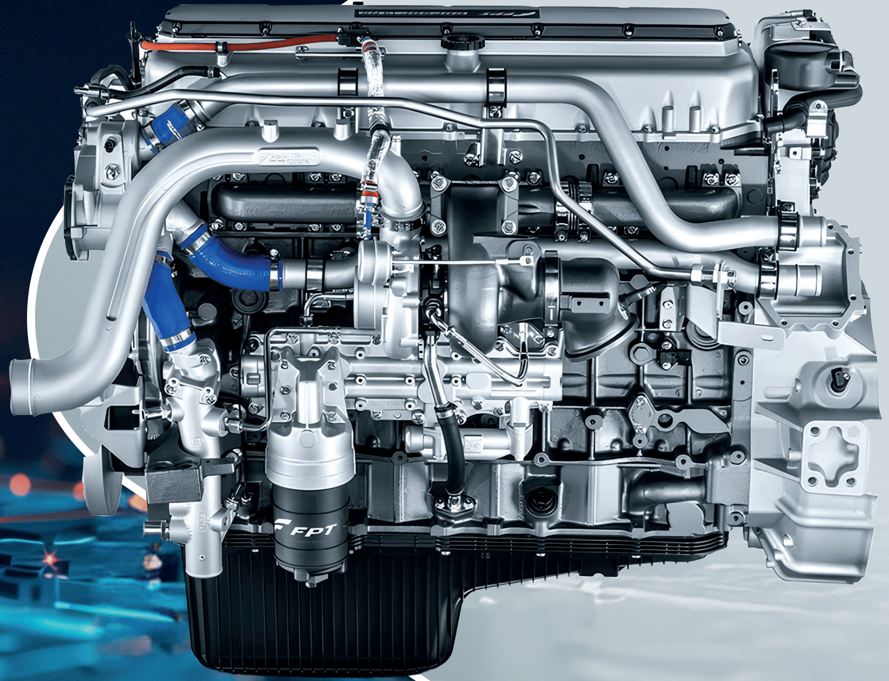
Internal Combustion Engines

Technology Roadmap

2024



Produced by the Advanced Propulsion Centre UK on behalf of the Automotive Council UK
Information correct at time of publication

Introduction to the technology roadmap

The 2024 technology roadmaps provide a view of technology adoption in the automotive industry. These roadmaps help academia, industry and policy-makers understand where research and development (R&D) efforts are likely to be focussed, highlight key milestones in technology adoption, and through the supporting documents explore challenges and opportunities.

The documents available for each roadmap are as follows:

The executive roadmap

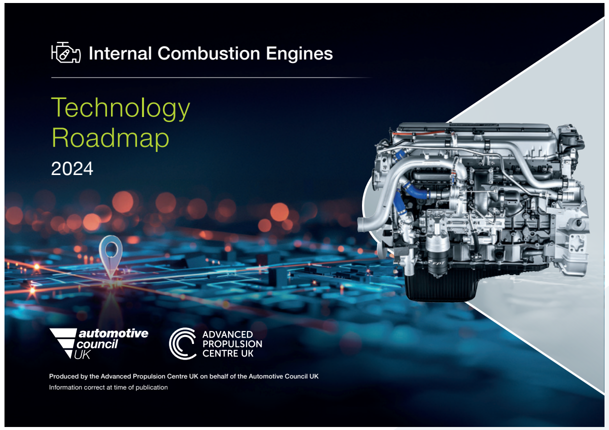
The executive roadmap provides a high-level view of forecast mass adoption of technology within the automotive industry. Mass adoption requires technology, supply-chain, manufacturing and market readiness and in some instances, regulatory readiness.

The narrative report

The narrative report supports the executive roadmap by providing the context behind the technologies on the roadmap. The narrative considers regulatory and market drivers alongside the work required to develop individual technologies and their supply chain.

The innovation opportunities report

The innovation opportunities report is intended to take a deeper dive in to the R&D steps required to enable technologies on the roadmap.



