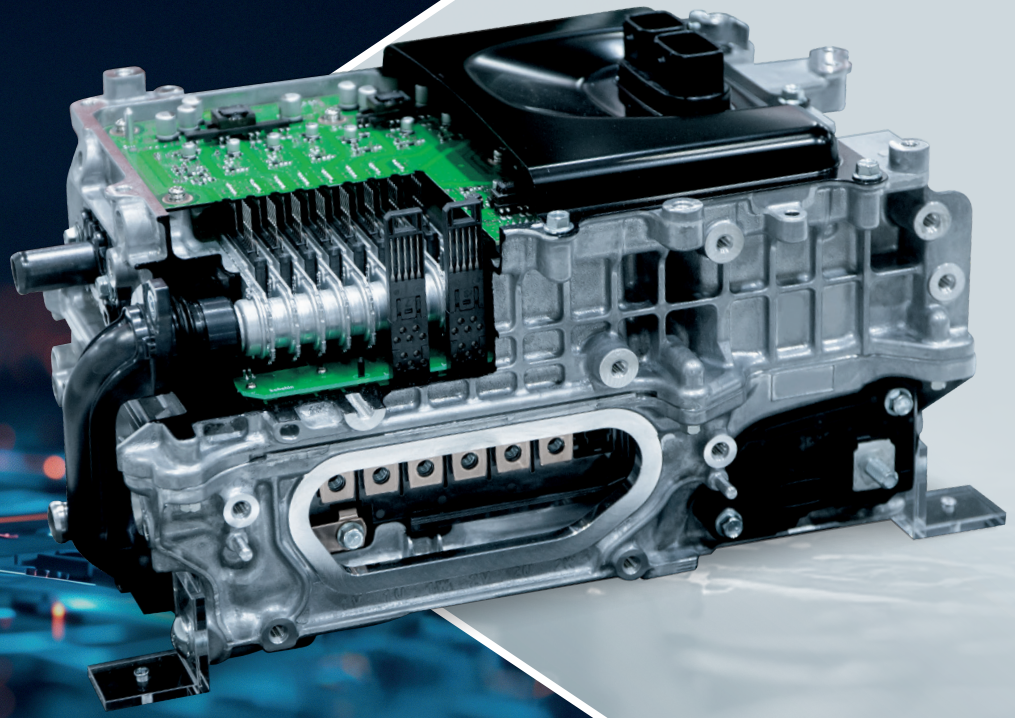
# Power Electronics

# Technology Roadmap

## 2024



automotive council UK

ADVANCED PROPULSION CENTRE UK

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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

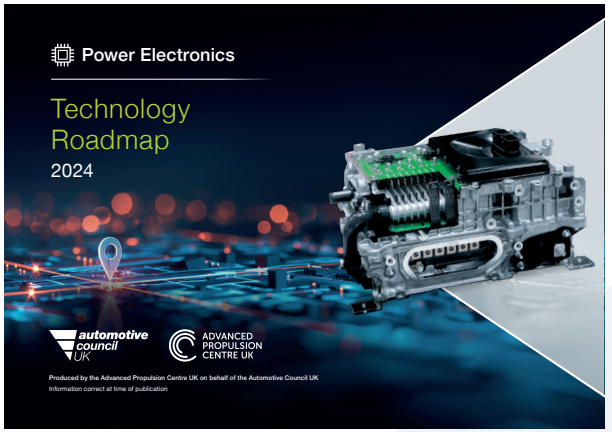
The executive roadmap provides a high-level view of forecast mass adoption of technology within the automotive industry. Mass adoption requires technology, supply-chain, manufacturing and market readiness and in some instances, regulatory readiness.

