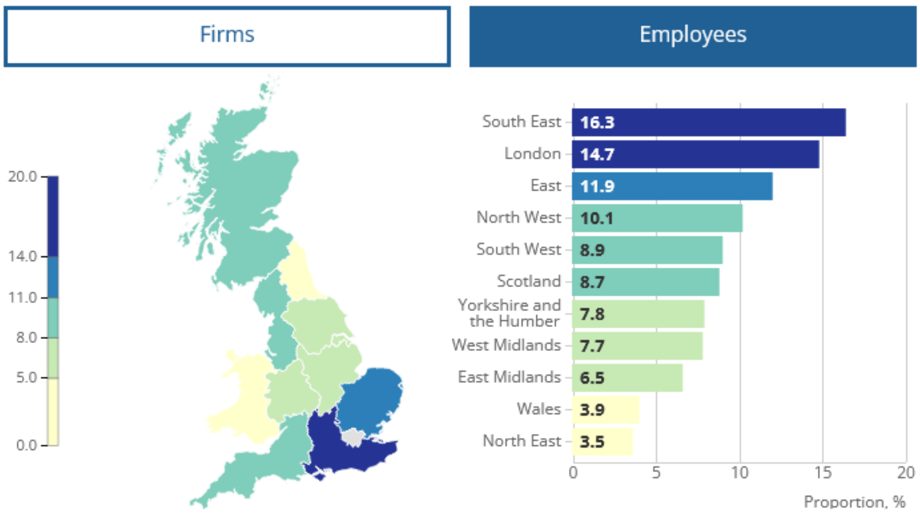
The study makes the case for EU OEMs and policy makers to invest heavily in the transition, and for policy makers to encourage and support EU-based manufacturing, in the face of the risk of non-EU production, particularly offshoring to China, and or overall Chinese imports.

Similar impacts could be expected in NRMM, particularly if hydrogen ICE is not supported. With global economic pressures and changes, and the massive levels of investment that is required in any event for the delivery of Net Zero, it is much easier to keep and safeguard jobs in existing skills, with known products and systems, than it is to have radical transformation of the sector and its supply chain. Supporting a UK skill base, with existing scaled manufacturing capability that has a proven track record competitively, should arguably provide the strongest case for economic support to deliver growth in the transition.

Jobs in the sectors

Construction: Total employment (employees and self-employment) data from the ONS[21] remained at 2.2 million workers in the construction industry throughout 2022. The jobs are spread throughout the country as detailed in Figure 34 below, demonstrating the widespread economic impact potential for this application of NRMM.

Proportion of total construction firms and employees in Great Britain, by ITL1 region of registration, classified as of Quarter 3 (July to Sept) 2022



Source: Construction statistics, Great Britain: 2022 (Table 3.3 and 3.6) from the Office for National Statistics

Figure 34: ONS statistics for employment in construction sector

Agriculture: According to Defra statistics[22] the total number of people working in agriculture in England was 285,000 on 1 June 2024, showing a decrease of 2.6% since 1 June 2023. In 2024 farmers, business partners, directors and spouses accounted for almost two thirds (61%) of the workforce and, at 173,000 people, saw a decline of 3.1%. This figure had remained relatively stable over the previous 3 years at around 179,000 people. Salaried managers make up a much smaller proportion of the total (4%) and decreased by 2.3% to 12,000 people in 2024. Regular employees and casual workers make up the remainder of the total workforce, accounting for 23% and 12% respectively, as shown in Figure 35.

[21] Office for National Statistics, Workforce jobs by region and industry 2024.
[22] Defra, Agricultural workforce in England at 1 June 2024

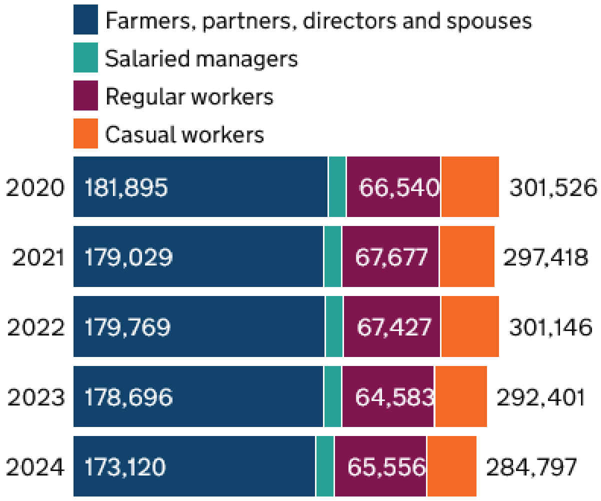


Figure 35: Total agricultural workforce in England at 1 June 2024

Clearly impacting the costs of this sector, that are heavily dominated direct owner businesses, is hugely impactful for their productivity and sustainability of employment.

Quarrying and Mining: According to the UK EiTi[23] the extractive industries in the UK comprise oil and gas production, mining and quarrying. These sectors play a major role in the UK economy, contributing a total of £2.4 billion Gross Value Added in 2022 (Figure 36) and employing some 50,000 people directly (Figure 37), with many more supported in the industries' wider supply chains.

[23] UK Extractive Industries: Mining and quarrying in the UK, 2024.

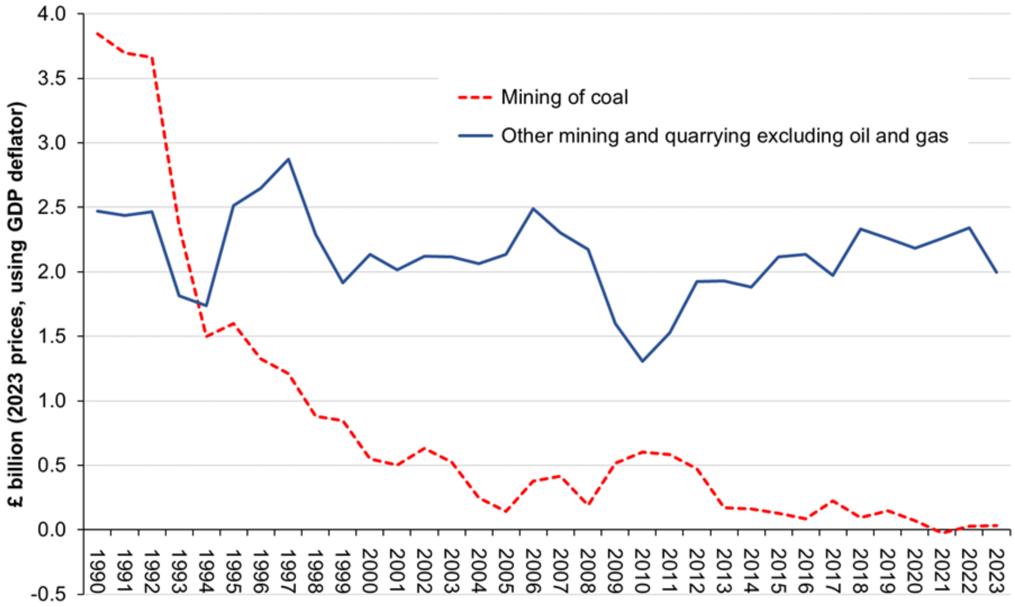


Figure 36: Gross Value Added (GVA) of UK mining and quarrying (excluding oil and gas)

Figure 37: ONS Mining and Quarrying employment levels.

