Industrial Non-Road Mobile Machinery Decarbonisation Options: Techno-Economic Feasibility Study

Final Report

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GLOSSARY

2021 NAEI Database – Estimates of the NRMM population and usage in the United Kingdom, forming part of the National Atmospheric Emissions Inventory for the United Kingdom (Ricardo, 2020; Ricardo, 2021). NAEI stands for National Atmospheric Emissions Inventory.

Bus bars – A metallic strip or bar used for local high current power distribution. They are generally uninsulated and can be supported above vehicles or machines to provide power or recharging from above the machine.

Carbon dioxide equivalent CO_2e – CO_2e emissions are emissions from seven greenhouse gases (GHG)[1] weighted by their global warming potential (GWP). The GWP for each gas is defined as its warming influence in relation to that of carbon dioxide over a 100-year period. Emissions are then presented in carbon dioxide equivalent units (CO_2e).

Gravimetric energy density – The available energy per unit mass of fuel and, where relevant, energy storage system (which includes the fuel tanks or batteries as well as the fuel itself). The higher the gravimetric energy density, the lower the mass of the fuel (or energy storage system) required to store a defined amount of energy. This means that energy storage systems with higher gravimetric energy densities can store the same amount of energy in a lighter system than energy storage systems with lower gravimetric energy densities, meaning the machine itself could be lighter.

Industrial NRMM decarbonisation database (IND-database) – A database summarising the current state of industrial NRMM, estimated future demand for industrial NRMM and indicative costs and performance of different powertrain options. The database was created as part of this study, with the 2021 NAEI database (defined above) as one of its key inputs.

Load factor – The ratio between the average power delivered during use and the power rating of the machine (see below).

Power rating – The maximum power that can be supplied by the powertrain (see below).

Powertrain – The part of a machine which powers the operation of the machine. This includes but may not be limited to engines, exhaust, fuel tanks, fuel cells, motors and batteries where applicable.

Powertrain efficiency – Ratio between the useful kinetic energy provided by the engine or motor and the energy in the fuel or battery consumed. A higher powertrain efficiency increases the amount of the fuel's energy that is converted into useful energy, and therefore less fuel is required to perform the same task. This does not include any energy losses in the rest of the machine outside of the powertrain (for example energy losses from hydraulic systems is not included).

Tailpipe emissions – Emissions of greenhouse gases and air pollutants directly from the machine (i.e., from the tailpipe of the machine).

Tank-to-wheel (TTW) emissions – Emissions of greenhouse gases that arise from the direct operation of the machine, not considering the emissions associated with the production of the fuel or energy. This generally is equal to the tailpipe greenhouse gas emissions, though for biofuels, this can consider the source of the fuel in some methods. For this report and the modelling performed, TTW emissions considers the source of fuel feedstocks, and therefore is not the same as tailpipe greenhouse gas emissions.

Useful energy – The amount of energy converted into useful work by a powertrain, after energy losses due to inefficiencies (e.g., heat, friction between components).

Volumetric energy density – The available energy per unit volume of fuel and, where relevant, energy storage system (which includes the fuel tanks or batteries as well as the fuel itself). The higher the volumetric energy density, the less volume of fuel (or energy storage system) required to

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[1] Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3).

store the same amount of energy. This means that fuel tanks or batteries can be smaller and easier to place on the machine.

Well-to-wheel (WTW) emissions – Emissions of greenhouse gases that arise from the operation of the machine, including the emissions associated with the extraction, production and distribution of the fuel before it reaches the machine. For example, this would include the emissions associated with electricity production for electric machinery.

ACKNOWLEDGEMENTS

The authors would like to thank the many stakeholders who shared their insights by taking part in an interview or attending a workshop.

DISCLAIMER

The purpose of this report is to inform the Department for Energy Security and Net Zero (DESNZ) of the techno-economic potential for decarbonisation options specific to non-road mobile machinery (NRMM). The findings of this report do not necessarily represent the views of HMG. The report does not provide an endorsement of any particular technology or approach and should not be relied upon by organisations to make business decisions or investments. Any references to companies or products throughout are not an endorsement.

EXECUTIVE SUMMARY

Project context, scope and approach

The UK Government recognises that further policy intervention is likely required to decarbonise industrial non-road mobile machinery (NRMM) in line with UK climate ambitions.[2] The Department for Energy Security & Net Zero (DESNZ) commissioned this study to develop the evidence base on industrial NRMM. The study presents an up-to-date assessment of how the industrial NRMM market operates, the techno-economic potential of different decarbonisation options available for industrial NRMM up to 2050, and the barriers to the development and deployment of these options. The scope of the study focuses on the use of NRMM within industrial sectors, specifically within the construction, mining, ports, and waste sectors, as well as other selected applications (such as warehousing, logistics, supermarkets, road surface treatment). This does not include NRMM used at airports, for agriculture, for domestic use or transport refrigeration units.

The key objectives of the study were to:

1. Evaluate the industrial NRMM market structure (for example, types of market actors, ownership models)
2. Develop an evidence base of decarbonisation options available for industrial NRMM
3. Identify barriers and enablers to deployment of the identified decarbonisation options
4. Produce illustrative deployment scenarios
5. Produce a model for the least-cost decarbonisation pathway for industrial NRMM.

Desk-based research, stakeholder engagement, and decarbonisation modelling were conducted to deliver a database of key technical parameters to industrial NRMM decarbonisation (technology costs, availability, fuel prices, etc.), a decarbonisation model used to compare three scenarios and a final report (this document) detailing the findings. The database delivered is referred to as the industrial NRMM decarbonisation database (IND-database) throughout the report.

Current use of industrial NRMM in the UK

The UK industrial NRMM sector emitted 5.6 MtCO$_2$e in 2021,[3] with most emissions coming from diesel machinery (83%). The construction sector is the highest polluting industrial sector with 46% of industrial NRMM emissions (Figure 1, left) coming from the close to 424,000 construction machines (Figure 1, right). Industrial NRMM population is dominated by low-power (<4 kW) generators in the 'other' sector.

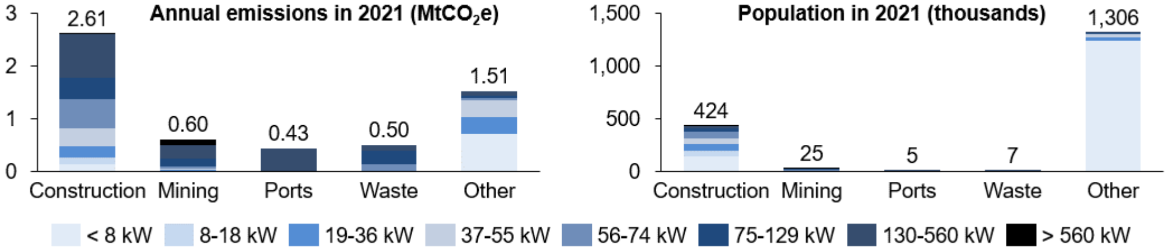

Figure 1 – Annual emissions in 2021 (MtCO$_2$e) [left] and population in 2021 (thousands of units) [right] by sector and machine power rating. Source: NAEI database, with ERM analysis

The majority of UK industrial NRMM is not owned by its operators, with 67% of construction NRMM either leased or hired by the operator, compared to only 37% leased or hired in Europe[4]. This

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[2] Net Zero Strategy: Build Back Greener (2021) DESNZ

[3] Analysis of 2021 National Atmospheric Emissions Inventory (NAEI) data, provided by DESNZ.

[4] CEA Power Hour Webinar – Off Highway Research: UK Market Update (23 Feb 2022)

highlights that lease and hire companies have a larger impact on the UK market, so are a more significant stakeholder for decarbonisation than elsewhere in Europe. The UK is the largest producer of construction equipment in Europe and was the fifth globally in 2022 (Construction Equipment Association, 2023). The UK is a net exporter of industrial NRMM, with the European Union (43%) and the USA (28%) representing the key export markets in 2022 (HMRC, 2023).

Archetypes and hard-to-deploy NRMM

To simplify the analysis and the findings from this study, ERM aggregated over 140 combinations of machinery types, power rating, sector, and usage levels into 14 archetypes that are likely to have the same alternative powertrain options (see Table 1). Machines were aggregated into archetypes based on the mobility of the machine ('Machinery category' in Table 1), power rating and utilisation level (relative to an 8 hour day, 365 days a year). These machinery parameters were chosen as they influence the ability to adopt different abatement options. These archetypes were used as the basis of the analysis performed in this report, with the commercial availability and deployment potential of abatement options summarised by archetype. It was noted that some decarbonisation options such as electric and hydrogen technologies require dedicated infrastructure and have attributes which could delay their deployment within segments of the markets where infrastructure deployment would be particularly difficult.

Machines were classified as **'hard-to-deploy'** if they satisfied **at least two** of the following four criteria: (1) they **regularly change sites**, (2) they are **used on smaller sites**, (3) they are **used intensively**, or (4) they are **used on remote sites**. Based on stakeholder feedback, it is estimated that 32% of all industrial NRMM is hard-to-deploy (560,000 machines). Mining has the highest proportion of hard-to-deploy machinery (76%, 19,000 machines), followed by waste (50%, 3,500 machines), other (36%, 470,000 machines, mostly low-powered generators), and construction and ports (15%, 64,000 and 750 machines, respectively).

Table 1 – Description and percentage of fuel use and population of the 14 archetypes created by ERM. Source data from the NAEI database, with ERM categories and analysis[5]

Archetype ID	Machinery category	Power rating	Utilisation level	% of population	% of total fuel use	Example machinery (highest fuel use)
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	14.2%	4.6%	Cement mixers, plate compactors
2		High (19-56 kW)	All	0.9%	4.4%	Welding equipment, concrete saws
3	Mobile machinery	Low (<37 kW)	Low (<50%)	1.9%	2.0%	Forklifts, Excavators
4		Medium (37-129 kW)	Low (<50%)	9.0%	23.6%	Forklifts, Excavators, telehandlers
5		High (130-560 kW)	Low (<50%)	0.8%	9.0%	Excavators, Dumpers/tenders
6		Medium (37-129 kW)	High (>50%)	0.6%	8.7%	Sweepers/scrubbers, forklifts
7		High (130-560 kW)	High (>50%)	0.2%	6.4%	Port tractors, Bulldozers
8		Very high (> 560 kW)	High (>50%)	0.04%	1.9%	Dumpers/tenders
9	Limited movement machinery	Medium (37-129 kW)	Low (<50%)	7.5%	9.6%	Mini excavators, Air compressors
10		High (130-560 kW)	All	0.6%	12.5%	Cranes, crushing equipment
11	Generators	Low (<8 kW)	Low (<50%)	63.7%	11.5%	
12		Medium (8-74 kW)	Low (<50%)	0.4%	2.4%	
13		High (75-560 kW)	Low (<50%)	0.3%	3.2%	
14		Very high (>560 kW)	Very Low (<25%)	0.01%	0.3%	

Abatement options for industrial NRMM

Three categories of abatement options were considered:

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[5] Due to limitations around the availability of data on NRMM, the NAEI database is itself an estimate. It is possible that the identified contributions of different machinery types could be an over- or underestimate.

- **Fuel-switching** options: shifting from fossil fuels to lower carbon energy sources, such as biodiesel, electricity or hydrogen.
- **Efficiency measures**: improvements to machines, operation or process that reduce the amount of energy and fuel needed to produce the same output.
- **Process change:** processes currently using NRMM are changed so that the machines are no longer required to complete a particular task. No examples of process change were found in the literature.

Fuel-switching options

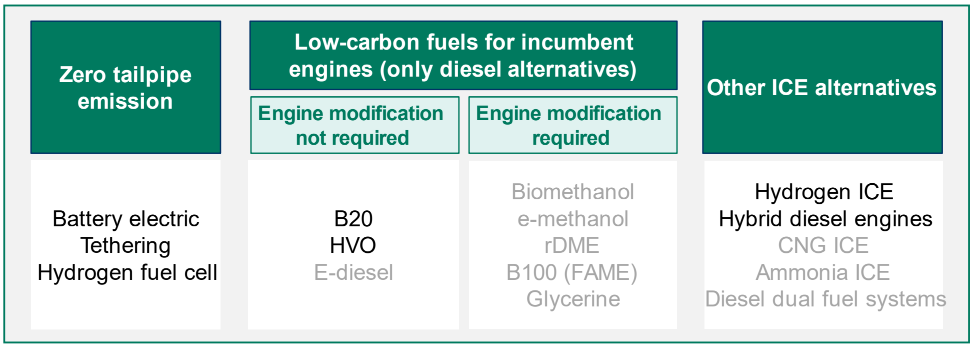
Three categories of fuel-switching options were considered for this study and a long list of options was identified for each category.

- **Zero tailpipe emission powertrains**: powertrains which do not have any tailpipe emissions (CO_2e, particulate matter (PM), or nitrogen oxides (NOx)).
- **Low-carbon fuels for incumbent engines:** alternative liquid fuels with lower lifecycle CO_2e emissions than incumbent, but still produce tailpipe emissions.
- **Other internal combustion engine (ICE) alternatives:** alternative ICE powertrains with fuels which cannot be used in a conventional (diesel) engine. The tailpipe emissions from these options vary depending on the fuel.

Abatement options were shortlisted for further assessment based on meeting criteria 1 and one of the remaining criteria (2-4) below:

1. **Essential:** option is actively in development specifically for at least two types of industrial NRMM
2. Option does not have any CO_2 tailpipe emissions
3. Option can be used directly in diesel engines
4. Option is currently widely commercially available for industrial NRMM.

The options considered and shortlisted are summarised in Figure 2 (options not shortlisted are shown in grey).

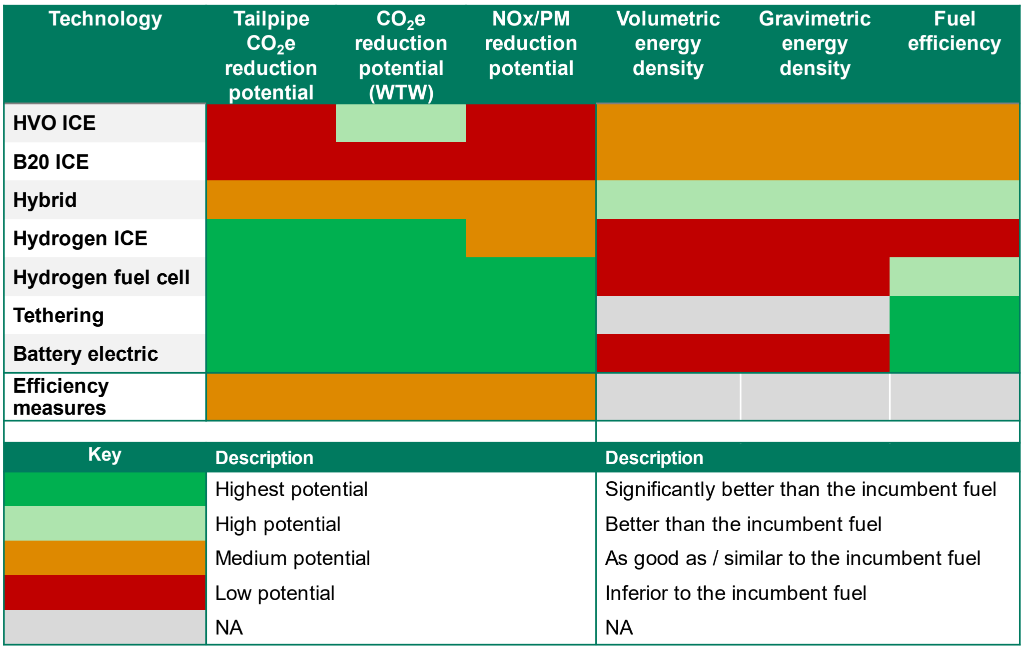


Zero tailpipe emission	Low-carbon fuels for incumbent engines (only diesel alternatives)		Other ICE alternatives
	Engine modification not required	Engine modification required	
Battery electric Tethering Hydrogen fuel cell	B20 HVO E-diesel	Biomethanol e-methanol rDME B100 (FAME) Glycerine	Hydrogen ICE Hybrid diesel engines CNG ICE Ammonia ICE Diesel dual fuel systems

Figure 2 – Long list of fuel switching options considered – options shortlisted are in black (only diesel low carbon fuel alternatives were considered given that 83% of industrial NRMM fuel use is diesel)

The shortlisted options were assessed and compared based on key technical characteristics, including the emissions reduction potential (tailpipe CO_2e, well-to-wheel CO_2e (WTW), and other air pollutants), energy density of storage options and the fuel efficiency of the powertrain (Table 2).

Table 2 – Comparison of shortlisted options on CO_2e and air pollutant reduction potential, energy density and fuel efficiency



Technology	Tailpipe CO_2e reduction potential	CO_2e reduction potential (WTW)	NOx/PM reduction potential	Volumetric energy density	Gravimetric energy density	Fuel efficiency
HVO ICE	🟥	🟢	🟥	🟧	🟧	🟧
B20 ICE	🟥	🟥	🟥	🟧	🟧	🟧
Hybrid	🟧	🟧	🟧	🟢	🟢	🟢
Hydrogen ICE	🟩	🟩	🟧	🟥	🟥	🟥
Hydrogen fuel cell	🟩	🟩	🟩	🟥	🟥	🟢
Tethering	🟩	🟩	🟩	⬜	⬜	🟩
Battery electric	🟩	🟩	🟩	🟥	🟥	🟩
Efficiency measures	🟧	🟧	🟧	⬜	⬜	⬜

Key	Description	Description
🟩	Highest potential	Significantly better than the incumbent fuel
🟢	High potential	Better than the incumbent fuel
🟧	Medium potential	As good as / similar to the incumbent fuel
🟥	Low potential	Inferior to the incumbent fuel
⬜	NA	NA

Efficiency measures

Three categories of efficiency measures (operational, machine and process) were identified as options that could reduce emissions by improving energy usage in NRMM (Table 3).

Table 3 – Summary of efficiency measure categories

Measure category	Description	Energy use reduction[6, 7]
Operational efficiency	Changes to how operators use NRMM	5 – 30%
Machine efficiency	Redesigning or replacing components and systems to improve energy efficiency	5 – 25%
Process efficiency	Changes to the workflows and processes that utilise NRMM	15 – 50%

An energy efficiency deployment pathway over time was created for each archetype. In general, across all machinery archetypes:

- Significant reductions can be made through efficiency gains in the next 5 to 10 years.
- The rate of reductions slow down once measures which have low cost or are operationally easy to deploy are fully deployed, leaving higher cost or more complex measures left to be deployed.

The progression over time and the ultimate peak in energy use reduction varies by archetype, as detailed in the full report.

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[6] Improvement compared to 2021 for each category.

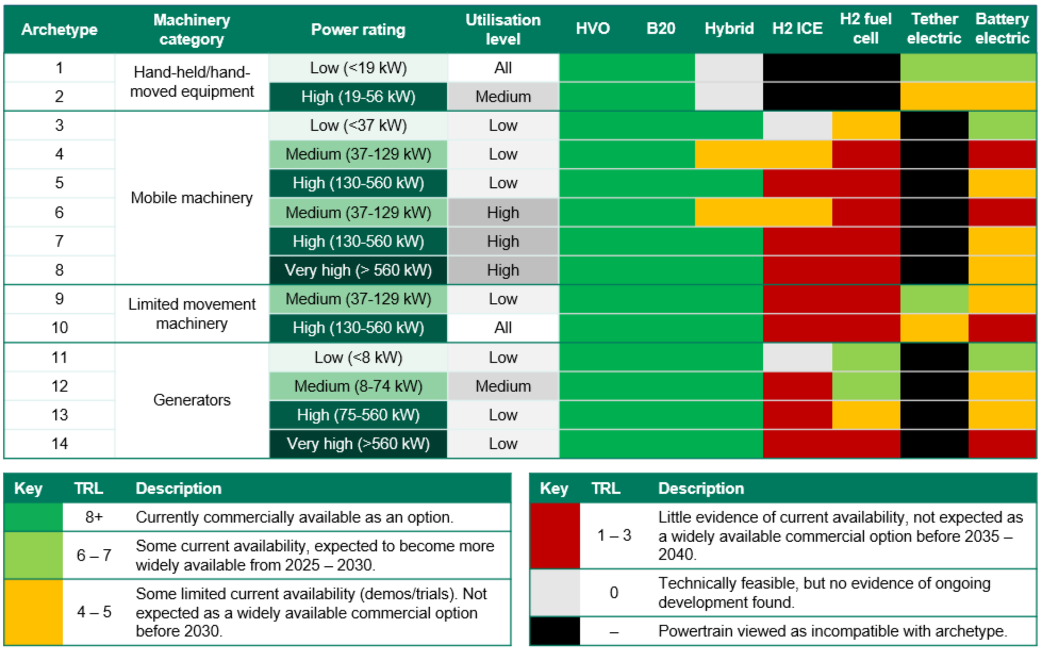
[7] Reduction based on literature (Committee for European Construction Equipment, 2018) and verified through stakeholder engagement - the ranges exclude overall site efficiency gains made beyond the NRMM equipment.

Comparison of abatement options

Powertrain availability matrix by archetype

The expected availability of abatement powertrain options for each archetype is summarised in Table 4. Table 4 suggests that a pathway to full low-carbon industrial NRMM deployment is possible by 2050, as there is at least one low carbon option commercially available for each archetype today, and at least one zero tailpipe emission option in development with potential for deployment by 2050. However, this matrix does not consider practicalities beyond the commercial availability of the technologies themselves. Increased requirements for infrastructure will particularly affect machines classed as **hard-to-deploy**, as they have characteristics which make infrastructure deployment either more challenging or more expensive.

Table 4 – Abatement powertrain option availability matrix by archetype. Source: ERM assessment



Archetype	Machinery category	Power rating	Utilisation level	HVO	B20	Hybrid	H2 ICE	H2 fuel cell	Tether electric	Battery electric
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	🟩	🟩	⬜	⬛	⬛	🟢	🟢
2		High (19-56 kW)	Medium	🟩	🟩	⬜	⬛	⬛	🟨	🟨
3	Mobile machinery	Low (<37 kW)	Low	🟩	🟩	🟩	⬜	🟨	⬛	🟢
4		Medium (37-129 kW)	Low	🟩	🟩	🟨	🟨	🟥	⬛	🟥
5		High (130-560 kW)	Low	🟩	🟩	🟩	🟥	🟥	⬛	🟨
6		Medium (37-129 kW)	High	🟩	🟩	🟨	🟨	🟥	⬛	🟥
7		High (130-560 kW)	High	🟩	🟩	🟩	🟥	🟥	⬛	🟨
8		Very high (> 560 kW)	High	🟩	🟩	🟩	🟥	🟥	⬛	🟨
9	Limited movement machinery	Medium (37-129 kW)	Low	🟩	🟩	🟩	🟥	🟥	🟢	🟨
10		High (130-560 kW)	All	🟩	🟩	🟩	🟥	🟥	🟨	🟥
11	Generators	Low (<8 kW)	Low	🟩	🟩	🟩	⬜	🟢	⬛	🟢
12		Medium (8-74 kW)	Medium	🟩	🟩	🟩	🟥	🟢	⬛	🟨
13		High (75-560 kW)	Low	🟩	🟩	🟩	🟥	🟨	⬛	🟨
14		Very high (>560 kW)	Low	🟩	🟩	🟩	🟥	🟥	⬛	🟥

Key	TRL	Description
🟩	8+	Currently commercially available as an option.
🟢	6 – 7	Some current availability, expected to become more widely available from 2025 – 2030.
🟨	4 – 5	Some limited current availability (demos/trials). Not expected as a widely available commercial option before 2030.

Key	TRL	Description
🟥	1 – 3	Little evidence of current availability, not expected as a widely available commercial option before 2035 – 2040.
⬜	0	Technically feasible, but no evidence of ongoing development found.
⬛	–	Powertrain viewed as incompatible with archetype.

Adopting **hydrotreated vegetable oil** (**HVO)**, **B20** (or other **drop-in** fuels) and **hybrid** powertrains does not require any additional refuelling infrastructure beyond what is required for diesel, so deployment of these is not expected to be limited by infrastructure requirements.

While **hydrogen** and **electric** abatement options have the highest potential to reduce emissions (when powered either by green hydrogen or renewable electricity), they have poor energy storage density. This will necessitate larger and heavier fuel tanks or batteries, or a requirement for more frequent refuelling or recharging. However, the weight of energy storage was considered less important for industrial NRMM compared to on-road vehicles by stakeholders, as there is not a legal weight limit for industrial NRMM. However, some concerns were raised over the weight of battery-powered hand-held machinery, or for high-power and high-utilisation machinery for which the weight of the hydrogen fuel tanks or batteries would be extreme.

For **battery electric** machinery, although charging solutions are widely available, the timeframe and (in some cases) cost of installing or upgrading a grid connection were identified as significant practical barriers which could delay deployment for some industrial sites.[8] Although low power or off-grid solutions (battery charged onsite at low power, battery charged offsite) are starting to emerge, these

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[8] It is hard to predict which sites will require a lengthy and or costly process to connect to the grid as these aspects are very site specific. Influencing factors include legal consents required, site distance from the primary substation, available power at the substation, pathway the cables will have to take, and the level of power requested.

have practical limitations too. The restriction of requiring a reliable grid connection also applies to **tethered** equipment.

For **hydrogen** powertrains, refuelling solutions exist in other sectors (such as road transport), however, developments could be transferrable to industrial NRMM once hydrogen refuelling systems for industrial NRMM become required. Barriers currently exist around accessing low-cost low-carbon hydrogen and delivery to remote sites, though these barriers may be reduced if the production of low-carbon hydrogen in the UK increases as planned.[9]

Barriers and enablers to the uptake of abatement solutions and international NRMM policy

Barriers and enablers

Key barriers and enablers for the deployment of abatement options by industrial NRMM are summarised in Table 5, highlighting the impact of each on the different market actors. The applicability of each barrier and enabler to each abatement option is given in Chapter 4.

Table 5 – Barriers and enablers by different market actor types (a green box indicates the barrier or enabler is applicable to the market actor)

	Barriers and enablers	OEMs	Users	Lease and hire companies	Site owners /clients	Fuel & inf providers	End of Life actors
Barriers	Immaturity of abatement options	🟩	🟩	🟩		🟩	🟩
	Limited fuel supply & infrastructure		🟩		🟩	🟩	
	Performance challenges	🟩	🟩				
	Safety challenges	🟩	🟩		🟩	🟩	
Both	Economic and financial differences or incentives		🟩	🟩			
	Policy and regulations	🟩	🟩	🟩	🟩	🟩	🟩
Enablers	Carbon reduction ambition	🟩	🟩	🟩	🟩	🟩	
	Air and noise pollution reduction	🟩	🟩		🟩		
	Transition technologies		🟩				

Of the market actors, users and original equipment manufacturers (OEMs) are affected by the highest number of barriers and enablers identified. When making decisions about decarbonisation, these actors are predominantly motivated by demands from their customers (such as site owners for users or users themselves for OEMs).

For the abatement options, the most significant barriers were identified for electric and hydrogen options, largely relating to fuel supply or infrastructure. These barriers were generally similar between the two but were deemed more severe for hydrogen technologies in some areas. For example, for fuel supply and infrastructure, hydrogen experiences barriers along the full supply chain (fuel production, distribution and dispensing), whereas electricity experiences significant barriers relating to distribution to the site only.

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[9] https://www.gov.uk/government/publications/uk-hydrogen-strategy

In general, current policy and regulations are seen by stakeholders as ‘holding back’ decarbonisation, particularly for zero CO_2e tailpipe emissions and any new powertrains, as there is no set net-zero date for industrial NRMM in the UK.[10]

International industrial NRMM policy

A review of international policy related to industrial NRMM showed that:

- Policy related to emissions abatement of industrial NRMM outside of the construction sector is scarce. Emissions policy within the construction sector is primarily set by local government and focuses on air quality improvement rather than decarbonisation.
- While public sector procurement has been successful in stimulating initial roll-out of zero emission industrial NRMM (notably in Norway, where sales of electric excavators and electric wheel loaders reached 191 in 2021 compared to 67 in the previous year), the potential impact of these policies is limited by the finite number of machines required for municipal construction projects.
- There are no industrial NRMM decarbonisation plans at the national level anywhere. The only national level intervention identified in this review was in Norway, where zero emission construction machinery and mobile charging stations are subsidised.[11]

Least-cost decarbonisation pathway modelling

A detailed techno-economic model was developed and used to estimate the least-cost decarbonisation pathway for each unique combination of industrial NRMM type, power rating and sector within the 2021 NAEI database, under several scenarios. The modelling performed was conducted on a social-cost basis (including the cost of carbon) – it is noted that private costs may not align with societal costs.[12] The key steps of the modelling are summarised below:

- **Calculate the total cost of ownership** for each abatement option for each unique industrial NRMM **and assign sales** to the cheapest abatement option which is commercially available for that machine.
- Combine the current industrial NRMM stock with predicted sales to **project the industrial NRMM stock to 2050**, broken down by abatement option used.
- **Calculate the total cost of the pathway** compared to baseline (no abatement options chosen) and the emissions savings.

Full assumptions and limitations of the modelling are detailed in section 5.1.

Modelling outputs

Three decarbonisation pathways were modelled and compared to a baseline scenario where NRMM do not switch from the incumbent powertrains (efficiency measures included in all scenarios). The abated tank-to-wheel (TTW) emissions for the three decarbonisation pathways are shown in Figure 3.

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[10] At the local authority level, the Greater London Authority has set increasingly stringent standards for 2025 and 2030, culminating in the requirement for zero emission machinery from 2040. There is no national level equivalent standard nor support schemes.

[11] Incentives of up to 40% of the price difference (capped at around £375,000) of zero emission construction machinery (compared to conventional) and up to 40% of the cost of mobile battery-powered charging stations (capped at around £150,000) minimum battery size of 70 kWh and charging speed of 100 kW) are available in Norway from 2023.

[12] The pathways reported here explore optimal deployment from a societal perspective and do not represent a prediction of what will happen without government intervention.

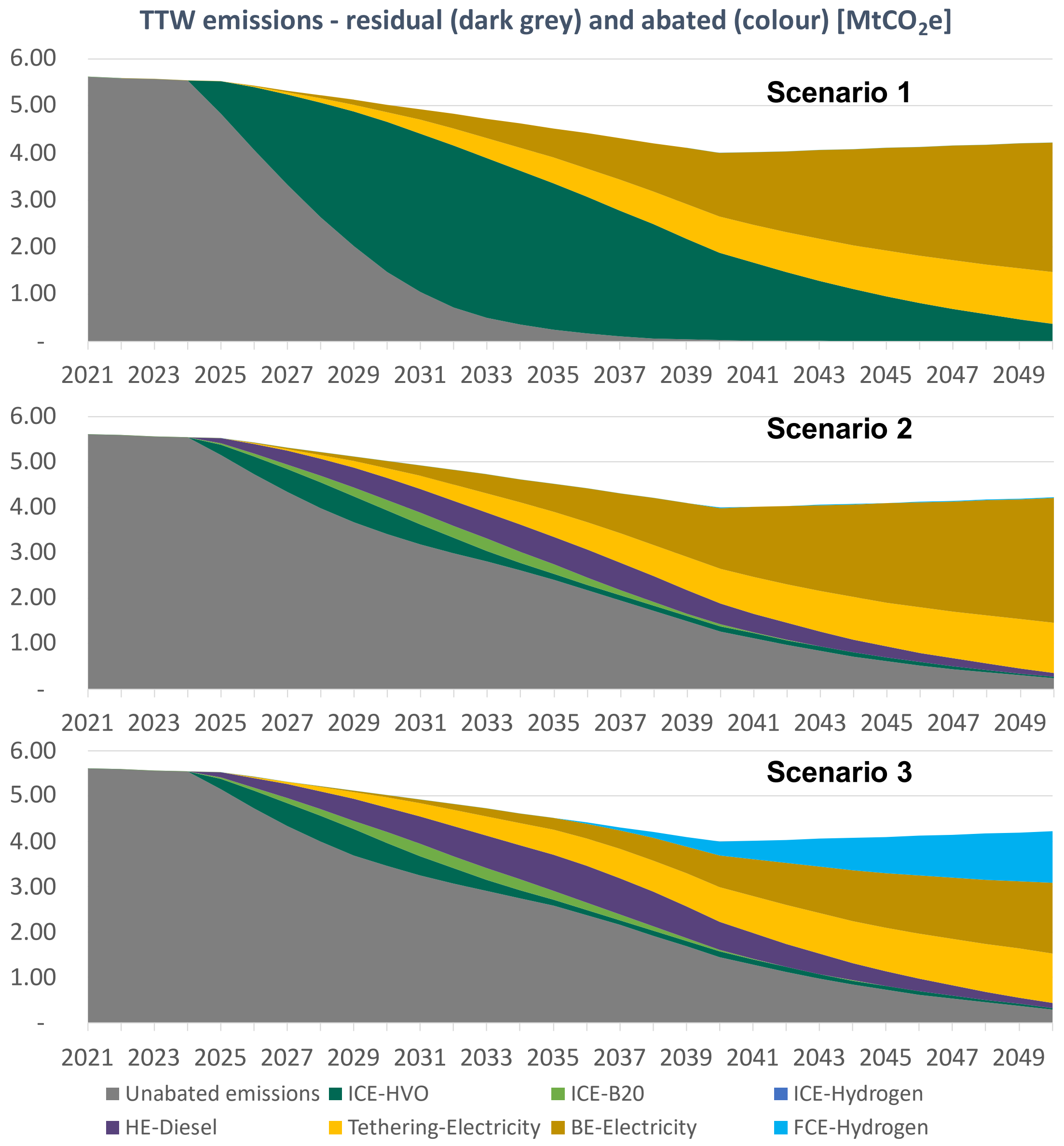

Figure 3 – Abated emissions CO_2e emissions for the three modelled scenarios

Scenario 1: Unconstrained view of the technical and economic potential of abatement options

Equipment rapidly transitions to HVO due to significant carbon cost saving compared to diesel.[13] However, this scenario predicts substantial use of HVO which may not be practically feasible (requiring nearly five times more annually than was sold under the Renewable Transport Fuel Obligation (RTFO) for all transport sectors in 2022). This transition to HVO is followed shortly by electrification of low-power archetypes (1, 3, 9, 10 and 11) in the early 2030s. As battery costs decrease and larger battery electric machines become available, NRMM with higher utilisations and power ratings start to electrify from 2035 onwards. Hydrogen abatement options are not found to be least-cost for any industrial NRMM in this scenario.

Scenario 2: HVO supply is constrained for industrial NRMM

The HVO supply limit results in a slower decarbonisation pathway, with more B20 and hybrid powertrains selected from 2025. However, the limited availability of HVO does not impact the electrification of NRMM which starts in the early 2030s and follows an identical trajectory to that in

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[13] The modelling performed for this study assumed zero tank-to-wheel emissions for HVO to align with Renewable Transport Fuel Obligation modelling.

Scenario 1, dominating the market by 2050. Hydrogen is only adopted for a small number of fuel cell generators sold between 2035 and 2045, before transitioning to battery electric solutions.

Scenario 3: Battery-electric assumed as not suitable for high use mobile machinery or generators – HVO constrained as in Scenario 2

The restrictions on the availability of battery electric machinery result in a decarbonisation pathway with a similar decarbonisation speed compared to Scenario 2. The key difference is the introduction of hydrogen as an abatement solution from 2035 onwards for higher utilisation archetypes and generators (where battery electric is modelled as unsuitable). Electrification remains as the dominant solution (with regard to abated emissions); however, hydrogen plays a more substantial role compared to the other scenarios.

Table 6 shows the emissions reductions achieved in each scenario relative to 2021 in 2035 and 2050. Scenario 1 sees the fastest reduction of emissions, reaching zero TTW emissions in 2044, due to the rapid adoption of HVO across all sectors. Scenarios 2 and 3 have a slower decarbonisation path and do not reach zero TTW emissions by 2050, as there are a small number of diesel hybrid machines still in the stock in 2050. The emissions reductions seen in the baseline scenario are due to the implementation of energy efficiency measures, reducing the total fuel demand in the sector.

The cumulative pathway resource cost[14] is also shown in Table 6, with all three decarbonisation pathways cheaper than the baseline. This reduction of cost is predominately due to machinery transitioning to electric powertrains (and to a lesser extent hydrogen fuel cell for Scenario 3). The lower resource costs of Scenario 2 (with supply of HVO limited) compared to Scenario 1 (unconstrained) are due to the lower costs associated with the higher-emission alternatives to HVO (B20 and hybrid powertrains) – see Figure 3.

Table 6 – Annual TTW emissions and percentage reduction from 2021 in 2035 and 2050 for each scenario, and the cumulative discounted resource costs for 2021-2050

Scenario	Annual emissions in 2035 ($MtCO_2e$) (% reduction on 2021)	Annual emissions in 2050 ($MtCO_2e$) (% reduction on 2021)	Cumulative pathway resource costs 2021-2050 (£bn, discounted)
Scenario 1	0.24 (96%)	0 (100%)	84.5
Scenario 2	2.40 (57%)	0.24 (96%)	84.1
Scenario 3	2.58 (54%)	0.29 (95%)	84.8
Baseline	4.52 (20%)	4.22 (25%)	87.4

Risks and opportunities to the transition to low carbon NRMM

The **risks and opportunities** associated with the transition to abatement options for industrial NRMM are:

- **Multiple abatement solutions (Risk) –** The development of multiple abatement options risk OEMs not achieving the economies of scale to realise cost reductions, and OEMs and purchasers risk having stranded assets if they commit to a technology that is later outcompeted by other abatement options. This risk will increase with the number of different abatement options developed for industrial NRMM.
- **Misalignment with global markets (Risk) –** Whilst decarbonisation policy for industrial NRMM is at an early stage internationally, if UK policy develops in a different direction to other markets, this could affect the UK's position as a net exporter of industrial NRMM. This particularly impacts machines that require specific infrastructure (e.g., hydrogen supply,

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[14] The resource cost is the sum of the machinery capital expenditure (CAPEX) of purchased equipment plus the cost to run all machinery (fuel costs based on long-run variable costs as for the Total Cost of Ownership (TCO) calculations) for the specified year. These costs are discounted by 3.5% per year, consistent with the Green Book discount rate. This excludes cost of carbon included in the TCO calculations.

charging infrastructure) given that the necessary infrastructure would need to be available in destination markets. This risk is highest in the near-term and is likely to reduce over time as decarbonisation strategies are developed for the UK and internationally for industrial NRMM.

- **Shared requirements with other sectors (Risk and Opportunity) –** For some abatement options, there is likely to be competition for feedstocks with other sectors (e.g., biofuel feedstocks could also be used to make sustainable aviation fuels). For other abatement options, shared requirements can be beneficial (e.g., increased adoption of hydrogen in other sectors would increase availability and decrease the cost of hydrogen for industrial NRMM). The risks are likely to decrease over time and the opportunities likely to increase, as supply bottlenecks are addressed, and infrastructure is deployed.
- **Innovation in businesses and market structure (Opportunity) –** As the NRMM market changes, there may be opportunities for new and existing businesses to fill new niches created in the transition. Increased data collection and analysis can improve the efficiency of NRMM activities, as well as allowing companies and governments to make more informed decisions for machinery procurement or designing policy. The opportunities are likely to increase over time, as the industrial NRMM transitions to low-carbon technologies.
- **Improved operator experience (Opportunity) –** Abatement options that reduce air and noise pollution or emit less heat will improve the operating experience for machinery operators. This may result in improvements to employee health and satisfaction, and a reduced impact on neighbouring residents and businesses. These benefits are seen most strongly for battery electric, tethering and hydrogen fuel cell solutions, as other abatement options do not significantly reduce both air and noise pollution.

Conclusions and areas for further work

- **The use of industrial NRMM is diverse and poorly documented:** This results in challenges when trying to analyse the whole sector. This means the analysis performed for this study comes with some uncertainties, which are highlighted where appropriate in the report.
- **A wide range of abatement solutions are being pursued for industrial NRMM:** The suitability of different technologies depends on a wide range of parameters which are specific to the site and machinery, including tasks performed, utilisation levels and the size, duration and location of the site.
- **From a social perspective, modelling suggests that electrification is the lowest cost abatement option if available:** Rapid electrification of NRMM could be seen by 2030, starting with smaller equipment and transitioning to larger equipment as technology improves. Biofuels could play a role in the short term before electrification occurs. Hydrogen and low-carbon drop-in fuels could be used in applications where electrification remains challenging in the long term. The size of this niche will depend on the ability to access grid electricity (or low-carbon off-grid electricity solutions).
- **Efficiency measures could reduce the energy demand of industrial NRMM:** An energy demand reduction of up to 25% by 2050 compared to 2021 could be achieved, despite projected increase in NRMM stock of 19%, but there is significant uncertainty on the level of energy reduction that efficiency measures could achieve across all industrial NRMM.
- **Uncertainty in NRMM decarbonisation policy and future fuel and infrastructure availability are key barriers:** These may reduce over time as policy is implemented and fuel supply and infrastructure deployment increases.
- **Industrial NRMM will be influenced by decarbonisation pathways of other sectors:** In the short term, competition for supplies (e.g., biofuels, low-carbon hydrogen, batteries) may hinder deployment of low-carbon solutions for industrial NRMM. However, in the long term,

industrial NRMM may benefit from supply chains (e.g., low-carbon hydrogen production, battery recycling) developed for other sectors if decarbonisation pathways align, reducing cost and increasing scale across the industrial NRMM market.

- **The UK NRMM market is part of a wider global market:** The UK's position as an industrial NRMM exporter would be at risk if policy to decarbonise UK industrial NRMM was substantially different to future (yet unannounced) policy in the EU and the USA (43% and 28% of NRMM exports by value in 2022). Ensuring alignment with these markets will protect the UK's position as a net exporter and protect UK businesses that currently export industrial NRMM.
- **Abatement options identified for industrial NRMM may also be applicable for other NRMM sectors:** Parallels can be drawn with agriculture, airport and domestic machinery. Battery electric options were identified as the most applicable for the other three identified sectors.

The following areas for further work are suggested to address data gaps or narrow uncertainties identified during the research:

- **Improve publicly available data and evidence on NRMM in the UK:** An accurate representation of industrial NRMM stock complements any evidence base on decarbonisation options, allowing the UK Government to take a more informed approach to policy development. In addition, this will benefit companies (OEMs, users) to develop and use low carbon machinery best suited to perform the tasks currently performed, as well as infrastructure providers to assess the needs of their clients. As the deployment of technologies increases, the inputs to the IND-database and modelling can be refined to best reflect the most recent developments. This would be particularly beneficial in the case of efficiency measures, where very limited data on the costs to implement measures was available and a pre-defined deployment pathway was applied equally to all modelled scenarios.
- **Conduct further analysis of industrial NRMM at a site-level:** Site-level factors such as number of NRMM on site and the size and duration of the site are likely to affect the ease of deploying hydrogen or electric-powered machinery which require new infrastructure. However, data on these is limited, as well as the feasibility of deploying multiple different solutions on a single site. Understanding whether multiple abatement solutions can be supported on one site and how the solutions may interact could help shape the overall approach to decarbonising the sector.
- **Assess the impact of proposed legislation on UK NRMM market dynamics:** Stakeholders indicated that legislation may create challenges for adopting some abatement options. Concerns were raised specifically on the safety requirements for hydrogen on site and the impact that the EU battery regulation may have on exports. Further research may be needed to identify the extent to which these are actual legislative barriers or perceived barriers from stakeholders.
- **Improve understanding of the end of first life process:** End of life actors were underrepresented during the stakeholder engagement. Further work may be needed to better quantify the impact of the deployment of abatement options on these market actors.
- **Update view of risks and opportunities as deployment of abatement options accelerates:** Currently, there is a lack of literature on risks and opportunities. The assessment of these was based solely on stakeholder engagement at a qualitative level. As the deployment of abatement options starts, these potential risks and opportunities will evolve, with some discounted and others arising. Frequent reassessment will help the NRMM sector tackle challenges, mitigate risks and take advantage of opportunities on its path to net zero.

CONTENTS

LIST OF ABBREVIATIONS

AC	Alternating Current
AD	Anaerobic Digester
ADR	European Agreement concerning the International Carriage of Dangerous Goods by Road
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation
AGV	Automated Guided Vehicle
APC	Advanced Propulsion Centre
B20	Fossil and biodiesel blend containing up to 20% biodiesel
BAM	Royal BAM Group
BEIS	Department for Business, Energy & Industrial Strategy
BESS	Battery Electric Storage System
BE(V)	Battery Electric (Vehicle)
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CAT	Caterpillar Inc.
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CEA	Construction Equipment Association
CECE	Committee for European Construction Equipment
CfD	Contract for Difference
CH_4	Methane
CI	Compression Ignition
CLC	Construction Leadership Council
CLEC	Centre for Low Emission Construction
CMB	Compagnie Maritime Belge
CNG	Compressed Natural Gas
CO	Carbon Monoxide
COMAH	Control of Major Accident Hazards Regulations 2015
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DC	Direct Current
Defra	Department for Environment Food and Rural Affairs
DESNZ	Department for Energy Security and Net Zero
DfT	Department for Transport
DME	Dimethyl Ether
DNO	Distributor Network Operator
DNV	Det Norske Veritas
DUKES	Digest of UK Energy Statistics
EIT	European Institute of Innovation and Technology
EPR	Extended Producer Responsibility
ERM	Environmental Resources Management
ESG	Environmental, Social, and Corporate Governance
ETI	Energy Technologies Institute
EU	European Union
EV	Electric Vehicle
EVCP	Electric Vehicle Charging Point
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FOAK	First of a Kind
FT	Fischer-Tropsch

GB	Great Britain
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GPS	Global Positioning System
GSE	Ground Support Equipment
GW	Gigawatt
GWP	Global Warming Potential
h or hr	Hour
H_2 or H2	Hydrogen
HC	Hydrocarbon
HCE	Hyundai Construction Equipment
HFC	Hydrofluorocarbons
HGV	Heavy Goods Vehicle
HMRC	HM Revenue and Customs
HRS	Hydrogen Refuelling Station
HSE	Health and Safety Executive
HTL	Hydrothermal Liquefaction
HV	High Voltage
HVO	Hydrotreated Vegetable Oil
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IND-database	Industrial NRMM Decarbonisation database
Inf.	Infrastructure
IPCC	Intergovernmental Panel on Climate Change
ITM	ITM Power plc
JCB	J.C. Bamford Excavators Limited
kt	Kilo Tonne
kVA	Kilovolt-amps
kW	Kilowatt
L	Litre
LIB	Lithium-Ion Battery
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LRVC	Long-run variable cost
M	Million or Mega
MJ	Megajoule
MJLHV	Megajoule using lower heating value
MT	Million Tonne
NA	Not applicable
NAEI	National Atmospheric Emissions Inventory
NE	No evidence found
NF_3	Nitrogen trifluoride
NGN	Northern Gas Networks
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NRMM	Non-Road Mobile Machinery
NRMM-RAS	NRMM Retrofit Accreditation Scheme
N_2O	Nitrous Oxide
OBR	Office for Budget Responsibility
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OGCI	Oil and Gas Climate Initiative
OHEEG	Off Highway Engine and Equipment Group

OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
PFC	Perfluorocarbons
PM	Particulate Matter
PPA	Power Purchase Agreement
PV	Photovoltaic
RAF	Royal Air Force
RAG	Red, Amber Green
RCF	Recycled Carbon Fuel
rDME	Renewable Dimethyl Ether
RDR	Red Diesel Replacement programme
RFAS	Renewable Fuels Assurance Scheme
RFNBO	Renewable Fuel of Non-Biological Origin
RIIO-ED1	Revenue = Innovation + Incentives + Outputs for Electricity Distribution
RTFC	Renewable Transport Fuel Certificate
RTFO	Renewable Transport Fuel Obligation
RTG	Rubber Tired Gantry [Crane]
SBT	Science Based Target
SBTi	Science Based Targets initiative
SF_6	Sulfur Hexafluoride
SI	Spark Ignition
sqm	Square metre
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
TTW	Tank to Wheel
UK	United Kingdom
UKPN	United Kingdom Power Networks
USA	United States of America
USD	United States Dollar
VAT	Value Added Tax
VSO	Vehicle Special Order
WTW	Well To Wheel

1 INTRODUCTION

1.1 Background

In its Net Zero Strategy (2021), the UK Government recognised that further policy interventions would likely be necessary to decarbonise industrial non-road mobile machinery (NRMM) in line with carbon budgets and net zero targets. Although many past studies have focused on greenhouse gas (GHG) emissions from industrial NRMM, the Department for Energy Security & Net Zero (DESNZ) now seeks an up-to-date assessment of how the industrial NRMM market operates, the techno-economic potential of different decarbonisation options available for industrial NRMM, and the barriers to the development and deployment of these options. For the purposes of this research, the term NRMM encompasses any mobile machine, transportable equipment, or vehicle with or without bodywork or wheels which:

- Is not intended for carrying passengers or goods on the road.
- Includes machinery installed on the chassis of vehicles intended for the transport of passengers or goods on roads.

1.2 Machinery in scope

This study covers the use of NRMM in the industrial sector only. This encompasses 36 equipment types, summarised in Table 7, operating across five sectors: construction, mining, ports, waste, and other (including applications such as warehousing, logistics, supermarkets, road surface treatment). This does not include NRMM used at airports, for agriculture, for domestic use or as transport refrigeration units. The operation of industrial NRMM within scope of this report currently accounts for approximately 5.6 million tonnes of carbon dioxide equivalent ($MtCO_2e$) GHG emissions per year, which represent just over 1% of total UK net territorial GHG emissions.[15]

The majority of GHG emissions (in CO_2e) from industrial NRMM are from the emission of CO_2, with minimal contributions from methane (CH_4) and nitrous oxide (N_2O).[15]

Table 7 – List of industrial NRMM in scope. Power ranges from the 2021 NAEI database

Name	Sector	Power Range	Example
Aerial lifts	Construction Mining Other	Small: 8-19kW Large:19-37kW	
Air compressor	Construction	Small: 19-37kW Medium: 37-56kW Large: 56-75kW	
Asphalt/Concrete pavers	Construction	Small: 36-56kW Large: 75-130kW	
Bore/Drill rigs	Construction Mining	130-560kW	

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[15] https://www.gov.uk/government/statistics/announcements/uk-greenhouse-gas-emissions-2021-final-figures: 2021 IPCC codes 1A2gvii and 1A4aii, excluding transport refrigeration units which are out of scope.

Name	Sector	Power Range	Example
Bulldozers	Construction Mining Waste	Small: 75-130kW Large:130-560kW	
Cement and mortar mixers	Construction Other	Small: 1-8kW Medium: 37-130kW Large:130-560kW	
Concrete/Industrial saws	Construction	19-56kW	
Concrete pumps	Construction	Small: 37-56kW Medium: 75-130kW Large: 130-560kW	
Cranes	Construction Ports	Small: 75-130kW Large: 130-560kW	
Crushing/Processing equipment	Construction Mining	Small: 75-130kW Large: 130-560kW	
Dumpers/Tenders	Construction Mining Waste	Small: 8-130kW Medium: 130-560kW Large: >560kW	
Excavators	Construction Mining Waste	Small: 8-37kW Medium: 37-130kW Large: 130-560kW	
Forklifts	Construction Mining Other Ports	Small: 19-56kW Large: 56-130	
Generators	Construction Other	Small: <19kW Medium: 37-130kW Large: >130kW	
Graders	Construction	130-560kW	
Loaders	Construction Mining Waste	Small: 19-37kW Medium: 37-130 kW Large: >130kW	

Name	Sector	Power Range	Example
Plate compactor	Construction	8-19kW	
Pressure washers	Construction Other	Small:<8kW Large: 8-19kW	
Pumps	Construction	<8kW	
Rollers	Construction	Small: 8-19kW Medium:19-37kW Large: 75-130kW	
Rough terrain forklifts	Construction Mining	37-56kW	
Scrapers	Construction	130-560kW	
Surfacing equipment	Construction	19-37kW	
Sweepers/Scrubbers	Construction Waste	Small: 56-75kW Large: 75-130kW	
Tampers/Rammers	Construction	<8kW	
Telehandlers	Construction Mining Port Waste	Small: 37-56kW Medium: 56-75kW Large: 75-130kW	
Trenchers/Mini excavators	Construction	Small: 8-37kW Medium: 37-56kW Large: 56-75kW	
Welding equipment	Construction Mining Other	19-37kW	

Name	Sector	Power Range	Example
Aggregate/Bitumen applicator	Other	75-560kW	
Gas compressor	Other	19-37kW	
Industrial tractor, Burden and Personnel carriers	Other	Small: 75-130kW Large: 130-560kW	
Reachstackers	Ports	130-560kW	
Rubber tyred gantry cranes	Ports	130-560kW	
Shuttle carrier/Straddle carrier	Ports	130-560kW	
Terminal tractors	Ports	130-560kW	
Landfill compactors	Waste	130-560kW	

1.3 Objectives of the study

The outputs from this study will inform DESNZ of the techno-economic potential of decarbonisation options specific to industrial NRMM, the barriers to development and adoption of these options, and an understanding of how the industrial NRMM market might change as it decarbonises. Eight specific research questions have been defined against these objectives, as shown in Figure 4.

Objectives of the study	Specific research questions to be answered
1. Develop an evidence base of decarbonisation options	Q1. **What machine archetypes are currently in use**, what costs are associated with their use and how is demand for the use of these machines expected to evolve to 2050? Q2. **What decarbonisation options are technically and practically suitable** for each of the machine archetypes? What are their characteristics, costs and availability and how could this change over time? Q3. How are these options applicable to **other NRMM sector** archetypes (e.g., agricultural, airport ground support vehicles)?
2. Identify barriers and enablers to adoption of those options	Q4. What are the **barriers and enablers to adoption** in the UK NRMM market?
3. Produce illustrative deployment scenarios	Q5. What are the **plausible pathways** to decarbonise the NRMM sector based on discrete scenarios factoring in technical, practical and infrastructure related uncertainties?
4. Evaluate the NRMM market structure	Q6. How does the development of decarbonisation options of NRMM **affect the market** over time? Q7. What are the economic and business **risks and opportunities** of implementing these options? Q8. What are the policy and infrastructure **deployment approaches** internationally we can learn from?
5. Produce a model for the least-cost decarbonisation pathways for the industrial NRMM archetypes	

Figure 4 – Objectives and research questions of the study

1.4 Overview of approach

The approach taken to answer the research questions was broadly divided into three phases, as shown in Figure 5.

Figure 5 – Overview of the approach taken for this research project

1.4.1 Literature and market review

The first step included a detailed literature review of decarbonisation options for industrial NRMM and the status and projections for industrial NRMM in the UK and globally. The review included previously published reports and techno-economic analysis, as well as announcements from NRMM original equipment manufacturers (OEMs). A list of the literature reviewed as part of this research can be found in Appendix 9.1.

This study is the first of its kind: no other publication investigating decarbonisation options for the whole industrial NRMM sector was found in the review phase. Consequently, there are significant gaps in the existing literature on this topic. Where possible, these gaps have been addressed through stakeholder engagement or by drawing analogies with other transport sectors (e.g., heavy goods vehicles). An assessment of the data quality used in this report is discussed in section 2.1.3 (specifically for the base NAEI database source), and in Appendix 9.11 (page 189).

1.4.2 Stakeholder engagement

Following the literature review, key stakeholders in the industrial NRMM market were consulted. The aims of the engagement were to verify and refine the conclusions of the interim report and to provide insight to fill gaps identified in the literature. The stakeholder engagement was conducted with the support of Cenex. It consisted of 21 one-to-one interviews and two workshops with a total of 75 attendees as summarised in Table 8. A list of consulted stakeholders can be found in Appendix 9.2.

Table 8 – Summary of the stakeholder engagement by market actor

Market actor	Number attending interview	Number attending workshops
Equipment and component manufacturers	6	21
Fuel and infrastructure providers	4	11
Equipment users	7	14
Lease and hire companies	3	5
Sector specialists (e.g., academia, trade associations)	1	24
Total	**21**	**75**

1.4.3 Final outputs

This document forms part of the final outputs provided to DESNZ, which address the eight questions set out in Figure 4.

In addition to this report, two further outputs are provided to DESNZ:

- **Industrial NRMM decarbonisation database (IND-database):** A database in Excel format providing:
    - A summary of the industrial NRMM sector in 2021, with projections on stock and sales up to 2050. The initial data used to provide this comes from the 2021 National Atmospheric Emission Inventory (NAEI) database for NRMM.
    - An assessment of the costs associated with the alternative powertrains identified in this report for industrial NRMM, including cost of the powertrain itself, indicative fuel costs and infrastructure costs where appropriate.
- **Industrial NRMM least-cost pathways model (least-cost pathways model):** An Excel model built to compare the relative cost of each powertrain option for each machine identified in the IND-database over time. This is used to estimate a least-cost pathway for the decarbonisation of the industrial NRMM sector up to 2050.

1.5 Structure of the report

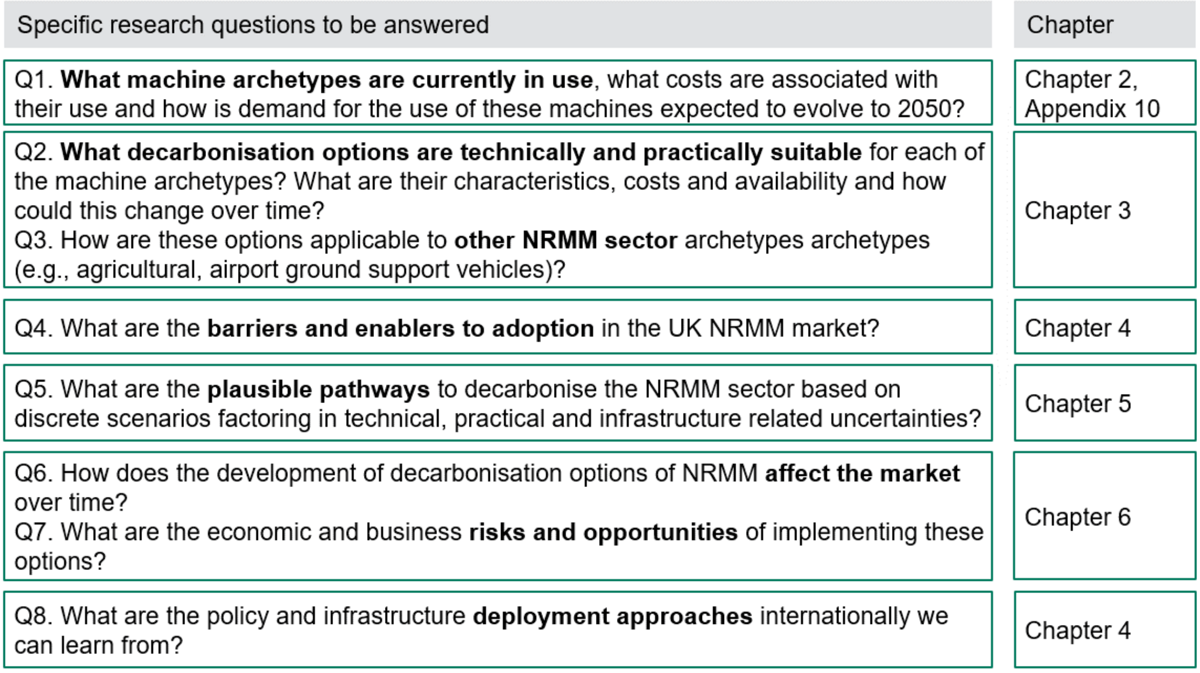
The report includes seven chapters including the current Chapter 1. The following chapters are described below. Figure 6 maps the chapters to the research questions (listed originally in Figure 4):

- **Chapter 2 – Current use of Industrial NRMM in the UK** (Page 28): This chapter provides an overview of the current state of the UK industrial NRMM market. This includes a summary of the machine archetypes currently in use, the market actors and projections of future industrial NRMM stock and sales up to 2050.
- **Chapter 3 – Industrial NRMM abatement options** (Page 45): This chapter details the abatement options available to industrial NRMM, and provides the technical characteristics, costs and availability of these alternatives including how these may change over time. The applicability of these alternatives to other NRMM outside the scope of this report is also highlighted.
- **Chapter 4 – Barriers and enablers for industrial NRMM abatement options** (Page 100): This chapter describes the barriers and enablers for industrial NRMM in their decarbonisation

journey, broken down by each barrier or enabler as well as by abatement option. Approaches to policy and infrastructure deployment internationally are also investigated, providing key learnings from progress that has been made outside the UK.

- **Chapter 5 – Decarbonisation scenarios** (Page 127): This chapter summarises the key outputs from the least-cost pathways model produced as part of this research. Three scenarios are presented based on different assumptions of the future, encompassing the technical, practical and infrastructure related uncertainties.
- **Chapter 6 – Risks, opportunities, and impacts** (Page 148): This chapter describes the economic and business risks and opportunities associated with the abatement options investigated. In addition, the effect of sector decarbonisation on the wider NRMM market and market structure is discussed.
- **Chapter 7 – Conclusions and recommendations for further work** (Page 156): The chapter summarises the key conclusions from the previous chapters and identifies opportunities for further work into the decarbonisation of industrial NRMM.

Bibliography and appendices can be found at the end of the document.



Specific research questions to be answered	Chapter
Q1. **What machine archetypes are currently in use**, what costs are associated with their use and how is demand for the use of these machines expected to evolve to 2050?	Chapter 2, Appendix 10
Q2. **What decarbonisation options are technically and practically suitable** for each of the machine archetypes? What are their characteristics, costs and availability and how could this change over time? Q3. How are these options applicable to **other NRMM sector** archetypes archetypes (e.g., agricultural, airport ground support vehicles)?	Chapter 3
Q4. What are the **barriers and enablers to adoption** in the UK NRMM market?	Chapter 4
Q5. What are the **plausible pathways** to decarbonise the NRMM sector based on discrete scenarios factoring in technical, practical and infrastructure related uncertainties?	Chapter 5
Q6. How does the development of decarbonisation options of NRMM **affect the market** over time? Q7. What are the economic and business **risks and opportunities** of implementing these options?	Chapter 6
Q8. What are the policy and infrastructure **deployment approaches** internationally we can learn from?	Chapter 4

Figure 6 – Summary of the research questions addressed and relevant chapters

2 CURRENT USE OF INDUSTRIAL NRMM IN THE UK

This chapter describes the current stock of industrial NRMM and how they are used, which is approached through an archetyping process (developed by ERM). Next, the chapter presents the market structure and actors. The final section explores past and future trends for industrial NRMM sales and stock. The current cost of incumbent industrial NRMM is covered in Appendix 9.10.

2.1 Industrial NRMM archetypes

The 2021 NAEI database provided by DESNZ was used to gain an initial understanding of industrial NRMM equipment in use and variation across sectors, power rating and urban or rural location. Given the high number of different combinations, 14 archetypes were developed to group machinery according to key metrics that are likely to influence the deployment of alternative powertrains and efficiency measures, constraints and opportunities. These two topics are presented in more detail next, whereas the gaps identified in the NAEI database are discussed in section 2.1.3.

2.1.1 The 2021 NAEI database

NRMM is a broad category encompassing machinery with a wide range of types, sizes and power requirements across a wide range of applications. The NAEI database covers over 50 different types of NRMM, out of which 36[16] (see Table 10) are relevant for the scope of this work.[17] In 2021, there were 1,830,000 units of industrial NRMM in the UK (1,200,000 of which were <4 kW generators), with an annual fuel consumption of 1.77 million tonnes of fuel, and tailpipe emissions of 5.6 $MtCO_2e$.[18] The database has several dimensions, and their relevance for the research questions are summarised in Table 9.[19]

The majority of CO_2e emissions from industrial NRMM comes from using diesel (83%) as shown in Figure 7.[20] Emissions from petrol use come predominately from low-powered generators in the 'other' sector, whilst LPG is only used for a small number of forklifts.

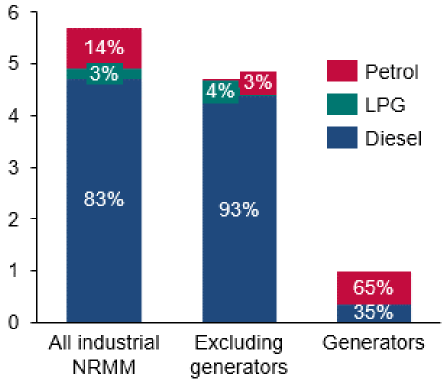


Figure 7 – Industrial NRMM annual emissions in 2021 ($MtCO_2e$) by fuel type. Source: NAEI database, with ERM analysis

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[16] We have reduced the 40 machinery types listed under 1A2gvii and 1A4aii codes in the NAEI database to 36 by excluding Transport Refrigeration Units (out of scope), grouping the 'aggregate applicator' and 'bitumen applicator' due to their similar use cases (together they represent 1.2% of industrial NRMM fuel use), and combining 'other general industrial equipment' and 'other material handling equipment' into generators due to their ambiguity and low fuel use (0.06% of industrial NRMM fuel use)

[17] Under the 1A2gvii and 1A4aii IPCC codes

[18] The values for fuel consumption, emissions and population in this section are from the IND-database, which is derived from the NAEI database with some additional ERM analysis.

[19] The data provided is for 2021 and the method to populate it is described in (Ricardo, 2020), whilst details of the analysis performed by ERM can be found in the IND-database.

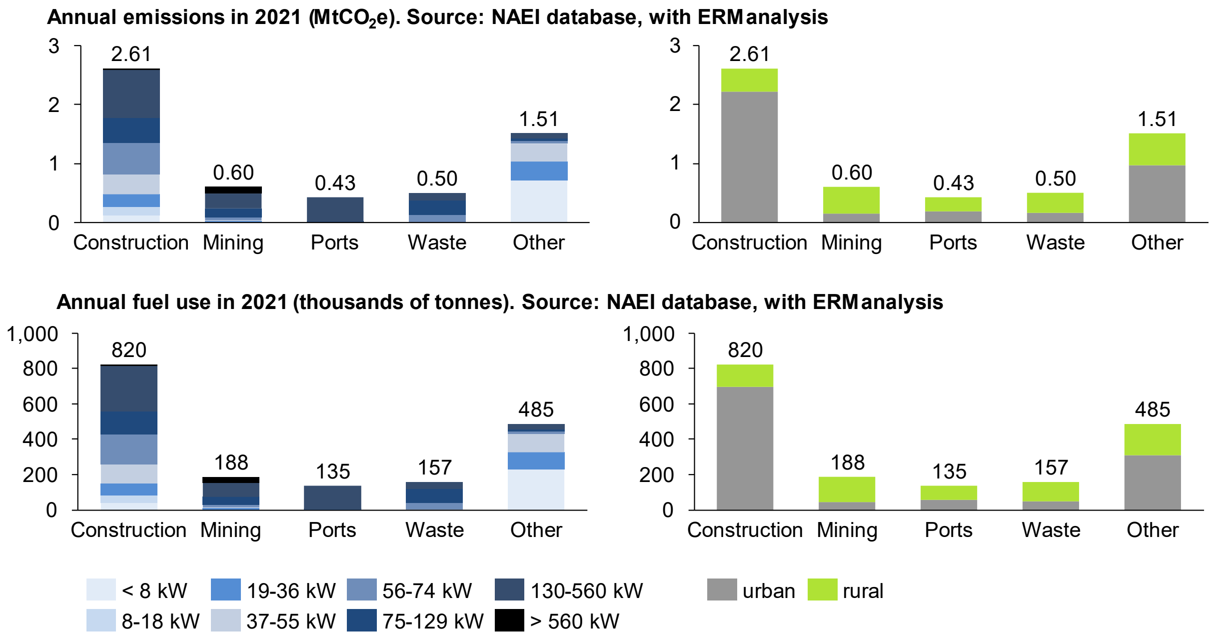
[20] The NAEI database does not include the use of biofuels or other low carbon energy sources. Some stakeholders indicated that other energy sources or powertrains (e.g., biofuels, battery electric, hybrid) are used in some machines. This usage is not captured within the 2021 NAEI database nor in the literature reviewed.

Table 9 – NAEI database dimensions of relevance[18]

Dimension	Values/number	Relevance for this work	Comments
Sector	5 sectors	High – actors and opportunities will vary with the sector, e.g., easier to have fixed refuelling or recharging options in a port compared to construction site	Sectors are construction, mining, ports, waste and other (including warehousing, logistics, supermarkets, road surface treatment)
Power rating	8 power bands	High – power needs might limit abatement options	NRMM with power rating 130kW to 560kW are the largest consumer of fuel (535 kt of a total 1,780 kt)
Load factor	Ratio (between 0 and 1)	Medium – used in conjunction with power rating and annual use to calculate annual fuel use	
Annual use	Hours, varies with age of equipment	High – it might limit some abatement options e.g., battery electric if no time available for recharging	The value is an average, there might be significant variations across days, weeks and months.
Location	Rural or urban	Medium – this factor could be used as a proxy for availability of infrastructure (e.g., grid connections) for alternative powertrains.	Fuel use is split 65% urban and 35% rural, with the mining and quarrying sector having the highest proportion of rural fuel use (25% urban and 75% rural), and construction having the highest proportion in urban (85% urban and 15% rural)
Annual fuel use	Tonnes of fuel used per year	Medium – useful to identify the highest polluters but not a direct parameter to identify abatement options (annual hours more relevant)	Construction by far the highest sector by fuel use

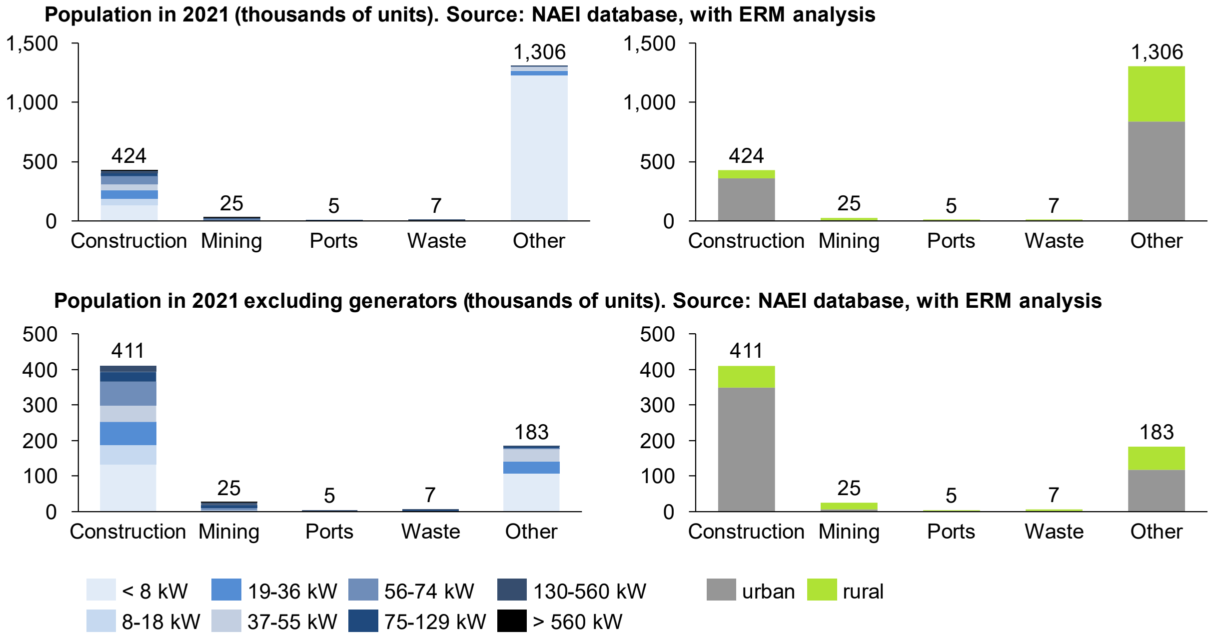
Figure 8 shows how industrial NRMM emissions (and fuel use) are split across sectors, power ratings and locations. Most emissions are from the construction sector (46%), which are predominately from an urban location. They are broken down across 8 different power bands, with 130kW-560 kW machinery cumulatively having the highest emissions (30%). Further analysis by power rating is performed in the machinery archetypes section (sub-section 2.1.2).