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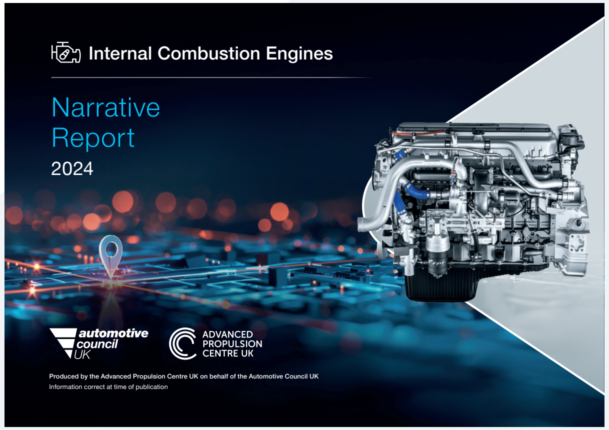
Technology roadmap



Internal Combustion Engines

Narrative Report

2024

Produced by the Advanced Propulsion Centre UK on behalf of the Automotive Council UK

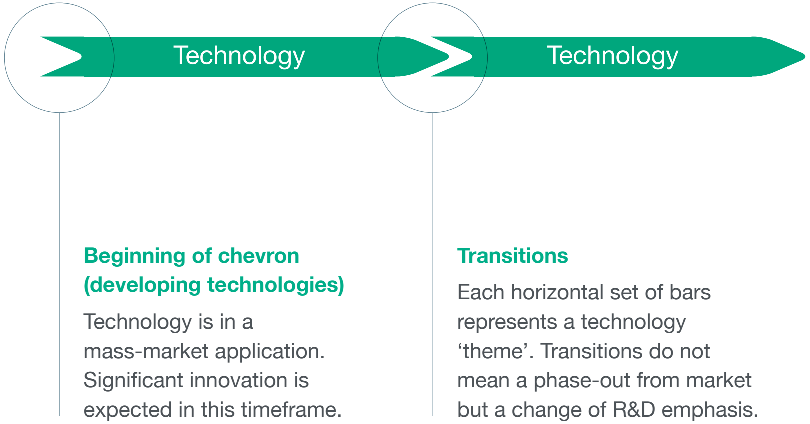
Information correct at time of publication

Narrative report

Introduction to the technology roadmap

This technology roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass-market adoption.

- Chevrons with text describing a technology indicate when a technology is expected to reach mass-market adoption in the automotive industry.
- Technology adoption will vary from region to region, this is recognised and discussed in the narrative report that accompanies this executive roadmap.
- Technology adoption varies within different sectors of the automotive industry and, where appropriate, this is indicated on the roadmap and discussed in the accompanying narrative report.
- Some technologies may be feasible before appearing on the roadmap, many technologies that do not appear until later are technically feasible now. However, the roadmap considers not just technology maturity but also market, supply chain and regulatory impacts. These are discussed in the accompanying narrative report.
- Some chevrons appear to start on the 2025 line, this is considered as equivalent to a technology being available now.



Beginning of chevron (developing technologies)

Technology is in a mass-market application. Significant innovation is expected in this timeframe.

Transitions

Each horizontal set of bars represents a technology ‘theme’. Transitions do not mean a phase-out from market but a change of R&D emphasis.

Technology roadmap

	2025	2030	2035	2040
▶ **Thermal efficiency**	Click to expand (page 5)			
▶ **Technology pathways**	Click to expand (page 6)			
▶ **Systems integration** - Fuel and emissions controls systems - Engine systems and control - Drivetrain and hydraulic systems	Click to expand (page 7)			
▶ **Life cycle** - Life cycle impact - Material recovery	Click to expand (page 8)			
▶ **Sustainable fuels**	Click to expand (page 9)			
	2025	2030	2035	2040