By its very nature these jobs in quarries and mines will be concentrated in specific regional locations and have major local impacts for competitiveness, local productivity and employment concentration in these areas.

These snapshots highlight the UK wide impacts for all the major NRMM using sectors, which will drive growth in the economy within the clean growth agenda and provide an overwhelming case for ensuring that the right, inflation minimised solutions for decarbonisation are embraced.

5.4.4 Building skill base that can be utilised in other sectors

As noted earlier, hydrogen combustion engines utilise the existing workforce and skill sets both in the UK and across the world. This enables a technology transfer of NRMM from the

UK to other countries – vitally important for machine resale into other countries, and export potential from the UK to a global market.

The most significant opportunity, however, is to apply the learning from NRMM to other transport applications, including heavy duty road vehicles, marine and rail applications. While rail and some marine propulsion systems are classified as NRMM, heavy duty road vehicles have their own regulation and UK policy direction is focused on achieving absolutely zero tailpipe emissions. While not the focus of this report, it can readily be inferred that the "95%-plus" air quality benefits offered by the H2ICE off-highway could also be accessed on-highway, more quickly than a transition to "more perfect" alternatives. As NRMM engines in the 3-15 litre category tend to be shared with trucks or buses (at least in base form), co-transition of off and on highway to H2ICE would bring further economy of scale. As explained in section 5.2, it is worth noting that the European Union has now classified the on-highway H2ICE as "zero emitting" for GHG purposes, so long as it meets Euro 7 emissions standards.

Additionally, the Hydrogen Innovation Initiative state in their Hydrogen Innovation Opportunity report[24] that the hydrogen technology market could bring £46bn of gross value add to the UK economy and directly support 410,000 jobs in the hydrogen technology supply chain. This is a combination of jobs across the technologies associated with the production, distribution, and consumption of hydrogen. Supporting hydrogen combustion development in the UK enables the transition of skills from fossil fuelled engine-development to decarbonised propulsion and contributes towards a critical mass that unlocks the potential for the UK to be a globally significant hydrogen technology provider.

5.4.5 Opportunities for accelerating industry and hydrogen adoption

Given the high energy demand in the sector, as defined by volume of diesel, the application represents a major opportunity for hydrogen scaled demand. Even a small share of this potential demand could be a valuable real-use application for the government's stated goal to have at least 10 GW of energy being available the energy system as hydrogen by 2030.

In both the short term and medium term H2ICE has the opportunity to facilitate and even accelerate demand for hydrogen fuel, by:

- Creating significant early demand for H_2 (being a more readily available, easier to deploy hydrogen technology)
- By creating demand, it will improve the investment case for H_2 production and supply, which then:
    - Reduces the length of time there is gap between demand and supply

[24] https://hydrogeninnovation.co.uk/wp-content/uploads/2024/04/UK-Hydrogen-Innovation-Opportunity.pdf

- Reduces the level of subsidies and/or the length of time subsidies are needed
- Facilitates the introduction of the fuel cell into markets where it is the appropriate solution, by ensuring that this new type of powertrain no longer needs to introduce its own new fuel

The policy focus should be to bring to market new machinery equipped with H2ICE, displacing Diesel sales as much as possible, in order to deliver the full greenhouse-gas and air quality advantages described in this report. In the nearer term (meaning, at least the next decade), there is also a re-powering and upgrading opportunity for types of machines where this is economically justified (typically larger, more specialised and expensive equipment like excavators, articulated dump trucks or combine-harvesters often owned for 12 years or more). It is therefore worthwhile considering what regulatory approvals and mechanisms might also be put in place to support innovation in this circular and sustainable economy approach, that is brought about by embracing H2ICE particularly where it is likely new OEM solutions will be further down the line.

Providing early demand also allows for the development of the hydrogen transport and supply infrastructure, which will particularly have cross over benefits to the transport sector as many of the core solutions for moving hydrogen around and for refuelling will be similar. In the long run having early opportunity for real-use and demand across the country will provide benefit to the business case and roll out of pipeline connected hydrogen refuelling solutions. This helps to spread the cost of the infrastructure and shorten the time for hydrogen the supply price to become affordable.

A more practical benefit of having a technology solution that is closer to market and more easily adopted, will be the opportunity government, local authorities, and other important organisations, to award contracts at least in part based on reducing emissions and sharing the risks of new technology use, which would then persuade contractors and NRMM owners to adopt low emission technologies of through competition and market forces.

In any event, creating demand for hydrogen, as part of the wider plans for the hydrogen economy, is a major opportunity for overall development of the hydrogen economy and the energy system benefits that that can accrue.

6. Key Enablers/Blockers

The overwhelming barrier to the adoption of H2ICE as a decarbonisation solution is that it is not recognised as a net zero technology in the UK. Currently, there is no CO_2 or GHG regulation in the Stage V emissions standard but, since many of the engines are also used in on-highway applications, it is worth noting that the European Union has recently adopted a "zero GHG emitting" standard for heavy duty on-highway vehicles, requiring that they (a) meet the Euro 7 emission standard, regardless of power source, and (b) emit no more than 1g CO_2 kWh^{-1}. Evidence presented here has clearly shown that H2ICE is able to meet these criteria and hence should be classified as a net zero-emission technology.

From a more practical perspective, the main blockers noted for hydrogen (both FC and ICE) in NRMM applications were:

- Availability and cost of hydrogen
- Space on site particularly in the transition when diesel is still being used
    - Space for safety mitigations
    - Need for electrical power for refuelling
- Inconsistency in planning requirements/assessment of sites
- Lack of clarity on cost allocation
    - Who is paying? Contract margins are already tight and there is no mechanism to get paid more for using net zero-emission equipment
    - Plant-hire companies' involvement in the supply chain
- Lack of incentives for adoption
- Uncertainty of new technology adoption especially when considering ownership models

Aside from the technical and economic challenges, the sector tends to be risk-averse with contractors and NRMM owners operating in a highly competitive business environment on complex projects, with onerous contract conditions which require them to deliver high quality work on time and to cost, in return for low to modest margins. With little appetite for risk-taking and use of unproven methods, contractors are wary of adopting any new and untried approaches (even H2ICE which is based on familiar technology) unless it is really required by the client, and unless there is a fair split of the associated extra costs and extra risks. Clients, including the government, local authorities, and other important organisations, will need to start awarding contracts at least in part based on reducing emissions and sharing the risks and costs of new technology in order to persuade contractors and NRMM owners to adopt low emission technologies of their own accord.

These market forces alone will therefore not drive change on the timescale needed to meet government emission commitments. Government regulation and incentives are essential to accelerate the change. This is seen clearly in other European countries which have adopted such policies. Zero-emission NRMM is more expensive to buy than conventional NRMM and owners in the UK report that they cannot get paid more for work carried out with zero-emission equipment. Until regulation and new forms of contract in the construction industry start to recognize and reward low emission solutions, and that construction projects measure and pay for emissions, change in the industry will be slow. Furthermore, tax breaks and financial incentives need to be in place specifically for NRMM if the pace of change is to be accelerated.