Most of the machinery population is in the ‘other' sector which is made up predominately of low-powered (< 4 kW) generators (Figure 9). Excluding generators, the sector with the most machinery is construction (Figure 9).


Annual emissions in 2021 (MtCO$_2$e). Source: NAEI database, with ERM analysis

Annual fuel use in 2021 (thousands of tonnes). Source: NAEI database, with ERM analysis

Figure 8 – Industrial NRMM annual emissions (MtCO$_2$e; top) and fuel use (thousands tonnes; bottom) in 2021, broken down by sector and power rating (left) and location (right). Source: NAEI database, with ERM analysis


Population in 2021 (thousands of units). Source: NAEI database, with ERM analysis

Population in 2021 excluding generators (thousands of units). Source: NAEI database, with ERM analysis

Figure 9 – Industrial NRMM population in thousands of units in 2021 with generators included (top) and excluded (bottom), broken down by sector and power rating (left) and location (right). Source: NAEI database, with ERM analysis

2.1.2 Machinery archetypes

Over 140 combinations of machinery types, power rating and usage level identified within the NAEI database have been categorised into 14 archetypes, using the methodology outlined in Figure 10. The archetypes have been designed to group the NAEI database entries into segments that are likely to have similar options to decarbonise. The NAEI database entries have been split into archetypes along three dimensions:

- **Degree of mobility of machine type:** mobility requirements can rule out some potential solutions such as tethered electric NRMM (the machine's mobility is limited by the cable length). The degree of mobility of machinery is not a dimension included in the NAEI database and has been created by ERM – see Figure 11 for the four mobility categories created and the corresponding fuel use split across sectors. Table 10 shows the assignment of machinery category to each machinery type.

- **Power rating:** impacts the feasibility of electrification and use of hydrogen. High power machines generally require more energy storage or more frequent refuelling than lower power machines, which can be more challenging for hydrogen and electric solutions due to the gravimetric energy density of batteries and hydrogen (see subsection 3.6.2 for further discussion on refuelling or recharging infrastructure). (Lajunen, et al., 2016), (Roland Berger, 2022).

  Utilisation level: directly linked to fuel consumption, a key determinant of the commercial competitiveness of different powertrain options (Lajunen, et al., 2016) as well as the ability to use certain options. For example, high utilisation and high-power requirements may limit the effectiveness of battery electric NRMM as these types of machinery would require larger batteries or more frequent charging. The % utilisation (based on an 8-hour day, 365 days a year) is used purely for archetyping. This parameter does not distinguish between equipment used lightly every day and equipment used rarely but intensely, as discussed further in sub-section 2.1.3 (under machine usage patterns).[21]

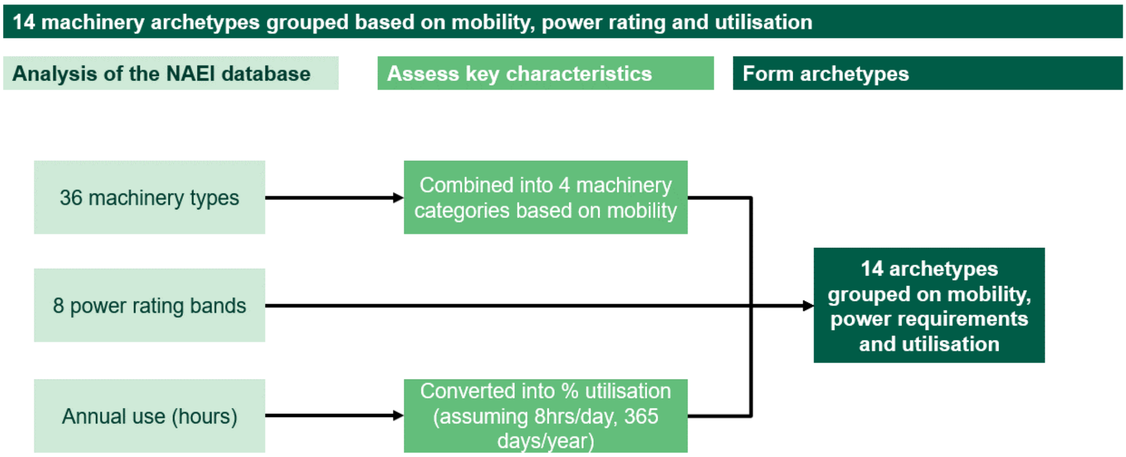


Figure 10 – Overview of the approach to generate 14 archetypes

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[21] For the modelling described in section 5, the total annual hours of use from the NAEI database is used to calculate the annual fuel use. Utilisation level is only used as a parameter to categorise machinery into archetypes.

Machine category name	Description	Example equipment
Hand-held/hand-moved equipment	Equipment is either hand-held during use, is free standing and is moved by hand between use, or is moved by hand during operation	Welding equipment, pressure washers
Limited motion machinery	Machinery that is either stationary, or can only move within a small area	Cranes/gantry cranes, gas compressors, trenchers/mini-excavators
Mobile machinery	Machinery that contains an engine that provides propulsion and is not confined to a small area of operation	Forklifts, dumpers, bulldozers, telehandlers
Generators	Generators of all sizes	

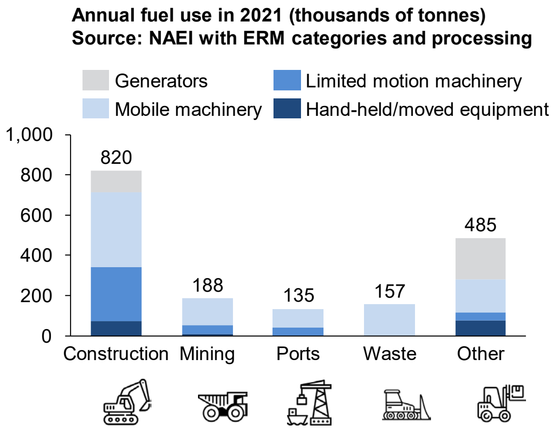
Annual fuel use in 2021 (thousands of tonnes)
Source: NAEI with ERM categories and processing

Figure 11 – Machinery categorisation created by ERM and corresponding fuel use

Table 10 – Assignment of machinery categories to machinery types, as performed by ERM

Machinery type	Machinery category	Machinery type	Machinery category
Aerial lifts	Mobile machinery	Landfill Compactors	Mobile machinery
Aggregate/Bitumen Applicator	Limited motion machinery	Loaders	Mobile machinery
Air compressors	Limited motion machinery	Plate compactors	Hand-held/moved equipment
Asphalt/concrete pavers	Hand-held/moved equipment (<56 kW) /Mobile machinery (>56 kW)	Pressure washers	Hand-held/moved equipment
Bore/drill rigs	Limited motion machinery	Pumps	Hand-held/moved equipment
Bulldozers	Mobile machinery	Reachstackers	Mobile machinery
Cement & mortar mixers	Hand-held/moved equipment (<19 kW) /Mobile machinery (>19 kW)	Rollers	Mobile machinery
Concrete /industrial saws	Hand-held/moved equipment	Rough terrain forklifts	Mobile machinery
Concrete pumps	Limited motion machinery	Rubber Tyred Gantry Cranes	Limited motion machinery
Cranes	Limited motion machinery	Scrapers	Mobile machinery
Crushing/processing equipment	Limited motion machinery	Shuttle Carrier/Straddle carrier	Mobile machinery
Dumpers /tenders	Mobile machinery	Surfacing equipment	Hand-held/moved equipment
Excavators	Mobile machinery	Sweepers/ scrubbers	Mobile machinery
Forklifts	Mobile machinery	Tampers /rammers	Hand-held/moved equipment
Gas compressors	Limited motion machinery	Telehandlers	Mobile machinery
Generators	Generators	Port terminal tractors	Mobile machinery
Graders	Mobile machinery	Trenchers/mini excavators	Limited motion machinery
Industrial tractors, burden and personnel carriers	Mobile machinery	Welding equipment	Hand-held/moved equipment

Table 11 outlines the key characteristics of the 14 archetypes created and the proportion of total fuel use from each archetype. The incumbent fuel for all the archetypes is diesel, except for archetype 11 where low-power generators from the ‘other’ sector run on petrol.[22] The key points are:

- Mobile machines (archetypes 3-8) use the most fuel overall. Of these archetypes, archetype 4 is the largest with respect to both population and fuel usage (9% of total population, 24% of total fuel use).
- Higher powered machines have a higher fuel consumption per unit than low powered machines for all machine categories.
- Archetype 11 contains the majority of NRMM units (64%), but only uses 12% of all fuel. This archetype is mainly made up of low-power (< 4 kW), low utilisation generators in the ‘other’ sector, as discussed previously in sub-section 2.1.1.

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[22] Within archetypes and besides small generators, tampers and rammers are the only machinery type where diesel is not currently the dominant fuel type. Tampers and rammers belonging to archetype 1 are assumed to run entirely on petrol in the NAEI dataset, representing 0.018% of total annual industrial NRMM fuel consumption. The only LPG usage in the NAEI database is a subset of forklifts, which represent 40% of the total forklift population and 30% of annual fuel consumption of forklifts (3% of annual industrial NRMM fuel consumption).

Regarding individual machinery types, after generators, excavators of all sizes (split between archetypes 3-5) have the highest fuel consumption (10% of all fuel consumed), followed by cranes (archetypes 9-10, 8% of all fuel consumed)[23].

Table 11 – Description and percentage of fuel use and population of the 14 archetypes created by ERM. Source data from the NAEI database, with ERM categories and analysis

Archetype ID	Machinery category	Power rating	Utilisation level	% of population	% of total fuel use	Example machinery (highest fuel use)
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	14.2%	4.6%	Cement mixers, plate compactors
2		High (19-56 kW)	All	0.9%	4.4%	Welding equipment, concrete saws
3	Mobile machinery	Low (<37 kW)	Low (<50%)	1.9%	2.0%	Forklifts, Excavators
4		Medium (37-129 kW)	Low (<50%)	9.0%	23.6%	Forklifts, Excavators, telehandlers
5		High (130-560 kW)	Low (<50%)	0.8%	9.0%	Excavators, Dumpers/tenders
6		Medium (37-129 kW)	High (>50%)	0.6%	8.7%	Sweepers/scrubbers, forklifts
7		High (130-560 kW)	High (>50%)	0.2%	6.4%	Port tractors, Bulldozers
8		Very high (> 560 kW)	High (>50%)	0.04%	1.9%	Dumpers/tenders
9	Limited movement machinery	Medium (37-129 kW)	Low (<50%)	7.5%	9.6%	Mini excavators, Air compressors
10		High (130-560 kW)	All	0.6%	12.5%	Cranes, crushing equipment
11	Generators	Low (<8 kW)	Low (<50%)	63.7%	11.5%	
12		Medium (8-74 kW)	Low (<50%)	0.4%	2.4%	
13		High (75-560 kW)	Low (<50%)	0.3%	3.2%	
14		Very high (>560 kW)	Very Low (<25%)	0.01%	0.3%	

Since different machines within a machinery type can have different degrees of mobility, power ratings or utilisation rates, a single machinery type can be split across multiple archetypes. For example, in the 2021 NAEI database, there are excavators with power ratings ranging from 16 kW to 155 kW with low utilisation. Therefore, there are excavators that occupy archetypes 3, 4 and 5.

2.1.3 Limitations of the 2021 NAEI database

The 2021 NAEI database (Ricardo, 2020; Ricardo, 2021) on NRMM population is a simplification, given the varied nature of the sector and the lack of registration data (compared to road vehicle registration databases maintained by DfT, for example). There are some parameters which are likely to have an impact on the suitability of decarbonisation options for industrial NRMM that are reliant on high-level assumptions or are not depicted at a granular level in the 2021 NAEI database, due to a lack of evidence. The evidence gaps deemed by ERM to be most relevant to decarbonisation pathways are summarised in Table 12 and discussed further in Appendix 9.11.

Site-specific and machine-specific limitations were identified. With regards to site location, size or duration, machinery was split by regional location (England, London, Scotland, Wales or Northern Ireland), and by urban or rural. However, information on the size and duration of sites is not included. Size and duration were identified as important factors that had had implications on the estimated fuel demand and on-site decarbonisation infrastructure requirements. For machine-specific information, the NAEI database provides lifetime values as a range of low, average and high in years for each entry[24] and usage data as an average annual hours of use for each entry. These were viewed as limiting given that machine usage can vary for across machines of the same type or throughout the year.

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[23] Due to limitations around the availability of data on NRMM, the NAEI database is itself an estimate. It is possible that the identified contributions of different machinery types could be an over- or underestimate.

[24] Each entry in the NAEI database represents a unique machine type, power rating and sector combination.

Table 12 – Summary of parameters which are relevant to decarbonisation and the extent to which these are included in NAEI database. Source: ERM assessment

Parameter	In NAEI?	Relevance to decarbonisation options	Comments
Location data	Yes, by region and as urban or rural	Medium	The split between urban and rural can be used as an initial estimate of the proportion of machines which may face additional complications around infrastructure.
Size of sites	No	Medium	Data not in NAEI database and will impact machine usage and decarbonisation infrastructure requirements
Lifetime of machinery	Yes	High	Lifetime ranges given in years show some disparity with OEM figures typically quoted in hours of use
Machine usage patterns (incl. continuous and annual running hours)	Limited – one average data point for each NRMM type	High	The single datapoint is an inevitable oversimplification of the wide range of annual hours typically seen in the sector
Duration of sites	No	Medium	Data not in NAEI database and will impact machine usage and decarbonisation infrastructure requirements. Mostly relevant for construction sites given their temporary nature.

2.1.4 Hard-to-deploy machinery

The deployment of abatement technologies is expected to be delayed for segments that are particularly difficult to decarbonise. The size and duration of sites, machine usage patterns and the remoteness of sites were identified and verified in stakeholder engagement as potential barriers to the deployment of electric or hydrogen technologies. These attributes either increased the complexity or cost of supplying energy to the machine. These machinery attributes are not provided within the NAEI database (as described above).

To address this limitation, machines were classified as ‘hard-to-deploy’ if they satisfy at least two of the four parameters below:

- **Used on smaller sites:** Smaller sites are more likely to struggle to obtain the cheapest fuel supply options or required infrastructure.
- **Regularly changes sites:** Machines that regularly move sites will need energy supply solutions at each site.
- **Used intensively:** Machines that have long shifts with minimum downtime may need higher power chargers installed for electric powertrains, or frequent refuelling and fuel deliveries for hydrogen powertrains.
- **Used on remote sites:** Charging infrastructure or hydrogen delivery may be more expensive for sites far away from central infrastructure.

An example of identifying hard-to-deploy machines is shown in Figure 12.

Excavator A:	**Excavator B:**	**Excavator C:**
Only used on one long-term site Site has the ability to install sufficient grid power and/or has space for hydrogen delivery/storage Machine is used intensively	Remote site, does not have reliable access to grid power/hydrogen storage Machine is used intensively, requiring extensive infrastructure/energy supply to perform the work.	Used across multiple sites for short period of times, low intensity at all sites All sites visited are large and have the potential to provide sufficient grid access/hydrogen supply
Not hard-to-deploy (alternate energy supply to machine can be achieved, even to match the intense usage)	**Hard-to-deploy (supply of alternate energy to machinery will need additional solutions and/or investment)**	**Not hard-to-deploy (alternate energy supply can be provided at all sites)**

Figure 12 – Illustrative application of the hard-to-deploy categorisation to three identical excavators with different usage patterns

In the modelling performed in Chapter 5, the availability of hydrogen and electric powertrain options for hard-to-deploy machinery is delayed by 10 years. This slows the transition of these machines to powertrains which have a high requirement for new infrastructure.

The proportion of machinery defined as hard-to-deploy was estimated at a sector level, initially using the split between urban and rural in the NAEI database and refined through stakeholder engagement (Table 13).

Table 13 – Percentage of machines assigned as hard-to-deploy based on the NAEI database and refined with stakeholder engagement

Sector	Urban or rural split (NAEI database)	% hard-to-deploy post-stakeholder engagement	Justification for change
Construction	15% rural	15%	Stakeholders did not provide estimates or evidence disagreeing with the estimate from rural proportion.
Mining	76% rural	76%	
Ports	58% rural	15%	Expected to be lower, given access to the grid. Hypothesis supported by stakeholders.
Waste	69% rural	50%	Expected to be lower than NAEI given grid access and (typically) space on-site. Higher than ports based on stakeholder feedback highlighting the high-power of machines adding an additional challenge.
Other	36% rural	36%	Stakeholders did not provide estimates or evidence disagreeing with the estimate from rural proportion
Total	**32%**	**32%**	Negligible change as port and waste equipment (the two sectors to change) collectively make up 1% of all industrial NRMM population

These proportions are high-level assumptions with a high level of uncertainty, with no granularity within sectors provided. Further research to better understand the scale of these potential barriers to deployment is recommended. The decarbonisation pathways of these machines are also likely to depend on a range of other factors such as public policy and private capital investment decisions.

2.2 Overview of industrial NRMM market

2.2.1 Market actors

The industrial NRMM market is comprised of a range of actors, whose interactions cover the whole lifecycle of industrial NRMM from production, through ownership and usage and ending with resale or export or scrappage. A summary of the key actors is shown in Table 14.

Table 14 – Overview of the constituent industrial NRMM market actors

Constituent actor	Short description
NRMM OEMs	Manufacturers of industrial NRMM who sell to UK and non-UK markets. They also typically offer remanufacturing of NRMM (change of engine and other key parts) and many offer related infrastructure for fuel switching options, e.g., charging solutions.[25]
Users	Users of industrial NRMM. They are sometimes, but not always, the owners of industrial NRMM. NRMM are often leased or hired for particular sites or jobs. Users might also be contracted by another company (for example a construction company) and have no influence on the NRMM specification.
Lease and hire companies	Third parties that purchase industrial NRMM to lease or hire to users but do not use NRMM themselves. Some other these companies may offer both leasing and hiring to users, whilst others only offer one of the two. Leasing is typically longer term (several years). Hiring can be for shorter periods or specific tasks.
Site owner or client	Organisation that contracts a company that uses industrial NRMM, for instance a local authority contracting a waste services firm, or a private developer contracting a construction company. Sometimes the site owner will provide or pay for the fuel for NRMM as part of the contract.
Fuel & infrastructure providers	Companies that sell and deliver fuel to industrial NRMM users or sites, or provider of on-site charging or refuelling solutions e.g., biofuel providers, utility companies, hydrogen supplier, etc
Used market and End of Life actors	Companies that recycle or scrap old machines, taking working parts for remanufacturing into other machines. Alternatively, auction houses buy used NRMM from owners (users or leasing companies) and resell them (domestically or internationally) for further use.
Regulators and policy makers	Set regulations and targets for the sector as well as creating incentive mechanisms for decarbonisation and air quality.

In some cases, the interaction between these market actors can be complex. Using a large UK construction site as an illustrative example:

- The site owner contracts the construction to one (or more) company. In some instances, the site owner will also provide fuel for the NRMM used on site. In the case where multiple

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[25] There is no data available on the split between manufacturing and remanufacturing of industrial NRMM by OEMs. Most OEMs do offer remanufacturing, but do not indicate how much of their business this makes up.

companies are contracted, further research and engagement would be required to better understand whether they report back to the site owner or a single point of contact (lead construction company).

- The construction companies either own their own NRMM or hire it from a hiring or leasing company.
- The hiring or leasing company has a fleet of NRMM, which are likely to be hired out over their lifetime to multiple users and sites.

These aspects mean that in some cases there is a disconnect between the companies buying and supplying the machinery (lease and hire companies) and those buying and supplying the fuel or infrastructure needed for the NRMM (clients or site owners). This highlights the importance of engaging all these market actors when looking at industrial NRMM decarbonisation, as cross-actor co-ordination may be required to achieve decarbonisation.

2.2.2 Machinery production

Production volumes per machine type for industrial NRMM are lower than other transport sectors, such as road transport, due to the large number of machine types and variations in size and use case (McKinsey & Company, 2016). In 2022, the UK was the largest producer of construction equipment in Europe and fifth globally, accounting for annual revenues of more than £14 billion. Of this revenue, OEMs accounted for just under half; there are 15 major equipment and engine companies in the UK (see Table 15). The other half is made up of many smaller plants that produce components for the OEMs (Construction Equipment Association, 2023).

Table 15 – UK construction NRMM OEM plant locations in 2022 (Construction Equipment Association, 2023)

Company	Main Locations
BG Pavers	Preston
Caterpillar	Desford, Peterborough, Peterlee
Hewitt Robins	Swadlincote
JCB	Cheadle, Foston, Rocester
Komatsu	Chester-le-Street
McCloskey	Dungannon
Mecalac	Coventry
NC Engineering	Richill (Armagh)
Phoenix Engineering	Chard
Red Rhino Crushers	Grantham
Sandvik	Ballygawley
Telestack	Omagh
Terex	Dungannon, Omagh
Thwaites	Leamington Spa
Volvo	Motherwell

Industrial NRMM contains a wide range of specialist machinery, which is used in many different sectors. Because of this diversity, some OEMs produce machinery which is only used in a subset of the sectors that make up industrial NRMM, as shown in Table 16.

Table 16 – Major OEMs of industrial NRMM (not exhaustive)

Industrial NRMM sector	Major OEMs in the sector
Construction	Caterpillar, Komatsu, JCB, CNH
Ports	Kalmar, Liebherr group
Mining or quarrying	Epiroc, Sandvik, Komatsu, Caterpillar
Waste	Caterpillar, Komatsu, JCB
Other	Caterpillar, Komatsu, JCB

2.2.3 Industrial NRMM ownership and usage

NRMM is either purchased by users, hiring companies or leasing companies.[26] Industrial NRMM which is owned by lease or hire companies is more likely to be used on multiple sites over its lifetime compared to operator-owned machinery. This may add additional challenges of providing infrastructure to these machines to accommodate some alternative powertrains (see sub-section 2.1.4). This will have a larger impact on industrial NRMM that is hired rather than leased, as machinery is typically hired for shorter time periods than leasing and therefore have the potential to be used across more sites.

For construction machinery,[27] two-thirds of construction NRMM is purchased by lease and hire companies (Figure 13), one of the highest proportions in the world.[28] This contrasts with Europe as a whole, where an average of 37% of construction machinery is bought by lease and hire companies. This highlights how lease and hire companies are a key stakeholder for decarbonisation of industrial NRMM in the UK, with a larger influence in the UK than in other European countries. This difference in market structure could present different opportunities as well as risks to decarbonising the sector compared to other countries, which are discussed further in chapters 4 and 6. Further research is needed to better understand the factors behind the larger proportion of leased and hired construction NRMM in the UK.

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[26] These may also be the OEM in some cases, or a subsidiary. For example, Volvo Construction Equipment provides financing options, and JCB has a subsidiary company JCB Finance.

[27] Which accounts for 65% of non-generator industrial NRMM in the UK (from the 2021 NAEI database)

[28] CEA Power Hour Webinar - Off Highway Research: UK Market Update (23 Feb 2022). ‘Lease and hire companies’ as described in this report are labelled as ‘rental’ companies in this webinar.

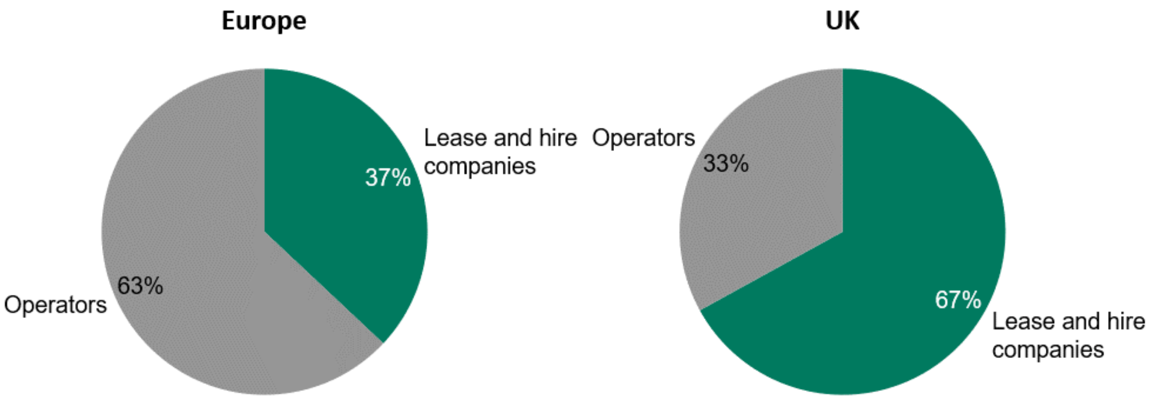

Figure 13 – Breakdown of buyers of construction NRMM in Europe and the UK (Source: CEA Power Hour Webinar – Off Highway Research: UK Market Update (23 Feb 2022))

Ownership models for lease and hire companies

Industrial NRMM can be leased or hired under a wide range of contract options from lease and hire companies, some of the most common models are summarised below:[29]

- **Contract hire:** Also referred to as 'rental', this option is typically a short-term contract (on a daily, weekly or monthly basis), where the machine is hired for a specific task or project. The user is generally not responsible for maintenance or repair costs in a contract hire (though may be liable for damage incurred).
- **Operating lease:** Operating lease is like contract hire but is typically for a longer period (up to and over a year). The machine remains owned by the hire or lease company during the leasing period, but the user may be liable for maintenance and repair costs during the lease. At the end of the lease, there might be an option for the user to purchase the equipment from the leasing or hiring company.
- **Capital lease:** Capital leases, like operating leases, are typically for a longer period (up to and over a year). The key difference is the machine is officially owned by the user during the leasing period, meaning the depreciation of the machine is on the account books of the operator which may provide a tax benefit. At the end of the lease, there might be an option for the user to purchase the equipment from the leasing or hiring company.

This list is not exhaustive, a wide range of contract terms may be available to depending on the leasing or hiring company and the needs of the user.

Lease and hire companies may experience different barriers, enablers, risks and opportunities to decarbonisation of their portfolio compared to users who own their NRMM. These companies may offer one or many types of lease and hire contracts, but their position in the market is similar for all these business models. In Chapter 4 and Chapter 6, the potential impacts on these companies are discussed, with differences between lease companies and hire companies (or between leased and hired equipment) highlighted where applicable.

2.2.4 Industrial NRMM after first life

When machinery can no longer meet the requirements of its first use, often it enters the second-hand market rather than being scrapped. If necessary, the machine may be repaired, remanufactured, or refurbished before beginning its second life.[30] Multiple lives of machinery are common, especially for large or complex machinery, as industrial NRMM can be expensive to purchase and retain a high

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[29] Leasing Equipment vs. Renting Equipment | The Cat Rental Store; Plant Machinery and Equipment: Hire Vs Purchase! | Tiger Plant; Construction Equipment – Rent, Buy, or Lease? (constructconnect.com)

[30] Should I Rebuild my Machine or Replace it? — Your Questions Answered - The Scoop (volvoceblog.com)

residual value, even after significant use. Machinery can be remanufactured in some cases: the process involves the disassembly and collection of old components to be rebuilt and restored with new parts.[31] This cycle can be repeated multiple times, with some machines achieving three or four lives. Later lives may be in a less intensive use case in the UK, such as part of a rental company's fleet. Ultimately, machinery is scrapped, with still functioning parts and valuable materials recovered for further use and recycling. According to the 2021 NAEI database, the lifetime of a machine in the UK can vary between 3 and 20 years, after which the machine would be exported or scrapped (not distinguished within the NAEI database).

Alternatively, industrial NRMM can be exported to other markets, either new or second hand. The UK is a net exporter of industrial NRMM as shown in Figure 14, which is made up of both new and second-hand machinery. The main origins of imports to the UK and destination of exports from the UK by region is illustrated in Figure 15, which shows Europe and the USA are major export destinations. In 2022, European Union countries made up the largest proportion of export trade value (43%) whilst the USA represented 28% and Asia and Oceania represented 11% (HMRC, 2023).[32] In contrast, the majority of imports to the UK come from the EU (61% in 2022), with Japan and China being the largest non-EU import origins. There is no data available on the age spread and equipment type of industrial NRMM imported to or exported from the UK.

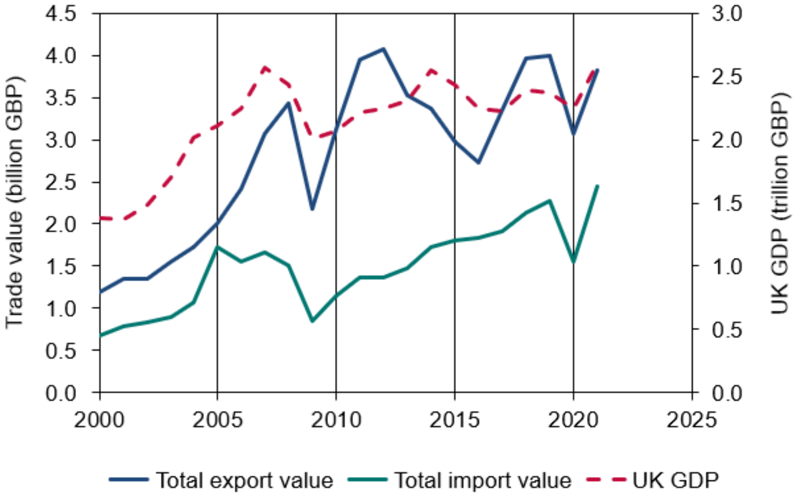

Figure 14 – UK import and export of industrial NRMM (new and second hand) compared to UK GDP over time. (HMRC, 2023)[33]

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[31] This is more common for more expensive and complex NRMM such as bulldozers, loaders, and dump trucks (Kanazawa, Matsumoto, Yoshimoto, & Tahara, 2022).

[32] HMRC data does not split the value by new and second hand so only the total value is available.

[33] The following Harmonised System Commodity Codes (HS) were used: 8429,820713, 820719, 8474, 8430, 870410, 84134000, 8426, 870911, 870919, 87051000, 87054000, 87059030, 84243001, 84243008.

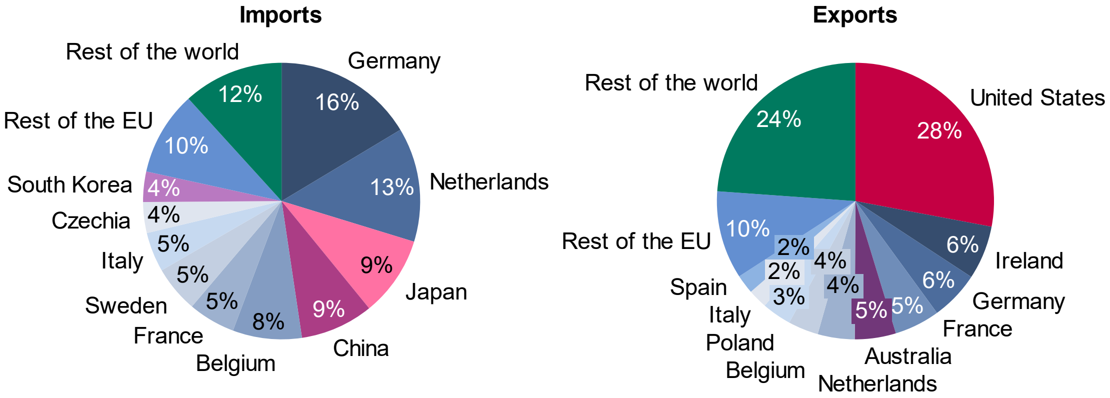

Figure 15 – UK imports and exports of new and second-hand industrial NRMM by trade value by region in 2022, showing 10 largest import and export countries, rest of the EU and rest of the world. (HMRC, 2023)

2.3 Past sales and future projections of industrial NRMM sales and stock

2.3.1 Past and current sales trends

From the NAEI database (which is an estimate in itself), it is possible to estimate the number of new industrial NRMM that enter the stock in the UK each year for the past 5 years.[34] This addition to the stock represents the number of new machines sold into the UK stock regardless of country of manufacture, excluding any units produced in the UK but exported to other countries. This addition to the stock of new machines is assumed to be equivalent to sales of new industrial NRMM in that year and has been treated as such in the following analysis.

From this data, a small annual increase in sales of industrial NRMM in the UK from 2017-2019 (pre-COVID), as shown in Figure 16. This increase is largely driven by the construction sector. Beyond the NAEI database, there is limited data on absolute sales numbers of industrial NRMM within the UK. However, the sales trends observed in the NAEI database match other proxies such as the value of imports and exports of industrial NRMM in the UK (Figure 14) and the annual global sales from six major NRMM OEMs (Figure 17). All three data sets show an increase from 2017 to 2019, followed a sharp decline in 2020 due to the COVID pandemic.

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[34] The 2021 NAEI database estimates machinery stock by age, for which the last five years are not affected by scrappage based on the methodology performed. Therefore, an estimate of the number of machines that enter the stock over these years can be obtained.

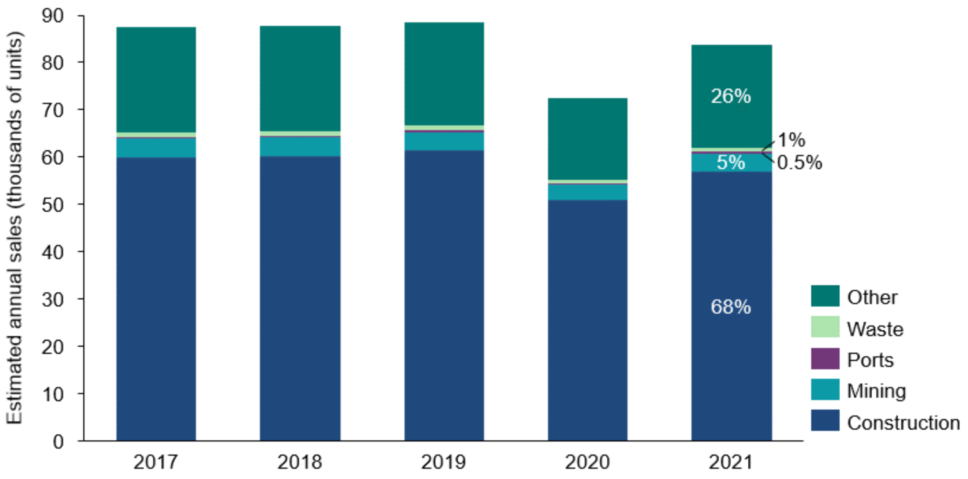

Figure 16 – Estimated historic addition of industrial NRMM to the UK stock (excluding generators) from the 2021 NAEI database. Sector proportion of sales remain roughly constant across the years examined.

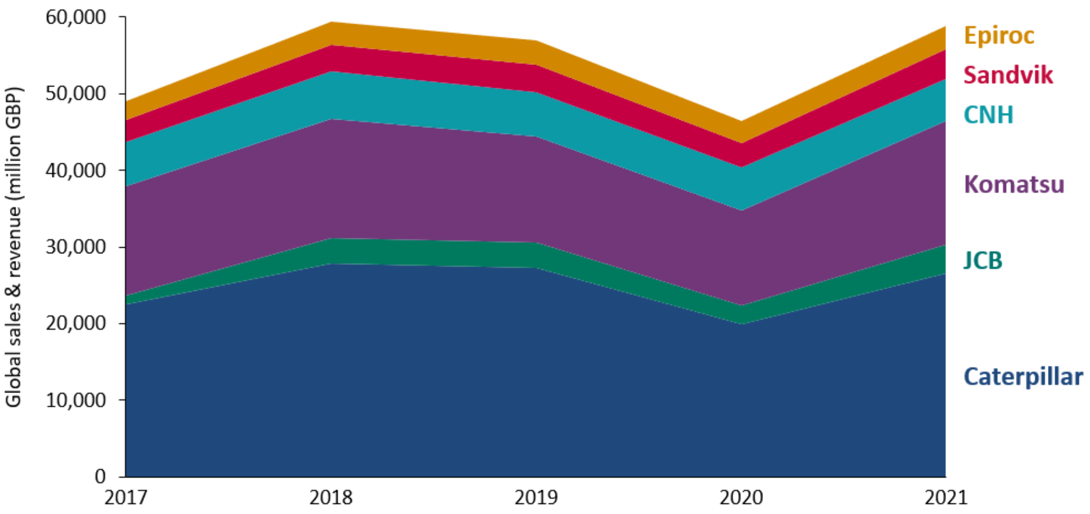

Figure 17 – Global sales and revenues of six major NRMM OEMs from 2017 to 2021[35]

2.3.2 *Forecasts to 2050*

Forecasts of industrial NRMM demand to 2050 could not be identified in the literature. Only two partial forecasts were identified for individual sectors of industrial NRMM, which provide some context for the UK industrial NRMM market:

- In a 2022 whitepaper, an American non-profit, CALSTART, details projections of USA forklift sales by powertrain type to 2030 (CALSTART, 2022). It suggests that forklifts sales in the USA will grow by over 30% by 2029, with battery electric making up the majority of sales. Interact Analysis is cited as the source but, as the original analysis was not made publicly available, drivers behind these projections could not be determined.
- Projections to 2025 of the construction NRMM population in the UK were produced in a paper from Imperial College London (Desouza, Marsh, Beevers, Molden, & Green, 2022). This projection was based on fleet lifetime and extrapolating average sales of the three years prior

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[35] Global sales and revenues taken from latest publicly available annual reports.

to 2018. As a result, the dip in industrial NRMM sales of 2020 seen in Figure 16 (due to the economic downturn created by the COVID-19 pandemic) was not captured, casting uncertainty over the remaining five years of the forecast. Projected sales varied with machinery type; backhoe loaders, rough terrain forklifts, skids steer loaders and wheeled excavators are shown with a clear decrease in sales, whilst compactors, crawler excavator, mini excavator, wheeled loader, and telehandler sales remain relatively constant albeit some with a minor increase or decrease. Notably, those showing a significant relative decrease in sales represent the lowest sales in terms of absolute volumes, with all under 4,000 per annum in 2018. This could suggest that small fluctuations in absolute sales in the three years prior to 2018 have been overly amplified by the average sales approach taken.

As these reports do not provide a long-term projection beyond 2030, and either focus on market segments outside the UK (CALSTART) or only a subset of UK industrial NRMM (Imperial College London), a new set of projections were developed to cover all industrial NRMM in the UK up to 2050.

2.3.3 Estimating future demand projections to 2050

To address the lack of data regarding future industrial NRMM demand as well as the lack of UK industrial NRMM sales data, two methods were considered to estimate NRMM sales up to 2050:

1. **Historic sales approach:** As seen in literature, using historical sales data to add to the current industrial NRMM population. While this approach showed limitations when used for short-term projects as in the paper from Imperial College London (Desouza, Marsh, Beevers, Molden, & Green, 2022), it remains a valid approach when looking at longer term horizons such as 2050.
2. **GDP approach:** Using UK GDP projections as a proxy for growth in industrial NRMM stock.

The detailed methodologies for the historic sales and GDP based approaches are described and compared in Appendix 9.4.

2.3.3.1 Method used in the IND-database for stock and sales projections.

There are two parameters that could be used to compare the accuracy of the future sales projections: comparing the projected future stock growth with historical stock growth or comparing the continuity of historical sales and future sales. These two parameters are compared below.

The predicted stock in 2050 differs between approaches, as shown in Figure 18. For the historic sales method, the total stock of industrial NRMM in 2050 is projected to be 2.1 million (19% increase on 2021 stock of 1.77 million), whilst the GDP method projects a 2050 stock of 2.5 million (41% increase on 2021 stock). However, as there are no national data sources of historical industrial NRMM stock, a comparison of historic stock growth and future projections cannot be made to assess the suitability of these two methods.

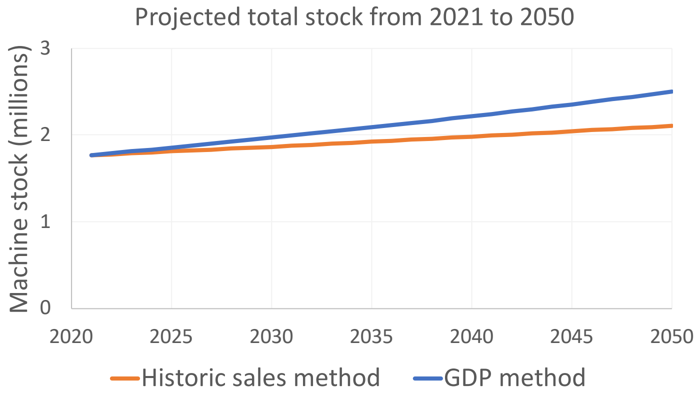

Figure 18 – Comparison of projected machine stock for all industrial NRMM up to 2050 for the two methods described above and in Appendix 9.4

As a comparison between historical stock growth and projected stock growth cannot be made, the continuity between sales projections is the best metric to decide between the two methods. As the historical sales method provides the smoother transition between historic and projected machinery sales (as shown in Appendix 9.4), this method was used for the projections in the IND-database.

2.3.3.2 Other factors that may affect future industrial NRMM stock

There are further nuances that are not addressed by either approach. External drivers such as policy and regulation could influence the demand for new industrial NRMM.

EU emission standards, adopted into UK law, only regulate air pollution emissions from new engines, with no regulation for older engines.[36] These regulations will improve air quality over time as machinery is replaced naturally but does not provide an incentive for machinery to be decommissioned early. Therefore, these standards do not drive demand for newer machinery by themselves.

However, some municipalities have extended these regulations to all NRMM on sites in the vicinity – not just new machinery. In London, all NRMM above 37 kW are required to be at least Stage IIIB (Stage IV on construction sites in some areas).[37] The application of a minimum emission standard to all machinery (not just new machinery) has led to some private companies adopting the regulations internally across the UK (Balfour Beatty, 2020). Other cities have set more ambitious targets; the city of Oslo is aiming for all local construction to be emissions-free by 2030 (City Council in Oslo, 2018). The above policies could result in an increase of sales of newer, compliant machinery, at the expense of older, non-compliant machinery. However, the limited geographical scope of such policy encouraging the purchase of new, lower emission NRMM makes untangling its impact from broader nationwide trends difficult.

Other factors such as improved efficiency of operations may also reduce NRMM sales demand by either extending the lifetime of equipment or reducing the number of machines required to complete a task. Increasingly, NRMM users are transitioning to digital tools and telematics to monitor activity and improve efficiency ((Morgan Sindall Group, 2022), (Kier Group, 2022), (Balfour Beatty, 2022)), which is discussed further in section 3.3.3.

However, any previous impact of improved efficiency on machine sales has been overshadowed by overall sector growth and increased activity, making it difficult to factor this into industrial NRMM demand projections. Therefore, in the IND-database, increases in industrial NRMM's operational, machine or process efficiency does not impact the projected stock or sales of machinery up to 2050.

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[36] EU emissions standards are included in Appendix 9.4.

[37] Non-Road Mobile Machinery (NRMM) | London City Hall. Emissions standards are planned to increase in 2025 and 2030, with only zero-emission machinery allowed from 2040.

3 INDUSTRIAL NRMM ABATEMENT OPTIONS

This chapter covers the research performed into the different abatement options that could be used in the industrial NRMM sector. Abatement options are measures that can be taken to reduce the airborne emissions of greenhouse gases causing climate change, whilst either maintaining or reducing the emission of pollutants contributing to poor air quality.

There are three families of abatement options:

- **Fuel switching** – involving the transition from using carbon intensive fuels, such as diesel, to using low or zero-emission fuels, such as biodiesel, electricity or hydrogen. This can involve a switch of fuel only (for example, using biodiesel) or a switch of equipment to new powertrains.
- **Improving energy efficiency** – reducing the quantity of energy needed to produce the same output. Efficiency measures include improvements that can be made in three categories of measures: operational, machine and process. Respectively these broadly involve changes in user behaviour, machinery components and workflows or processes that can generate savings in industrial NRMM energy or fuel consumption.
- **Process change** – whereby a process currently using NRMM is changed so that the NRMM is no longer required (e.g., by replacing it with fixed machinery powered from the grid, or a change in practice that avoids the use of machinery altogether). No substantial evidence or data was found in the literature or during stakeholder engagement. Consequently, there are no quantified metrics related to process change and is not discussed further in this chapter; however, process change is discussed in the following chapter regarding barriers.

This chapter is structured as follows:

- **Abatement options overview (Page 46):** Introduces the possible abatement options, covering fuel switching options, efficiency measures and process change.
- **Technical characteristics (Page 55):** Provides the relevant technical characteristics associated with the identified alternative powertrains or fuels compared to the incumbent (e.g., energy density, powertrain efficiency).
- **Relative costs (Page 58):** Provides the costs relative to the incumbent for the alternative powertrains or fuels (e.g., fuel price, powertrain costs, relative maintenance costs) as well as some high-level commentary on cost implications of efficiency measures.
- **Commercial availability (Page 66):** Summarises the market review performed on the development of alternative powertrains and presents a snapshot of status of each powertrain by the 14 archetypes presented in the previous chapter.
- **Abatement potential (Page 72):** Summarises the abatement potential of each powertrain option, relative to the incumbent option and reiterates the potential for efficiency measures to reduce emissions by improving fuel consumption.
- **Deployment potential (Page 74):** Provides an overview of the extent to which each powertrain could be deployed, a discussion of the practical considerations for switching to alternative powertrains, as well as a pathway for the deployment of efficiency measures.
- **Implications of findings on other NRMM sectors (Page 88):** Highlights the similarities (and differences) between industrial NRMM and other NRMM sectors, and how these findings could apply to these other sectors.
- **Suitability of abatement options (Page 93):** Concludes the research presented in the earlier sections. Mappings of the proposed commercial availability timeline and efficiency measure deployment pathways to archetype are presented, as well as a summary of key findings from this section.

3.1 Abatement options overview

This sub-section presents fuel switching options and efficiency measures available to reduce emissions from industrial NRMM.

3.1.1 *Fuel switching*

Fuel switching options can broadly be split into three subcategories, based on whether the solution has zero tailpipe emissions (GHG and air pollutants), and whether the solution can be used in incumbent engines or requires significant modifications or a bespoke powertrain. These three categories of fuel switching options are summarised in Table 17.

Table 17 – Summary of the different categories of fuel switching options

Fuel switching categories	Description	Examples
Zero tailpipe emission	Powertrain which does not have any tailpipe emissions (CO_2, particulate matter (PM), or nitrogen oxides (NOx)).	Battery electric Hydrogen fuel cell Tethering
Low carbon fuels for incumbent engines	Alternative liquid fuels with lower lifecycle CO_2e emissions than incumbent, but still produce tailpipe emissions.	Hydrotreated Vegetable Oil (HVO) B20 'E-fuels'
Other internal combustion engine (ICE) fuels alternatives	Alternative ICE powertrains with fuels that cannot be used in a conventional engine. The tailpipe emissions from these vary depending on the fuel.	Hydrogen ICE Ammonia ICE Compressed natural gas (CNG) ICE

Diesel engines are the dominant incumbent option for the majority of industrial NRMM (83% of all fuel consumption, see Section 2.1.1). The notable exceptions are small generators in the 'other' sector and tampers or rammers where the incumbent fuel type is petrol. Petrol is also used in some low-power cement or mortar mixers and LPG in some forklifts in the 'other' sector, but diesel is still dominant for both machinery types.

A longlist of fuel switching options was compiled, which included all options being considered for industrial NRMM. This includes the successful projects in Phase 1 of the Red Diesel Replacement Competition,[38] as well as low carbon fuels considered by the British Ports Association.[39] From the longlist, fuel switching options identified as likely candidates for widespread deployment within industrial NRMM were added to a shortlist.

Abatement options were shortlisted for further assessment based on meeting criteria 1 and one of the remaining criteria (2-4) below:

1. **Essential:** Option is actively in development specifically for at least two types of industrial NRMM.
2. Option does not have any CO_2 tailpipe emissions.
3. Option can be used directly in diesel engines without modifications.
4. Option is currently widely commercially available for industrial NRMM.

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[38] Phase 1 Red Diesel Replacement competition: successful projects - GOV.UK (www.gov.uk)

[39] British Ports Association

The aim of this study is to investigate methods to reduce the current 5.6 $MtCO_2e$ per year tailpipe emissions of industrial NRMM to as close to zero as possible. As machines with zero tailpipe CO_2 emissions have no CO_2e tailpipe emissions,[40] these are seen as the preferred long-term solutions. For the short term, only fuels which can be used directly in diesel engines or are already widely commercially available are likely to achieve widespread deployment.

This shortlist is not intended to include every single possible switching option that could potentially be used in industrial NRMM in the future, but to narrow down to options which currently have the highest potential for deployment either in the short or long term. This shortlist should be revisited by 2026 at the latest[41] to account for the latest technological advancements.

These shortlisted fuel switching options are explored in more detail in this report and are the fuel switching options that are included in the IND-database and the least-cost pathways modelling in Chapter 5.

3.1.1.1 Zero tailpipe emission powertrains

Zero emission powertrains do not have any tailpipe emissions of either greenhouse gases or air pollutants. Three zero emission powertrains are considered in this report:

- **Battery electric:** uses chemical energy stored in a rechargeable battery pack to power an electric motor instead of using an internal combustion engine. The battery needs to be recharged from an external power supply.
- **Tethering:** uses power cables or bus bars to power electric machinery such as large excavators, loaders, and stackers without disconnecting from the electric power supply. Tethering is referred to as an abatement option in this report as it is assumed that machines will be tethered to a clean or cleaner source of electricity (such as the grid or a low emission generator), as opposed to more polluting sources of power (such as diesel generators).
- **Hydrogen fuel cell:** uses the chemical energy of hydrogen to produce electricity that powers an electric motor. Hydrogen is the energy carrier stored on board, but there is also a battery, that is charged on-board, to help regulate the power sent to the drivetrain and keep the fuel cell in optimum operational mode. The fuel cell would typically be a proton exchange membrane (PEM) fuel cell, which can operate at low temperatures.

All three of these are shortlisted as they satisfy shortlisting criteria 1 and 2. In addition, these powertrains will have additional advantages in operations that are sensitive to air quality (for example indoor working, underground working), where zero emission machinery can negate the need for additional ventilation (discussed further in sub-section 4.1.8).

3.1.1.2 Low-carbon fuels for incumbent engines

Low-carbon fuels for incumbent engines are liquid fuels that can be used in current fossil fuel engines with no or minimal engine modification and provide a lifecycle reduction in GHG emissions. These fuels are hydrocarbon-based like fossil-fuel derived liquid fuels. Therefore, they have similar tailpipe emissions of both greenhouse gases and air pollutants. However, a lifecycle reduction in GHG emissions relative to fossil fuels can be achieved if these fuels are derived from a renewable source and the carbon in the fuel would otherwise be released into the atmosphere (e.g., waste).[42] In the UK, low-carbon transport fuels are supported by the Renewable Transport Fuels Obligation (RTFO) where large fuel suppliers must ensure a minimum percentage of their fuel supply comes from

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[40] H_2 ICE does have some tailpipe NOx (a mix of NO and NO_2) emissions, but as these are not considered greenhouse gases so therefore also has zero CO_2e tailpipe emissions.

[41] This allows for one year after the end date of the Phase 2 Red Diesel Replacement competition, at which point results and implications can be assessed Red Diesel Replacement Phase 2 Competition Guidance Notes (publishing.service.gov.uk)

[42] This can be achieved in a wide range of ways, including but not limited to using biological material as a feedstock, or by producing the fuel from carbon dioxide captured from the atmosphere.

renewable sources (Department for Transport, 2023). The Obligation is split across two targets – the ‘main’ obligation which covers all renewable fuels that meet the eligibility criteria, and the ‘development fuel’ obligation, which covers fuels defined as those ‘which need greater support and fit the UK’s long-term strategic needs’. The development fuel target was created to incentivise novel fuel pathways which require additional support, these development fuels receive double the support compared to fuels that satisfy the main obligation (Department for Transport, 2023).

The longlist of low-carbon fuels considered in this study is summarised in Table 18.

Table 18 – Longlist of low-carbon fuel options considered[43]

INCUMBENT ENGINE:		DIESEL	PETROL	LPG
No engine modification	**FUEL BLENDS**	• B20 (FAME biodiesel)	• E10 (bioethanol) • M3 (bio or e-methanol)	• rDME (20% blend)
	DROP-IN FUELS	• HVO • e-diesel • other drop-in development fuels	• e-gasoline	• bio-LPG
Engine modification required		• biomethanol or e-methanol • rDME (dimethyl ether) • B100 (FAME biodiesel) • glycerine (waste product from biodiesel production)		

As diesel is the incumbent for all but a few industrial NRMM, only options identified as replacements to diesel were considered for shortlisting.

Fuels identified as requiring modifications to existing engines were not shortlisted. These powertrains do not satisfy any of 2-4 in the shortlisting criteria. Widespread modification of existing engines for these fuels was considered unlikely due to:

- **The development and increasing availability of industrial NRMM with zero CO_2 tailpipe emissions**, as well as reduced air pollutant emissions. This reduces the incentive for widespread modification of existing engines to accommodate another fuel with tailpipe CO_2 emissions over transitioning to a zero-tailpipe emission solution.
- **The timeframe and low feasibility of more than one technological change**. It is unlikely that more than one change in vehicle or equipment and infrastructure is possible before 2050 (E4tech & Cenex, 2021).
- **Fuel specific considerations.** For example, blends of FAME biodiesel can crystalise at low temperature, presenting challenges to operation. These issues would be amplified with pure (100%) biodiesel compared to current 20% blends. (Dwivedi & Sharma, 2014)

Renewable dimethyl ether (rDME) has received some recent interest for usage in industrial NRMM but was not included in the shortlist as it does not satisfy any of criteria 2-4 (page 46). There are some projects investigating rDME use in industrial NRMM which received funding under the Red Diesel Replacement (RDR) competition run by DESNZ and rDME was mentioned by rDME producers during stakeholder workshops (satisfying criteria 1). rDME still has tailpipe CO_2 emissions, so does not satisfy criteria 2.

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[43] FAME: Fatty acid methyl ester; rDME: Renewable dimethyl ether; HVO: Hydrotreated vegetable oil; LPG: Liquified petroleum gas.

Whilst rDME can be blended into LPG for LPG ICE, since LPG usage is small in industrial NRMM this is not considered viable for widespread deployment. Pure rDME can also be used in an existing diesel engine, however it requires additional modifications to the fuel system and injection to accommodate the gaseous nature of rDME and its low lubricity (it does not lubricate the engine during use like diesel does (E. M. Chapman, 2003)).[44] In addition, the volumetric energy density of rDME is 50% lower than that of diesel, meaning that retrofitting a diesel machine to rDME would require a fuel tank twice the size or refuelling twice as often. In discussions with stakeholders, it was highlighted that the installation of additional or larger fuel tanks on existing diesel machines can be challenging as the machines are not designed with additional space to accommodate the modifications. These points were raised in relation to retrofitting diesel for hydrogen powertrains[45] and will also apply to rDME. Given that modifications to the machine and powertrain would be required to use rDME in a current diesel machine, it does not satisfy shortlisting criteria 3.

Calor Gas has announced the first rDME plant from municipal waste in the UK, with rDME available for purchase from 2025 (predominately for off-grid heating).[46] However, industrial NRMM powered by rDME are not currently commercially available, with only a handful of generators in development funded through the RDR competition. Therefore, rDME does not satisfy criteria 4 for shortlisting.

Similar arguments apply to modification of existing engines for methanol, either bio-methanol or e-methanol. Tailpipe CO_2 emissions, requiring diesel engine modifications and with little current commercial availability mean that methanol has not been shortlisted.

As a result, only liquid drop-in fuels and diesel blends were shortlisted for further analysis. Due to the large number of feedstocks and processes that may be used, this report will refer to liquid drop-in fuels and diesel blends as general categories.

For liquid drop-in fuels, this includes:

- **Hydrotreated vegetable oil (HVO):** typically produced by hydrogenating or hydrocracking vegetable oils, tallows or greases. To qualify as a development fuel under the RTFO and receive double credits, only non-segregated oils and fats may be used, such as fatbergs from sewer systems (Department for Transport, 2023).[47] This study uses HVO to refer to all HVO which is supported under the RTFO, not just as a development fuel.
- **Other drop-in development fuels:**
    - **E-fuels:** This includes e-diesel from Fischer-Tropsch (FT) or alcohol catalysis routes. In this report, 'e-fuel' is used to refer to a fuel that meets the definition of Renewable Fuels of Non-Biological Origin (RFNBO) in the RTFO. RFNBOs must use renewable electricity which meets several production criteria, as set out in the RTFO guidance for RFNBOs (Department for Transport, 2023).
    - **Advanced biofuels and recycled carbon fuels (RCFs):** This includes routes such as gasification and FT, second generation alcohol catalysis, hydrothermal liquefaction (HTL), and pyrolysis with upgrading. Feedstocks for development biofuels and RCFs include agricultural residues, municipal solid waste, and bio-methanol.

In 2022, 267 million litres of HVO qualified under the RTFO, representing just under 1% of total diesel supply. In comparison, the use of development diesel[48] was considerably lower (approximately 18 million litres,15 times less than HVO) (Department for Transport, 2023). As a result, HVO is considered the default drop-in fuel in the abatement options section (Section 3), as well as in the IND-

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[44] Fuel of the Future - DME | Thomas E Murphy Engine Research Laboratory (umn.edu)

[45] By a company that performs diesel to hydrogen conversions

[46] https://www.calor.co.uk/news-and-views/futuria-dme-propels-calors-2040-vision

[47] HVO produced from segregated oils or fats contributes to the main obligation but will not qualify as a development fuel.

[48] Development diesel as used in the RTFO report includes a variety of alternative renewable diesel solutions, of which 'e-diesel' is a small percentage.

database and least-cost pathways modelling (Chapter 5). However, some of the barriers and enablers that apply to e-fuels are fundamentally different from HVO and other drop-in development fuels, most notably when considering feedstocks limitations. E-fuels are discussed distinct from other drop-in fuels in Chapter 4 for these characteristics.

For Diesel blends, B20 was considered the default blend. B20 is an 80:20 blend of fossil diesel to fatty acid methyl ester (FAME) biodiesel. Approximately 1,494 million litres of biodiesel were supplied in the UK in 2022, representing 5.4% of total diesel supply. 3.7% of the biodiesel was supplied to the off-road sector (Department for Transport, 2023).[49] As with HVO, only biodiesel produced from non-segregated oils or fats qualifies as a development fuel under the RTFO (Department for Transport, 2023). Biodiesel produced from segregated oils or fats will only contribute to the main obligation. This study uses biodiesel to refer to all biodiesel which is supported under the RTFO, not just as a development fuel.

While HVO and other liquid drop-in fuels can also be blended into fossil diesel, the ultimate aim is to phase out fossil diesel and these fuels will only be considered in the drop-in fuel category.

B20 is considered the default fuel blend in the abatement options section (Section 3), as well as in the IND-database and least-cost pathways modelling in chapter 5.

3.1.1.3 Other ICE alternatives

This category covers all other combustible fuels which could be used in an ICE but are not compatible with the current engine types used in industrial NRMM (diesel or petrol or LPG). The longlist of powertrains considered in this section are summarised in Table 19, with further discussion below.

Table 19 – Longlist of ICE alternatives considered, and whether they were included in the shortlist for further consideration

Powertrain	Included in short-list?	Justification for inclusion or exclusion
Hydrogen ICE	Yes	Actively in development by OEMs and a zero CO_2 tailpipe emission solution (satisfies shortlisting criteria 1 and 2).
Hybrid engines (using diesel or a drop-in fuel)	Yes	Commercially available for a wide range of industrial NRMM (satisfies shortlisting criteria 1 and 4).
Compressed natural gas (CNG) ICE	No	Does not satisfy shortlisting criteria 2, 3 or 4 (see below for discussion).
Ammonia ICE	No	Does not satisfy shortlisting criteria 1. This may change for future studies on industrial NRMM decarbonisation, depending on technological development.
Dual fuel systems (e.g., ammonia and diesel, ammonia and hydrogen, hydrogen and diesel)	No	Does not satisfy shortlisting criteria 2, 3 or 4.

Hydrogen ICE machinery is an area of development by some industrial NRMM OEMs, with hydrogen ICE machinery entering real-world trials (see sub-section 3.4.2). Whilst hydrogen ICE produces NOx

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[49] The 'off-road sector' encompasses industrial NRMM as well as other NRMM sectors (such as agriculture).

emissions (see sub-section 3.5 for further discussion) and is therefore not a fully zero tailpipe emission solution, it does have zero CO_2 tailpipe emissions so satisfies shortlisting criteria 2.

Hybrid engines enable the reduction in size of the internal combustion engine by using an on-board battery and electric motor to meet peak power demands. A range of hybrid options are currently commercially available (satisfying criteria 1 and 4, see sub-section 3.4.2) and provide an immediate reduction in fuel consumption (and therefore tailpipe emissions). The ICE component will typically be compatible with either diesel or petrol fuels, so can be used in conjunction with the low carbon fuel blends and drop-in fuels identified in sub-section 3.1.1.2. In this report, hybrid engines are considered to run on diesel for analysis, to provide the clearest comparison with conventional diesel ICE machinery.

Fossil and bio-compressed natural gas (CNG) machinery was included in the longlist as there are some CNG NRMM models available for niche industrial applications (see Appendix 9.8). However, it does have tailpipe CO_2 emissions and cannot be used directly in a diesel engine so does not satisfy shortlisting criteria 2 and 3. Whilst there are some CNG industrial NRMM models available now, these are only for small niches and no announcements expanding the range of CNG machinery offered were seen from any OEMs (see Appendix 9.8). Therefore, CNG also does not satisfy shortlisting criteria 4, so has not be included in the shortlist. This is consistent with the conclusions from (Zemo Partnership, 2022a), where they are not expecting that resources will be diverted away by OEMs to grow their limited CNG offering or start developing such engines, given the current focus of OEMs towards developing zero-emission solutions. Finally, stakeholder engagement also confirmed that this is not an option significantly considered by most NRMM OEMs or end users.

Ammonia ICE and fuel cell alternatives were included in the longlist but were not taken forward into the shortlist. The development of ammonia powertrains in general is at an early stage and is predominately focused on shipping (Tornatore Cinzia, 2022). Beyond a single project funded by the RDR competition phase one,[50] there has been minimal wider interest from other industrial NRMM OEMs to date. This means that ammonia powertrains do not satisfy shortlisting criteria 1, and therefore have not been taken forward. However, interest in ammonia powertrains may increase in the future, so this powertrain may require further consideration in future decarbonisation reports if ammonia powered machinery starts to be developed more widely. In addition, there are barriers around the toxicity of ammonia and its suitability for use in populated areas, concerns which were raised during stakeholder engagement.[51]

Dual fuel ICE systems have some potential in industrial NRMM and have been used in trials[52] and as a retrofit option,[53] but development in these areas is generally lower than in the equivalent zero CO_2 tailpipe emission single-fuel option. Therefore, dual-fuel systems have not been considered as distinct decarbonisation options in this report.

3.1.1.4 Shortlist of fuel switching options

From the longlist of options discussed above, a shortlist of 7 fuel switching options have been analysed in detail within this report. The summary of these is shown in Table 20.

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[50] MAHLE powertrain, Clean Air Power and University of Nottingham to demonstrate ‘two methods of decarbonising heavy-duty engines, using ammonia and hydrogen or a combination of both’.

[51] 65% of all industrial NRMM fuel use is in an urban setting (NAEI database 2021).

[52] https://www.transportengineer.org.uk/transport-engineer-news/dual-fuel-hydrogen-road-sweeper-achieving-50-hydrogen-burn-in-aberdeen/247027/

[53] https://ulemco.com/hydrogen-dual-fuel/ ULEMCo provides retrofitting of diesel powertrains to diesel/hydrogen hybrids, however they currently focus on road transport applications rather than industrial NRMM.

Table 20 – Shortlist of fuel switching options analysed in this report

Fuel switching categories	Description	Shortlisted options
Zero tailpipe emission	Powertrain which does not have any tailpipe emissions (e.g., CO_2, PM, NOx)	Battery electric Hydrogen fuel cell Tethering
Low carbon fuels for incumbent engines	Alternative liquid fuels with lower lifecycle CO_2e emissions than incumbent, but generally still produce tailpipe emissions	HVO (representing the wider class of drop-in fuels) B20
Other ICE alternatives	Alternative combustible fuels which cannot be used in a conventional engine. The tailpipe emissions from these vary by fuel.	Hydrogen ICE Diesel hybrid

3.1.2 *Efficiency measures*

Due to the technical complexity of industrial NRMM equipment and the intensity with which they are used, opportunities exist to improve their efficiency at the operator, machine, and process levels (Committee for European Construction Equipment, 2018). These separate efficiency measure categories are summarised in Table 21 with some examples given. The range of CO_2e emissions reduction potential is also provided based on values reported in (Committee for European Construction Equipment, 2018).[54]

The following paragraphs give more detailed examples for all three categories of efficiency measures. While some variety is expected in how process efficiency measures are implemented across different industrial sectors, all three types of efficiency measures are viewed as cross-sector compatible. However, due to the varied utilisation characteristics across archetypes, it is expected that the potential benefits associated to each efficiency measure category varies by archetype – see Appendix 9.6 for a breakdown of potential efficiency gains by archetype for each category of measures.

Operational Efficiency

A 2018 report by CECE presents several examples of operational efficiency measures that can reduce NRMM fuel consumption in construction (Committee for European Construction Equipment, 2018). Such measures include regular checks to ensure machines are running with appropriate tyre pressures which can reduce fuel consumption by 10% and ‘eco-driving courses’ offered at a construction company delivering a 5% reduction in fuel used to power its machines. Anti-idling measures are another form of operational efficiency that have potential to reduce fuel use and emissions. Literature estimates show that NRMM can be idling for 45% of the time (e.g., as reported by an NRMM digital solutions provider[55] and further verified by data reported in (Desouza, Marsh, Beevers, Molden, & Green, 2021). An example of an operational efficiency measure is Volvo’s start/stop-equipped off-road engine – if operators are instructed to enable it, this feature is claimed to save 5% – 15% in fuel consumption.[56]

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[54] The source interchangeably reports estimates for improvements in productivity, reduction in fuel consumption or direct reductions in the level of emissions. The values here have been maintained as reported in (Committee for European Construction Equipment, 2018), with productivity improvements and reductions in fuel use assumed to be proportional to emissions reductions – i.e., a 15% improvement in productivity is assumed to be equivalent to a 15% potential reduction in fuel use and emissions.

[55] Driving efficiency through data standardisation (machinemax.com)

[56] Start/stop feature now for Stage IV/Tier 4 Final | Volvo Penta

Table 21 – Summary of different categories of efficiency measures

	Operational efficiency	Machine efficiency	Process efficiency
Description	Changes to how operators use industrial NRMM	Redesigning or replacing components or systems on the machine itself to improve energy consumption (excluding fuel-switching)	Changes to the workflows or processes that utilise industrial NRMM
Example	Training operators to drive more fuel efficiently and avoid unnecessary idling	Upgrading the hydraulics or transmission system to more energy efficient systems on a machine Installing a telematics-driven start and stop system to reduce engine idling time	Using telematics data to ensure machines are assigned to appropriate energy-efficient jobs Using advanced software and hardware to digitalise manual site surveying done for levelling processes in earthmoving activities
Complexity	Low	High	Medium
Cost[57]	Low	High	Medium – High
CO_2e emissions reduction potential[58]	5% – 30%	5% – 25%	15% – 50%

Machine Efficiency

Considering the complexity of industrial NRMM and the various drive systems within them[59] there are many opportunities to improve efficiency.[60] OEMs are targeting efficiency improvements at multiple levels from single components to wider powertrain or system improvements. For example, switching a single component in an excavator (digital displacement pump) has been claimed to deliver up to 15% fuel savings, with future improvements targeting up to 50% fuel savings.[61] Within wider powertrain or system-level changes, improvements in fuel consumption can come from replacing an entire system (e.g. replacing hydraulic systems such as actuators with all-electric ones[62]), wider system optimisation (e.g. an articulated dump truck being equipped with a mix of hybridisation and efficiency measures delivering up to 28% less fuel consumption[63]), or structural optimisation (e.g. optimising the structure of an RTG crane).

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[57] High-level indicative costs relative to other categories of efficiency measures – see sub-section 3.3.3 for more detail.

[58] The range excludes overall site efficiency gains made beyond the NRMM equipment (e.g., Balfour Beatty EcoNet and asphalt cold in-situ recycling cases discussed under process efficiency)

[59] For example, the propulsion, slew and work systems on an excavator required to move, rotate and dig respectively.

[60] https://www.kit.edu/kit/english/pi_2022_036_hybrid-drive-construction-machinery-fuel-efficient-excavators.php

[61] Claimed by a component OEM, Danfoss, who have received funding from the UK's Red Diesel Replacement competition https://www.danfoss.com/en-us/about-danfoss/news/dps/uk-government-awards-grant-to-danfoss-power-solutions-to-decarbonize-construction-machinery/

[62] An all-electric compacter launched by Doosan Bobcat is claimed to deliver the same endurance with a 62 kWh battery pack as a similar electric (propulsion-end) or hydraulic (equipment-end) compactor running a 300+ kWh battery pack (Solving the Challenges of Mobile Construction Machine Electrification | IDTechEx Research Article); Similarly, EIT InnoEnergy highlights the improvements in productivity that can be made by replacing hydraulic actuators with electric linear actuators in heavy-lifting applications such as forklifts or container-handling trucks (EIT InnoEnergy, 2022); Kalmar also claim that replacing hydraulic systems with all-electric actuators can reduce an RTG crane's fuel consumption by 2 litres per hour of operation (Smart choices help in enhancing RTG eco-efficiency | Kalmarglobal)

[63] A demo version of Caterpillar's CAT-275 Articulated Truck equipped with measures such as an optimised cooling system and hydraulic energy storage system was developed under the Energy Technologies Institute's Heavy Duty Vehicle Program ETI programme announces technology demonstration… | The ETI

Process Efficiency

Process efficiency measures reduce industrial NRMM fuel consumption by optimising how machines are utilised on sites by using data and advanced software or hardware solutions. For example, simple telematics or GPS data can be used to reduce fuel consumption by potentially 10% to 15% (e.g. using GPS and task status to reduce idle queuing times on a site by synchronising the excavation, loading and unloading processes of excavators and dump trucks (Committee for European Construction Equipment, 2018; The Society of Motor Manufacturers and Traders, 2018); or using telematics to highlight inefficient deployment of machinery to NRMM users[64]). To achieve further gains, advanced software such as smart active control systems[65] or digital surveying tools[66] can be deployed to achieve fuel use reductions of up to 30% and 50% respectively. Moreover, advanced hardware such as specialised cold recycler machines can be used in conjunction with asphalt pavers to deliver up to a 68%[67] reduction in emissions, a process known as cold in-situ recycling (Committee for European Construction Equipment, 2018).[68] Site-wide process efficiency measures that can bring emissions reductions of up to 83% also exist.[69] This can be achieved using technology that actively monitors the energy consumption on construction sites from electric vehicle charging, heating, lighting, etc in order to reduce energy demand from the grid and on-site generators – note this includes site-wide savings beyond the NRMM being used[69].