## 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.



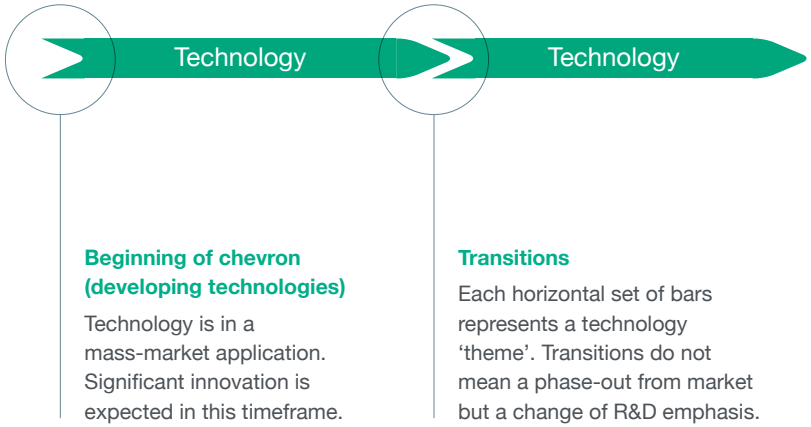

Technology roadmap


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)**

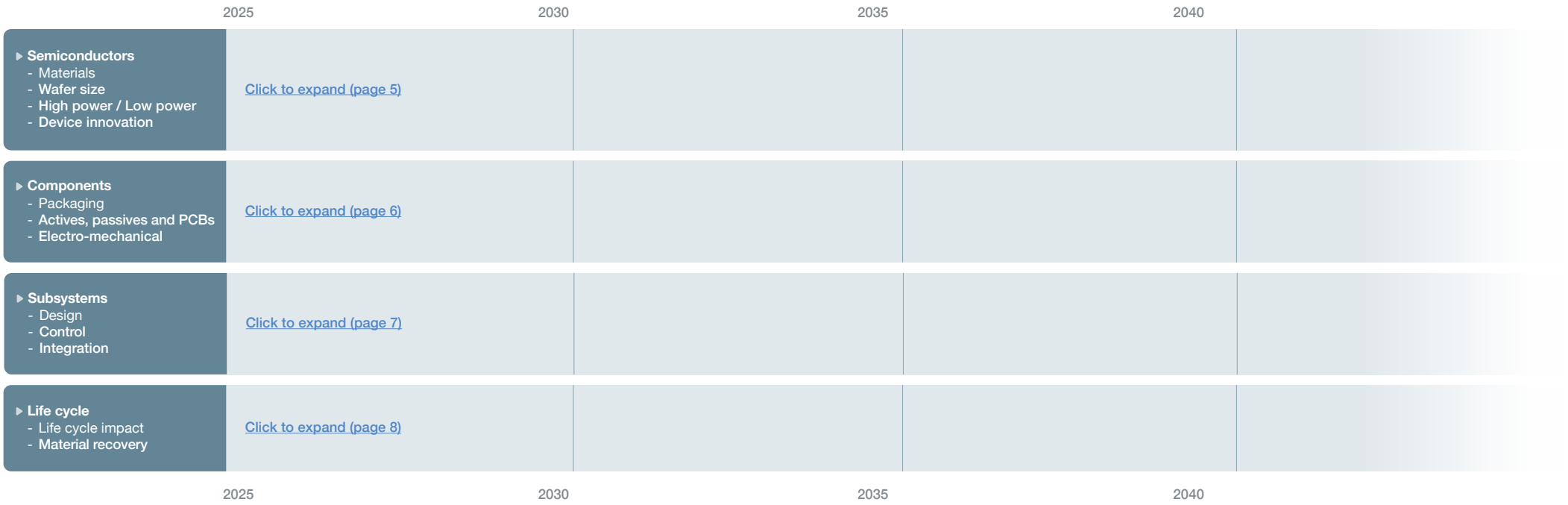
Technology is in a mass-market application. Significant innovation is expected in this timeframe.

**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.

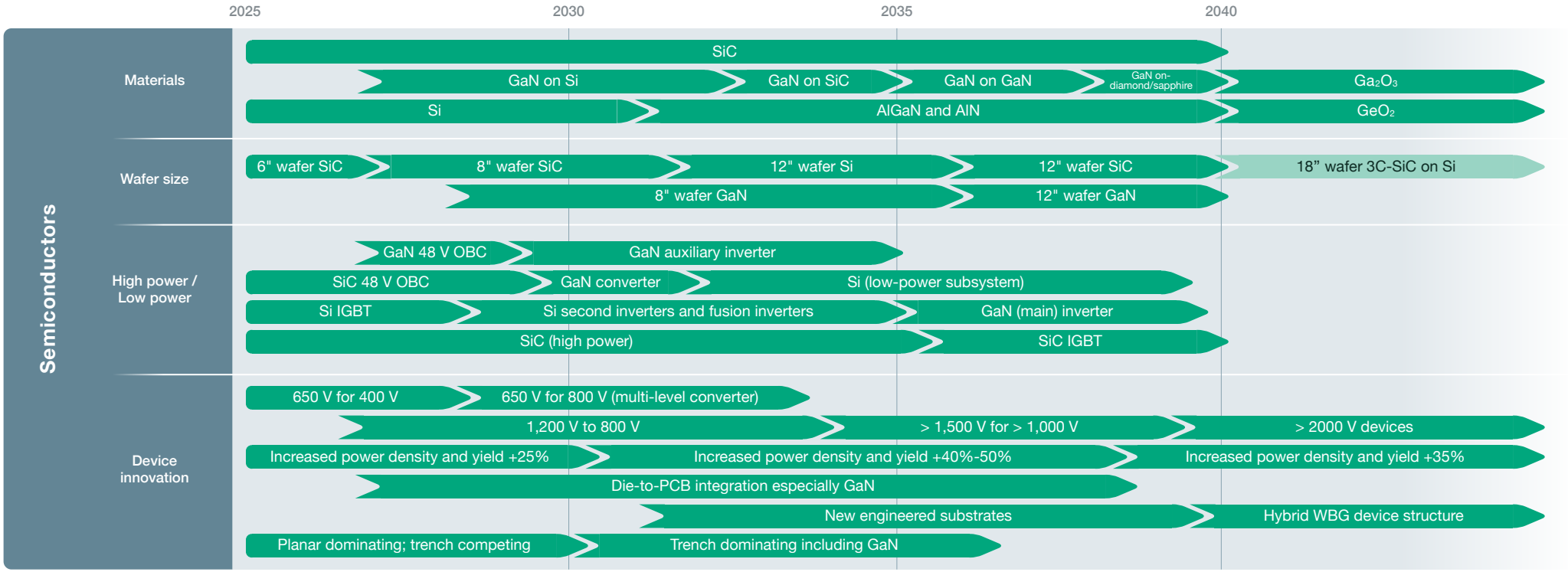
# Technology roadmap






Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

*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.*




▸ Components — Click to expand (page 6)