▶ Technology is in a mass market application. Significant innovation is expected in this timeframe.
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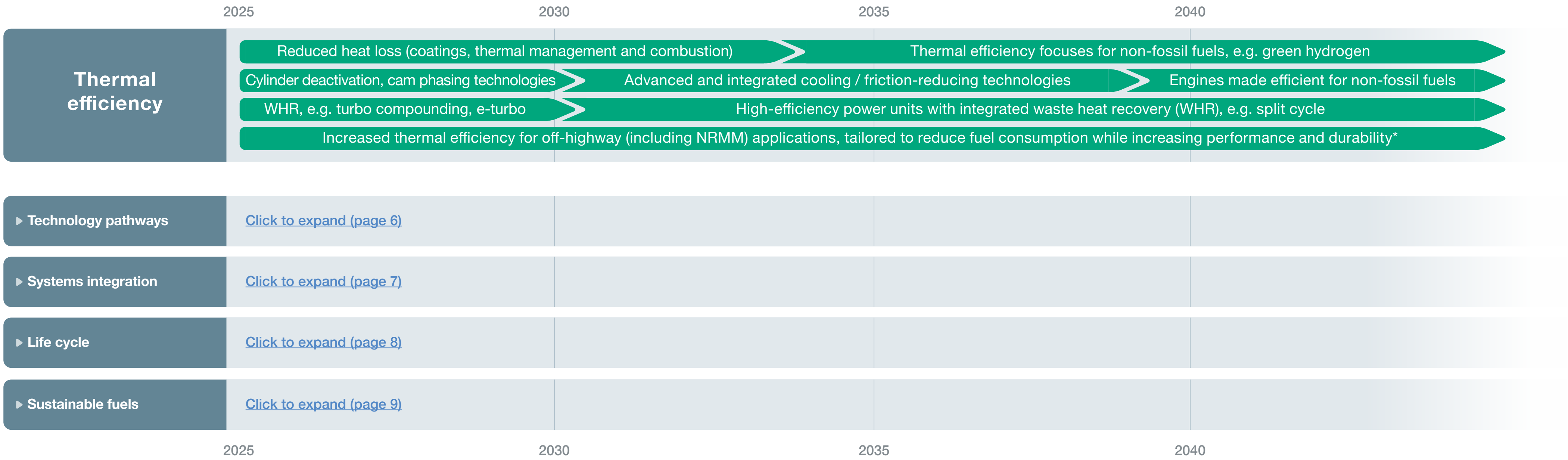
This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption.
Specific application-tailored technologies will vary from region to region.

Technology roadmap



2025 2030 2035 2040

Thermal efficiency

- Reduced heat loss (coatings, thermal management and combustion) → Thermal efficiency focuses for non-fossil fuels, e.g. green hydrogen
- Cylinder deactivation, cam phasing technologies → Advanced and integrated cooling / friction-reducing technologies → Engines made efficient for non-fossil fuels
- WHR, e.g. turbo compounding, e-turbo → High-efficiency power units with integrated waste heat recovery (WHR), e.g. split cycle
- Increased thermal efficiency for off-highway (including NRMM) applications, tailored to reduce fuel consumption while increasing performance and durability*

▸ **Technology pathways** — Click to expand (page 6)

▸ **Systems integration** — Click to expand (page 7)

▸ **Life cycle** — Click to expand (page 8)

▸ **Sustainable fuels** — Click to expand (page 9)

2025 2030 2035 2040

Compress all

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*Conforming to off-highway (including NRMM) specific legislations, such as European Commission Stage V non-road emission standards and EPA emissions standards for Nonroad Vehicles and Engines

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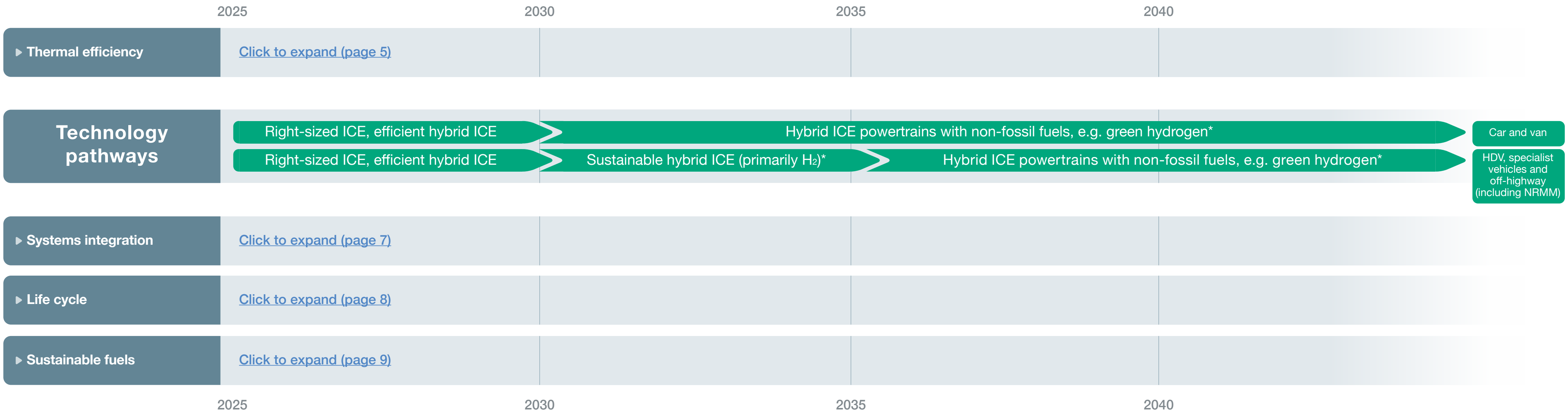

