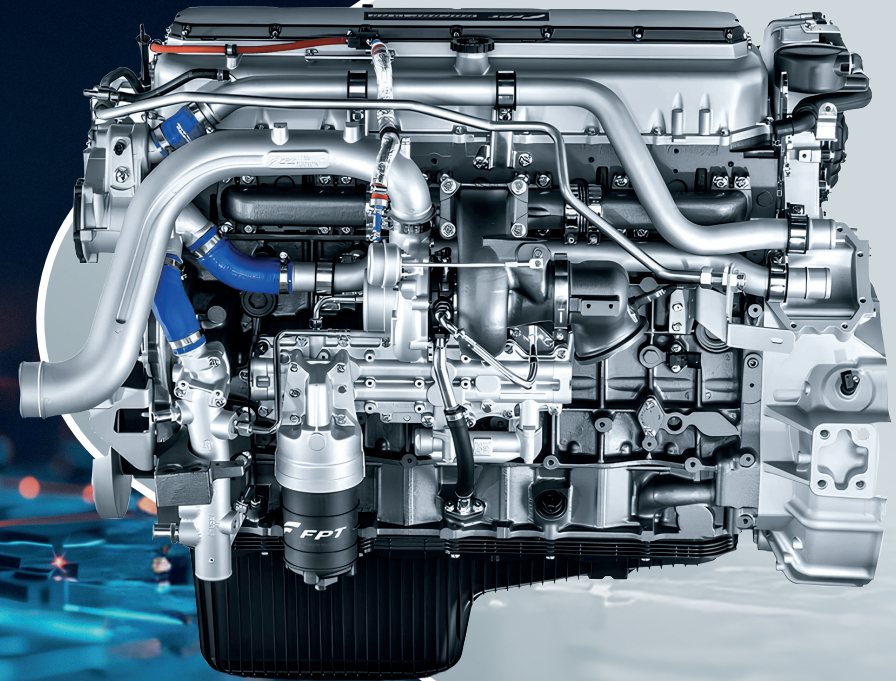


Internal Combustion Engines

Innovation Opportunities Report

2026



Information correct at time of publication.
All views and recommendations in this report are independent and do not necessarily reflect government policy.



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1 | Foreword



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Global demand for clean mobility is growing. To support the UK's competitiveness, secure jobs, and achieve the transition to zero-emission vehicles and towards a net-zero automotive industry, innovation will be key. Yet, taking innovative technologies to rapid commercialisation is a challenge for the automotive industry and the broader industry supply chain. Even then, possibilities are limited by supply chain's capabilities, strengths, and gaps. Building on the Automotive Council UK's Technology Roadmaps, this series of Innovation Opportunities reports examine key technology priorities and associated supply chain opportunities for the UK automotive industry.

The Innovation Opportunities reports provide insights on how strategic collaboration and investment can accelerate the commercialisation of these key technologies for the transition of the automotive industry to net zero, including: batteries, power electronics, electric machines, lightweighting technologies, hydrogen fuel cells and storage, and internal combustion engines (ICE). By focusing industry efforts on the trends and drivers outlined in the Automotive Council roadmaps and associated innovation opportunities, the UK can secure leadership in the global clean mobility revolution. We highlight areas where collaboration between industry, government, and research institutions can accelerate commercialisation and encourage investment. These can future-proof the UK automotive industry.

The Innovation Opportunities report for internal combustion engines (ICE) provides a deep dive into all themes and sub-themes identified on the ICE roadmap and maps them against the European and UK supply chain capabilities. This analysis provides an overview of key focus areas and associated strengths and gaps to guide the industry's direction of travel, as we transition from ICE towards zero-emission solutions. This report sits within the framework of the UK's statutory Zero Emission Vehicle (ZEV) mandate, under which policy continues to reflect the current phase-out timelines for petrol and diesel vehicles. Nevertheless, UK manufacturers are also developing technologies and components for export-focused platforms and international markets, particularly in harder-to-decarbonise applications.

Five innovation themes are identified for ICE technologies:

- 1 Fuels
- 2 Air handling
- 3 Fuel systems
- 4 Advanced combustion
- 5 Energy management

with the aim of defining decarbonisation pathways for the transition of the automotive powertrain solution to zero-emission technologies.