UK regulations also need to be harmonised with the EU regulations. Continued acceptance of CE-marked-only NRMM in the UK is vital as divergence will cause OEMs to deprioritise the needs of the UK market in their product development plans. Commonality of regulations for on-road trucks and NRMM would be helpful to drive industry economies of scale e.g. 700 bar infrastructure for hydrogen trucks and NRMM.

To this end, the UK government needs to set and communicate a clear vision, strategy, and legislation timeline for net zero requirements in the construction industry and for NRMM specifically. This allows the whole value chain to plan and invest accordingly.

6.1 Policy Interventions Required

- Accept and promote H2ICE as a net-zero technology for NRMM, recognising that the conclusions from this report are equally applicable to other sectors including on-road applications.
    - This will also unlock funding support and investment for further research and development, drive innovation, protect and create jobs, skills etc, and drive scale to address the economics.
- Review emissions regulations and standards to ensure “best in class” emissions (GHG and air quality)
    - Taking into account any future EU/international regulations
- Establish regulation and new forms of contract in the construction industry to recognise and reward low carbon, NO_x and PM emission solutions, and that construction projects measure and pay for emissions
- Create consistent, harmonised planning regulation/best practice/shared learning on hydrogen safety and on-site requirements
    - Ensure consistency of assessment
- Put in place appropriate financial mechanisms (from capital incentives to technology demonstration funding and fuel price support) to make hydrogen available and cheaper to use than diesel that creates early-stage demand and accelerates the pace of change in the application.

To this end, the UK government needs to set and communicate a clear vision, strategy, and legislation timeline for net zero requirements in the construction industry, and for NRMM specifically. This allows the whole value chain to plan and invest accordingly.

7. Conclusions and Recommendations

A number of conclusions can be drawn from this study and these have been organised under the same headings as the more detailed sections in the main body of this report.

Performance and Efficiency

This study illustrates that modern hydrogen internal combustion engines have efficiencies and performance that are similar or better than equivalent diesel fuelled engines, depending on the technology adopted for hydrogen injection and the engine boosting system. For NRMM applications H2ICE will be able to achieve:

- 40% to 43% BTE depending on rating using first generation PFI (2024/5 launch)
- 42% to 46% BTE for engines using second-generation low-pressure DI (2026/7+ launch)
- 45% to 50% BTE for future heavy-duty engines utilising high-pressure DI (2030+ launch)

In addition, H2ICE de-risks H_2 infrastructure investments while offering a viable option for NRMM decarbonisation. H2ICEs can provide an immediate switch to H_2 as a fuel and help increase the demand and user base for hydrogen infrastructure.

Air Quality

Similarly, available data from stakeholders and the public domain has been gathered on two critical air-quality emissions (NO_x and particulate matter) for hydrogen ICEs fitted with well-established standard exhaust after-treatment technologies (AdBlue-based systems for NO_x control, filters for particles). All stakeholder data provided here demonstrated that hydrogen engines can now be designed to improve on diesel engines very significantly in terms of their air quality performance, with tailpipe emissions well below current limits.

The scale of Improvement has already been shown to be of the order 14-20 times better than the most modern diesel equivalent engines, and it would be anticipated that this will be further improved upon. At these levels of emissions, the adoption of hydrogen ICEs in offroad equipment, if it displaces a diesel vehicle, would result in a direct and immediate air quality improvement. The benefits of adopting hydrogen ICE would likely be greatest in terms of directly reducing NO_x/NO_2 concentrations in city centres but, given the regional and global effects of both NO_x and $PM_{2.5}$, Hydrogen ICEs would deliver air quality benefits even if used in more remote environments.

Whilst the primary air quality benefit of using hydrogen engines would be to reduce ambient concentrations that directly impact on people, there are further regulatory gains that would arise via reductions in national emissions. For NO_x, PM (and other diesel generated pollutants such as HCs, CO and SO_2), the UK is subject to caps on total national emissions as part of the National Emissions Ceiling Regulations. These are broadly mirrored in the UNECE Gothenburg Protocol to which the UK is a signatory. Widespread adoption of hydrogen ICEs in place of diesel or other fossil-derived hydrocarbon fuels would help support attainment of challenging future limits, particularly for $PM_{2.5}$ where the UK does not currently meet international obligations.

An estimate has been made of the cost savings arising from avoided damage to the environment, human health and productivity, using the current Stage V diesel standard as a baseline, compared to widespread adoption of the hydrogen ICE. This estimate indicates damage costs avoided of £150 M/yr (central estimate) to £505 M/yr (high sensitivity upper bound).

Greenhouse Gas Emissions

The use of hydrogen ICE in NRMM can reduce emissions of the main greenhouse gas, CO_2, by 99.95%, and the aggregate GWP of all greenhouse gases by up to 99.9%. The potential timing and scalability of the technology is significant, since it is likely that reductions in greenhouse gas emissions from the NRMM sector could be delivered quicker with a hydrogen ICE than alternative technologies. This is important since greenhouse gases impact the climate cumulatively, meaning that CO_2 avoided today, brings greater climate benefits than the promise of CO_2 saved at some point in the future.

The speed of potential deployment of hydrogen ICE Is possible Ie It uses existing components, supply chains and assembly lines. Servicing and repair can use the same skills, with added training on high pressure hydrogen pipework and safety (which is already available). New components such as fuel regulators and valves can be industrialised quickly to automotive standards, while the hydrogen tank has benefitted from recent progress in carbon-fibre production and winding. And finally, a hydrogen ICE can be retrofitted to a diesel ICE vehicle or machine, the only major practical consideration being packaging of the larger fuel tanks. This creates an opportunity, with the right support and incentives to achieve more than 99% reduction in GHGs in years rather than decades.

Practicalities

The subgroup concluded that most of the experience and concerns regarding hydrogen deployment in NRMM applications are related to the generic use of hydrogen fuel rather than the propulsion system, be it H2ICE or H2FC. These include the engineering challenges associated with packaging hydrogen fuel onboard the equipment, on-site safety and space requirements for hydrogen storage, exclusion zones and the associated extra costs in refuelling facilities and site management. However, the positive practical benefits of using H2ICE in NRMM as a decarbonisation solution are:

- Use of a familiar combustion-based technology results in less change to maintenance requirements, operator training and experience than other net-zero or hydrogen technology approaches
- H2ICE is least likely, if at all likely, to be inflationary
- Repowering and upcycling are easier and cheaper using H2ICE than other zero-emission approaches

Given the positive conclusions from the emissions and performance assessments, which confirm the GHG saving opportunity, the benefits to air quality and the current scaled production capacities for engines, H2ICE in NRMM offers a hugely significant opportunity for delivering volumes at scale, reducing the time to deliver cost-effective zero-carbon solutions, with additional benefits to the wider hydrogen component supply chain.