2025 2030 2035 2040

Thermal efficiency Click to expand (page 5)

Technology pathways

Right-sized ICE, efficient hybrid ICE → Hybrid ICE powertrains with non-fossil fuels, e.g. green hydrogen* — Car and van

Right-sized ICE, efficient hybrid ICE → Sustainable hybrid ICE (primarily H_2)* → Hybrid ICE powertrains with non-fossil fuels, e.g. green hydrogen* — HDV, specialist vehicles and off-highway (including NRMM)

Systems integration Click to expand (page 7)

Life cycle Click to expand (page 8)

Sustainable fuels Click to expand (page 9)

2025 2030 2035 2040

Compress all

* **Hydrogen storage**

Hydrogen is expected to become a widely used fuel in internal combustion engines. The hydrogen storage roadmap reflects this change with next generation technologies projected to become used mass-market applications from 2030 onwards, in-line with the timings on the internal combustion engine roadmap. Such technologies include:

- Type 3, Type 4 and Type 5 gaseous storage alongside cryo-compressed, liquid hydrogen and solid-state storage (see Hydrogen Storage roadmap)
- Pressure regulation moving to consistent 700 bar with fuel supply flow rates increasing towards 5 kg / min and beyond (see Hydrogen Storage roadmap)

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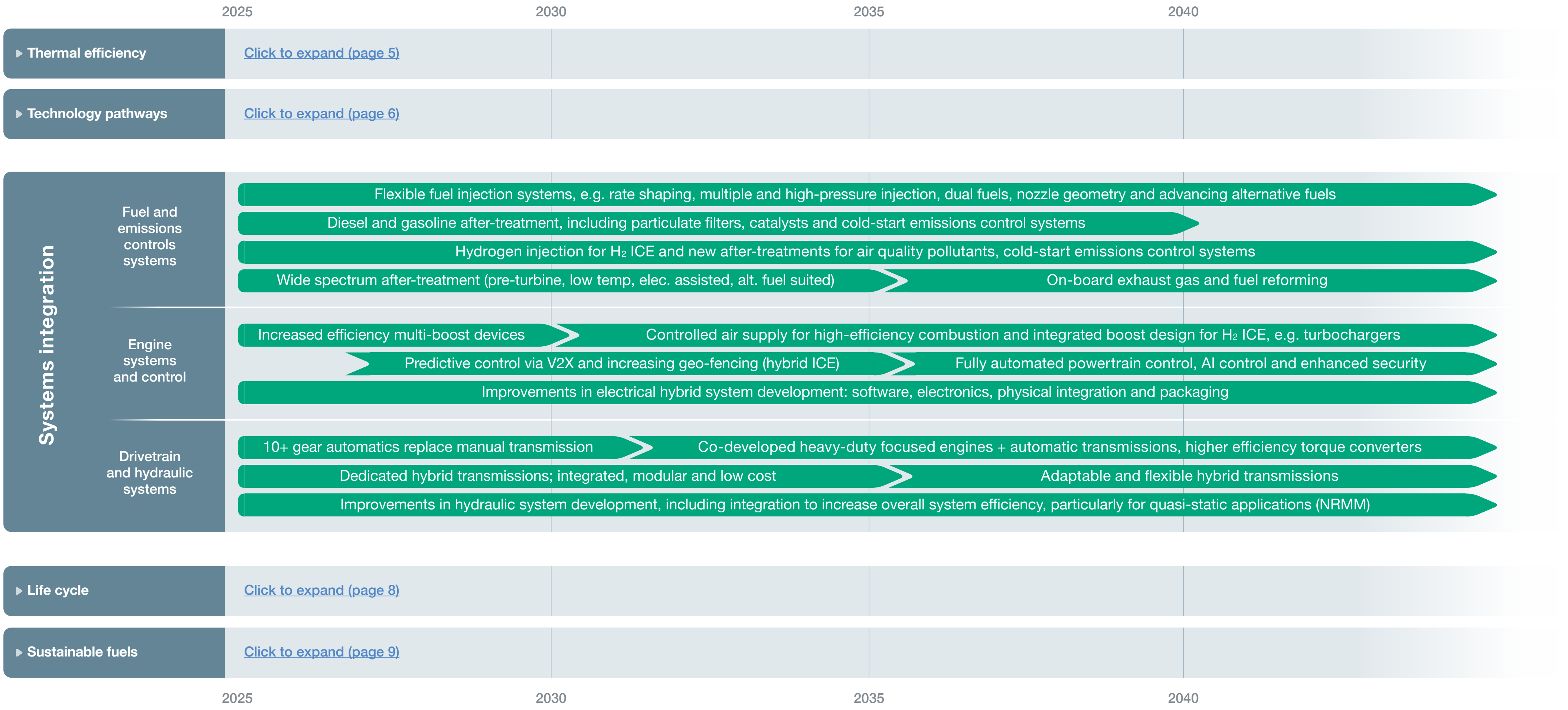