The report also identifies three clusters of cross-cutting enablers to facilitate the decarbonisation journey for ICE-led powertrains:

- 1 Artificial intelligence and digitalisation
- 2 Advanced manufacturing and materials and eventually a major trend across the global automotive industry
- 3 Hybridisation

ICE technology will remain part of the powertrain mix throughout the transition journey to zero-emission solutions, particularly in harder-to-decarbonise applications such as off-highway, non-road mobile machinery (NRMM), and specialist sectors. This report clarifies key industry challenges and associated R&D opportunities in ICE technologies in building a resilient and competitive supply chain for the UK automotive industry.



2 | Introduction

Whilst the passenger car market is choosing battery electric technology for the vast majority of road transport applications in the UK, internal combustion engines (ICE) continue to play a pivotal role in global mobility, particularly in harder-to-decarbonise applications such as off-highway, non-road mobile machinery (NRMM), and specialist vehicles. This report examines where UK capability can support emissions reduction, air-quality improvement, and competitiveness through component, system and controls innovation in these continuing ICE applications.

There is a significant export opportunity for UK manufacturers, driven by legislative developments in overseas markets that support a transition pathway keeping combustion technologies viable when paired with low-carbon fuels. This is reflected in the European Commission's proposed December 2025 amendments to CO₂ emission standards for cars and vans, which preserve a role for compliant combustion engines within future regulatory frameworks. For heavy-duty applications the EU has already adopted a phased approach to a 90% reduction by 2040, with some amendments proposed to ease the transition to zero. This report examines where UK capability can support emissions reduction, air-quality improvement, and competitiveness through component, system and controls innovation in these continuing ICE applications.

This report builds on the Automotive Council UK 2024 ICE [roadmap](#), authored by the Advanced Propulsion Centre UK (APC), and is informed by industry feedback and takes a market-led perspective. Whilst UK policy remains committed to the current phase-out dates for petrol and diesel vehicles, many UK manufacturers continue to develop technologies and components for export platforms and international markets

where ICE is expected to remain part of powertrain strategies for longer. In this context, EU regulations such as Euro 7 remain important and will influence design, calibration and validation requirements for export-facing products.

The findings of this study reflect workshop discussions, market analysis and stakeholder perspectives, and do not necessarily indicate current or future APC funding priorities.

For continuing ICE applications, decarbonisation depends on a combination of combustion efficiency, air handling, thermal management, fuel-system control and, where relevant, the fuel pathway.

Commercial realities mean that efficiency, simplicity, and serviceability remain decisive factors for adoption, especially in NRMM and fleets. The UK's strong ICE supply chain and testing capability provides an opportunity for continued investment through expertise and export potential as global markets decarbonise at varying rates of speed. If there is an unclear direction for innovation however, capability can erode or move offshore.

The UK is well positioned to lead in several areas and can leverage these strengths to secure these global opportunities.

These are:

- High-efficiency turbocharging and after-treatment integration
- Precision fuel systems and smart sensors
- Advanced combustion strategies
- Digital tools for system-level optimisation



3 | Methodology

The priorities in this report were developed through industry workshops and follow-up analysis, using a market-informed assessment of significance, commercialisation feasibility, and relevance to UK supply chain capability.

Workshop design and data collection

Innovation opportunities were collected through a series of workshops initially structured around three themes: thermal efficiency, systems integration, and sustainable fuels. Discussions were open-ended and recorded in shared canvases and notes, capturing perceived benefits, applicability by segment and duty cycle and feasibility constraints. Workshop participants included a wide array of automotive OEMs, Tier N suppliers, off-highway and niche performance specialists, and academia.

Consolidation and mapping of innovations

All workshop inputs were consolidated and terminology was standardised. Innovations were then mapped from the three themes to the four report themes: advanced combustion, air handling, energy management and fuel system.

Content appraisal

A desk-based review of the notes was undertaken to extract positive and negative sentiments and to identify practical enablers and barriers for the innovations. Statements were assessed qualitatively, and direct participant commentary was used to weight the significance and feasibility. Significance was measured by discussion around impact, breadth, and frequency, with feasibility measured by technology readiness, cost, complexity, and risk.