▸ Subsystems — Click to expand (page 7)

▸ Life cycle — Click to expand (page 8)

2025 2030 2035 2040

Compress all

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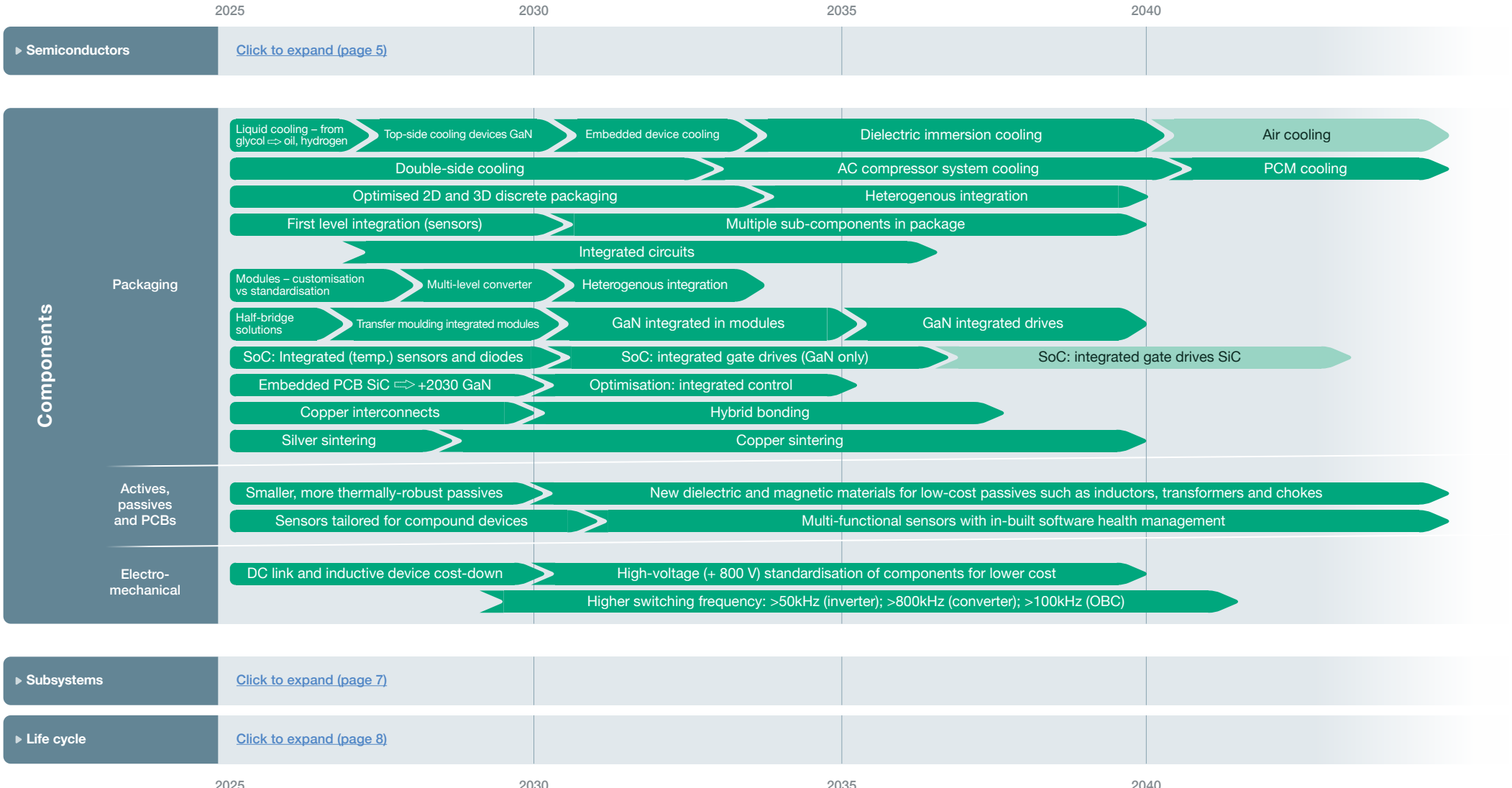