2025 2030 2035 2040

Thermal efficiency — Click to expand (page 5)

Technology pathways — Click to expand (page 6)

Systems integration

Fuel and emissions controls systems

- Flexible fuel injection systems, e.g. rate shaping, multiple and high-pressure injection, dual fuels, nozzle geometry and advancing alternative fuels
- Diesel and gasoline after-treatment, including particulate filters, catalysts and cold-start emissions control systems
- Hydrogen injection for H_2 ICE and new after-treatments for air quality pollutants, cold-start emissions control systems
- Wide spectrum after-treatment (pre-turbine, low temp, elec. assisted, alt. fuel suited) → On-board exhaust gas and fuel reforming

Engine systems and control

- Increased efficiency multi-boost devices → Controlled air supply for high-efficiency combustion and integrated boost design for H_2 ICE, e.g. turbochargers
- Predictive control via V2X and increasing geo-fencing (hybrid ICE) → Fully automated powertrain control, AI control and enhanced security
- Improvements in electrical hybrid system development: software, electronics, physical integration and packaging

Drivetrain and hydraulic systems

- 10+ gear automatics replace manual transmission → Co-developed heavy-duty focused engines + automatic transmissions, higher efficiency torque converters
- Dedicated hybrid transmissions; integrated, modular and low cost → Adaptable and flexible hybrid transmissions
- Improvements in hydraulic system development, including integration to increase overall system efficiency, particularly for quasi-static applications (NRMM)

Life cycle — Click to expand (page 8)

Sustainable fuels — Click to expand (page 9)

2025 2030 2035 2040

Compress all

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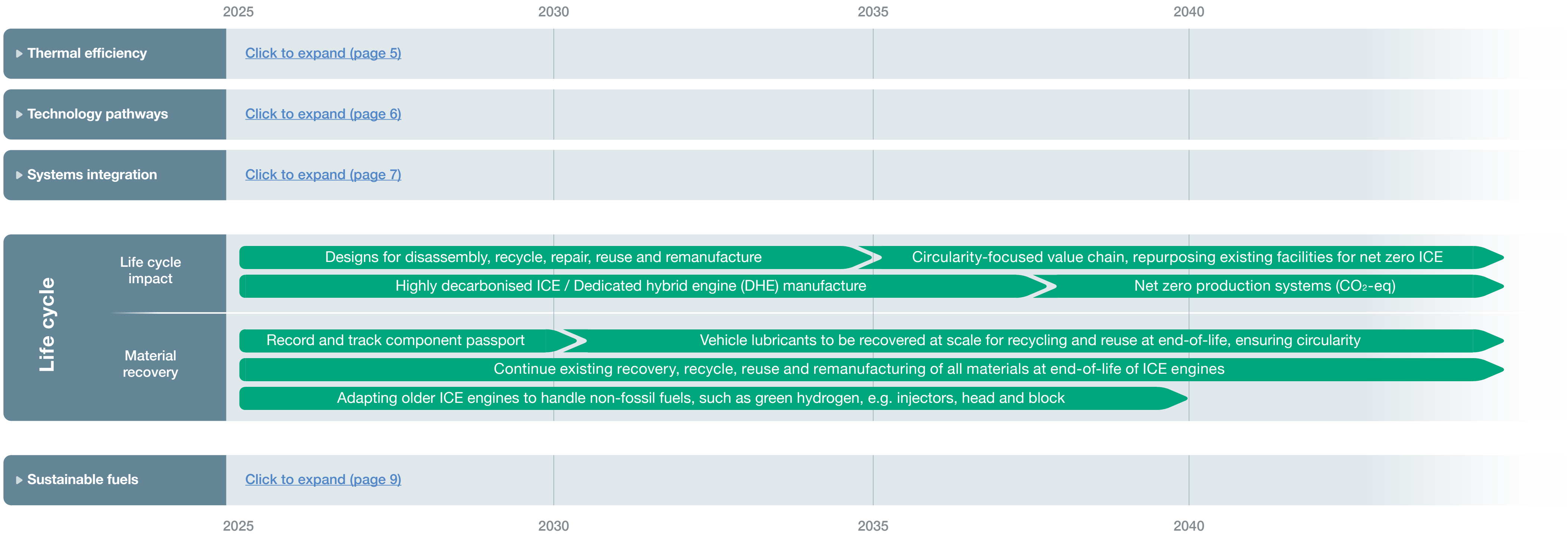