Scoring and filtration

Each innovation was assigned a score for significance to UK supply chain (x-axis) and commercialisation feasibility (y-axis), using a 1-5 scale representing lower to higher, respectively. These scores were then screened internally, and the highest ranked for both axes were agreed upon and prioritised for further discussion in the report.



4 | Drivers and outcomes

Internal combustion engine (ICE) innovation in the UK is predominantly about delivering cleaner and more efficient propulsion solutions that remain competitive across the global market, particularly in hybridised, off-highway and non-road mobile machinery (NRMM) applications. Given this global context, this report focuses on opportunities that demonstrate how technology delivers real-world impact, while ensuring the UK industry protects its established supply chain and expertise as well as actively develops a supply chain to meet future needs. The innovations highlighted in this report represent critical enabling technologies required to deliver the following high-level outcomes:

Carbon dioxide equivalent (CO₂e) emissions

For continuing ICE applications, greenhouse gas emissions are influenced by the combined effect of engine efficiency, combustion strategy, air handling, thermal management, fuel-system control and fuel pathway. In harder-to-decarbonise sectors, reducing lifecycle emissions will depend on improving the efficiency and emissions performance of the engine system while enabling compatibility with lower-carbon operating conditions where appropriate. These are supported by calibrations and combustion strategies that maximise efficiency with these fuels. Engine platforms capable of adapting to multiple fuel types, blends, and evolving specifications are paramount to decarbonising existing fleets, while leveraging established supply chains and tooling. For UK suppliers serving international markets, emissions and durability requirements in export regions are a critical driver of innovation priorities.

Air quality

Air quality encompasses both regulated exhaust pollutants, such as nitrogen oxides (NO_x), particulate matter, carbon monoxide, and hydrocarbons, as well as increasingly significant non-exhaust sources, including brake wear particles and tyre abrasion. The EU's Euro 7 standard has a broadened scope to include non-exhaust sources as well as lifetime durability requirements, reinforcing the need for advanced aftertreatment systems, smarter air handling, and integrated system level controls.

Total cost of ownership (TCO)

TCO is a critical factor in vehicle adoption, particularly for heavy-duty vehicle applications, however it also influences light-duty vehicle ownership, particularly for fleets and leasing models. Efficiency improvements and increasing part lifetime are two key critical levers to reducing TCO. This can be achieved in several ways such as advanced combustion phasing, friction reduction, and thermal management. Despite higher upfront costs, hybridised powertrains can leverage electrification to reduce TCO through electrified auxiliaries, smart energy management, and operating profiles that produce lower emissions and improved efficiency compared to conventional duty cycles.

Legislation

Legislation not only sets minimum performance standards but also drives the direction of technological innovation, shaping how manufacturers respond to environmental, safety, and durability requirements. Euro 7, now adopted in the EU, consolidates requirements for light-duty and heavy-duty vehicles under a single, unified legal framework. Engine development is not only shaped by these new standards but also by the legacy of previous legislation, which has progressively tightened emissions across the entire vehicle system. These legislative shifts ripple through the supply chain, influencing component design, material choices, and manufacturing processes, and driving investment in advanced aftertreatment, thermal management, and system-level integration.

Power density

High power density remains essential for applications requiring compact packaging, fast transient response, and high torque delivery. This is particularly relevant for high-performance vehicles, heavy-duty and NRMM applications, as well as range extenders where packaging and payload constraints influence adoption and usability. Innovations in forced air induction, thermal management, and high-performance materials and coating enable increased power output without compromising durability. However, performance gains must be delivered in a way that does not impact user experience and drivability.



5 | Innovation themes

Building on the outcomes covered in Section 4, there are four priority innovation themes. These represent the core technology areas driving the development and decarbonisation of internal combustion engines. Each theme is supported by cross-cutting enablers that accelerate implementation, improve real world usability, and extend component lifecycle. Together, these innovations not only contribute to technical progress but also strengthen the resilience and competitiveness of the UK supply chain.