3.1.3 Process change

Process change differs from process efficiency in that it refers to processes currently using NRMM being changed so that the NRMM is no longer required to complete a particular task. No examples of process change could be found in the literature; however, this category of change is relevant given potential for redundancy in current operations. For example, there are about 1.6 million low power generators (<5 kW) in the UK that are each used very rarely (200 hrs/year). Therefore, options such as 'vehicle to load' (V2L), whereby electric NRMM could provide electricity from its battery to replace the use of low usage small generators should be considered. Given that electric NRMM with sufficiently large batteries to support V2L are emerging technologies, no current examples of V2L being used in industrial NRMM could be found. However, an Australian mining company has recently purchased 8,500 EV pickup trucks which will have 'V2L with 240V power points for powering equipment'.[70] Similarly, no evidence or reports of using solar PV and a battery pack to replace a small generator in the industrial NRMM context were found but could be an option given that suitable products are available.[71]

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[64] A telematics platform developed by MachineMax allows NRMM users to identify cases where machines are incorrectly deployed, and has delivered improved fuel use, machine availability and site safety for operators like Cemex Empowering Cenex to deliver their sustainability and efficiency goals - MachineMax, 2023

[65] Tadano Europe's Eco-Mode smart crane management system is claimed to reduce fuel consumption by up to 30% through active control of engine speeds Eco-Mode System - Europe (tadanoeurope.com)

[66] Construction activities can require a level of surveying in advance of any earthmoving activities. This typically involves the manual operation of NRMM equipment to establish the desired grade (level) at which work can commence; OEMs like Caterpillar (Cat Grade Technology | Cat | Caterpillar) and Komatsu (Intelligent Machine Control Excavators & Bulldozers - Marubeni-Komatsu.) have advanced digital solutions on offer that can boost the productivity of machines performing such tasks

[67] Claim by cold recycling machine OEM Wirtgen: Developments in Asphalt Plant and Equipment past papers (soci.org)

[68] This process has been trialled in the UK with a National Highways contractor reporting a 50% CO_2 saving carrying out work on the A1 in September 2021 (90% of the existing carriageway being recycled eliminated 1,400 lorry movements travelling 40 km to and from the site delivering asphalt) SPL A1 Newton on the Moor Northumberland (stabilisedpavements.co.uk); note that emissions reductions include those associated with the fewer lorry movements.

[69] Within six months of rolling it out, the EcoNet technology (developed by Balfour Beatty with Sunbelt and Invisible Systems) is reported to have delivered an 83% reduction in emissions at a Balfour Beatty site in Leeds in May 2020 https://www.balfourbeatty.com/news/balfour-beatty-set-to-reduce-carbon-emissions-on-construction-sites-by-up-to-80-with-the-installation-of-econet-technology/

[70] 8500 electric Toyota HiLuxes and LandCruisers for mining, in billion-dollar deal | CarExpert

[71] Solar Energy Store Hire For Site - Off-Grid Site Solar Store (garic.co.uk) and ProPower Solar Hybrid Generator | Prolectric | Prolectric Ltd

3.2 Technical characteristics

This section discusses technical characteristics of the powertrains and fuels investigated, including the energy density of fuels and fuel storage systems, powertrain efficiency, lifetime and size relative to incumbent engines. A definition of the terms used in this section can be found in the Glossary.

3.2.1 *Energy density*

Figure 19 shows the energy density of the alternative fuels considered, in comparison to diesel. It should be noted that:

- The efficiency of the powertrain (values laid out in Table 22) has been accounted for, to compare the amount of useful energy stored. The energy density of the energy store itself (fuel and tank, or battery) is shown under the X axis.
- Drop-in fuels (HVO, B20) have similar energy densities as diesel, as they are all liquid fuels with similar gravimetric and volumetric energy densities.
- Hybrid equipment have the highest energy density, due to the increased efficiency of the powertrain whilst still using energy dense diesel, alongside a second form of energy storage (most typically batteries but can be other methods such as flywheels for some applications). For Figure 19, a hypothetical hybrid powertrain where 90% of the energy is stored in diesel form and the other 10% in a battery is used.
- Tethering is not included in the graph as a value, as there is no energy storage on board.
- For battery electric, lithium-ion batteries (LIB) are shown in the graph as these have a superior energy density to lead-acid batteries and are currently the dominant battery technology. Lead-acid batteries are limited to a practical upper bound of 50Wh/kg [0.18MJ/kg] whereas LIB energy density ranges are currently 125-210Wh/kg [0.45-0.75 MJ/kg] (depending on the cathode chemistry, total battery size and packaging approach). LIBs have scope for improvement, with 270Wh/kg [0.97 MJ/kg] plausible by 2030 (BloombergNEF, 2022), and theoretical values around 500Wh/kg [1.8 MJ/kg] for electrodes or electrolytes still at development stage (Matsuda, Ono, Yamaguchi, & Uosaki, 2022). However, batteries still have significantly lower energy densities than liquid fuels.
- For hydrogen fuel cells and hydrogen ICE, hydrogen fuel has a gravimetric energy density of 33.3 kWh/kg [120 MJ/kg]. However, the weight of the 350 bar tanks reduces the overall gravimetric energy density of hydrogen storage systems to between 1.4 and 1.9 kWh/kg [5 to 7 MJ/kg] (The International Council on Clean Transportation, 2022; Element Energy, 2020).[72] Pressurised hydrogen storage systems have significantly lower energy densities than liquid fuels, though have a higher gravimetric energy density than batteries.

Compared with diesel, gravimetric and volumetric energy densities are significantly lower for the zero emission technologies. It is worth noting that:

- Neither gravimetric nor volumetric energy density of the energy storage systems alone fully reflect the changes in weight or volume when switching to a zero-emission powertrain (battery electric or hydrogen fuel cell), since the weight and volume savings associated with replacing a diesel engine, gearbox and transmission by an electric motor or fuel cell are significant. In the case of long-haul trucking, an article by Traton Group states that removing a diesel powertrain from an HGV can save up to 2 tonnes, whilst the weight of an equivalent fuel cell or electric motor would be less than this.[73] This weight saving by switching powertrains will

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[72] These data describe 700 bar tanks, but consideration of the basic physics of hydrogen storage (350 bar tanks will have walls around half the thickness, so weigh approximately half as much, but approximately twice as many will be needed) reveals that figures for 350 bar storage will be very similar to those for 700 bar storage.

[73] https://traton.com/en/newsroom/current-topics/why-the-battery-electric-drive-represents-the-future-for-trucks.html

mitigate some (or all) of the extra weight of the new energy store (batteries or hydrogen fuel tanks).

- Gravimetric energy density is less relevant for industrial NRMM compared to on-road vehicles because industrial NRMM are not subject to weight limits (indeed, for some excavators and other industrial NRMM, extra weight can add useful stability).
- The impact of lower energy densities on zero emission technologies is highly dependent on the equipment duty cycles. For low utilisation NRMM, smaller energy storage systems (batteries or fuel tanks) can be deployed to reduce this impact, whereas for high utilisation equipment, energy density has a higher impact on the practicality of these technologies.

During stakeholder engagement, energy density constraints were highlighted in selected cases:

- Hand-held equipment, where battery weights may be a limiting factor.
- Extremely high powered (over 500 kW) and high utilisation (over 50%) equipment where limited energy density would require frequent refuelling or recharging, else requiring substantial batteries or fuel tanks. This category of equipment represents under 0.05% of the NRMM population and around 2% of the fuel use, based on our analysis of the NAEI database.

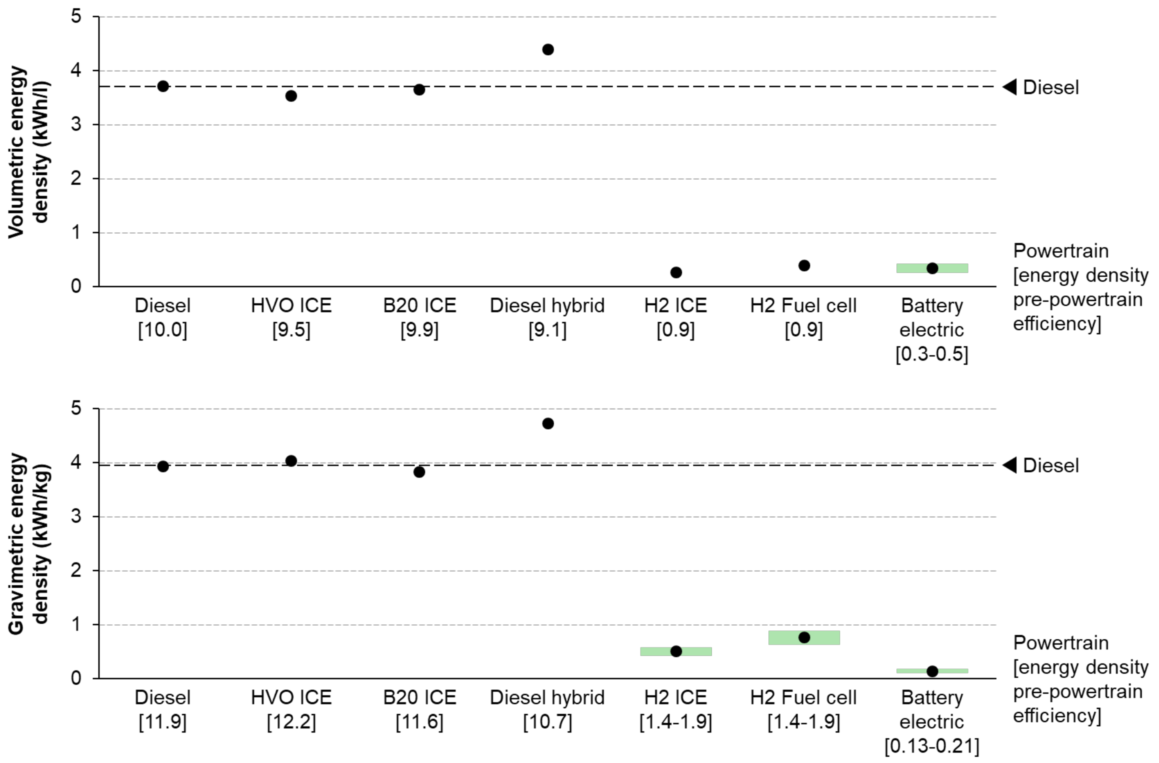

Figure 19 – Useful (kWh of useful work) volumetric energy density (top) and gravimetric energy density (bottom) of abatement options. Dashed lines show diesel energy densities, green ranges shown for battery electric and hydrogen. The energy density of the energy storage system (before powertrain efficiency is factored in) is shown in square brackets.[74]

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[74] When not mentioned in the above text energy density values are from the supplementary files of (E4tech & Cenex, 2021) or from DESNZ GHG reporting conversion factors 2022. Hybrid values are calculated assuming 90% of the energy is stored in diesel form, hydrogen gravimetric energy densities are for the weight of the fuel and tank.

3.2.2 *Powertrain efficiency, lifetime and size*

Table 22 summarises the technical characteristics of the fuel switching options considered.[75]Some characteristics have scope to improve in future, for example the battery energy density or the lifetime of battery electric and fuel cell powertrains. The powertrain efficiency in this table refers to the powertrain (engine and/or motor) – a hydraulic system can further diminish industrial NRMM powertrain efficiency, reducing it by a factor of around 3 (Ge, Quan, Zhang, Dong, & Yang, 2019).

With regards to the size of machinery, this covers the engine size (power output) in addition to that of any energy storage components (volume or weight). For engine size (power output), no upper limit was identified on the capabilities of alternative powertrains as they could all be scaled as required (see IND-database for sources for high-power examples).[76] This was also validated at the stakeholder interviews and workshops where no concerns about the technical possibility of high-power abatement options were raised. Attendees were most concerned with the energy supply and storage for high power and high utilisation equipment rather than the capability to achieve the power rating itself.

Table 22 – Technical characteristics of fuel switching options

Technology	Powertrain efficiency [77]	Lifetime[78]	Size
Diesel ICE (considered the incumbent powertrain)	33% (NAEI database)	• Roughly 8,000 to 22,000 hours depending on use case [AFLEET data]	Varies with machine – this is the incumbent powertrain used to compare to alternative technologies
HVO ICE	33% (same as diesel)	• Similar lifetime to diesel engine (Roughly 8,000 to 22,000 hours depending on use case) [AFLEET data]	Same as incumbent
B20 ICE	33% (same as diesel)	• Similar lifetime to diesel engine	Same as incumbent
Hybrid	37% - 66% (Lajunen, et al., 2016)[79]	• Similar lifetime to diesel engine	Usually have a smaller engine than an equivalent diesel, but requires additional components such as an electric motor and battery
Hydrogen ICE	30%	• Expected to be similar to diesel engine but no NRMM-specific data yet. 300,000km quoted for	Similar engine size to diesel but requires an additional fuel tank

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[75] The AFLEET model was developed by the Argonne National Laboratory (USA Department of Energy research centre) and is accessible online: AFLEET Tool - Argonne National Laboratory (anl.gov)

[76] This study has not investigated the practicalities of packing the energy storage and heat exchanger for high usage machines, which may provide a practical limit to some powertrains.

[77] Supplementary files of Red Diesel Report (supplementary data sheet produced with (E4tech & Cenex, 2021)) except where indicated.

[78] The main source used was data from the Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) model, however this data is limited for battery electric and hydrogen industrial NRMM as there is currently insufficient real-world data available. For indication, trends from the HGV sector have been included; The AFLEET model was developed by the Argonne National Laboratory (USA Department of Energy research centre) and is accessible online: AFLEET Tool - Argonne National Laboratory (anl.gov)

[79] The source cites a reduced fuel consumption of between 10% and 50% resulting from hybridisation. In order to convert this to a powertrain efficiency, the diesel incumbent fuel consumption value (33%) was divided by [1 – the value in the study] (i.e., hybrid efficiency low-end = 33%/ [1 – 10%]; high-end = 33%/ [1 – 50%]).

Technology	Powertrain efficiency [77]	Lifetime[78]	Size
		cars (Candelaresi, Valente, Iribarren, Dufour, & Spazzafumo, 2021)	
Hydrogen fuel cell	45% (Ricardo, 2020)	- For non-steady state (start/stop) operation it is roughly 5,000 hours, but closer to 2,000 – 3,000 hours before a performance loss of >10% is experienced (Kirtz, Sprik, Saur, & Onorato, 2019). Even at the higher end of the range, this is shorter than the lifetime of a diesel engine - For HGVs, a fuel cell operational lifetime of 20,000 hours is claimed to be possible for steady-state operations, and aimed to be replicated for non-steady state operations[80]	Requires a larger tank than incumbent due to its relatively low volumetric energy density
Tethering	90%	- Expected to match or exceed diesel engine given fewer moving parts, no hard data found	Does not require an engine or large battery so reduced weight and space compared to incumbent
Battery electric	80%	- Potentially shorter than diesel engine, with the AFLEET model using roughly 5000 to 14,000 hours – presumably due to the battery	Low volumetric energy density so requires a relatively large sized powertrain at high power ratings compared to incumbent

3.3 Relative costs

The costs associated with machinery vary between technology used. The key costs considered to vary between powertrain types are machinery CAPEX, fuel OPEX, maintenance OPEX and the CAPEX of any additional infrastructure required. Further details on the cost of counterfactual machinery types can be found in Appendix 9.10.

3.3.1 Capital expenditure (CAPEX)

The CAPEX of a technology includes the CAPEX of the equipment itself, and the CAPEX of additional infrastructure, such as battery charging or hydrogen refuelling equipment required for the technology type. The equipment CAPEX difference can be attributed to differences in engine costs (per kW delivered), energy storage (e.g., fuel tanks, batteries), and additional R&D and manufacturing costs associated with small scale production. These costs are outlined in Table 23, with indicative costs of infrastructure.

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[80] A claim made by Hyzon Motors, a fuel cell commercial vehicles OEM https://www.hyzonmotors.com/in-the-news/state-of-competition-between-hydrogen-fuel-cells-and-batteries-in-the-heavy-duty-truck-market

Table 23 – Indicative CAPEX costs for different technology options – more detail on sources & assumptions is provided in the IND-database

Technology	Powertrain CAPEX	Energy store CAPEX	Infrastructure CAPEX	Cost reduction at scale
Diesel ICE (considered the incumbent powertrain)	£80/kW, based on quotes for generators with different power ratings (see Appendix 9.10 for more details). This is consistent with the range provided for the £/kW range between HGVs (The International Council on Clean Transportation, 2017) and cars (Ricardo, 2016)	Negligible (fuel tanks are cheap and can store a lot of fuel)	Minimal (incumbent technology, can use public stations if needed)	N/A
HVO and B20	Same as incumbent (same engine used)	Same as incumbent	Minimal	N/A
Hybrid	Increase of powertrain cost of £50/kW to £60/kW compared to incumbent quoted for the case of HGV, including the battery (The International Council on Clean Transportation, 2017)	Moderate, e.g., battery is smaller than for a fully battery electric model, so lower cost than battery electric (cost of diesel fuel tank is negligible).	Minimal	Minor to moderate – established technology in other sectors (cars), but may need bespoke systems that will benefit from scale up
Hydrogen ICE	Likely to be similar to incumbent ICE when at scale (approximately £80/kW) (Westport Fuel Systems, 2020)	Hydrogen tanks (350 bar) £20/kW to £45/kWh stored (The International Council on Clean Transportation, 2017; Roland Berger, 2020; The International Council on Clean Transportation, 2021)	Moderate to significant infrastructure needed for hydrogen storage and transportation £7/kg of hydrogen delivered to NRMM on-site[81]	Moderate – ICE technology is established, requires scale up for hydrogen
Hydrogen fuel cell	£250/kW to £500/kW for fuel cells (Roland Berger, 2020; Ahluwalia, Wang, Star, & Papadias, Performance and cost			Major – significant cost improvements of fuel cells possible at scale

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[81] Combining £750k for a 200kg/day station (Clean Hydrogen Partnership, 2022) and £1/kg for distribution over the average distance of 100 km (International Energy Agency, 2019) with further assumptions that the infrastructure is financed over 10 years with an interest rate of 5%, annual operation + maintenance are 1% of station CAPEX and station utilisation is at 25%

Technology	Powertrain CAPEX	Energy store CAPEX	Infrastructure CAPEX	Cost reduction at scale
	of fuel cells for off-road, 2022; Argonne, 2021) £15/kW to £20/kW for electric motors (The International Council on Clean Transportation, 2017)			
Tethering	£51/kW for electric motors, inverter and transmission systems (The International Council on Clean Transportation, 2022) £60/m of connection cable (Up to 700m used for some mining applications (Paraszczak, Svedlund, Fytas, & Laflamme, 2014)	Minimal or no energy storage	Potentially significant for high kW NRMM, requires direct grid connection (Committee for European Construction Equipment, 2021) Grid connection or upgrade costs could be significant for some sites	None or minor – established technology in other sectors (electric motors)
Battery electric	£51/kW for electric motors, inverter and transmission systems (The International Council on Clean Transportation, 2022) £10/kW to £50/kW for any additional components (regenerative braking, wiring, charger, HV systems etc.) (The International Council on Clean Transportation, 2017), (Ricardo, 2016)	£230/kWh to £280/kWh batteries, for HGVs[82] (Element Energy, 2020; The International Council on Clean Transportation, 2021)	Very low (e.g., charging cable plugging into domestic socket) to very high for the hardware & installation, depending on kW need and technology chosen (see 3.6.2.2 for discussion on practicalities) Grid connection or upgrade costs could be significant for some sites	Major – significant cost improvements possible for batteries, in particular for machinery with larger batteries

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[82] It is worth noting that NRMM OEMs are small volume buyers, and it is likely that they will see higher prices than those stated; during stakeholder engagement, some stakeholders suggested that a price of £500/kWh was an average price for NRMM battery packs in 2022.

Pure ICE solutions (HVO, B20, hydrogen ICE) have similar engine costs as the technology is either identical to incumbent (HVO, B20), or similar (hydrogen ICE). However, the cost of hydrogen engines is expected to remain higher than diesel engines until they are produced at scale due to additional R&D costs (Westport Fuel Systems, 2020). Hybrids have a higher engine cost due to the additional electrical components required.

Electrical solutions (BE or tethering) have a significantly cheaper motor compared to incumbent ICE units. The cost of the motor unit could be decreased even further, due to the increased efficiency of electric powertrains compared to ICE (80% to 90% compared to 33%). This allows a smaller motor to provide the same level of power as a larger ICE, further decreasing costs (Paraszczak, Svedlund, Fytas, & Laflamme, 2014; Sandvik, 2022; Sandvik, 2023).

Compared to incumbent powertrains, hydrogen fuel cells can cost more than sixfold currently (£250/kW to £500/kW against £80/kW for diesel), though this price is expected to decrease by 2030 depending on the scale of production (£100/kW to £250/kW by 2030, (Roland Berger, 2020)).

Energy storage costs of liquid fuels (incumbent, HVO, B20) are negligible (£0.16/kWh to £0.25/kWh[83]) when compared to those of the hydrogen and battery-powered options. Costs are between £20/kWh and £45/kWh for hydrogen technologies (equivalent to around £4,500 for a 4.5 kg tank, equivalent to 150 kWh). Battery electric has the highest energy storage cost (£250/kWh, equivalent to around £40,000 for a 150-kWh pack), though more of this can be converted into useful energy compared to hydrogen (both fuel cells and ICE) due to greater powertrain efficiency. Based on trends in on-road vehicles, battery costs are likely to decrease with the scaling up of production (batteries for cars are already near £100/kWh due to the larger scale currently than the battery electric HGV and NRMM sectors[84]) (Mauler, Duffner, Zeier, & Leker, 2021). For tethering, there are no storage costs, though the cost of the connecting cable could be significant and is reliant on a reliable connection to the grid or provision of an onsite renewable power source.

Costs of novel technologies in industrial NRMM are currently higher than the estimated component costs due to models being predominately prototypes or in small-scale production. For example, converting diesel buses, tractors, vans or trucks to fuel cell in small volumes can cost between twice as much to almost six times the cost of the equivalent diesel vehicle.[85] This premium for new technologies is typical initially but is expected to decrease as production volumes increase.

Infrastructure cost

Charging solutions are varied for industrial NRMM (see Section 3.6.2). In the case of static chargers, costs for depot chargers are in the range of £100/kW to £200/kW for AC solutions and £400/kW to £600/kW for DC solutions,[86] excluding grid connection costs. The usage of AC or DC chargers will depend on the machine use case, access to the grid and operator requirements. For faster charging times, DC chargers are usually required and can re-charge, for example the Volvo ECR25 electric excavator's 20 kWh battery in 1 hour, compared to 6 hours using a 240-volt, Level 2 AC charger.[87]

For gaseous hydrogen storage and dispensing at 350 bar pressure, costs are in the order of £750k to £1m for temporary refuellers (for 800 kg/day operation, (US Department of Energy, 2021)) and £2.5m to £3m for a permanent station (for 1t/day station, (Reddi, Elgowainy, & Rustagi, 2017)) – these are based on learnings from the bus sector, since there are very limited hydrogen solutions deployed for industrial NRMM to date. Learnings from the bus sector are likely to be most applicable to industrial NRMM sites which are long-term, such as ports, waste and mining, though the amount of hydrogen

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[83] Using £1,000 for a 400L HGV fuel tank (Truck Fuel Tanks for sale (mwtruckparts.co.uk)) and £32.50 for a 20L jerry can (Jerry Cans & Petrol Cans | Halfords UK) to represent small machinery fuel tanks; diesel gravimetric and energy densities of 0.841 kg/L and 11.91 kWh/kg used respectively

[84] https://about.bnef.com/blog/increase-in-battery-prices-could-affect-ev-progress/

[85] Figures observed by ERM through direct work with demonstration projects in the commercial vehicles field.

[86] ERM analysis of quotes for depot chargers received across several assignments.

[87] Electric Construction Equipment: Your Charging Questions Answered - The Scoop (volvoceblog.com)

demand at a site may be lower than for a bus station. Smaller hydrogen refuelling stations (HRS) (<200 kg/day or around 6,700 kWh/day[88] at 350 bar) most likely to be required for industrial NRMM sites have an estimated cost of £500k to £750k (Clean Hydrogen Partnership, 2022). Additionally, distribution costs of hydrogen by tube trailers can add approximately£0.5/kgH_2 to £1/kgH_2 (equivalent to £0.015/kWh to £0.030/kWh[88]) for every 100 km the hydrogen is transported, based on studies in the USA (International Energy Agency, 2019). This results in a total cost of approximately £7/kg of hydrogen delivered to NRMM on-site currently (see Appendix 9.7). For short-term sites such as construction sites, a long-term hydrogen refuelling station may not be appropriate and other solutions may be required (discussed further in sub-section 3.6.2.2)

For charging solutions (and for the hydrogen storage & dispensing if using a power supply), a new or greater grid connection might be required. Grid connection costs vary on a site-by-site basis so cannot be estimated based on the industrial NRMM size or archetypes, also noting:

- Sites with good proximity to the grid can have grid connection costs below around £100/kVA, including a new substation.[89] Case study examples provided in the UKPN connection charges document cited suggest that sites need to be within approximately 150 to 200 metres of an existing HV cable in the distribution network to achieve these grid connection costs.
- Data published by Ofgem for the first four years of the RIIO-ED1 price control period (from 2015 to 2018) on connection offers issued by DNOs shows the median cost quoted was approximately £190/kVA, with 10% of quotes exceeding approximately £710/kVA.[90]
- However, the numbers quoted above are all prior to April 2023. Since April 2023, upstream reinforcement costs are paid by the Distribution Network Operator, rather than by the connection customer (who pays only for the cost of the cables linking their site to the grid asset). Therefore, grid connection costs are not increased if the site triggers upstream reinforcement (unless costs exceed a cap of £1,720/kVA,[91] in which case reinforcement costs are not socialised).[92] The costs quoted in the previous bullet points would have had some instances where reinforcement was triggered and part of the cost.

3.3.2 Operating costs

The main difference in operating costs between technology types will come from fuel costs and maintenance costs. There may be extra costs to train operators to use the new technology, though these are expected to be minimal compared to cost of fuel or maintenance – it is also expected that OEMs will provide operators with the necessary training associated with running their machines.[93] Another operating cost may arise from the replacement of powertrains that reach the end of their life. As discussed in 2.2.3, it is common practice for some larger machinery to be remanufactured at the end of the powertrain life. This is considered end of life for the machinery, so engine replacements are not considered an operating cost. For alternative powertrains, component replacements have not

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[88] Value converted using hydrogen's lower heating value of 33.33 kWh/kg.

[89] UKPN, Statement of methodology and charges for connection to the electricity distribution systems of eastern power networks plc, London Power Networks plc & South Eastern Power Networks plc, 2021 LINK

[90] Access SCR - Final Decision (ofgem.gov.uk)

[91] This is a threshold which DNOs say is rarely exceeded based on their own observation of the quotes they have made through the years. The £/kVA required to make a connection is driven by site-specific characteristics such as distance from the primary substation, the available power at the substation, the kVA requested (which in turns depends on the number of NRMM and their associated utilisation, on site storage/generation presence). A certain kVA rating requirement and corresponding cost will be determined and assessed against the threshold of £1,720/kVA to determine if the upstream reinforcement costs are socialised.

[92] Access and Forward-Looking Charges Significant Code Review: Decision and Direction | Ofgem. In the case of temporary connections that are not turned into a permanent connection, the upstream reinforcement costs would be paid by the connection customer rather than socialised. There is no official record of the number of connections that are truly temporary (as opposed to permanent or temporary then turned permanent). Discussion with a DNO suggest 'truly temporary' connections are rare (less than 5% of all connection requests).

[93] At a stakeholder engagement workshop, an OEM indicated they will be providing a half-day 'upskill' course for operators migrating to their hydrogen ICE machines.

been considered (e.g., batteries, fuel cells), as the lifetimes of these components will be highly dependent on the vehicle use case (see sub-section 3.2.2 for discussion of powertrain lifetimes).

Table 24 shows the indicative fuel costs per useful kWh of energy for each powertrain type and how the maintenance cost may vary from the incumbent technology.

The cost of fuel or energy will in general be larger than the maintenance cost over the vehicle's lifetime, and this cost will be highly dependent on the cost of energy in the future. The fuel costs summarised in Table 24 are for a snapshot of recent fuel or electricity prices, which will vary over time and the lifetime of a vehicle.

Maintenance costs per hour of use of incumbent machinery vary significantly between machine size and use case. Some of this variability will be due to maintenance of the non-powertrain parts of the machinery (e.g., maintenance of excavator buckets, articulation joints and tyres); maintenance of these components will not significantly vary with powertrain type and in general will increase with machine size.[94] Powertrain maintenance costs can vary compared to the incumbent for some powertrain types, as shown in Table 24.

Table 24 – Indicative current operating costs for different powertrain types (excluding recharging or refuelling infrastructure costs and hydrogen distribution costs) – further detail on sources and assumptions is provided in the IND-database (except for hydrogen costs)

Technology	Fuel cost per useful energy output[95]	Maintenance costs	Cost reduction at scale
Incumbent (mainly diesel ICE)	£0.41/kWh useful energy for diesel (£1.37/l, 33% efficiency) <£0.01/kWh useful power for diesel exhaust fluid	Varies by machine size and use case, trend of 0.95p/hr/kW (e.g., £9.50/hr for a 1,000kW machine) Compared to diesel 44t HGV maintenance costs of £4.10-5.60/hour (Logistics UK, 2019)[96]	N/A
HVO ICE	£0.48-£0.64/kWh useful energy (£1.52-2.00/l,[97] 33% efficiency)	Likely to be similar to incumbent (within 5%) (Zemo Partnership, Cenex, 2021)	Potential increase in cost – increased demand could lead to higher costs due to limited waste feedstocks
B20 ICE	£0.41-£0.45/kWh useful energy (33% efficiency)[98]	Likely to be similar to incumbent (within 5%) (Zemo Partnership, Cenex, 2021)	Potential minor increase – limited feedstock supply results in cost increases

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[94] Power rating can be used as a proxy for machine size in most cases and the correlation between power rating and maintenance cost per hour of use is shown in Appendix 9.10.2. One notable exception is an RTG crane which has a large size-to-power rating ratio.

[95] Unless otherwise stated, all fuel prices were obtained from the DESNZ Green Book (Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal - GOV.UK (www.gov.uk)) – all prices shown in the table exclude VAT and are shown in 2022£

[96] With maintenance costs of 10.4-11.1p/mile and an average driving speed of 40 mph to 50 mph

[97] Argus (Issue 22-160, 2022 and Issue 23-26, 2023) – Daily international market prices and commentary

[98] The p/kWh price was evaluated using 80% of the diesel price + 20% of the B100 price to make up B20.

Technology	Fuel cost per useful energy output[95]	Maintenance costs	Cost reduction at scale
	Using £1.37/l for diesel and £1.20/l -£1.77/l for B100[99]		
Hybrid	£0.31/kWh useful energy (£1.37/l, 44% efficiency assuming a 25% fuel consumption reduction)	Slightly lower than incumbent (10%) (Argonne, 2021).	N/A
Hydrogen ICE	£0.39/kWh useful energy (£3.9/kg H_2 from (International Energy Agency, 2019), 30% efficiency)[100]	Higher than diesel due to additional maintenance of hydrogen compressors (Westport Fuel Systems, 2020)	Significant decrease – demand will increase supply, leading to cost reductions at scale. Highly dependent on other hydrogen demands from industry and HGVs
Hydrogen fuel cell	£0.26/kWh useful energy (£3.9/kg H_2 from (International Energy Agency, 2019), 45% efficiency) [100]	Lower than diesel (40% reduction) (Argonne, 2021)	Significant decrease – demand will increase supply, leading to cost reductions at scale. Highly dependent on other hydrogen demands from industry and HGVs
Tethering	£0.28/kWh useful energy (£0.25/kWh, 90% efficiency)	Lower than diesel (40% reduction) (Argonne, 2021) Cable damage and replacement can add to maintenance cost (Paraszczak, Svedlund, Fytas, & Laflamme, 2014)	Possible minor decrease – large electricity consumption may allow operators to purchase PPAs with lower electricity prices
Battery electric	£0.31/kWh useful energy (£0.25/kWh, 80% efficiency)	Lower than diesel (40% reduction) (Argonne, 2021)	Possible minor decrease – large electricity consumption may allow operators to purchase PPAs with lower electricity prices

Hydrogen for fuel cells shows the lowest cost per useful kWh in Figure 20. This figure is based on cost estimates and while this may not be fully reflective of the true cost of hydrogen in the UK today,[100] hydrogen has the potential to reduce costs through scale (International Energy Agency,

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[99] Argus (Issue 22-160, 2022 and Issue 23-26, 2023) – Daily international market prices and commentary

[100] Estimates of current low-carbon hydrogen production costs have a high level of uncertainty due to the low number of projects currently deployed. The IEA (International Energy Agency, 2019) estimates a cost of approximately $5/kg (£3.90/kg, £0.12/kWh) for an electrolyser operational 90% of the time with an electricity cost of $100/MWh (£77/MWh, compared to 2019 domestic energy price of £135.2/MWh). This cost of hydrogen would be higher if the cost of electricity used is higher. This report is international, it does not provide an insight into potential hydrogen costs specifically in the UK.

2019). This cost reduction will rely on larger sectors transitioning to low carbon hydrogen (e.g., industry, heavy goods vehicles) as industrial NRMM alone are unlikely to provide sufficient hydrogen demand to trigger a significant cost reduction. However, even if hydrogen demand from industrial NRMM and other sectors is sufficient to achieve significant cost reductions, it is unlikely without a substantial reduction of electricity prices (which would also benefit battery electric and tethered machinery).

HVO and B20 fuels are unlikely to see significant cost reductions at scale as these are produced from waste feedstocks (E4tech & Cenex, 2021).[101] As these resources are limited and demand for the waste feedstocks is likely to increase for other sectors such as aviation (to make sustainable aviation fuels), any substantial demand increase from industrial NRMM is likely to result in an increase in price.

Electricity for tethering or battery electric may see a modest decrease in cost if the amount of energy purchased increases significantly by the operator. Electricity prices are lower for companies with higher energy demand,[102] alternatively operators may be able to negotiate Power Purchase Agreements with energy suppliers with more advantageous prices.[103] The price decrease will be steepest for large sites with high electricity demand, perhaps allowing electrification to be cost-competitive sooner on larger sites compared to smaller sites. It should be noted that there might be sites with a power demand profile and grid connection where electricity storage brings economic advantages (quantifying such economic threshold was not part of this study). Moreover, electric machines have higher fuel efficiencies which contribute to their lower costs (see Table 22).

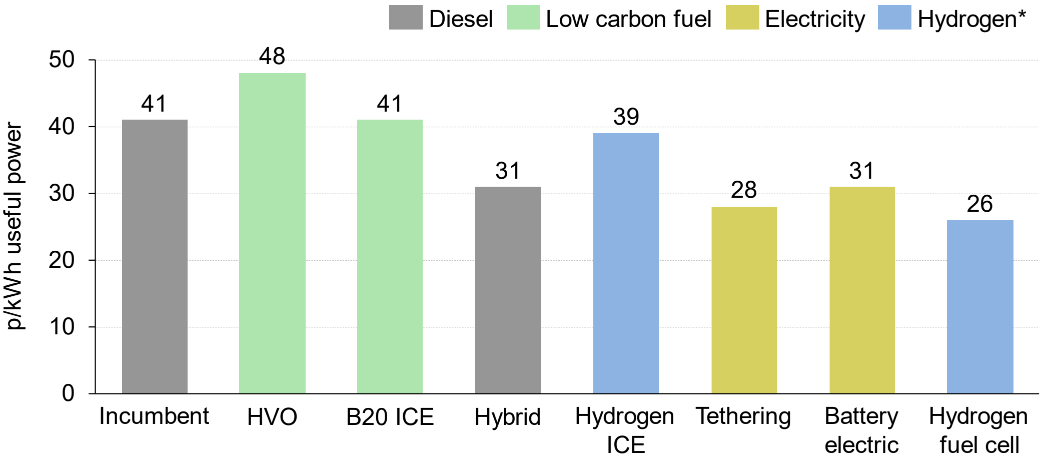

Figure 20 – Cost of fuel per kWh of useful energy in 2023 excluding infrastructure costs (*with distribution also excluded from the hydrogen cost – see assumptions in Table 24 above)

3.3.3 *Efficiency measures*

The up-front CAPEX costs of efficiency measures are not well documented. However, the total cost of ownership (TCO) returns on efficiency measures could be significant for certain industrial NRMM operators given that fuel costs are typically the largest contributor to an industrial NRMM's TCO (e.g. 50%-64% in diesel excavators and 73%-76% in diesel wheel loaders according to (Argonne, 2021)). However, given that the purchase of the fuel or energy consumed is not necessarily the responsibility of the machine owner, the relevant stakeholders may not be incentivised to invest in such fuel-saving

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[101] This feedstock requirement is a requirement for the fuel to be classed as renewable under the RTFO and have certified emissions savings.

[102] Gas and electricity prices in the non-domestic sector - GOV.UK (www.gov.uk)

[103] Fixed vs Variable PPA: What's best for my business? | UKSE (uk-se.com)

measures – see sub-section 4.1.5 for a more detailed discussion. The impacts different efficiency measures can have on industrial NRMM CAPEX and OPEX are summarised in Table 25.

Table 25 – Summary of different efficiency measures' impacts on industrial NRMM CAPEX and OPEX

	Operational efficiency	Machine efficiency	Process efficiency
Impact on CAPEX	Expected to be negligible	Typically, higher CAPEX - generally requires more expensive parts (can be partially offset if it allows a smaller and cheaper energy storage to be used)	Can be high depending on digital solution licensing terms and training required for users
Impact on OPEX	Time penalty of additional steps for operators to follow, offset by higher productivity	Substantial savings to be made throughout the machine's lifetime	Reduced fuel and maintenance costs as running hours and associated component wear are reduced

These savings can be realised as improvements to machine efficiency or task productivity (i.e., reducing kW power output or machine hours required to complete a job respectively) result in a direct reduction in fuel consumption and consequently the running costs (The Society of Motor Manufacturers and Traders, 2018). The manufacturer of the digital displacement pump discussed in 3.1.2 above, for example, expects the TCO of a 25t battery-electric excavator using their technology to be 5% and 13% cheaper than similar conventional (diesel + conventional hydraulics) and battery-electric with conventional hydraulic excavators within the next 5 years.[104] Beyond the reduction of energy costs, efficiency measures can reduce the energy storage capacity required on machinery, partially offsetting any additional CAPEX costs required to deploy the measures (examples of this can be found in Section).

3.4 Commercial availability

To assess abatement technologies and their commercial availability dates by archetype, the following approach was used:

1) OEM roadmaps and industry reports were reviewed to understand industrial NRMM product development timelines.
2) Industrial NRMM product launch announcements were reviewed to establish the abatement option technology readiness levels (TRL) for 63 combinations of industrial NRMM type and sectors – this was done by powertrain for the shortlisted abatement options.
3) Identified industrial NRMM from step 2 were assigned to their respective archetypes, building a matrix of powertrain TRL levels by archetype.
4) Findings from steps 1 – 3 were fed into the matrix to map TRLs within the industry to likely commercial availability dates.
5) Matrix was validated (and updated in places) through stakeholder engagement.

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[104] Claim made in CEA Power Hour Webinar - Digital Displacement - Reduce CO2 Emissions and Costs (23/06/2021) – ERM believes the quoted cost reductions over the lifetime are plausible, as fuel usage can be a significant proportion of the TCO (Argonne, 2021). This depends on the relative cost of the digital displacement pump compared to conventional hydraulics, which has not been reported.

The following subsections discuss steps 1 – 2 of the outlined approach in more detail. The final powertrain availability matrix is in Section 3.8.2.

3.4.1 Development time

Industrial NRMM product development cycles tend to stretch over longer time horizons of up to 10 years when compared to the light-duty automotive sector (Zemo Partnership, 2021).[105] This is largely due to the smaller production volumes, high product durability and challenging compliance requirements placing additional risks on NRMM OEMs.

OEM science-based targets and national carbon reduction targets, such as those set by the UK, have driven investment into researching and developing zero emissions or net-zero emissions solutions for industrial NRMM. Examples include JCB investing £100m into their hydrogen ICE.[106] In the mining sector, Epiroc have developed a line-up of battery-electric underground mining products which includes drilling rigs, loaders and mine trucks. Due to the ability of zero emission technology to reduce ventilation requirements and costs underground, Epiroc have prioritised the mining sector and aim to offer a full line-up of zero emission underground machinery by 2025 (primarily through electrification via batteries or tethered equipment) and have plans to replicate this for their surface machinery by 2030 (Epiroc, 2022). OEMs outside the EU are also following science-based targets and policy drivers to develop a line-up of zero emission products. Hyundai CE, for example, have set a roadmap to zero emissions by 2050 which includes 83% and 97% shares of sustainable products in their portfolio by 2030 and 2040 respectively. These plans include launching a full line-up of compact and small-sized electric excavators to be available by 2026 and releasing an industry-first 14-ton hydrogen-fuelled wheeled excavator by 2026.[107]

Considering these OEM commitments to developing zero CO_2 tailpipe emission solutions and the long development cycles for industrial NRMM, non-zero CO_2 tailpipe emission alternatives that are not commercially available or technically mature today (i.e. TRL 8+) are not expected to develop in time to become viable intermediate solutions before zero CO_2 tailpipe emission solutions are widely deployed (i.e. it is assumed that there is only enough time for a transition to the ultimate zero CO_2 tailpipe emission solutions via abatement options that are available today) (E4tech & Cenex, 2021).

3.4.2 Readiness levels by abatement technology

Abatement technology availability was reviewed for 63 combinations of machinery type and sector for each of the shortlisted abatement options identified. The reviewed technologies were each assigned to the appropriate TRL band from Table 26. The archetype TRLs were then assigned using findings of the full review. The TRL bands used in this report were adapted from those used by the Advanced Propulsion Centre (APC).[108]

Ahead of the refinement through stakeholder engagement, the main sources used in preparing this review were:

- ERM market research of OEM announcements, industrial NRMM user pilot project reports and industry publications
- AFLEET model from the Argonne National Laboratory (US Department of Energy research centre)
- The San Pedro Bay Ports 'Feasibility Assessment for Cargo-Handling Equipment' report (Tetra Tech and Gladstein, Neandross & Associates, 2022)

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[105] Published under the Zemo Partnership's former name: Low Carbon Vehicle Partnership

[106] https://www.jcb.com/en-gb/campaigns/hydrogen

[107] https://www.hyundai-ce.com/en/media/englishNews/811

[108] APC TRL levels A4 version v01.indd (apcuk.co.uk)

Table 26 – Adapted TRL bands and their descriptions

TRL band	Description
8+	Currently widely commercially available as an option
6 – 7	Some current commercial availability, expected to become more widely available from 2025 – 2030
4 – 5	Some limited current availability (demos/trials). Not expected as a widely available commercial option before 2030.
1 – 3	Little evidence of current availability, not expected as a widely available commercial option before 2035 – 2040.
NE	Technically feasible, but no evidence of ongoing development found.
NA	Powertrain viewed as incompatible with archetype.

Detailed discussions for each abatement technology option are presented below. It is worth noting that it is not guaranteed that all abatement options identified and discussed below will make it to commercial maturity, particularly those currently with a TRL below 6. For each technology, a table summarising the NRMM categories and the highest and lowest TRL levels for archetypes within the categories is also presented – a full powertrain availability matrix by archetype can be found in subsection 3.8.2. The emission abatement potential for each of the technologies is discussed in Section 3.5. A table of TRLs for each equipment type and sector combination and sector by sector summary charts for each powertrain can be found in Appendix 9.8.

HVO and B20

Table 27 – TRL bands for HVO and B20

NRMM Categories	Min. TRL	Max. TRL
Hand-held / moved	8+	8+
Mobile	8+	8+
Limited motion	8+	8+
Generators	8+	8+

HVO and B20 biodiesel have a TRL level of 8+ considering a large number of engine OEMs offer HVO and B20-certified products – i.e., HVO and B20 are commercially available abatement solutions for compatible technology and require little to no changes on the equipment end. JCB, for example, allows for 100% EN15940-compatible HVO being used in its machines – this covers products which use their own JCB 430, 444 and 448 Stage IIIB – Stage V engines and any JCB machines running on Cummins, Kohler, Perkins, Volvo, John Deere and Agco and Sisu Stage IIIA – Stage V engines.[109] Moreover, JCB approved B20 biodiesel for use in its Dieselmax engines back in 2007.[110] Similarly, HVO and biodiesel have been approved for use in Caterpillar generators for over a decade.[111] It is worth noting that HVO and B20 are only suitable for NRMM which use diesel as the incumbent fuel.

Hybrid ICE

Table 28 – TRL bands for hybrid ICE

NRMM Categories	Min. TRL	Max. TRL
Hand-held/moved	NE	NE
Mobile	4 – 5	8+
Limited motion	8+	8+
Generators	8+	8+

Hybrid powertrains are the only commonly deployed and fairly mature alternative powertrain across the sector. The use of hybrid powertrains can be seen in smaller machinery like sub-19 kW aerial lifts[112] to larger dump trucks, such as the 1,330 kW diesel-electric hybrid mining truck offered by Sany in China which utilises 2 diesel engines 2 electric motors and a 128 kWh battery pack.[113] In addition to the classic hybrid powertrains, there are a number of electric drive series hybrids that have been deployed across the sector,

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[109] https://www.jcb.com/en-gb/campaigns/hvo

[110] https://waste-management-world.com/artikel/jcb-engines-developed-to-use-b20-biodiesel/

[111] https://www.cat.com/en_GB/by-industry/electric-power/electric-power-industries/renewable-liquid-fuels.html

[112] https://www.genielift.com/docs/default-source/product-specifications/articulated-boom-lift/en-gb/2022/zboomspec_z45_dc_z45_fe_en-gb_emear_lr85e4b37ee68245f98d420273bf6459ed.pdf?sfvrsn=d4785c18_7

[113] https://product.sanyglobal.com/truck/off-highway_mining_truck/136/

particularly for larger machines such as CAT's D6 and D11 bulldozers (XE series).[114] Electric drive machines still utilise the counterfactual diesel engines, however, the torque converter and gearbox are replaced with a generator and electric motors that power the final drive (equipment-end of the machine). While diesel is still burnt throughout the duty cycles of such machines, the amount of fuel required is reduced due to the higher efficiency of the generator and electric motor combination when compared to the torque converter and gearbox arrangement (due to fewer moving parts, engine speed optimisation and ability to provide maximum torque at all motor speeds). Another form of hybridising powertrains includes the use of flywheels for recovering and storing the kinetic energy of machines. Such an example is the PUNCH Flybrid module which has been trialled in industrial NRMM.[115] The only area where hybrid machinery was not found to be widely available was medium-power mobile machinery (archetypes 4 and 6). This was in line with feedback from the stakeholder workshops which suggested medium-power machinery (corresponding to archetypes 4 and 6) would be the most challenging to decarbonise.

Hydrogen ICE

Table 29 – TRL bands for H_2ICE

NRMM Categories	Min. TRL	Max. TRL
Hand-held/moved	NA	NA
Mobile	1 – 3	4 – 5
Limited motion	1 – 3	1 – 3
Generators	1 – 3	6 – 7

Only a limited number of pure hydrogen combustion powertrains (hydrogen ICE) pilot projects or demos were found in the TRL 4 – 5 band. A couple of examples are JCB's prototype backhoe loader and telehandler which are currently being tested on JCB's spark-ignition hydrogen combustion engine.[116] Liebherr have also announced plans to develop a hydrogen ICE for use in industrial NRMM and recently unveiled a concept excavator which they are testing the technology in.[117] In addition to these, there are solutions being developed away from NRMM-specific use-cases that were consequently assigned a TRL band rating of 1 – 3. An example of these is the B6.7H hydrogen engine being developed by Cummins for use in trucks.[118] Furthermore, a number of trials on 100% hydrogen generator sets are also being run, with CMB.Tech in Belgium running tests on their 50 kW pre-production prototype.[119] In January 2023, a National Grid substation completed a 10-week trial of a pure hydrogen 250kW power unit as a potential replacement to diesel backup generators.[120] CAGE are also developing a multigas engine capable of running on natural gas or hydrogen with funding from the Red Diesel Replacement competition.[121]

Whilst hydrogen ICE is currently at a low TRL for industrial NRMM, there is potential that hydrogen ICE machinery will develop faster than other powertrains currently at a similar TRL, due to the similarities between hydrogen ICE and current internal combustion engines and the relative simplicity of the powertrain compared to electric or hydrogen fuel cell solutions. This may be an area of rapid change and the progress of hydrogen ICE development should be reviewed in 1-2 years to assess whether the technology is likely to reach the market faster than other technologies currently at a similar TRL. It remains to be seen whether hydrogen ICE will develop faster than other technologies at low TRL. Despite its potential to develop faster than other technologies, hydrogen ICE is still likely to reach mass market later than other powertrains which currently have a higher TRL due to the head start that these technologies have (e.g., battery electric, tethering, hydrogen fuel cell in some markets).

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[114] https://www.cat.com/en_GB/news/machine-press-releases/new-cat-d6-debuts-worlds-first-high-drive-electric-drive-dozer-top-grading-performance-fuel-efficiency-gains.html

[115] HS2 uses F1 tech to accelerate carbon emissions cut

[116] Hydrogen | Building a Greener Future | JCB.com and Wraps come off Hydrogen Refueller| News | JCB.com

[117] Liebherr hydrogen excavator receives Bauma Innovation Award | Liebherr

[118] Cummins to Reveal Zero-Carbon H2-ICE Concept Truck Powered by the B6.7H Hydrogen Engine | Cummins Inc.

[119] https://cmb.tech/gensets-products

[120] https://www.nationalgrid.com/national-grid-goes-carbon-free-hydrogen-powered-substation-trial

[121] Phase 1 Red Diesel Replacement competition: successful projects - GOV.UK (www.gov.uk)

Hydrogen fuel cells

Table 30 – TRL bands for H_2 fuel cells

NRMM Categories	Min. TRL	Max. TRL
Hand-held/moved	NA	NA
Mobile	1 – 3	8+
Limited motion	1 – 3	4 – 5
Generators	1 – 3	6 – 7

Hydrogen fuel cell technology has some commercial availability for some industrial NRMM niches, in particular for forklifts which are the only machine type which is widely commercially available today (TRL of 8+). At the end of 2021, Plug Power had deployed a total of 50,000 material handling fuel cell systems globally, with around 10,000 of those added in 2021 (E4tech, 2022). However, all other mobile fuel cell powered industrial NRMM are at lower TRL levels, with most machine types having a TRL of 4-7. Several types of fuel cell machinery are being demonstrated with pre-production units being tested in real-world conditions. Such demonstrations include Anglo American's nuGen mining dump truck, a 220t truck with a 290t payload, 1.2 MWh battery pack and 800 kW fuel cell power pack. The nuGen has been undergoing tests at a platinum mine in South Africa at the end of 2022, with Anglo American planning to roll it out to seven of their open pit sites by 2030.[122] It is expected that more hydrogen fuel cell industrial NRMM equipment types will be rolled out commercially over the next 10 years, particularly in heavier-duty applications where battery-electric technology might struggle to compete due to the amount of energy storage that would be required onboard and/or access to a power supply for charging. For generators, low-powered fuel cell generators were found to have some commercial availability,[123] with larger options like GeoPura's 250kVA system being trialled within the sector.[124]

Tethering

Table 31 – TRL bands for tethering

NRMM Categories	Min. TRL	Max. TRL
Hand-held/moved	4 – 5	8+
Mobile	NA	NA
Limited motion	4 – 5	6 – 7
Generators	NA	NA

Tethering is a common technology across hand-held or hand-moved and limited movement machinery, and is an effective abatement option when connected to a low carbon source of power. It is already commercially available for some equipment types such as surfacing equipment, pumps, pressure washers, cranes and crushing or processing equipment among others. In addition, tethered solutions are being developed for special use-cases of some mobile machinery like Sandvik's tethered mining loader which operates off the grid or site power supply and includes a small battery to allow for the mobility required on-site.[125] Tethering is also used extensively to power RTG cranes at ports (including in the UK[126]) with zero-emission electric RTGs on offer by Kalmar.[127]

Battery electric

Table 32 – TRL bands for battery electric

NRMM Categories	Min. TRL	Max. TRL
Hand-held/moved	4 – 5	8+
Mobile	1 – 3	8+
Limited motion	1 – 3	6 – 7
Generators	1 – 3	6 – 7

This abatement option was found to be prevalent across the highest number of different machinery and sector combinations. While largely available for hand-moved or hand-held machines and lower-power mobile or limited-motion machines, developments are taking place that signal battery electric solutions could be a viable solution for larger industrial NRMM equipment types. One such development was Caterpillar demonstrating its prototype battery electric CAT 793 mining dump truck

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[122] https://southafrica.angloamerican.com/our-difference/futuresmart-mining/nugen

[123] One of many options on the market: 1kW Portable Generator - H2 Generators

[124] Construction world first: GeoPura hydrogen fuel cell system to provide combined heat and power to National Grid's Viking Link construction site - GeoPura

[125] https://www.rocktechnology.sandvik/en/products/underground-loaders-and-trucks/electric-underground-lhds/lh514be/

[126] Six electric RTG crane arrival at Immingham - Container News (container-news.com)

[127] kalm0011_-electrification-brochure-final-web.pdf (kalmarglobal.com)

in late 2022.[128] While exact specifications of the prototype were not disclosed, the prototype was noted as a battery-electric 793 mining truck, the diesel version of which has a gross power of 1,975 kW and rated payload of 231 tonnes.[129] Other developments include a battery-electric version of Epiroc's SmartROC T35 surface drill rig which was tested in-field in the summer of 2022.[130] At ports, Kalmar has a battery-electric straddle carrier (originally trialled in the UK in 2018[131]) on offer.[132] Furthermore, battery-electric terminal tractors and automated guided vehicles (AGVs) have been developed for use at ports.[133] In the mining sector, electrification of equipment has been accelerated by the added benefit they bring in reducing ventilation costs, with OEMs like Epiroc and Sandvik offering extensive ranges of battery-electric products. In February 2023, Sandvik confirmed an order of 19 battery-electric mining equipment from Rana Gruber to support its target of operating a carbon-free iron ore mine before 2026.[134] With regards to battery-electric 'generators', this category refers to battery packs that can replace generators to power sites, such as JCB's E-Tech Powerpack range which is currently commercially available.[135] There are also third-party providers offering larger battery solutions for powering sites using industrial NRMM such as Nordic Booster who offer a wide range of solutions for zero-emission construction sites.[136] In addition, Porta Cell is a UK-based company planning on offering construction sites with batteries on power-as-a-service contracts from September 2023.[137]

Cross-technology retrofits

While not a common solution, there are some examples of zero-emission retrofit pilot projects being run in-house by construction companies and smaller technology partners. A construction company in the Netherlands has run several such projects converting its diesel equipment to run on electric or hydrogen powertrains instead. [138] This is indicative of how users of industrial NRMM can bring about quicker action and emissions reductions in advance of OEMs releasing zero emission products (in January 2023, Volvo announced they will be launching an electric road roller to the market in Q1 of 2024).[139] Moreover, retrofits of RTGs from diesel to tethered-electric have been carried out extensively with the Port of Felixstowe in the UK reportedly carrying out such a conversion in 2014.[140] In February 2023, Volvo CE launched a battery electric conversion for their 20 tonne L120H wheel loader as part of expanding their electric range to medium duty machines.[141]

In the UK, the Energy Saving Trust offers independent certification for NRMM retrofits through its NRMM Retrofit Accreditation Scheme (NRMM-RAS). While the large share of certifications has been

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[128] Caterpillar | Caterpillar Successfully Demonstrates First Battery Electric Large Mining Truck and Invests in Sustainable Proving Ground

[129] https://www.cat.com/en_GB/products/new/equipment/off-highway-trucks/mining-trucks/18092621.html

[130] https://www.epirocgroup.com/en/media/corporate-press-releases/2022/20220705-epiroc-trials-first-ever-battery-electric-surface-drill-rig

[131] Kalmar FastCharge at DP World London Gateway (transportandlogisticsme.com)

[132] https://www.kalmarglobal.com/equipment-services/straddle-carriers/fastcharge-straddle/

[133] HHLA terminal accelerates electrification project with 16 new automated guided vehicles - Port Technology International; 268794_Kalmar-Ottawa-Electric-Terminal-Tractor-T2E-_Brochure-web.pdf.pdf (kalmarglobal.com)

[134] Sandvik partners with Rana Gruber for BEV fleet in Norway — Sandvik Mining and Rock Technology

[135] JCB E-TECH Power Pack | Generators | JCB.com

[136] Zero-Emission Construction | Nordic Booster

[137] Porta Cell are developing a battery system with a capacity of up to 3.1MWh and multiple outputs rated up to 500kW specifically for the NRMM sector – Our technology - Portacell

[138] Royal BAM Group have reported conversion of a paver to run on two electric motors and a 270 kWh battery pack; a paver to run on a hydrogen ICE powertrain, and a road roller to run on electric motors and a battery that enables 8 hours of operation on a full charge; World first: electric asphalt paver for BAM | Koninklijke BAM Groep / Royal BAM Group; BAM introduces first construction machine with hydrogen combustion engine | Koninklijke BAM Groep / Royal BAM Group; BAM takes the world's first electric road roller into service | Koninklijke BAM Groep / Royal BAM Group

[139] Volvo CE introduces first electric machine for road segment

[140] https://www.portoffelixstowe.co.uk/press/news-archive/the-port-of-felixstowe-commissions-greener-electric-rubber-tyred-gantry-cranes/

[141] To be made commercially available for a selection of European customers throughout 2023 Volvo CE expands mid-size electric offering with L120H Electric Conversion

awarded for NOx and PM abatement systems, Magtec offers an NRMM-RAS approved zero emission electric drive re-powering service (available for variable speed engines from 37kW – 560 kW).[142] However, it is not clear if it has already repowered any equipment. Eminox have also received funding from the DfT-funded Small Business Research Initiative's first of a kind (FOAK) 2022 competition to develop a battery electric repower solution for excavators.[143]

Efficiency measures

Three categories of efficiency measures were identified (operational, machine, and process – see Section 3.1.2). All three categories were found to have measures which are currently available for industrial NRMM users to adopt. Due to the wide array of options available and considering that some are not specific to an equipment type, a TRL level was not given for abatement options or archetypes. Moreover, it is expected that efficiency measures will continuously develop in parallel to any technology changes within the industry.

3.5 Abatement potential

In this section, we present the emissions abatement potential of fuel switching options and efficiency measures, starting with the CO_2e emissions abatement potential before moving onto particulate matter (PM) and NOx emissions.

Figure 21 shows the range of well-to-wheel (WTW) emission abatement possible for each powertrain, compared to a mineral diesel counterfactual – the ranges shown vary depending on the source of feedstocks or electricity. Government publications for liquid fuel and electricity emissions factors were used, with some calculations and assumptions used for hybrids, electricity and hydrogen technologies:

- For HVO and B20, abatement potential ranges from the UK Government's renewable fuels statistics were used (Department for Transport, 2023).
- The range of hybrid[144], electric[145] (tethering and battery electric) and hydrogen[146] (ICE and fuel cell) abatement potentials were calculated per kilowatt hour of useful work (by factoring in powertrain efficiencies) compared to diesel.[147] As shown in Figure 21, the benefits of low carbon fuels such as HVO can leverage the efficiencies of hybrid powertrains and generate significant CO_2e reductions compared to a hybrid running on fossil fuels.
- The carbon intensity used for hydrogen (Department for Energy Sectурity & Net Zero, 2023) excludes its transportation to sites using the fuel. This means that emissions from any additional deliveries required to deliver hydrogen to sites are not included (considering that hydrogen has a lower volumetric energy density than diesel).

It should be noted that Figure 21 shows the range of WTW emission abatement possible for cases where feedstocks are RTFO compliant or use grid electricity at worst. Abatement could be lower than shown:

- HVO and the FAME in B20 used in industrial NRMM could be made from feedstocks that yield lower CO_2e emission reduction benefits – this is unlikely to be the case in practice given

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[142] Non-road mobile machinery certification - Energy Saving Trust

[143] Microsoft Word - FOAK 2022 winners - all.docx (ktn-uk.org)

[144] This was calculated by dividing the carbon intensity of diesel reported by Defra by the range of efficiency improvements of hybrid powertrains in industrial NRMM from (Lajunen, et al., 2016). The powertrain efficiency was calculated from the percentage range of improvement in fuel consumption for hybrid NRMM compared to diesel.

[145] The lower abatement potential uses the current UK grid carbon intensity reported by Defra (194 gCO_2/kWh), and the maximum assumes zero carbon electricity used (100% abatement potential).

[146] The lower abatement potential uses the standard intensity of 72 gCO_2/kWh [20gCO_2e/MJLHV (Department for Energy Secturity & Net Zero, 2023)] and the maximum assumes zero-carbon electricity for electrolysis (100% abatement potential).

[147] 269.4 gCO_2e/kWh, equivalent to 818 gCO_2e/kWh of useful work (using a powertrain efficiency of 33%)

the RTFO incentive and certification schemes such as the Renewable Fuels Assurance Scheme (RFAS).[148]

- Hydrogen used in industrial NRMM could be fossil fuel derived – as for HVO and FAME, the RTFO and the RFAS provide some incentives for the production and purchase of low carbon hydrogen.
- Electricity used in industrial NRMM could be 100% fossil fuel derived electricity if a diesel generator is used – operators have an economic incentive to use grid electricity over a diesel generator (given it is cheaper) but might have practical barriers or delays to grid access (see sub-section 3.6.2.2).

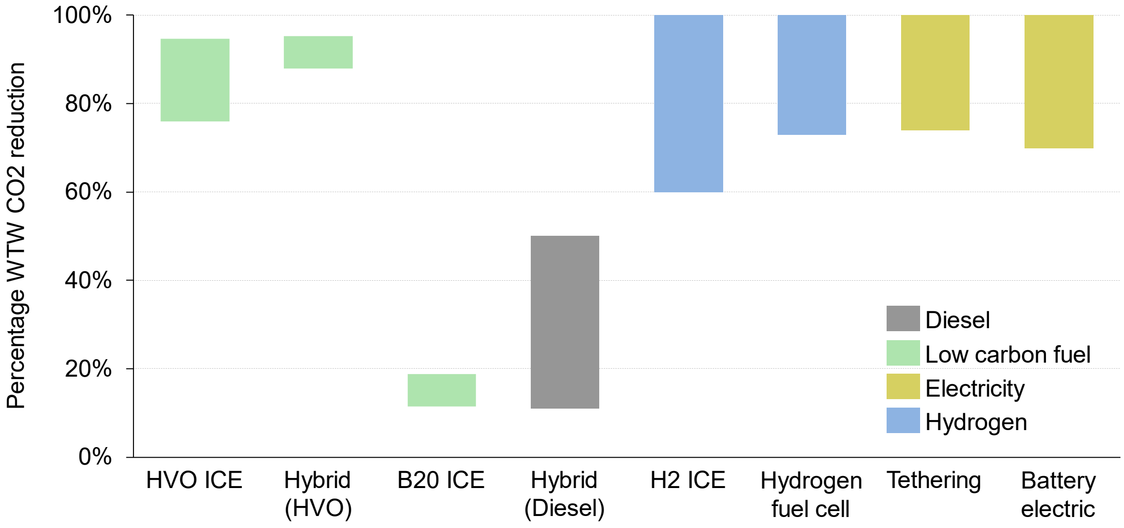

Figure 21 – Well To Wheel CO_2e abatement potential of technology options compared to incumbent. Sources: refer to text above

Table 33 shows the abatement potential of NOx and PM emissions for each powertrain type .[149] HVO and B20 do not consistently reduce NOx or PM emissions. Hybrid engines show a reduction in both NOx and PM due to the greater powertrain efficiency of hybrid powertrains. Tethering, battery electric and hydrogen fuel cell powertrains significantly reduce NOx and PM emissions. While hydrogen ICE powertrains significantly reduce PM emissions compared to diesel engines, quantities of NOx are still produced due to the high temperature interactions of oxygen and nitrogen present in air. The exact levels of NOx compared to diesel remain uncertain due to the low TRL of hydrogen ICE powertrains in NRMM (Lewis, 2021). Future commercial hydrogen ICE NRMM may require aftertreatment similar to that of diesel engines.[150] However, the NOx emissions may still lead to hydrogen ICE machinery not being permitted in or chosen by operators in urban areas or underground settings (Heid, Martens, & Orthofer, 2021).

As outlined in Section 3.1, abatement options were split into fuel-switching and efficiency measures. The latter contributes to emissions abatement by reducing the amount of fuel or energy required by a machine to perform tasks. The potential for efficiency gains identified in the literature are 5% – 50%

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[148] Renewable Fuels Assurance Scheme | Fuels | Zemo Partnership

[149] https://learninglegacy.hs2.org.uk/document/alternative-fuels-and-additives-in-construction/ for HVO and B20 NOx, Red Diesel Report supplementary files (supplementary data sheet produced with (E4tech & Cenex, 2021)) for rest of table.

[150] Bernhard-Biermann.-Hydrogen-Combustion.pdf (fpc-event.co.uk)

for the three categories of efficiency measures: operational (5% – 30%), machine (5% – 25%) and process (15% – 50%) – see Table 21 for more information.

Table 33 – NOx & PM abatement potential of technology options compared to incumbent[149]

Air quality abatement potential ■ Reduced greatly ▨ Reduced □ Similar to incumbent	**HVO**	**B20 ICE**	**Hybrid**	**H2 ICE**	**Hydrogen fuel cell**	**Tethering**	**Battery electric**
NOx	□	□	▨	□	■	■	■
PM	□	□	▨	■	■	■	■

3.6 Deployment potential

This section provides an overview of the deployment potential for the evaluated abatement options. The deployment potential for fuel switching options is presented first, followed by an assessment of practical considerations that can impact the deployment of these technologies. The deployment pathway for efficiency measures is presented last (Section 3.6.3).

3.6.1 Fuel switching

The deployment potential varies across fuels and technologies, depending on a number of factors. The key considerations for each fuel are summarised below.

HVO, B20 and hybrid technologies are limited by the fact that they are not true zero CO_2 tailpipe emissions solutions. As such these fuels are considered to offer an interim solution until zero CO_2 tailpipe emission options become available, and their deployment is likely to be limited to the short-to-medium term. HVO may also suffer from supply constraints if it is widely adopted within industrial NRMM, depending on how HVO use changes in other transport sectors, competition over feedstock could increase.

Hydrogen combustion and fuel cell deployment potential is highly dependent on the availability of low-cost hydrogen. If hydrogen supply becomes readily available at low cost, hydrogen could be a solution for most sectors of industrial NRMM. Hydrogen fuel cell-powered machines are also currently limited by the high CAPEX of the powertrain, but this has the potential to decrease significantly as the technology becomes more developed. There are also practical considerations, discussed in the next sub-section.

The potential for **tethering** is highly limited to specific machinery types and use cases which have both a reliable grid connection and do not require significant movement (e.g., machinery that cover short distances or well-defined simple paths that minimise the risk of entanglement). Example use cases include cranes, crushing equipment or pumps used on permanent sites such as ports,[151] mines,[152] or long-term construction sites (HS2, 2022). However, within these specific use cases, the low CAPEX and OPEX of this option means it is likely to be the preferred zero emission option when available.

Battery electric powertrains are already deployed in low power use cases (see Section 3.4.2 on battery electric industrial NRMM) and are seen as a potentially suitable option for a wide range of archetypes. Uptake may be limited in sectors where obtaining a reliable grid connection would be expensive or too slow (see discussion on hard-to-deploy machinery, sub-section 2.1.4), for very high

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[151] https://container-news.com/six-electric-rtg-crane-arrival-immingham/

[152] LH514BE Battery Assisted Electric loader — Sandvik Mining and Rock Technology

utilisation of machinery, or for machinery which regularly moves sites – e.g. high utilisation mobile machinery in archetype 6 or generators in archetypes 12 – 14 where recharging suitably sized batteries could be challenging. For these market sectors, the supply of hydrogen and installation of hydrogen infrastructure for hydrogen powered machinery might also pose significant challenges. In the USA the penetration rate of battery electric loaders and excavators is forecast to be between 4-15% by 2029 (CALSTART, 2022).

Table 34 summarises the deployment potential of each abatement technology option. The potential is based on our own assessment as no projections were found in the literature, beyond an isolated case in the USA that forecasts the penetration rate of battery electric loaders and excavators.

Table 34 – Summary of the deployment potential of each powertrain

Technology	Grading	Deployment potential
HVO ICE	▨	• High fuel cost and supply could be limited due to competing demand • Deployment potential limited as not zero emission solution – suitable as short-term solution
B20 ICE	▨	• Higher fuel cost than incumbent • Deployment potential limited as not zero emission solution – suitable as short-term solution
Hybrid	▨	• Deployment potential limited as not zero emission solution – suitable as short-term solution
Hydrogen ICE	🟨	• Limited products available (as of early 2023), although products are starting to come to market – see section 3.4 • Deployment potential limited by fuel supply (practicalities and cost) and emission of NOx
Hydrogen fuel cell	🟨	• Limited products available (as of early 2023), although products are starting to come to market – see section 3.4 • Deployment potential limited by fuel supply (practicalities and cost)
Tethering	🟥	• Already commercially available for repetitive use cases in defined spaces e.g., loaders • Deployment potential limited by use case
Battery electric	🟩	• Low and high-power commercially available machines across industrial NRMM sectors • High deployment potential in majority of sectors • Deployment potential could be limited by grid expansion in places and/or operation constraints related to hours of use between charges

Colour code	Key
▨	Technology is not a zero CO_2 tailpipe emission solution, deployment limited to the near future
🟥	Technology deployment is highly limited to specific machinery types and use cases
🟨	Technology deployment is currently limited by fuel supply or infrastructure availability, but may improve in the future
🟩	Technology has high deployment potential across most machinery types and use cases, only with some limitations in challenging circumstances

3.6.2 Practical feasibility of switching

Even in cases where the products themselves are commercially and technically viable, there are practical considerations that can impact the readiness with which certain abatement technologies can be deployed. These considerations can be broadly summarised into three categories:

- **Equipment supply:**
  - Maturity of the supply chains required to produce the abatement technologies
  - Scalability of the products by OEMs and development of the capability to deliver products against industry-standard lead times
- **Refuelling or recharging infrastructure:**
  - The ease and availability of fuel delivery and dispensing solutions
  - The availability of an electric connection and recharging solutions
- **New workflows to accommodate the new machine or infrastructure system**
  - Need for operator training to use alternative technologies
  - Need for modified duty cycles to suit changes in product capabilities

The impacts of the above practical considerations on the feasibility of switching to each of the abatement technology options are summarised in Table 35 below. Note that abatement option suitability by archetype was considered for this assessment, meaning the practicalities of abatement options were only assessed against archetypes they are compatible with (see sub-section 3.8.2). For example, the fact that tethered NRMM was deemed not suitable for mobile machinery did not further impact their practicality score in this section. Moreover, the assessment excludes machinery on hard-to-deploy sites where the recharging category would be red for tether and battery solutions.