▶ **Thermal efficiency** — Click to expand (page 5)

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Life cycle

Life cycle impact
- Designs for disassembly, recycle, repair, reuse and remanufacture
- Circularity-focused value chain, repurposing existing facilities for net zero ICE
- Highly decarbonised ICE / Dedicated hybrid engine (DHE) manufacture
- Net zero production systems (CO_2-eq)

Material recovery
- Record and track component passport
- Vehicle lubricants to be recovered at scale for recycling and reuse at end-of-life, ensuring circularity
- Continue existing recovery, recycle, reuse and remanufacturing of all materials at end-of-life of ICE engines
- Adapting older ICE engines to handle non-fossil fuels, such as green hydrogen, e.g. injectors, head and block

▶ **Sustainable fuels** — Click to expand (page 9)

Compress all

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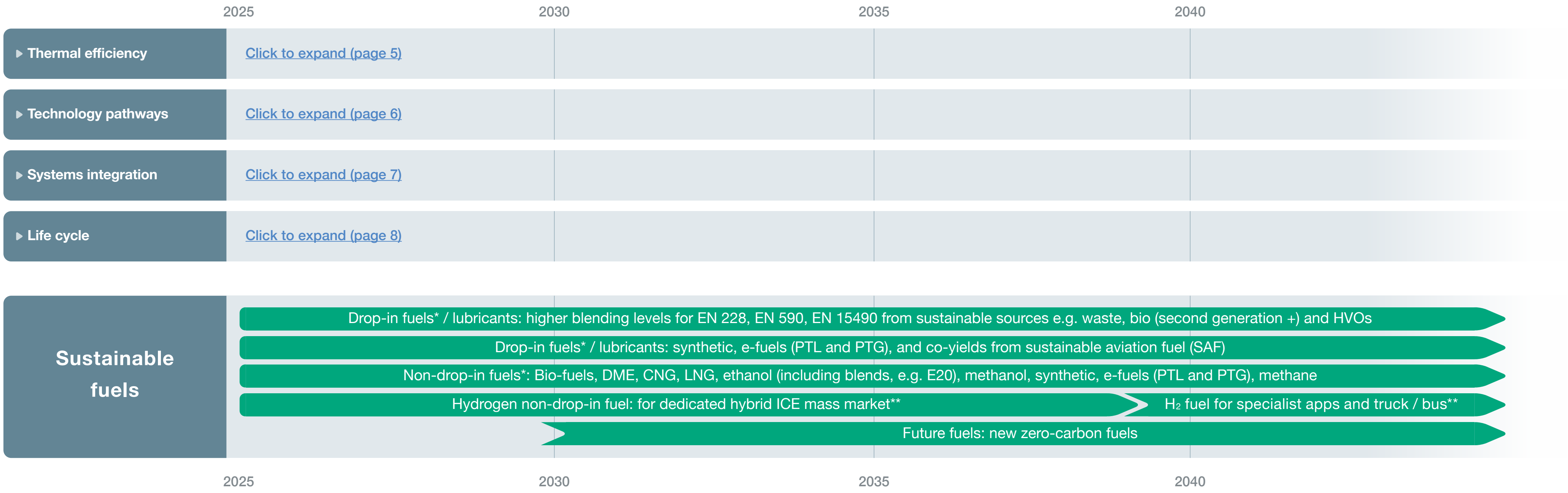

- **Thermal efficiency** — Click to expand (page 5)
- **Technology pathways** — Click to expand (page 6)
- **Systems integration** — Click to expand (page 7)
- **Life cycle** — Click to expand (page 8)

Sustainable fuels

- Drop-in fuels* / lubricants: higher blending levels for EN 228, EN 590, EN 15490 from sustainable sources e.g. waste, bio (second generation +) and HVOs
- Drop-in fuels* / lubricants: synthetic, e-fuels (PTL and PTG), and co-yields from sustainable aviation fuel (SAF)
- Non-drop-in fuels*: Bio-fuels, DME, CNG, LNG, ethanol (including blends, e.g. E20), methanol, synthetic, e-fuels (PTL and PTG), methane
- Hydrogen non-drop-in fuel: for dedicated hybrid ICE mass market** → H_2 fuel for specialist apps and truck / bus**
- Future fuels: new zero-carbon fuels

Compress all

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* **Drop-in fuels and non-drop-in fuels**

Drop-in fuel solutions are an industry focus for the nearer term, with the aim to decarbonise the current global fleet of over 1.2 billion internal combustion engine passenger cars. These fuels are suitable to be used with current specification engines.