Innovation theme one – advanced combustion

Advanced combustion is the highest-priority innovation theme in this report because it directly affects thermal efficiency, emissions formation, performance and usability across a wide range of continuing ICE applications. Innovations in combustion strategy, compression, chamber design and heat management can deliver meaningful improvements in both efficiency and pollutant control while strengthening export-facing engineering capability.

Innovation theme two – air handling

Air handling is central to real-world emissions performance, transient response and compliance with tightening durability and air-quality requirements in global markets. Developments in boosting, aftertreatment integration and thermal control remain critical for export-facing products and harder-to-decarbonise ICE applications.

Innovation theme three – energy management

Energy management is the third priority innovation theme because system-level control of heat, electrical loads and auxiliaries is increasingly important for improving efficiency, emissions performance and operational robustness. This includes opportunities in electrified auxiliaries, thermal architectures, waste-heat use and control strategies that support continuing ICE applications and hybridised systems.

Innovation theme four – fuel system

Fuel system innovation remains a core priority because precise, durable and adaptive fuel delivery is critical to engine efficiency, emissions robustness and long-life performance. This theme focuses on injection quality, sensing, control and durability across demanding duty cycles and evolving operating requirements.

Innovation theme one: advanced combustion

Advanced combustion methods aim to deliver higher thermal efficiency and specific power output while maintaining emissions compliance, acceptable noise, vibration and harshness (NVH) and cold start behaviour. This theme focuses on combustion and compression strategies, alternative chamber geometries, heat-flow optimisation, and modular architectures applicable across multiple cylinders and duty cycles.

Benefits of innovation

- Increased brake thermal efficiency
- Improved power density and packaging flexibility
- Reduced tailpipe emissions and reduced fuel consumption in real world driving duty cycles

Challenges against innovation

- Controlling combustion phasing at lower temperatures
- Achieving stable ignition and reducing knock caused by fuel variability and non-optimised fuel systems
- High tooling and development costs for alternative geometries

Innovation opportunities

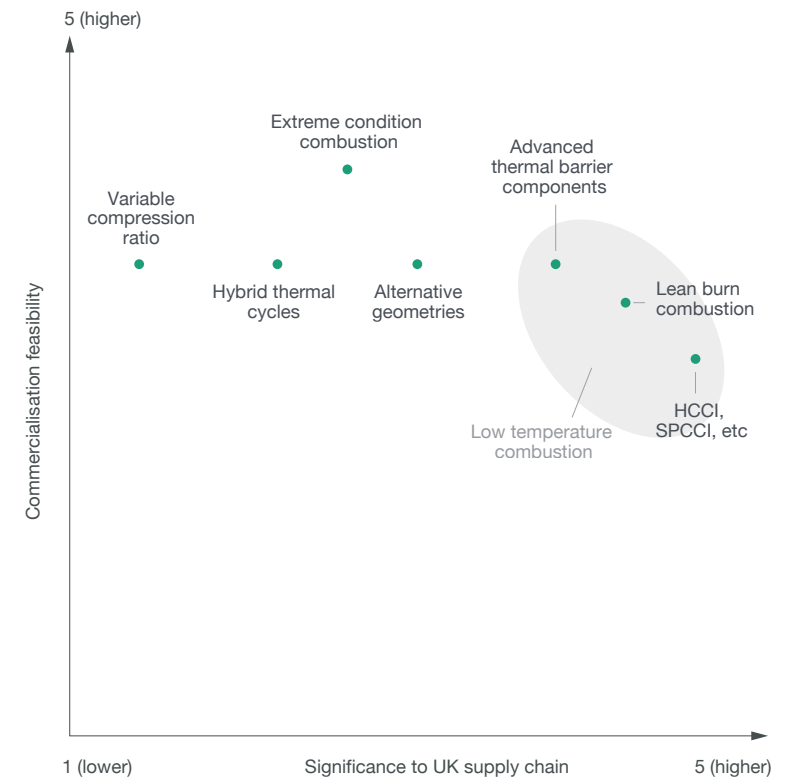
Low temperature combustion, including lean burn strategies, is a key innovation priority because it enables ultra-low NO_x and particulate emissions without sacrificing efficiency. Achieving this outcome requires multiple sub-innovations, such as:

- 1 Alternative combustion techniques such as homogenous charge compression ignition (HCCI) and spark assisted compression ignition (such as Spark Controlled Compression Ignition (SPCCI)).
- 2 **Advanced thermal barrier coatings** also support through improving heat management, and whilst lower in significance than HCCI, it represents a highly feasible near-term opportunity.