An initial assessment of the practical considerations was carried out based on literature and public data, with each of the three categories discussed in more detail in the following sub-sections. For most fuel types, information was readily available and accessible regarding refuelling or recharging infrastructure and the associated solutions being developed or provided by OEMs and third-party suppliers; where there were gaps, developments in the on-road sector were assessed for transferrable solutions. More limited data is available regarding the supply of abatement technologies at scale and associated OEM production ramp-up plans. Similarly, limited literature is available regarding the attitudes of industrial NRMM operators towards necessary workflow and operational changes required to make the switch. The initial assessment was refined based on feedback from the stakeholder engagement, which largely supported the reported findings on practical considerations of switching.

Table 35 – Summary of feasibility considerations impacting switching today

	HVO	**B20**	**Hybrid**	**H_2ICE**	**H_2FC**	**Tether**	**Battery**
Equipment supply	🟩	🟩	🟨	🟥	🟥	🟨	🟨
Refuelling/recharging	🟩	🟩	🟩	🟥	🟥	🟨	🟨
Workflow/operational changes	🟩	🟩	🟩	🟨	🟨	🟨	🟥

Colour-code	Description
🟩	Minimal impact on feasibility of switch
🟨	Some impact on feasibility of switch
🟥	High impact on feasibility of switch

3.6.2.1 Equipment supply

Due to the various equipment types available, the high levels of configurability and low production volumes compared to on road vehicles, industrial NRMM typically experience longer lead times than on-road vehicles (usually in the order of months[153] and up to more than a year[154]). While little data is available regarding the range of lead times for different equipment type, it has been reported that post-pandemic recovery demand and global supply chains issues are still impacting NRMM OEMs, with equipment lead times consequently growing.[155]

NRMM running on HVO or B20 will have the same level of equipment supply to the incumbent as they use the same powertrain. Lead times for emerging zero-emissions technologies are initially expected to be longer due to new supply chains and manufacturing lines required for new technologies. However, it is ERM's view that lead times for these new technologies will match those of the incumbent powertrains when the product and supply chains reach maturity and economies of scale are achieved by OEMs. Current battery electric industrial NRMM production volumes are still low[156] and hydrogen industrial NRMM are only currently commercially available for forklifts and small generators in low volumes (see Table 79, Appendix 9.8), indicating that these technologies are still far from achieving scale. Longer lead times present industrial NRMM operators with planning challenges and expose them to higher risks, such as the risk of being locked-in to one technology if more suitable products come to market while waiting for delivery.

3.6.2.2 Refuelling and recharging infrastructure

To ensure that alternatively fuelled industrial NRMM can be utilised, suitable supporting infrastructure needs to be put in place. This ranges from infrastructure required to deliver the fuel or energy to the site and the refuelling infrastructure required to supply the equipment with fuel or energy during use.

For **HVO and B20**, the practical considerations for refuelling are expected to be minimal (identical refuelling experience to diesel). With regards to fuel supply, while scale-up would be required this does not present a major barrier at present (see Section 4.1.2 for a more detailed discussion). The main practical consideration for fuel storage and supply is cold flow issues with B20 fuel, where the FAME component can result in crystallisation in the winter (Department for Transport, 2021; Dwivedi & Sharma, 2014) which hinders refuelling – see also sub-section 4.2.2).

Hybrid powertrains are also expected to have minimal practical considerations since hybrids deployed in industrial NRMM will still largely rely on the incumbent diesel fuel and are not typically 'plug-in' machines (see Hybrid-ICE examples given in sub-section 3.4.2). As such, they do not require any additional infrastructure.

For **electric** (through tethering or batteries) and **hydrogen** (ICE or fuel cell) industrial NRMM abatement technologies, refuelling and recharging infrastructure considerations become particularly relevant, and they are discussed next.

3.6.2.2.1 Tethering and battery electric industrial NRMM

Access to power through a grid connection

To operate high-powered tethered machines, a reliable power source is required. This reduces the feasibility of running tethered machines at sites where an electricity grid connection is not available. If a site does not have a grid connection (or not enough available power left in the existing connection),

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[153] JCB sells out of products as infrastructure boom adds to supply chain strain | Financial Times (ft.com); Construction plant shortages start to bite | Construction Enquirer News

[154] CEA Power Hour Webinar - Off Highway Research: UK Market Update (23 Feb 2022)

[155] Record-breaking year for equipment sales - International Construction (international-construction.com)

[156] While reviewed OEM filings do not report any sales figures for zero emissions NRMM, it was reported in Epiroc's 2021 sustainability report that revenues from battery-powered equipment and related services were 'still small' (Epiroc, 2022)

a request for a connection or upgrade will be needed, which can be a lengthy and costly process (see ‘Practicality of securing a grid connection upgrade or a new connection’ sub-section).

The challenges of securing a new or upgraded grid connection (and related substation onsite) also apply to battery electric industrial NRMM, particularly for sites with high-powered machinery or sites where multiple pieces of machinery need to be charged at once. However, this may be reduced for certain applications as 1) some electric NRMM will require only low kW or have long windows of opportunity to recharge and 2) off-grid low carbon charging solutions are currently under development for the case of remote sites (discussed below).

Practicality of securing a grid connection upgrade or a new connection

Beyond the cost of a grid connection, there is a time impact: the process takes between 12-16 weeks for simple works and several years where reinforcement of the network is required.[157] The complexity of the grid connection is driven by site-specific characteristics such as:

- The distance to the site from the primary substation and available power at the substation;
- The pathway of the cables, which could trigger road closures or could require the Distributor Network Operator (DNO) to obtain lengthy legal consents e.g., way leave for cables crossing someone else’s property;
- The level of power requested, which depend on the number of industrial NRMM on-site, their duty cycles, their charging profiles and presence of energy storage or generation.

Some of the challenges that could be faced by industrial NRMM stakeholders when requesting a grid upgrade or connection, as reported by road fleet operators (HGVs, vans and car clubs), include the lack of a standardised process for new applications across different DNOs, leading to challenges at both the pre-application (lack of information from DNOs on existing grid capacity) and application (different information being required from different DNOs) stages.[158] In the case of industrial NRMM, it is ERM’s view that the level of familiarity with the application process, and the difficulty in assessing power needs, will vary across sectors[159]:

- **Ports, waste sites and other (logistics) sites** will be similar to road fleet depots: due to the largely permanent nature of these sites, they are likely to have a power connection that was established when the site was first built and to be unfamiliar with the power upgrade process. The nature of operations is likely to be regular, making the assessment of power need relatively easy.
- **Large construction sites** are likely to be familiar with applying for temporary connections given the longer duration of sites justifying the waiting times involved and more equipment being used on site.[160] However, applying for a larger connection to serve electric machinery may add extra complexities. The assessment of the power need is likely to be very complex, due to the variety of machinery involved and the variations in power use across different phases of the construction process. An innovative approach that has been trialled is to ensure that the final power connection required at a site is installed early on in a project (HS2, 2022). However, this approach can be complicated by mismatches in the final power required by a site on completion and that required for its construction. Additionally, the requirements to power electric machinery at a large site will likely exceed those of temporary connections developers are accustomed to.

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[157] Install a new electricity supply (over 70 kVA) | UK Power Networks

[158] BVRLA Fleet Charging Guide

[159] Based on ERM’s experience in on-road vehicle charging infrastructure deployment

[160] Defined as less than 5 years and are offered by all DNOs, for instance Temporary connection - Cost, time and what's involved (ukpowernetworks.co.uk), National Grid - Temporary connection. The application process is similar to the permanent connection process.

  - **Examples of large construction** sites include high-rise or industrial estate construction sites and large infrastructure projects (motorway or rail) with 10 or more machines on-site (Cenex, 2022).
- **Mining sites and small construction sites** are less likely to be familiar with the application process, due to their remote or short nature, although some might be familiar with the process if already requesting temporary connections. This group is the most likely to need a new connection or to need off-grid solutions if NRMM at these sites electrify (off-grid solutions are discussed under alternatives to new and upgraded grid connections from page 79). Assessing the power need for a transition to electric machinery is likely to be more difficult than for permanent sites such as ports, but will vary, as some small construction sites might use a limited number of machines at a given time.
  - **Examples of mining sites and small construction sites** include small limestone quarries and commercial warehousing or retail construction sites with fewer than 5 machines on-site (Cenex, 2022).

This indicative assessment of the expected difficulty associated with the grid connection or upgrade application process is summarised in Table 36. After applying, the complexity of the actual grid connection or upgrade will vary significantly across and within industrial NRMM sub-sectors, and will depend on site-specific criteria such as distance to substation, cable pathway, legal consents needed, etc.

Table 36 – High-level description of likely grid connection requirements and grading of application complexity for industrial NRMM sites. Source: ERM assessment

	Ports, waste sites and other (logistics)	Mining and small construction sites	Construction (large site)
Actor familiarity with process	**Low**	Medium to **Low**	**High**
Ease of power need assessment	**High**	Medium to **Low**	**Low**
Likely grid requirement	Upgrades to existing connection	New connection or off-grid solutions	New connection

Where the length or complexity of the grid connection or upgrade is prohibitive, there is a risk that industrial NRMM sites will use diesel generators to power or recharge electric machinery, or not transition to electric machinery altogether. However, there are alternatives to grid connections and upgrades, discussed next.

Alternatives to new grid connections

For sites without access to the grid, charging solutions have been developing as electric vehicles are becoming more widely adopted in the road transport sector, and relatively mature solutions exist that address some of the impracticalities mentioned above. See Table 37 (page 83) for an overview of charging options available for industrial NRMM. These solutions include battery swap stations[161] and off-grid charging such as solar[162] or battery-powered mobile chargers.[163,164]

Alternatives to grid connection upgrades

For sites with an existing but inadequate grid connection, a potential alternative to a grid upgrade is to use batteries as ‘generators’ – such a product and service has been deployed on construction sites in Hong Kong, Singapore, Australia, and recently in London.[165] These batteries have a power output sufficient for the on-site machinery and can either be plugged in all day to trickle-charge from the low-power grid connection or recharged using off-grid sources.[166] This removes the need to recharge battery-electric machinery off-site or through diesel generators and can also improve the mobility of tethered machines (given the mobile power source). This is particularly useful on sites where a tethered machine may be required to operate at multiple locations (Committee for European Construction Equipment, 2021). The battery-powered chargers discussed above can also operate while powered by the grid.[167] There is also the option for some sites to complement an existing grid with on-site generation from renewables such as solar power.[168]

Limitations to new or upgraded grid connection alternatives

Given that the industry is not accustomed to the downtime associated with moving machinery off-site for recharging, it is expected that that recharging infrastructure will need to be available on-site (Committee for European Construction Equipment, 2021).The alternatives to new or upgraded connections discussed above enable this. However, workshop attendees stated that on-site recharging facilities could also introduce impracticalities if the safety protocols put in place for a site (e.g., parking restrictions or fire guidance on charger or machine proximity) [169] limit the mobility of certain equipment across the site, making it challenging to move machinery to their chargers or vice-versa.

Footprint requirements of the associated infrastructure

There are site-specific practicalities regarding the footprint of the associated infrastructure required. For temporary sites with a grid connection where permanent infrastructure cannot be installed, mobile solutions are needed and can have a footprint ranging from as little as 3sqm (for a mobile charging unit)[170] to 136sqm for mobile battery charging or swapping stations (including space for machinery to manoeuvre) .[171] For sites with no grid access, larger solutions are expected to accommodate the higher energy storage requirements (e.g., a 20ft container-shaped mobile charge with a 1,000kWh battery has a footprint of approximately 14sqm) .[172] For permanent sites like ports, investments can be made in utility-side equipment (such as the equipment required to tether RTG cranes, which has a footprint of around 10sqm to 20sqm (Tetra Tech and Gladstein, Neandross & Associates, 2022)).

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[161] Mobile Charging Station — Sandvik Mining and Rock Technology

[162] Volvo Electric Construction Equipment : How to Effectively Charge Electric Construction Equipment via Beam Global EV ARC™ | Beam (beamforall.com)

[163] For example, the supplier Nordic Booster has developed charging solutions specifically for construction sites with no power supply, designed in the shape of standard containers for ease of transport to and from sites Zero-Emission Construction | Nordic Booster

[164] Zero-Emission Construction | Nordic Booster

[165] Ampd Energy partners with Select to reduce emissions in central London | Press Releases | Asia | Sustainable Business (eco-business.com)

[166] “How it works: …The Enertainer can use any power source but works best with a small utility power input to charge 24 hours a day and easily support the high-power demands of typical construction equipment. “ Home | Ampd Energy

[167] BoostCharger | Nordic Booster

[168] In this example, Rio Tinto deployed a 34MW solar plan that provides 65% of the mine’s average electricity demand (it is assumed that the remaining 35% are delivered by the local grid): Our first solar plant to power new iron ore mine (riotinto.com)

[169] These are some of the aspects raised by stakeholders during the stakeholder engagement workshop.

[170] Caterpillar’s MEC500 mobile charger (mains-powered, no battery) has a footprint of 3sqm and can deliver 500kW, weighing 2 tonnes and is supplied with a metal jacketed 10 or 15m charging cable Specalog for Cat MEC500

[171] Mobile Charging Station — Sandvik Mining and Rock Technology

[172] Nordic Booster offers a 20ft container shaped solution that can deliver 300kW to 2 machines simultaneously from either the grid or its 1,000kWh battery BoostCharger | Nordic Booster

Where cable management and footprint can be an issue, permanent sites can invest in innovative solutions such as inductive chargers which are being trialled in the USA (no similar examples found in the UK).[173] These trials are still at early stages and the technology has disadvantages such as high capital cost, modifications to machines, substantial subsurface work, and risk of failed charging sessions due to misalignment (Tetra Tech and Gladstein, Neandross & Associates, 2022).

3.6.2.2.2 Hydrogen

The supply of cost-effective low carbon hydrogen presents a challenge for switching to fuel cells and hydrogen ICE (see Section 4.2.4). Assuming that a supply of low carbon hydrogen is available, there are other practical considerations involved in its delivery to sites and then into the machinery using it.

There are 9 publicly accessible permanent refuelling stations for hydrogen mobility in the UK, as of early 2023.[174] However, these stations are not relevant for industrial NRMM as they target the road vehicle market (typically cars & buses) and are often deployed as part of funded demonstration projects in combination with vehicles.

There are five main options for hydrogen delivery in the UK: tube trailer road transport (gaseous), mobile refuelling solutions, drop-and-swap solutions, on-site electrolysis, and hydrogen pipelines.

Most hydrogen in the UK is transported in gaseous form via road in a tube trailer, which typically has around 300 kg hydrogen storage capacity.[175] Table 39 below summarises the five main hydrogen delivery options.

Once at the site, hydrogen must be dispensed either through a permanent station or directly from the tube trailer. To justify the capital investment of a permanent refuelling station for industrial NRMM, high offtake (>500 kg/day) and amortisation periods of over 15 years would be required. In an unpublished study carried out by Cenex for the construction sector (Cenex, 2022), only the largest 'mega projects' are expected to reach such hydrogen demand levels (e.g., HS2, Battersea Power Station Redevelopment or the Heathrow Airport Expansion).

Refuelling hydrogen directly from a tube trailer (a mobile refueller) helps to reduce the burden of the infrastructure capital contribution to the fuel price. While the reliability of mobile refuellers has been found to be lower than traditional refuelling stations, solutions are being developed to improve this. One such example is CATAGEN's high pressure hybrid pumping system (funded through the Red Diesel Replacement Competition), which is designed to overcome the thermal issues and slow refuelling times of existing solutions.[176] Another example is NanoSUN's Pioneer mobile refuelling system which has been awarded funding through the Red Diesel Replacement Competition to be developed for use by NRMM.[177]

Table 39 gives an overview of practical considerations for temporary and permanent refuelling stations, while Figure 22 shows the impact of station utilisation on station reliability.

A further consideration is the land required on-site to accommodate the necessary hydrogen refuelling and storage infrastructure. Depending on the site and amount of hydrogen needed, which can range from 10 to 680 kg/day (Cenex, 2022), the footprint required can vary significantly. This can be as little as the size of a standard 20ft container (approximately 14 sqm)[178] for some mobile refuelling

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[173] Multiple projects either already underway or planned at the Port of Los Angeles Ports - WAVE (waveipt.com) to run 125kW, 250kW, 380kW and 500kW wireless WAVE chargers Ports - WAVE (waveipt.com)

[174] https://www.ukh2mobility.co.uk/stations/

[175] Capacity given at 228 bar. There are also now high-capacity 300 bar tube trailers on the market, whilst 500 bar tube trailers are being deployed which could store up to 1,100 kg (Hydrogen Europe, 2021) Calvera develops hydrogen transport tube trailer model for Shell - Calvera

[176] Phase 1 Red Diesel Replacement competition: successful projects - GOV.UK (www.gov.uk)

[177] NanoSUN Awarded Significant Funding to Develop Pioneer HRS

[178] Assuming NanoSUN's Pioneer is used (420kg H_2 capacity, 30 mins to refuel a 20kgH_2 machine). Excludes space for delivery of H_2, the size of the industrial NRMM being refuelled and associated turning circles required Refuelling Hydrogen Construction Equipment | NanoSUN

solutions, 30 sqm per electrolyser for on-site electrolysis,[179] or as large as 2,000 sqm for stations delivering 600kg/day (Sandia National Laboratories, 2020).

Overall, hydrogen refuelling solutions are expected to develop as more hydrogen solutions are made commercially available in on-road and industrial NRMM applications. This can be seen already with JCB developing a mobile hydrogen refuelling bowser to support tests of their prototype hydrogen ICE products[180] and Anglo American trialling on-site electrolysis for hydrogen production in South Africa.[181]

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[179] 141552 | Proposed Hydrogen Fuelling Station with on site hydrogen generation and fuel cells systems. | Langdykes Road Aberdeen (aberdeencity.gov.uk)

[180] Understanding Hydrogen Fuel | Hydrogen Refuelling | JCB.com

[181] nuGen™ – Anglo American South Africa

Table 37 – Overview of charging options for electric industrial NRMM. Source: ERM market review

Technology		Description	Power connection needed	TRL	Comment
Charging cable		No new infrastructure, just a dedicated cable that plugs into a domestic 230V socket. >8h charge	No need connection, use existing	8-9 – Already sold by several NRMM OEMs	Example suppliers: JCB
Charging station with battery swapping		Battery swapping: chargers (with associated cooling units if necessary) can be installed near the operating area of the vehicles. Vehicles drop their current empty battery and pick up another full battery. Takes <5min to swap, but at least 1hr to fully recharge the spare battery.	It will vary depending on operations, in some cases it could be up to 450kVA for one charging unit (charger and cooling unit). In other cases, it may be that only a low input is required as the battery can recharge over a long period as the vehicle can operate while a spare battery is recharging.	8-9 – Already common for warehouse equipment such as electric forklifts but not as common for large battery swap (e.g., trials at a USA port with battery packs of up to 500kWh[182])	Example suppliers: Komatsu (micro excavator only currently available in Japan) Sandvik, Urban Mobility Systems (example vehicle: crane), JCB Products seen for logistics, ports, mining and construction
Mobile charger	Battery-charger combined unit	Mobile chargers deployed on-site to be used by the NRMM. Unit combining a battery and inbuilt chargers (up to the size of a shipping container). Charging takes 30mins to hours	Variable with battery size. Typically, does not require high kW input from the grid for <100kWh case. Container site ones would require 3-phase connection and up to 125A. Smaller units would be taken off-site for recharging.	8-9 – already commercialised by several NRMM and charger OEMs	Example suppliers: Nordic Booster Typically, from non NRMM OEMs with charging outputs ranging from 100kW up to 300kW
	Moveable single charger	An easily movable single charger with no battery. Charging takes 30 mins to hours	Most can be fed with 3-phase 32A	8-9 – already commercialised by several NRMM and charger OEMs	Example suppliers: Epiroc, JCB, CAT Typically low power (up to 40kW AC or 20kW DC) with CAT offering a high-power 500kW DC solution
Fixed charger		Higher power chargers can usually come with power cabinets stacked together, and charging posts. Charging takes 30mins-hours.	Requires high kW input from the grid. Least suitable to short-term sites.	9 – already commercialised by several charger OEMs	Not specific to NRMM sector, so many suppliers. Industry benefit from learnings from bus depot charging, power split and control well developed. Can be >300 kW
Vehicle to load		Discharging the battery from an industrial NRMM with a large battery to an industrial NRMM with a small battery or a smaller tethered industrial NRMM.	None dedicated (but the larger electric NRMM would use one of the solutions listed above)	Low (<5)	No industrial NRMM example found but technically possible as already done in cars. Would be <50kW
Inductive charger			Similar to fixed charger	Low (<5)	Some trials underway[183]

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[182] Battery packs cited in a USA port case study as having a capacity of up to 5 times that of a Tesla Model S (100kWh) – TEREX

[183] Multiple projects either already underway or planned at the Port of Los Angeles to run 125kW, 250kW, 380kW and 500kW wireless WAVE chargers Ports - WAVE (waveipt.com)

Table 38 – Overview of the five main compressed hydrogen delivery options. Source: ERM market review

	Road – tube trailer	Mobile refuelling solutions	Road – Drop-and-swap solutions	On-site electrolysis	Hydrogen pipelines
Description	Hydrogen transported in tube trailers[184]	Small hydrogen cylinders or hydrogen tube trailers with a dispensing system	HGV delivers pressurised container to site, and retrieves empty ones for off-site refills	Using on-site electrolysers to produce hydrogen	Distribution through repurposing existing gas-grid polyethylene-based pipelines[185]
Delivery	Into on-site storage	Direct into NRMM	Reusable hydrogen tanks	Into on-site storage	Direct to connected sites
Required on-site infrastructure	Storage and dispensing equipment	None	Dispensing equipment	Electrolyser, storage and dispensing equipment	Purification and/or deblending equipment,[186] dispensing equipment
Current use	Most common form of hydrogen delivery in the UK today	Commercially available in the UK today[187]	Deployed in the UK at a Metroline bus depot [188]	Deployed at refuelling stations in Aberdeen and Tyseley[189]	Not expected before 2025[190]
Current use in NRMM	No example found, but assumed to be applicable across sectors	Available for forklifts[191] and under development for other NRMM[192]	No example found, but assumed to be applicable across sectors	Being trialled at a mine in South Africa[193]	Not applicable
Site suitability	Larger sites with on-site storage and H_2 dispensing infrastructure	Smaller or temporary sites with demand insufficient to justify a permanent station	Sites with permanent dispensing infrastructure	Larger sites which can accommodate production, storage and dispensing equipment	Dependent on site connection to gas grid and hydrogen availability – likely to be unsuitable for most industrial NRMM sites

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[184] Typical capacity of 300 kg at 228 bar (Hydrogen - UKPIA); 500 bar, 1 ton trailers are also being deployed Calvera develops hydrogen transport tube trailer model for Shell - Calvera

[185] https://www.dnv.com/oilgas/perspectives/switching-city-from-natural-gas-to-hydrogen.html

[186] Hydrogen delivered from the grid would need to be purified before use in fuel cells. If a natural gas/hydrogen blend is delivered, the hydrogen would need to be separated at its point-of-use.

[187] Fuel Cell Systems have several mobile solutions commercially available in the UK today Fuel Cell Systems

[188] Source: ERM, from work with depot owner

[189] For refuelling buses in Aberdeen (Aberdeen's Hydrogen Buses - Aberdeen City Council); For cars, busses and tube trailers at Tyseley (Tyseley Refuelling Station - Tyseley Energy Park)

[190] National Gas plans for 2 – 5% of Hydrogen to flow through the national transmission network in 2025 UK - Hydrogen to be Added to Britain's Gas Supply by 2025 - Hydrogen Central

[191] Air Products claim that their portable refueller has been used to refuel forklifts Portable Hydrogen Fueler (airproducts.co.uk);

[192] NanoSUN Awarded Significant Funding to Develop Pioneer HRS

[193] On-site electrolysis in South Africa by Anglo American nuGen™ – Anglo American South Africa

	Road – tube trailer	Mobile refuelling solutions	Road – Drop-and-swap solutions	On-site electrolysis	Hydrogen pipelines
Disadvantages	Depending on site size and storage available, hydrogen demand could necessitate multiple lorry deliveries per day.	Fuel supply and dispensing are linked, which limits scope for optimising operational efficiency (as opposed to sites where the two aspects are decoupled). Currently less reliable than a permanent station but solutions are being developed (discussed in main text).	Limited to sites with permanent dispensing capabilities.	Limited to sites with permanent dispensing capabilities and access to power and water for the electrolysers.	Whilst the repurposing has been shown to be technically and economically feasible,[194] would require high and widespread H_2 demand to justify the operation.

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[194] https://www.dnv.com/oilgas/perspectives/switching-city-from-natural-gas-to-hydrogen.html

Table 39 – Overview of practical considerations for temporary and permanent hydrogen refuelling stations

Temporary refuellers	Permanent station
Pressure achievable without compressors is inconsistent, impacting fuel efficiency and refuelling times	Demand needs to justify scale of investment required Specialist technicians required to maintain stations (UK H2 Mobility, 2021)

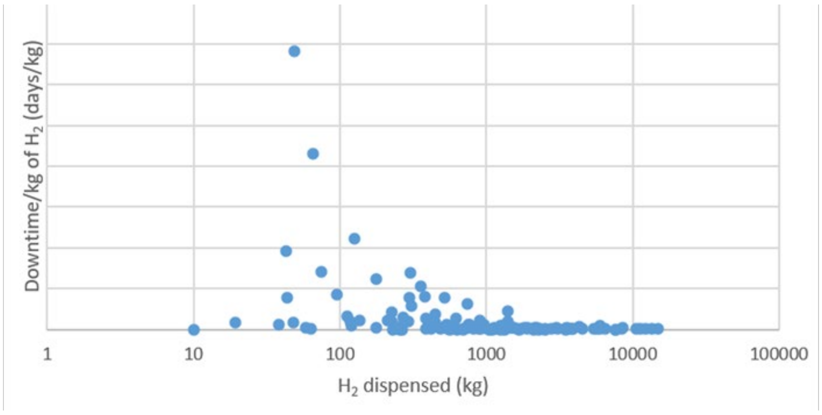

Figure 22 – Downtime per kg hydrogen dispensed for specific HRS across two EU-funded hydrogen FC cars projects. Station reliability varies depending on station utilisation (Element Energy, 2022)

3.6.2.3 *Workflow and operational changes*

In addition to the supply of alternatively powered machinery and the infrastructure to support them, the impact of the new technology on the site's workflow and operations needs to be considered. Potential impacts include:

- The need for training for operators both for machine operation and refuelling or recharging.
- Changes to workflow to accommodate longer refuelling or recharging times, or more frequent refuelling or recharging.
- Additional safety considerations for fuel storage on sites.
- Additional practical factors specific to certain solutions (e.g., the use of long high-power cables for tethered equipment).

With regards to machinery running on **HVO or B20 and hybrid** powertrains, minimal adjustments are expected to be needed considering the comparable energy densities, fuel efficiencies and fuel properties to the incumbent.

For **hydrogen powered machinery** (ICE and fuel cell), training will be required around the operation of the machinery, refuelling and on related safety measures (see sub-section 4.1.4). For high utilisation and high-power machinery, concerns were raised by stakeholders that hydrogen (and electric) machinery would not be able to store sufficient energy to operate for long periods of time, resulting in regular breaks to refuel the machine. There are also some concerns around operating hydrogen fuel cell equipment in harsher environments where they could be subjected to high levels of dust and vibrations (see sub-section 4.2.5), which could mean hydrogen fuel cell machinery is not well suited to intense work on mining sites for example.

For **tethered** equipment, training will be required around the operation of the machinery and safety measures associated with high power cables (for high power tethered machinery). Machinery will have a range limited to the length of the attached cable. Even for stationary equipment, this would have implications on large sites where the machine needs to be operated at several locations, with operators needing to reel and unreel the cables when moving the machine – some applications such as RTG cranes can use busbars instead of cables to reduce these complications. Moreover, the requirement for cables reduces the number of tethered machinery able to work nearby to prevent cable entanglement and damage (the cost of cable replacement can be in the order of £60/m, as well as the additional safety risk of damaging high power electric cables) (Paraszczak, Svedlund, Fytas, & Laflamme, 2014).

For **battery electric** machinery, training will be required for the operation and recharging of the machinery as well as safety considerations arising from using high-voltage equipment (in particular for higher power battery electric machinery). In addition, the reduced on-board energy storage compared to diesel and consequential re-charging downtime will need to be factored into workflows and processes. This will impact high utilisation and high-power machinery the most, as the limited energy density of batteries may result in these machines being unable to operate for long periods without recharging, thus requiring regular breaks to recharge the machine. There is evidence of OEMs testing and developing solutions that address the practical feasibility of their products in real construction environments covering aspects such as machine suitability for certain tasks, machine recharging and site energy supply.[195] Furthermore, opportunity charging can be integrated into existing workflows (such a solution was piloted at DP World London Gateway on fully electric straddle carriers where 30 to 180 second fast-charging cycles were used).[196] These solutions can reduce the impact of the deployment of battery electric machinery on operations, integrating the recharging of machinery into the operations itself.

3.6.3 Efficiency measures

Limited data is available regarding the deployment potential of efficiency measures (operational, machine and process). However, a deployment pathway was proposed and presented for consultation at the stakeholder workshops. The pathway was developed based on the assumption that significant efficiency gains could be made in the next 5 – 10 years (see examples given in Section 3.1.2). Following that, a slowing down in the rate of progress was assumed (once low cost or operationally easy measures are fully deployed, only higher cost or more complex measures are left). A number of stakeholders expressed agreement with the assumptions and proposed pathway. An illustration of the pathway is shown in Figure 23, which shows the modelled reduction in fuel use[197] for industrial NRMM purchased each year compared to the average fuel consumption of stock in 2020. The proposed pathway shows a slow rise in the deployment of measures until 2025, quicker adoption until 2040 and a plateau from 2040 onwards. Section 3.8.3 will present archetype-specific pathways based on the deployment pathway described here and the suitability of efficiency measure categories for each archetype.

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[195] Volvo CE develops full power of electric ecosystem with E Worksite

[196] FastCharge charging solution piloted by Kalmar Kalmar FastCharge™ shuttle carrier powers up at DP World London Gateway | Kalmarglobal

[197] The fuel reduction reported is a combination of all three efficiency measure categories: operational, machine and process.

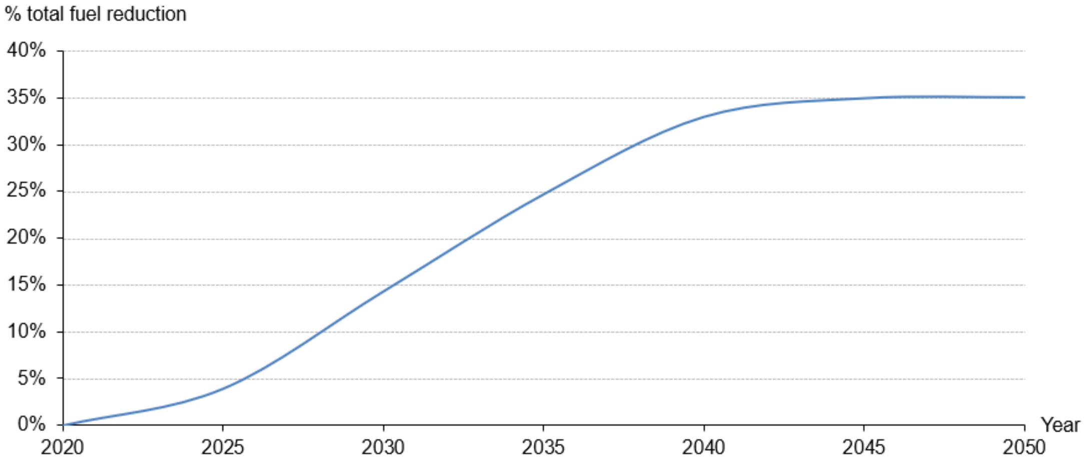

Figure 23 – Illustrative efficiency measures deployment pathway for Archetype 8 (combination of operational, machine and process efficiency measure gains)

3.7 Implications of findings on other NRMM sectors

Abatement options identified for industrial NRMM may also be applicable for other sectors. NRMM used in other sectors could be mapped into archetypes using the same methodology as for industrial NRMM, and these should have the same applicable abatement options as industrial NRMM. However, there may be sector-specific constraints or opportunities that are not present in industry, for instance farms having the space for on-site power generation or the permanency of sites in other sectors justifying investment in the necessary infrastructure.

It is beyond the scope of the report to review these options in detail; however, this section outlines the main abatement options applicable to agricultural, aircraft, or domestic NRMM as well as any potential technological crossovers with industrial NRMM and the impact on supply chains and costs.

3.7.1 Applicable abatement options and crossovers

The key abatement options and crossovers for NRMM in the agricultural, airport, and domestic sectors are highlighted in Table 40.

Agriculture

Agriculture has a wide range of abatement options, with battery electric being the most promising option for low powered NRMM. Biomethane could be a viable option for large machinery due to its fast-refuelling time and suitability for high power machinery (Royal Agricultural Society of England, 2022) but the supply of biomethane to tractors will limit the scope to users that are located in the vicinity of a CNG refuelling station (either within half an hour drive for direct refuelling or within 100 miles for delivery of a refill for an onsite portable refuelling unit). Given the difficulties of electrifying heavy machinery, electrification may be better suited to small autonomous equipment. This forthcoming process change of current agricultural practices towards automation has the advantage of requiring less electrical power, making it more suited to current infrastructure.[198] Several OEMs including JCB, New Holland and Case manufacture both agricultural and industrial NRMM which should result in technological crossovers. Examples of agricultural NRMM developments include the New Holland T6.180 biomethane tractor prototype, Fendt's hydrogen-powered tractor[199] and the CASE IH

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[198] Driving the electric revolution in AgriFood (ukri.org)

[199] Fendt shows first hydrogen tractor at German Hydrogen Summit

Autonomous Concept Vehicle (Royal Agricultural Society of England, 2022).[200] To facilitate the electrification of agricultural NRMM the UK Government has pledged an £80m investment into the Driving the Electric Revolution challenge, of which several projects have a direct relevance to the agricultural industry[198].

Airport and Domestic NRMM

Battery electric is currently the most applicable abatement option for both airport NRMM and domestic NRMM, with battery electric ground support equipment and garden and hobby equipment already commercially available (Table 40). There are several crossovers with industrial machinery types used in each sector such as forklifts in the wider aviation sector, and low power pressure washers in the domestic sector.

3.7.2 Supply chain and cost

Figure 24 shows that the industrial and agricultural sectors dominate the NRMM market in terms of fuel use. This implies that the adoption of technologies in agricultural NRMM could have an impact on the supply chain and cost by increasing the economies of scale of the adopted technologies, though it should be noted that biomethane-fuelled agricultural NRMM is not expected to lead to its adoption in other sectors (Zemo Partnership, 2022a). Conversely, due to their small market share the uptake of abatement options in the aircraft and domestic sectors will not have a significant impact on industrial NRMM.

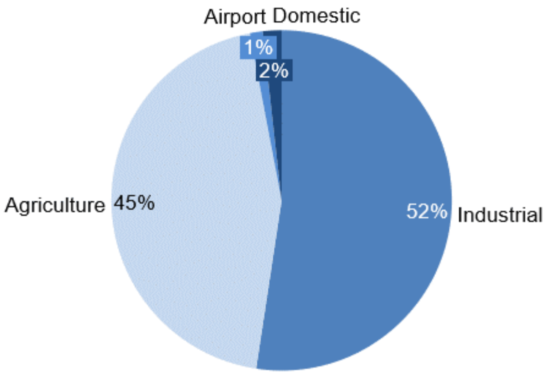

Figure 24 – Percentage sector NRMM fuel use Source: 2021 NAEI Database[201]

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[200] CNH Industrial Newsroom: Case IH Premieres Concept Vehicle at Farm Progress Show

[201] Domestic value is calculated from scaling domestic NRMM GHG emissions relative to industry in (Lajunen, et al., 2016) to industrial NRMM fuel use in the 2021 NAEI database.

Table 40 – Abatement option applicability (colour) and sector crossover (white)

Colour code	Description
🟩	Applicable option or examples found
🟨	Barriers to applicability or limited or low TRL examples
⬜	Unlikely to be applicable or no examples found

	Agriculture	Airport	Domestic
Biomethane	Biomethane is a promising option for agricultural NRMM as it can accommodate high power vehicles (150kW to 300kW+) and has comparable refuelling time to diesel. Furthermore, some farms could also use their own biomethane if their local AD plant install a refuelling site (albeit through mass balancing as biomethane would need to be injected to attract a Renewable Transport Fuel Certificate) (Royal Agricultural Society of England, 2022)	Drop-in for incumbent NRMM with CNG engines but have found no examples being used	No examples found. Very unlikely to be applicable: (bio)CNG is sold only at commercial/industrial scale and no domestic CNG NRMM developed
HVO	A drop-in fuel that can substitute diesel with no operational impact, however, due to its high production costs it is likely to be a niche option in the agriculture sector (Royal Agricultural Society of England, 2022)	A drop-in fuel that can substitute current diesel NRMM with no operational impact. Schiphol airport, the main international airport of the Netherlands, will use HVO as an intermediate solution for all ground support equipment (GSE) until they transition to electricity or hydrogen[202]	A drop-in fuel technically feasible for incumbent domestic NRMM, but have found limited examples being used, including the HVO compatible Ferris lawnmower
Biodiesel	Biodiesel is already used in some farm vehicles. Several suppliers including John Deere and Deutz offer engine configurations for B20 and higher biodiesel blends. Prior to 2030 more OEMs may move to B100 blends. Converted diesel ICE	A drop-in fuel, so technically feasible for incumbent domestic NRMM, but have found no examples being used	A drop-in fuel for incumbent domestic NRMM, examples include Toro whose diesel power products (lawnmowers

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[202] https://www.dieselprogress.com/news/schiphol-to-use-hvo-in-all-ground-support-equipment/8025347.article

	powertrains have been run successfully on B100 and could be used on farms (Royal Agricultural Society of England, 2022)		and garden tools) are all B20 compatible
Biomethane/ electric Hybrid	Biomethane machinery cannot operate for longer than 4 hours due to the requirement for large gas cylinders, so for longer runtimes (12 hours plus) biomethane-electric hybrids is an alternative that is currently being tested[203]	No examples found. Biomethane / electric hybrid is a niche technology only being tested in the agricultural sector	
Electric	Battery electric agricultural NRMM offer several advantages over incumbent such as lower operating and maintenance costs and improved efficiency. Several manufacturers are developing electric tractors and farming equipment including the Fendt e100 set to go into development in 2025, and the fully autonomous John Deere Joker concept.[204] Battery electric has the highest potential for low power machinery. For large high-powered machines the required battery would exceed weight limits and create concerns over soil compaction. There are also challenges associated with the charging infrastructure required, and reduced operation from long charge times (Van Leeuwen, 2020). However, John Deere are trialling a tethered tractor (GridCON) that offers a favourable power to weight ratio for high power applications while also having lower machine and operating costs compared to battery electric[205]	Suitable for airport GSE due to their low power, non-continuous operation, and short ranges. Deployment of electric GSE is promising because the purchasers are generally large airlines or airports with centralised procurement and maintenance departments. Battery electric GSE is currently widely operational at airports and includes equipment such as container loaders, luggage tugs and belt loaders (National Renewable Energy Laboratory, 2017)	Domestic NRMM consists of low power garden and hobby equipment such as leaf blowers and lawnmowers. Battery electric lawnmowers and leaf blowers are already commercialised
Hydrogen	Due to the fast refuelling time and relative light weight hydrogen may play a role in high power machinery. Hydrogen ICE may facilitate the transition to hydrogen fuel cells but due to rural supply limitations and the extended life cycle of agricultural machinery this is seen as unlikely before 2050 (Van Leeuwen, 2020)	Hydrogen fuel cells can be used for GSE, an example of this is FedEx who are operating 15 hydrogen fuel cell powered cargo tractors in the USA (Plug Power, 2017). There is no hydrogen GSE currently deployment	Limited examples found including a prototype hydrogen riding lawnmower.[207] Unlikely to be suitable option for domestic

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[203] AUGA group presents the first batch of the AUGA M1 hybrid tractor - AUGA

[204] https://electronsx.com/electric-farm-vehicle-directory.php

[205] https://www.fwi.co.uk/machinery/tractors/john-deere-develops-400hp-electric-cable-powered-tractor

[207] https://www.mahytec.com/en/mahytec-creates-worlds-first-hydrogen-powered-riding-lawnmower/

		in the UK, however RAF is trialling hydrogen powered GSE with DfT support[206]	NRMM due to storage and infrastructure limitations
Ammonia	Ammonia is being explored for use agricultural NRMM. Recently, Amogy demonstrated an ammonia-powered fuel cell tractor.[208] In some regions, particularly North America, ammonia is applied directly as a fertiliser, i.e., not used to create other fertilisers such as urea.[209] As a result, there is already appropriate infrastructure and health and safety protocols for storage and handling in place. This makes ammonia an attractive decarbonisation option. However, ammonia is not used directly in the UK at present.	No examples found. Very unlikely to be seen in domestic applications given the toxicity of ammonia.	
Crossover	There is a major crossover between agricultural and construction equipment with several OEMs including JCB, New Holland and Case manufacturing both. Agricultural NRMM with similar power ratings, mobility and utilisation levels (used to define industrial NRMM archetypes used in this report) are likely to have similar abatement options	Several crossovers with industrial NRMM including generators and forklifts. Airport NRMM with similar power ratings, mobility and utilisation levels (used to define industrial NRMM archetypes used in this report) are likely to have similar abatement options	Some crossovers with low power industrial NRMM machinery such as pressure washers. Domestic NRMM with similar power ratings, mobility and utilisation levels (used to define industrial NRMM archetypes used in this report) are likely to have similar abatement options

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[206] https://www.raf.mod.uk/our-organisation/units/astra/news/project-zehyda/

[208] https://amogy.co/amogy-demonstrates-first-ammonia-powered-zero-emissions-tractor/

[209] Filtered products for ‘Ammonia dir. applic. (N)’ https://www.ifastat.org/databases/plant-nutrition

3.8 Suitability of abatement options

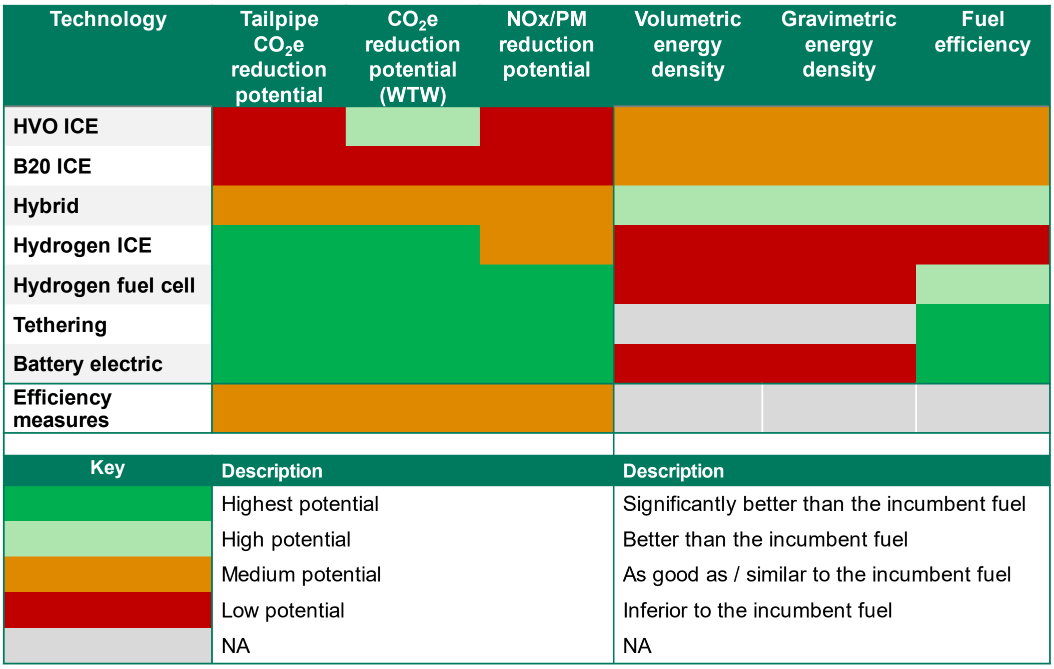
This section summarises the findings from sub-sections 3.2 to 3.6, starting with parameters that do not change for the different archetypes identified (e.g. CO_2e abatement potential, air pollution reduction potential, energy density, powertrain efficiency, refuelling or recharging solutions). These are presented for fuel-switching options and efficiency measures in sub-section 3.8.1. The powertrain availability matrix, efficiency measure suitability and practical constraint applicability are then each presented by archetype in sub-sections 3.8.2 – 3.8.4. A summary table that brings all these parameters together is provided in Appendix 9.9.

3.8.1 Summary of archetype-independent parameters

Table 41 below summarises the archetype-independent parameters discussed in previous sub-sections by fuel-switching options and efficiency measures. The CO_2e reduction potential is separated into tailpipe emissions and WTW emissions in this table, assuming a decarbonised grid or low-carbon sources for electricity and hydrogen production and government figures for biofuel emissions.[210] As noted in Section 3.5, the WTW CO_2e reduction potential of hydrogen and electric solutions is the highest, assuming access to low-carbon sources, but would be low if fossil-based hydrogen or electricity from a diesel generator were used.

Another archetype-independent factor is the readiness of hydrogen refuelling and electric charging solutions for industrial NRMM. Overviews of these are given in Table 42 below – see sub-section 3.6.2.2 for more detailed discussions. For the readiness rating of hydrogen tube trailers and drop-and-swap solutions, while NRMM-specific examples were not found, it is assumed that these solutions are applicable across sectors.

Table 41 – Summary of abatement options considered, compared to the incumbent solution (diesel). Source: ERM assessment



Technology	Tailpipe CO_2e reduction potential	CO_2e reduction potential (WTW)	NOx/PM reduction potential	Volumetric energy density	Gravimetric energy density	Fuel efficiency
HVO ICE	🟥	🟢	🟥	🟧	🟧	🟧
B20 ICE	🟥	🟥	🟥	🟧	🟧	🟧
Hybrid	🟧	🟧	🟧	🟢	🟢	🟢
Hydrogen ICE	🟩	🟩	🟧	🟥	🟥	🟥
Hydrogen fuel cell	🟩	🟩	🟩	🟥	🟥	🟢
Tethering	🟩	🟩	🟩	⬜	⬜	🟩
Battery electric	🟩	🟩	🟩	🟥	🟥	🟩
Efficiency measures	🟧	🟧	🟧	⬜	⬜	⬜

Key	Description	Description
🟩	Highest potential	Significantly better than the incumbent fuel
🟢	High potential	Better than the incumbent fuel
🟧	Medium potential	As good as / similar to the incumbent fuel
🟥	Low potential	Inferior to the incumbent fuel
⬜	NA	NA

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[210] The tailpipe rating given for HVO in Table 41 (red) considers the physical emissions at the tailpipe and is separate to the TTW emissions discussed elsewhere. Approaches differ as to where the benefits of HVO are accounted for (WTW or TTW),for the modelling carried out for this study, HVO TTW emissions used are consistent with the RTFO which defines them as 0 gCO_2e /kWh (equivalent to a green rating).A relatively low 4 gCO_2e /kWh is assigned for WTW emissions according to Defra ghg-conversion-factors-2022-full-set.xls (live.com). Emissions related to the production or disposal of machinery is not considered in this table (it was not part of the research scope).

Table 42 – Overview of industrial NRMM electric recharging and hydrogen refuelling solutions. Source: ERM assessment

COLOUR CODE	DESCRIPTION
🟩	Currently commercially available for NRMM
🟨	Currently available in other sectors or under trial/development for NRMM
🟥	Under trial/development for other sectors

Battery electric charging solutions

	Charging cable (domestic socket)	Battery swapping	Mobile charger (with battery)	Mobile charger (no battery)	Fixed charger	Vehicle to load (V2L)	Inductive charger
Charging power output	3kW	NA	100kW – 300kW	100kW – 300kW	3kW – 300kW+	<50kW	Up to 500kW
Readiness	🟩	🟩	🟩	🟩	🟩	🟥	🟨
Connection required on site	Yes	No	No	Yes	Yes	No	Yes

Hydrogen refuelling solutions

	Road – tube trailer	Mobile refuelling solutions	Drop-and-swap solutions	On-site electrolysis	Hydrogen pipelines
Delivery	Into on-site storage	Directly into the equipment	To site in reusable tanks	Into on-site storage	Direct to connected sites
Required on-site infrastructure	Storage and dispensing equipment	None (besides the mobile refueller)	Dispensing equipment	Electrolyser, storage and dispensing equipment	Dispensing, purification and/or deblending equipment
Readiness	🟩	🟩	🟩	🟨	🟥
Site suitability	Larger sites with permanent dispensing equipment	Smaller or temporary sites	Sites with permanent dispensing equipment	Larger sites which can accommodate production, storage and dispensing equipment	Depends on connection to the gas grid and availability of hydrogen

3.8.2 *Powertrain availability matrix by archetype*

The evidence presented in Section 3.4.2 shows that solutions being developed vary by OEM, with several distinct decarbonisation options emerging. Overall, the key findings are:

- HVO and B20 fuelling are the most developed technologies as they can technically be adopted now by all diesel industrial NRMM.
- Battery electric industrial NRMM have the widest range of zero tailpipe emission products commercially available across all sectors and are part of all major OEM roadmaps.
- Tethered and hybrid industrial NRMM are well established technologies in some sectors or equipment types, but further development is expected to be limited.
- Hydrogen solutions have no or limited commercially available products, other than forklifts and some generator categories, but feature in OEM testing and research and development plans so are expected to grow.

The TRL assignment of the abatement powertrain options for each archetype is shown in Table 43. The current commercial availability of industrial NRMM discussed in Section 3.4, Appendix 9.8 and the IND-database were used to determine the overall expected availability of abatement options per archetype. For most cases, the most common TRL rating within an archetype was used. In some instances, the rating was adjusted up to reflect the potential for technology transfer between archetypes, or from other sectors to industrial NRMM (see IND-database for detailed sources and assumptions).

Table 43 – Abatement powertrain option availability matrix. Source: ERM assessment

Archetype	Machinery category	Power rating	Utilisation level	HVO	B20	Hybrid	H2 ICE	H2 fuel cell	Tether electric	Battery electric
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	🟩	🟩	⬜	⬛	⬛	🟢	🟢
2		High (19-56 kW)	Medium	🟩	🟩	⬜	⬛	⬛	🟨	🟨
3	Mobile machinery	Low (<37 kW)	Low	🟩	🟩	🟩	⬜	🟨	⬛	🟢
4		Medium (37-129 kW)	Low	🟩	🟩	🟨	🟨	🟥	⬛	🟥
5		High (130-560 kW)	Low	🟩	🟩	🟩	🟥	🟥	⬛	🟨
6		Medium (37-129 kW)	High	🟩	🟩	🟨	🟨	🟥	⬛	🟥
7		High (130-560 kW)	High	🟩	🟩	🟩	🟥	🟥	⬛	🟨
8		Very high (> 560 kW)	High	🟩	🟩	🟩	🟥	🟥	⬛	🟨
9	Limited movement machinery	Medium (37-129 kW)	Low	🟩	🟩	🟩	🟥	🟥	🟢	🟨
10		High (130-560 kW)	All	🟩	🟩	🟩	🟥	🟥	🟨	🟥
11	Generators	Low (<8 kW)	Low	🟩	🟩	🟩	⬜	🟢	⬛	🟢
12		Medium (8-74 kW)	Medium	🟩	🟩	🟩	🟥	🟢	⬛	🟨
13		High (75-560 kW)	Low	🟩	🟩	🟩	🟥	🟨	⬛	🟨
14		Very high (>560 kW)	Low	🟩	🟩	🟩	🟥	🟥	⬛	🟥

TRL band	Description
🟩 8+	Currently commercially available as an option
🟢 6 – 7	Some availability now, expected to become more widely available from 2025 – 2030
🟨 4 – 5	Some limited current availability (demos/trials). Not expected as a widely available commercial option before 2030
🟥 1 – 3	Little evidence of current availability, not expected as a widely available commercial option before 2035 – 2040
⬜ NE	Technically feasible, but no evidence of ongoing development found
⬛ NA	Powertrain viewed as incompatible with archetype

The above matrix was discussed with stakeholders at the engagement workshop and there was agreement with the assigned categories. Importantly, some stakeholders suggested that technology could transfer to other similar archetypes sooner than indicated, despite limited evidence of this currently. This resulted in a change to the categorisations of hydrogen equipment (hydrogen ICE and hydrogen fuel cells) in archetype 12 being upgraded; as currently shown Table 43.

Another outcome from the workshop was that infrastructure readiness needs to be considered alongside technical readiness in determining overall deployment timeframes – see 3.8.1 for summaries of charging and hydrogen refuelling infrastructure options respectively (and Table 37 and Table 38 in sub-section 3.6.2.2 for the detailed versions). Table 46 in sub-section 3.8.4 presents an assessment of practical constraints (such as infrastructure readiness) of the different abatement options by archetype.

3.8.3 *Efficiency measures and applicability by archetype*

Following on from the examples given in Section 3.1.2, we have estimated the relevance of each category of efficiency measures and its potential to reduce the energy use of the associated industrial NRMM by archetype, this is summarised in Table 44.

Table 44 – Potential of different efficiency measures by industrial NRMM archetype. Source: ERM assessment

Archetype	Machinery category	Power rating	Utilisation level	Operational efficiency	Machine efficiency	Process efficiency
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	🟥	🟨	🟥
2		High (19-56 kW)	Medium	🟥	🟨	🟥
3	Mobile machinery	Low (<37 kW)	Low	🟩	🟨	🟩
4		Medium (37-129 kW)	Low	🟩	🟨	🟩
5		High (130-560 kW)	Low	🟩	🟨	🟩
6		Medium (37-129 kW)	High	🟨	🟩	🟩
7		High (130-560 kW)	High	🟨	🟩	🟩
8		Very high (> 560 kW)	High	🟨	🟩	🟩
9	Limited movement machinery	Medium (37-129 kW)	Low	🟨	🟨	🟩
10		High (130-560 kW)	All	🟥	🟨	🟩
11	Generators	Low (<8 kW)	Low	🟨	🟨	🟩
12		Medium (8-74 kW)	Medium	🟨	🟨	🟩
13		High (75-560 kW)	Low	🟨	🟨	🟩
14		Very high (>560 kW)	Low	🟨	🟨	🟩

Colour code	Description
🟩	Potential for efficiency measures (seen examples with reasonable efficiency improvements)
🟨	Limited potential for efficiency measures (not seen but plausible, or seen but high barrier to implementation/lower savings)
🟥	Low potential for efficiency measures (implausible or plausible with very low potential)

The suitability ratings were predominantly based on evidence presented in Section 3.1.2 and the following assumptions and observations:

- **Hand-held or moved equipment:** no evidence was found in the literature. These archetypes were consequently capped at the lower ends of examples stated in Section 3.1.2 (anti-idling operator training, eco-driving courses, etc.).
- **Mobile machinery:** evidence was found of efficiency measures being used for mobile machinery. Low utilisation archetypes (3 – 5) were assigned higher potential for operational efficiency (e.g., anti-idling), whereas high utilisation archetypes (6 – 8) were assigned higher potential for machine efficiency measures considering the equipment would be used more frequently. For process efficiency, evidence of up to 50% improvements were found to be possible in earth-moving machinery using smart grading software (see examples given in Section 3.1.2).
- **Limited movement machinery:** little evidence was found on operational efficiency measures and the suitability was matched to that of mobile machinery with similar power and utilisation ratings for archetype 9. For archetype 10, given the stationary nature and large size of these machines, the potential for operational efficiencies is limited (eco-driving, anti-idling, etc.). The machine and process efficiency measures were assigned based on the Kalmar RTG and Tadano smart crane management system referred to in Section 3.1.2.
- **Generators:** little evidence was found on efficiency measures. For operational and machine efficiency, the values were set to match the lowest-saving mobile archetype, considering anti-idling and component improvement measures would be transferrable to generators. For process efficiency, potential savings were based on the Balfour Beatty EcoNet example given in Section 3.1.2, assuming half the site-wide savings were associated with the generators. The potential reduction was then graduated by power rating, with the highest power generators have the largest reduction through efficiency measures.

Based on the discussion above, a set of archetype-specific deployment pathways for combined efficiency gains (across operational, machine and process measures) were defined as per Table 45 – see Appendix 9.6 for the approach used to develop these pathways.

Table 45 – Combined efficiency gain deployment pathways by archetype. Source: ERM projections

Archetype	Machinery category	Power rating	Utilisation level	2020	2025	2030	2035	2040	2045	2050
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	0%	0%	4%	8%	11%	11%	11%
2		High (19-56 kW)	Medium	0%	0%	4%	8%	11%	11%	11%
3	Mobile machinery	Low (<37 kW)	Low	0%	5%	15%	24%	34%	34%	34%
4		Medium (37-130 kW)	Low	0%	5%	17%	29%	41%	41%	41%
5		High (131-560 kW)	Low	0%	5%	17%	30%	42%	42%	42%
6		Medium (37-130 kW)	High	0%	5%	18%	31%	44%	44%	44%
7		High (131-560 kW)	High	0%	5%	19%	32%	46%	46%	46%
8		Very high (> 560 kW)	High	0%	5%	15%	25%	34%	34%	34%
9	Limited movement machinery	Medium (37-130 kW)	Low	0%	5%	15%	25%	35%	35%	35%
10		High (131-560 kW)	All	0%	0%	10%	20%	30%	30%	30%
11	Generators	Low (<8 kW)	Low	0%	5%	14%	22%	31%	31%	31%
12		Medium (8-75 kW)	Medium	0%	5%	14%	24%	33%	33%	33%
13		High (76-560 kW)	Low	0%	5%	15%	26%	36%	36%	36%
14		Very high (>560 kW)	Low	0%	5%	15%	26%	36%	36%	36%

3.8.4 *Practical constraints and applicability by archetype*

Table 46 provides a current rating of each powertrain and archetype combination based on the practical feasibility considerations assessed in sub-section 3.6.2 (equipment supply, refuelling or recharging and workflow or operational changes). The assigned ratings are discussed in more detail below (technologies identified as not applicable to an archetype in Table 43 were also not assessed here). The mappings shown in Table 43 (sub-section 3.8.2) and Table 46 were essential to the development of the least-cost pathways model built for this study.[211]

Table 46 – RAG rating of practical constraints and applicability by archetype for all abatement options considered. Source: ERM assessment

Archetype	Machinery category	Power rating	Utilisation level	HVO B20 & Hybrid	H2 ICE	H2 fuel cell	Tether electric	Battery electric
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	🟩	⬛	⬛	🟨	🟩
2		High (19-56 kW)	Medium	🟩	⬛	⬛	🟨	🟨
3	Mobile machinery	Low (<37 kW)	Low	🟩	🟩	🟩	⬛	🟩
4		Medium (37-130 kW)	Low	🟩	🟨	🟨	⬛	🟨
5		High (131-560 kW)	Low	🟩	🟨	🟨	⬛	🟨
6		Medium (37-130 kW)	High	🟩	🟥	🟥	⬛	🟥
7		High (131-560 kW)	High	🟩	🟥	🟥	⬛	🟥
8		Very high (> 560 kW)	High	🟩	🟥	🟥	⬛	🟥
9	Limited movement machinery	Medium (37-130 kW)	Low	🟩	🟨	🟨	🟩	🟨
10		High (131-560 kW)	All	🟩	🟥	🟥	🟨	🟥
11	Generators	Low (<8 kW)	Low	🟩	🟩	🟩	⬛	🟩
12		Medium (8-75 kW)	Medium	🟩	🟨	🟨	⬛	🟨
13		High (76-560 kW)	Low	🟩	🟨	🟨	⬛	🟥
14		Very high (>560 kW)	Low	🟩	🟨	🟨	⬛	🟥

Colour code	Description
🟩	Minimal impact on feasibility of switch
🟨	Some impact on feasibility of switch
🟥	High impact on feasibility of switch
⬛	Powertrain viewed as incompatible with archetype.

HVO and B20 were set to minimal impact across all archetypes considering that they can be used in the same powertrains as diesel industrial NRMM, require little to no new infrastructure and present no changes to workflows. Hybrid powertrains were also set to minimal impact given their similarity to incumbent powertrains and superior fuel efficiencies. Hydrogen and electric options are discussed by archetypes or machine categorisations below:

- **Hand-held or hand-moved equipment:** Tethered electric industrial NRMM are identified as amber for both archetypes due to the impact on the manoeuvrability of equipment. For battery electric equipment, a rating of green was assigned to the lower-power NRMM in archetype 1, with the heavier equipment in archetype 2 rated as amber due to the implications of heavier batteries on the manoeuvrability of these machines.

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[211] It is worth noting that the least-cost pathways model incorporates infrastructure costs to account for this aspect in the TCO calculation.

- **Mobile machinery:** The key consideration was the refuelling or recharging of industrial NRMM and associated changes to workflows depending on how duty cycles and charging or refuelling cycles line up. Consequently, the rating diminishes with higher power outputs and utilisation across all hydrogen and electric options (excluding tethering).
- **Limited movement machinery:** Both hydrogen options and battery electric were set as amber for archetype 9 and red for archetype 10 due to the duty cycle capabilities and delivering the associated quantities of fuel or energy to sites (similar ratings to archetypes 4 and 7 respectively). For tethering, archetype 9 was set to green due to the compatibility between tethering and the limited motion of these equipment types. For archetype 10, an amber rating was assigned due to the potential requirement for new or upgraded grid connections.
- **Generators:** Low-powered low-utilisation equipment in archetype 11 were assigned as green due to the relatively low energy and associated infrastructure requirements. For hydrogen options in archetypes 12 – 14 and battery options in archetype 12, an amber rating was assigned to factor in the higher energy requirements and refuelling or recharging challenges. For battery options in archetypes 13 and 14, a red rating was assigned due to higher energy requirements of generators compared to other industrial NRMM. Moreover, in the absence of a connection, the battery packs would need to be moved off-site for recharging, as opposed to hydrogen options where the fuel can still be delivered to sites.

4 BARRIERS AND ENABLERS FOR INDUSTRIAL NRMM ABATEMENT OPTIONS

This chapter discusses the barriers and enablers to the deployment of the abatement options discussed in Chapter 3. Barriers are factors which might stop or slow down the deployment of abatement options. Enablers are factors that might speed up the deployment of abatement options. Risks and opportunities of deployment are discussed in Chapter 6.

Following a comprehensive review of industrial NRMM literature and engagement with key stakeholders, key barriers and enablers were identified. These are summarised in Table 47 and described in more detail in Section 4.1.

When applied to each abatement option, a factor may be a barrier for one option and an enabler for another. For instance, air pollution reduction is an enabler for battery electric industrial NRMM but a barrier for HVO. The same applies to different market actors who each face a different set of challenges and requirements. As a result, barriers and enablers are also discussed for each market actor type (at the end of Section 4.1) and each abatement option (in Section 4.2).

The chapter ends with a review of approaches to policy and infrastructure deployment internationally, to provide key learnings from progress that has been made outside the UK (Section 4.3).

Table 47 – Summary of barriers and enablers to the deployment of industrial NRMM abatement options identified in literature and confirmed through stakeholder engagement

	Barrier or enabler to deployment	Short description
Barriers	Immaturity of abatement options	The low TRL of abatement options contributes to the: • Limited availability of abatement options and of dedicated infrastructure solutions; • High costs and uncertainty in the residual value of abatement options; • Lack of awareness of abatement options; and • Lack of supply chain skills for novel powertrains and infrastructure.
	Limited fuel supply and infrastructure	Low availability of the required fuels and infrastructure may limit deployment of abatement options.
	Performance challenges	Mismatched technical performance relative to requirements and operational difficulties.
	Safety challenges	Additional health and safety requirements and concerns related to the decarbonisation solutions.
Either	Economic and financial differences or incentives	Changes in the TCO of abatement options relative to the incumbent NRMM may impact access to finance for different market actors and therefore uptake of abatement options.
	Policy and regulations	The role current and future policy may play in targeting industrial NRMM emissions or specific abatement options.
Enablers	Carbon reduction ambition	Company targets set at each stage of the industrial NRMM market for scope 1,2 and 3 emissions.
	Air and noise pollution reduction	Reduction in air and noise pollution associated with some abatement options is particularly advantageous in some industrial NRMM applications.
	Transition technologies	Fuel and infrastructure that may be used in the transition period to enable zero-emission options in the future.

4.1 Barriers and enablers

The following section describes the barriers and enablers to the deployment of abatement options. These were identified as part of the literature review, interviews, and workshops with stakeholders.

4.1.1 Barrier – Immaturity of abatement options

This barrier has four distinct topics, all related to the low maturity of abatement options: 1) there is limited availability of abatement options, 2) high costs and uncertainty in the residual value, 3) potential buyers have limited awareness of options and 4) there are gaps in the supply chain. These are discussed in turn below.

4.1.1.1 Limited availability of abatement options and related infrastructure

The vast majority of industrial NRMM continues to rely on diesel, although OEMs are increasingly offering fuel-switching options, particularly battery electric (see sub-section 3.4.2). The range and quantity of abatement options supplied is key. In 2019, the lack of practical alternatives was quoted as one of the top reasons for businesses not switching to red diesel alternatives (IFF Research, 2019). In stakeholder interviews conducted as part of this study, the shortage of options from OEMs was still cited as a barrier to decarbonisation by industrial NRMM users.

> **‘A general barrier is the lack of low emission equipment being supplied by manufacturers.’** User

Hesitancy to purchase new low-carbon industrial NRMM is likely exacerbated by the long lifetimes of industrial NRMM and therefore the long-term consequences of investment decisions for purchasers (Komatsu, 2021). Further up the supply chain, several OEMs stated they would not invest in developing abatement options until customer demand becomes apparent. With no clear first mover in the market, decarbonisation is being delayed.

> **‘We have no plans for full electric, HVO or hydrogen. Investment is driven by regulation and customer demand.’** OEM

As many abatement options are not fully commercial, there are a range of requirements for fuel and infrastructure providers. For example, the required hydrogen pressure may vary across types of industrial NRMM, models and manufacturers, and the charging solutions might be specific to industrial NRMM brands instead of being universal.

> **‘A key enabler is to standardise technical standards for types of charging connectors and refuelling nozzles.’** Lease and hire company

The lack of standardisation also creates challenges when designing, servicing, repairing and remanufacturing; this impacts OEMs and end of life companies as well as users, lease and hire companies who carry out maintenance. The stakeholder workshop revealed how recent advances in hydrogen fuel cell technology have coincided with changes in the dimensions of the fuel cell. Not only does this make finding replacement fuel cells for older machinery difficult, but it also means new fuel cell machinery must be redesigned rather than using previous designs and simply replacing the fuel cell. In turn, this may increase R&D and production costs.

4.1.1.2 High costs and uncertainty in residual value

With many of the fuel switching options not fully commercialised, production volumes for these NRMM options are low. As economies of scale cannot be achieved, manufacturing costs are high. This compounds an existing issue in the industrial NRMM sector: production volumes for incumbent NRMM are already low compared to other vehicle sectors due to the large number of machine types, variations in size, and differences in use case (McKinsey & Company, 2016). In the long term, as abatement options are advanced and volumes increase, the cost of manufacture will likely fall.

There is also uncertainty in the residual value of machinery after its first life, which can be exacerbated by the uncertainty in the lifetime of new powertrains (due to battery degradation or fuel cell lifetimes for example).[212] At the end of their first life, NRMM are typically either remanufactured and sold on the second-hand market in the UK, exported or scrapped (with any metal components recycled). Several stakeholders emphasised how future residual value was important in NRMM purchase decisions.

'If a machine doesn't have residual value [at the end of its first life], people won't purchase it.' Sector specialist

Novel powertrains will also introduce uncertainty into the purchase decisions, at least during the early stages of adoption. As seen from the interview extract below, some parts of industry are taking early action. However, it remains an area of significant uncertainty which, if unresolved, could contribute to delays in purchasing low-carbon industrial NRMM.

'Residual values for low and zero emission NRMM are uncertain…[We] are conducting workshops to advise lenders on how to value second-hand equipment.' Lease and hire company

4.1.1.3 Lack of awareness of abatement options

In a 2019 survey for HMRC, two thirds of companies surveyed had not considered any non-diesel alternatives for their machinery. Users not knowing enough about the alternative options and a perceived lack of viable alternatives were the two main reasons behind this (IFF Research, 2019). The survey was not replicated as part of this study, but engagement with stakeholders suggested that awareness of abatement options has increased since the 2019 survey. However, there remains room for improvement as familiarity with abatement options was not equal across stakeholders. During interviews and workshops, the risk of choosing the 'wrong' option was cited as a reason that purchasers of industrial NRMM were delaying adoption of new technologies. How this could best be tackled was more contentious. Some OEMs felt clear direction from government was critical. Other market actors felt that technology neutral policy was paramount, and the market should be left to decide, whilst others advocated for enough steer to avoid choosing the wrong technologies but not picking winners. The role of policy is discussed further in section 4.1.6. Initiatives such as the Centre for Low Emission Construction (CLEC) aim to address this gap by testing and evaluating emerging technologies to provide independent evidence to sector actors.[213]

4.1.1.4 Lack of supply chain skills

Novel powertrains require new skillsets across the supply chain. Stakeholders in the workshop and interviews saw the shortage of skills as an important barrier to the development and deployment of abatement options. Based on their input, this applies to:

- **R&D and design**: some abatement options require significant redesigning of machinery due to differences in powertrain dimensions, weight and installation.
- **Production:** stakeholders were sceptical that existing production lines would be suitable for abatement options.
- **Operation and refuelling or recharging:** users will require training to safely operate machinery. Examples of this include safety around high voltage tethered machinery, how to refuel and recharge machinery, and the safe storage and handling of hydrogen on site.
- **Servicing and repairs:** the maintenance requirements of electric machinery will differ from that of diesel NRMM, requiring companies to retrain employees.

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[212] Battery degradation or fuel cell lifetimes were not brought up explicitly as a concern by stakeholders, however ERM believes uncertainty around these, especially if the warranty periods are not judged long enough by users, could affected residual value once the technologies become more established.

[213] https://clec.uk/about/what-clec

- **End of life:** decommissioning, scrappage and recycling skills may also differ. However, depending on future recycling policy, the responsibility may not fall on existing end of life companies. This is discussed later in the policy sub-section.

If multiple decarbonisation powertrain options are in use across the sector, this may compound the issue as employees across the supply chain are required to train for each powertrain options. When abatement options comprise the majority of the industrial NRMM stock, this may create opportunities for companies to specialise (e.g., a maintenance company that exclusively works on battery electric). However, this is unlikely to occur at scale soon, which makes a skills' bottleneck likely.

'Skills would be a significant supply chain constraint if net zero technology adoption is accelerated.' Sector specialist

4.1.2 *Barrier – Limited fuel supply and infrastructure*

Availability of fuel and infrastructure in the UK directly impacts fuel and infrastructure providers, NRMM users, and clients and site owners in the case that they are responsible for fuel purchase. A lack of availability may also be a barrier to development for OEMs and adoption for lease and hire companies due to concerns that the users will not be able to access the required fuel. Particularly in the construction sector, NRMM may be regularly used across multiple sites and require supporting infrastructure at each site (see sub-section 2.1.4). Limited infrastructure issues are exacerbated in this case.