Non-drop-in fuels will be more suitable for niche applications and low-volume markets, and these fuels will be suitable for new specification engines designed today and in the future.

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Technology indicators

Technology indicators for light-duty and heavy-duty applications that industry is likely to achieve in a global mass-market competitive environment

Brake Thermal Efficiency (BTE)

- BTE refers to Peak Brake Thermal Efficiency, a common indicator for engine efficiency. The values listed are best-in-class figures.
- Although single point peak BTE values are shown, these are not accurate indicators of real-world vehicle efficiency, which will vary across propulsion technologies and product applications.
- There may be future developments in non-fossil fuel technologies for low volume and niche market applications.

		2025	2030	2040
Light-duty	Hydrogen ICE	43%	46-48%	50-52%
	Gasoline ICE	46%	48-50%	52-55%
	Non-fossil fuels	46%	48-50%	52-55%

		2025	2030	2040
Heavy-duty and off-highway (incl. NRMM)	Hydrogen ICE	45%	48-50%	52-55%
	Diesel ICE	49%	51-53%	55-58%
	Non-fossil fuels	49%	51-53%	55-58%

Greenhouse Gas and Air Quality Regulation Drivers

<table>
<tr><th></th><th></th><th>2025</th><th>2030</th><th>2035</th><th>2040</th><th>2045</th><th>2050</th><th>…</th></tr>
<tr><td rowspan="2">Light-duty</td><td>CO_2-eq Emission</td><td>PC 93.6 g//km /
Van 153.9 g/km(WLTP)</td><td>PC 49.5 g//km /
Van 90 g/km(WLTP)</td><td colspan="5">EU fleet-wide CO_2: emission targets for cars and vans reaches 0 g/km</td></tr>
<tr><td>Pollution and Resource</td><td colspan="2">Euro 7 / EPA Emission standards (light-duty)</td><td colspan="5">Holistic environmental impact legislation (VOC, resource use, land use) and life cycle impact compliance</td></tr>
<tr><td rowspan="2">Heavy-duty</td><td>CO_2-eq Emission</td><td>CO_2: -15%</td><td>CO_2: -45%</td><td>CO_2: -65%</td><td>CO_2: -90%</td><td colspan="3">Towards net zero CO_2:-eq and life cycle impact compliance</td></tr>
<tr><td>Pollution and Resource</td><td colspan="2">Euro VII / EPA Emission standards (heavy-duty)</td><td colspan="5">Holistic environmental impact legislation (VOC, resource use, land use) and life cycle impact compliance</td></tr>
<tr><td>Off-highway (incl. NRMM)</td><td>Emissions legislation</td><td colspan="2">EU Stage V legislation / EPA Tier 4 standards</td><td colspan="5">EU Stage VI / EPA Tier 5 and beyond, holistic environmental impact legislations and life-cycle impact compliance</td></tr>
</table>

Defined driver
Predicted driver

This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption.
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Technology indicators