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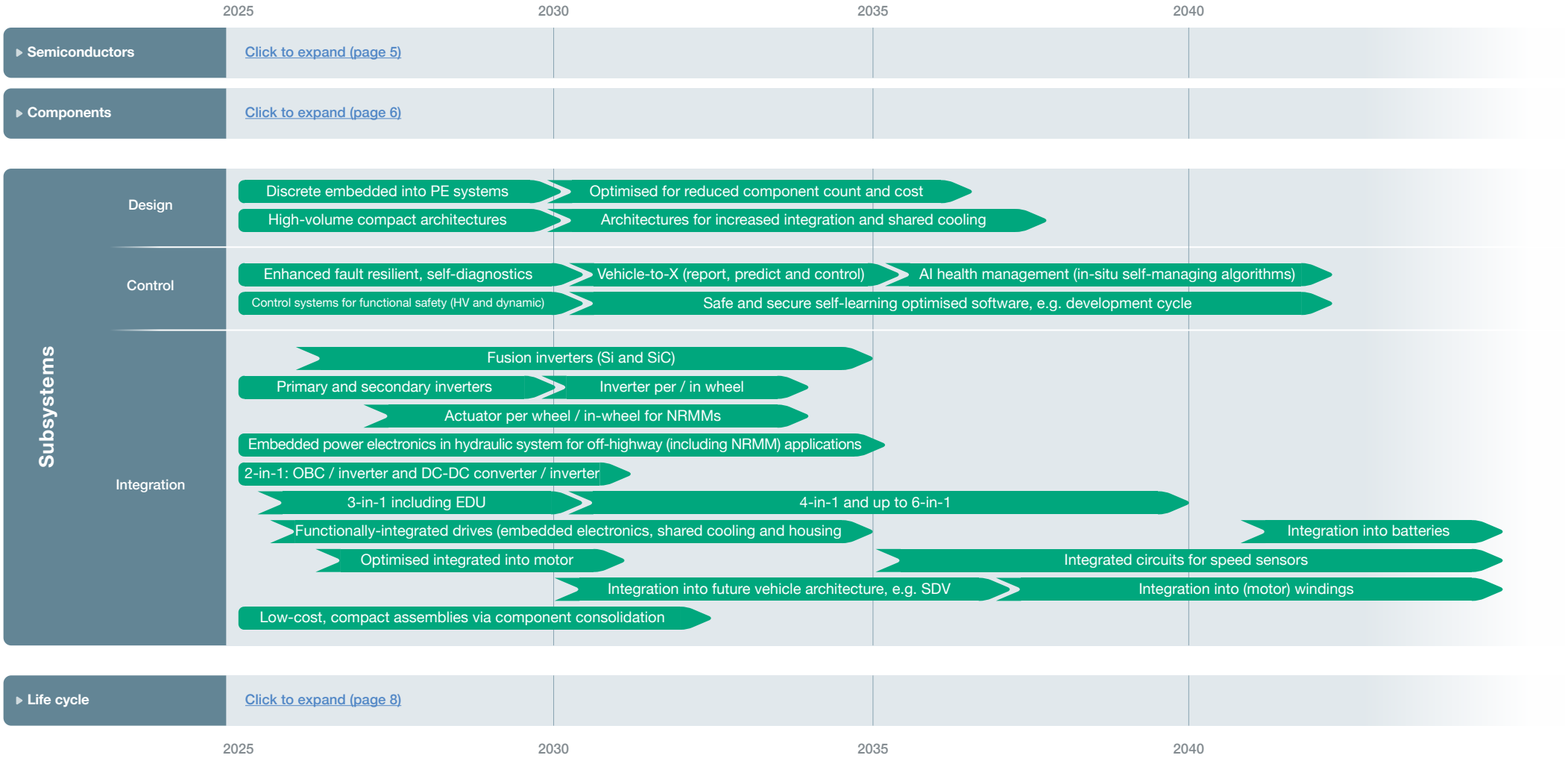