'I cannot emphasise enough the importance of supporting infrastructure for electric or hydrogen solutions.' User

Uptake of renewable fuels in the UK is supported by the RTFO, where large fuel suppliers must ensure a minimum percentage of their fuel supply comes from renewable sources. This includes drop-in and non-drop-in renewable fuels and hydrogen (Department for Transport, 2021). To illustrate the fuel supply challenge, Table 48 compares the supply required (in TWh) for each fuel or energy vector (if they were to power all industrial NRMM in 2050) with the current supply. It shows that, for all energy vectors except low carbon electricity, there are, or will be, supply limitations. Beyond production, hydrogen and electricity have added constraints around the distribution, which is discussed in more detail in sub-section 3.6.2.2.

Table 48 – Comparison of theoretical maximum demand for alternative fuel with current supply

	If powering all industrial NRMM in 2050[214]	Total current UK supply in transport (except electricity)	Comments
Drop-in fuels	14 TWh	2.5 TWh for HVO. 0.2 TWh for other drop-in diesel[215] (Department for Transport, 2023)	If drop-in fuels were used for all industrial NRMM, a large increase in supply would be required (either from biological sources or low-carbon hydrogen for e-fuels).
FAME for B20	3 TWh	13 TWh (Department for Transport, 2023)	B20 is not a full decarbonisation option, as 80% of the fuel is of fossil origin.
Low carbon hydrogen	15 TWh	0.0012 TWh (Department for Transport, 2023)	Even if the UK Government's target of 10 GW of low-carbon hydrogen[216] (up to 88 TWh if the load factor was 100%) by 2030 is met and a sufficient amount is made available for transport, constraints around distribution of hydrogen will also need to be addressed.
Low carbon electricity	6 TWh	170 TWh in 2021 (including nuclear, 120 TWh excluding nuclear) (Department for Energy Security and Net Zero, 2022)[217]	Main constraint is not low carbon electricity production but distribution and connecting to the network (cost and lead time). Worst-case theoretical peak power demand nationally would be about 5 GW in 2050[218]

4.1.3 Barrier – Performance challenges

Abatement options such as battery electric do not match the incumbent solutions on all technical specifications, as shown in sub-section 3.2. In a 2021 study, insufficient onboard energy storage for duty cycle requirements was identified as a barrier to adoption by stakeholders across electric and hydrogen-based abatement options (E4tech & Cenex, 2021). Customer concerns about duty cycles

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[214] As calculated by the least-cost pathways model. For hydrogen, assuming that all generators are fuel cell and everything else is H_2 ICE. For electricity, assuming that hand-held and limited motion machinery are tethered, with everything else battery electric.

[215] 'Other drop-in diesel' encompasses the 'development diesel' in the RTFO report. This includes a variety of alternative renewable diesel solutions, of which 'e-diesel' is a small percentage.

[216] https://www.gov.uk/government/publications/uk-hydrogen-strategy

[217] These numbers are for the total electricity use in GB as the use of low carbon electricity for transport is not measured or reported.

[218] This is a theoretical upper bound, if all battery electric industrial NRMM charge at the same time for 2 hours a day, across the nation. In reality, the peak is likely to be much lower as many will be able to charge slower overnight, and any rapid charging is unlikely to line up on a national level. This compares to a winter national peak of around 55GW in GB, but these two peaks would be unlikely to be additive (unlikely to be at the same time of the day).

have been recognised by OEMs; commercially available abatement options typically suggest the same or similar performance to the incumbent. Marketing materials include runtimes which refer to a 'day's work' or a 'full shift'.[219] However, concerns persisted during stakeholder engagement and present a barrier to adoption for NRMM users. This barrier also applies to OEMs if intrinsic characteristics of the technology mean that they are or feel unable to meet the user's requirements. Opportunities to address concerns by understanding duty cycles in detail are discussed in sub-section 6.1.4.2.

'Flexibility is really valued…there is no in-built preference for a power source, but need to show that the alternative solution is better or equal to the current power source.' OEM

4.1.4 Barrier – Safety challenges of storage and distribution

Some abatement options may also bring additional safety requirements for production, operation, fuel storage, handling, and refuelling or recharging. This impacts OEMs, fuel and infrastructure providers, industrial NRMM users and site owners and clients who may be responsible for meeting health and safety regulations. Some stakeholders felt this was an important barrier to deployment whilst others saw it as a minor concern.

'We have a significant training and upskilling need to observe new protocols [for electric and hydrogen options]. However, it is not that significant a barrier for us.' User

Stakeholders cited safety concerns and uncertainty over procedure as a barrier to adoption of some abatement options. There was also some confusion over which set of regulations applied to hydrogen storage in NRMM contexts. Clarification and guidelines on the safety regulations and procedures for new technologies were identified by some as areas for government intervention. From stakeholder engagement, it appears that the issue is a combination of insufficient awareness of relevant regulation combined with a lack of sector-specific guidance. At the time of writing, the Construction Leadership Council's roadmap for zero diesel sites is still under development. However, the draft document made available for public consultation indicates the Council aims to publish safety guidance on electricity-based solutions in 2023 and to develop guidance with the Health and Safety Executive on the safe delivery, management and use of hydrogen on site (CLC, 2022).

'[There is a] low understanding of the safety impacts of hydrogen – who sets the requirements?' OEM

4.1.5 Barrier or Enabler – Economic and financial differences or incentives

In some cases, abatement options may offer lower TCOs than the incumbent solutions, particularly as fuel costs contribute significantly to the TCO (Argonne, 2021). This will impact actors who own industrial NRMM, which will include users, lease and hire companies particularly if the proportion of upfront costs to fuel operating costs is altered relative to the incumbent. For example, if the capex of an abatement option is higher than the incumbent, lease and hire companies will offset this higher cost by raising lease payments. However, some stakeholders highlighted that smaller industrial NRMM purchasers, both users and lease and hire companies, may not have sufficient capital to purchase abatement options with higher upfront costs.

Another potential economic barrier is the traditional market structure involving users, clients, lease and hire companies. In construction, a common business model involves lease and hire companies owning the machinery which is then leased to construction companies who use the machinery. These machinery users are not always responsible for the purchase of the fuel or energy consumed by the machine. Instead, it is common for the fuel or energy to be paid for by the client who commissions the construction. Therefore, the operators, who have some control over the amount of fuel consumed, are

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[219] Examples include the Sandvik TH665B, Caterpillar 320 Z-line, and JCB 30-19E Teletruk

not necessarily financially incentivised to use less fuel[220]. In the same vein, rental and hire companies are not incentivised to choose more efficient machines for their fleets as they are not responsible for fuel purchase. This finding from the stakeholder engagement is important as the UK has a higher proportion of renting and hiring of industrial NRMM compared to other countries (as discussed in section 2.2).

> **'There is a trend towards rental. Unfortunately, there may not be the incentives for rental fleet owners to select higher efficiency machinery as they do not pay the fuel bill and can't make a TCO judgement like fleet owners/operators.'** User

As a result, the decision-making power is dispersed between different actors and there may be some distance between decisions made by actors and their consequences. This could delay deployment of abatement options by creating more steps and requiring consensus from a wider range of stakeholders. Alternatively, this could help spread the costs of decarbonisation, depending on the relative changes in TCO of the abatement option to the incumbent.

> **'There are no impacts expected on insurance premiums.'** Financing firm

Some NRMM users mentioned higher insurance costs as a barrier to adoption of abatement options. However, interviews with insurance and financing companies suggested that this was unlikely to be an issue in the long term.

> **'At the beginning of adoption of unproven technology, we may see some more conservative estimates for insurance, i.e. higher premiums.'** Financing firm

4.1.6 Barrier or Enabler – Policy and regulations

4.1.6.1 Policy for OEMs, lease and hire companies, and users of NRMM

Beyond air pollution regulations detailed in Appendix 9.4, UK decarbonisation policy for NRMM has largely been limited to the removal of the red diesel rebate for selected sectors. NRMM remain one of the only transport-related areas without a national net-zero target date, and that there is no definition of a low emission NRMM (Zemo Partnership, 2022). Certainty and clarity on sector decarbonisation targets and timelines were consistently mentioned by stakeholders as key enablers of adoption. Public procurement policy could also play a role in initiating action from the industry.

An area of lower consensus was whether policy should help the industrial NRMM industry choose the 'best' abatement options. In interviews, technology neutral policy was cited as a constraining factor as it was felt that customers are concerned about the risk of choosing the 'wrong' technology. However, several stakeholders in the workshops viewed technology neutrality as a crucial aspect of any future industrial NRMM policy. Others felt that guidance should be given to 'avoid backing the wrong horse' but that any government intervention should stop short of picking winners.

> **'A technology neutral approach should support a level playing field. Established technologies have a natural advantage, so government intervention is required to level the surface.'** Sector specialist

Some stakeholders felt that technology neutral policy did not necessarily mean treating all technologies equally, as some technologies were perceived to have a head start due to interventions in other sectors. For example, electric options may benefit from developments in electric vehicles for light duty vehicles. These stakeholders felt policy intervention is needed to create supportive ecosystems for other technologies, independent of the end use case. In one example given, UK Government hydrogen strategy was perceived as focused on burner operations for heating and replacing piped natural gas supply. The alternative would be creating a sector-agnostic supply of

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[220] It is not known whether NRMM users who do not purchase their own fuel bear the costs of fuel consumption in a more indirect way. No evidence could be found to support or disprove this.

green hydrogen that would not necessarily require a gas network connection to access. This relates to the previous sub-section on confidence in fuel supply and infrastructure; policy does not necessarily need to target industrial NRMM specifically to address barriers to deployment of abatement options.

At the local authority level, the Greater London Authority (GLA) restricts the use of older, highly polluting NRMM within greater London: all NRMM above 37 kW are required to be at least Stage IIIB (Stage IV on construction sites in some areas). The GLA has also set increasingly stringent standards for 2025 and 2030, culminating in the requirement for zero emission machinery from 2040 (Cleaner Construction for London, 2022). Whilst emissions here refer to air pollutants such as NOx, such reductions are not possible from improvements in the incumbent diesel-powered machinery, nor from low carbon liquid fuels such as HVO and B20 (and limited from hydrogen ICE, discussed later). Instead, abatement options such as hydrogen fuel cell, BEV and tethering options will be best placed to meet these standards. Air pollution reduction is discussed later in sub-section 4.1.8.

4.1.6.2 Policy for fuel and infrastructure providers

As discussed previously, uptake of renewable fuels in the UK is supported by the RTFO, where large fuel suppliers must ensure a minimum percentage of their fuel supply comes from renewable sources. This minimum percentage increases year on year until 2032, after which the proportion remains constant. The obligation can be split into two targets – the 'main' obligation which covers all renewable fuels, and the 'development fuel' obligation, which covers fuels defined as those 'which need greater support and fit the UK's long-term strategic needs'. The development fuel target was created to incentivise novel fuel pathways which need greater support and fit the UK's long-term strategic needs. As such, development fuels are rewarded with double Renewable Transport Fuel Certificate (Department for Transport, 2023). The level of support from the RTFO for each of the abatement options explored in this study varies; for each option, the case of fuel is discussed later in sub-section 4.2.9, in addition to other technology-specific fuel and infrastructure policies.

4.1.6.3 Policy for end of life

If the equipment is exported abroad, it is subject to the policy of its destination. As seen in Figure 25, the EU is a major destination for industrial NRMM exports, representing 46% of total industrial NRMM export value in 2021 (HMRC, 2023).[221] Stakeholders expressed concerns about how the export of second-hand NRMM to the EU may be affected by Brexit and the recently approved EU Battery Regulation.[222] This regulation will see extended producer responsibility (EPR) applied to producers of battery products (for batteries over 2 kWh, including battery electric NRMM), making the producers responsible for the waste collection and management of the batteries (EU Commission, 2020). This will apply to OEMs or re-sellers based in the UK who sell battery electric NRMM into the EU market. Stakeholders expressed concern that such legislation could disrupt NRMM trade flows. However, further analysis is required to be able to fully understand the impact of such legislation if adopted; a lack of familiarity with the yet-to-be adopted regulation could be a substantial part of the barrier.

Separately, if the UK were to adopt similar legislation, it could add an additional step to the decommissioning and scrapping process of battery electric NRMM (and hybrid and fuel cell NRMM, given the on-board battery) operating in the UK as OEMs collect and dispose of the battery. Whilst batteries are the current focus, efforts to promote a more circular economy could lead to similar requirements for other powertrains and components in the future.

> **'[Regarding the impact of abatement options on the end of life process] There are a lot of unknowns. New markets and little information on scenarios and potential impact.'** User

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[221] HMRC data does not split the value by new and second hand so only the total value is available.

[222] Council adopts new regulation on batteries and waste batteries - Consilium (europa.eu)

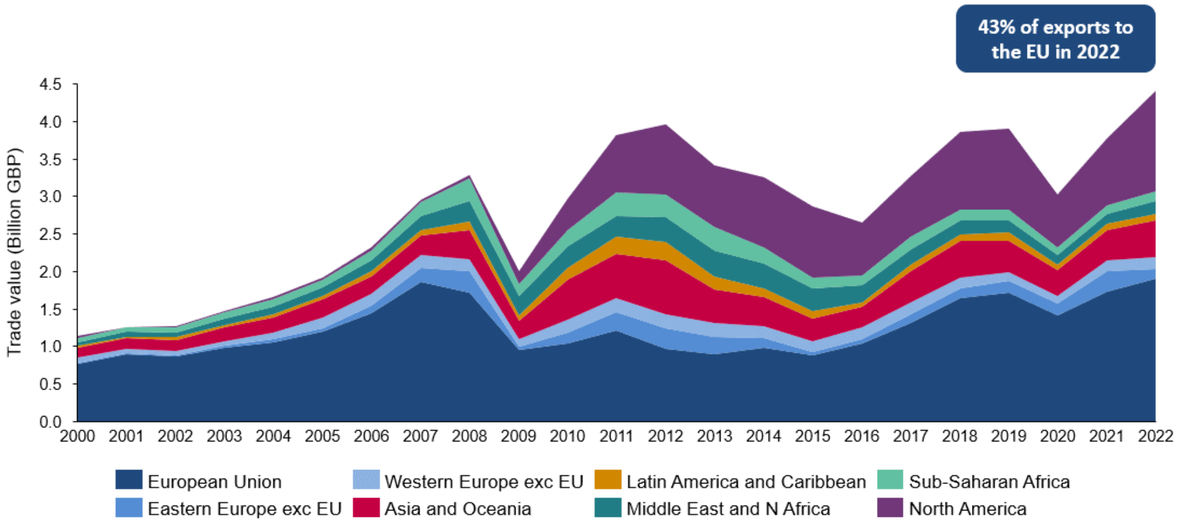

Figure 25 – Value of industrial NRMM export from the UK since 2000 to EU and non-EU destinations (HMRC, 2023) – includes both new and second hand NRMM[12]

4.1.7 Enabler – Carbon reduction ambition

In addition to policy and targets set by government, all market actors increasingly face pressure to set net zero targets from clients, supply chains, and investors as well as internally. A recent study into ESG in the mining sector found that 63% of investors 'would be willing to divest or avoid investing in mining companies that failed to meet their decarbonisation targets' or pursued inadequate decarbonisation targets (Accenture, 2022). Figure 26 illustrates this progression as well as highlighting Science Based Targets (SBTs) set by relevant market actors and validated by the Science Based Targets initiative (SBTi).[223]

> **'[We] are keen to support customers in their net zero journeys but are customer-led and will support alternative fuel assets when our customers ask us to.'** Lease and hire company

The coverage of the market by SBTs remains uneven with several key industrial NRMM OEMs with UK production centres yet to engage.[224] SBTi also allows a 'committed phase' where companies have 24 months to submit targets for validation; key companies including JCB, Sandvik and Case New Holland are at this stage (as of January 2023). Of company targets analysed, users of industrial NRMM tended to have more quantitative carbon reduction targets than NRMM OEMs, although not all had been submitted to or validated by SBTi. Figure 27 displays the key announcements and timelines for scope 1 & 2 reduction targets by these NRMM users. This distinction between market actors is likely the consequence of several factors including the difficulty of estimating scope 3 emissions versus scopes 1 and 2. However, despite having more defined targets, NRMM users tended to have more ambiguity in the actions needed to achieve their targets. Engagement with stakeholders confirmed the decision paralysis facing the NRMM market because of high uncertainty in the performance, availability, infrastructure, total cost of

> **'[Our] focus is on air quality; we have no strategy in place for net zero.'** User

> **'The aim is for net zero by 2035 but this is driven by client goals and contracts.'** User

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[223] SBTi is a network of international non-governmental organisations (United Nations Global Compact, World Wide Fund for Nature, World Resources Institute, Carbon Disclosure Project). The SBTi is a leading body for certifying 1.5°C-aligned company emissions reduction targets and the only corporate standard for certifying long-term net zero emission targets. Ambitious corporate climate action - Science Based Targets

[224] Based on ERM analysis of 14 NRMM OEMs and 23 NRMM users from construction, mines and ports. The companies were searched for on SBTi for announced SBTs, and any other commitments found on the companies' websites were noted.

ownership and policy for abatement options as well as dependence on other parts of the supply chain.

Ultimately, each industrial sector (construction, waste, mining etc.) will have market actors who are best positioned to be the first mover in the sector's supply chain. For example, construction companies will likely adapt to meet procurement requirements set by clients who commission the construction. However, as discussed in sub-section 4.1.1, initiating this first movement is proving challenging.

In the case of incumbent diesel fuel and infrastructure providers, ambitions to decarbonise operations may lead to increased production of HVO and biodiesel. An example of this is HVO production at the Phillips 66 Humber Refinery (Phillips 66, 2022).

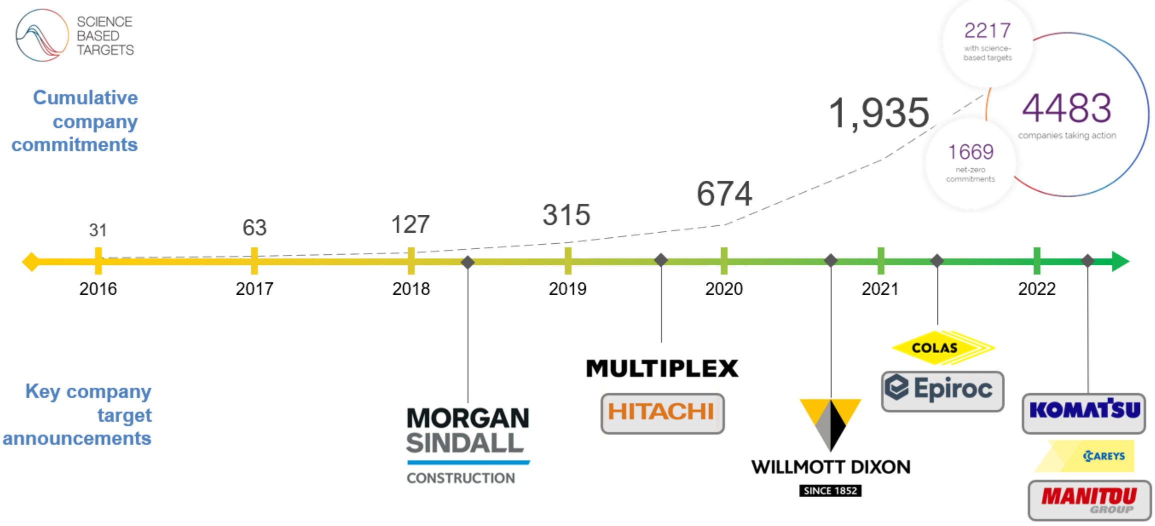

Figure 26 – A non-exhaustive timeline of Science Based Targets as of February 1st, 2023. Source: SBTi Target Dashboard.[225] Highlighted target announcements cover scopes 1 & 2 for industrial NRMM users and scope 3 for industrial NRMM OEMs (OEMs are indicated with a grey box).

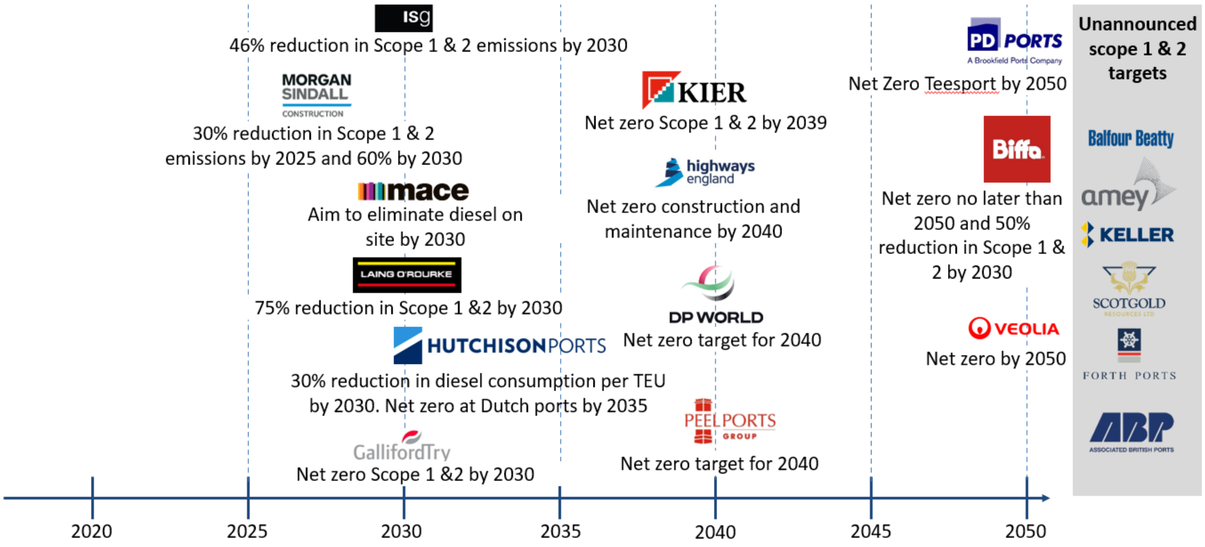

Figure 27 – Emission reduction targets announced by industrial NRMM users[226]

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[225] Science Based Targets, '*Companies Taking Action*', *https://sciencebasedtargets.org/companies-taking-action (Accessed: 30.01.2023)*

[226] Targets taken from latest publicly available annual reports and sustainability reports.

4.1.8 Enabler – Air and noise pollution reduction

Historically, much of the regulation applicable to NRMM has focused on reducing air pollution, with OEMs required to produce engines meeting power-dependent standards. NRMM was identified as a key area in Defra's 2019 Clean Air Strategy, accounting for 7.3% of NOx emissions in London alone (Greater London Authority, TfL Air Quality, 2023). Reducing impact on air quality continues to be a key aim across sectors; machinery users tend to be drawn to abatement options that align more closely with this aim. This is relevant to the mining and quarrying sector as additional ventilation and air pumping are required when mining underground to make the environment safe for workers. In this case, the additional energy required for ventilation represents a tangible financial cost to NRMM users (often the site owners in these sectors) and the benefits of reducing emissions of air pollutants are widely marketed as part of battery electric, tethered, hybrid and fuel cell abatement options.[227] Zero-tailpipe emission options are also advantageous for indoor applications, for example, forklifts in warehouses. As the current regulations focus on reducing air pollution, the adoption of technologies which reduce air pollution will be enabled as these technologies address both decarbonisation and air quality regulations. This preference for zero emission powertrains where possible was verified during stakeholder engagement.

> **'Our customer base is driving decisions to change to other propulsion forms on the basis of carbon emissions throughout the supply chain, as well as local air pollution emissions.'** Lease and hire company

> **''We want no tailpipe emissions on-site at all.'** User

In addition to air pollution, some abatement options may prove more attractive as they can reduce noise pollution and unwelcome levels of heat. However, others such as hydrogen ICE, may produce higher external noise levels than diesel fuelled engines – again, a consideration which may be important in certain areas with low acoustic pollution limits for NRMM (Arana, Martín, Urroz, & Dieguez, 2022). In stakeholder engagement, air pollution was largely seen as more important than noise pollution. Noise reduction potential seemed to be viewed as an additional benefit rather than a driver for change in decision making.

4.1.9 Enabler – Transition technologies

For some alternative powertrains, there are fuels and infrastructure that industrial NRMM users can use in the transition period to enable the deployment of these powertrains in the future. For example, hydrogen fuel cells can be run on fossil fuel-based hydrogen until low-carbon hydrogen is readily available, or diesel generators can be used to power or recharge electric machinery. However, there is a risk associated with these transition approaches if they are used long term rather than as a stepping stone to lower emission options. Another example is the 'fuel-agnostic' engine for heavy-duty off-highway applications recently announced by Cummins. The engine can run on diesel, gasoline, natural gas, biomethane, propane or hydrogen with some minor changes in components compared to full retrofit.[228]

4.1.10 Summary of barriers and enablers

Table 49 summarises the impact of the identified barriers and enablers on market actors, as discussed throughout section 4.1. There is limited literature available on the barriers and enablers for each market actor, particularly regarding the magnitude of impact. Therefore, the assessment for each market actor is based on insights that could be found in literature, stakeholder engagement findings, and ERM judgement based on experience in decarbonisation of other forms of transport. Whilst all market actors are somewhat impacted by the barriers and enablers discussed, only the

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[227] Epiroc, '*Underground electric loaders*', https://www.epiroc.com/en-sa/products/loaders-and-trucks/electric-loaders

[228] Cummins, '*Cummins unveils industry-first fuel-agnostic internal combustion powertrain solutions*', https://www.cummins.com/news/releases/2022/02/14/cummins-unveils-industry-first-fuel-agnostic-internal-combustion

market actors directly impacted are highlighted in Table 49. The assessment should be taken as indicative of the applicability and not definitive.

Table 49 – Summary of barriers and enablers to deployment of abatement options and their applicability to NRMM market actors

	Barriers and enablers	OEMs	Users	Lease and hire companies	Site owners /clients	Fuel & inf. providers	End of Life actors
Barriers	Immaturity of abatement options	■	■	■		■	■
	Limited fuel supply & infrastructure		■		■	■	
	Performance challenges	■	■				
	Safety challenges	■	■		■	■	
Both	Economic and financial differences or incentives		■	■			
	Policy and regulations	■	■	■	■	■	■
Enabler	Carbon reduction ambition	■	■	■	■	■	
	Air and noise pollution reduction	■	■		■		
	Transition technologies		■				

4.2 Summary by abatement option

This section discusses the applicability of identified barriers and enablers to the deployment of each abatement option today. A summary table is provided at the start of each sub-section. The justification and method for determining the colour code for each barrier and enabler is shown in Table 50. There is limited literature available on barriers to and enablers of deployment of industrial NRMM abatement options. Therefore, the colour ratings represent ERM’s judgment based on insights that could be gained from literature and validation of hypotheses during stakeholder engagement. These ratings are indicative and will likely change as the abatement options progress technically and commercially.

The ratings given in the following sub-sections (and summarised in Table 59, sub-section 4.2.9) are for machinery which is not considered hard-to-deploy. For machinery which is hard-to-deploy, the ratings will be the same for drop-in fuels, fuel blend and hybrid. However, for hydrogen and electric technologies, the barrier associated with fuel supply and infrastructure will be significantly larger, and the 'financial differences or incentives' may be a larger barrier (if more expensive electricity or hydrogen supply solutions are required).

Discussion of the costs, maturity and carbon reduction potential of each abatement option can be found in sections 3.3, 3.4 and 3.5 respectively. Detailed discussion of these barriers and enablers is not included in the following section as a result, other than high-level discussions of costs where appropriate.

Table 50 – Method for determining rating for each barrier and enabler for each abatement option. This is used throughout section 4.2.

	Barriers and enablers	**Enabler**	**Not applicable or neither a barrier nor an enabler**	**Potential barrier**	**Major barrier**
Barriers	Immaturity of abatement options	NA	Commercially available across most archetypes	Across all archetypes, modest commercial availability.	Across all archetypes, low commercial availability. See section 3.4 for details.
	Limited fuel supply & infrastructure	Reduces barriers (efficiency measures only)	Minimal issues relating to fuel supply or infrastructure.	Limited fuel supply or limited infrastructure.	Limited fuel supply and infrastructure.
	Performance challenges	NA	No or minimal alterations to site operations required.	Some alterations to site operations or maintenance required.	Major alterations to site operations required.
	Safety challenges	NA	No change	Some additional health and safety risks	Significant increase in health and safety risks
Both	Economic and financial differences or incentives	Likely to have lower total cost of ownership (TCO) than the incumbent if deployed now (before 2025)	Likely to have a similar TCO if deployed now (before 2025)	Likely to have a slightly higher TCO if deployed now (before 2025)	Likely to have a significantly higher TCO if deployed now (before 2025)
	Policy and regulations	Policy support exists where required.	NA	Additional policy support seen as necessary for one or two of fuel, powertrain,	Additional policy support seen as necessary for all of fuel, powertrain, and

				or infrastructure provision	infrastructure provision
Enabler	Carbon reduction ambition	Significant Well to Wheel CO_2e reduction	Minimal reduction	NA	
	Air and noise pollution reduction	Zero tailpipe emissions, some noise reduction	Has tailpipe emissions, no reduction in noise levels	NA	
	Transition technologies	There are existing technologies for this abatement option, see sub-section 4.1.9 for definition.	No enabling technologies exist for this powertrain or are not required.	NA	

4.2.1 Drop-in fuels

Table 51 – Summary of barriers and enablers for deployment of drop-in fuels today. Refer to Table 50 for colour code.

HVO is used to represent other drop-in biofuels and RCFs as they share similar barriers and enablers. E-fuels are separated due to the difference in characteristics.

Drop-in fuels: barriers and enablers today					
	HVO	**E-fuels**		**HVO**	**E-fuels**
Immaturity of abatement options	⬛	🟥	Policy and regulations	🟩	🟩
Limited fuel supply & infrastructure	🟨	🟨	Carbon reduction ambition	🟩	🟩
Performance challenges	⬛	⬛	Air and noise pollution reduction	⬛	⬛
Safety challenges	⬛	⬛	Transition technologies	🟩	🟩
Financial differences or incentives	🟨	🟥			

The drop-in fuels considered in this study are supported by the RTFO. Overall, the RTFO has assisted in increasing drop-in fuel supply over time, particularly of HVO (Department for Transport, 2022). It is likely, however, that the absolute volumes of renewable fuel may decrease if targets are not amended as cars and light duty vehicles electrify (Zemo Partnership, 2022).

For the most part, HVO is not considered to be a development fuel under the RTFO. This is because the primary feedstocks of segregated oils and fats are excluded (for example: used cooking oil and tallow). There are also concerns from intergovernmental organisations and the low-carbon fuels industry about the global supply limitations of waste oils and fats as overall demand for HVO increases across sectors, which is explored in sub-section 6.1.3 (International Energy Agency, 2022) – echoed by some stakeholders during engagement . The emissions reduction potential of HVO is controversial for industrial NRMM. In 2022, the UK's Environment Agency asked its contractors to stop using HVO on its sites due to concerns that it was not 'as environmentally friendly as advertised'.[229] The agency has since softened its stance, allowing use of HVO on the condition that provenance can be verified.[230] Balfour Beatty has also published a position paper on HVO which sets out an effective ban on its sites due to feedstock sustainability and lifecycle carbon emission concerns and the opaque nature of HVO supply chains.[231] Some stakeholders echoed these concerns. However, many stakeholders, particularly users, saw HVO as an interim solution as other decarbonisation solutions are being developed.

> **'We aspire to use alternative fuel equipment, but we are dependent on supply from manufacturers. In the meantime, HVO is being prioritised.'** User

> **'Promoting HVO and biofuels as low emission fuels is a barrier to uptake of cleaner technologies as organisations may feel they have met their [net zero] targets.'** Sector specialist

Other drop-in development fuels considered in this study, such as advanced biofuels, fall into the development fuel category of the RTFO and so receive additional support (Department for Transport, 2023). However, HVO remains the most widely available diesel drop-in fuel due to the maturity of the technology. Generally, these advanced biofuels and RCFs have similar barriers and enablers to deployment as HVO, albeit with a lower TRL.

The use of drop-in fuels in ICE offers no reductions in air and noise pollution. Air quality is an important decision-making factor for many NRMM users and so drop-in fuels are typically not favoured as a long-term solution by users.

> **'[Some drop-in fuels] are currently being explored and used and will play an important role in the transition in the short term. However, the other consideration in terms of emissions is air quality and therefore these ICE options will not be the long-term solutions.'** User

As discussed in sub-section 3.1.1.2, drop-in fuels may be used in existing diesel engines and infrastructure with no or minimal modifications. If there are supply, infrastructure or cost constraints due to increased demand, drop-in fuels can also be blended with diesel enabling some reduction of greenhouse gas emissions.

4.2.1.1 E-fuels

As discussed in sub-section 3.1.1.2, e-fuels are drop-in fuels. Like HVO, they result in no additional performance challenges, changes in refuelling patterns, storage, safety assessments or infrastructure requirements. Also, like HVO, e-fuels offer no reduction in air or noise pollution as an ICE is still used. There are several defining characteristics of e-fuels that result in different barriers and enablers to HVO, such as:

- **Lower TRL**: e-fuels are not yet produced at a commercial scale and significant production is not expected for several decades (International Energy Agency, 2022).

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[229] Article from September 2022: Environment Agency looks to block HVO (theconstructionindex.co.uk)

[230] Article from June 2023: Environment Agency softens HVO stance and sponsors study (theconstructionindex.co.uk)

[231] Hydrotreated Vegetable Oil (HVO) FAQs - Sustainable supply chain - Supply chain - How we work - Balfour Beatty plc

- **Higher cost:** production costs are significant, making e-fuels expensive. Production costs are impacted by the cost of low-carbon hydrogen, renewable electricity, carbon capture (either from a source of emissions or direct air capture, as well as greater efficiency losses compared to using low-carbon hydrogen directly (Cazzola, Gerard, Gorner, & Gibbs, 2023)).
- **Carbon reduction ambition:** if the e-fuel meets RFNBO requirements set out in the UK RTFO, they result in significant greenhouse gas emission savings. E-fuels do not face the same feedstock sustainability concerns or feedstock limitations as HVO and are dependent on renewable electricity generation capacity.

> **'E-fuels are expensive and still result in air pollution.'** OEM

> **'We are trying anything but e-fuels. The cost of e-fuels and demand for renewable energy really make e-fuels a 'last-resort.'** Sector specialist

Stakeholder views on the barriers and enablers to e-fuel deployment for industrial NRMM were mixed. Air pollution remains a major driver of NRMM user decisions. However, some pointed out that the long lifetimes of industrial NRMM mean that abatement solutions will be needed for diesel NRMM produced today that will still be around in a few decades.

> **'We are looking at funding for research into e-fuels.'** OEM

4.2.2 Fuel blends

Table 52 – Summary of barriers and enablers of deployment of B20 today. Refer to Table 50 for colour code.

Fuel blends: barriers and enablers today			
Immaturity of abatement options	⬛	Policy and regulations	🟩
Limited fuel supply & infrastructure	⬛	Carbon reduction ambition	⬛
Performance challenges	🟨	Air and noise pollution reduction	⬛
Safety challenges	⬛	Transition technologies	🟩
Financial differences or incentives	🟨		

As discussed in 3.1.1.2, biodiesel is the most common biofuel blend with fossil diesel fuel. In 2022 1,494 million litres of biodiesel were supplied in the UK, representing 5.4% of total diesel supply. 3.7% of the biodiesel was supplied to the off-road sector (Department for Transport, 2023). It is currently available at forecourts at a 7% blend, B7, and is supported under the main RTFO obligation (the same as HVO) (Zemo Partnership, 2022). Whilst they offer some reduction in greenhouse gas emissions, low-carbon fuel blends still involve the combustion of fossil fuels and so are not conducive to reaching net zero targets. Use of biodiesel also does not result in improvements in air quality; PM, CO and HC emissions decrease but NOx formation increases (O'Malley & Searle, 2021).

The feasibility of high blends in existing engines varies by NRMM manufacturer. During stakeholder interviews, one OEM said they could only support 5% blends whilst others supported blends of 20% across all their recent engines. A 20% blend is assumed in Table 55 as it offered the greatest abatement potential of the blend levels suggested by stakeholders and in literature. Providing that the blend level is compatible with the engine, biodiesel blends are largely compatible with existing operations, infrastructure and refuelling patterns. Large scale modification of engines for FAME biodiesel blends higher than 20% is unlikely because of these operational difficulties and the wider sustainability concerns discussed earlier for HVO (biodiesel and HVO use the same feedstocks).

FAME, the dominant component of biodiesel in the UK, also has poor cold flow properties which can result in crystallisation in winter (Department for Transport, 2021; Dwivedi & Sharma, 2014). This in turn can clog pipes and hinder refuelling and site operation.

As with drop-in fuels, fuel blends are used in existing diesel engines and can be seen as transition technologies. However, their use offers no air or noise pollution reduction benefits.

4.2.3 Hybrid

Table 53 – Summary of barriers and enablers of deployment of hybrid industrial NRMM today. Refer to Table 50 for colour code.

Hybrid: barriers and enablers today			
Immaturity of abatement options	🟨	Policy and regulations	🟨
Limited fuel supply & infrastructure	⬛	Carbon reduction ambition	⬛
Performance challenges	⬛	Air and noise pollution reduction	⬛
Safety challenges	⬛	Transition technologies	⬛
Financial differences or incentives	⬛		

As discussed in section 3.4, diesel electric hybrids are commercially available for a wide range of industrial NRMM. With the battery typically charged through regenerative braking or the diesel engine, the machine only needs to be refuelled with diesel (or e.g., HVO) and so there are no additional fuel or operational challenges. Hybrid powertrains offer some greenhouse gas emission and air pollution reduction benefits. However, as for low carbon fuel blends, the combustion of fossil fuels in an ICE is still involved. Therefore, hybrid machinery is not the final solution for reaching net zero targets. Using drop-in fuels instead of diesel would also not address the tailpipe emission issues.

Hybrid machinery received less attention than other abatement solutions during stakeholder engagement. Diesel-electric hybrid machinery was viewed as a short-term solution as the industry transitions to options with greater decarbonisation potential.

> **‘Hybrids offer a great interim solution at present with great carbon savings.’** OEM

Some OEMs speculated that their role might be so short-term that hybrid options may not achieve major market share; the large R&D costs associated with developing new machinery designs might not be paid back if other decarbonisation solutions are in demand and come to market first. The risk and financial implications for OEMs of R&D projects for multiple technologies is discussed in sub-section 6.1.1.

> **‘The cost of development might mean that hybrid is skipped.’** OEM

Hybrid NRMM will have lower fuel costs as the engine is more efficient, however they will be more expensive to purchase as they need both an engine and battery power system (refer to Section 3.3 for references). For highly utilised equipment, the TCO can be lower than incumbent machines (as the lower operating costs outweigh the higher CAPEX), whereas the TCO of hybrid could be higher for equipment which is not utilised highly (so CAPEX is the dominant factor of the TCO).

4.2.4 Hydrogen ICE

Table 54 – Summary of barriers and enablers of deployment of hydrogen ICE today. Refer to Table 50 for colour code.

Hydrogen ICE: barriers and enablers today			
Immaturity of abatement options	🟥	Policy and regulations	🟥
Limited fuel supply & infrastructure	🟥	Carbon reduction ambition	🟩
Performance challenges	🟨	Air and noise pollution reduction	⬛
Safety challenges	🟥	Transition technologies	🟩
Financial differences or incentives	🟨		

Hydrogen ICE is being considered by several OEMs as an alternative to conventional diesel ICE, whilst maintaining many of the same components and operating philosophy. It is under development and is not commercially available for any NRMM archetype at present. The low TRL also leads to uncertainty in the potentially high upfront costs and performance. Onboard energy storage for high usage applications was a concern cited by stakeholders. However, this concern was greater for battery electric, as it is expected that hydrogen refuelling times will be shorter than recharging times for battery electric machinery.

There is a lack of confidence from stakeholders in the future availability of low-carbon hydrogen and the associated infrastructure. This was seen as one of the most important barriers to deployment of any hydrogen-based solution. Low-carbon hydrogen is supported under the development fuel obligation of the RTFO as a RFNBO. Low-carbon hydrogen has also received other forms of policy support; the UK recently having doubled the low-carbon hydrogen production target to 10 GW by 2030.[232] In 2022, the UK Government also launched the first two strands of the Net Zero Hydrogen Fund as well as the first Electrolytic Hydrogen Allocation Round to support this production target (Department for Business, Energy & Industrial Strategy, 2022). However, this support for future projects has not translated into confidence in availability nor infrastructure to supply hydrogen to site. Fossil fuel-based hydrogen is being used by some stakeholders to fill gaps in low-carbon hydrogen supply as production ramps up.

'We need a clear plan to deliver 10 GW of green hydrogen by 2030 and improved infrastructure to deliver hydrogen. There is a lack of affordable green hydrogen on the market. This should be supplied by energy and fuel suppliers. Instead, [OEMs] are needing to get involved in the fuel supply chain to support their equipment.' **OEM (in the context of barriers to hydrogen ICE and**

'Whilst we don't use green hydrogen at the moment, we are looking to transition to green as the country builds networks and supply chains.' **Lease and hire company**

As discussed in sub-section 4.1.4, the safety of storing hydrogen on site is also a prominent concern. This is partly a practical concern and partly a lack of clarity on which set of regulations is applicable.

'The barriers for hydrogen include operational safety factors and the associated regulatory environment.' **Sector specialist**

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[232] https://www.gov.uk/government/publications/uk-hydrogen-strategy. There are several low-carbon hydrogen production projects under development in the UK. Full lists of the projects under development as of mid-2023 can be found at https://www.gov.uk/government/publications/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc/cluster-sequencing-phase-2-track-1-project-negotiation-list-march-2023 and https://www.gov.uk/government/publications/hydrogen-production-business-model-net-zero-hydrogen-fund-shortlisted-projects/hydrogen-business-model-net-zero-hydrogen-fund-shortlisted-projects-allocation-round-2022

Another potential legislative barrier was highlighted by stakeholders, where currently hydrogen (or natural gas) powered machinery would need individual Vehicle Special Orders (VSOs) for them to be used. This is the case as "The Road Vehicles (Authorised Weight) and (Construction and Use) (Amendment) 2017"[233] states:

> 'No person shall use, or cause or permit to be used, a vehicle that is fitted with a hydrogen fuel system or a natural gas fuel system unless that vehicle has been approved under the Road Vehicles (Approval) Regulations 2009 for that system at the time of registration.'

In the "Road Vehicles (Approval) Regulations 2020" (superseding the 2009 regulations), refers to the EU type approval (covered in EU 2018/858)[234] which require machinery used in construction and quarries to conform to these regulations to be type approved. Some stakeholders were concerned that some machinery would not pass these regulations due to the requirement for suspension and approved braking systems, which would mean that hydrogen machinery which does not pass this would require individual VSOs for every unit, increasing the administrative burden of deploying this technology.

Any form of combustion engine will produce noise and some emissions. In the case of hydrogen ICE, this is predominantly water vapour, although quantities of NO_x are still produced due to the high temperature interactions of oxygen and nitrogen present in air. The likely levels of NOx compared to diesel remain uncertain due to the low TRL of hydrogen ICE powertrains in NRMM (Lewis, 2021). Future commercial hydrogen ICE NRMM may require aftertreatment similar to that of diesel engines. However, their NOx emissions may still lead to hydrogen ICE machinery not being permitted in or chosen by operators in urban areas or underground settings (Heid, Martens, & Orthofer, 2021). Engagement with stakeholders reinforced this; several stakeholders stating a strong preference for zero tailpipe emissions, including air pollutants (see sub-section 4.1.8).

A hydrogen ICE NRMM would be more expensive to purchase and run today than a diesel ICE NRMM. The purchase costs of hydrogen ICE are uncertain due to its low TRL in industrial NRMM; however, it is expected that hydrogen ICE machinery could achieve purchase cost parity with diesel ICE once commercial (refer to Section 3.3 for references). The cost of hydrogen will be higher than diesel, once the costs associated with hydrogen distribution and refuelling infrastructure (estimated £6/kg to £7/kg today, approximately 20 p/kWh, see Appendix 9.7) are included. These costs may be higher for hard-to-deploy machinery which may require more expensive infrastructure solutions.

4.2.5 Hydrogen fuel cell

Table 55 – Summary of barriers and enablers of deployment of hydrogen fuel cell today. Refer to Table 50 for colour code.

Hydrogen fuel cell: barriers and enablers today			
Immaturity of abatement options	🟥	Policy and regulations	🟥
Limited fuel supply & infrastructure	🟥	Carbon reduction ambition	🟩
Performance challenges	🟥	Air and noise pollution reduction	🟩
Safety challenges	🟥	Transition technologies	🟩
Financial differences or incentives	🟥		

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[233] https://www.legislation.gov.uk/uksi/2017/881/contents/made

[234] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018R0858

Hydrogen fuel cell technology broadly shares the same barriers and enablers as hydrogen ICE for fuel supply, infrastructure, safety challenges, policy, carbon reduction ambition and transition technologies. However, fuel cells require hydrogen of higher purity and so some sources of low-carbon hydrogen will require further purification before use (Wróbel, et al., 2022). Fuel cell solutions for industrial NRMM are more developed than hydrogen ICE, particularly for replacing generators. However, fuel cell industrial NRMM are projected to have a higher capital cost than hydrogen ICE in 3.3.1. There is uncertainty over the residual value and the end of life process, particularly for the battery (see sub-section 4.1.6.3). Overall, the technology remains at a low TRL and requires more development before reaching full commercialisation.

In terms of performance challenges, there is contention about the suitability of hydrogen fuel cells for off-road applications due to the high levels of dust and vibrations experienced. These factors reportedly contributed to JCB's decision[235] to switch fuel cell powertrain development to hydrogen ICE. However, other studies have found vibrations to benefit fuel cell operation, improving the water removal process in particular (Mortazavi, Santamaria, Benner, & Chauha, 2019; Sitong Chen, 2019).

The air and noise pollution reduction potential of hydrogen fuel cell is an enabler of adoption; the operation of fuel cells is quiet and does not emit NOx, CO_2 or PM, only water and air.[236] This aligns with the pollution reduction aims of many NRMM users.

Hydrogen fuel cells are significantly more expensive than diesel engines currently, and the hydrogen fuel costs will be higher than for diesel when distribution and refuelling infrastructure costs are included (refer to Section 3.3 for references). The costs may be even higher for hard-to-deploy machinery for the reasons listed in sub-section 2.1.4.

4.2.6 Tethering

The following sub-section details barriers and enablers for tethering options in the limited applications for which it is suitable (mostly in the limited movement machinery and hand-held or hand moved equipment categories, see section 3.8.1 for further explanation). There remain some performance and operational challenges for these applications, such as ensuring tethers are not crossed during use.

Table 56 – Summary of barriers and enablers of deployment of tethering today in suitable applications (see section 3.83.6.2 for further detail). Refer to Table 50 for colour code.

Tethering barriers and enablers today – for limited movement and hand-held/hand moved machinery			
Immaturity of abatement options	⬛	Policy and regulations	🟨
Limited fuel supply & infrastructure	🟨	Carbon reduction ambition	🟩
Performance challenges	🟨	Air and noise pollution reduction	🟩
Safety challenges	🟥	Transition technologies	🟩
Financial differences or incentives	🟩		

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[235] https://fuelcellsworks.com/news/hydrogen-takes-pole-position-in-race-to-decarbonise-heavy-equipment/

[236] https://afdc.energy.gov/fuels/hydrogen_benefits.html

Tethered options are available across hand-held or hand-moved and limited movement machinery. Solutions are being developed for special use-cases of mobile machinery in mining and ports. Compared to battery electric, the upfront cost is reduced as a much smaller battery is required. Tethering is particularly suited to underground mining applications due to the air, heat and noise pollution reduction benefits. This reduces the amount of pumping and ventilation required to meet health and safety requirements. The reduction in noise from electric NRMM is significant enough that some users felt that the lack of noise may need to be flagged in future health and safety assessments and training.[237] The safety of high voltage tethered equipment on site was a concern for some sector specialist stakeholders. This was not explicitly mentioned as a barrier by users; hydrogen storage on site took precedence in conversations about safety.

> **'From research and case studies seen, we see tethering as a reasonable prediction for less mobile machinery. For larger equipment there is some evidence that tethering may be an option but remains to be seen.'** User

Inadequate grid infrastructure to support tethering and charging of battery electric industrial NRMM can be a major barrier to electrification.[238] Several stakeholders called for more open dialogue with distribution network operators to gain a clear understanding of what network operators require from NRMM users for sites to be able to connect to the grid. This request for a better dialogue with DNOs mirrors the views of on-road fleet operators, as voiced in a recent BVRLA report[239] (see sub-section 3.6.2 for further discussion on the practicalities of acquiring a grid connection).

> **'Our equipment is semi-mobile and is often well suited to tethering if the infrastructure is available…Global and regional infrastructure is not available to power these machines – the cost of electrification infrastructure is very important.'** OEM

In the short term, diesel generators could be used where the required infrastructure is lacking. It would not decrease greenhouse gas emissions compared to diesel NRMM and would result in higher emissions compared to tethered NRMM connected to the grid. However, it would enable the early deployment of tethering options on site. This could allow other challenges to start to be addressed, such as the practicalities of tethers on a construction site for example. Beyond diesel generators, the carbon intensity of any electricity source used will impact the abatement potential. Renewable electricity generation is supported in the UK by the Contracts for Difference (CfD) scheme which is currently in its fourth round.

Tethered options are likely to be cheaper to use than diesel machinery, where the use case is suitable for tethering (refer to Section 3.3 for references). However, for hard-to-deploy machinery, this may not be the case if grid connection is expensive, or non-grid power supply solutions are required which will add additional costs.

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[237] https://www.balfourbeatty.com/sustainability/cop26/towards-a-zero-carbon-construction-site/our-zero-carbon-construction-site-diary/march-2023/

[238] Despite this, the rating for "Limited fuel supply & infrastructure" is still orange, as there are not limitations on electricity production (see the start of Section 4.2 for definitions for each rating).

[239] BVRLA Fleet Charging Guide

4.2.7 Battery electric

Table 57 – Summary of barriers and enablers of deployment of battery electric today. Refer to Table 50 for colour code.

Battery electric barriers and enablers today			
Immaturity of abatement options	🟨	Policy and regulations	🟥
Limited fuel supply & infrastructure	🟨	Carbon reduction ambition	🟩
Performance challenges	🟥	Air and noise pollution reduction	🟩
Safety challenges	🟨	Transition technologies	🟩
Financial differences or incentives	🟨		

Battery electric is the most popular alternative powertrain at present, as seen in sub-section 3.4. As observed in the road transport sector, there continues to be an EV skills gap in the UK labour market which may hinder the transition to electric (Business, Energy and Industrial Strategy Committee, 2018). This general shortage is acute for industrial NRMM due to the wide range of machinery types and sizes that require maintenance (Zemo Partnership, 2021).

Battery electric industrial NRMM shares the same grid carbon intensity and infrastructure constraints as tethering options, as well as transition technologies and the potential for reducing air and noise pollution. As well as concerns about manual handling of batteries, high voltage charging infrastructure is a health and safety consideration for stakeholders.

The industrial NRMM sector is concerned about the ability of battery electric options to meet the current duty cycle requirements for diesel industrial NRMM (as discussed in sub-section 4.1.3). Largely, battery electric industrial NRMM is marketed as capable of a full day's work on a single charge. However, the definition of a day's work varies across sectors, sites, NRMM types and even machine tasks. Balfour Beatty recently published their mixed experience with an all-battery electric site.[240] The report highlights the uneven duty cycle capabilities across battery electric NRMM at present. In the future, rapid charging infrastructure and battery swapping may reduce the impact of charging cycles on site operations.

The end of life requirements for batteries are discussed in section 4.1.6.3; it is uncertain whether the UK will adopt similar legislation to the EU which will make OEMs responsible for battery collection, recycling, and waste management.

Battery electric machinery are more expensive to buy currently, predominately due to the cost of the battery. However, as they are significantly cheaper to run than diesel, the TCO can be comparable (or even cheaper) depending on the level of utilisation (refer to Section 3.3 for references). However, for hard-to-deploy machinery, battery electric solutions may be more expensive as the cost grid connections or other off-grid power supply solutions is likely to be higher.

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[240] https://www.balfourbeatty.com/sustainability/cop26/towards-a-zero-carbon-construction-site/our-zero-carbon-construction-site-diary/march-2023/

4.2.8 Efficiency measures and process change

4.2.8.1 Efficiency measures

Table 58 – Summary of barriers and enablers of deployment of efficiency measures today. Refer to Table 50 for colour code.

Efficiency measures barriers and enablers today			
Immaturity of abatement options	▨	Policy and regulations	▨
Limited fuel supply & infrastructure	🟩 *Lessen barriers of fuel switching options*	Carbon reduction ambition	🟩
Performance challenges	▨	Air and noise pollution reduction	🟩
Safety challenges	▨	Transition technologies	▨
Financial differences or incentives	🟩		

Efficiency measures can enable the deployment of other abatement options when used together. More efficient fuel use and the resulting reduced fuel demand can help alleviate the impacts of higher cost and supply limited fuels. Even when deployed alongside incumbent diesel industrial NRMM, improvements in machine and operational efficiency will result in some reduction in greenhouse gas emissions and air pollution. Whilst companies have been making continuous improvements in operational, machine and process efficiency, purchasers of industrial NRMM can face difficulties justifying the upfront cost premium of more efficient machines due to the lack of data demonstrating the efficiency benefits. Lack of operational data is explored further in sub-section 6.1.4.2. Justification of investment in efficiency can also be challenging due to the distance between who operates the machinery and who pays the fuel bill, as discussed in sub-section 4.1.5.

4.2.8.2 Process change

Process change is where a process using industrial NRMM is changed reduce the number of industrial NRMM required, including by using fixed machinery to remove the need of industrial NRMM entirely. No substantial evidence of deployment or consideration by the sector was found in the literature or during stakeholder engagement. Stakeholder interviews and workshops suggested that industrial NRMM users strongly prefer options which result in minimal changes to site operations. As changes in refuelling and fuels storage are already seen as a significant change, combined with the lack of evidence of industry use cases, it seems unlikely that there will be any significant changes to processes as part of abatement strategies.

4.2.9 Summary of barriers and enablers by abatement options

Table 59 brings together the barriers and enablers by abatement options discussed above.

These ratings are for machinery which is not considered hard-to-deploy. For machinery which is hard-to-deploy, the ratings will be the same for drop-in fuels, fuel blend and hybrid. For hydrogen and electric technologies, the barrier associated with fuel supply and infrastructure will be significantly larger, and the ‘financial differences or incentives’ may be a larger barrier (if more expensive electricity or hydrogen supply solutions are required).

Table 59 – Summary of barriers and enablers as applied to the abatement options today. Refer to Table 50 for colour code.

Abatement options	ICE & not zero tailpipe emissions					Zero tailpipe emissions			
Barriers and/or enablers	Drop-in fuels – HVO	Drop-in fuels – e-fuel	Fuel blends	Hybrid	Hydrogen ICE	Hydrogen fuel cell	Tethering	Battery electric	Efficiency measures
Immaturity of abatement options	⬛	🟥	⬛	🟨	🟥	🟥	⬛	🟨	⬛
Limited fuel supply & infrastructure	🟨	🟨	⬛	⬛	🟥	🟥	🟨	🟨	🟩
Performance challenges	⬛	⬛	🟨	⬛	🟨	🟥	🟨	🟥	⬛
Safety challenges	⬛	⬛	⬛	⬛	🟥	🟥	🟥	🟨	⬛
Economic and financial differences or incentives	🟨	🟥	🟨	⬛	🟨	🟥	🟩	🟨	🟩
Policy and regulations	🟩	🟩	🟩	🟨	🟥	🟥	🟨	🟥	⬛
Carbon reduction ambition	🟩	🟩	⬛	⬛	🟩	🟩	🟩	🟩	🟩
Air and noise pollution reduction	⬛	⬛	⬛	⬛	⬛	🟩	🟩	🟩	🟩
Transition technologies	🟩	🟩	🟩	⬛	🟩	🟩	🟩	🟩	⬛

Colour code	Description
🟩	Enabler of adoption
🟨	Could be a barrier to adoption
🟥	Barrier to adoption
⬛	Not applicable / neither a barrier nor an enabler

4.3 International policy and infrastructure deployment

Available literature on international policy and infrastructure deployment was reviewed,, with a strong coverage of Europe and some coverage of India, South Korea, Australia, North America and China (for instance (Desouza, Marsh, Beevers, Molden, & Green, 2021; Huang, Fan, Shen, & Du, 2021). Overall, there are few policies in place that focus explicitly on industrial NRMM, with the exception of three types of policy mechanism introduced in the construction sector (discussed and referenced later):

- Market initiation: city authorities stipulating use of zero emission industrial NRMM in public sector construction contracts – as done in various Scandinavian cities;
- ‘Carrots’: purchase incentives for zero emission construction machines and chargers;
- ‘Sticks’: future bans on non-zero emission industrial NRMM at a city level.

The findings of the literature review are summarised below, followed by a case study on Oslo and some conclusions. Literature coverage of policies in Japan and South Africa appears sparse, although it is noted that the latter nation is at an early stage in its development of decarbonisation policy and may choose to initially focus on larger emitting sectors such as coal fired power generation.

4.3.1 Literature findings

Across the sectors of construction, port machinery, waste treatment and mining, NRMM in the construction sector has received by far the most attention from policymakers and regulators (with policy around NRMM in ports limited to high-level emissions reduction targets, and policy around mining NRMM virtually non-existent). The focus on construction reflects the fact that construction machinery primarily operates in cities and therefore influences urban air quality. The main exception is California, where the California Air Resources Board has announced its intention to modify port regulations to drive implementation of zero emission equipment. The regulations are intended to come into force in 2026, with the aim of over 90 per cent of the port equipment being zero emission by 2036. The exact regulatory details are still under development. (California Air Resources Board, 2020).

In Europe (outside of Scandinavia), North America, China, India and South Korea emissions regulation and policy in the construction sector has been set at a national level and focused on improving air quality, in a manner analogous to the Euro standards for road vehicles (for example, (Lajunen, et al., 2016; Janin, et al., 2018; Knibb Gormezano & Partners, 2017; Hagan, et al., 2022; The International Council on Clean Transportation, 2022; The International Council on Clean Transportation, 2018)). Historically, the air quality regulations have been focused on reducing non-CO_2 emissions from diesel engines rather than decarbonisation, although these standards are beginning to tighten to include zero emission industrial NRMM – for example in London, where a steady increase in emissions standards will culminate in a 2040 ban on operation of non-zero emission industrial NRMM in the city.[241]

USA policymakers have signalled intent to apply a number of further policies to incentivise zero emission industrial NRMM deployment (including funding for early adopters, strategic demonstrations, and R&D), but these policies are still at a development stage (U.S. Department of Energy; U.S. Department of Transportation; U.S. Environmental Protection Agency; U.S. Department of Housing and Urban Development, 2023). Within the USA, policy ambition is particularly strong in California (California Air Resources Board, 2020; Executive Department State of California, 2020), where the Governor has ordered the California Air Resources Board to determine a pathway for, as far as possible, all of California's industrial NRMM to be zero emission by 2035 (part of this is the port machinery regulation described earlier). The National Renewable Energy Laboratory (NREL) has highlighted the need for (where practical) an internationally consistent framework for creating demand for zero emission industrial NRMM, including indirect emissions regulation as well as tailpipe emissions (National Renewable Energy Laboratory, 2022).

Australia has earmarked around AUS$280 million (£146 million) over 10 years for the 'Safeguard Crediting Mechanism' to reward highly emitting facilities such as mines that engage in deep decarbonisation. However, this measure is not aimed only at industrial NRMM, and plans for implementation are still under development (Australian Government, 2021).[242] Australia has also established a research centre focused on developing hydrogen technologies for applications including mining.[243]

Globally, a policy that appears to have had some success in driving the early deployment of zero emission industrial NRMM in the construction sector has been city authority procurement (Big Buyers

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[241] Non-Road Mobile Machinery (NRMM) | London City Hall

[242] https://www.iea.org/policies/13815-safeguard-crediting-mechanism-for-large-greenhouse-gas-emitters - source does not clarify the currency but assumed to be in Australian dollars.

[243] Hydrogen's key role in decarbonising the mining industry - CSIRO

Initiative Working Group, 2020; Carbon Neutral Cities Alliance, 2019).[244,245] By their nature, these policies are deployed at a local authority level rather than a national government level. In this approach, city councils specify in their tender criteria for municipal construction projects that the industrial NRMM used must be zero emission. The approach has been deployed in several large Scandinavian cities, notably Oslo.

In Oslo, engagement of local authorities with the decarbonisation of construction machinery has started with pilot projects, avoiding challenges associated with grid infrastructure through a combination of site selection based on grid capacity and making use of new grid connections being installed for the building to power electric industrial NRMM.[245,246]

It is noted that there is a limit to the number of new, zero emission construction machinery sales that can be directly driven by city procurement, since the number of machines required to perform municipal construction contracts is finite (for example, 20% of Oslo's construction market is municipal projects).[246] As the Norwegian funding agency Enova notes,[247] while the number of zero emission excavator purchases that they supported rose rapidly up until 2021, the number dropped from 2021-2022.[248] A lack of additional demand from projects requiring zero emission machinery, alongside constraints imposed by OEM model availability, is cited as a key limiting factor.

City procurement policies have been complemented by additional policies that give industry the confidence to invest[249] (such as setting a date for a ban on the use of non-zero emission construction equipment,[246] for example 2030 in Oslo) and alleviate financial barriers to deployment in private sector projects (purchase incentives). Through the government-owned organisation Enova,[250] Norway has been a leader in providing purchase incentives for zero emission industrial NRMM and has been funding zero emission industrial NRMM projects since 2017.[251] Notable examples include 13 million Norwegian Kroner (approximately £1 million) allocated in 2020 to projects deploying mobile batteries to replace generators on construction sites, and the recent introduction in 2023 of two purchase incentives schemes tackling the vehicle capital cost and infrastructure barriers to zero emission industrial NRMM deployment. In these schemes:[252,253,254]

- up to 40% of the price difference between a zero emission and a conventional piece of construction machinery is granted (max subsidy equivalent to approximately £375,000).
- up to 40% of the cost of a mobile charging station fitted with a battery (max subsidy equivalent to approximately £150,000) is granted, with conditions on battery size and charging speed (at least 70kWh and at least 100kW). The battery can be trickle charged with a small grid connection in between rapid top-ups for the construction machine.

The schemes will run in 2023 and 2024, with a number of application rounds within that period. Applications for the schemes are competitive. The variety of industrial NRMM covered may be larger in 2024 than 2023 in response to market developments.

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[244] https://www.c40knowledgehub.org/s/article/Clean-Construction-Policy-Explorer?language=en_US – This source tracks all the local policies deployed across the world to decarbonise the construction sector.

[245] https://www.klimaoslo.no/2021/12/29/norway-expects-a-large-increase-in-electric-excavators-in-2022/

[246] https://www.c40knowledgehub.org/s/article/How-Oslo-is-driving-a-transition-to-clean-construction?language=en_US

[247] https://cdn.sanity.io/files/gjbuax4h/production/0b37f5df591a6149831985db8b15d248fe4ad62b.pdf?dl=enova-arsrapport-2022.pdf

[248] Zero emissions excavator sales financially supported by Enova rose from 5 in 2018, to 11 in 2019, to 50 in 2020, to 143 in 2021. Combined excavator and wheel loader sales supported by Enova declined from 200 in 2021 to 112 in 2022.

[249] ERM's expectation is that, if conventional construction machinery will shortly be banned in a city, construction firms will be encouraged to invest in zero emission machines to allow them to continue to operate, and manufacturers will invest in production of zero emission machinery in the knowledge that this demand is guaranteed.

[250] https://www.enova.no/about-enova/

[251] https://www.enova.no/download?objectPath=/upload_images/F00FA2198797415D9B8FBC7F46F68E2B.pdf

[252] https://www.electrive.com/2023/04/17/norway-to-subsidize-electric-construction-vehicles/

[253] Utslippsfrie anleggsmaskiner | Enova | Enova

[254] Mobile ladestasjoner for elektriske anleggsmaskiner | Enova | Enova

4.3.2 Deep dive into Norway and the City of Oslo

Norway and the city of Oslo's journey to zero emission industrial NRMM demonstrates how rapid progress can be made:[246]

- 2016: municipal construction tender criteria in Oslo require the use of sustainable biofuels.
- 2017-2019: tender criteria in Oslo updated, requiring contractors to use electric construction machinery wherever the technology is available, and to clearly justify why they need to use alternative solutions (biofuels) where applicable.
- 2020: announcement that all municipal construction sites in Oslo must use zero emission construction machinery by 2025, and non-municipal sites must do the same by 2030.
- 2021: 191 electric excavators and wheel loaders are sold in Norway in a single year, compared to 67 in 2020 and 12 in 2019.[255]
- 2023: Norway introduces scheme of purchase incentives for zero emission construction machinery (discussed earlier).

The tender criteria for municipal procurement in Oslo have also been designed to de-risk the transition to electric industrial NRMM for construction companies in the following ways:

- the city pays the electricity bill, so construction firms face no fuel cost risk.
- the city has engaged with a rental firm to allow companies to lease the equipment on a project-by-project basis, meaning that the construction firms do not have to invest in the full capital cost of a piece of zero emission construction machinery with uncertainty over whether it will be used sufficiently to justify such an investment.

Similar policies are replicated in other Scandinavian cities, such as Stockholm.[244]

4.3.3 Conclusions on international policy

The following conclusions have emerged from the review of international policy:

- Policy regulating emission abatement of industrial NRMM sectors outside construction is scarce, and policy relating to the construction sector is primarily local and focused on air quality improvement rather than a national decarbonisation effort.
- There are no industrial NRMM decarbonisation plans at the national level anywhere. The only national level intervention identified in this review was in Norway, where zero emission construction machinery and mobile charging stations are subsidised.
- Public sector procurement (with tenders designed to minimise risk for the construction firm), alongside grants and phase-out dates for the use of non-zero emission in cities, have been deployed with the aim of stimulating zero emission industrial NRMM uptake, for example in Norway.
- Public sector procurement has been successful in stimulating initial roll-out of zero emission industrial NRMM, but the number of machines that it can deploy is limited by the finite number of machines required for municipal construction projects.

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[255] Page 177 in https://cdn.sanity.io/files/gjbuax4h/production/0b37f5df591a6149831985db8b15d248fe4ad62b.pdf?dl=enova-arsrapport-2022.pdf

5 DECARBONISATION SCENARIOS

The following chapter presents the modelling carried out for this study. An overview of the least-cost pathways modelling approach taken and its key assumptions and limitations is given in section 5.1. The modelled scenarios are described in section 5.2. Results for each scenario, and a comparison across scenarios, are presented in section 5.3, which shows the residual emissions and emissions reductions for tank-to-wheel emissions.

5.1 Least-cost pathways model overview

As part of this research, a least-cost pathways model was developed to produce potential decarbonisation pathways for the industrial NRMM sector, based on the research in this report. This model follows the structure shown in Figure 28**.**

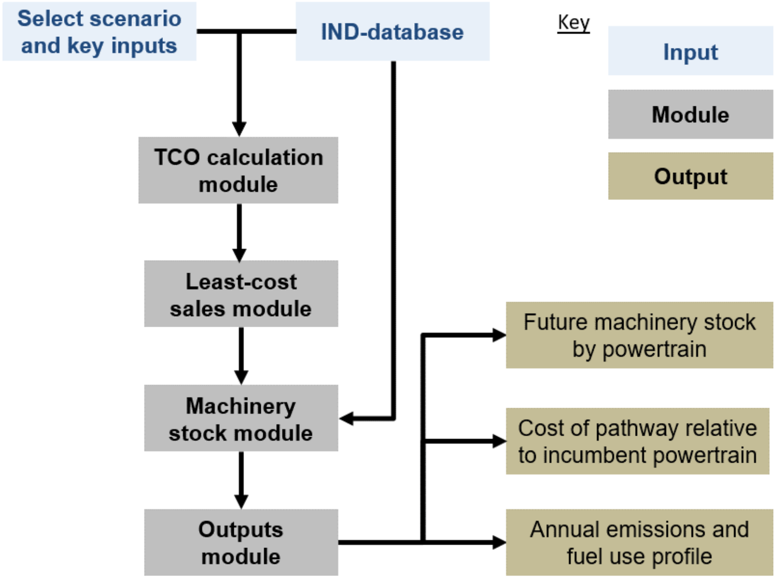


Figure 28 – High-level flow diagram of the least-cost pathways model developed as part of this research

5.1.1 Modelling approach

The model calculates a least-cost pathway for each machine type, sector and engine power combination present in the 2021 NAEI database, which has been compiled into the IND-database. For the purposes of this report, the analysis was conducted on a social-cost basis. It is noted that private costs may not align with societal costs (i.e., these pathways explore optimal deployment from a societal perspective and do not represent a prediction of what will happen without government intervention). For each of these machine type, sector and engine power combinations (henceforth referred to as 'IND-database rows'), the following process is followed. The model uses the archetypes defined in sub-section 2.1.2. These are summarised again in Table 60 for reference.

Table 60 – Description of the 14 archetypes created by ERM. Source data from the 2021 NAEI database, with ERM categories and analysis

Archetype ID	Machinery category	Power rating	Utilisation level	% of population	% of total fuel use	Example machinery (highest fuel use)
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	14.2%	4.6%	Cement mixers, plate compactors
2		High (19-56 kW)	All	0.9%	4.4%	Welding equipment, concrete saws
3	Mobile machinery	Low (<37 kW)	Low (<50%)	1.9%	2.0%	Forklifts, Excavators
4		Medium (37-129 kW)	Low (<50%)	9.0%	23.6%	Forklifts, Excavators, telehandlers
5		High (130-560 kW)	Low (<50%)	0.8%	9.0%	Excavators, Dumpers/tenders
6		Medium (37-129 kW)	High (>50%)	0.6%	8.7%	Sweepers/scrubbers, forklifts
7		High (130-560 kW)	High (>50%)	0.2%	6.4%	Port tractors, Bulldozers
8		Very high (> 560 kW)	High (>50%)	0.04%	1.9%	Dumpers/tenders
9	Limited movement machinery	Medium (37-129 kW)	Low (<50%)	7.5%	9.6%	Mini excavators, Air compressors
10		High (130-560 kW)	All	0.6%	12.5%	Cranes, crushing equipment
11	Generators	Low (<8 kW)	Low (<50%)	63.7%	11.5%	
12		Medium (8-74 kW)	Low (<50%)	0.4%	2.4%	
13		High (75-560 kW)	Low (<50%)	0.3%	3.2%	
14		Very high (>560 kW)	Very Low (<25%)	0.01%	0.3%	

Eight powertrains are considered for each IND-database row as shown in Table 61: seven alternative powertrains and the incumbent powertrain (diesel, petrol or LPG ICE). Incumbent technologies that are not the one currently used for a certain IND-database row are not considered as a possible powertrain (i.e., a machine which currently runs on diesel will not be able to switch to a petrol powertrain).

Table 61 – List of powertrains considered within the least-cost pathways model

Powertrains considered in the model (Powertrain – fuel source)	
Incumbent (ICE - diesel/petrol/LPG)	Battery electric (BE) – Electricity
ICE – HVO	Tethering – electricity
ICE – B20	Fuel cell electric (FCE) – Hydrogen
Hybrid (HE) – Diesel	ICE – Hydrogen

5.1.1.1 TCO calculation module

This module calculates the total cost of ownership (TCO) for each available powertrain for a machine purchased every five years from 2020 to 2050. This total cost of ownership is the sum of the following costs:

- **Machinery CAPEX:** made up of chassis CAPEX (based on incumbent machinery minus the engine cost) and the cost of the powertrain.
- **Infrastructure costs:** This includes estimated costs of infrastructure to supply the required energy source to the machinery. This includes the cost of a charger for battery electric, the tethering cable for tethered machinery and the cost of hydrogen dispensation equipment for hydrogen technologies (provided as a £/kg delivered cost, see Appendix 9.7 for breakdown of hydrogen infrastructure cost). This does not include the cost of acquiring a grid connection for electric powertrains (or for on-site hydrogen generation), as this cost is highly dependent on the specific site the machinery occupies and the total power need from the site.