Impact

The main impact of defining a positive role for H2ICE in NRMM decarbonisation strategy comes from capitalising on a highly valuable, export led industry that is fundamental to essential sectors driving UK growth and infrastructure development. In a sector worth at least £17.6 Billion to the UK economy in 2022 and employing almost 100,000 people, H2ICE represents the best opportunity to mitigate the risk of job losses and retention of skills in the energy transition. In fact, by leading and embracing the UK's already globally leading industry with 80% of its revenue today from exports, there is an overwhelming likelihood that first mover advantage will help to fill current skills gaps, and generate disproportionate benefit to UK economic growth, influence and standing from the transition.

Equally, given the high energy demand in the sector, and therefore potential volumes of hydrogen that could be used, with a technology that is nearer to proven than fuel cells, H2ICE in NRMM could help accelerate the overall development of the hydrogen economy and the energy system benefits that that can accrue.

Summary

It is strongly recommended that H2ICE is accepted as a net-zero technology (in line with EU policy) and appropriate for rapid decarbonisation of the NRMM sector (by 99.9%). This would achieve the co-benefits of significantly improved air quality (up to 95% reduction in NOx and 99.8% reduction in Pm) whilst achieving the same or better performance than a conventional diesel equivalent. Indeed, alignment with the EU's definition of zero emission technology would enable H2ICE to be an acceptable technology for on-road applications as well. This, when coupled with the UK's leading position on ICE engine research, development and manufacture, H2ICE represents:

- An opportunity to capitalise on a highly valuable, export led industry that is fundamental to essential sectors driving UK growth and infrastructure development

- The least disruptive and inflationary change option when compared to other technologies; and

- The maximum opportunity to establish the UK as leaders in H2ICE, protecting existing jobs and potentially creating new jobs in the manufacture and supply chain

- The best opportunity to kick-start the hydrogen economy through leveraging that existing manufacture and supply chain and the proven robustness of ICEs in this demanding application

Based on the work presented in this report, a summary of the main machine attributes and how the individual propulsion systems are able to contribute towards both GHG emission reduction and air quality improvements is shown in Table 13.

Technology	**Tailpipe GHG**	**Well to Work GHG**	**Air Quality (NOx, Pm/Pn)**	**Onboard Storage**	**Refuelling Speed**	**Fuel Costs**	**Fuel Supply to Site / Machine**	**CapEx & Other Costs**	**Implementation Readiness (large NRMM)**
HVO ICE									
Hydrogen ICE									
Hydrogen Fuel Cell									
Battery Electric									
Tethered Electric									

		Definition for all except Product Readiness	**Definition for Readiness**
	Highest Potential	Perfect or near-perfect solution for the attribute	Products ready now
	High Potential	Significantly better than incumbent Stage V Diesel	Easily adapted / limited product
	Neutral	Similar to the incumbent Stage V Diesel	Some readiness challenge
	Surmountable Challenge	Worse than the incumbent Stage V Diesel, but maybe acceptable	Significant readiness challenge
	Maybe Infeasible	Significantly worse than the incumbent Stage V Diesel, likely not acceptable	Not ready

Table 13: Comparison of the relative opportunities for GHG emission reduction, air quality improvements and readiness levels for various propulsion systems

Recommendations

As a result of this study, the H2ICE task and finish group make the following recommendations:

- H2ICE to be classified and actively promoted as a net zero emissions technology (in line with EU policy) across all sectors (including on-highway, not just NRMM)
    - This will send a clear signal to the industry that investment in this technology is meaningful and will result in new areas of research and development that will further cement the UK's position as leaders in ICE technology
- Further to the above, NRMM using H2ICE to be classified as net zero emissions machines
- Ensure emissions regulations and standards are reviewed and updated to ensure "best in class" emissions (GHG and air quality) in line with Europe
- Establish a UK voluntary NRMM standard to recognise and incentivise H2ICEs which achieve the very low NO_x and particulate emissions performance detailed in this report; encourage user incentives around meeting this standard.
- Establish regulation and new forms of contract in the construction industry in order to recognise and reward low greenhouse gas and air pollution emission solutions, and that construction projects measure and pay for emissions
- Create consistent, harmonised planning regulation/best practice/shared learning on hydrogen safety and on-site requirements
    - Ensure consistency of assessment
- Develop tax breaks and financial incentives specifically for NRMM if the pace of change is to be accelerated
    - Establish security of supply for hydrogen fuel as defined by the low carbon hydrogen standard
    - Establish pricing mechanisms to offset the price differential with diesel

To this end, the UK government needs to set and communicate a clear vision, strategy, and legislation timeline for net zero requirements in the construction industry, and for NRMM specifically. This allows the whole value chain to plan and invest accordingly.

8. Acknowledgements

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Appendix 1: Market sizes for various NRMM applications

Off-Highway Research estimates that the UK NRMM construction fleet volumes are increasing year on year, with the sector having grown by 35% since 2013 in terms of machine volume. A further growth of 4% is predicted by the end of 2026 (compared to 2023 volume figures). The historic and forecast growth of the UK construction NRMM fleet is shown in Figure A1.