Compress all

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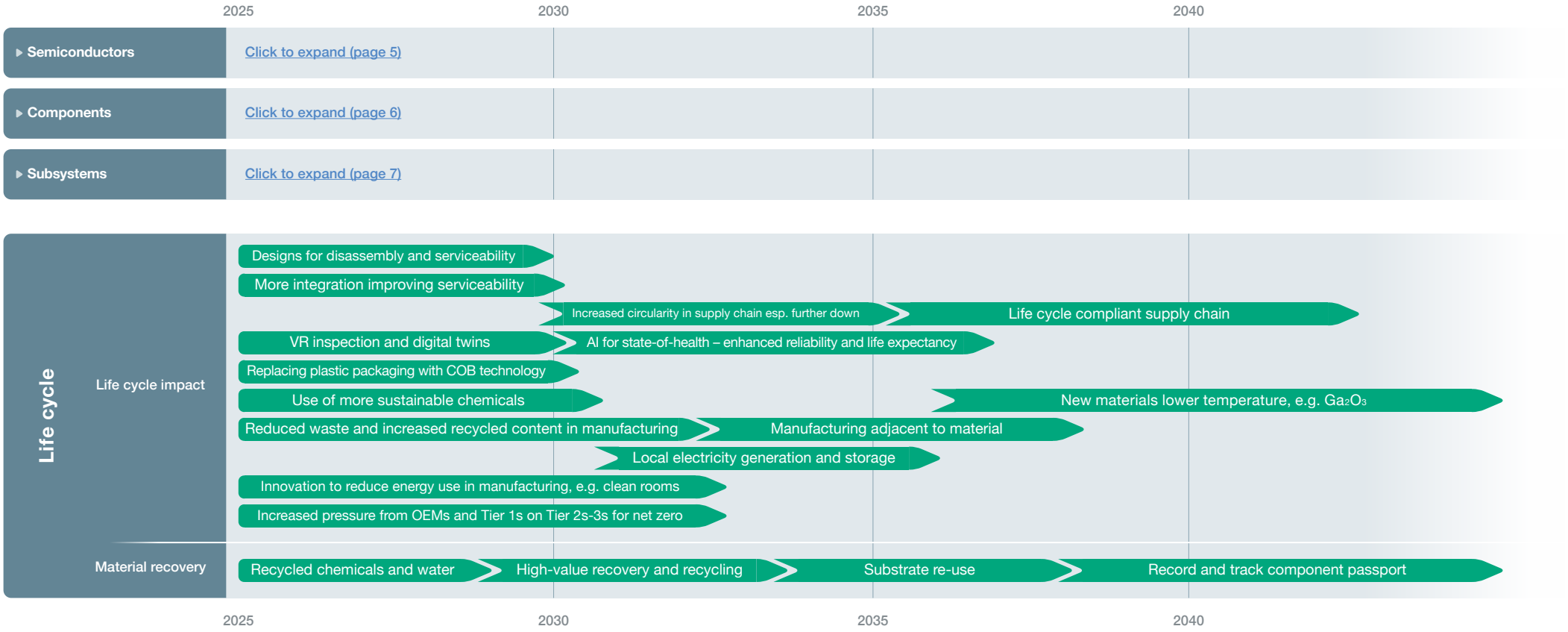


Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

*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 indicators for INVERTERS for light-duty vehicles

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Light-duty vehicles | Urban mobility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2025 | Peak power (kW) | <100 | 250 | 350 | 600* |
| | Continuous power (kW) | 50 | 150 | 230 | 450-600 |
| | Input voltage (max) (V) | 400 | 400/800 | 800 | 800 |
| | Output current (A rms) | 300 | 450/550 | 850 | 1,000 |
| | Coolant inlet temp. (ºC) | 65 | 65 | 65 | 75 |
| | Production volume | >100k | >100k | >100k | <10k |

*Single inverter, multi-level; multi-phased system

| | Light-duty vehicles | Urban mobility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2030 | Peak power (kW) | <150 | 250 | 500* | 800* |
| | Continuous power (kW) | 75 | 150 | 350-375 | 650-800 |
| | Input voltage (max) (V) | 400 | 800 | 800 | 1,200 |
| | Output current (A rms) | 200-350 | 550 | 1,000 | 1,500 |
| | Coolant inlet temp. (ºC) | 65 | 65 | 75 | 85 |
| | Production volume | >100k | >100k | >100k | <10k |

| | Light-duty vehicles | Urban mobility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2040 | Peak power (kW) | 150 | 250 | 1,400 | 1,500 |
| | Continuous power (kW) | 90 | 150 | 800 | 1.0MW – 1.5MW |
| | Input voltage (max) (V) | 400 | 400/800 | 1,200 | 1,500 |
| | Output current (A rms) | 350 | 450/550 | 1,000 | 1,500 |
| | Coolant inlet temp. (ºC) | 65 | 75 | 85 | Air cooled |
| | Production volume | >100k | >100k | >100k | <10k |

| | | 2025 | 2030 | 2040 |
|---|---|---|---|---|
| All LDVs | Volumetric density(kW/l) | 60-80 | 120 | 200 |
| | Gravimetric density (kW/kg) | 60-80 | 120 | 200 |
| | WLTP** average efficiency | 98% | 98.5% | 99% |

Continuous power = 30 minutes
*Single inverter, multi-level; multi-phased system
**Worldwide Harmonised Light-Vehicle Test Procedure

*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 indicators for DC-DC CONVERTERS for light-duty vehicles

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Light-duty vehicles | Urban Utility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2025 | Peak power (kW) | <2 | >3 | 3.5 | 4 |
| | Continuous power (kW) | <2 | >3 | 3.5 | 2.5 |
| | Input / output voltage (nominal) (V) | 400 | 400 | 800 | 800 |
| | Output / input voltage (nominal) (V) | 12 | 12/48 | 12/48 | 12/48 |
| | Coolant inlet temp. (ºC) | 65 | 65 | 65 | 75 |
| | Production volume | >100k | >100k | >100k | <10k |

| | Light-duty vehicles | Urban Utility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2030 | Peak power (kW) | 2 | >3 | 4 | 5.2 |
| | Continuous power (kW) | 2 | >3 | 4 | 5.2 |
| | Input / output voltage (nominal) (V) | 400 | 800 | 800 | 1,200 |
| | Output / input voltage (nominal) (V) | 12 | 12/48 | 48 | 48 |
| | Coolant inlet temp. (ºC) | 65 | 65 | 75 | 85 |
| | Production volume | >100k | >100k | >100k | <10k |