Overall low temperature combustion is critical for maximising efficiency gain and emissions reduction.

Alternative geometries, such as rotary engines for range-extender applications, offer potential benefits such as a higher power density, smoother operation, and improved efficiency. These technologies are considered more feasible as they already exist in niche applications, but their overall significance is lower due to limited adoption and market interest. However, even in low-volume segments, there is still a UK opportunity, particularly for specialist applications. Barriers such as higher tooling cost and lack of widespread adoption interest must be overcome before broader implementation.

Figure 1: Innovation opportunity – advanced combustion



Innovation theme two: air handling

Air handling plays a critical role in combustion stability, specific power output, and emissions performance across transient and low-temperature operation. The aim is to deliver consistently low pollutants and maintain responsive, smooth vehicle performance under real-world conditions, whilst supporting durability and competitive TCO. Airflow dynamics in the system vary with fuel and engine geometries. Innovation in this area is not just an enabler but a focal point for leveraging ICE in both current and future fleet decarbonisation.

Benefits of innovation

- Improved low speed torque and transient response
- Lower NO_x and particulate emissions in real driving emissions
- Faster catalyst activation and sustained conversion efficiency
- Reduced fuel consumption through optimised intake and exhaust airflow

Challenges against innovation

- Maintaining turbocharger turbine and compressor efficiency when not at full load
- Managing exhaust thermal for catalyst light-off and minimising back-pressure losses from filtration
- Addressing calibration complexity across multiple fuel vectors and hybrid duty cycles

Innovation opportunities

Particulate filters are a priority as Euro 7, and other global legislation, tighten the particle number measurements allowed to ultrafine levels, making high-efficiency filtration a necessary innovation for compliance.

Integrated thermal management, including fast catalyst light-off and low temperature control is also a priority. Since cold starts account for most emissions in a typical duty cycle, reducing start up times and pre-heating catalysts through integrated thermal management can significantly cut tailpipe pollutants, without compromising drivability.

Compact and modular aftertreatment solutions were also identified as highly feasible, but with slightly lower impact, representing a clear quick-win opportunity for nearer term implementation. These solutions address the packaging constraints for bulkier systems, especially in the short term. Technologies may include integrated selective catalytic reduction and particulate filters, which are also ranked as higher in significance.

Electrified and hybridised turbochargers can improve transient response and enables regulatory compliance. Turbocharger technologies directly improve fuel economy and drivability, bridging potential performance gaps which may arise from alternative and sustainable fuels.

Figure 2: Innovation opportunity – air handling



Innovation theme three: energy management

Energy management focuses on delivering high system-level efficiency by coordinating thermal flows, electrical energy, and optimising auxiliary systems. The goal is to maximise energy reuse at the system level as much as possible. Innovations include waste-heat recovery, advanced thermal architectures, electrified transmissions, electrified auxiliaries (including hydraulics for off-highway/NRMM), as well as packaging and material optimisation.

Benefits of innovation

- Lower fuel consumption through improved heat utilisation and optimised operating points
- Faster warm-up performance for better emissions control
- Increased uptime and easier serviceability, contributing to TCO reductions

Challenges against innovation

- Highly variable duty cycles limit recoverable heat and predictability
- Complex, heavy systems can compromise packaging and efficiency
- Managing transient thermal performance impacts emissions control