- **Lifetime OPEX:** This includes the cost of fuel and the cost of maintenance across the machine's lifetime. The fuel costs used in the scenarios below are the social long-run variable costs (LRVC) as provided by DESNZ.
- **Cost of carbon:** This is the cost of CO_2e emissions across the lifetime of the machine. This is applied to well-to-wheel (WTW) emissions, using the central cost of carbon from the DESNZ Green Book Supplementary Guidance (November 2022 Update).[256]

To assess the relative running costs of the powertrain, the efficiency of the powertrain must also be included. This is shown for 2030 and 2050 in Figure 29, which highlights that electricity is the cheapest fuel to use due to the high efficiency of electric powertrains. Hydrogen fuel cell is cheaper to run than diesel by 2030, whereas hydrogen ICE is only cheaper than diesel closer to 2050 due to the lower efficiency of the ICE powertrain.

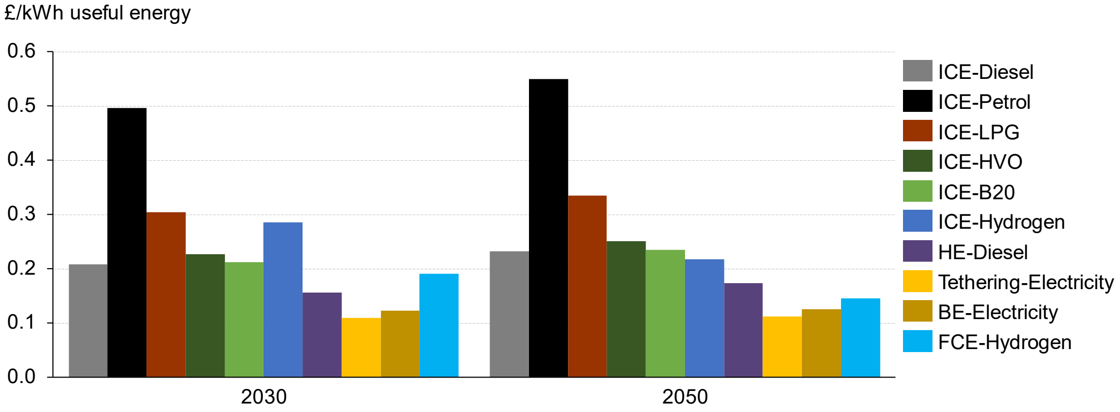
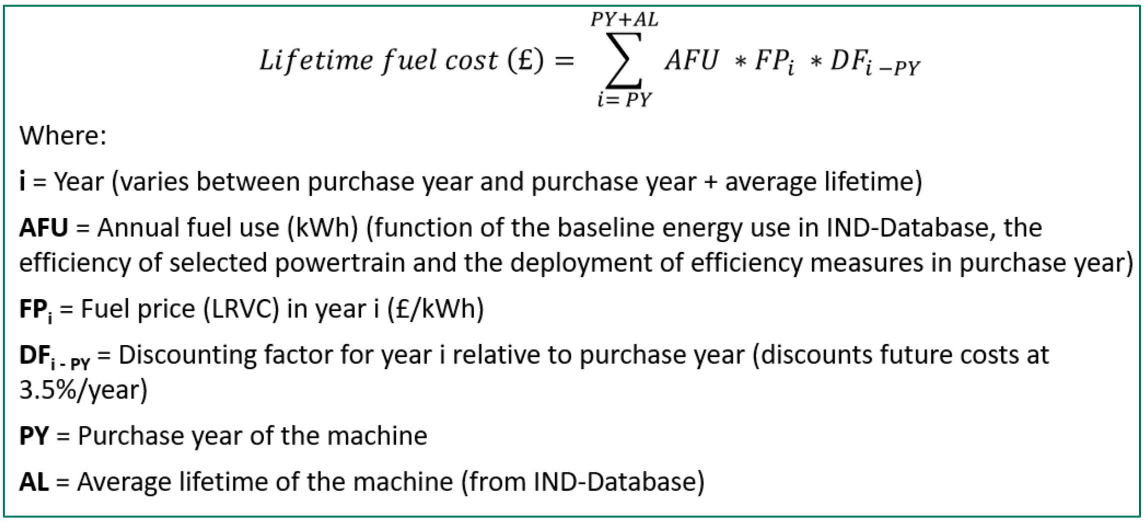


Figure 29 – Social costs (LRVC) of fuels per kWh of useful energy in 2030 and 2050 (in 2022£). These costs do not include distribution costs for hydrogen and infrastructure costs for electricity or hydrogen.

For costs which are spread across the lifetime (e.g., fuel and maintenance costs, hydrogen infrastructure costs), these costs are discounted at 3.5% per year relative to the year of purchase and account for prices changing over the lifetime of the machine where appropriate. This is illustrated in Figure 30 for lifetime fuel costs.



$$Lifetime\ fuel\ cost\ (£) = \sum_{i=PY}^{PY+AL} AFU \ * FP_i \ * DF_{i-PY}$$

Where:

i = Year (varies between purchase year and purchase year + average lifetime)

AFU = Annual fuel use (kWh) (function of the baseline energy use in IND-Database, the efficiency of selected powertrain and the deployment of efficiency measures in purchase year)

FP_i = Fuel price (LRVC) in year i (£/kWh)

DF_{i-PY} = Discounting factor for year i relative to purchase year (discounts future costs at 3.5%/year)

PY = Purchase year of the machine

AL = Average lifetime of the machine (from IND-Database)

Figure 30 – Equation used to calculate the lifetime fuel cost of a machine, accounting for discounting and variable fuel prices

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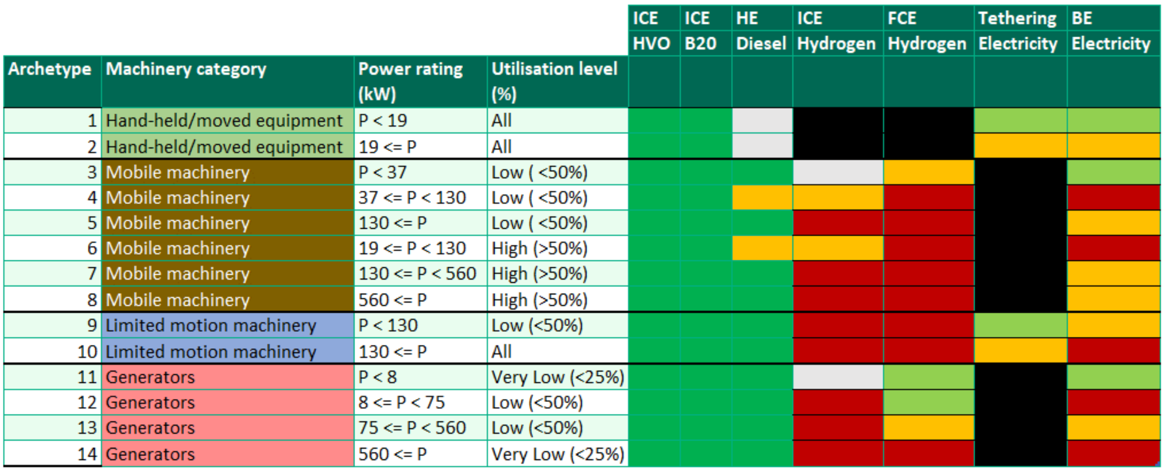
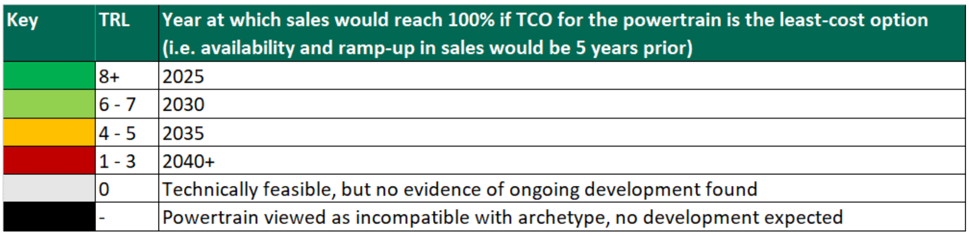
[256] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

The availability of powertrains varies by archetype and is based on the research performed on commercial availability in sub-section 3.4. This is summarised in Table 62.[257] Note that the years corresponding to the colours in the table are the years in which the powertrain technology can reach 100% sales. If this powertrain is chosen as the least-cost option, sales are modelled to increase 5 years before the powertrain reaches 100% sales (see subsection 5.1.1.2 for more details). For the portion of machinery that has been assigned as hard-to-deploy (see subsection 2.1.4), the availability of hydrogen and electric powertrains is delayed by 10 years compared to what is shown in Table 62**.** This acknowledges the additional challenges that may exist to provide the infrastructure to refuel or recharge some industrial NRMM, requiring more innovative or expensive solutions which will delay the deployment of these technologies.

Table 62 – Baseline availability of powertrains used within the model. Year shown is the earliest TCO year in which the powertrain will be considered, with sales starting four years earlier if the powertrain is the lowest cost option. Source: ERM assessment



				ICE HVO	ICE B20	HE Diesel	ICE Hydrogen	FCE Hydrogen	Tethering Electricity	BE Electricity
Archetype	Machinery category	Power rating (kW)	Utilisation level (%)							
1	Hand-held/moved equipment	P < 19	All	🟩	🟩	⬜	⬛	⬛	🟢	🟢
2	Hand-held/moved equipment	19 <= P	All	🟩	🟩	⬜	⬛	⬛	🟧	🟧
3	Mobile machinery	P < 37	Low (<50%)	🟩	🟩	🟩	⬜	🟧	⬛	🟢
4	Mobile machinery	37 <= P < 130	Low (<50%)	🟩	🟩	🟧	🟧	🟥	⬛	🟥
5	Mobile machinery	130 <= P	Low (<50%)	🟩	🟩	🟩	🟥	🟥	⬛	🟧
6	Mobile machinery	19 <= P < 130	High (>50%)	🟩	🟩	🟧	🟧	🟥	⬛	🟥
7	Mobile machinery	130 <= P < 560	High (>50%)	🟩	🟩	🟩	🟥	🟥	⬛	🟧
8	Mobile machinery	560 <= P	High (>50%)	🟩	🟩	🟩	🟥	🟥	⬛	🟧
9	Limited motion machinery	P < 130	Low (<50%)	🟩	🟩	🟩	🟥	🟥	🟢	🟧
10	Limited motion machinery	130 <= P	All	🟩	🟩	🟩	🟥	🟥	🟧	🟥
11	Generators	P < 8	Very Low (<25%)	🟩	🟩	🟩	⬜	🟢	⬛	🟢
12	Generators	8 <= P < 75	Low (<50%)	🟩	🟩	🟩	🟥	🟢	⬛	🟥
13	Generators	75 <= P < 560	Low (<50%)	🟩	🟩	🟩	🟥	🟧	⬛	🟧
14	Generators	560 <= P	Very Low (<25%)	🟩	🟩	🟩	🟥	🟥	⬛	🟥



Key	TRL	Year at which sales would reach 100% if TCO for the powertrain is the least-cost option (i.e. availability and ramp-up in sales would be 5 years prior)
🟩	8+	2025
🟢	6 - 7	2030
🟧	4 - 5	2035
🟥	1 - 3	2040+
⬜	0	Technically feasible, but no evidence of ongoing development found
⬛	-	Powertrain viewed as incompatible with archetype, no development expected

5.1.1.2 Least cost sales, stock and outputs modules

For each year that the TCO of all available powertrains for a given IND-database row is calculated (2020, 2025, 2030 … 2050), 100% of sales are assigned to the powertrain that has the lowest TCO. For all TCO years from 2030 onwards, if a new powertrain is chosen compared to the previous TCO year, sales transition linearly between the two technologies in the four years between, this is illustrated in Figure 31.[258]

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[257] The modelled availability here is slightly different to that presented in 3.8.2: BE-Electricity is orange for archetype 12 in sub-section 3.8.2 rather than red as used here. The discrepancy is due to new announcements post the running of the least-cost pathways model. These changes can be used by DESNZ in future modelling.

[258] For the TCO year 2020, only the incumbent powertrain is available. For the TCO year 2025, if a non-incumbent powertrain is the cheapest, there is no linear transition between incumbent and new powertrain. In 2024, 100% of sales will be the incumbent and in 2025, 100% of sales will be of the new powertrain. This is to ensure that no non-incumbent powertrains are sold at the present day, as reported in the NAEI database.

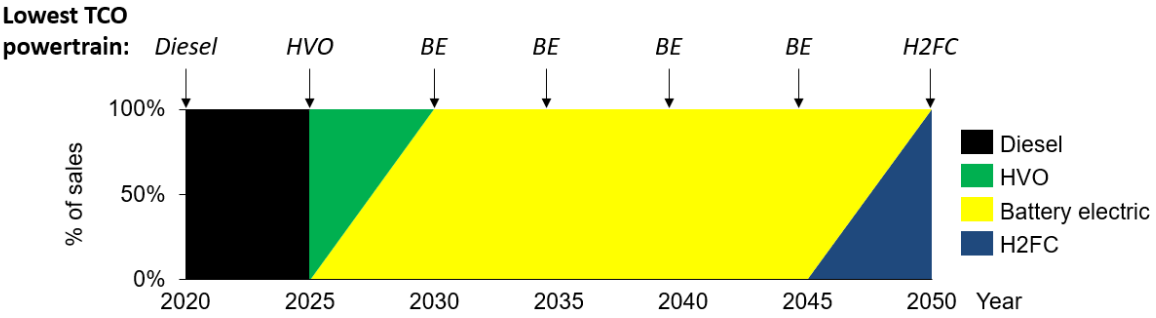

Figure 31 – Illustrative example of how the lowest TCO powertrains are converted into percentage sales

These sales are then combined with the 2021 stock data from the IND-database and NAEI database to produce a stock projection for each IND-database row broken down by powertrain type. As time progresses through the model, older machinery is gradually removed from the stock resulting in a gradual transition to alternative powertrains as these new technologies are introduced and older incumbent machines are removed. The rate of removal of old machinery is determined from the 2021 NAEI Database which provides a minimum, average and maximum lifetime for each IND-database row. Machinery is gradually removed from the stock between their minimum and maximum lifetime, resulting in an average lifetime which is consistent with the NAEI Database.

The machinery stock broken down by powertrain calculated above is then processed to provide an annual cost projection for the least-cost pathway compared to an 'incumbent-only' baseline pathway where no powertrain switching occurs. Additionally, the total tank-to-wheel (TTW) annual emissions of the pathway are calculated compared to the baseline pathway, and reductions in emissions are split between the powertrains that lead to the TTW emissions reduction.

5.1.2 Key assumptions and limitations of the least-cost pathways model

The key assumptions made within the model are summarised below.

- **The TCO is calculated every 5 years and 100% of sales are assigned to the cheapest powertrain:** In reality, a mix of technologies is expected, especially in the short term as multiple solutions are developed and tested. However, this model calculates the least-cost pathway that the majority of industrial NRMM is likely to follow. This means that multiple solutions may be selected within a single archetype, but a single solution is identified for each IND-database row.
- **Industrial NRMM cannot be scrapped prematurely to switch to another powertrain:** Alternative powertrains are only introduced through new sales, which includes the drop-in fuels B20 and HVO. The model uses the TCO calculations to assign new sales to the cheapest powertrain.
- **Carbon costs use WTW emissions:** The carbon cost is evaluated and forms part of the TCO calculations using WTW emissions, to account for the costs associated with the impact of indirect emissions.
- **Biofuels are modelled to have zero TTW emissions[259]:** The TTW emissions of HVO have been modelled as zero and B20 as 80% of diesel, to be consistent with the RTFO. In reality there are CO_2, NOx and PM tailpipe emissions from machinery running on HVO or B20, which will be at similar levels than for incumbent powertrains.

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[259] The residual emissions and emissions reductions presented in Section 5.3 are for TTW emissions.

- **A proportion of industrial NRMM is classified as hard-to-deploy:** This percentage varies by sector (construction, mining, waste, ports, other), see sub-section 2.1.4 for further details. Zero tailpipe CO_2e emission solutions have a 10-year availability delay built in for these hard-to-deploy machines. These estimates are highly uncertain.
- **Social fuel costs are used:** Baseline modelling has been performed using LRVC fuel costs rather than retail costs. The same cost for hydrogen is used for both hydrogen ICE fuel cell, even though hydrogen ICE can technically run on lower purity hydrogen. The electricity cost is based on the cost of grid electricity, this does not consider other solutions such as on-site renewables and battery storage systems.
- **Efficiency measures are deployed equally over time for all pathways and the baseline scenario, and do not have an implementation cost associated with them:** As no detailed costs of the efficiency measures were found, the efficiency measures are applied equally across all pathways to reduce the impact of not having cost data attributed to them.

The key limitations of the least-cost pathways model are described below.

- **Machinery lifetime does not vary between powertrains:** The machinery lifetime for all alternative powertrains is assumed to be the same as the incumbent powertrain. There is insufficient evidence currently to vary machinery lifetime between powertrains for industrial NRMM due to the low commercial deployment of novel technologies,[260] and any differences seen currently may change in the future as technologies develop and increase their commercial availability. If machinery lifetime does vary with powertrain, this will have a material impact on the relative TCO of each powertrain (i.e., if a machine can run for an extra year, the machine needs replacing less often, resulting in a more favourable TCO).
- **Machinery CAPEX is assumed to vary only by powertrain component cost:** The model assumes that the CAPEX of a machine with powertrain x is:

$$\begin{aligned}&Machine\ CAPEX\ powertrain\ x\\ &\quad = (Incumbent\ machine\ CAPEX - Incumbent\ engine\ cost) + cost\ of\ powertrain\ x\end{aligned}$$

  This assumes that the only difference in cost is the difference between the two powertrains (including any energy storage costs such as batteries or hydrogen fuel tanks). This is unlikely to be the case for new technologies currently, as additional costs for R&D and supply chain development will result in higher costs for machinery with novel powertrains. However, this assumption may be more accurate when the powertrain option reaches widespread commercial deployment, which is the earliest that the powertrain can be deployed within the model.
- **There are no limits imposed on fuel or electricity supply:** Due to modelling constraints, a limit on the maximum amount of a fuel used in a year has not been included. This means that the model may predict a higher demand for a fuel than can be reasonably provided. A supply restriction can be indirectly applied by increasing the price of the fuel, reducing its use.
- **There are no adjustments made to the energy consumption of a machine to account for any potential additional machinery weight associated with heavier batteries or hydrogen tanks:** The same useful energy demand is used across powertrains (reducing over time with the deployment of efficiency measures), with the powertrain efficiency ultimately dictating the fuel consumption of different abatement options. For some industrial NRMM, extra weight may not necessarily result in higher energy consumption (e.g., for an excavator which does not move often or a generator), as well as some incumbent machinery which already carries additional weight for stability, reducing the weight impact of batteries or hydrogen tanks. Therefore, any additional energy consumption related to weight increases

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[260] The available evidence is discussed in section 3.2

was considered less important to industrial NRRM compared to on-road sectors, with other uncertainties and limitations (such as refuelling and recharging requirements) considered to have a higher impact on technology deployment.

- **HVO and B20 can be selected by all incumbent machinery, not just those running on diesel:** In reality, HVO and B20 cannot be used in a petrol or LPG engine. For these engines, other suitable drop-in fuels may be used instead (e.g., e-gasoline or E10 for petrol), which are not explicitly modelled.
- **Additional benefits of reducing emissions are not monetised within this model:** Whilst a carbon cost is included in the TCO, additional benefits linked to lower emission technologies such as reduced air and noise pollution and health benefits are not accounted for within the model. These additional benefits could be significant.
- **Total machinery stock does not change depending on the abatement options chosen:** Potential secondary impacts on machinery stock such as a reduction of the number of machines required to perform the same task due to improved efficiencies, or an increase in generator numbers to power or recharge electric machinery are not considered in the model.

5.2 Scenario descriptions

There are multiple potential pathways to decarbonise industrial NRMM, which are dependent on the development and availability of low carbon technologies, the decarbonisation pathways chosen in other sectors and policy support provided. Three pathways have been investigated using the least-cost pathways model developed as part of this project. These are representative of the range of possibilities, but inevitably do not cover the entire range of possibilities:

- **Scenario 1:** This scenario represents an **unconstrained view** of the technical and economic potential of abatement options: supply constraints (e.g., for drop-in fuels, batteries, hydrogen) are not considered. Powertrain, fuel and infrastructure costs are as presented within this report and abatement options reaching commercial availability are as described in section 3.8.
- **Scenario 2:** This scenario is similar to Scenario 1, apart from a supply constraint on HVO for industrial NRMM modelled by increasing the cost of HVO. This pathway assumes that the maximum amount of HVO available annually to industrial NRMM is roughly equivalent to the total amount of HVO sold through the RTFO in 2022 to all sectors (270 million litres[261]), resulting in higher HVO prices as demand exceeds supply.
- **Scenario 3:** This scenario builds on Scenario 2 with further limitations set on the archetypes that battery electric can be deployed in. Battery electric is set as unsuitable for all generators (archetypes 11-14) and high utilisation mobile machinery (archetypes 6-8). This represents a world where pure electric alternatives to generators such as delivery of battery packs or acquiring grid connections become significantly more challenging than currently thought, thus battery electric solutions for generators are not widespread.[262] Additionally, battery electric is deemed unsuitable for high-utilisation machinery, where there might not be sufficient time or grid capacity for machinery to be charged between uses.

These three scenarios were run within the developed least-cost pathways model, with the key outputs discussed below.

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[261] https://www.gov.uk/government/statistics/renewable-fuel-statistics-2022-fourth-provisional-report

[262] There are some solutions for remote off-grid battery already being developed by Nordic Booster and PortaCell, see section 3.4.2. The scenario aims to explore the case where these solutions remain limited to small volume/niche cases.

5.3 Scenario modelling results

Results of the modelled decarbonisation scenarios described above are presented alongside analysis of the baseline. The baseline (counterfactual) assumes that industrial NRMM do not switch powertrain type and all sales are allocated to the incumbent powertrain for each machinery type. The efficiency gain deployment pathways described in Section 3.8.3 were applied to all pathways, including the baseline unless otherwise stated.

The impact of the projected efficiency gains alone can be seen in Figure 32. In the baseline, the fuel use (and equivalently TTW emissions) is 25% lower in 2050 than in 2021, despite an increase in stock of 19%. Excluding efficiency gains, the same 19% growth in industrial NRMM stock results in a 15% increase in fuel use (and equivalently TTW emissions). Across all scenarios, there is a mismatch in the proportion of fuel used by petrol-powered industrial NRMM and the stock of such machines[263] – this can be seen when comparing the fuel use and stock graphs for any scenario (e.g. Figure 36 and Figure 37).

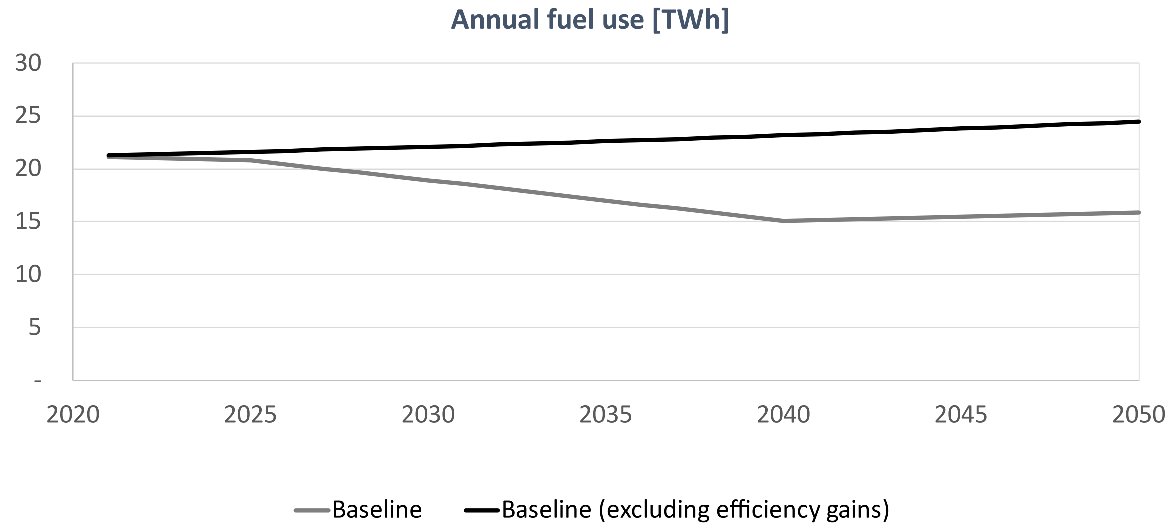

Figure 32 – Baseline scenario fuel use with and without efficiency measures

5.3.1 Scenario 1

Equipment rapidly transitions to HVO due to significant carbon cost saving compared to diesel (see Figure 33). This transition to HVO is followed shortly by electrification of low-power archetypes (1, 3, 9, 10 and 11) in the early 2030s. As battery costs decrease[264] and larger battery electric machines become available, industrial NRMM with higher utilisation rates and power ratings start to electrify from 2035 onwards. This scenario also sees industrial NRMM powered by incumbent fuels entirely phased out by 2044. Moreover, electrification ultimately displaces HVO as the dominant fuel with the latter almost entirely phased out by 2050. Overall, emissions are reduced by around 96 $MtCO_2e$ cumulatively between 2021 and 2050 in Scenario 1 compared to the baseline scenario (including efficiency gains).

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[263] This is largely due to just under 1.2 million units (around 60% of the industrial NRMM population) of low-powered and low utilisation petrol generators within Archetype 11 only accounting for around 2.5 TWh of fuel use in 2021 (around 12% of total fuel used by industrial NRMM).

[264] As observed in the on-road electric vehicle sectors (See sub-section 3.3.1 for further details).

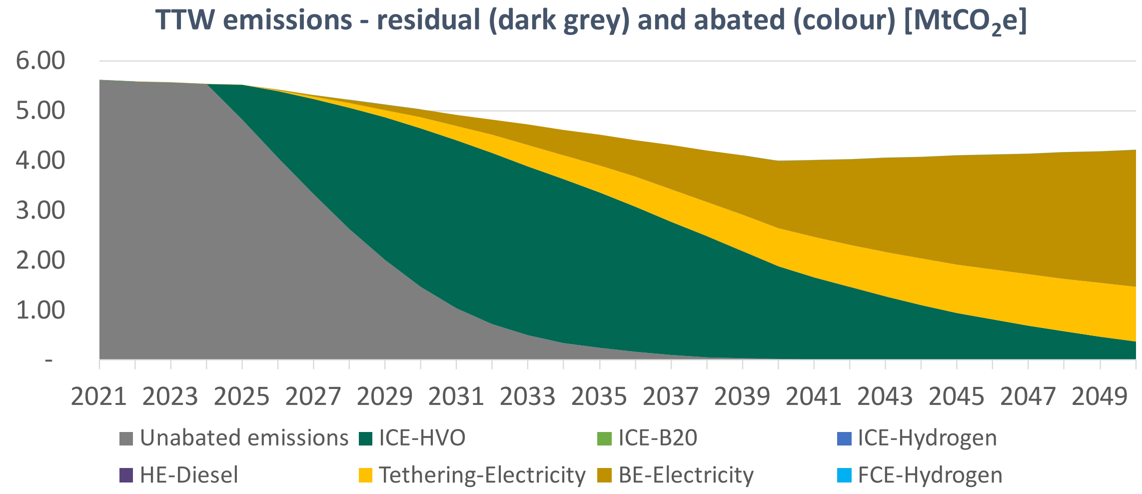

Figure 33 – Scenario 1 residual and abated CO_2e emissions profile

The switch to HVO sees industrial NRMM TTW emissions drop sharply from 2025 to 2035 as incumbent fuels are phased out (see Figure 34). Compared to 2021 levels, TTW CO_2e emissions from industrial NRMM in Scenario 1 are 96% and 100% lower in 2035 and 2044 respectively – these figures also include savings from the deployment of efficiency measures. The £84.5bn resource cost[265] of the decarbonisation pathway in Scenario 1 across all industrial NRMM is slightly lower than the baseline pathway at £87.4bn (Figure 35).[266] The majority of savings come from the lower energy costs from electric solutions as, even though the price of the fuel is higher, the powertrain is over twice as efficient as diesel (33% for diesel, 80% for battery electric including charging losses, 90% for tethering), resulting in a lower cost per kWh of useful work (see Figure 29, sub-section 5.1.1).

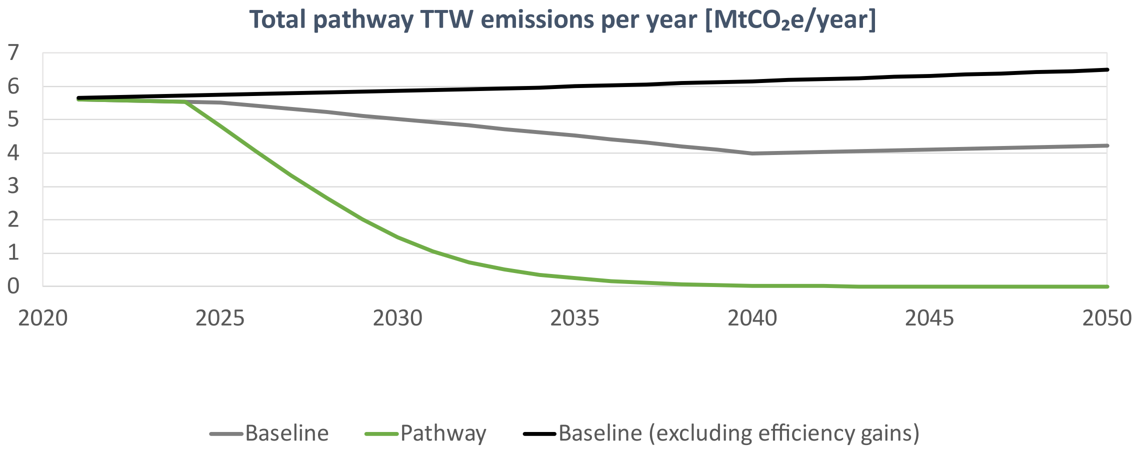

Figure 34 – Scenario 1 total decarbonisation pathway emissions compared against the baseline pathway, with and without efficiency gains

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[265] The resource cost is the sum of the machinery CAPEX of purchased equipment plus the cost to run all machinery (fuel costs based on LRVC as for the TCO calculations) for the specified year. This excludes the carbon costs included in the TCO calculations.

[266] Although the total pathway resource cost (excluding carbon costs) is lower than the incumbent pathway, this does not mean that this pathway would be chosen if carbon costs were not included in the TCO. For machinery running on HVO, the resource costs will be higher than the baseline pathway as HVO is more expensive than diesel. However, this slight increase in resource cost is outweighed by the reduction in resource cost from machinery switching to battery electric or tethering, resulting in an overall lower cost pathway across all industrial NRMM than in the baseline.

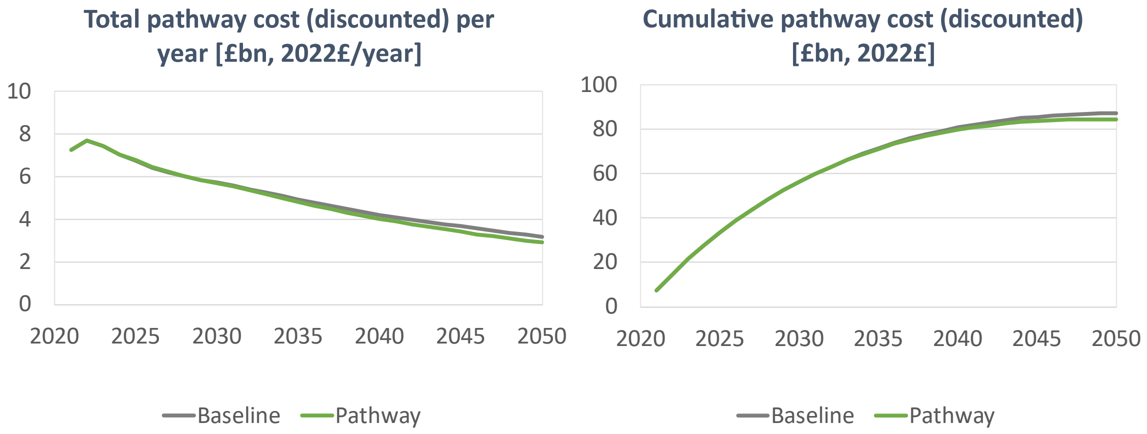

Figure 35 – Scenario 1 annual pathway resource cost [left]; cumulative pathway resource cost [right]

As shown in Figure 36, the superior efficiency of electric powertrains over internal combustion engines and the introduction of efficiency measures results in a 70% reduction in total energy used by industrial NRMM from 2021 to 2050, despite a 19% increase in the total stock over the same period (see Figure 37) – efficiency gains alone accounted for a 25% reduction in the baseline (see Figure 32). At its peak in 2032, 12 TWh of HVO is required by industrial NRMM, equivalent to 1.3 billion litres of HVO – almost five times the amount of HVO traded under the RTFO in all transport sectors in 2022 (Department for Transport, 2023). In this scenario, hybrid, B20 and hydrogen options (FC or ICE) are never identified as the least-cost powertrain, with machinery exclusively transitioning to HVO or electric powertrains (BE or tethering).

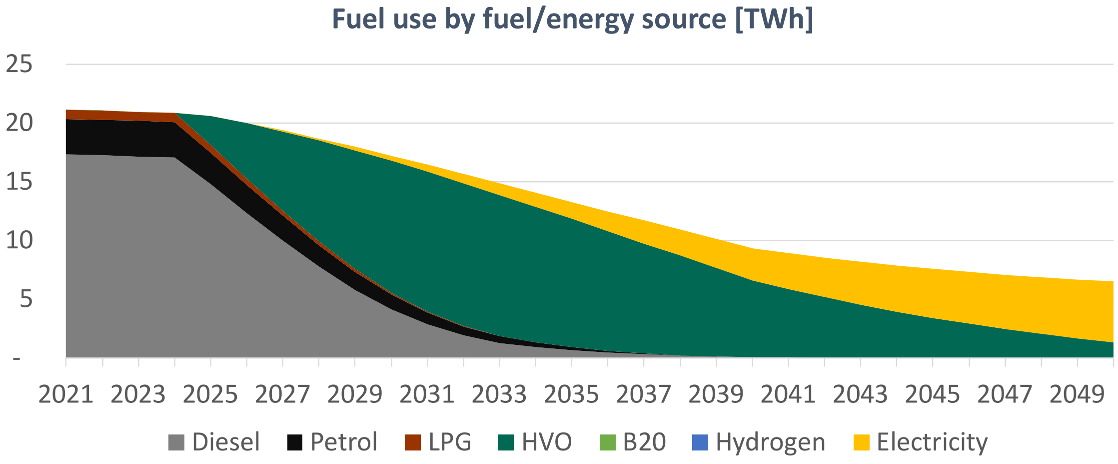

Figure 36 – Scenario 1 fuel use by fuel or energy source

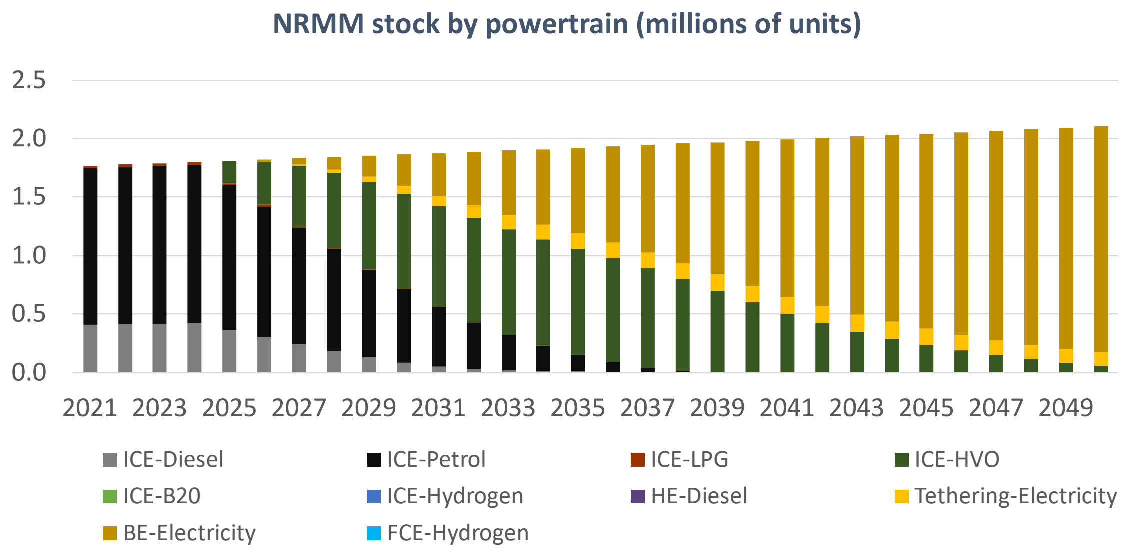

Figure 37 – Scenario 1 industrial NRMM stock by powertrain[267]

5.3.2 Scenario 2

Limiting the supply of HVO in Scenario 2 shows a slower overall rate of decarbonisation (see Figure 38), where the reduction in emissions through a transition to HVO, B20 and hybrid powertrains from 2025 is much lower than Scenario 1. This is particularly the case for B20 and hybrid powertrains which have residual TTW emissions associated with their use of diesel. Consequently, this scenario shows incumbent fuels still being used by 2050 (largely in hybrid-diesel equipment). However, the limited availability of HVO does not impact the electrification of industrial NRMM where, like Scenario 1, this starts in the early 2030s and follows an identical trajectory to that shown in Figure 33 where electrification dominates the market by 2050. Overall, emissions are reduced by 63 $MtCO_2e$ cumulatively between 2021 and 2050 in Scenario 2 compared to the baseline scenario (including efficiency gains).

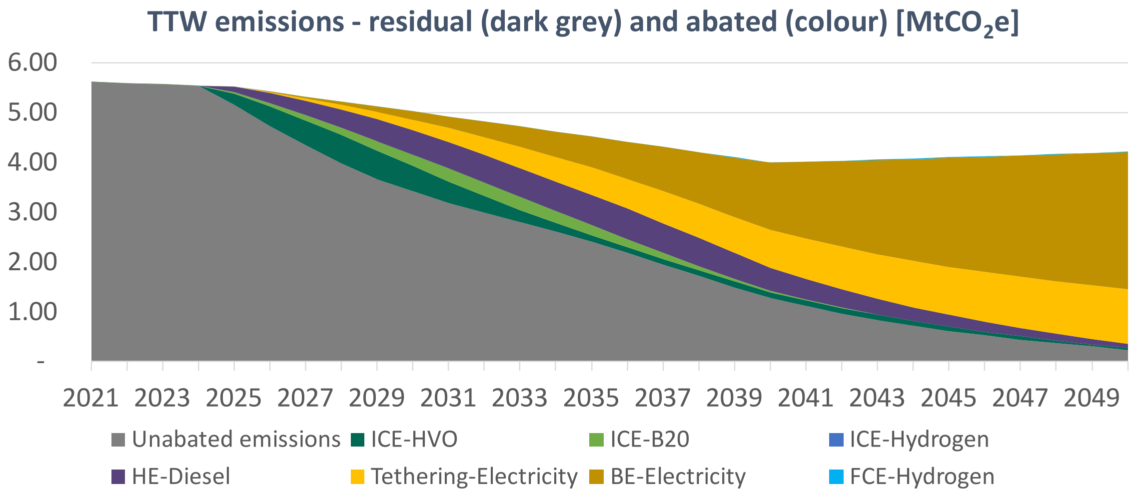

Figure 38 – Scenario 2 residual and abated CO_2e emissions profile

Without the sector-wide switch to HVO seen in Scenario 1, this decarbonisation pathway sees industrial NRMM TTW emissions follow a more gradual decline from 2025 to 2050 as incumbent fuels

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[267] Note that the stock is dominated by petrol powered machinery: these are predominately generators in archetype 11 which account for >60% of the total stock in 2021, but only account for 12% of all fuel use and emissions in 2021.

are slowly phased out (see Figure 39). Compared to 2021 levels, industrial NRMM in Scenario 2 emit 57% and 96% less CO_2e in 2035 and 2050 respectively – these figures also include savings from the deployment of efficiency measures. The remaining emissions in 2050 come from hybrid diesel powertrains, mostly from hard-to-deploy units in archetypes 4 and 6. In these two archetypes, transitioning to either battery electric or hydrogen fuel cells can only happen after 2045 for hard-to-deploy subsets, therefore there is a substantial number of machines still in use in 2050 which are not zero TTW emissions.[268] The £84.1bn resource cost of the decarbonisation pathway in Scenario 2 is slightly lower than the incumbent's £87.4bn (Figure 40), with most of the savings coming from the reduced fuel cost of electric machinery. Despite the HVO supply limit slowing down the reduction in emissions, Scenario 2 still results in substantial emissions abatement.

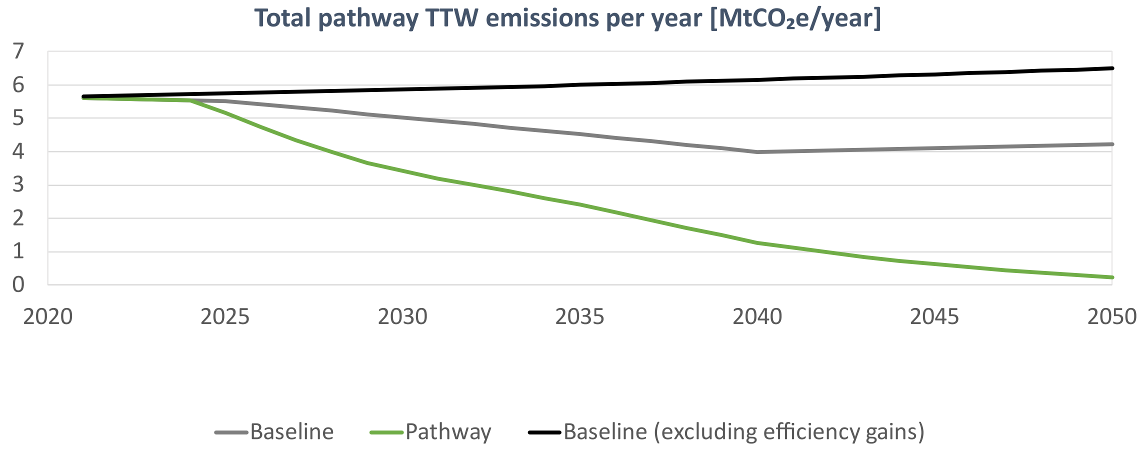

Figure 39 – Scenario 2 total decarbonisation pathway emissions compared against the incumbent (i.e., no fuel switching) pathway, with and without efficiency gains

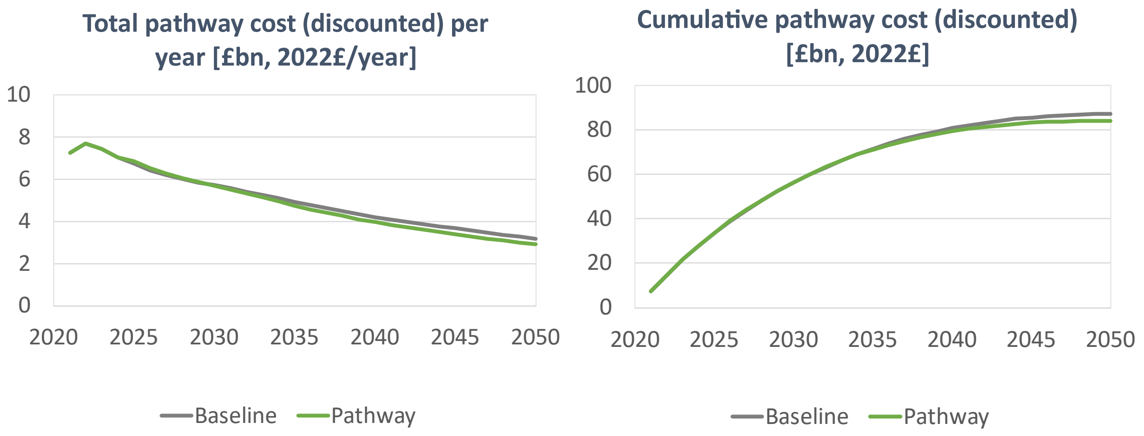

Figure 40 – Scenario 2 annual pathway resource cost [left]; cumulative pathway resource cost [right]

Given that the HVO supply constraint in Scenario 2 did not impact the electrification of industrial NRMM seen in Scenario 1, and the fact that electric powertrains are more efficient than ICE, a similar 70% reduction in total energy used by industrial NRMM from 2021 to 2050 to that reported in Scenario 1 can be seen (Figure 41). With regards to the stock of industrial NRMM, it can be seen from Figure 42 that electrification is still identified as the dominant powertrain by 2050, albeit via a transition through hybrid powertrain given HVO's limited supply. The substantial amount of B20 fuel use that can be seen in

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[268] For hard-to-deploy archetypes 4 and 6, the only zero CO_2 tailpipe emission solution available before 2045 is H_2 ICE (available from 2041), however this does not have a TCO lower than diesel hybrid so is not chosen.

Figure 41 compared to its limited role in abating emissions (Figure 38) is due to 80% of the fuel being diesel (B20 is classed as a separate fuel but is effectively 20% B100 and 80% diesel). The amount of biodiesel required to satisfy the B20 demand is not likely to suffer from a lack of supply, as it significantly less than currently sold through the RTFO (<1 TWh/year, where current RTFO supply is 13 TWh/year (Department for Transport, 2023)). A limited amount of hydrogen use (too small to be seen on the graph below) is predicted in Scenario 2 where hard-to-deploy (see sub-section 2.1.4) machinery within archetype 12 (8 – 74 kW and <50% utilisation generators) adopt hydrogen fuel cells for new sales between 2035 – 2045. In this period, incumbent, HVO, B20, hybrid and hydrogen fuel cells are the only powertrains available for these generators. In Scenario 1, new generators use HVO until transitioning to battery electric from 2045. However, in Scenario 2, HVO is more expensive, so hydrogen fuels are the cheapest powertrain and are adopted for new sales between 2035 and 2045. Battery electric solutions still are cheaper by 2050 and new sales start transition to battery electric from fuel cell in 2045. Hydrogen use amounts to 0.03 TWh in 2050 (0.5% of the 6.20 TWh for the total stock).

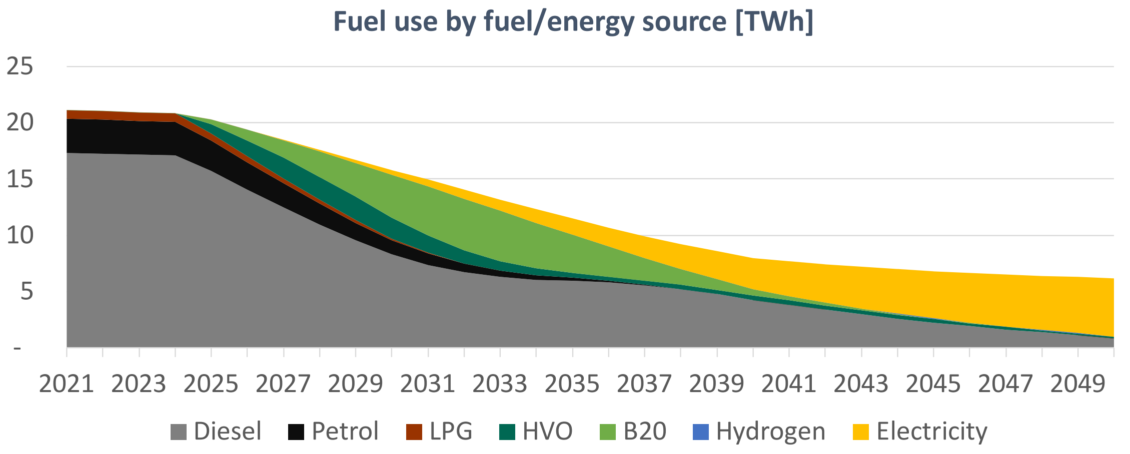

Figure 41 – Scenario 2 fuel use by fuel or energy source

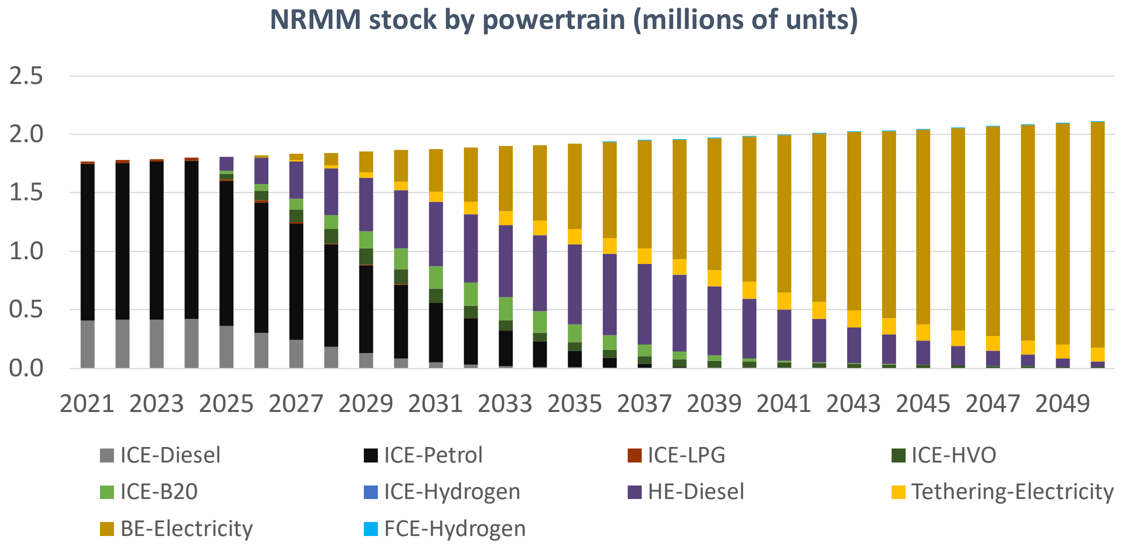

Figure 42 – Scenario 2 industrial NRMM stock by powertrain

5.3.3 *Scenario 3*

In addition to the limited HVO supply in Scenario 2, Scenario 3 restrictions on the availability of battery electric machinery result in a decarbonisation pathway that is very similar to that of Scenario 2, with the key difference in the introduction of hydrogen as an abatement solution from 2035 onwards for higher utilisation archetypes and generators (see Figure 38 for Scenario 2 pathway, Figure 43 for Scenario 3). Electrification is still seen as the dominant solution (with regards to abated emissions); however, hydrogen can be seen to play a more substantial role compared to the other scenarios. Overall, emissions are reduced by about 61 $MtCO_2e$ cumulatively between 2021 and 2050 in Scenario 3 compared to the baseline scenario (including efficiency gains).

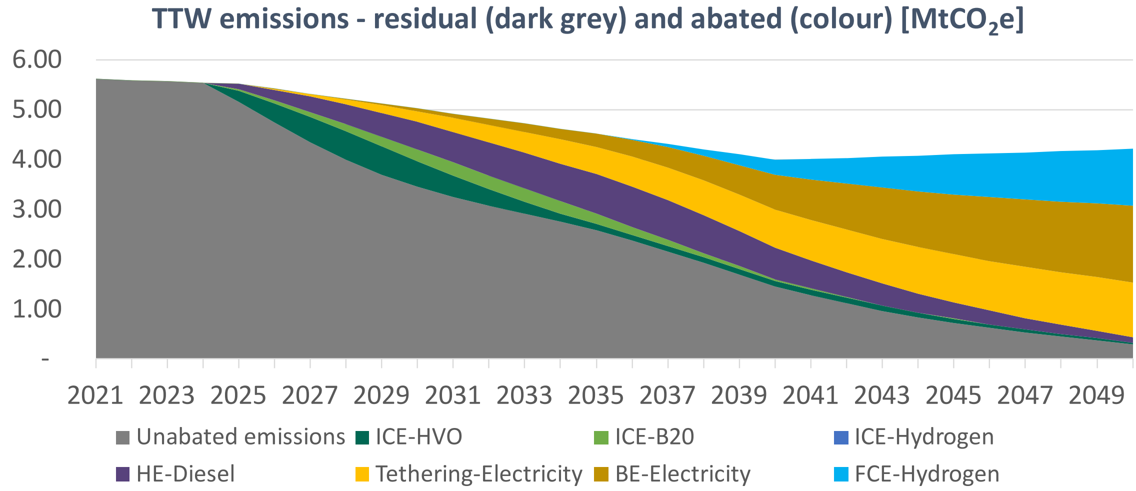

Figure 43 – Scenario 3 residual and abated CO_2e emissions profile

As in Scenario 2, this decarbonisation pathway sees industrial NRMM TTW emissions follow a more gradual decline from 2025 to 2050 than Scenario 1 as incumbent fuels are slowly phased out (Figure 44). Compared to 2021 levels, industrial NRMM in Scenario 3 emit 54% and 95% less CO_2e in 2035 and 2050 respectively – these figures also include savings from the deployment of efficiency measures. The remaining emissions come from hard-to-deploy units, predominately from archetypes 4 and 6 as seen for Scenario 2. Emissions in 2050 are slightly higher in Scenario 3 than Scenario 2, as archetypes 7 and 8 (High utilisation and power mobile machinery) can only transition to hydrogen fuel cells after 2045, whereas in Scenario 2 they start transitioning to battery electric after 2040. The £84.8bn resource cost of the decarbonisation pathway in Scenario 3 is slightly lower than the incumbent pathway of £87.4bn (Figure 45), with most of the savings coming from the reduced cost of fuel for electric and hydrogen machinery compared to diesel.

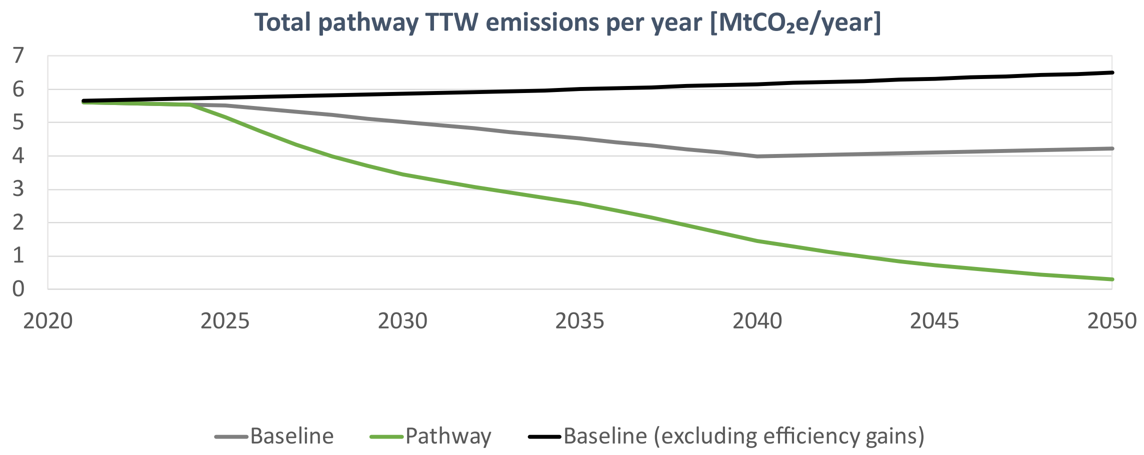

Figure 44 – Scenario 3 total decarbonisation pathway emissions compared against the incumbent (i.e., no fuel switching) pathway, with and without efficiency gains

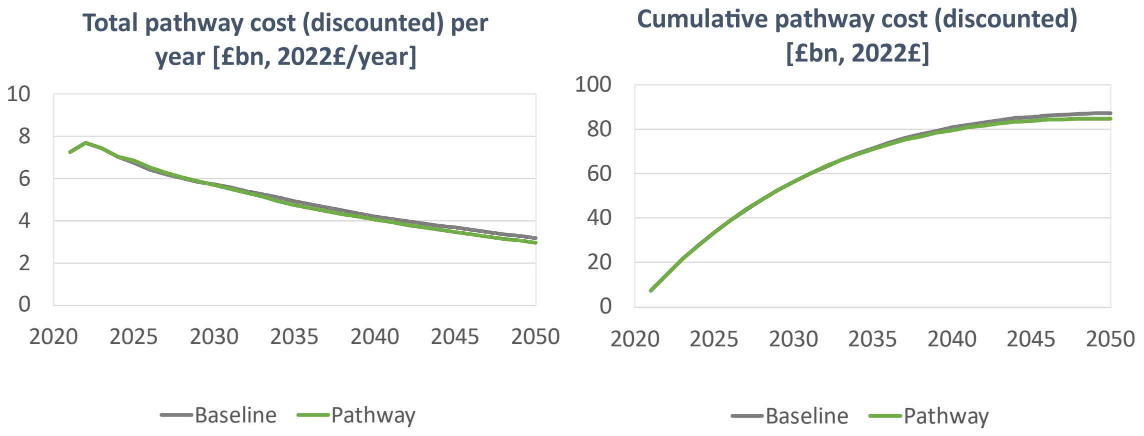

Figure 45 – Scenario 3 annual pathway resource cost [left]; cumulative pathway resource cost [right]

Given the deployment of hydrogen powertrains in Scenario 3, their lower efficiencies compared to electric options result in a lower reduction in total energy used by industrial NRMM from 2021 to 2050 (Figure 46; 65% reduction compared to 70% for both Scenarios 1 and 2). Comparing the fuel use and stock levels of hydrogen-fuelled industrial NRMM in Figure 46 and Figure 47, it can be seen that electricity is the most-used energy source in 2050 despite hydrogen fuel cells being the dominant powertrain. This is primarily due to archetype 11 (<8kW, low utilisation generators) transitioning to fuel cells, which account for 64% of population but only 12% of fuel used in 2021. All of hydrogen's fuel consumption in Scenario 3 comes from the high utilisation mobile machinery (archetypes 6 – 8) and generators (archetypes 11 – 14), highlighting the potential role for hydrogen in areas where electrification might be too impractical to implement despite the lower operating costs of electrification. Furthermore, as in Scenario 2, a substantial amount of B20 fuel use with little impact on emissions abatement can be seen (B20 is classed as a separate fuel but is effectively 20% B100 and 80% diesel), which is again substantially lower than the current RTFO as discussed for Scenario 2.

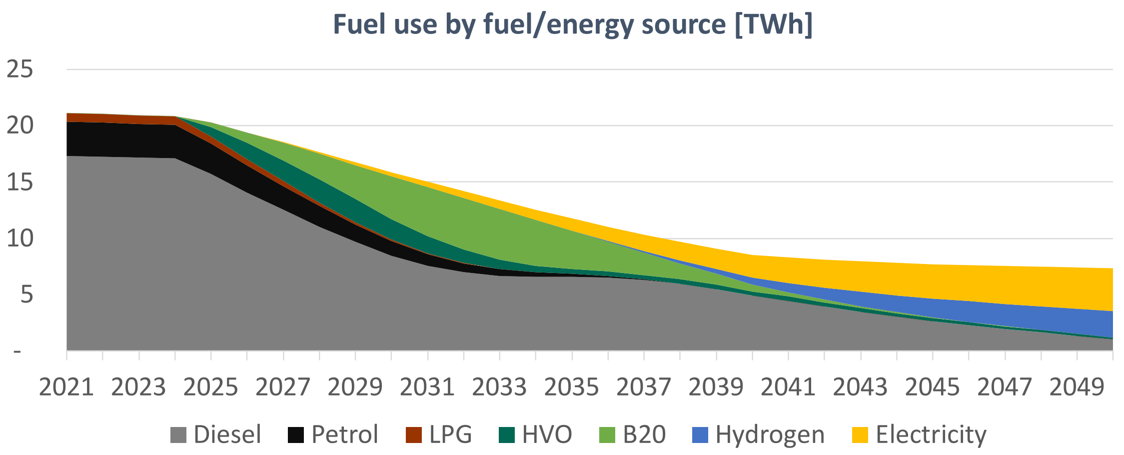

Figure 46 – Scenario 3 fuel use by fuel or energy source

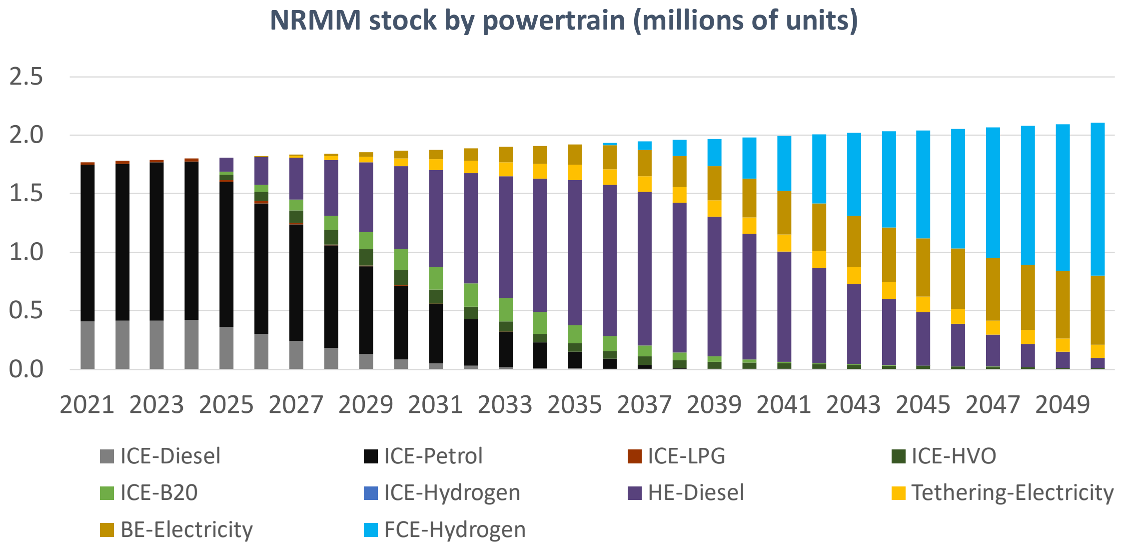

Figure 47 – Scenario 3 industrial NRMM stock by powertrain

5.3.4 Scenario modelling results comparison

Table 63 shows the annual TTW emissions and % reduction from 2021 in 2035 and 2050 for each scenario while Figure 48 shows the total cumulative resource cost and CO_2e emissions for each of the three scenarios by 2050. Since the model was developed as a least-cost pathways model, it is expected that all three scenarios come at a lower cost than the baseline scenario when including the social cost of carbon. However, the key takeaway is that, in this social fuel price setting, all three scenarios show lower cumulative resource costs up to 2050 even when excluding carbon costs. This is largely due to electrified industrial NRMM (prominent across all three scenarios) having significantly lower annual costs compared to the incumbent fuels. Comparing the individual scenario annual cost curves (Figure 35, Figure 40 and Figure 45), noticeable savings (compared to the baseline scenario) coincide with the start of industrial NRMM electrification in the late 2030s. The lower resource costs of Scenario 2 (with supply of HVO limited) compared to Scenario 1 (unconstrained) are due to the lower costs associated with the higher-emission alternatives to HVO (B20 and hybrid powertrains) – see Figure 50.

Table 63 – Annual TTW emissions and percentage reduction from 2021 in 2035 and 2050 for each scenario, and the cumulative discounted resource costs for 2021-2050

Scenario	Annual emissions in 2035 ($MtCO_2e$) (% reduction on 2021)	Annual emissions in 2050 ($MtCO_2e$) (% reduction on 2021)
Scenario 1	0.24 (96%)	0 (100%)
Scenario 2	2.40 (57%)	0.24 (96%)
Scenario 3	2.58 (54%)	0.29 (95%)
Baseline	4.52 (20%)	4.22 (25%)

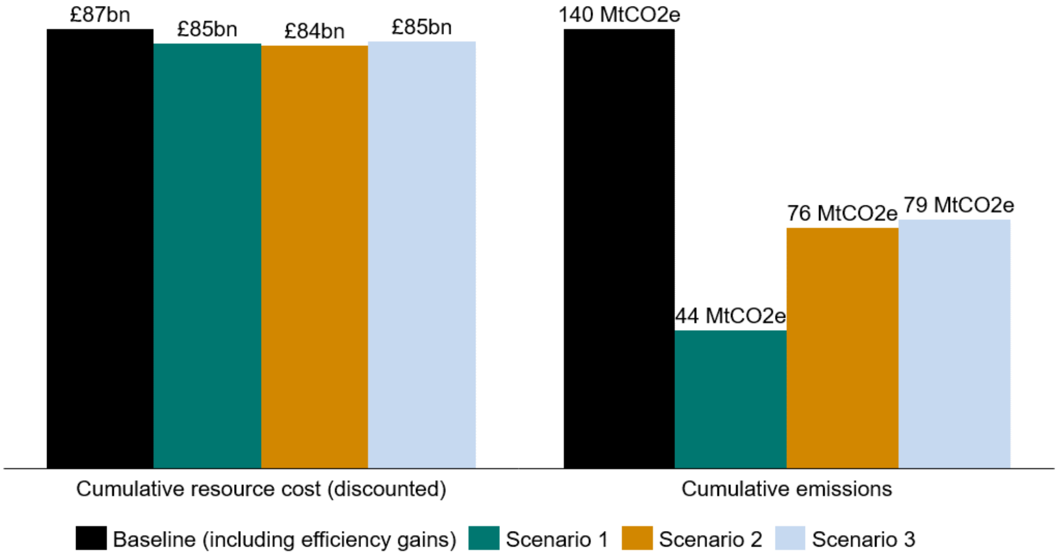

Figure 48 – Comparison of total cumulative pathway resource costs (discounted) and cumulative emissions across modelled decarbonisation pathways between 2021 and 2050. Source: ERM modelling

Figure 49 shows the peak annual fuel or energy consumption values for HVO, electricity and hydrogen across all three scenarios. With regards to HVO, a peak of 12.1 TWh in 2032 was identified in the Scenario 1, which is significantly higher than the current supply of HVO for all transport sectors (see sub-section 5.3.2). In Scenarios 2 and 3, the HVO price is increased to simulate a constraint on supply, leading to reduced HVO uptake, with peaks of 2.1 TWh demand in 2029 for both scenarios.

For electricity, which was identified as the dominant solution in all scenarios, the peak demand occurs in 2050 for all scenarios. It is likely that electricity demand will increase further beyond 2050, as historic stock (running on drop-in fuels or hybrids) is phased out completely for electric solutions (and hydrogen in Scenario 3). These peaks are 5.2 TWh for both Scenarios 1 and 2, and 3.8 TWh for Scenario 3.

For hydrogen, there is no demand in Scenario 1 and a relatively small peak which occurs in 2046 for Scenario 2. The Scenario 2 peak of 0.04 TWh (1,200 tonnes H_2/year) is due to archetype 12 generators (8 – 74 kW and <50% utilisation) switching to hydrogen fuel cells from 2035 before ultimately transitioning to battery electric starting from 2045. In Scenario 3, as discussed above, hydrogen powertrains largely displace battery-powered equipment in generators and high-utilisation mobile machinery, with peak fuel demand occurring in 2050. Due to the differing powertrain efficiencies, around 2.4 TWh (72,000 tonnes H_2/year) is needed to displace 1.4 TWh of electricity. As with electricity, the demand for hydrogen in Scenario 3 is likely to increase slightly beyond 2050 as historic stock (running on drop-in fuels or hybrids) is phased out for hydrogen and electric machinery.

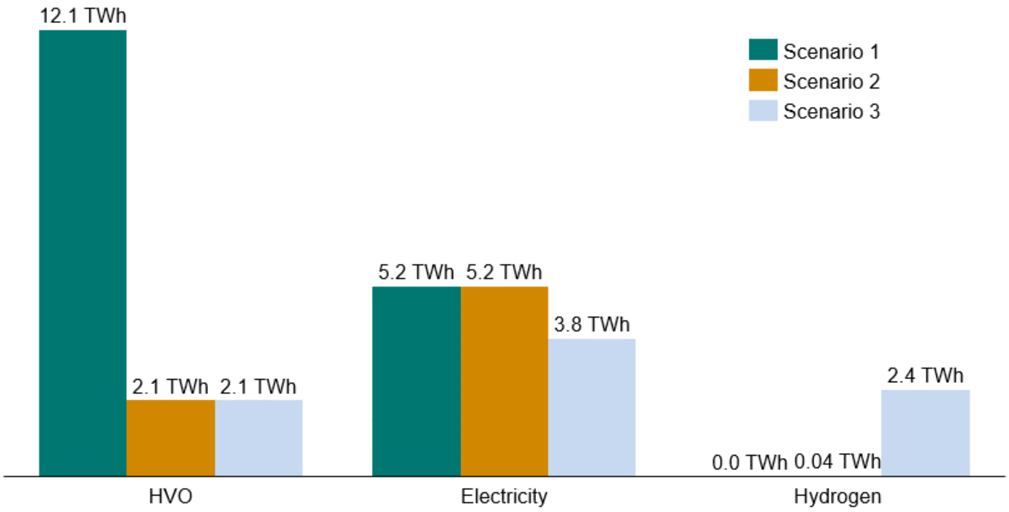

Figure 49 – Comparison of peak fuel or energy consumption values per scenario for HVO, electricity and hydrogen (TWh). Source: ERM modelling

Comparing the profile of industrial NRMM stock by powertrain in Figure 50, Scenarios 1 and 2 are both battery-electric dominated by 2050 transitioning via HVO and hybrid-diesel powertrains respectively. In Scenario 3, hydrogen fuel cells ultimately dominate the market in 2050, largely transitioning via hybrid powertrains.

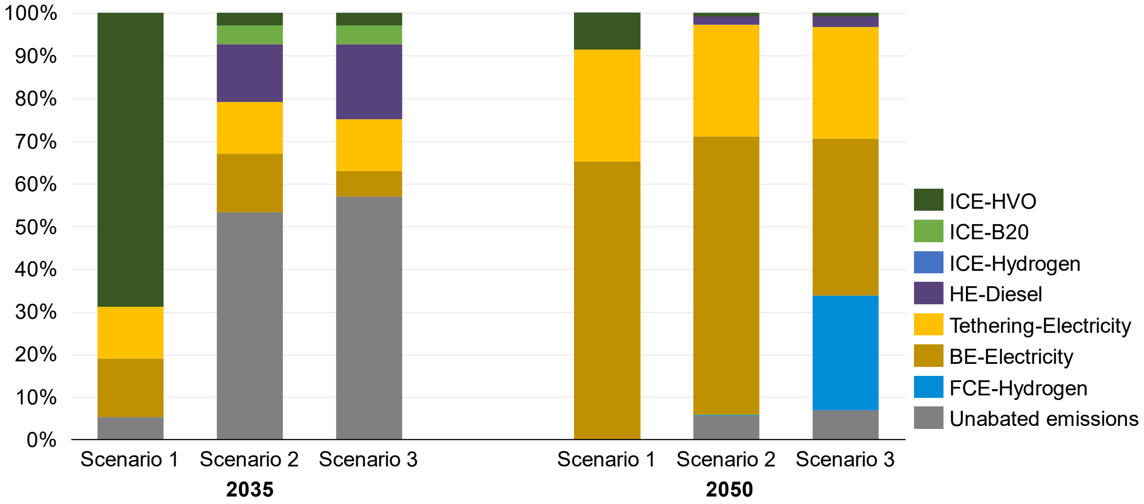

Figure 50 – Industrial NRMM TTW emissions profile in 2035 and 2050 (% relative to the baseline in the same year). Source: ERM modelling

5.3.4.1 Archetype and sector specific comparisons

A cross-scenario comparison of abated emissions by powertrain is presented below for archetype 6 and archetype 11. These were selected as they represent two contrasting contexts:

- **Archetype 6: medium-powered (19 – 129 kW), high utilisation (>50%) mobile machinery.** This archetype accounts for 9% of industrial NRMM fuel use in 2021 and was identified as the most challenging to decarbonise by stakeholders. This was largely due to the lack of low emission options from OEMs and the significant practical refuelling or recharging challenges their demanding duty cycles impose.
- **Archetype 11: low-powered (<8 kW), low utilisation (<50%) generators.** This archetype accounts for 12% of industrial NRMM fuel use and 64% of the population in 2021. Compared

to archetype 6, this archetype has one of the least demanding duty cycles and would potentially be one of the first to decarbonise. Consequently, a more detailed look at the possible pathways to decarbonise archetype 11 is presented.