Continuous power = 30 minutes

| | Light-duty vehicles | Urban Utility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2040 | Peak power (kW) | 3 | >3 | 4 | 6.5 |
| | Continuous power (kW) | 3 | >3 | 4 | 6.5 |
| | Input / output voltage (nominal) (V) | 400 | 400/800 | 800 | 1,500 |
| | Output / input voltage (nominal) (V) | 12 | 12/48 | 48 | 85 |
| | Coolant inlet temp. (ºC) | 65 | 75 | 85 | air cooled |
| | Production volume | >100k | >100k | >100k | <10k |

| | | 2025 | 2030 | 2040 |
|---|---|---|---|---|
| All LDVs | Volumetric density(kW/l) | 3 – 4 | 3 – 5 | 3 – 6 |
| | Gravimetric density (kW/kg) | 2 – 2.75 | 2.5-4 | 2.5-4.5 |
| | WLTP** average efficiency | 98% | 98.50% | >99% |

Continuous power = 30 minutes
**Worldwide Harmonised Light-Vehicle Test Procedure

*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 indicators for ON-BOARD CHARGERS for light-duty vehicles

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Light-duty vehicles | Urban Utility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2025 | Peak power (kW) | ~3 | ~7 | 11 | 11 |
| | Continuous power (kW) | ~3 | ~7 | 11 | 11 |
| | Output / input voltage (nominal) (V) | 400 | 400/800 | 800 | 800 |
| | Coolant inlet temp. (ºC) | 65 | 65 | 65 | 75 |
| | Production volume | >100k | >100k | >100k | <10k |

| | Light-duty vehicles | Urban Utility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2030 | Peak power (kW) | ~3 | 11 | 22 | 22 |
| | Continuous power (kW) | ~3 | 11 | 22 | 22 |
| | Output / input voltage (nominal) (V) | 400 | 800 | 800 | 1,200 |
| | Coolant inlet temp. (ºC) | 65 | 65 | 75 | 85 |
| | Production volume | >100k | >100k | >100k | <10k |

| | Light-duty vehicles | Urban Utility | Mass volume | Luxury / SUV | Performance |
|---|---|---|---|---|---|
| 2040 | Peak power (kW) | ~3 | 22 | 22 | 22 |
| | Continuous power (kW) | ~3 | 22 | 22 | 22 |
| | Output / input voltage (nominal) (V) | 400 | 400/800 | 800 | 1,500 |
| | Coolant inlet temp. (ºC) | 65 | 75 | 85 | air cooled |
| | Production volume | >100k | >100k | >100k | <10k |

| | | 2025 | 2030 | 2040 |
|---|---|---|---|---|
| All LDVs | Volumetric density(kW/l) | 2.5 – 3<br>n/a* | >4<br>n/a* | 5<br>n/a* |
| | Gravimetric density (kW/kg) | 3 – 3.5<br>4.5* | 4.5<br>12* | 5.5<br><20* |
| | WLTP** average efficiency | 98% | 98.50% | 99% |

*Applies to performance cars
** WLTP = Worldwide Harmonised Light-Vehicle Test Procedure

*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 for INVERTERS for heavy-duty vehicles

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Heavy-duty vehicle | HDV 7.5 t - 26 t | HDV 26 t – 44 t* |
|---|---|---|---|
| 2025 | Peak power (kW) | 280-300 | 400* |
| | Continuous power (kW) | 100-180 | 200* |
| | System voltage (V) | 800 | 800 |
| | Charging voltage (V) | 650 | 750 |
| | Output current (A rms) | 750 | 820 |
| | Coolant inlet temp. (°C) | 65 | 65 |

| | Heavy-duty vehicle | HDV 7.5 t - 26 t | HDV 26 t – 44 t* |
|---|---|---|---|
| 2030 | Peak power (kW) | 300 | 400* |
| | Continuous power (kW) | 180 | 250* |
| | System voltage (V) | 800 | 800 |
| | Charging voltage (V) | 750 | 1,200 |
| | Output current (A rms) | 750 | 820 |
| | Coolant inlet temp. (°C) | 65 | 65 |

| | Heavy-duty vehicle | HDV 7.5 t - 26 t | HDV 26 t – 44 t* |
|---|---|---|---|
| 2040 | Peak power (kW) | 400 | 500* |
| | Continuous power (kW) | 250 | 300* |
| | System voltage (V) | 1,000 | 1,000 |
| | Charging voltage (V) | 1,200 | 1,800 |
| | Output current (A rms) | 820 | 1,000 |
| | Coolant inlet temp. (°C) | 75 | 75 |