Innovation opportunities

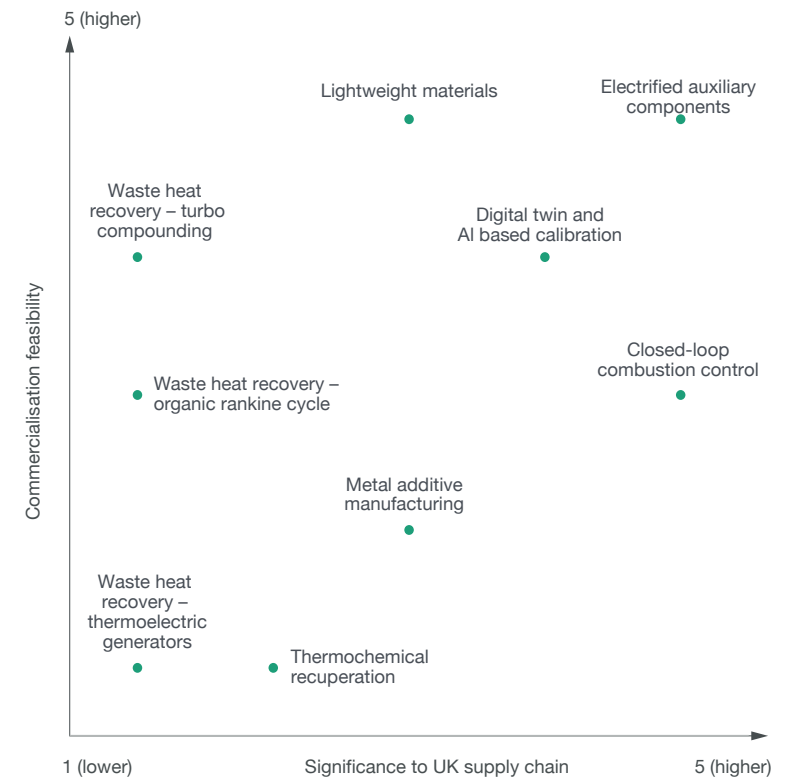
Electrified auxiliary components such as pumps, compressors, and hydraulics (for heavy-duty/off highway) help reduce parasitic load, improve controllability, and lower noise and emissions. These improvements can directly support lower TCO through reduced fuel consumption and maintenance, especially as electrification technologies mature. Reduced engine load can maximise output efficiency or introduce rightsizing as an option.

Digital twin and AI based calibration are increasingly critical across design and validation through to in-use monitoring and real-time data management. Realtime data management combined with model-based and software-in-the-loop workflows allows for shorter calibration cycles, allowing earlier validation and a faster route to market. This approach allows component and vehicle manufacturers to deliver updates and new designs to end-users more quickly.

Closed-loop combustion control enables precise management and advanced control of combustion phasing, knock mitigation, and fuel efficiency, whilst maintaining emissions compliance across different fuels as well as adapting for engine ageing via continuous monitoring.

Lightweight materials reduce overall mass, improving fuel economy and offsetting additional mass from hybridisation systems. Mass reduction enhances efficiency and emissions compliance without compromising component durability, safety, or performance.

Figure 3: Innovation opportunity – advanced combustion



Innovation theme four: fuel system

The fuel system is a complimentary innovation area to fuels development, defining injection quality and combustion reliability. Both contributing directly to engine efficiency, emissions output, and component durability. Fuel system innovations aim to deliver precise, adaptable fuelling to the combustion process and maintains performance and usability across multiple fuel vectors.

Benefits of innovation

- Reduced fuel consumption through optimised and precise injection timing, spray pattern and consistency
- Stable emissions across diverse fuel vectors and throughout component lifecycle
- Extended service intervals, improving TCO and user experience
- Improved cold start performance and transient response

Challenges against innovation

- Variability in properties of multiple fuels
- Injector wear and damage sustained from operating outside of normal parameters
- Ignition stability for some fuels (such as hydrogen) under lean operation
- Progressive lifetime degradation affecting long term emissions cycles