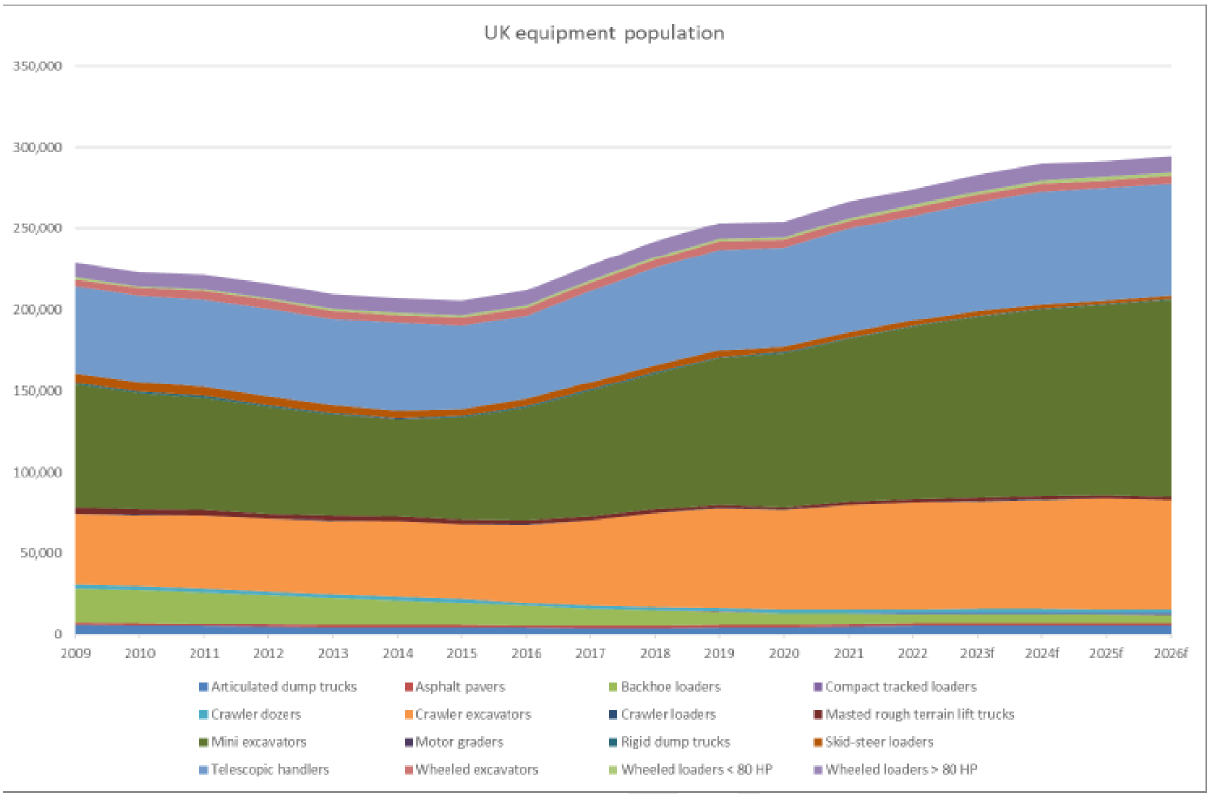

Figure A1: Historic UK Equipment Population and Future Projections (Source Off-Highway Research)

The Agricultural Engineers Association (AEA), provides market statistics for the UK tractor market[2], including annual registration numbers for tractors over 50 hp as shown in Figure A2. Assuming a 15-year life for tractors, this would represent a total UK tractor fleet size (over 50hp) of around 184,000 units.

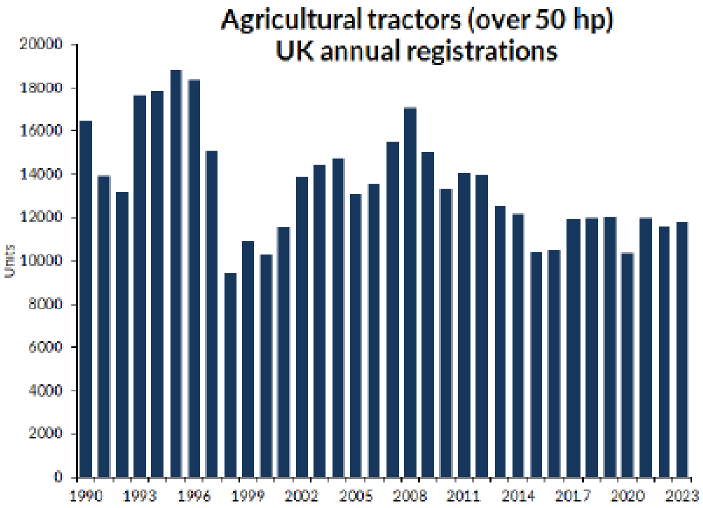

Figure A2: Agricultural Tractors (over 50 hp) – UK Annual Registrations (Source: AEA)

The UK Power Generation fleet consists of around 95,000 units over 7.6 kVA.

Powergen Consulting is an independent provider of market information, which works with OEMs to provide data for the global power generation market. The data from Powergen Consulting, assuming a 9-year life for all powerbands for the UK market is shown in Table A1(for the power bands reported):

Power Band	2023 UK Power Generation Estimated Fleet Size (Number of Units)	
7.6-30 kVA	27,668	29%
31-75 kVA	20,311	21%
76-375 kVA	34,828	37%
376-750 kVA	7,428	8%
751-2000 kVA	2,546	3%
2001+ kVA	2,271	2%
Total	**95,052**	

Table A1: UK Power Generation Estimated Fleet Size (Source Powergen Consulting)

Off-Highway Research also produces estimates for average life of equipment in the UK for a wider set of product types, which is used for their analysis of the UK NRMM fleet.

Off-Highway Research NRMM Population estimate	
	Average Life in Years
Articulated dump trucks	10
Asphalt pavers	10
Backhoe loaders	9
Compact tracked loaders	6
Crawler dozers	11
Crawler excavators	8
Crawler loaders	10
Masted rough terrain lift trucks	12
Mini excavators	7
Motor graders	15
Rigid dump trucks	15
Skid-steer loaders	7
Telescopic handlers	8
Wheeled excavators	10
Wheeled loaders < 80 HP	8
Wheeled loaders > 80 HP	10

Table A2: UK NRMM Population Average Life Estimates (Source: Off-Highway Research)

Appendix 2: Engine peak thermal efficiency for lean combustion mode from numerous studies

	Base Engine	Engine Capacity	Cylinder Volume	Engine Type, #Cylinders	Fuel Injection Pressure	Lambda	BTE/ (ITE)	Company	Year of publication	Ref
Unit	SI/CI/NG	L	L		bar		%			
1	SI	0.49	0.49	SCRE	45-150	1	(37)	BMW	2004	**Error! Reference source not found.**
2	SI	0.49	0.49	SCRE	150	1.3-2.7	(41)	BMW	2005	9.21
3	SI	0.5	0.5	SCRE	100	2.5	(35)	University	2022	9.22
4	SI	0.66	0.66	SCRE	100	1.0-5.0	(45.3)	Argonne National Laboratory	2012	9.23
5	SI	0.66	0.66	SCRE	100-140	1.0-5.0	(47.1)	Argonne National Laboratory	2011	9.24
6	SI	1	0.33	3cylinder	20	1.0-3.3	41	FEV, Ford	2021	9.25
7	SI	1.48	0.49	3cylinder	50-150	2.3	42.5	Geely	2022	9.26
8	SI	1.6	0.4	4cylinder	40	1.0-3.0	41	Hyundai	2023	9.27
9	SI	1.99	0.5	4cylinder	200	2.0-3.5	42.2	FAW Group	2022	9.28
10	SI	1.99	0.5	4cylinder	25-175	1.8-2.3	36	University	2023	9.29
11	SI	2	0.5	4cylinder	70	1.3-1.4	39.1	University	2023	9.30
12	SI	2	0.5	4cylinder	100	2.4	37.7	Changan	2023	9.31

13	SI	2	0.5	4cylinder	40-200	1.0-4.0	42	University	2022	9.32
14	SI	2	0.5	4cylinder	40-200	1.7-2.9	42.6	University	2022	9.33
15	SI	2	0.5	4cylinder	100	1.8-3.0	45	Bosch	2021	9.34
16	SI	2.99	0.5	6cylinder	n/a	1.7-2.0	43.5	University	2023	9.35
17	NG	1.3	1.3	SCRE	110-170	1.7-2.3	(42)	SWRI	2023	9.36
18	NG	13	2.17	6cylinder	300	n/a	51.5	Westport	2021	9.37
19	NG	7.7	1.28	6cylinder	n/a	2.0-5.0	42	FEV	2021	9.38
20	CI	1.84	1.84	SCRE	n/a	1.8-4.4	(48.3)	University	2022	9.39
21	CI	2	0.5	4cylinder	30	1.0-3.0	45	IAV	2021	9.40
22	CI	2	0.5	4cylinder	20-40	1.6-2.6	37.5	BorgWarner	2023	9.41
23	CI	2.13	2.13	SCRE	60-100	2.4-3.0	(44)	FEV	2022	9.42
24	CI	2.17	0.54	4cylinder	25-35	1.6-2.7	34	University	2023	9.43
25	CI	2.53	2.53	SCRE	20	2.0-3.0	(46.5)	University	2023	9.44
26	CI	12.8	2.13	6cylinder	250-300	1.4-2.9	42	KEYOU	2021	9.45
27	CI	16	2.67	6cylinder	n/a	2.0-3.1	42	Volvo	2023	9.46
28	CI	16.8	2.8	6cylinder	22	2.0-4.0	47	AVL	2021	9.47
29	CI	2.1	2.1	SCRE	35	1.5-5.0	(47.5)	Ricardo	2024	9.48

Appendix 3: NRMM Stage V In Service Emissions

Background

EU Stage V regulation (2016/1628) requires the monitoring and reporting of exhaust emissions from engines in use, using portable emissions measuring (PEMS) equipment. The intent of this requirement is to gather data on real use emissions compared to certification results.