*This vehicle typically has two motors. The output is per motor.

| | | 2025 | 2030 | 2040 |
|---|---|---|---|---|
| Heavy-duty 7.5 t - 26 t | Volumetric density(kW/l) | 18.3 | 20.7 | 36.7 |
| | Gravimetric density (kW/kg) | 15 | 18.2 | 22 |
| | WLTP** average efficiency | >97% | >98% | >98% |

| | | 2025 | 2030 | 2040 |
|---|---|---|---|---|
| Heavy-duty 26 t - 44 t | Volumetric density(kW/l) | 36.7 | 36.7 | 40.0 |
| | Gravimetric density (kW/kg) | 22.0 | 22.0 | 30.0 |
| | WLTP** average efficiency | >97% | >98% | >98% |

**Worldwide Harmonised Light-Vehicle Test Procedure

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*Specific application-tailored technologies will vary from region to region.*

## Technology indicators for DC-DC CONVERTERS for heavy-duty vehicles

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Output/input voltage (nom.) | 28 V | 48 V | 750 V* |
|---|---|---|---|---|
| 2025 | Peak power (kW) | 3 | >3 | 7 |
| | Continuous power (kW) | 3 | >3 | 7 |
| | Input / output voltage (nom.) (V) | 800 | 800 | 800 |
| | Coolant inlet temperature (°C) | 65 | 65 | 65 |

| | Output/input voltage (nom.) | 28 V | 48 V | 750 V* |
|---|---|---|---|---|
| 2030 | Peak power (kW) | 3 | 5 | 10 |
| | Continuous power (kW) | 3 | 5 | 10 |
| | Input / output voltage (nom.) (V) | 800 | 1,200 | 1,200 |
| | Coolant inlet temperature (°C) | 65 | 65 | 65 |

*This vehicle has two powerlines

| | Output/input voltage (nom.) | 28 V | 48 V | 750 V* |
|---|---|---|---|---|
| 2040 | Peak power (kW) | 5 | 12 | 15 |
| | Continuous power (kW) | 5 | 12 | 15 |
| | Input / output voltage (nom.) (V) | 1,200 | 1,800 | 1,800 |
| | Coolant inlet temperature (°C) | 75 | 75 | 75 |

## Technology indicators for ON-BOARD CHARGERS for heavy-duty vehicles

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Heavy-duty vehicle | HDV 7.5 t - 26 t | HDV 26 t – 44 t |
|---|---|---|---|
| 2025 | Peak power (kW) | 22 | n/a |
| | Continuous power (kW) | 22 | n/a |
| | Output / input voltage (nominal) (V) | 850 | n/a |
| | Coolant inlet temp. (ºC) | 65 | n/a |

| | Heavy-duty vehicle | HDV 7.5 t - 26 t | HDV 26 t – 44 t |
|---|---|---|---|
| 2030 | Peak power (kW) | 22 | n/a |
| | Continuous power (kW) | 22 | n/a |
| | Output / input voltage (nominal) (V) | 1,200 | n/a |
| | Coolant inlet temp. (ºC) | 65 | n/a |

| | Heavy-duty vehicle | HDV 7.5 t - 26 t | HDV 26 t – 44 t |
|---|---|---|---|
| 2040 | Peak power (kW) | 22 | n/a |
| | Continuous power (kW) | 22 | n/a |
| | Output / input voltage (nominal) (V) | 1,200 | n/a |
| | Coolant inlet temp. (ºC) | 75 | n/a |

## Technology indicators for INVERTERS for off-highway (including non-road mobile machinery)

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t | 15 t - 44 t |
|---|---|---|---|---|
| 2025 | Peak power (kW) | <55 | ~83 | 300 |
| | Continuous power (kW) | ~35 | ~54 | 150 |
| | System voltage (V) | <100 | 400 | 800 |
| | Charging voltage (V) | <100 | n/a | n/a |
| | Charging current (A rms) | 300 | n/a | n/a |
| | Coolant inlet temp. (ºC) | Air cooled | 65 | 65 |

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t | 15 t - 44 t |
|---|---|---|---|---|
| 2030 | Peak power (kW) | ~55 | ~83 | 400 |
| | Continuous power (kW) | ~35 | ~54 | 250 |
| | System voltage (V) | <100 | 400 | 800 |
| | Charging voltage (V) | <100 | n/a | n/a |
| | Charging current (A rms) | 300 | n/a | n/a |
| | Coolant inlet temp. (ºC) | Air cooled | 65 | 65 |

<5 t = BEV  8 t - 14 t = MHV  15 t - 44 t = MHV

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t | 15 t - 44 t |
|---|---|---|---|---|
| 2040 | Peak power (kW) | 55 | 100 | 500 |
| | Continuous power (kW) | 35 | 50 | 300 |
| | System voltage (V) | 100 | 400 | 800-1,000 |
| | Charging voltage (V) | 100 | n/a | n/a |
| | Charging current (A rms) | 300 | n/a | n/a |
| | Coolant inlet temp. (ºC) | Air cooled | 75 | 75 |