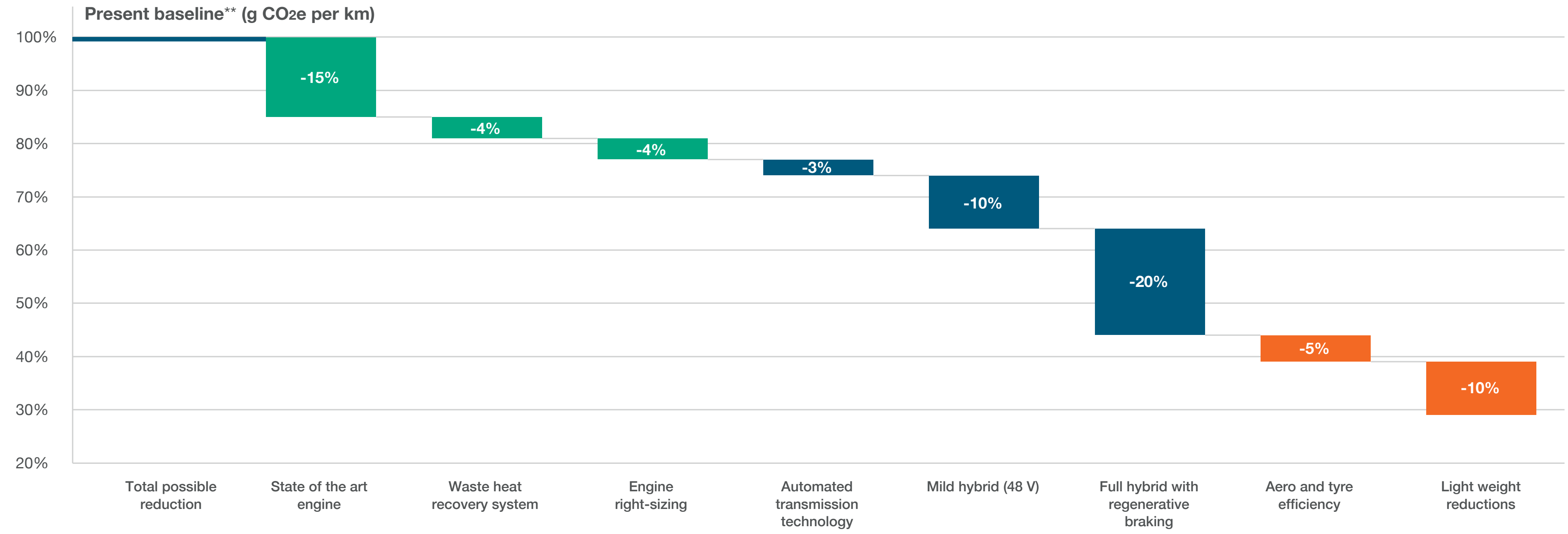
Technology pathways for CO_2-eq reduction in light-duty vehicles

(possible configurations and innovations, may not include all in a vehicle)

*2019 baseline with no hybridisation or advanced transmission technologies

Technology pathways for CO_2-eq reduction in heavy-duty vehicles*

(possible configurations and innovations, may not include all in a vehicle)



🟩 Engine level 🟦 Transmission level 🟧 System level

* Not applicable to off-highway
** 2019 baseline with no hybridisation or advanced transmission technologies

Glossary

AFIR	Alternative fuel infrastructure regulation
AI	Artificial intelligence
BEV	Battery electric vehicle
BTE	Brake thermal efficiency
CAD	Computer aided development
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CVT	Continuously variable transmission
DI	Direct injection
DME	Dimethyl ether
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
EU	European Union
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gases
HDV	Heavy-duty vehicle
HGV	Heavy goods vehicle
ICE	Internal combustion engines
NEV	New energy vehicle
NFC	Near field communication
NOX	Nitrogen oxides
NRMM	Non-road mobile machinery
ORC	Organic rankine cycle
PFI	Port fuel injection
PM	Particulate matter
R&D	Research and development
RFID	Radio frequency identification
RPM	Revolutions per minute
SAF	Sustainable aviation fuel
TEN-T	Trans-European Network for Transport
TWC	Three-way catalysts
UK	United Kingdom
ULEZ	Ultra-low emission zone
V2X	Vehicle-to-everything
VVT	Variable valve timing
WHR	Waste heat recovery
WLTP	World harmonised light-duty vehicles test procedure
ZEV	Zero emission vehicle

System-Level Roadmaps

Mobility of People

Mobility of Goods

Technology Roadmaps

Electric Machines

Power Electronics

Electrical Energy Storage

Lightweight Vehicle and Powertrain Structures

Internal Combustion Engines

Hydrogen Fuel Cell System and Storage

Find all the roadmaps at

www.apcuk.co.uk/technology-roadmaps

automotive council UK

ADVANCED PROPULSION CENTRE UK

Established in 2013, the Advanced Propulsion Centre UK (APC), with the backing of the UK Government's Department for Business and Trade (DBT), has facilitated funding for 304 low-carbon and zero-emission projects involving 538 partners. Working with companies of all sizes, this funding is estimated to have helped to create or safeguard over 59,000 jobs in the UK. The technologies and products that result from these projects are projected to save over 425 million tonnes of CO_2.

The APC would like to acknowledge the extensive support provided by industry and academia in developing and publishing the roadmaps.

V01 09/24