Testing requirements are detailed in the regulation (as amended) and these aim to collect results from a wide range of applications and use cases. Results are reported without exclusions as well as with exclusions (for non-working running, cold-starting and extreme ambient conditions). The length of test and quantity of tests is specified, and a Moving Average Window method of data analysis is specified including validation protocols. Engine manufacturers are required to perform the tests and supply the results to their certification authority per an agreed plan.

EUROMOT has been collecting this data from member companies to monitor progress and for discussion with EU commission regarding potential future in-service compliance requirements.

Results

Data from circa 150 test programmes across agriculture, construction and industrial applications has shown a good level of compliance of in-service emissions with certification emissions results.

CO and Total Hydrocarbons (THC) emissions results are much lower than Stage V limits (as are the certification results) with 90th percentile windows having a compliance factor of <0.25 (or less than a quarter of the emissions limit) – without non-working data exclusions.

The NO_x median (i.e. 50th percentile test) compliance factor is < 0.7 for the 90th percentile Moving Average Window analysis without exclusions.

In the context of in-service emissions testing, Compliance Factor (CF) is defined as the emissions measured in machine (or vehicle) when running a real-world work cycle, divided by the certification emission limit (measured when running the certification test cycle on an engine test bed).

For example, if NO_x emissions of 200mg kWh^{-1} were measured from an excavator digging trenches compared to the Stage V limit of 400mg kWh^{-1}, the Compliance Factor is 200mg kWh^{-1} divided by 400mg kWh^{-1} giving a CF of 0.5.

Hence a CF of less than one means the vehicle is performing better in the real-world than legislative limit on the test bed.

Appendix 4: About the Authors, Contributors and Editors

Editors:

Amanda Lyne – Managing Director, ULEMCo Ltd.

Amanda has 20 years' experience in the hydrogen industry, having previously founded fuel cell company ACAL Energy and delivered various consultancy projects for a range of companies active in the UK's hydrogen industry, such as BOC and Fuel Cell Systems. She founded ULEMCo in 2014 to commercialise globally innovative UK capability that enables specialist vehicles to use hydrogen at scale, now, through dual fuel and with zero carbon emissions using fuel cell or 100% hydrogen combustion. Almost concurrently she has been actively involved in the UK industry associations, as both chair and deputy-chair of the Hydrogen Energy Association (formerly the UK Hydrogen and Fuel Cell Association) as well as recently leading the industry's Co-ordination Forum and being an active participant in a number of industry advisory groups on the role of hydrogen for delivering the UK's net zero target.

Steve Sapsford – Managing Director, SCE

Steve spent most of his career at Ricardo where he had various technical, operational, commercial and board-level roles. In September 2018 to set up his own consultancy with a focus on future propulsions systems and the role for sustainable fuels in complementing electrification. He is an Industrial Advisor for Transport at the University of Nottingham and a member of the Industrial Advisory Board (School of Engineering) at the University of Cardiff. Steve was also the chair of the Powertrain Systems and Fuels Group at the IMechE until June 2022. He is currently the chair of the industrial advisory group for the EPSRC MariNH3 programme researching the role of ammonia in marine engines.

Authors and Contributors

Performance and Efficiency Section

Sam Akehurst – IAAPS, University of Bath

Sam Akehurst is Professor of Advance Powertrain systems at the University of Bath and Research Director of the Institute for Advanced Automotive Propulsion Systems (IAAPS). He has more than 25years research experience in the field of combustion systems and currently leads a range of research programmes in the field of electrification, H2 fuel cells and H2 combustion-based propulsion systems.

Andreas Öberg – Chief Engineer at Volvo Construction Equipment

Andreas Öberg possesses extensive expertise in various capacities related to the development of internal combustion engines, engine aftertreatment systems and fuel cell propulsion systems within the Non-Road Mobile Machinery industry. For the past 17 years, Andreas has been an integral part of Volvo Construction Equipment, contributing his knowledge and skills to the company's operations.

Emissions Section

Nick Owen – Power & Energy, Woodford Owen Consulting Limited

Nick Owen is an experienced engineer in the field of innovative propulsion and power devices, focused on internal combustion; he has held senior roles at Ricardo and two technology start-ups in the field of net zero power.

Professor Alastair Lewis – Atmospheric Chemistry, University of York

Alastair Lewis is professor of atmospheric chemistry at the University of York and the National Centre for Atmospheric Science (NCAS), based in the Wolfson Atmospheric Chemistry Laboratories. He is Chair of the Defra Air Quality Expert Group (AQEG), the Department for Transport Science Advisory Council. He is a member of the Civil Aviation Authority Environmental Sustainability Panel.

Ryan Ballard – Engineering Director at JCB

Alan Tolley – Managing Director APT Strategic Consulting Ltd.

Work with OEMs, SMEs, Start Ups and Trade Associations on powertrain strategies and planning. This is currently mainly focused on decarbonisation. Formally Group Director of Powertrain at JCB. Fellow of the Institution of Mechanical Engineers and a board member of the Powertrain Systems and Fuels Group. Chair of the CO_2 Task Force, and member of the High-Level Technical Policy Advisory Group of the Committee for European Construction Equipment (CECE).

Richard Payne – EMEA Non-Road Regulatory Affairs Director for Cummins

Richard has over 40 years of experience in the diesel engine business working for Cummins in various engineering and commercial roles. Richard has held his current role since 2007 supporting policymakers and regulators to give them the information to provide ambitious and enforceable regulation to improve air quality in the non-road sectors including the construction, industrial, mining, marine and power generation sectors. Working towards decarbonisation in those sectors Richard is providing goal-based and technology neutral regulation for all types of powertrain to support the path to net zero greenhouse gas emissions by 2050. Richard also works with a number of UK, EU and international trade associations.

Andreas Öberg – Chief Engineer at Volvo Construction Equipment (as above)

John Goodwin – Regulatory Affairs Director, Johnson Matthey.