## Technology indicators for DC-DC CONVERTERS for off-highway (including non-road mobile machinery)

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t<br>15 t - 44 t |
|---|---|---|---|
| 2025 | Peak power (kW) | <3 | >3 |
| | Continuous power (kW) | <3 | >3 |
| | Input / output voltage (nom.) (V) | 400 | 400/800 |
| | Output / input voltage (nom.) (V) | 12 | 28 |
| | Coolant inlet temp. (°C) | 65 | 65 |

<5 t = BEV  8 t - 14 t = MHV  15 t - 44 t = MHV

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t<br>15 t - 44 t |
|---|---|---|---|
| 2030 | Peak power (kW) | 3 | >3 |
| | Continuous power (kW) | 3 | >3 |
| | Input / output voltage (nom.) (V) | 400 | 400/800 |
| | Output / input voltage (nom.) (V) | 12 | 28 |
| | Coolant inlet temp. (°C) | 65 | 65 |

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t<br>15 t - 44 t |
|---|---|---|---|
| 2040 | Peak power (kW) | 3 | 4-5 |
| | Continuous power (kW) | 3 | 4-5 |
| | Input / output voltage (nom.) (V) | 400 | 400/<br>800-1,000 |
| | Output / input voltage (nom.) (V) | 12 | 28 |
| | Coolant inlet temp. (°C) | 75 | 75 |

## Technology indicators for ON-BOARD CHARGERS for off-highway (including non-road mobile machinery)

Technology indicators that industry is likely to achieve in a mass-market competitive environment.
All the performance metrics are ambitious and dependant on technology development but relate to the same technology.

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t<br>15 t - 44 t |
|---|---|---|---|
| 2025 | Peak power (kW) | 3 | n/a |
| | Continuous power (kW) | 3 | n/a |
| | Output / input voltage (nominal) (V) | 230* | n/a |
| | Coolant inlet temp. (ºC) | 65 | n/a |

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t<br>15 t - 44 t |
|---|---|---|---|
| 2030 | Peak power (kW) | 7 | n/a |
| | Continuous power (kW) | 7 | n/a |
| | Output / input voltage (nominal) (V) | 230* | n/a |
| | Coolant inlet temp. (ºC) | 65 | n/a |

<5 t = BEV  8 t - 14 t = MHV  15 t - 44 t = MHV  *AC main 230 V

| | Off-highway (including NRMM) | <5 t | 8 t - 14 t<br>15 t - 44 t |
|---|---|---|---|
| 2040 | Peak power (kW) | 7 | n/a |
| | Continuous power (kW) | 7 | n/a |
| | Output / input voltage (nominal) (V) | 230* | n/a |
| | Coolant inlet temp. (ºC) | 75 | n/a |

# Glossary

| | |
|---|---|
| ACER | European Union Agency for the Cooperation of Energy Regulators |
| AI | Artificial intelligence |
| AlGaN | Aluminium gallium nitride |
| AlN | Aluminium nitride |
| ANN | Artificial neural networks |
| AWD | Automatic wheel drive |
| BEV | Battery electric vehicle |
| $CO_2$ | Carbon dioxide |
| Cu | Copper |
| E/E architecture | Electrical/electronic architecture |
| EU | European Union |
| EV | Electric vehicle |
| FCEV | Fuel cell electric vehicle |
| FWD | Forward wheel drive |
| $Ga_2O_3$ | Gallium oxide |
| GaN | Gallium nitride |
| $GeO_2$ | Germanium oxide |
| GVW | Gross vehicle weight |
| HDV | Heavy-duty vehicle |
| HEV | Hybrid electric vehicle |
| IC | Integrated circuit |
| IGBT | Insulated-gate bipolar transistor, |
| LCA | Life cycle assessment |
| LDV | Light-duty vehicle |
| ML | Machine learning |
| MOSFET | Metal–oxide–semiconductor field-effect transistor |
| MPC | Model predictive control |
| NEV | New energy vehicles |
| NRMM | Non-road mobile machinery |
| OBC | On-board charger |
| OEE | Overall equipment effectiveness |
| OEM | Original equipment manufacturer |
| PCB | Printed circuit board |
| PCM | Phase changing materials |
| PFAS | Per-and polyfluoroalkyl substance |
| PHEV | Plug-in hybrid electric vehicle |
| R&D | Research and Development |
| RTM | Resin transfer moulded |
| RWD | Rear wheel drive |
| Si | Silicon |
| SiC | Silicon carbide |
| US | United States |
| V2G | Vehicle-to-grid |
| V2H | Vehicle-to-home |
| WBG | Wide bandgap |
| WLTP | World harmonised light-duty vehicles test procedure |
| xEV | Any type of electric vehicle (BEV, FCEV, HEV, NEV, PHEV) |
| ZEV | Zero-emission vehicle |

*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.*

## 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 $CO_2$.

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