Innovation opportunities

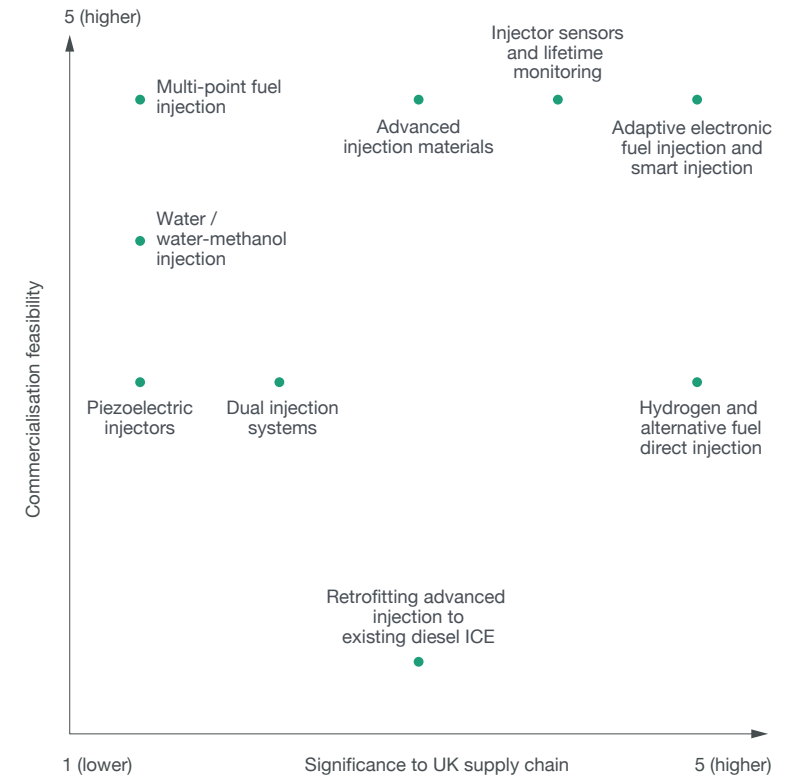
Adaptive electronic fuel injection and smart injection are a key priority, maintaining optimal air-fuel ratios throughout engine life, ensuring efficiency and emissions-compliant combustion. They also enable fuel flexibility.

Injector sensors and lifetime monitoring are crucial for fuel system innovation. Advanced smart systems, utilising tools such as AI, can adapt in real-time to changing conditions or using predictive model-based control to adjust proactively rather than reactively.

Hydrogen direct injection targets consistent, safe, and reliable hydrogen injection. This innovation area enables higher thermal efficiency and lean operation with low emissions. With respect to H2 injection, precise timing and calibration support reducing NOX emission spikes and reducing overall duty cycle emissions.

Alternative fuel direct injection is equally important to maintain precise control over multiple fuel vectors to achieve operation with low carbon emissions.

Figure 4: Innovation opportunity – fuel system





Cross-cutting enablers

Cross-cutting enablers support all four priority innovation themes by improving development speed, manufacturability, durability and system-level optimisation. These enablers strengthen the delivery of advanced combustion, air handling, energy management and fuel-system innovation across continuing ICE applications. Lower-carbon fuels may provide an interim decarbonisation option in harder-to-abate ICE applications, particularly where duty-cycle constraints or export-market requirements limit near-term electrification.

Artificial intelligence and digitalisation

AI and model-based tools enable end-to-end optimisation from design to in-use monitoring. Key capabilities include:

- Digital twins of engines, fuel systems and aftertreatment to test realistic duty cycles without physical prototypes.
- Model-based design workflows (software- and hardware-in-the-loop) that accelerate calibration and validation.
- Fuel system calibration and control across varying operating conditions.
- Adaptive calibration and controls to manage variable operating requirements and evolving specifications.
- Air handling improvements, where data driven calibration optimises turbochargers, thermal management and compact aftertreatment for Euro 7 durability.

These capabilities can cut time-to-market, improve lifecycle CO_{2e}, and create exportable UK expertise in software-defined propulsion solutions.

Advanced manufacturing and materials

New production methods and advance materials improve the feasibility of hardware-intensive innovations. Key capabilities include:

- Additive manufacturing enables complex geometries for high-efficiency turbochargers, and integrated selective catalytic reduction system, reducing backpressure and improving transient response.
- Lightweight alloys and thermal-barrier coatings enhance durability for low-temperature combustion and lean burn.
- Material robustness against varied fuel chemistries that can cause degradation or change the combustion environment (e.g. hydrogen embrittlement).
- Compact heat exchangers and waste-heat recovery components benefit from mass reduction and improved thermal performance.
- Advanced coatings support Euro 7 lifetime requirements without compromising packaging or serviceability.