For the high-utilisation mobile machinery in archetype 6, Figure 51 shows that HVO in Scenario 1 is largely displaced by hybrid-diesel and B20 equipment in both Scenarios 2 and 3. The electrification seen in Scenario 1 is not impacted by the HVO supply limit set in Scenarios 2 and 3, with the key difference being that battery electric NRMM are entirely displaced by hydrogen fuel cells in Scenario 3 for this archetype, as battery electric is deemed unsuitable for archetype 6 in this scenario. For Scenario 2 and 3, there are still unabated emissions in 2050, corresponding to older hard-to-deploy machinery which has not been replaced with newer battery electric or hydrogen fuel cell alternatives which become available from 2046.

Archetype 6 (medium-powered (19 – 129 kW), high utilisation (50%) mobile machinery) abated emissions charts for each scenario:

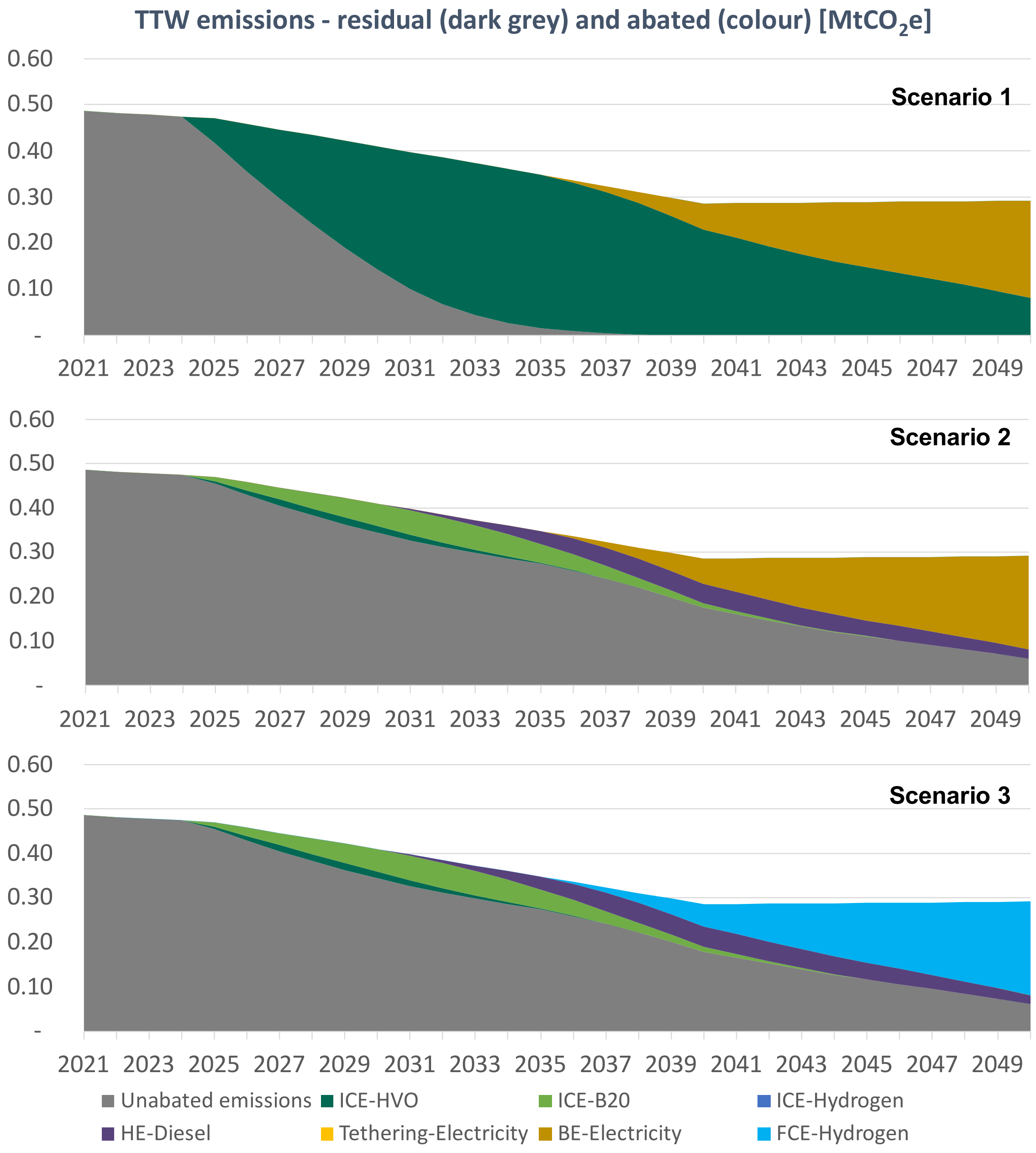

Figure 51 – Archetype 6 abated CO$_2$e emissions across all scenarios

The low-powered generators in archetype 11 (see Figure 52) show a different decarbonisation pathway than archetype 6. For Scenario 1, both archetypes initially transition to HVO from 2025. However, archetype 11 sees the introduction of battery electric units from 2026 with a full transition to battery electric by 2050, whereas the transition to electric only starts in the late 2030s for archetype 6.

As seen for archetype 6, the introduction of the HVO supply limit results in a transition via hybrid powertrains in Scenario 2 versus HVO in Scenario 1. For archetype 11 these hybrid powertrains are almost completely phased out by 2050, whereas they are not fully phased out for archetype 6.

In Scenario 3, an initial transition to hybrids is seen for archetype 11 compared to drop-in fuels for archetype 6. For both archetypes, hydrogen fuel cells start to dominate sales in the late 2030s once available. However, there is still a small number of old hybrid powertrains in use in 2050 for archetype 11, which have not been removed from the stock. As seen for archetype 6, battery electric solutions are deemed unsuitable for archetype 11 in Scenario 3, hence their exclusion.

Archetype 11 (low-powered (<8kW), very low utilisation (<25%) generators) abated emissions charts for each scenario:

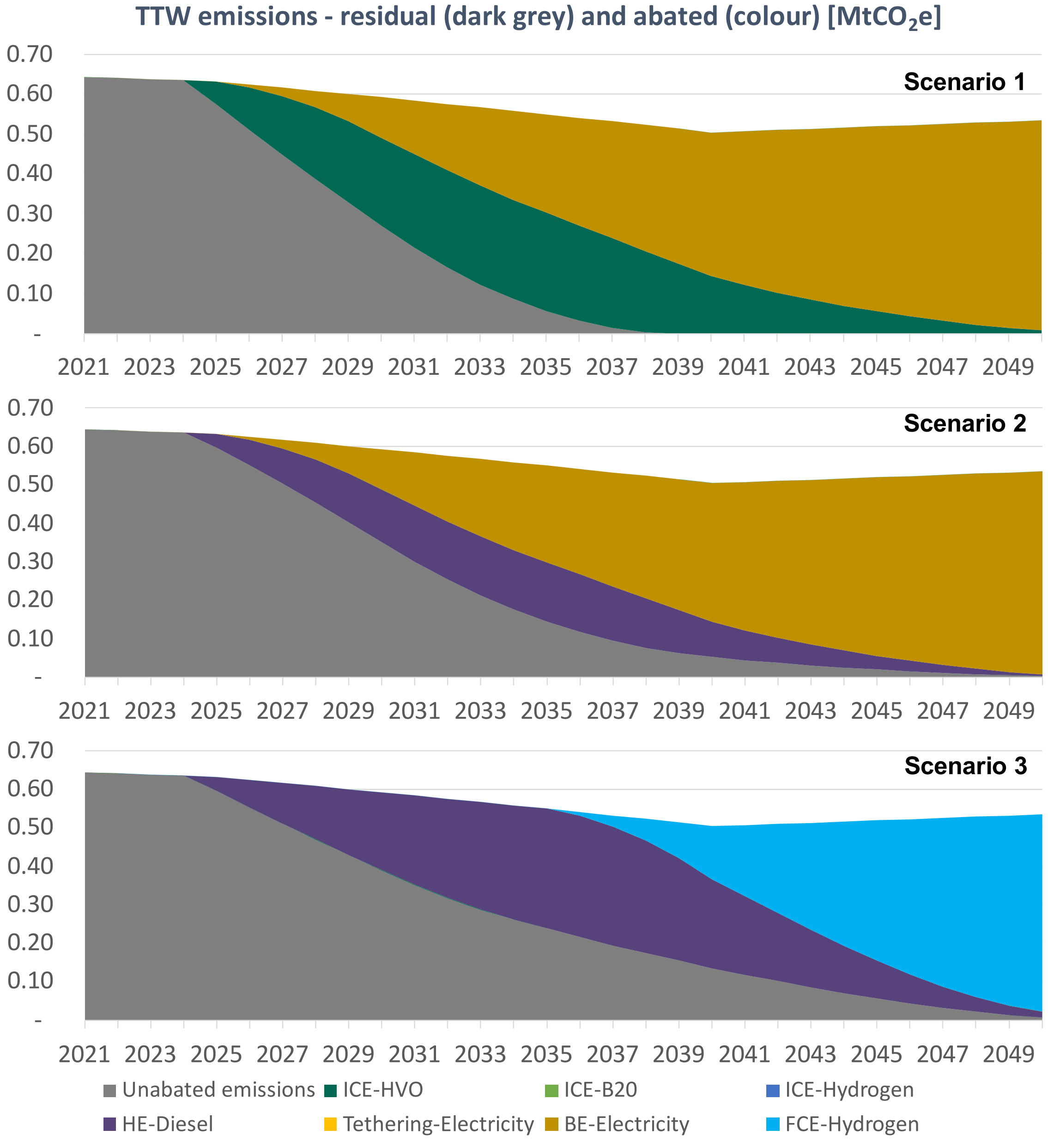

Figure 52 – Archetype 11 abated CO$_2$e emissions across all scenarios

For the construction sector (largest industrial NRMM sector in terms of fuel use), the decarbonisation pathways observed are consistent with the overall scenarios described in sub-sections 5.3.1 – 5.3.3, see Figure 53. The key themes observed are the widespread electrification of industrial NRMM, transitioning through HVO in Scenario 1 and uptake B20 or hybrid powertrains in both Scenarios 2 and 3. Scenario 3 also shows hydrogen fuel cells playing a bigger role and slightly reducing the dominance battery-electric powertrains had shown in Scenarios 1 and 2.

Construction sector abated emissions charts for each scenario:

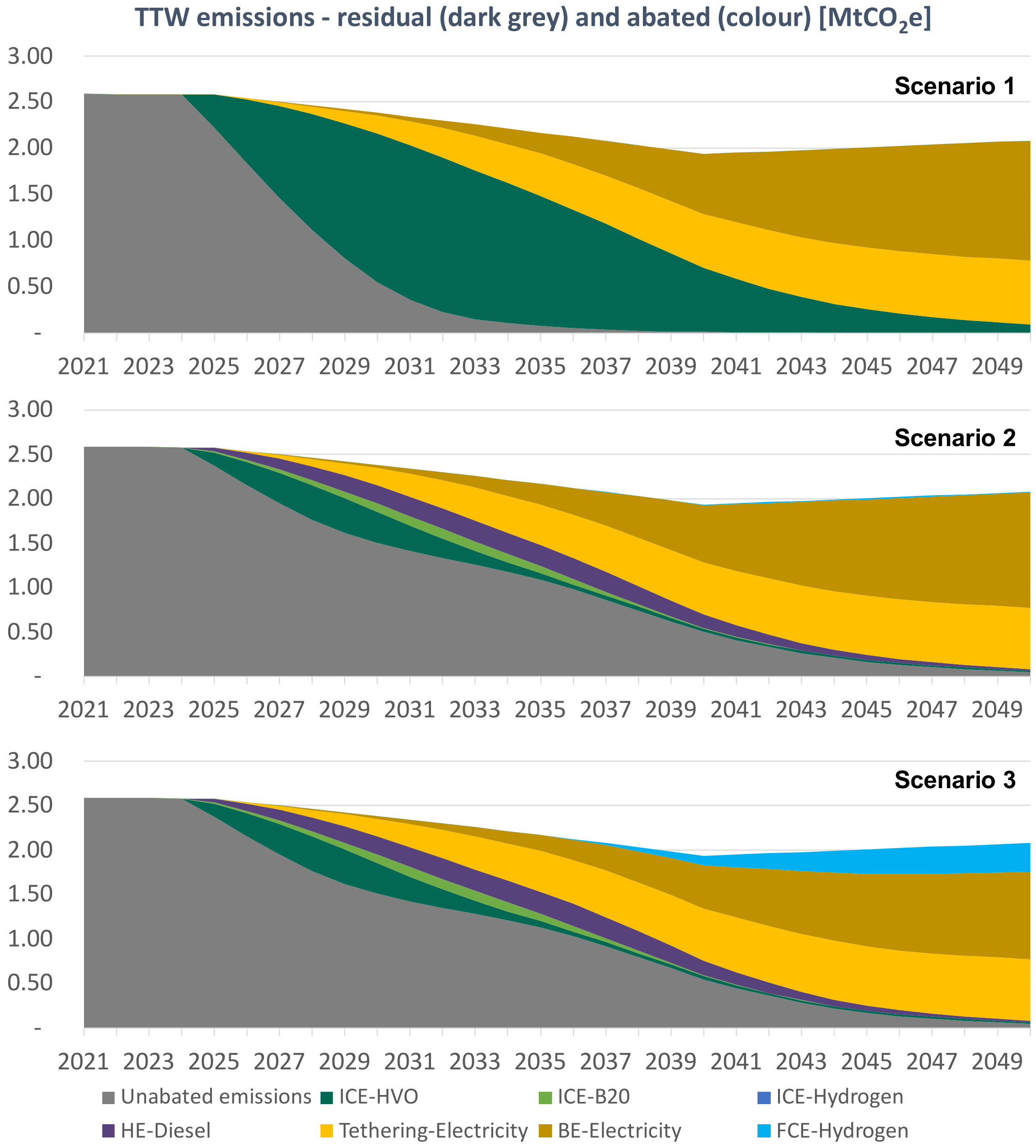

Figure 53 – Construction sector abated CO_2e emissions across all scenarios

6 RISKS, OPPORTUNITIES AND IMPACTS

This chapter discusses the risks and opportunities which occur with or following deployment of abatement options. The first section describes the risks and opportunities of deployment and the impact on market actors. This analysis was developed during the literature review and validated and adapted following feedback from stakeholders. The second section suggests how the risks and opportunities might evolve over time.

As current deployment of many of the abatement options is limited, there is limited literature or data available on the risks and opportunities related to their deployment. Therefore, the impact of each risk and opportunity on a market actor is ERM judgment based on insights gained from literature and validation of hypotheses during stakeholder engagement. Due to the limited evidence available, the analysis of impact on each market actor is necessarily qualitative and is subject to change as the industrial NRMM market and policy develop.

6.1 Risks and opportunities: The impact on market actors

6.1.1 Risk: Multiple solutions

At least within this decade, it is highly likely that multiple decarbonisation solutions for industrial NRMM will be developed and deployed. This is exacerbated by the use of the same type of industrial NRMM across multiple sectors with different requirements. For example, loaders are used in construction, mining and the waste sector. There was consensus among stakeholders that multiple solutions will play a part in the net zero transition; this idea is supported by the range of options being developed for each archetype, as seen in section 3.4.2.

> **‘We may have multiple solutions across different sites – four or five solutions may be needed as there is no ‘silver bullet’.’** OEM

Whilst potentially necessary to meet technical requirements, developing and deploying multiple solutions also has associated risks. This can be split into two broad categories of impact (described in the next sections): 1) loss of economies of scale and 2) the potential obsolescence of abatement solutions as all of the solutions advance technologically.

6.1.1.1 Loss of economies of scale

In the next decade, the loss of economies of scale is likely the most prominent risk associated with developing multiple solutions. For OEMs, each novel powertrain requires its own R&D budget which increases total R&D costs for the company. In the NRMM industry, volumes are low compared to other industries such as passenger vehicles. Therefore, the financial risk is increased as the ratio of R&D costs to margin is smaller.

Costs may also increase for NRMM users, end of life companies, leasing and hiring companies as resources might be split between solutions. For example, if a hiring company transitions to offering only battery electric and hydrogen ICE powertrains, two separate maintenance teams may be required when previously only one team was needed.

> **‘We need decisive infrastructure policy from government; we need to target our R&D and manufacturing investment budget towards a small set of well-defined fuels.’** OEM

> **‘[For deployment on site] The scale of investment is a challenge for multiple fuel types.’** Sector specialist

6.1.1.2 Technology obsolescence

As abatement options advance over time, the best solutions for different use cases, sectors and types of industrial NRMM will become more apparent. Abatement options deployed earlier may become obsolete if they are sub-optimal for the application they were developed for. Investments in these abatement solutions may not pay back or may become stranded assets as a result, exacerbated by the typically long lifetimes of industrial NRMM. Examples of investments specific to abatement options include:

- R&D costs and manufacturing capabilities invested in by OEMs.
- Machinery purchased and operation or maintenance training for NRMM users and lease and hire companies.
- Specialist equipment and infrastructure for end of life processes.

Fuel and infrastructure providers are unlikely to be affected as their product may be used in other sectors, whilst the machinery may have limited applications beyond industrial NRMM.

Table 64 - Summary of the risks associated with multiple abatement solutions. A square indicates potential impact on a market actor.

Risk	OEMs	Users	Lease and hire companies	Site owners /clients	Fuel & inf providers	End of Life actors
Loss of economies of scale	■	■	■			■
Potential obsolescence	■	■	■			■

6.1.2 Risk: Misalignment with the global market

Industrial NRMM is a global market; as such, differences in market requirements could risk the UK’s position as a leading producer of industrial NRMM. This would impact all industrial NRMM market actors.

6.1.2.1 Disruption to exports

The UK is a net exporter of industrial NRMM (see section 2.2.4). If UK industrial NRMM and fuel regulations differ significantly from those in key export markets such as the EU and USA, OEMs and fuel and infrastructure providers may face higher costs complying with multiple standards for different markets. During interviews and workshops, stakeholders also felt that the flow of second-hand machinery to Europe is under threat because of the UK no longer being part of the EU. However, no specific regulatory changes were referenced so it is hard to gauge to what extent this feeling is based on perception or expectation as opposed to being factual.

The availability of fuel and supporting infrastructure for abatement options outside of the UK is also a concern voiced by stakeholders. As discussed in Section 4.3, no countries have NRMM decarbonisation plans yet so there is no developed infrastructure supply chain dedicated to NRMM. However:

- The case of Norway, which has a support programme for electric NRMM, shows that the private sector developed charging solutions dedicated to the construction sector (see section 4.3).
- Among the UK main export markets of the EU, USA and Australia (see section 2.2.4), all have recharging network support programmes or targets – see Table 65. If there is overlap in fuel switching solutions between road transport and industrial NRMM, the skills and supply chains that may develop for road transport could be transferable to the industrial NRMM sector when zero emission NRMM reaches the market. In the case of hydrogen, the table shows the speed of refuelling infrastructure is more uncertain in the USA and Australia than in Europe.

Table 65 – Hydrogen and charging infrastructure status in main NRMM export markets[269]

	Electric charging	Hydrogen
European Union	>400,000 public electric vehicle charging points (EVCPs) as of Dec 2022.[270] Alternative Fuel Infrastructure Regulation has EV charging points targets in place for road transport.[271] *No specific plans for NRMM at national level*	<200 public hydrogen refuelling stations (HRS) as of 2021, most in Germany.[270] Alternative Fuel Infrastructure Regulation has hydrogen refuelling stations targets in place for road transport by 2030.[271] *No specific plans for NRMM at national level*
USA	>130,000 public EVCPs as of February 2023.[272] The Biden administration intends to build a network of 500,000 EV chargers along American highways, partly by providing funding through the National Electric Vehicle Infrastructure program available through 2026.[272] *No specific plans for NRMM at national level*	57 public HRS as of 2023, 56 of which are in California[273] The USA National Clean Hydrogen Strategy and Roadmap outlines targets for the development of hydrogen and related technologies, such as targeted prices for hydrogen production, delivery and storage, but no specific targets for the number of refuelling stations to be built[274] *No specific plans for NRMM at national level*
Australia	Nearly 5,000 public EVCPs across 2,000 locations as of December 2022.[275] Targets for a further 700 fast and ultra-fast charging locations by 2027.[275] *No specific plans for NRMM at national level*	2 HRS currently in Australia.[276] Government has agreed to fund 'at least 4' more between Sydney and Melbourne, potentially by 2026.[277] *No specific plans for NRMM at national level*

In section 2.2.4, the analysis of top export markets is based on trade value, so it is skewed towards destinations which import higher value new machinery rather than lower value second-hand machinery. Stakeholders suggested that other key destinations for second-hand NRMM currently do not have ambitious net zero strategies in place or at all and that these locations are unlikely to have the fuels and infrastructure to support low emission powertrains in the near future. Without publicly available data disaggregating new and second-hand exports, this could not be verified as part of the study. However, this effect has been observed by sector specialists when the UK introduced stage V requirements for air pollution emissions from NRMM.

> **'Highlighted by hire companies that traditional second life export markets have reduced in Africa, Asia and Europe due to not having parts to support exhaust emission technology for existing stage V machines .'** Sector specialist

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[269] Public EV charging points and public hydrogen station deployments are mostly not relevant as industrial NRMM are unlikely to use public points. These statistics are shown as a proxy for the presence of skills and hardware for recharging/ hydrogen refuelling infrastructure.

[270] https://alternative-fuels-observatory.ec.europa.eu/

[271] https://www.europarl.europa.eu/meetdocs/2014_2019/plmrep/COMMITTEES/TRAN/AG/2023/05-24/1278140EN.pdf

[272] FACT SHEET: Biden-Harris Administration Announces New Standards and Major Progress for a Made-in-America National Network of Electric Vehicle Chargers | The White House

[273] Alternative Fuels Data Center: Alternative Fueling Station Locator (energy.gov)

[274] U.S. National Clean Hydrogen Strategy and Roadmap: DOE Hydrogen Program (energy.gov)

[275] Australia's desperate need for more reliable fast-chargers as EV numbers jump (thedriven.io), EVC-State-of-EVs-2022.pdf (electricvehiclecouncil.com.au)

[276] Hydrogen superhighway to link Victoria with Queensland | CarExpert

[277] Landmark Renewable Hydrogen Highway To Link Eastern States | Premier of Victoria

Disruption to exports of second-hand industrial NRMM would impact owners of machinery (users, leasing and hiring companies) as well as auction houses.

6.1.2.2 Disruption to imports

If not aligned with major markets, the UK NRMM market could also face difficulties importing NRMM. This would directly impact those purchasing and leasing NRMM, as well as clients and users if supply chain difficulties result in delays.

Similar sentiments were echoed by other OEMs, who felt the UK was too small to 'go it alone' in such a global market. Whilst the UK is a net exporter, imports of NRMM are still substantial, as seen in Figure 14. Between 2017 and 2021, the average annual trade value of NRMM imports to the UK was £2.1 billion.

> **'If the UK [policy and regulation] diverts too far from the path of the rest of Europe and the USA, then we would not sell to the UK. The UK market is a drop in the ocean comparatively.'** OEM

Table 66 – Summary of the risks of misalignment with the global market. A square indicates potential impact on a market actor.

Risk	OEMs	Users	Lease and hire companies	Site owners /clients	Fuel & inf providers	End of Life actors
Disruption to exports	■	■	■		■	■
Disruption to imports		■	■	■		

6.1.3 Risk and opportunity: Shared requirements with other sectors

Pathways to decarbonise industrial NRMM are affected by decarbonisation of the rest of the UK economy. There is a risk of competition from other sectors for enabling resources such as low-carbon fuels and infrastructure. As part of the sixth carbon budget, the Climate Change Committee assumes that, after 2040, off-road mobile machinery is only decarbonised through electrification and hydrogen; bio- and waste-based fuels are not included due to prioritisation of these feedstocks in other areas of the energy system where they are more effective abatement options than zero emission technology (E4tech & Cenex, 2021), (Climate Change Committee, 2020). Alternative demands for biomass include sustainable aviation fuel production, industrial heat, or combination with CCS for hydrogen production. This potential risk was confirmed during stakeholder engagement. Restricted availability of fuels and infrastructure would impact users, leasing and hiring companies, and clients if there are delays as a result (see section 4.1.2).

> **'With sustainable aviation fuel, waste might be a competitive resource. This is not a problem now because there is more than enough waste, but it may be a problem in 10-15 years if it becomes a commodity. For now, we are not competing for feedstock or technology.'** Fuel supplier

Production and end of life process concerns could also be compounded, such as accelerating the risk of raw material bottlenecks in battery production or insufficient recycling capabilities to meet demand. Availability of lithium was noted as a potential supply chain bottleneck during stakeholder workshops.

There could also be risks if other sectors do not follow the same decarbonisation pathway. If industrial NRMM switches to a transition technology (for example using fossil fuel-based hydrogen or diesel generators to allow earlier deployment of hydrogen or electric machinery), but access to low carbon hydrogen or electricity does not improve, industrial NRMM could be stuck using these transition technologies which do not reduce emissions significantly in the long term.

However shared decarbonisation requirements could also be seen as an opportunity. Mass manufacture, shared infrastructure, cross-sector efforts to increase low-carbon fuel availability, and common skill requirements with other sectors could aid NRMM and other sectors in bringing down costs, accelerating deployment of abatement options and establishing the UK as a producer of low-carbon NRMM in the global market.

> **'More than one consumer for a market is a benefit, at least in the short term.'** OEM

Table 67 – Summary of the risks and opportunities of shared requirements with other sectors. A square indicates potential impact on a market actor.

Risk	OEMs	Users	Lease and hire companies	Site owners /clients	Fuel & inf providers	End of Life actors
Shared requirements with other sectors	🟩	🟩	🟩	🟩	🟩	🟩

6.1.4 Opportunity: Innovation in the industrial NRMM business and market structure

6.1.4.1 New business opportunities and market entrants

As the market evolves, new business models and entrants may come into play. This has already happened in the decarbonisation of HGVs, where new companies are introducing new technologies. For example, Volta's battery electric truck Volta Zero,[278] and Nikola's hydrogen fuel cell semi-truck Tre FCEV.[279] Additionally, existing companies may develop new strategies to align with the low-carbon transition. For example, Phillips 66, traditionally an oil and gas company, is producing HVO at its Humber refinery (Phillips 66, 2022).

As the technology progresses and commercial suitability of abatement options for industrial NRMM become more apparent, retrofit business models may also develop. This allows market actors to take advantage of the existing industrial NRMM fleet instead of scrapping otherwise high value machinery. As discussed in section 4.1.9, several OEMs are already beginning to design machinery with future low-carbon powertrains and fuels in mind. Such developments have the potential to impact all market actors, presenting opportunities for innovation in the production, usage, trading, fuelling and disposal of NRMM. Stakeholder engagement revealed mixed views on the potential for retrofit. Some market actors felt that lifetime extension of equipment was advantageous whilst some felt the high cost of retrofit would be prohibitive except for very high value machinery. Others felt that the physical constraints of the existing engine bay would make retrofit with options of lower volumetric energy density challenging.

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[278] Volta, Volta Zero

[279] Nikola, Tre FCEV

6.1.4.2 Improved data collection and use for operations

Improved data collection and use could also be an opportunity to improve efficiency across industrial NRMM operations, as well as purchase and leasing decision making. Stakeholders indicated that the use of telematics data to inform operations, processes and approaches to tasks is uneven. Several stakeholders identified an opportunity to use telematics to increase process efficiency in the future.

'We have got access to telematics data for much of our own fleet and hired fleet but are not yet using the data to drive behavioural changes such as targeting reduced idle times. However, we intend to make better use of this data in the future.' User

Digital tools aimed at increasing fleet efficiency and cloud-based operation monitoring are starting to be used. Several NRMM users have trialled these options, particularly in port and quarry applications where the potential for autonomous vehicles is being explored (EIT InnoEnergy, 2022; Hutchison Ports, 2021; Volvo Construction Equipment, 2018). Further detail on these tools can be found in section 3.1.2 under process efficiency.

There may also be an opportunity for the wider industry and stakeholders to understand how industrial NRMM is used. The lack of complete, comprehensive, and publicly available data on industrial NRMM was a constraint throughout this study and has hindered previous research into industrial NRMM emissions (T. Cao, 2016; Hagan, et al., 2022). The issue is not limited to the UK: no public national NRMM inventories could be found during the literature review for this study. NRMM users also face difficulties obtaining data to justify purchasing, renting or leasing more efficient machinery.

'Opening up telematics data will be helpful to reveal the actual efficiency of different models of excavators. We [the UK] could incentivise this data-sharing by linking it to an incentive… [It is] hard to get the data (for renter and rentee) in order to justify that there is a fuel efficiency gain, and therefore justify higher rental costs.' User

It is likely the same issue would apply when justifying the upfront cost of some abatement options compared to fuel savings, such as battery electric or hydrogen fuel cell NRMM. This would impact users of the equipment and, in the construction sector, site clients and owners who typically purchase the fuel (see sub-section 4.1.5). Using data to understand the current utilisation patterns and duty cycles of industrial NRMM across sectors, tasks, site types, and geographies could also address some concerns about performance challenges. Industrial NRMM users lean towards 'overspeccing' equipment (choosing options which can meet the most extreme use case specifications, even if it is uncertain or unlikely that the machine will be needed for those use cases). As discussed in section 4.1.3, not all abatement options currently match the current refuelling and duty cycle requirements of some NRMM users. As well as providing industry case studies, allowing users to compare their NRMM requirements for a task to the duty cycles supported by NRMM on the market could help users feel more confident picking abatement options. This is particularly relevant to abatement options which require different recharging or refuelling patterns.

Table 68 – Summary of the risks and opportunities of innovation in the industrial NRMM business and market structure. A square indicates potential impact on a market actor.

Risk	OEMs	Users	Lease and hire companies	Site owners /clients	Fuel & inf providers	End of Life actors
New market entrants and business models	■	■	■	■	■	■
Improved data collection and use for operations		■	■	■		

6.1.5 *Opportunity: Improved operator experience*

Some abatement options reduce air and noise pollution as well as unwelcome levels of heat. Whilst this will benefit the wider public, there is also an opportunity to improve the experience of NRMM operators on site. Mining workers identified the noise reduction and air quality benefits of battery electric machinery as an improvement to their working conditions (Halim, J. Lööw, Gustafsson, Wageningen, & Kocsis, 2021). Both factors improve employee satisfaction. Additionally, the staff health benefits of switching to diesel alternatives were recognised by almost half of respondents in a 2019 survey conducted on behalf of HMRC (IFF Research, 2019). However, these benefits are not associated with all abatement options; solutions that use ICEs, such as hydrogen ICE and drop-in fuels, still generate noise and air pollution, as discussed in section 4.1.8. This opportunity applies only to NRMM users.

'There is an opportunity to reduce noise and vibration in urban environments, benefitting workers and the public.' User

6.2 Changes in risks and opportunities over time

As deployment of industrial NRMM abatement solutions accelerates, the sector will gain clarity on the exact risks and opportunities faced. Table 69 summarises the likely evolution over time of the risks and opportunities identified above. This was informed by stakeholder engagement activities. The table also highlights the impacts of pathway dependent risks and opportunities on the modelling performed for this study (see Chapter 5).

Table 69 – Potential evolution of risks and opportunities of deployment of abatement options over time compared to now

	Risk or opportunity	Likely evolution by		Justification
		2030	2050	
Risks	Multiple solutions	Increase	Pathway dependent	In the short term, multiple options are being developed. Depending on the decarbonisation trajectory, this could remain the case in the long term, or one abatement option may be favoured over the others. This risk is higher for Scenario 3 as described in Chapter 5 as both hydrogen and electric solutions are deployed, whereas electrification is the dominant solution in Scenarios 1 and 2.
	Misalignment with the global market	Increase	Decrease	As discussed in section 4.3, there is limited national-level NRMM decarbonisation policy at present. Given national net-zero commitments, governments are likely to develop this policy soon, increasing the risk of misalignment in the short term but with harmonisation more likely in the longer term.
Both	Shared requirements with other sectors	Increase	Decrease risk. Increase opportunity	Common abatement option requirements with other sectors may result in supply chain bottlenecks in the short term. This should ease as fuel and infrastructure capability ramps up. Opportunities to share these capabilities are likely to increase as deployment accelerates.
Opportunities	Innovation in the industrial NRMM business and market structure	Increase	Increase	New business models and market entrants are likely as abatement options are deployed.
	Improved operator experience	Small increase	Pathway dependent	In the short term, zero tailpipe emission options are likely to be deployed at least at a small scale, following current trends. In the long term, this is dependent on the decarbonisation pathway taken by the sector: electric and hydrogen fuel cells provide the biggest improvement to operator's experience over other solutions. These benefits would be seen in all three scenarios in Chapter 5, as they all transition to a combination of fuel cell, battery electric and tethered solutions.

7 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

7.1 Conclusions

The use of industrial NRMM is diverse and poorly documented, resulting in challenges when analysing the sector as a whole.

- Unlike other areas of transport (e.g., cars, road freight), there is no central register of machinery or regular survey of utilisation patterns.
- The use of industrial NRMM is diverse and includes a vast array of machinery performing diverse tasks with a wide range of utilisation patterns that can complicate the understanding of current and future trends across all industrial NRMM. Power rating, mobility and high-level utilisation characteristics were used to create archetypes of NRMM with similar decarbonisation options.
- Interaction between different market actors related to industrial NRMM can be complex, co-ordination between stakeholders is likely to be required in order to achieve decarbonisation.

A wide range of abatement solutions are being pursued for industrial NRMM.

- The number and technical diversity of low and zero emission options has significantly increased in the last 5 years, with some options in early commercialisation and others advancing rapidly. The development of multiple powertrain options could lead to increased R&D costs for OEMs and has led to uncertainty among NRMM purchasers about which abatement option and infrastructure will be the best investment.
- Drop-in fuels (characterised by HVO as the current sector leader) have an important role as a transitional solution to reduce lifecycle GHG emissions until other abatement technologies become available. However, these fuels do not reduce tailpipe emissions and so do not provide improvements to tailpipe CO_2e emissions or air quality.
- Of solutions with zero tailpipe emissions, battery electric is currently the most mature, especially for smaller, low powered machinery where high-power charging and large batteries are not required. Currently, hybrid solutions are the most mature non-drop-in fuel alternative for medium to large machinery.
- The suitability of technologies depends on a wide range of parameters that are very specific to the site and machinery, including tasks performed, utilisation levels and the size, duration, and location of the site. Care should be taken therefore when drawing conclusions about the future of industrial NRMM.

From a social perspective, the least-cost pathways modelling performed suggests electrification is the lowest-cost pathway to decarbonise.

- A least-cost pathways model was developed by ERM to provide a high-level assessment of the relative costs of a selection of decarbonisation options.
- Low carbon fuels (characterised by B20 and HVO in the model) are selected in the short term, though their widespread adoption in industrial NRMM is likely to be limited by the available supply of these fuels.
- Electric solutions (battery electric or tethering) are consistently the cheapest low tailpipe emission option for all machinery which were suited to these technologies. These electric machines start to outcompete HVO once they become widely available in some areas from the late 2020s or early 2030s.

- Hydrogen solutions (fuel cell or internal combustion engines) were only chosen in scenarios where battery electric options were deemed unsuitable for subsets of industrial NRMM.
- Biofuels, e-fuels and hydrogen could be used to decarbonise in situations where electrification remains challenging in the long term. These alternatives are likely to be more expensive than electrification, so will likely be adopted predominantly in applications where electrification is not a viable option. The size of this niche will depend on the feasibility for sites to access grid electricity, or the development of low-carbon off-grid solutions (such as large batteries charged slowly on-site or delivered to site).
- Efficiency measures have the potential to bring substantial energy demand reduction (up to 25% by 2050 compared to 2021, despite projected increase in industrial NRMM stock of 19%) but there is uncertainty around their implementation cost and the achievable level of uptake.
- For all three pathways, the decarbonisation pathway has a lower resource cost compared to the baseline, with most of the savings coming from electrification of machinery, and to a lesser extent conversion to hydrogen for Scenario 3.

Uncertainty in potential NRMM decarbonisation policy and limited confidence in future fuel and infrastructure availability are key barriers.

- Insufficient policy support and the absence of decarbonisation targets or timelines were reported as critical barriers to adoption during stakeholder engagement. However, there was no consensus among stakeholders on whether the government policy should be technologically neutral or give a steer towards a particular technology over others.
- Reliable supply of affordable low-carbon hydrogen and improving the process and speed of grid connections for charging were seen as important enablers by stakeholders. Investment in abatement options is difficult for stakeholders to justify if there is uncertainty that the required refuelling or recharging infrastructure will exist throughout the machine's lifetime.

The UK NRMM market does not sit in isolation; its deep ties with the global NRMM market and other transport sectors presents both risk and opportunity.

- 'Joined-up' thinking was strongly advocated for by NRMM stakeholders. This was both to avoid misalignment and to take advantage of common resources and requirements.
- NRMM decarbonisation policy is still under development globally. NRMM market actors are concerned that the UK's prominent NRMM trade relationships will be undermined if UK policy and regulation differ significantly from those in the EU or the USA in future. Additionally, a lack of understanding and familiarity from NRMM market actors with new regulations could become a barrier in itself. Uncertainty about the effect of new regulations can amplify the perception of the barrier (if any) presented by the regulation alone.
- NRMM abatement options have common resources, fuels and infrastructure with decarbonisation options in other transport sectors, such as aviation and passenger cars. There is a risk of competition for resources leading to limited availability and higher costs. However shared decarbonisation requirements could also be an opportunity. Mass manufacture, shared infrastructure, cross-sector efforts to increase low-carbon fuel availability and upskilling workers could aid NRMM and other sectors in bringing down costs, accelerating deployment of abatement options and establishing the UK as a global producer of low-carbon NRMM.

7.2 Recommendations for further work

There are several areas where further work would be beneficial, to address data gaps or to narrow uncertainties identified during the research.

Improve publicly available data and evidence on NRMM in the UK

- Data scarcity makes decision making challenging for NRMM market actors and policymakers. With limited data on the UK NRMM fleet and typical duty cycles, it is difficult to create sector-wide decarbonisation strategies and justify investment in abatement options, particularly efficiency improvements. For example, understanding the power draw and impact of wide-scale electrification of NRMM is challenging without machinery-specific usage profiles and daily recharging patterns combined with local network capacity and constraints.
- Increased data collection can also benefit companies, as improved telematics can improve site efficiencies and better inform operators about the type of NRMM to hire for a job. This could enable operators to pick machinery that are the best size for the job (e.g., selecting a generator that has the correct power rating rather than oversizing due to demand uncertainty). In addition, operators who know the usage profiles of their machines will be better placed to transition to hydrogen or electric powertrains, as they can determine how much energy storage the machine will need and when to schedule charging or refuelling breaks to minimise disruption. An increase in data collection will also help infrastructure solution providers, to help them decide on what solutions should be developed and what the optimal solution will be for a customer.
- Whilst a challenging task, collecting data on UK NRMM will help inform future decarbonisation strategies and benefit companies building and using this machinery. Examples of important data to collect include: a UK NRMM stock inventory, domestic sales volumes, exports separated into new and second-hand, duty cycles (profiles by sector, machinery and even task), and refuelling patterns. An accurate representation of industrial NRMM stock complements any evidence base on decarbonisation options, allowing the UK Government to take a more informed approach to policy development.
- Any additional or higher quality data collected as technologies mature can be used to refine the IND-database and least-cost pathways modelling cost inputs. This would be particularly beneficial in the case of efficiency measures, where very limited data on the costs to implement measures was available and a pre-defined deployment pathway was applied equally to all scenarios.

Conduct more site-level analysis

- Characterising site types would provide insights into the practicalities of deploying abatement options and would help quantify the share of NRMM that fall into the hard-to-deploy category. Site-level analysis could identify the opportunities and specific tasks where hydrogen and other abatement options make the most sense, particularly compared to electric options. Understanding whether multiple abatement solutions can be supported on one site and how the solutions may interact could help shape the overall approach to decarbonising the sector.
- A better understanding of market actor interactions is needed, particularly in complex cases such as multiple companies contracted by the site owner. This would help identify who the key decision makers are with regards to deploying decarbonisation options on such sites.
- During this study, no evidence was found to suggest that process change is under consideration. Looking at individual sites and tasks may reveal opportunities where methods could be changed to remove the need for industrial NRMM for particular tasks.

Assess the impact of proposed legislation on UK NRMM market dynamics

- Stakeholders indicated that several pieces of legislation may create challenges for adopting abatement options. In particular, some stakeholders raised concerns over safety requirements of hydrogen on site and the EU battery regulation which would involve producers who place batteries on the EU market being responsible for their recycling and safe disposal at end of life.[280] Untangling the perceived risks of the legislation from the likely impacts on the UK NRMM market will require further analysis.
- The Construction Leadership Council is undertaking some of this analysis; the zero-diesel route map actions industry to work with Health and Safety Executive to develop guidance on hydrogen delivery, handling, storage and use on site (CLC, 2022).
- The UK is unusual within Europe for having a significantly larger proportion of machinery purchased by lease and hire companies rather than operators (67% leased or hired in the UK compared to 37% in Europe). Given the size of this portion of the market, further research could be beneficial on the different barriers facing lease and hire companies versus owner-operators (expanding on the insights in Chapter 4). Additionally, further research is needed to better understand the factors behind the larger proportion of leased and hired construction NRMM in the UK.

Improve understanding of the end of first life process

- The interviews and workshops involved stakeholders from across the NRMM market; however, actors involved in end of life processes were underrepresented. This aspect of the supply chain and how it might be impacted by deployment of abatement options remains uncertain. Further work to gain insights into the disposal, recycling, export and retrofit of second-hand NRMM could provide clarity.
- Retrofit and re-engineering were explored, and qualitative responses were received from stakeholders. Understanding the techno-economic limitations could help quantify the potential opportunity for retrofit.

Update view of risks and opportunities as deployment of abatement options accelerates

- There is a relative lack of literature relating to the risks and opportunities arising from decarbonising industrial NRMM, with the research relying predominately on stakeholder engagement. These risks and opportunities were not graded or assessed for applicability across the sector by the stakeholders, further research would be required to further quantify the risks and opportunities.
- As barriers are addressed and adoption accelerates, the associated risks and opportunities will evolve. New questions will need to be addressed, for example the training requirements for upskilling the supply chain. Further niche opportunities may also arise; for example, leased infrastructure business models or the use of off-grid NRMM batteries in grid balancing. Frequent reassessment will help the NRMM sector tackle challenges, mitigate risks and take advantage of opportunities on its path to net zero.

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[280] The participating stakeholders commented on safety legislations in general but did not mention any specific bills or statutory instruments.

8 BIBLIOGRAPHY

Accenture. (2022). *How investors view mining's new role as a champion of decarbonization.*

Ahluwalia, R., Wang, X., Star, A., & Papadias, D. (2022). Performance and cost of fuel cells for off-road. *International Journal of Hydrogen Energy*.

Ahluwalia, R., Wang, X., Star, A., & Papadias, D. (2022). Performance and cost of fuel cells for off-road. *International Journal of Hydrogen Energy*.

Arana, M., Martín, R. S., Urroz, J. C., & Dieguez, P. M. (2022). Acoustic and psychoacoustic levels from an internal combustion engine fueled by hydrogen vs. gasoline. *Fuel*.

Argonne. (2021). *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains.*

Argonne. (2021). *Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Off Road Heavy-Duty Applications –Preliminary Results.*

Australian Government. (2021). *Australia long term emissions reduction plan .*

Balfour Beatty. (2020). *Non-Road Mobile Machinery (NRMM) Emissions Regulations.*

Balfour Beatty. (2022). *Balfour Beatty Annual Report and Accounts 2021.*

Big Buyers Initiative Working Group. (2020). *Procuring Zero-Emission Construction Sites Cities' current and future procurement plans.*

BloombergNEF. (2022). *Electric Vehicle Outlook 2022.*

Business, Energy and Industrial Strategy Committee. (2018, October). Electric vehicles: driving the transition. UK Parliament. Retrieved from https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/383/38302.htm

California Air Resources Board. (2020). Zero-Emission Off-Road Strategies.

CALSTART. (2022). *Technology and Market Assessment of Zero-Emission Off-Road Equipment.*

Candelaresi, D., Valente, A., Iribarren, D., Dufour, J., & Spazzafumo, G. (2021). Comparative life cycle assessment of hydrogenfuelled passenger cars. *International Journal of Hydrogen Energy*.

Carbon Neutral Cities Alliance. (2019). *Scandinavian green public procurement alliance on non-road mobile machinery - Lessons Learned Report.*

Cazzola, P., Gerard, F., Gorner, M., & Gibbs, M. (2023). *Assessment of the potential of sustainable fuels in transport.* European parliament.

Cenex. (2022). *H2 Construction (redacted version).*

City Council in Oslo. (2018). *Climate and Energy Strategy for Oslo.* Oslo.

CLC. (2022). *Consultation Draft: Zero diesel sites route map.* Retrieved from https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2022/11/CLC-Consultation-Draft-Zero-diesel-sites-route-map-CLC-Zero-diesel-sites-working-group.pdf

Clean Hydrogen Partnership. (2022). *Strategic Research and innovation agenda.*

Cleaner Construction for London. (2022). *Non-Road Mobile Machinery (NRMM) Practical Guide v.5.* Mayor of London.

Climate Change Committee. (2020). *The Sixth Carbon Budget.*

Climate Change Committee. (2020). *The UK's transition to electric vehicles.*

Committee for European Construction Equipment. (2018). *Optimising our industry 2 reduce emissions.*

Committee for European Construction Equipment. (2021). *The role of construction equipment in decarbonising Europe.*

Construction Equipment Association. (2019). *The UK's Construction Equipment Sector Report 2019.*

Construction Equipment Association. (2023). *The UK's Construction Equipment Sector Report 2023.*

DEFRA. (2022). *Environment Act Targets Impact Analysis: Waste Reduction.* London: UK Government. Retrieved 2022

DEFRA, DAERA, Government, W., & Government, S. (2020). Circular Economy Package policy statement. UK Government.

Department for Business, Energy & Industrial Strategy. (2020). *Gigastack Phase 2: Pioneering UK Renewable Hydrogen.*

Department for Business, Energy & Industrial Strategy. (2022). *Appendix I: Electricity Networks Modelling.*

Department for Business, Energy & Industrial Strategy. (2022). *Hydrogen Strategy update to the market: July 2022.*

Department for Energy Secturity & Net Zero. (2023). *UK Low Carbon Hydrogen Standard - Guidance on the greenhouse gas emissions and sustainability criteria (Version 2).*

Department for Energy Security and Net Zero. (2022, August 2). *UK energy in brief 2022.* Retrieved from DESNZ website: https://www.gov.uk/government/statistics/uk-energy-in-brief-2022

Department for Transport. (2021). *Targeting net zero: Next steps for the Renewable Transport Fuels Obligation.*

Department for Transport. (2022). Renewable Fuel Statistics, 2021 (final).

Department for Transport. (2023). *Renewable fuel statistics 2022: Fourth provisional report.*

Department for Transport. (2023, May 11). *Renewable fuel statistics 2022: Fourth provisional report.* Retrieved from Department for Transport website: https://www.gov.uk/government/statistics/renewable-fuel-statistics-2022-fourth-provisional-report

Department for Transport. (2023). *RTFO compliance guidance 2023.*

Department for Transport. (2023). *RTFO Guidance for Renewable Fuels of Non-Biological Origin.* Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1164946/rtfo-guidance-for-renewable-fuels-of-non-biological-origin.pdf

Desouza, Marsh, D., Beevers, S., Molden, N., & Green, D. (2021). A spatial and fleet disaggregated approach to calculating the NOX emissions. *Atmospheric Environment: X*.

Desouza, Marsh, D., Beevers, S., Molden, N., & Green, D. (2022). Emissions from the construction sector in the United Kingdom.

Desouza, Marsh, D., Beevers, S., Molden, N., & Green, D. (2022). Emissions from the Construction Sector in the United Kingdom. *Social Science Research Network*.

Dolan, G. (2019). *Overview of Global Methanol Fuel Blending.* Methanol Institute.

Dwivedi, G., & Sharma, M. (2014). Impact of cold flow properties of biodiesel on engine performance. *Renewable and Sustainable Energy Reviews*, 650-656.

E. M. Chapman, A. B. (2003). *IMPACT OF DME-DIESEL FUEL BLEND PROPERTIES ON DIESEL FUEL INJECTION SYSTEMS.* U.S. Department of Energy. doi:10.2172/821275

E4tech & Cenex. (2021). *Red Diesel Replacement Stakeholder Engagement Pre Innovation Study.*

E4tech. (2022). *The Fuel Cell Industry Review 2021.*

Economic Commission for Europe Inland Transport Committee. (2020). ADR: Agreement Concerning the International Carriage of Dangerous Goods by Road. United Nations.

EIT InnoEnergy. (2022). *A practical guide to decarbonising ports: catalogue of innovative solutions.*

Element Energy. (2020). *Analysis to provide costs, efficiencies and roll-out trajectories for zero emission HGVs, buses and coaches.*

Element Energy. (2022). *Hydrogen Mobility Europe Emerging Conclusions .*

Energy Saving Trust. (2019). *Electric RCV Fleet review – Electric Refuse Collection Vehicles.*

Environment Act. (2021). Environment Act 2021, Ch 57.

Epiroc. (2022). *Annual and Sustainability Report 2021.*

EU Commission. (2020). *Proposal for a regulation of the european parliament and of the council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020.*

European Environment Agency. (2022). Europe is not on track to halve non-recycled municipal waste by 2030. Retrieved from https://www.eea.europa.eu/highlights/europe-is-not-on-track

European Parliament. (2022). *ReFuelEU Aviation initiative.*

Executive Department State of California. (2020). *Executive Order N-79-20.*

Fraunhofer ISE, Fraunhofer IPA, E4tech. (2018). Industrialisation of hydrogen electrolysis in Germany. Retrieved from https://www.ipa.fraunhofer.de/content/dam/ipa/de/documents/Publikationen/Studien/Studie-IndWEDe.pdf%20(In%20German)

Ge, L., Quan, L., Zhang, X., Dong, Z., & Yang, J. (2019). Power matching and energy efficiency improvement of hydraulic excavator driven with speed and displacement variable power source. *Chinese Journal of Mechanical Engineering*.

Greater London Authority, TfL Air Quality. (2023). London Atmospheric Emissions Inventory (LAEI) 2019. *Emissions - Summary Dashboards*. Retrieved from https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory--laei--2019

Hagan, R., Markey, E., Clancy, J., Keating, M., Donnelly, A., O'Connor, D., . . . McGillicuddy, E. (2022). Non-Road Mobile Machinery Emissions and Regulations: A Review. *Air*.

Halim, A., J. Lööw, J. J., Gustafsson, J., Wageningen, A. v., & Kocsis, K. (2021). Improvement of Working Conditions and Opinions of Mine Workers When Battery Electric Vehicles (BEVs) Are Used Instead of Diesel Machines - Results of Field Trial at the Kittilä Mine, Finland. *Mining, Metallury & Exploration*, 203-219.

Heid, B., Martens, C., & Orthofer, A. (2021). *How hydrogen combustion engines can contribute to zero emissions.* McKinsey.

HMRC. (2023, January 05). *Overseas trade data table.* Retrieved from UK Trade Info: https://www.uktradeinfo.com/trade-data/ots-custom-table/

HMRC. (2023, June 12). *Overseas trade data table.* Retrieved from UK Trade Info: https://www.uktradeinfo.com/trade-data/ots-custom-table/

HS2. (2022). *Diesel-Free Plan - Building a net zero future.* HS2.

Huang, Z., Fan, H., Shen, L., & Du, X. (2021). Policy instruments for addressing construction equipment emission - A research review from a global perspective. *Environmental Impact Assessment Review*.

Hutchison Ports. (2021). *Buidling a Smart and Sustainable Port.*

Hydrogen Europe. (2021). *Hydrogen Transport and Distribution.*

IFF Research. (2019). *Non-agricultural use of red diesel for non-road mobile machinery.* HM Revenue & Customs; HM Treasury.

International DME Association. (2010). *IDA Fact Sheet: DME/LPG Blends.*

International Energy Agency. (2019). *The future of hydrogen.*

International Energy Agency. (2020). Renewables 2020.

International Energy Agency. (2022). *Is the biofuel industry approaching a feedstock crunch?: Renewables 2022.* Retrieved from https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch

International Energy Agency. (2022). *World Energy Outlook 2022.* Retrieved from https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf

IRENA. (2020). Green Hydrogen Cost Reduction.

Janin, O., Viaggi, R., Bandry, J., Rasselet, A., Scherm, P., Diedrich, F., & Blything, P. (2018). *Frequently asked questions - EU Regulation 2016/1628.* European Agricultural Machinery Society; Committee for European Construction Equipment; European Garden Machinery Federation; European Association of Municipal Equipment Manufacturers; Europgen; Euromot.

JCB. (2021). *Global Environmental Sustainability Strategy.*

Kalmar. (2022). *The Kalmar Ottawa T2E+ Electric Terminal Tractor.*

Kanazawa, T., Matsumoto, M., Yoshimoto, M., & Tahara, K. (2022). Environmental Impact of Remanufacturing Mining Machinery. *Sustainability*.

Kier Group. (2022). *Kier Annual Report and Accounts 2022.*

Kirtz, J., Sprik, S., Saur, G., & Onorato, S. (2019). *Fuel Cell Electric Vehicle Durability and Fuel Cell Performance.* National Renewable Energy Laboratory.

Knibb Gormezano & Partners. (2017). *Non-road mobile engine and aftertreatment forecast.*

Komatsu. (2021). *Decarbonization Approaches Mining.*

Komatsu. (2022). PC210 Electric: Electric hydraulic excavator specification.

Lajunen, A., Suomela, J., Pippuri, J., Tammi, K., Lehmuspelto, T., & Sainio, P. (2016). Electric and hybrid electric non-road mobile machinery – present situation and future trends. *World Electric Vehicle Journal* .

Lewis, A. (2021). Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NOx emissions. *Environmental Science: Atmospheres*, 201-207.

LoCITY. (2016). *The road to reducing commercial vehicle emissions.*

Logistics UK. (2019). *Managers guide to distribution costs.*

Matsuda, S., Ono, M., Yamaguchi, S., & Uosaki, K. (2022). Criteria for evaluating lithium–air batteries in academia to correctly predict their practical performance in industry. *Royal Society of Chemistry*.

Mauler, L., Duffner, F., Zeier, W., & Leker, J. (2021). Battery cost forecasting: a review of methods and. *Royal Society of Chemistry*.

McKinsey & Company. (2016). *Reengineering construction equipment: from operations focused to consumer centric.*

McKinsey. (2021). *Decabonization in mining.*

Morgan Sindall Group. (2022). *Morgan Sindall Group Annual Report 2021.*

Mortazavi, M., Santamaria, A. D., Benner, J. Z., & Chauha, V. (2019). Enhanced Water Removal from PEM Fuel Cells Using Acoustic Pressure Waves. *Journal of The Electrochemical Society*, 143-153.

Moskalik, T., & Gendek, A. (2019). Production of Chips from Logging Residues and Their Quality for Energy: A Review of European Literature. *Forests, 10*.

Nardell, G., Leigh-Doyle, C., & Ross, A. (2021). Hydrogen projects: regulation and consents. *Practical Law UK Practice Note*.

National Grid. (2022). *Network Options Assessment 2021/22 Refresh.*

National Renewable Energy Laboratory. (2017). *Electric Ground Support Equipment at Airports.*

National Renewable Energy Laboratory. (2022). *Off-Road Vehicle Decarbonisation and Energy Systems Integration: R&D Gaps and Opportunities.*

O'Malley, J., & Searle, S. (2021). Air quality impacts of biodiesel in the United States. *International Council on Clean Transportation*.

Paraszczak, J., Svedlund, E., Fytas, K., & Laflamme, M. (2014). Electrification of Loaders and Trucks – A Step Towards More Sustainable. *International Conference on Renewable Energies and Power Quality*.

Phillips 66. (2022). *2022 Sustainability Report.*

Plug Power. (2017). *MT011 Ground Support Equipment Demonstration.*

Reddi, K., Elgowainy, A., & Rustagi, N. (2017). Impact of hydrogen refueling configurations and. *International Journal of Hydrogen Energy*.

Ricardo. (2016). *Improving understanding of technology and costs for CO2 reductions from cars and LCVs in the period to 2030 and development of cost curves.*

Ricardo. (2020). *Development of heavy-duty hydrogen powertrains for 2025+.*

Ricardo. (2020). *Research to inform policy development to address emissions from NRMM.* Department for Environment, Food and Rural Affairs.

Ricardo. (2021). *Extension Report: Update to the Emission Inventory - Research to inform policy development to address emissions from NRMM.*

Roland Berger. (2020). *Fuel Cells Hydrogen Trucks.*

Roland Berger. (2022). *The Future of Off-Highway Electric Vehicles 2022.*

Royal Agricultural Society of England. (2022). *Decarbonising Farm Vehicles and Future Fuels.*

Sandia National Laboratories. (2020). *Hydrogen refueling reference station lot size analysis for urban sites.*

Sandvik. (2022). *Sandvik LH409E Electric Loader .*

Sandvik. (2023). *Toro LH410 underground loader.*

Scania. (2021). *Lifecycle assesment of distribution vehicles: Battery electric vs diesel driven.*

Sitong Chen, X. W. (2019). Interaction of Vibration and Air Flow-Accelerating Droplet Emission from the Gas Diffusion Layer of Proton Exchange Membrane Fuel Cell. *International Journal of Photoenergy*.

Slough Borough Council. (2016). *Slough Borough Council Refuse Collection Vehicles (RCV) Options Appraisal.*

T. Cao, T. D. (2016). Evaluations of in-use emission factors from off-road construction equipment. *Atmospheric environment*, 234-245.

Tetra Tech and Gladstein, Neandross & Associates. (2022). *San Pedro Bay Ports Clean Air Action Plan 2021 Update: Feasibility Assessment for Cargo-Handling Equipment.*

The International Council on Clean Transportation. (2017). *Transitioning to zero-emission heavy-duty freight vehicles.*

The International Council on Clean Transportation. (2018). *India Bharat Stage IV and V Non-road Emission Standards.*

The International Council on Clean Transportation. (2021). *E-Truck Virtual Teardown Study.*

The International Council on Clean Transportation. (2022). *A meta-study of purchase costs for zero-emission trucks.*

The International Council on Clean Transportation. (2022). *Fuel cell electric tractor-trailers: Technology overview and fuel economy.*

The International Council on Clean Transportation. (2022). *Low-emission zones and zero-emission construction equipment in China: An untapped policy opportunity.*

The Society of Motor Manufacturers and Traders. (2018). *Response on Call for Evidence on Red Diesel and NRMM.*

Tornatore Cinzia, M. L. (2022). Ammonia as Green Fuel in Internal Combustion Engines: State-of-the-Art and Future Perspectives. *Frontiers in Mechanical Engineering, 8*. doi:10.3389/fmech.2022.944201

U.S. Department of Energy. (n.d.). *Dimethyl Ether*. Retrieved 2023, from Alternative Fuels Data Center: https://afdc.energy.gov/fuels/emerging_dme.html

U.S. Department of Energy; U.S. Department of Transportation; U.S. Environmental Protection Agency; U.S. Department of Housing and Urban Development. (2023). The U.S. National Blueprints for Transportation Decarbonization.

UK Extractive Industries Transparency Initiative. (2023). *Mining & Quarying in the UK*. Retrieved January 23, 2023, from https://www.ukeiti.org/mining-quarrying

UK H2 Mobility. (2021). *UK H2Mobility White Paper on Hydrogen Refuelling Station Reliability.*

US Department of Energy. (2021). *21002 - Hydrogen Fueling Stations Cost.*

Van Leeuwen, L. (2020). Hydrogen or battery tractors: what potential for sustainable grape growing? *International Viticulture & Ecology Society*.

Volvo Construction Equipment. (2018). *Electric Site – site management system .* Retrieved from https://www.volvoce.com/-/media/volvoce/global/global-site/this-is-volvo-ce/brochures/volvo-ce-press-information-electric-site-site-management-factsheet.pdf?v=RmdAPw

Westport Fuel Systems. (2020). *TCO analysis of Heavy duty Hydrogen fuelled powertrains.*

World Bank. (2021). *GDP (current US$) - United Kingdom*. Retrieved from https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=GB

Wróbel, K., Wróbel, J., Tokarz, W., Lach, J., Podsadni, K., & Czerwiński, A. (2022). Hydrogen internal combustion engine Vehicles: A review. *Energies*, 8937.

Zemo Partnership. (2021). *Heavy Duty and Specialist Vehicle Low and Zero Emission Market Opportunities.* Scottish Enterprise.

Zemo Partnership. (2022). *Decarbonising Heavy Duty Vehicles and Machinery.*

Zemo Partnership. (2022a). *Opportunities for biomethane as a transport fuel in Scotland.*

Zemo Partnership, Cenex. (2021). *The Renewable Fuels Guide - Helping fleet operators cut carbon emissions.* Zemo.

9 APPENDICES

9.1 Appendix 1: Database of reviewed documents

A database of the documents referenced in this report has been shared with DESNZ – summary statistics are shown in Table 70. All of these are included in the bibliography.

Table 70 – Summary of the literature referenced within this report, broken down by source of publication and relevance to industrial NRMM decarbonisation in the UK

Publication source	Number of high relevance	Number of medium relevance	Number of low relevance	Total
Government commissioned	11	6	28	**45**
Scientific or academic	5	4	15	**24**
Other (e.g., NGOs, thinktanks, market actors)	13	16	23	**52**
Total	**29**	**26**	**66**	**121**

The publications were graded by relevance to the research questions:

- **High relevance:** source contains detailed information relating to industrial NRMM decarbonisation. These are either specific to the UK, or contain detailed case studies of analysis from elsewhere which are likely to be applicable to the UK.
- **Medium relevance: s**ource contains information relevant to industrial NRMM, and is either (but not both) about decarbonisation or is UK-based research (or elsewhere which is likely to be applicable).
- **Low relevance:** source is not directly about industrial NRMM decarbonisation but could contain information about industrial NRMM outside of decarbonisation, or contains a detailed piece of information (e.g., an estimate of cost) which is highly specific and not more generally relevant.

9.2 Appendix 2: Stakeholder engagement – list of interviewees and attendees

Table 71 lists the organisations who took part in an interview or participated in a workshop, indicating their market actor group. A few other organisations contributed but did not want their name to be listed (listed in Table 71 as 'Anonymised contributor'). The Centre for Low Emission Construction, Imperial College London has also reviewed the report and intermediary deliverables.

Table 71 – List of stakeholders who contributed through interviews or workshop

Company	Sector	Attendance
Action Sustainability/ Supply Chain Sustainability School (BAM Nuttall)	Sector specialist	Workshop
Addvantage Global	Fuel and infrastructure providers	Workshop
Advanced Propulsion Centre UK	Sector specialist	Workshop
AGCO Finance	Lease and hire companies	Workshop
Anonymised contributor	Lease and hire companies	Interview
Anonymised contributor	Lease and hire companies	Workshop

Company	Sector	Attendance
Anonymised contributor	Equipment users	Workshop
Anonymised contributor	Sector specialist	Workshop
Anonymised contributor	Sector specialist	Workshop
Anonymised contributor	Sector specialist	Workshop
Anonymised contributor	Equipment and component manufacturers	Workshop
Arup	Equipment users	Interview and Workshop
Atomictractor Limited	Equipment and component manufacturers	Workshop
AvantiGas Limited	Fuel and infrastructure providers	Workshop
BAM Nuttall	Equipment users	Interview and Workshop
BorgWarner	Equipment and component manufacturers	Workshop
Bosch	Equipment and component manufacturers	Workshop
bp plc	Fuel and infrastructure providers	Interview
British Metals Recycling Association	Sector specialist	Workshop
British Ports Association	Sector specialist	Workshop
CAGE Technologies Ltd	Equipment and component manufacturers	Workshop
Calor Gas GB	Fuel and infrastructure providers	Workshop
Catagen	Fuel and infrastructure providers	Workshop
Caterpillar	Equipment and component manufacturers	Workshop
CCfL/Merton	Equipment users	Workshop
CLDN CRO Ports	Equipment users	Interview
CNG Services	Fuel and infrastructure providers	Interview and Workshop
CNH Industrial	Equipment and component manufacturers	Workshop
Cold Chain Federation	Sector specialist	Workshop
Construction Equipment Association	Sector specialist	Interview and Workshop
Construction Plant-hire Association	Sector specialist	Interview and Workshop
Costain Ltd	Equipment users	Interview
Cummins	Equipment and component manufacturers	Interview
Danfoss Scotland Ltd.	Equipment users	Workshop
Department for Transport	Sector specialist	Workshop
Dolphin N2 Limited	Fuel and infrastructure providers	Workshop
dpworld	Equipment users	Workshop
Eminox Ltd	Equipment and component manufacturers	Workshop
Finning UK Ltd	Equipment and component manufacturers	Workshop
Green Biofuels LTD	Fuel and infrastructure providers	Workshop

Company	Sector	Attendance
Hickman Shearer	Lease and hire companies	Interview
Hire Association Europe (HAE)	Sector specialist	Workshop
HS2	Equipment users	Interview and Workshop
Hydrologiq	Fuel and infrastructure providers	Workshop
Imperial College London	Sector specialist	Workshop
Intelligent Energy	Equipment and component manufacturers	Interview and Workshop
InterBay Asset Finance	Lease and hire companies	Workshop
ITM Power	Equipment and component manufacturers	Interview
JCB	Equipment and component manufacturers	Workshop
JouleVert Limited	Sector specialist	Workshop
Keltbray Ltd	Equipment users	Workshop
Knibb Gormezano Partners	Equipment and component manufacturers	Workshop
Láidir. Circular Mobility	Fuel and infrastructure providers	Workshop
London Borough of Merton	Equipment users	Workshop
McCloskey International	Equipment and component manufacturers	Interview and Workshop
Merton	Equipment users	Workshop
Mineral Products Association	Sector specialist	Workshop
Motive Fuels	Infrastructure Provider	Interview
National Highways	Equipment users	Workshop
Perkins	Equipment and component manufacturers	Interview
Queen's University Belfast	Sector specialist	Workshop
Shell plc	Fuel and infrastructure providers	Workshop
Simply finance	Lease and hire companies	Interview and Workshop
SMMT	Sector specialist	Workshop
Tarmac	Equipment users	Interview and Workshop
Taylor Construction Plant LTD	Equipment users	Workshop
Terex Materials Processing	Equipment and component manufacturers	Interview and Workshop
UK Material Handling Association	Sector specialist	Workshop
UKPIA	Sector specialist	Workshop
University of Bath	Sector specialist	Workshop
URBAN MOBILITY SYSTEMS NL	Equipment and component manufacturers	Workshop
Valero Energy Ltd	Fuel and infrastructure providers	Workshop
Veolia	Equipment users	Interview
WAE Technologies	Sector specialist	Workshop
Zemo Partnership	Sector specialist	Workshop

9.3 Appendix 3: Archetypes description and machine categories

The archetypes developed by ERM are based on the 2021 National Atmospheric Emissions Inventory (NAEI) database. The number of machinery types has been reduced from the 40 machinery types listed under 1A2gvii and 1A4aii codes in the 2021 NAEI database to 36. This has been achieved by excluding Transport Refrigeration Units (out of scope), grouping the ‘aggregate applicator’ and ‘bitumen applicator’ due to their similar use cases (together they represent 1.2% of industrial NRMM fuel use), and combining ‘other general industrial equipment’ and ‘other material handling equipment’ into generators due to their ambiguity and low fuel use (0.06% of industrial NRMM fuel use).

The following tables show the archetypes summary, allocation of machinery by category and the archetype(s) each machinery occupies.