John leads policy advocacy and engagement as part of the Government Affairs team, supporting the use of sustainable technologies that help clean the air and catalyst the transition to net zero. Prior to taking a wider cross-company role this year, John led policy interpretation and engagement on emission control regulation around the world, particularly in the EU, with EU institutional, trade association, industry and NGO stakeholders. John has been with JM for 19 years, and comes from a technical background in chemistry, harnessing the power of platinum group metals to deliver cleaner air, and is a named inventor on some 175 patents globally.

Impacts and Practicalities Sections

Daniel Fung – Advanced Propulsion Centre

Daniel is the Head of Strategy and Performance at the Advanced Propulsion Centre UK. In his role, he focuses on preparing the automotive industry for a net-zero future by supporting technology R&D, capital projects, and developing insights to shape the industry. Daniel works closely with government, academic, and industry stakeholders to address future challenges and industrialise new technologies, particularly in the realm of decarbonised vehicles. Prior to joining the APC, Daniel worked with Heavy Duty Diesel exhaust systems, developing products that would help depollute off highway equipment.

Amanda Lyne (as above)

Appendix 5: H2ICE Task and Finish Group Delegates

Name	Position	Affiliation
Amanda Lyne (Co-Chair)	Managing Director	ULEMCo
Prof Steve Sapsford (Co-Chair)	Managing Director	Sapsford Consulting Engineers
Prof Alastair Lewis	Professor of Atmospheric Chemistry	University of York, National Centre for Atmospheric Science
Prof Sam Akehurst	Research Director and Professor of Advanced Powertrain Systems	University of Bath, Institute of Advanced Automotive Propulsion Systems
Charles Stevenson	General Manager	JCB
Nick Owen	Managing Director	Woodford Owen Consulting
Richard J Payne	EU Off Highway Regulatory Affairs Director	Cummins
Ankit Patel	Director - EU Research & Technology	Cummins
Kevin Randall	Sustainability, Safety & Engineering Director	Balfour Beatty
Victoria Limbrick	Energy Manager	Balfour Beatty
Tim Richardson	Commercial Manager Great Britain, Ireland & Iceland	Volvo Construction Equipment
Andreas Öberg	Chief Engineer	Volvo Construction Equipment

David Mason	Environmental Technical Director	Skanska
John Goodwin	Regulatory Affairs Director	Johnson Matthey
Daniel Fung	Head of Strategy and Planning	Advanced Propulsion Centre
Dr Jonathan Scurlock	Chief Adviser, Renewable Energy and Climate Change	National Farmers Union
Prof Penny Atkins	CEO	International Fugitive Emissions Abatement Association
Prof Savvas Tassou	Director, Institute of Energy Futures	Brunel University
Prof Alasdair Cairns	Director of Powertrain Research Centre	University of Nottingham
Chris Matthew	Head of Business Strategy, ESG & Communications	P. Flannery Plant Hire
Dr Dan Skelton	Managing Director	Clean Air Power
Dr Richard Osborne	Global Technical Expert – Sustainable Engines	Ricardo
Additional contributions from:		
Robert Eriksson	Senior Technical Leader	Volvo Construction Equipment
Stuart McLeod	Energy Manager	Balfour Beatty
Tim Burnhope	Group Director – Special Projects	JCB
Tom Beamish	Principal Engineer - Executive Support	JCB
Ryan Ballard	Engineering Director – Powertrain	JCB
Alan Tolley	Managing Director	Advanced Powertrain Technologies Ltd

Appendix 6: JCB Hydrogen Internal Combustion Engine Stage V Certification

UTAC

Test report

Reference: **23/06853**

Applicant	J. C. Bamford Excavators Ltd. (JCB) Rocester, Staffordshire England ST14 5JP		
Subject	**Vehicle on test**: JCB 3CX Backhoe Loader **Power Unit**: JCB Hydrogen Internal Combustion Engine, 71kW fitted with Selective Catalytic Reduction aftertreatment. UTAC conducted machine emissions testing at the request of JCB. The testing was conducted to the provisions of EU regulation 2017/654 as relating to engine category NRE-v-5 and according to the requirements of EU regulation 2017/655.		
Unit / Test site	Wardlow Quarry, Cauldon Low, Stoke-on-Trent, Staffordshire, England, ST10 3HA		
Testing date	06/07/2023	***Internal reference***	ARC SAS 2305452

Comments

The testing was conducted to the provisions of EU regulation 2017/655 as relating to engine category NRE-v-5, using the work-based windows approach. Note that this is a performance test report and does not constitute an approval under EU 2016/1628.

- Fuel: Hydrogen to ISO 14687 Grade D
- Testing: Cold start, site and standard roading, medium stone rehandling & hill climb.

The work performed during the test was six times the reference work. UTAC test reference JCB_ESSAI FROID 1_20230706_1_3_MDT_Result_V2.

Results of Tailpipe NOx measurements:

	Stage V NOx Limit*	JCB H2ICE NOx Result	Stage V NOx Limit*	JCB H2ICE NOx Result
	g/kWh		mg/kWh	
0th Percentile Result	0.4	0.013	400	13
90th Percentile Result	0.4	0.024	400	24
100th Percentile Result	0.4	0.026	400	26

***2016/1628 NRE-v-5**

Hydrogen is carbon-free, so burning it does not create CO_2.

Name	Arthur VALLERON
Contact	arthur.valleron@utac.com +33 (0)1 70 84 91 40
Functions	*Test Project Manager*
Date (day/month/year)	28/08/2023
Signature	DIGITALLY SIGNED

NB : UTAC shall not be liable for any industrial or commercial applications that occur as a result of this report. This report may only be reproduced in the form of a full photographic facsimile. Possible tests results are only available for the materiel submitted to tests or materiel identified in the present test report. Accreditation by the COFRAC test department only certifies the technical competence of the laboratory for the tests or analyse covered by this accreditation. (*) / In order to notify the conformity or no conformity in the requirements, the uncertainty of the test results has not been taken into account.

Manufacturer :	J. C: Bamford Excavators Ltd. (JCB), Rocester, Staffordshire, England ST14 5JP
Enginetype :	JCB Hydrogen Internal Combustion Engine, 71 kW with SCR aftertreatment

Subject

TÜV NORD has witnessed the emissions test on behalf of FEV Europe GmbH. FEV Europe GmbH conducted mashine emissions testing at the request of JCB. The testing was conducted to the provisions of EU regulation 2017/654 as relating to engine category NRE-v-5 and according to the requirements of EU regulation 2017/655.

Date and time of test :	07.02.2024, 15:08 - 16:42 Uhr
Commercial name(s) (if applicable) :	3CX ECO
Test Location :	JCB Wardlow Validation Center, Stoke-on-Trent ST10 3HA, England
Brief description of the work performed :	Site and standard roading as well as Medium stone rehandling
Test fuel specifications :	Gaseous Hydrogen Qualitygrade D

Averaging window conformity factors (calculated in accordance with Appendices 2 to 5) :

	Work averaging window			
	Min.	Max.	90.percentile	Limit
Brake-specific NOx emissions [g/kWh] :	0,00	0,01	0,011	0,40
Brake-specific NOx emissions [mg/kWh] :	1,81	14,55	11,194	400

Hydrogen is carbon free, no CO_2 is produced during combustion.