The UK, as a leader in materials science and additive design, can benefit from the clear export advantage, anchoring domestic supply chains for next generation ICE components and enabling rapid industrialisation of sustainable propulsion technologies.

Hybridisation

Hybridisation complements combustion, air handling and energy-management innovations while enhancing overall powertrain efficiency. Hybridisation and electrification can offer:

- Electrified auxiliaries (pumps, compressors, hydraulic systems) can reduce parasitic loads and stabilise emissions in transient operation.
- Electrified turbochargers and hybrid powertrains improve responsiveness and offset performance deficits from less energy-dense next-generation fuels.
- Rightsizing potential, enabling smaller engines while maintaining torque and drivability characteristics.
- Support for advanced fuel systems, maintaining constant rail pressure and atomisation at lower loads, enabling next-generation adaptive injection.

These hybrid powertrains and electrified components can reduce TCO, improve the lifecycle CO_{2e} performance and position the UK to lead in hybrid ICE solutions for light-duty, heavy-duty and off-highway markets.



6 | Recommendations for the UK

The findings in this report show that internal combustion engines remain a practical and necessary partner to decarbonisation globally, particularly for NRMM, off-highway and specialist applications. ICE-related innovation capitalises on the UK's industrial strengths and supports international competitiveness by unlocking export opportunities. Such innovation complements, rather than substitutes for, progress in electrification. Progress is now less dependent on engine architecture and more on how effectively the UK integrates air handling and aftertreatment, modernises fuelling and combustion control, and applies electrification and digital tools to manage energy across the system. The UK can reduce lifecycle CO₂e and improve air quality without sacrificing the industrial base that underpins growth and exports.

Air handling and fuel systems

Air handling and fuel systems must be developed as one emissions solution. Compact and modular aftertreatment, integrated thermal management, and electrified boosting should be proven on cold start and transient windows, where most emissions occur. In parallel, adaptive injection, cylinder pressure based control and on vehicle fuel flow measurement can stabilise combustion across varying fuels and component ageing, with hydrogen direct injection advanced through focused durability and safety programmes.

Advanced combustion and energy management

Advanced combustion and energy management should raise efficiency without compromising usability. Low temperature and lean strategies can be translated into practical playbooks, supported by thermal barrier materials validated for demanding cycles. Electrified auxiliaries, lightweight structures, and digital twin/AI based calibration should be adopted to cut test loops, shorten time to calibration, and enable rightsizing.

To commercialise these innovations, the UK can package these elements into exportable solutions that combine fuel pathways, hardware, controls, and digital assurance. Over the coming years, success will be measured by verified reductions in end-to-end lifecycle and ultrafine particulate/NO_x reductions, supported by lower fleet TCO and faster development cycles, giving the UK a competitive edge on the global market. By acting on these priorities, the UK can decarbonise faster across all technologies while protecting and expanding a globally competitive ICE supply chain.



Glossary

AI	Artificial intelligence
CO ₂ e	Carbon dioxide equivalent
HCCI	Homogenous charge compression ignition
ICE	Internal combustion engine
LCA	Life cycle analysis
NO _x	Nitrogen oxides
NRMM	Non-road mobile machinery
NVH	Noise, vibration and harshness
SCR	Selective catalytic reduction
SPCCI	Spark controlled compression ignition
TCO	Total cost of ownership
ZEV	Zero Emission Vehicle



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Further information

If you have any questions or would like more detail on any of the graphs or data, email info@apcuk.co.uk

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Established in 2013 and jointly funded by the Department for Business and Trade (DBT and the automotive industry, the APC accelerates the technologies that support the transition to zero-emission vehicle manufacturing and towards a net-zero automotive supply chain in the UK.

With a proven track record, the APC has facilitated funding for 354 low-carbon and zero-emission projects involving 614 partners. Working with companies of all sizes, this funding since 2013 is estimated to have helped create or safeguard over 59,000 jobs in the UK. The technologies and products are projected to save over 425 million tonnes of CO₂.