Table 72 – Description and percentage of fuel use and population of the 14 archetypes created by ERM. Source data from the NAEI database, with ERM categories and analysis

Archetype ID	Machinery category	Power rating	Utilisation level	% of population	% of total fuel use	Example machinery (highest fuel use)
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	14.2%	4.6%	Cement mixers, plate compactors
2		High (19-56 kW)	All	0.9%	4.4%	Welding equipment, concrete saws
3	Mobile machinery	Low (<37 kW)	Low (<50%)	1.9%	2.0%	Forklifts, Excavators
4		Medium (37-129 kW)	Low (<50%)	9.0%	23.6%	Forklifts, Excavators, telehandlers
5		High (130-560 kW)	Low (<50%)	0.8%	9.0%	Excavators, Dumpers/tenders
6		Medium (37-129 kW)	High (>50%)	0.6%	8.7%	Sweepers/scrubbers, forklifts
7		High (130-560 kW)	High (>50%)	0.2%	6.4%	Port tractors, Bulldozers
8		Very high (> 560 kW)	High (>50%)	0.04%	1.9%	Dumpers/tenders
9	Limited movement machinery	Medium (37-129 kW)	Low (<50%)	7.5%	9.6%	Mini excavators, Air compressors
10		High (130-560 kW)	All	0.6%	12.5%	Cranes, crushing equipment
11	Generators	Low (<8 kW)	Low (<50%)	63.7%	11.5%	
12		Medium (8-74 kW)	Low (<50%)	0.4%	2.4%	
13		High (75-560 kW)	Low (<50%)	0.3%	3.2%	
14		Very high (>560 kW)	Very Low (<25%)	0.01%	0.3%	

Table 73 – Assignment of machinery categories to machinery types, as performed by ERM

Machinery type	Machinery category	Machinery type	Machinery category
Aerial lifts	Mobile machinery	Landfill Compactors	Mobile machinery
Aggregate/Bitumen Applicator	Limited motion machinery	Loaders	Mobile machinery
Air compressors	Limited motion machinery	Plate compactors	Hand-held/moved equipment
Asphalt/concrete pavers	Hand-held/moved equipment (<56 kW) /Mobile machinery (>56 kW)	Pressure washers	Hand-held/moved equipment
Bore/drill rigs	Limited motion machinery	Pumps	Hand-held/moved equipment
Bulldozers	Mobile machinery	Reachstackers	Mobile machinery
Cement & mortar mixers	Hand-held/moved equipment (<19 kW) /Mobile machinery (>19 kW)	Rollers	Mobile machinery
Concrete /industrial saws	Hand-held/moved equipment	Rough terrain forklifts	Mobile machinery
Concrete pumps	Limited motion machinery	Rubber Tyred Gantry Cranes	Limited motion machinery
Cranes	Limited motion machinery	Scrapers	Mobile machinery
Crushing/processing equipment	Limited motion machinery	Shuttle Carrier/Straddle carrier	Mobile machinery
Dumpers /tenders	Mobile machinery	Surfacing equipment	Hand-held/moved equipment
Excavators	Mobile machinery	Sweepers/ scrubbers	Mobile machinery
Forklifts	Mobile machinery	Tampers /rammers	Hand-held/moved equipment
Gas compressors	Limited motion machinery	Telehandlers	Mobile machinery
Generators	Generators	Port terminal tractors	Mobile machinery
Graders	Mobile machinery	Trenchers/mini excavators	Limited motion machinery
Industrial tractors, burden and personnel carriers	Mobile machinery	Welding equipment	Hand-held/moved equipment

Table 74 – Assignment of industrial NRMM to archetypes, as performed by ERM. Since different machines within a machinery type can have different degrees of mobility, power ratings or utilisation rates, a single machinery type can be split across multiple archetypes

Equipment	Archetypes occupied by machinery
Aerial lifts	3
Aggregate/bitumen applicator	9, 10
Air compressors	9
Asphalt/concrete pavers	2, 9
Bore/drill rigs	10
Bulldozers	4, 5, 6, 7
Cement & mortar mixers	1, 4, 5
Concrete/industrial saws	2
Concrete pumps	9, 10
Cranes	9, 10
Crushing/processing equip	9, 10
Dumpers/tenders	3, 4, 5, 7, 8
Excavators	3, 4, 5
Forklifts	3, 4, 6
Gas compressors	9
Generators	11, 12, 13, 14
Graders	5
Industrial tractors, burden and personnel carriers	4, 5
Landfill compactors	5
Loaders	3, 4, 5, 6, 7
Plate compactors	1
Pressure washers	1
Pumps	1
Reachstackers	7
Rollers	3, 4
Rough terrain forklifts	4
Rubber tyred gantry cranes	10
Scrapers	5
Shuttle carrier/straddle carrier	7
Surfacing equipment	2
Sweepers/scrubbers	4, 6
Tampers/rammers	1
Telehandlers	4
Port terminal tractors	7
Trenchers/mini excavators	9
Welding equipment	2

The next tables show the breakdown of fuel consumption in the 2021 NAEI database by machinery mobility category, power rating and utilisation level. The fuel is diesel in majority, refer to sub-section 2.1.1 for commentary on fuel split between diesel, petrol and LPG. The % utilisation is based on an 8-hour day, 365 days a year.

Hand-held or hand-moved equipment

Annual fuel consumption (tonnes/year) of hand-held equipment, broken down by power rating and utilisation

Power bands:	**Utilisation level:**	**<25%**	**25-50%**	**50-75%**	**>75%**	**Total t/year**
< 8 kW		44,369	15,481		1,484	61,334
8-18 kW		351	20,467			20,818
19-36 kW		1,472	3,475	61,047	8,350	74,343
37-55 kW		3,401				3,401
56-74 kW						
75-129 kW						
130-560 kW						
> 560 kW						
Total		49,593	39,423	61,047	9,834	159,897

Archetype 1

Archetype 2

Sectors: Construction Mining Other


Pressure washers


Rammer

Mobile machinery

Annual fuel consumption (tonnes/year) of mobile machinery, broken down by power rating and utilisation level

Power bands:	**Utilisation level:**	**<25%**	**25-50%**	**50-75%**	**>75%**	**Total t/year**
< 8 kW						
8-18 kW		2,020				2,020
19-36 kW		6,277	27,428		12,510	46,216
37-55 kW		23,235	106,993		20,777	151,005
56-74 kW		111,099	18,027		45,237	174,363
75-129 kW		104,489	56,048	12,778	63,620	236,935
130-560 kW		25,633	133,529	28,605	84,446	272,213
> 560 kW			747	33,051		33,798
Total		272,754	342,773	74,434	226,590	916,550

Archetype 3	Archetype 6
Archetype 4	Archetype 7
Archetype 5	Archetype 8

Sectors: Construction Mining Ports Waste Other


Bulldozer


Dumptrucks

Limited motion machinery

Annual fuel consumption (tonnes/year) of limited motion machinery, by power rating and utilisation level

Power bands:	Utilisation level:	<25%	25-50%	50-75%	>75%	Total t/year
< 8 kW						
8-18 kW		16,836				16,836
19-36 kW		56,121				56,121
37-55 kW		33,671				33,671
56-74 kW		44,918				44,918
75-129 kW		1,426	18,592			20,018
130-560 kW			161,487	17,304	44,091	222,822
> 560 kW						
Total		152,972	180,080	17,304	44,091	394,446

Archetype 9

Archetype 10

Sectors: Construction Mining Ports Other

Crane

Gantry crane

Generators

Annual fuel consumption (tonnes/year) of generators, broken down by power rating and utilisation level

Power bands:	Utilisation level:	<25%	25-50%	50-75%	>75%	Total t/year
< 8 kW		205,073	326			205,398
8-18 kW			3,748			3,748
19-36 kW						0
37-55 kW			27,012			27,012
56-74 kW			15,245			15,245
75-129 kW		136	17,054			17,190
130-560 kW		307	38,604			38,911
> 560 kW		5,961				5,961
Total		211,477	101,989	0	0	313,466

Archetype 11	Archetype 13
Archetype 12	Archetype 14

Sectors: Construction Other

Small generators

Large generator

9.4 Appendix 4: Approaches to estimating future NRMM sales

As discussed in sub-section 2.3.3, two methods of estimating future NRMM population and sales were considered:

- Using historic sales to estimate future sales and stock;
- Using GDP as a proxy for stock growth across all industrial NRMM.

For the analysis in this report, the historic sales approach was used. The two approaches are described below, with an illustrative example to highlight the differences.

9.4.1 Historic sales approach

The historic sales approach follows a similar method to that employed in the paper from Imperial College London (Desouza, Marsh, Beevers, Molden, & Green, 2022). However, instead of using an average of sales data, a compound annual growth rate in sales would be calculated from the information in the NAEI database. As discussed at the start of sub-section 2.3.3, the age profile of machinery within the 2021 NAEI database can be used as an estimate of the sales in that year, as no scrappage has been assumed to occur before the full machinery lifetime is reached within the 2021 NAEI database.[281] This provides an estimated historical sales profile for each machinery type, extending back a number of years equal to the 'high lifetime' provided in the NAEI database for that machinery type.

This can be used to estimate an annual stock growth, which is consistent with the reported age distribution of machines in the 2021 NAEI database and provides a smooth transition between historic sales and projected sales up to 2050. The methodology for this is detailed below.

Firstly, the annual change in sales is calculated from the historic sales data from the NAEI database, by taking the first and last datapoint and calculating the annual growth rate implied by these values.

$$Sales\ \%\ change\ over\ n\ years = \frac{Sales\ in\ year\ x - Sales\ in\ year\ (x-n)}{Sales\ in\ year\ x + Sales\ in\ year\ (x-n)}$$

$$Annual\ \%\ sales\ growth = \ (1 + \%\ sales\ change\ in\ n\ years)^{1/n} - 1$$

The first and last value were taken as machinery sales are likely to have some periodicity across the length of the machine's lifetime. Most machinery will be replaced near the end of its estimated life, hence sales in year x are related to the sales that occurred in year (x – machinery lifetime). The first and last value of machinery sales from the NAEI database nearly encompass a full machinery lifetime, therefore these points provide the best estimate to the annual growth excluding fluctuations between years.

The projected stock growth was set to the square-root of the historical annual sales growth, as this generally provided a smooth transition between historic and projected sales values.

$$Annual\ \%\ stock\ growth = \sqrt{1 + Annual\ \%\ sales\ growth} - 1$$

Example results of this analysis are shown in Figure 54 for 265 kW reachstackers used in ports, which have a calculated stock growth of -2.9% annually using this method (original data from the 2021 NAEI database, with ERM analysis).

The key limitation of this approach is the reliability of the data in the NAEI database: if the age distribution of machinery does not accurately portray historic sales, then future projections will also be affected.

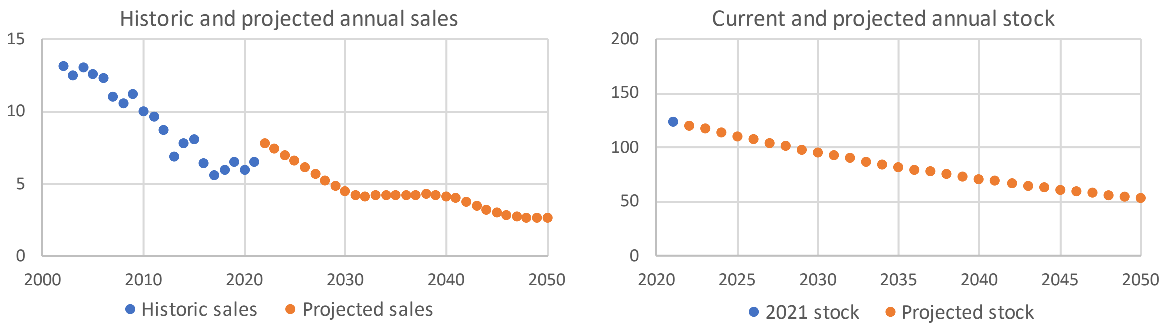

Figure 54 – Example of historic and projected sales and stock calculated for 265 kW reachstackers in the port sector, using the historic sales approach

9.4.2 Using GDP as a proxy for stock growth

The second approach would utilise GDP projections for the UK from the OECD to 2050,[282] assuming that economic growth or shrinkage would result in the same trend in industrial NRMM demand and

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[281] For example, if 100 units of age 2.5 years is reported in the NAEI database, it is assumed that there were 100 units sold in 2019 (2 years before the inventory date of 2021).

[282] OECD projections were used rather than OBR, as OBR projections stop at 2027, whereas OECD projections extend to 2050.

stock. Annual sales reports from OEMs support this with recent sales decreasing during the COVID-19 pandemic,[283] as did UK exports and imports of industrial NRMM during the 2007-2008 financial crisis as shown in Figure 14 (HMRC, 2023). However, there are a few exceptions to this assumption, particularly regarding sector-specific trends. For example, whilst non-energy mining and quarrying in the UK has stays roughly constant, coal mining has reduced significantly over the last few decades.[284] This is at odds with the UK's continued economic growth on average over this same period (World Bank, 2021).

Linking stock growth to GDP for all machines can lead to irregular sales projections or discontinuous jumps in sales between historical (based on NAEI data) and projected sales (based on GDP growth), especially if the estimated historic sales are in decline. This is demonstrated in Figure 55, which shows the projected sales and stock for 265 kW reachstackers in the port sector (which would have a stock growth of -2.9% based on the historical sales method) by linking stock growth to GDP growth (1.2% average annual growth 2023-2050, OECD). [285] As shown, this leads to a discontinuous jump in sales between historical and projected sales. This effect is more pronounced the bigger the difference between the calculated historic sales annual growth and GDP growth projection, leading to significant jumps in sales if sales are in decline historically.

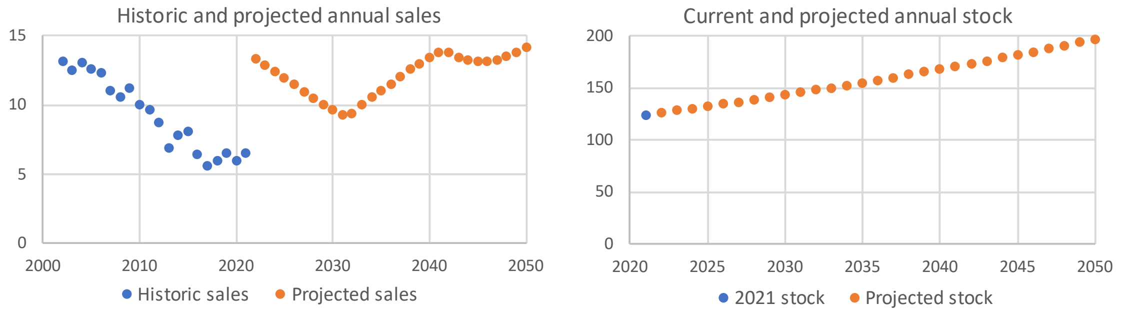

Figure 55 – Historic (based on NAEI data) and projected stock and sales for 265 kW reachstackers in the port sector, when assuming that future stock growth is equal to projected GDP growth

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[283] Annual sales taken from latest publicly available annual reports from six major NRMM OEMs in Figure 17 (page 42).

[284] https://www.ukeiti.org/mining-quarrying

[285] https://data.oecd.org/gdp/real-gdp-long-term-forecast.htm#indicator-chart

9.5 Appendix 5: Emissions regulations

European emission standards for engines used in NRMM. Stage I-IV regulations for diesel engines were specified by Directive 97/68/EC. Stage V includes regulations for all NRMM engines specified in Regulation 2016/1628.

Table 75 – Overview of stages of European emission standards for NRMM engines, including date of implementation

Engine category	Engine type	Net power (kW)	Date	g/kWh				
				CO	HC	HC+NOx	NOx	PM
Stage I								
A	CI	130 ≤ P ≤560	01/1999	5.0	1.3	-	9.2	0.54
B	CI	75 ≤ P ≤130	01/1999	5.0	1.3	-	9.2	0.70
C	CI	37 ≤ P ≤75	04/1999	6.5	1.3	-	9.2	0.85
Stage II								
E	CI	130 ≤ P ≤ 560	01/2002	3.5	1.0	-	6.0	0.2
F	CI	75 ≤ P < 130	01/2003	5.0	1.0	-	6.0	0.3
G	CI	37 ≤ P < 75	01/2004	5.0	1.3	-	7.0	0.4
D	CI	18 ≤ P < 37	01/2001	5.5	1.5	-	8.0	0.8
Stage III A								
H	CI	130 ≤ P ≤ 560	01/2006	3.5	-	4.0	-	0.2
I	CI	75 ≤ P < 130	01/2007	5.0	-	4.0	-	0.3
J	CI	37 ≤ P < 75	01/2008	5.0	-	4.7	-	0.4
K	CI	19 ≤ P < 37	01/2007	5.5	-	7.5	-	0.6
Stage III B								
L	CI	130 ≤ P ≤ 560	01/2011	3.5	0.19	-	2.0	0.025
M	CI	75 ≤ P < 130	01/2012	5.0	0.19	-	3.3	0.025
N	CI	56 ≤ P < 75	01/2012	5.0	0.19	-	3.3	0.025
P	CI	37 ≤ P < 56	01/2013	5.0	-	4.7	-	0.025
Stage IV								
Q	CI	130 ≤ P ≤ 560	01/2014	3.5	0.19	-	0.4	0.025
R	CI	56 ≤ P < 130	10/2014	5.0	0.19	-	0.4	0.025
Stage V								
NRE-v/c-1	CI	P < 8	2019	8.0	-	7.5	-	0.4
NRE-v/c-2	CI	8 ≤ P < 19	2019	6.6	-	7.5	-	0.4
NRE-v/c-3	CI	19 ≤ P < 37	2019	5.0	-	4.7	-	0.015
NRE-v/c-4	CI	37 ≤ P < 56	2019	5.0	-	4.7	-	0.015
NRE-v/c-5	All	56 ≤ P < 130	2020	5.0	0.19	-	0.4	0.015
NRE-v/c-6	All	130 ≤ P ≤ 560	2019	3.5	0.19	-	0.4	0.015
NRE-v/c-7	All	P > 560	2019	3.5	0.19	-	3.5	0.045
NRG-v/c-1	Generator sets	P > 560	2019	3.5	0.19	-	0.67	0.035

9.6 Appendix 6: Efficiency measures

The examples identified for each of the three efficiency measure categories (operational, machine and process) from sub-section 3.1.2 and the assumptions stated in sub-section 3.8.3 were used to assign potential efficiency gains to each of the defined archetypes as shown in Table 76.

Table 76 – Potential efficiency gains by measure category and archetype. *For process efficiency, a weighted average was used (2/3 to low and 1/3 to high). Source: ERM assignment of % values reported in the literature

Archetype ID	Machinery category	Power rating	Utilisation level	Operational			Machine			Process		
				Low	Avg	High	Low	Avg	High	Low	Avg*	High
1	Hand-held/hand-moved equipment	Low (<19 kW)	All	0%	3%	5%	5%	8%	10%	0%	2%	5%
2		High (19-56 kW)	All	0%	3%	5%	5%	8%	10%	0%	2%	5%
3	Mobile machinery	Low (<37 kW)	Low (<50%)	10%	15%	20%	5%	10%	15%	10%	13%	20%
4		Medium (37-129 kW)	Low (<50%)	10%	18%	25%	5%	10%	15%	10%	20%	40%
5		High (130-560 kW)	Low (<50%)	10%	20%	30%	5%	10%	15%	10%	20%	40%
6		Medium (37-129 kW)	High (>50%)	5%	8%	10%	10%	18%	25%	15%	27%	50%
7		High (130-560 kW)	High (>50%)	5%	10%	15%	10%	18%	25%	15%	27%	50%
8		Very high (> 560 kW)	High (>50%)	5%	10%	15%	10%	18%	25%	10%	12%	15%
9	Limited movement machinery	Medium (37-129 kW)	Low (<50%)	5%	8%	10%	5%	10%	15%	15%	22%	35%
10		High (130-560 kW)	All	0%	3%	5%	5%	10%	15%	15%	20%	30%
11	Generators	Low (<8 kW)	Low (<50%)	5%	8%	10%	5%	10%	15%	15%	17%	20%
12		Medium (8-74 kW)	Low (<50%)	5%	8%	10%	5%	10%	15%	15%	20%	30%
13		High (75-560 kW)	Low (<50%)	5%	8%	10%	5%	10%	15%	15%	23%	40%
14		Very high (>560 kW)	Very Low (<25%)	5%	8%	10%	5%	10%	15%	15%	23%	40%

With these potential gains defined by archetype, the assumptions shown in Table 77 were used to build a potential efficiency gains deployment pathway for each archetype (as shown in Table 44, sub-section 3.8.3, and illustrated for Archetype 8 in Figure 23). For the combined average gains in 2040, simple averages of the high and low operational and machine efficiencies were used. For process efficiency, a weighted average (2/3 to low, 1/3 to high) of the potential efficiency gains per archetype was used. This was done because the high potential process efficiency measures identified were highly use-case or machine-specific.

Table 77 – Assumptions made to build efficiency measures deployment pathway (general agreement expressed through stakeholder engagement)

2020	2025	2030 2035	2040	2045 2050
Assumed no new efficiency measures adopted	Assumed the lowest potential measure (out of all categories) is adopted for all archetypes	Linear ramp up to 2040	Peak efficiency gain assumed to be a combination of the average savings across all measure categories (see text for method used to average process efficiencies)	Hold 2040 value

9.7 Appendix 7: Hydrogen infrastructure costs

Hydrogen infrastructure costs were estimated per kg hydrogen delivered to provide a representative cost for a machine using hydrogen fuel (given that hydrogen refuelling infrastructure is likely to be shared across multiple machines). The calculation values used to estimate the cost per kg hydrogen delivered are shown for present-day and potential lower cost scenario in the future (Table 78).

Utilisation is the ratio of the average amount of hydrogen delivered compared to the capacity of the hydrogen refuelling station (HRS). Current utilisation for an HRS is expected to be low, due to the low prevalence of hydrogen powered industrial NRMM (and other on-road hydrogen powered vehicles). This utilisation could increase significantly as more hydrogen powered machinery reach commercial availability and deployment. This utilisation parameter has the most significant impact on the cost per kg hydrogen delivered.

In addition, the cost of transport may decrease in a high deployment scenario, assuming that low-carbon hydrogen is widely available across the UK, reducing the transport distance (and cost) for hydrogen deliveries to industrial NRMM sites.

For the least-cost pathways modelling in Chapter 5, the cost of hydrogen infrastructure is modelled per kg hydrogen used, with the cost modelled at £7/kg (21 p/kWh) in 2020 and decreasing linearly to £2/kg (6 p/kWh) in 2050.

Table 78 – Values used to estimate the cost per kg of hydrogen delivered to industrial NRMM in the present day and in a future high utilisation scenario

Parameter	Value today	Value in future high utilisation scenario	Unit	Source of value
HRS lifetime	15	15	years	Assumption
Capacity	200	200	kg/day	Assumption, consistent with CAPEX below
Utilisation	20%	80%		Variable (Expected to be 15-90%)
Lifetime H_2 dispensed	219,000	876,000	kg	Calculation
Interest rate	5%	5%		Assumption
Capital cost	750,000	750,000	£	(Clean Hydrogen Partnership, 2022)
Interest paid over lifetime	333,851	333,851	£	Calculation
Annual operation and maintenance costs	1%	1%	Of CAPEX	Assumption
Total operation and maintenance over life	112,500	112,500	£	Calculation
Total costs	1,196,351	1,196,351	£	Calculation
Cost per kg for site infrastructure	**5.5**	**1.4**	**£/kgH_2**	Calculation
Cost of transport	**1**	**0.5**	**£/kg**	(International Energy Agency, 2019), assuming transport distances of 100 km and 50 km respectively.
Total cost per kg	**6.5**	**1.9**	**£/kgH_2**	Calculation

9.8 Appendix 8: Commercial availability and TRL

Detailed TRL review of fuel switching options

Table 79 shows the outcome of our review of the abatement options available across industrial NRMM types and sectors (construction, mining, port, waste, other). Whilst Table 79 covers all industrial NRMM types identified in the 2021 NAEI database, it does not break machinery down by power bands. Therefore, the TRL assigned shows that of the most advanced model found for a machine type. For example, if small sub-37 kW battery-electric excavators are available on the market, the battery-electric field for excavators will show in the colour-scale corresponding to 'commercially available': TRL 8+. Moreover, this also explains the low count of TRL 4–5 equipment types in the table where, for example, a commercially available low-powered electric excavator masks the R&D work going into larger excavators. The powertrain availability matrix by archetype in the main report (Table 43, sub-section 3.8.2) supersedes this table and does differentiate by power rating as per the archetype definitions. Table 79 is also present in the IND-database with the sources for the ratings.

While most machinery types are cross-sector compatible (e.g., aerial lifts), there are some differences across sectors and the specifications required of the same machine (e.g., drill rigs). The following sector-specific and powertrain-specific charts summarise the number of equipment types (by abatement technology option) under each defined TRL band.

Table 79 – TRL bands and TRL status of industrial NRMM

TRL Band	Description
🟩 8+	Available on the market for consumers to purchase
▨ 6-7	Pilots or pre-production prototype tests in real-world conditions by OEMs or with clients (expected by 2030)
🟧 4-5	Announcements of concepts/plans/designs. No product being tested in real-world conditions (not expected before 2030).
🟥 0-3	No evidence found, or announcements by OEMs to ‘explore’ tech with no evidence of on-going R&D

NRMM types	Sector	CNG	H_2ICE	H_2 FC	Tether	Hybrid	BE
Aerial lifts	All sectors	🟥	🟥	🟧	🟩	🟩	🟩
Aggregate/bitumen Applicator	Other	🟥	🟥	🟥	🟩	🟥	🟥
Air compressor	Construction	🟥	🟥	🟥	🟩	🟥	🟥
Asphalt/concrete pavers	Construction	🟥	▨	🟥	🟥	🟩	▨
Bore/drill rigs	Construction	🟥	🟥	🟧	🟥	▨	▨
	Mining	🟥	🟥	🟧	🟥	🟩	🟩
Bulldozers	Const. & Waste	🟥	🟥	🟥	🟥	🟩	▨
	Mining	🟥	🟥	🟥	🟥	🟩	🟥
Cement & mortar mixers	All sectors	🟥	🟥	▨	🟩	🟥	▨
Concrete / industrial saws	Construction	🟥	🟥	🟥	🟩	🟥	🟩
Concrete pumps	Construction	🟥	🟥	🟥	▨	▨	🟥
Cranes	Construction	🟥	🟥	🟥	🟩	🟩	🟩
	Port	🟥	🟥	▨	▨	🟩	🟩
Crushing/ processing equipment	Const. & Mining	🟥	🟥	🟥	🟩	🟩	🟧
Dumpers /tenders	Construction	🟥	🟥	▨	🟥	🟩	🟩
	Mining & Waste	🟥	🟥	▨	🟥	🟩	▨
Excavators	All sectors	🟥	▨	🟧	🟧	🟩	🟩
Forklifts	All sectors	🟩	🟥	🟩	🟥	🟩	🟩
Gas compressor	Other	🟥	🟥	🟥	🟩	🟥	🟥
Generators	All sectors	🟩	▨	▨	🟥	🟩	🟩
Graders	Construction	🟥	🟥	🟥	🟥	🟥	▨
Industrial tractors, burden and personnel carriers	Other	🟥	🟥	🟥	🟥	🟥	🟩
Landfill Compactors	Waste	🟥	🟥	🟥	🟥	🟥	🟥
Loaders	All other sectors	▨	▨	🟧	🟥	🟩	🟩
	Mining	▨	▨	🟧	🟩	🟩	🟩
Plate compactors	Construction	🟥	🟥	🟥	🟥	🟥	🟩
Pressure washers	All sectors	🟥	🟥	🟥	🟩	🟥	🟩
Pumps	Construction	🟥	🟥	🟥	🟩	🟥	🟩
Reachstackers	Port	🟥	🟥	▨	🟥	🟩	🟩
Rollers	All sectors	🟥	🟥	🟥	🟥	🟥	▨
Rough terrain forklifts	All sectors	🟥	🟥	🟥	🟥	🟥	🟩
Rubber Tyred Gantry Cranes	Port	🟥	🟥	🟧	🟩	🟩	🟩
Scrapers	Construction	🟥	🟥	🟥	🟥	🟥	🟥
Shuttle Carrier/Straddle carrier	Port	🟥	🟥	▨	🟥	🟩	🟩
Surfacing equip	Construction	🟥	🟥	🟥	🟩	🟥	🟥
Sweepers/ scrubbers	All sectors	🟥	▨	🟥	🟥	🟩	🟩
Tampers /rammers	Construction	🟥	🟥	🟥	🟩	🟥	🟩
Telehandlers	Mining	🟥	🟧	🟧	🟥	🟥	🟩
	All other sectors	🟥	▨	▨	🟥	🟩	🟩
Terminal tractors	Port	▨	🟥	▨	🟥	▨	🟩
Trenchers/mini excavators	Construction	🟥	🟥	🟥	🟥	🟩	🟩
Welding equip	All sectors	🟥	🟥	🟥	🟥	🟥	🟩

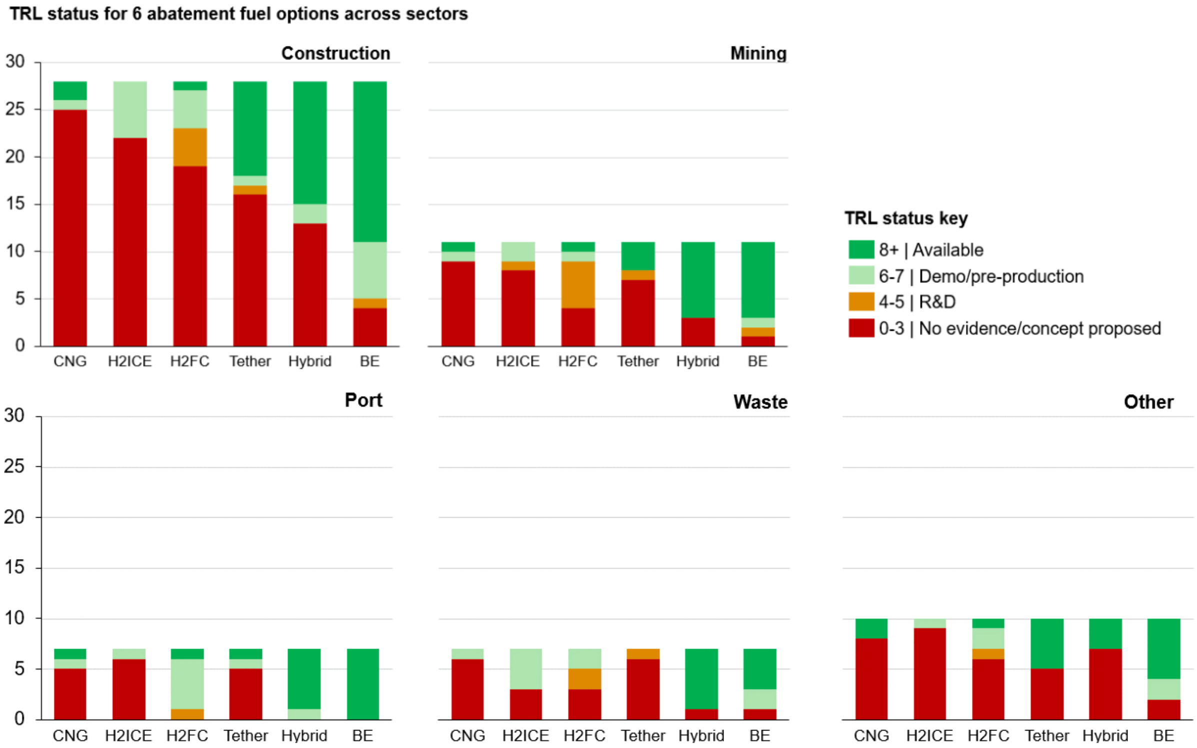

Figure 56 – Summary of TRL status by abatement option across the different sectors (y-axis: number of machinery and sector combinations)

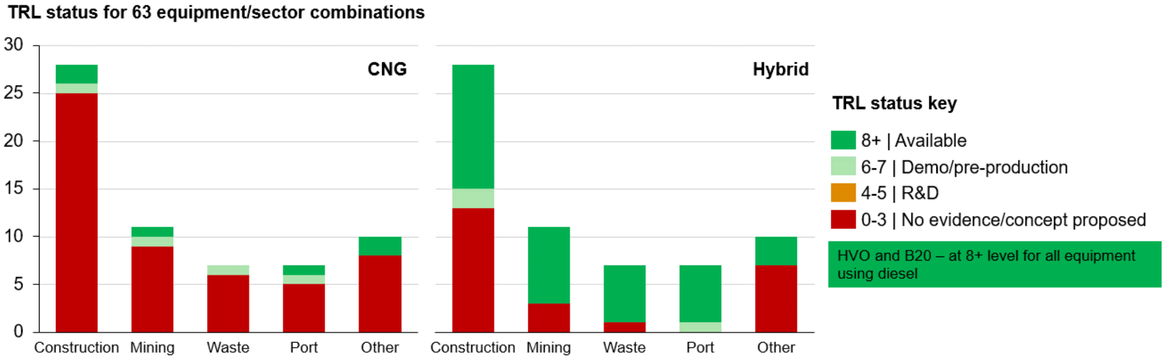

Figure 57 – TRL status for CNG and Hybrid industrial NRMM across all sectors (y-axis: number of machinery and sector combinations)

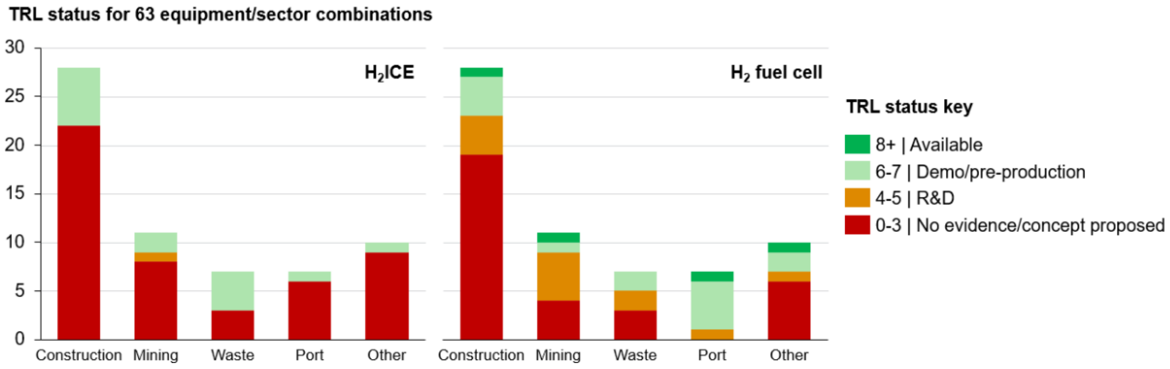

Figure 58 – TRL status for hydrogen ICE and fuel cell industrial NRMM across all sectors (y-axis: number of machinery and sector combinations)

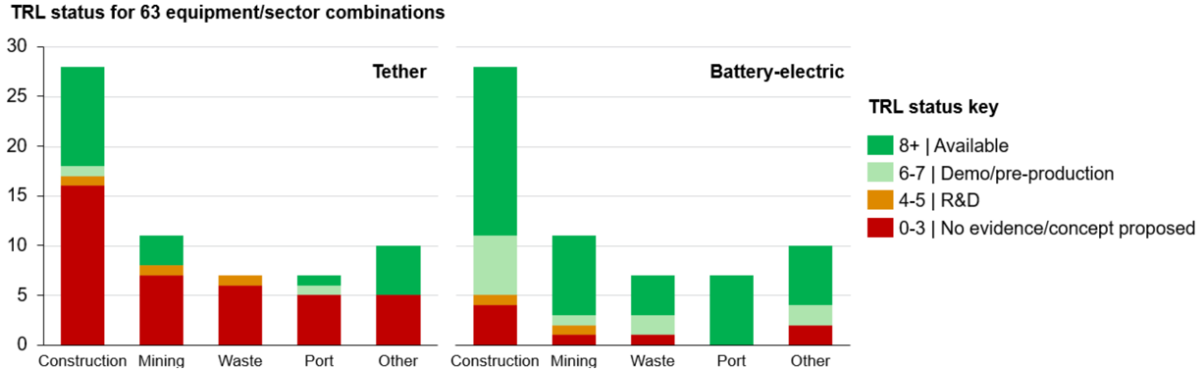

Figure 59 – TRL status for tethered and battery-electric industrial NRMM across all sectors (y-axis: number of machinery and sector combinations)

9.9 Appendix 9: Summary table of all parameters assessed

Table 80 – Summary table of all assessed archetype-dependent and independent parameters

Technology	Tailpipe CO_2e reduction potential	CO_2e reduction potential (WTW)	NOx/PM reduction potential	Energy density (volume)	Energy density (mass)	Fuel efficiency
HVO ICE	🟥	🟢	🟥	🟧	🟧	🟧
B20 ICE	🟥	🟥	🟥	🟧	🟧	🟧
Hybrid	🟧	🟧	🟧	🟢	🟢	🟢
Hydrogen ICE	🟩	🟩	🟧	🟥	🟥	🟥
Hydrogen fuel cell	🟩	🟩	🟩	🟥	🟥	🟢
Tethering	🟩	🟩	🟩	⬜	⬜	🟩
Battery electric	🟩	🟩	🟩	🟥	🟥	🟩
Efficiency measures	🟧	🟧	🟧	⬜	⬜	⬜

Technology	Powertrain availability by archetype														Applicability of practical constraints by archetype													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
HVO ICE	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
B20 ICE	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Hybrid	🟩	🟩	🟩	🟧	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Hydrogen ICE	⬛	⬛	⬜	🟧	🟥	🟧	🟥	🟥	🟥	🟥	⬜	🟥	🟥	🟥	⬛	⬛	🟩	🟧	🟧	🟥	🟥	🟥	🟧	🟥	🟩	🟧	🟧	🟧
Hydrogen fuel cell	⬛	⬛	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟢	🟢	🟧	🟥	⬛	⬛	🟩	🟧	🟧	🟥	🟥	🟥	🟧	🟥	🟩	🟧	🟧	🟧
Tethering	🟢	🟧	⬛	⬛	⬛	⬛	⬛	⬛	🟢	🟧	⬛	⬛	⬛	⬛	🟧	🟧	⬛	⬛	⬛	⬛	⬛	⬛	🟩	🟧	⬛	⬛	⬛	⬛
Battery electric	🟢	🟧	🟢	🟥	🟧	🟥	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟥	🟩	🟧	🟩	🟧	🟧	🟥	🟥	🟥	🟧	🟥	🟩	🟧	🟥	🟥

Archetypes 1 – 2: Hand-held/hand-moved; Archetypes 3 – 8: Mobile machinery; Archetypes 9 – 10: Limited movement machinery; Archetypes 11 – 14: Generators

Key	Description	Description
🟩	Highest potential	Significantly better than the incumbent fuel
🟢	High potential	Better than the incumbent fuel
🟧	Medium potential	As good as / similar to the incumbent fuel
🟥	Low potential	Inferior to the incumbent fuel
⬜	NA	NA
⬛		

Description	Description
Currently commercially available as an option	Minimal impact on feasibility of switch
Some current availability, expected to become more widely available from 2025 – 2030	*Not used*
Some limited current availability (demos/trials). Not expected as a widely available commercial option before 2030	Some impact on feasibility of switch
Little evidence of current availability, not expected as a widely available commercial option before 2035 – 2040	High impact on feasibility of switch
Technically feasible, but no evidence of ongoing development found	*Not used*
Powertrain viewed as incompatible with archetype	Powertrain viewed as incompatible with archetype

9.10 Appendix 10: Incumbent industrial NRMM Costs

9.10.1 Capital cost

Table 81 provides a summary of the counterfactual equipment type cost data, along with comments on quality and gaps. Capital cost data for new equipment is very fragmented. The main sources used, by order of relevance, are:

- Price list from UK manufacturers, in GBP (£), such as JCB[286]
- Other sources, such as NRMM sellers (e.g., https://www.trucksdirectuk.co.uk/, https://www.liftstoday.co.uk/, https://www.hampshiregenerators.co.uk)
- AFLEET model (2020), USD, converted to 2023GBP with inflation factor of 1.1505 from https://www.bls.gov/data/inflation_calculator.htm and 1 USD=0.8288 GBP from December 2022 exchange rate: monthly exchange rates - GOV.UK (publishing.service.gov.uk)
- Price list from USA manufacturers, in USD, converted to GBP as above. There are limitations with using USA market costs as they differ to UK market costs due to factors such as state discounts (for example Minnesota Department of Transportation, MnDOT, providing state aid for local transportation[287] and tax deductions). Therefore, prices from USA manufacturers were used only when data was not available from the other sources.

Table 81 – Summary of equipment cost. Counterfactual = diesel, petrol

Equipment	Power band	Counterfactual CAPEX £k for given kW power ratings	Comments on data quality / gaps
AERIAL LIFTS	8kW-37kW	£38k-£120k for 18kW-36kW	2020 USD single cost datapoints for an 18kW scissor lift and 36kW boom lift. Missing for low kW
AIR COMPRESSOR	19kW-75kW	£28k-£38k for 30kW-45kW	Good CAPEX data for rotary screw compressors between 30kW to 45kW. Missing for low and high kW
BULLDOZERS	75kW-560kW	£140k-£950k for 69kW-447kW	2020 USD single cost datapoints for a 69kW and 447kW bulldozer
CONCRETE / INDUSTRIAL SAWS	37kW-56kW	£28k-£45k for 36kW-55kW	Good CAPEX data on diesel walk behind concrete saws from 36-55kW
DUMPERS/TENDERS	8kW->560kW	£20k-£1.7M for 16kW-758kW	Good CAPEX data between 16-55kW. Limited data found above this with a single 2006 USD cost datapoint for 758kW
EXCAVATORS	10kW->560kW	£91k-£440k for 55kW-129kW	Good CAPEX data for tracked excavators between 55-129kW, good 2021 USD CAPEX data for 90kW-129kW wheeled excavators. Missing data for higher power bands

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[286] https://machinestore.jcb.com/en-GB/machines

[287] https://www.dot.state.mn.us/equipment-contracts/excavators.html

FORKLIFT	20kW-100kW	£25k-£79k for 35kW-70kW	Good CAPEX data between 35-55kW. Good 2015 USD CAPEX data between 40kW-70kW
GENERATORS	0.5kW->560kW	£2.5k-£62k for 3.2kW-640kW	Good UK data between 3.2 and 640kW
GRADERS	130kW-560kW	£760k for 205kW	Limited data found. Single 2006 USD CAPEX datapoint
LOADERS	19kW->560kW	£37k- £210k for 50kW-168kW	Good range of 2023 USD costs from 50kW to 69kW, limited data for higher power bands with a single 2020 USD datapoint for 168kW
ROLLERS	8kW-190kW	£18k-£94k for 14.5kW-100kW	Good data between 14.5kW-18.5kW, limited data above this power rating with a single 2020 USD datapoint for 100kW
ROUGH TERRAIN FORKLIFTS	37kW-56kW	£57k for 58kW	Limited data found. Single 2020 USD datapoint
RUBBER TYRED GANTRY CRANES	130kW-560kW	£1.8M for 272kW	Limited data found. Single 2020 USD datapoint
SCRAPERS	130kW-560kW	£1.3M-£1.8M for 211kW-337kW	Scrapers have 2 engines; we have used the scraper engine for the power rating. Single 2006 USD CAPEX datapoints for 211kW and 337kW
SHUTTLE CARRIER/STRADDLE CARRIER	130kW-560kW	£480k for 142kW	Limited data found. Single 2020 USD datapoint
TAMPERS /RAMMERS	<8kW	£2.0k-3.8k for 2.3kW-3.5kW	Good CAPEX data for rammers between 2.3kW-3.5kW
TERMINAL TRACTORS	130kW-560kW	£130k for 105kW	Limited data found. Single 2020 USD datapoint
TRENCHERS/MINI EXCAVATORS	8kW-75kW	£18k-£85k for 9kW-55kW	Good CAPEX data between 9kW-55kW

For a given machinery type, the capital cost varies due to several factors, including the manufacturer, engine power, equipment specification (such as operating weight, lift height, etc), and selected additional options. Additional variation in capital costs comes from price reductions from bulk purchases and contract negotiations for future purchases, including securing a quantity of a certain specification and options in advance. Overall, the higher the engine power, the higher the cost, as shown on the graphs below in Figure 61, made from the data shown in the previous table.

One of the contributors to industrial NRMM CAPEX costs is the powertrain cost. No sources were found that estimate the cost of industrial NRMM powertrains by their power rating, so proxies in the on-road sectors were investigated. The ICCT quotes a price of $118/kW (£119/kW when accounting for inflation 2022) for heavy goods vehicles in their 2017 paper (The International Council on Clean Transportation, 2017). However, when looking at light duty vehicles, a 2014 cost of €34/kW (£40/kW when accounting for inflation to 2022) could be used (Ricardo, 2016). These were compared to a selection of quotes for generator sets (which are predominately an engine) with differing engine powers,[288] which showed a linear correlation between price and power rating with a gradient of

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[288] https://www.hampshiregenerators.co.uk/product-category/generators/diesel-generators/page/24/?orderby=price-desc, data points used are included in the IND-database.

£82/kW (Figure 60). A value of £80/kW for diesel powertrains was used in the IND-database and modelling, as this is consistent with the trend seen for generators and is the midpoint between the heavy-duty and light-duty on-road costs referenced above.

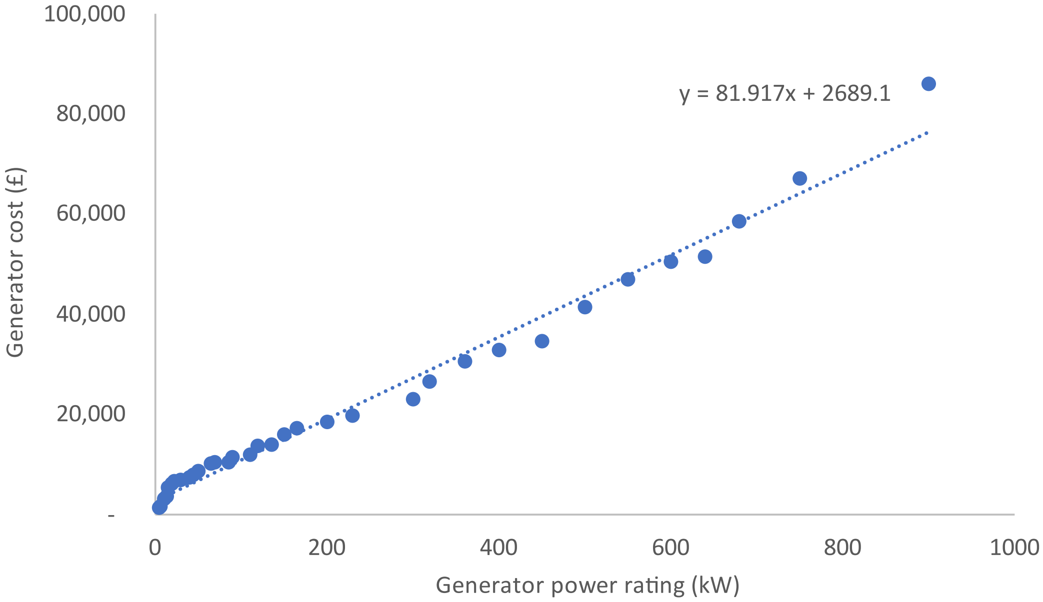

Figure 60 – A graph of purchase cost (excluding VAT) of generator sets against their power rating[288]

The cost data gathered covers 18 machinery types. In order to fill a cost database for the 36 machinery types (and their corresponding power band), we analysed the data collected to derive a 'base cost' (cost of the machinery without the powertrain), which is expected to be a function of the machine's power rating (as a proxy for machine size) and differs between different groups of machinery. The total cost of the machinery is then comprised of the base cost and the powertrain cost, using powertrain costs from the literature.

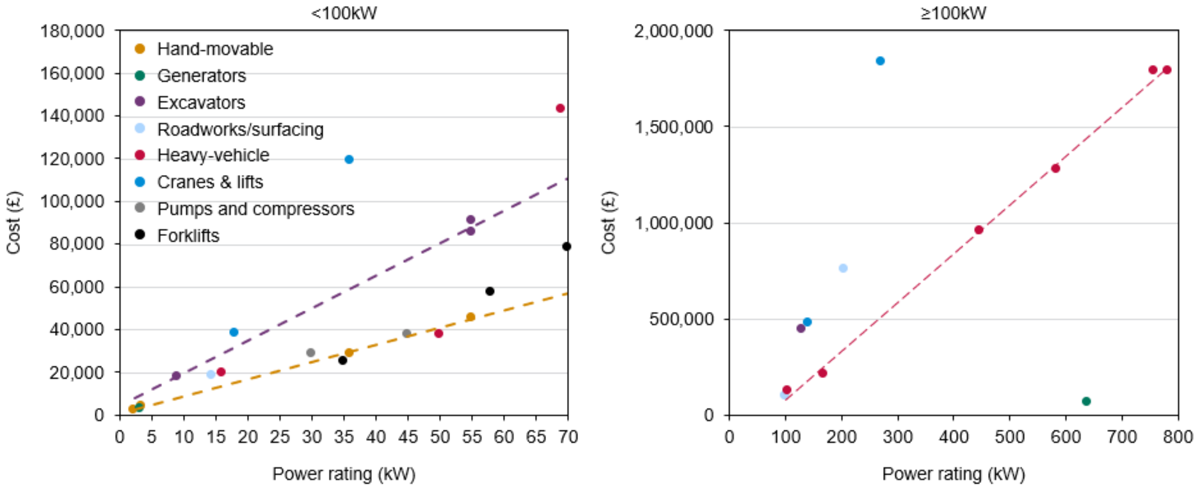

Figure 61 – Industrial NRMM capital cost against power rating broken down by broad equipment type and separated by <100kW (left) and ≥ 100kW (right). Dashed lines show trendlines for series of the same colour (not all lines are shown for clarity). Sources described above

9.10.2 Operating costs

The next table provides a summary of the OPEX data for diesel and petrol machinery, with comments on quality and gaps.

Table 82 – Summary of operating costs (all excluding VAT)

Cost type	Unit	Value	Comments on relevance across equipment type, data quality / gaps
Diesel fuel cost	£/L	1.4273	Good data available but value is highly volatile – see below for discussion.
Petrol fuel cost	£/L	1.2371	Good data available but value is highly volatile – see below for discussion.
Maintenance	£/h	0.086-5.631	Value varies depending on equipment type and use case, with similar trends for petrol and diesel engines. Trend of 0.95p/hr/kW (excluding cranes). No UK data found. AFLEET model values converted from 2020 USD values with inflation factor of 1.1505 and 1 USD=0.8288GBP. Some stakeholders suggested these values were slightly lower than expected but did not provide alternative values to use.
Diesel exhaust fluid	£/L	0.57	Relevant for diesel engines only. Market value available. Estimated consumption of 4% of diesel consumption.

Fuel cost

Fuel costs are the main OPEX, and these are calculated from the fuel cost per litre above with fuel use data from the NAEI database. For instance, fuel costs account for 76% of a construction wheel loader total cost of ownership (Argonne, 2021). Fossil fuel costs are linked to the cost of oil, which varies over time depending on global supply and demand. The price of petrol and diesel is very volatile, for example fuel costs have recently been high due to disruptions in supply chains (related to COVID-19 and war in Ukraine). The price for diesel and petrol (Figure 62) in January 2023 were 142.73p and 123.71p respectively excluding VAT.[289] None of the literature reviewed explicitly added a cost of infrastructure and distribution for delivery of incumbent fuel to NRMM sites, suggesting the use of standard diesel price is adequate.

Since April 2022, industrial NRMM is no longer permitted to use (lower duty rate) red diesel.[290]

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[289] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1131140/table_411_413.xlsx

[290] https://www.gov.uk/government/publications/reform-of-red-diesel-entitlements/reform-of-red-diesel-and-other-rebated-fuels-entitlement

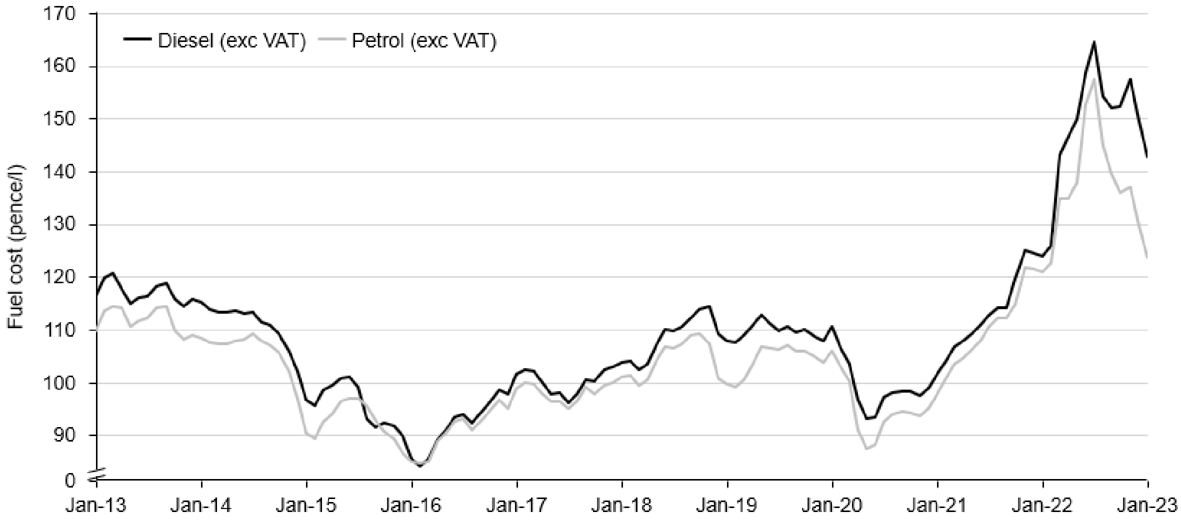

Figure 62 – 2013-2023 UK pump diesel and petrol prices (excluding VAT). Source: BEIS

Maintenance

A large proportion of the UK industrial NRMM fleet are leased or rented, with leasing and rental accounting for 66% of UK construction NRMM sales.[291] Given leasing costs include maintenance, repairs and financing costs, maintenance costs are not readily published. An approximation could be made based on NRMM capital costs and assumptions over lease agreements.[292] However, currently we have only found total annual lease liabilities from NRMM users financial reports without a breakdown of the leasing costs, so maintenance costs cannot be derived (e.g., (Morgan Sindall Group, 2022)).

We were able to collect 2020 USD maintenance costs from the AFLEET data for 12 of the 36 equipment types. Using USD inflation rates and USD=0.8228GBP this equates to maintenance costs between £0.086/hour and £5.63/hour depending on the equipment size and use case. In general, maintenance costs increase with machine size. Therefore, in most cases power rating can be used as a proxy for machine size and this correlation can be seen in Figure 63. The trend derives a maintenance cost increase of 0.95p/hr/kW. One notable exception is an RTG crane (highlighted below) which is an abnormally large machine compared to its power rating.

To put maintenance cost in perspective: using the maintenance cost trend of 0.95p/hr/kW, a high power (168kW) loader has a maintenance cost of £1.60 per hour, and using the operating hours (1330 hours/year) and the average lifetime (7 years) from the NAEI dataset this would equate to £2,139 per year and £14,970 over the 7-year lifetime of the vehicle. For comparison, assuming today's diesel price and fuel consumption from the NAEI dataset, the same loader would see fuel costs of £28,500 per year and £199,500 over the 7-year lifetime.

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[291] CEA Power Hour Webinar - Off Highway Research: UK Market Update (23 Feb 2022)

[292] https://www.caterpillar.com/en/brands/cat-financial.html

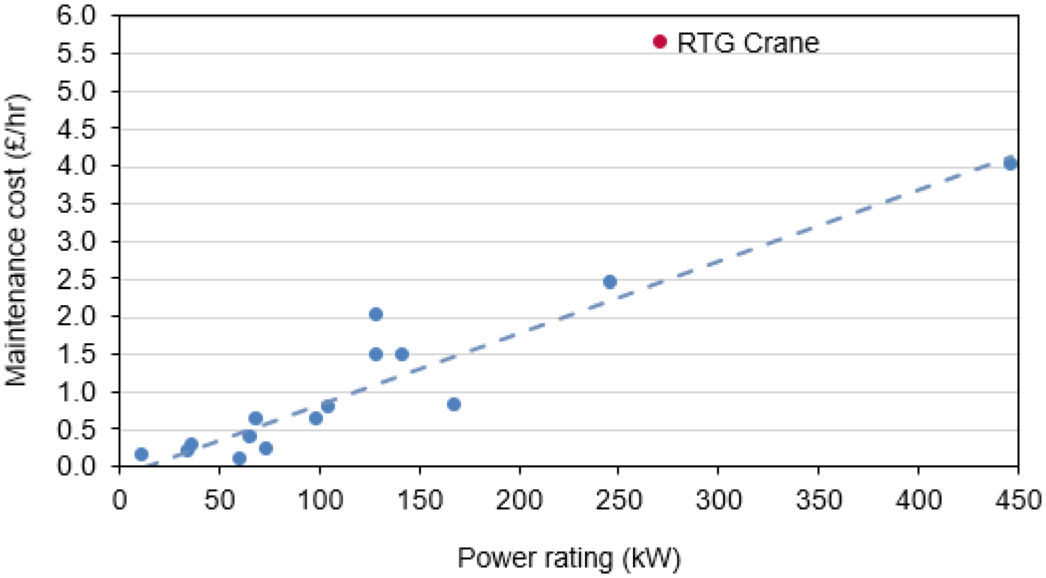

Figure 63 – Industrial NRMM maintenance cost against power rating, Source: AFLEET

Diesel exhaust fluid

Diesel exhaust fluid is an additive fluid that helps reduce NOx tailpipe emissions from diesel vehicles to keep in line with EU NRMM emissions standards. It is added to the machine's exhaust system with an estimated consumption of 4% of diesel consumption in the case of refuse collection vehicles (Slough Borough Council, 2016). 2019 literature proposes a cost of £0.35/L (Energy Saving Trust, 2019), however, the price has increased significantly since then with a bulk buy of 1,000L currently costing £0.57/L ex. VAT.[293] Using the fuel consumption from the NAEI dataset in the example of a high-power loader this price of £0.57/L translates to £604 per year and £4,227 over the lifetime of the machinery.

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[293] https://www.qus.uk/product/1000l-ibc/

9.11 Appendix 11: Data quality

We reviewed over 100 reports (see Appendix 9.1) but the level of relevance of the published studies to the research questions is variable.

A qualitative assessment of the data quality is detailed in Table 83. This summarises the main types of data and gives a visual grade of the quality of data and impact on results or findings in the form of a red, amber, green scale. In addition, more detailed discussions of data gaps identified in the 2021 National Atmospheric Emissions Inventory (NAEI) are discussed after Table 83.

The ‘Quality’ measures the availability and robustness of the data and how appropriate it is for its intended use. For example, robust data or evidence refers to data from published data sources such as DUKES or independent research conducted specifically on NRMM, and data from a partly applicable context (e.g., road transport) is assessed as lower quality. A green rating indicates relevant robust data is available, amber indicates limitations in the availability of such data, and red indicates robust data is severely limited or not available.

The ‘Impact’ measures the sensitivity of the results or conclusions to changes in the data. Green indicates negligible impact, amber represents some impact, and red indicates a material impact on the results or conclusions.

Where data availability or quality was not considered sufficient at the end of the literature phase, it was addressed during the stakeholder engagement phase as far as was practical.

Table 83 – Assessment of the quality of the data

Colour code	Quality	Impact
🟩	Relevant and robust data is available	Negligible impact on results or conclusions
🟧	Limitations in the availability of robust data	Some impact on results or conclusions
🟥	Robust data is severely limited or not available	Material impact on the results or conclusions

Type of data	Quality	Impact	Notes
2021 NAEI – fuel use	🟧	🟧	The Digest of UK Energy Statistics (DUKES) does not differentiate between the use of gas oil in NRMM and stationary sector-specific power sources (Ricardo, 2020; Ricardo, 2021). With the former considered an uncertainty, its value is adjusted to ensure a balance is maintained in the overall energy usages being reported. This leads to additional uncertainty in industrial NRMM fuel use and emission estimates. It means the starting point for industrial NRMM fuel use and emissions has some uncertainty, but this does not have a high impact identifying options for decarbonisation, only the relative size of each segment of the market considered.
Data on share of industrial NRMM in situations making it harder to adopt electric/hydrogen powered technology	🟧	🟧	Data is lacking in literature and the NAEI database, with data in the NAEI being incomplete and a generalisation for each sector (see sub-section 2.1.4). Parameters lacking data which impact the ability to adopt electric/hydrogen technology include variability of usage levels, variability of sites and lifetime of vehicle. The general data in the NAEI database has been refined during stakeholder engagement, bringing quality and impact to orange level. The least-cost pathways model has been built with explicit assumption made for ‘hard-to-deploy’ by sector so this can be updated with better data in future. Improving site-level data would help refining this share of hard-to-deploy NRMM and is a recommended area for further work.
Sales & demand forecasts	🟥	🟧	No forecast to 2050 in the public domain. Forecasts found cover a single machine type in specific geographies to 2030. We made our own projections, validated with DESNZ. Not a high impact on decarbonisation pathways unless actual sales are significantly higher than forecasted, potentially leading to fuel or machinery supply issues in some decarbonisation pathways.
Efficiency measures	🟧	🟧	Literature was available on the different types of efficiency measures that could be taken and on examples being used by OEMs or NRMM operators. However, limited data was available with regard to how widely deployed these measures were across the industry. With regards to applicability by archetype, some OEM/3rd party efficiency solutions specified applicability by machine, whereas others were assessed based on the duty cycles of machines and other characteristics of archetypes. Further clarification on the latter two aspects was sought in the stakeholder engagement. While new or substantial data was not attained from this, stakeholders generally agreed with the

	🟧	🟧	reported findings on the potential impact and deployment pathways of efficiency measures. Stakeholder feedback was not received on costs of these measures, and this is an area flagged as needing further research.
Incumbent CAPEX	🟧	🟧	Limitations with availability of capital cost data. Missing cost data for 18 of the 36 equipment types, and for many of the equipment types with cost data identified the data does not cover all the power bands. Good data found from UK manufacturers and NRMM sellers was used where available, and where this was not available USD costs were used (which is not always directly relevant). Stakeholders were unable or unwilling to comment on machinery costs. The £/kW cost trends observed were not refined further by stakeholders, though some suggested we are in 'the right ballpark' for these costs. Overall impact is not red as the cost differential between incumbent and low carbon technology is more important than the absolute capex.
Incumbent fuel costs	🟩	🟩	Good historic data available, and projections available from DESNZ.
Maintenance cost	🟧	🟩	Maintenance cost data for industrial NRMM was limited. 2020 USD maintenance costs have been for 12 of the 36 equipment types and have been converted to current GBP and used to plot the trend of maintenance cost against power. This was used to calculate the maintenance cost of vehicles of different power ratings. Some stakeholders suggested these costs were lower than they expected, but no further data or information was provided. Impact is green as maintenance costs are a small component of a machine's total cost of ownership, which has a negligible impact on the decarbonisation pathway chosen.
CAPEX of zero emission technologies	🟧	🟥	Limited cost data available for zero emission machinery. Powertrain costs for some technologies have been found for industrial NRMM, otherwise cost data has been estimated by comparison with the road freight sector. Cost of powertrains will have an impact on the TCO, therefore on the uptake of alternative powertrains across the sector. Future cost of technologies is highly uncertain and will significantly affect pathways.
Engine efficiency and emissions abatement potential	🟧	🟩	The gCO_2e/kWh data for the low carbon fuels considered is available from the UK Government's renewable fuels statistics and the NAEI dataset provides the fuel use/kWh useful work for incumbent fuels. Newer powertrains (hybrid, H2, BE) have not been deployed enough to support independent reporting of their real-world energy use/emission performance. However, the transferable knowledge from other transport segments on powertrain efficiency gains means we have reasonable estimates and therefore do not think this lack of data will impact the findings.
H2 and battery electric technology lifetimes and non-fuel OPEX	🟥	🟧	Non-fuel OPEX (such as maintenance) and lifetime values for battery electric and hydrogen industrial NRMM are limited as there is currently no real-world data available, and this will have an impact on the TCO of technologies. Maintenance costs relative to incumbent technology and lifetimes were estimated by analogy with other transport segments. The impact is reduced as maintenance costs are a small part of the overall TCO so do not significantly affect the chosen decarbonisation pathway.
TRL and speed of change	🟩	🟧	Technical and performance data for products currently being developed or launched by OEMs was largely well-documented. There was some limited visibility on launch dates for products under development and scale of production/ramp up plans for commercially-available abatement technology options. Set to orange for impact as the latter two factors impact when certain solutions are expected to become widely available.

Practical feasibility	🟨	🟥	As with TRL, limited data on product availability dates and production ramp up plans will have a high impact on when certain technologies are expected to be available and have improved performance to overcome some of the current limitations. We have found good data on recharging solutions dedicated to NRMM sites but limited data on infrastructure solutions for other fuels and for other practical considerations. Moreover, there is limited data on operator attitudes towards making operational/workflow changes to accommodate abatement options. Stakeholder views were sought at the stakeholder engagements associated with this study. While new or substantial data was not attained from these, stakeholders generally agreed with the reported findings.
Deployment potential and decarbonisation pathways	🟥	🟨	This study is the first of its kind conducted (as far as we are aware) – we have found no published study that maps abatement option deployment potential and decarbonisation pathways for industrial NRMM. This is not surprising given policy has focused on transport sectors that represent a larger share of emissions. Impact is set to orange given the archetyping, detailed research and stakeholder engagement we have conducted (on TRL, technical characteristics, cost, emission abatement and practicality constraints). This gives us confidence that the pathways proposed are a solid starting point. These can be fine-tuned as required in future studies, as the least-cost pathways model can be updated as new data is collected.
Application to other NRMM sectors	🟩	🟩	Some published research explicitly commented on the cross over and opportunities, and we completed this by researching the status of fuel switching options in the agricultural, aircraft and domestic sectors, which was overall well documented for the agricultural and aircraft sectors. There was limited published literature found on domestic NRMM, but this sector is very small.
Enablers and barriers	🟩	🟩	Enablers and barriers were well documented in literature dedicated to industrial NRMM, and we have expanded the list with addition from adjacent sectors such as heavy-duty road transport. Enablers and barriers identified were validated during stakeholder engagement and refined to reflect feedback.
Risks and opportunities (impact on the market)	🟨	🟨	Risks and opportunities were not often explicitly discussed in the literature on industrial NRMM (although there are overlaps with enablers & barriers), so an initial list that we established mostly draws on hypothesis & learning from other sectors. These topics were discussed alongside enablers and barriers during stakeholder engagement. Gathering the perspectives of various market actors allowed for some validation and refinement. Risks and opportunities applying to end of life companies were the least well documented in both literature and stakeholder engagement.
Policy review	🟩	🟩	We reviewed available literature, with a strong coverage of Europe and some coverage of India, South Korea, Australia, China and North America. There are very few policies in place that focus on NRMM, as opposed to a lack of published information.

9.11.1 Limitations of the 2021 NAEI database

In sub-section 2.1.3, Table 12 summarises the most relevant parameters to industrial NRMM decarbonisation pathways. Below we discuss each of these factors in more details.

Location data

The location data in the 2021 NAEI database is available on a very high regional level (England, London, Scotland, Wales, Northern Ireland) and provides a further rural or urban classification within these regions. The split of machinery between urban and rural locations was used as an initial estimate of the proportion of machinery considered 'hard-to-deploy' (see sub-section 2.1.4). This data is a high-level estimate and is an area for future improvement. Moreover, the size of the sites using NRMM is not provided by the database (see discussion below). In addition to size of site, the movement of machinery across different sites over time (particularly valid for hired equipment) is not captured by the NAEI dataset. While data which can be used as a proxy was found (e.g., construction site info[294] and port maps[295]), these sources do not indicate whether mapped sites are operational.

Size of sites

The 2021 NAEI database lacks information on the size of sites where the equipment is deployed. This factor has implications on the fuel demand and subsequent on-site decarbonisation infrastructure requirements for different abatement options. This is highlighted in an (unpublished) Cenex study prepared for a construction company where the feasibility of building the necessary hydrogen production and distribution infrastructure for use in construction NRMM was assessed. The size of sites was identified as a key parameter in the amount of infrastructure required to adopt some technologies and their ability to deploy this infrastructure (Cenex, 2022). Larger sites with more machinery are expected to have higher fuel consumption and therefore more refuelling or recharging infrastructure demands but may benefit from economies of scale to deploy the required infrastructure.

Lifetime of machinery

The lifetime data available in the 2021 NAEI database is provided as a range, with a low, average and high lifetime scenario given in years of operation. This is particularly limiting as OEMs and NRMM operators tend to report equipment lifetimes in hours of use (due to the wide range in usage patterns within NRMM types – see below). Consequently, the lifetime (in years) of certain equipment types is expected to vary dramatically as a function of equipment usage patterns. This is not seen in the NAEI dataset where lifetimes of 6 (low), 7 (average) and 10 (high) years are given for all loaders in the construction sector regardless of power rating or annual usage hours. This is equivalent to an NAEI-evaluated lifetime (multiplying lifetime scenario values by average hours per year) of 1,500 to 6,400 hours as opposed to the 8,000 to 15,000 hours lifetime quoted for loaders.[296] Similar static lifetime ranges are observed for other equipment types throughout the NAEI database. Comprehensive data on typical machinery lifetime is not available in the literature, though a recent paper contains average lifetimes for some machinery which are within the ranges identified within the NAEI database (Desouza, Marsh, Beevers, Molden, & Green, 2022).

Machine usage patterns (incl. continuous and annual running hours)

The 2021 NAEI database only reports the average annual hours of use across all machines in each machine type, power rating and sector combination. This single value does not capture that variance between machines, nor the variation of usage throughout the year of an individual machine. Variation in total annual usage and usage variations throughout the year will strongly influence the choice of abatement technology. For example, a machine which is operated for 20 hours a day but only for 40

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[294] https://www.constructionmap.info/

[295] https://uk-ports.org/uk-ports-map/

[296] https://thompsontractor.com/blog/average-lifespan-of-common-construction-equipment/

days a year would have much higher energy storage requirements than a machine used for 4 hours a day for 200 days a year. In the NAEI database, both would be reported with the same number of hours used in a year (800 hours per year).

Evidence is given in (Lajunen, et al., 2016) of the impact of usage patterns on abatement options. A long-haul dumper is an example which can have repetitive and highly predictable usage patterns, which present opportunities for regenerative charging during downhill sequences in hybrid or battery-electric alternatives. This is compared to the duty cycle of a straddle carrier, which shows a series of power consumption or regeneration spikes ranging from 120 kW to 225 kW throughout its operation. While the peak power is relatively high at 225 kW, the average power throughout the cycle and subsequent energy demand are low, dictating the need for lower-energy but higher-power and quick-response abatement solutions. This is further supported by data gathered as part of an Imperial College study into London's 2018 & 2019 NRMM fleet (Desouza, Marsh, Beevers, Molden, & Green, 2021) which reports usage variations both across different NRMM types and different applications of the same machinery type. The study used engine telemetry data to analyse the average daily idle and working hours by NRMM type and reported findings on 7 types of equipment: backhoe loaders, dumpers, excavators, forklifts, loaders, mini-excavators and telehandlers. Using the reported information and assuming an 8-hour working day, the minimum, maximum and average utilisations for these NRMM types are summarised in the table below, in comparison with the values in the NAEI database.[297] The wide ranges between minimum and maximum utilisation across different machines of the same type indicate the variation of use-cases within the sector. The aspects discussed above highlight the limitations associated with a single 'annual hours of use' entry per NRMM type within the NAEI database.

Table 84 – Estimated utilisation by NRMM types in construction from (Desouza, Marsh, Beevers, Molden, & Green, 2021) compared against the NAEI database

ESTIMATED UTILISATION IN CONSTRUCTION (ASSUMING 8-HOUR DAY)					
NRMM TYPE	Minimum	Maximum	Median	Average	NAEI database average
Backhoe loaders	10%	49%	41%	38%	13%
Dumpers	0%	33%	22%	20%	11%
Excavators	20%	71%	63%	56%	17%
Forklifts	11%	50%	29%	27%	71%
Loaders	20%	55%	39%	37%	13%
Mini excavators	17%	51%	38%	36%	10%
Telehandlers	18%	46%	40%	36%	11%

Duration of sites

The 2021 NAEI database does not provide a breakdown of equipment being used in short-term vs. long-term sites. The impact of this on machine utilisation was highlighted by members of SMMT's Off Highway Engine and Equipment Group (OHEEG) in a January 2023 meeting conducted by ERM. It was noted in the meeting that, with a relatively large share of new NRMM equipment purchases going to leasing or hiring companies, the same machine could be hired out for a one-day job requiring close to 100% utilisation, before being rented out onto a six-month project where its used sporadically throughout. Machinery used on short-term sites may face additional challenges transitioning to a powertrain which requires additional infrastructure (such as charging or hydrogen refuelling infrastructure), the proportion of machines which may face these challenges cannot be identified from the NAEI database. These challenges linked to short-term sites are likely to affect machinery most in the construction sector compared to the others, due to the intrinsic temporary nature of a construction site. However, no data was found to quantify the distribution of industrial NRMM between sites of different durations.

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[297] These values are not directly comparable as they are for different years (2018-2019 for Desouza et al., 2021 for NAEI database), and cover different geographical regions (London for Desouza et al., GB for NAEI database). The variance in utilisation found in the analysis of London NRMM by Desouza et al highlights the limitations of using a singular value as provided in the NAEI database.

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