Average NO_x concentration [ppm] :	0,48	ppm
Integrated mass of NO_x emissions [g] :	0,37	g
Work performed during the test [kWh] :	54,03	kWh

Office : Essen
Date : 19.02.2024

created :

M.Eng. André Piller

approved :

E-Mail : apiller@tuev-nord.de
Phone : +49 160 888 5442

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POWERTRAIN ENGINEERING DIVISION

ISO 9001 Certified
ISO 14001 Certified

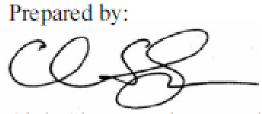
February 16,2024

JC Bamford Excavators LTD (JCB)
Rocester, Staffordshire
England ST14 5JP

SUBJECT: Summary Report for Field Testing Result for JCB 3CX Hydrogen-Fueled Backhoe Loader.

<table>
<tr><td>Test Article Description</td><td>Test Vehicle/Machine: JCB 3CX Backhoe Loader
Power Unit: JCB Hydrogen ICE, 4.8L 71kw @ 2200rpm
ESN: 180-V031514r20M98D2
Emission Control System: Selective Catalytic Reduction</td></tr>
<tr><td>Test Location</td><td>JCB Wardlow Validation Centre</td></tr>
<tr><td>Test Date:</td><td>February 07, 2024</td></tr>
<tr><td>SwRI Project Ref</td><td>03-28519.03</td></tr>
<tr><td>Test Result Summary</td><td>Proposed Tier 5 3B-MAW Result
<table>
<tr><th>Bin</th><th>Units</th><th>Result</th><th>Proposed Tier 5 Limit</th><th>Tier 4 Lab Cert. Limit[1]</th></tr>
<tr><td>A</td><td>g/hr</td><td>0.14</td><td>8.2</td><td>n/a</td></tr>
<tr><td>B</td><td>g/kw-hr</td><td>0.016</td><td>0.09</td><td rowspan="2">0.40</td></tr>
<tr><td>C</td><td>g/kw-hr</td><td>0.009</td><td>0.06</td></tr>
</table>
Note that CARB Tier 5 Limit values are not yet finalized.
[1]Tier 4 Lab Cert Limit is for NRTC/RMC lab cycles only.</td></tr>
<tr><td>Test Notes</td><td>Data analysis was conducted according to CARB draft 3-Bin Moving Average Window (3B-MAW) methodology.
Operations consisted of cold-start, site roading, and medium stone handling.
Results for 3 test events compiled for a total of 6.2 hours of logged operation.
Number of Bin A and Bin B windows below proposed data threshold.</td></tr>
<tr><td>Test Witness Contact</td><td>Christopher Sharp
Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78238-5166, USA
Desk: +01 (210) 522-2661
Mobile: +01 (210) 204-8165
chris.sharp@swri.org</td></tr>
</table>

Prepared by:



Chris Sharp, Institute Engineer
Commercial Vehicle R&D Department
Powertrain Engineering Division

Disclaimer: This test report summary does not constitute approval of the test engine or machine for use or sale under EU or U.S. regulations, nor does this summary in anyway constitute a statement of compliance with any published emission standards.

FEV

feel evolution

FEV Europe GmbH • Neuenhofstr. 181 • 52078 Aachen, Germany

J.C. Bamford Excavators Ltd (JCB)
Rocester, Staffordshire
England ST 14 5JP

FEV Europe GmbH, Aachen
Register of companies Aachen HRB 1649

Executive board:
Dr.-Ing. Johannes Scharf
Dr.-Ing. Christoph Menne
Dipl.-Kfm. Martin Reim

P +49 241 5689-0
extension -6149
PEMS@fev.com

26 February 2024

our sign: JCB / Certificate H2 ICE

Emission Measurement Summary

- PEMS measurement conducted on JCB 3CX ECO equipped with H2 ICE engine
- Date: 7th of February 2024
- Time: 15:08 - 16:42 GMT
- Work performed in kWh: 54.03 (6.84 x NRTC < 7)

Results

NOx Limit* in g/kWh	Result (Min/Max/90%) in g/kWh			NOx Limit* in mg/kWh	Result (Min/Max/90%) in mg/kWh		
0.4	0.0018	0.0147	0.0104	400	1.84	14.72	10.44

*Acc. To EU NRMM 2016/1628 NRE-V-5

The burning of Hydrogen does not produce CO2.

Dr.-Ing. Christoph Menne
Chief Technical Officer, Managing Director
FEV Europe GmbH

fev.com

Ricardo Ref: Simulation Report Extract
Ref: ED - 16882

April 4, 2023

Customer: JCB Power Systems Ltd.

Ricardo conducted an air quality assessment case study to quantify the potential impact of a technology transition to hydrogen powered NRMM in an example urban area, Greater London. The atmospheric dispersion modelling assessment tested a number of possible future scenarios, one of which was to include the adoption of all NRMM >19kW to be powered by H2ICE, with a NOx emission rate of 0.02 g/kWh. For this assessment scenario, the report concluded the following:

- **The modelled impact of H2ICE NRMM on annual mean NOx concentrations is very small, almost imperceptible.** The maximum impact we see is 0.019 $\mu g.m^{-3}$. When rounding predicted concentrations to one decimal place as presented in our mapped outputs, the impact of the H2ICE NRMM is rounded out and therefore becomes imperceptible.
- Assessing this impact using the current UK best practice guidance for assessing air quality impacts for planning purposes; concludes that any impact of less than 0.5% of the air quality objective being assessed is classified as negligible. **When assessing NO2 impacts using this method 0.5% of the 40 $\mu g.m^{-3}$ objective equals 0.2 $\mu g.m^{-3}$; any predicted change less than 0.2 $\mu g.m^{-3}$ is therefore classified as negligible.**
- This conclusion could also be considered as robust to significant input variance of the NOx emissions from H2ICE. **Even if H2ICE emissions were doubled, then the impact on annual mean NO_2, at the worst case locations assessed, would still be lower than that required for a "negligible" classification, against either the 40 $\mu g.m^{-3}$ UK objective, or the more stringent 10 $\mu g.m^{-3}$ WHO guidance (0.5% of 10 $\mu g.m^{-3}$ = 0.05 $\mu g.m^{-3}$).**
- The limit of detection for automatic analysers in use in the UK air quality measurement networks range from 0.2 to 1.2 ppb (~0.4 $\mu g.m^{-3}$ to 2.3 $\mu g.m^{-3}$); any change in concentration less than that could therefore be considered beyond the limit of detection using current reference measurement methods.

Tailpipe NOx emission rate for H2ICE NRMM >19kW	WHO Guideline – NO_2 annual mean ($\mu g.m^{-3}$)	Future WHO guideline – NO_2 annual mean ($\mu g.m^{-3}$)	Maximum modelled NO2 annual mean for H2ICE NRMM>19kW ($\mu g.m^{-3}$)
0.02 g/kWh	40	10	0.019

Approved by:

Sean Christiansen

Practice Director – Air Quality & Environment

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Email: sean.christiansen@ricardo.com