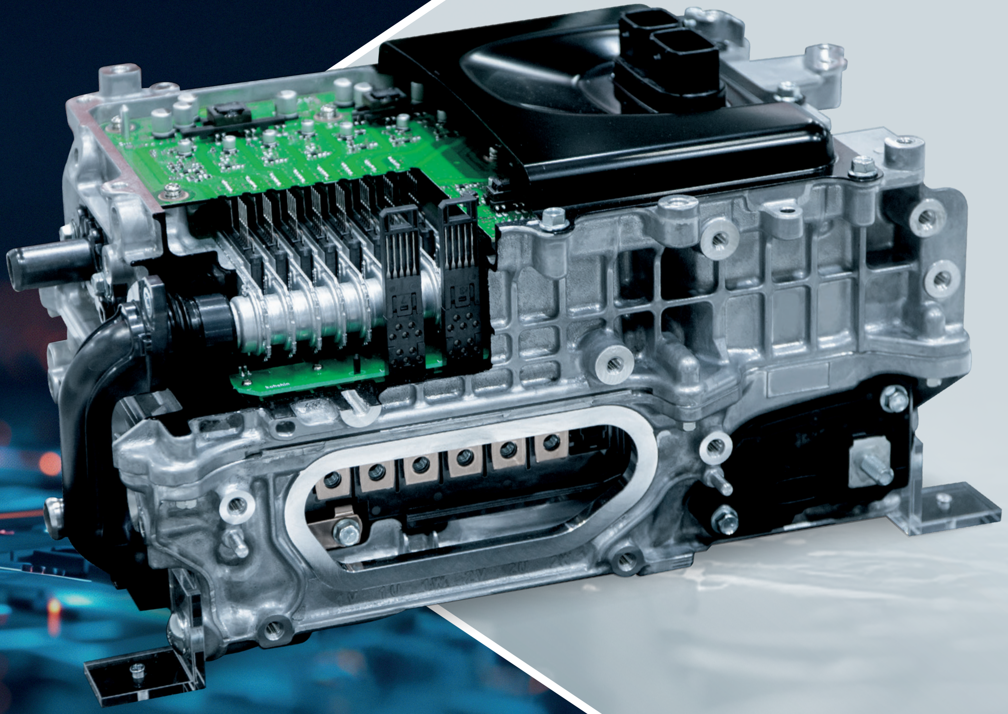
Power Electronics

Narrative Report

2024



automotive council UK

ADVANCED PROPULSION CENTRE UK

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

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1 | Introduction

1.1 | Foreword to the 2024 roadmaps

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The UK Automotive Council is well known for producing robust and detailed technology roadmaps that define potential routes for Automotive including Commercial Vehicles and Off-Road machinery and related products to achieve our UK environmental and societal goals. Roadmaps are a function of current knowledge and as new ideas and technologies emerge, must be regularly renewed. This exercise, led by the Advanced Propulsion Centre UK, has generated the fourth generation of these roadmaps.

Whilst many organisations develop roadmaps as part of their product planning process, the Automotive Council roadmaps are unique in providing a consented view from the Automotive sector including Commercial Vehicle and Off-Road Machinery, in the UK. This enables us to define common future challenges and where to focus collaborative R&D and capital resources in developing successful, sustainable, net-zero solutions.

These solutions must also meet future consumer needs and not introduce challenges in experience or limitations in operation. Often, more than one technical approach appears viable to meet future needs. It is important that all of these approaches are explored and introduced to market as the carbon reduction goal becomes more urgent. Ultimately, it is possible that one approach may dominate but we cannot afford to wait for this to emerge.

1.2 The purpose of the 2024 roadmaps

The Automotive Council UK roadmaps outline key themes, trends and drivers in the global automotive industry. This narrative report explains and provides insights to support the roadmap's themes. It helps clarify the reasons behind the roadmap's content and how it should be used.

The report aims to guide research and development (R&D), innovation, and cross-sector collaboration. A list of recommendations for how industry, academia, and government can use this information is shown opposite:

Industry

- Compare in-house R&D priorities with industry trends and drivers in the automotive sector.
- Evaluate supply chain risks and develop strategies for sustainable and circular business models in automotive products.
- Help start-ups by guiding their technology focus, investment choices, and collaboration plans.

Academia

- Address long-term research challenges that need to be solved.
- Align university research, education, and skills development with the automotive industry's needs.
- Strengthen partnerships between academia and industry to apply research to real-world solutions.

Government and policymakers

- Understand key themes and trends in automotive technologies.
- Direct policy and funding to support R&D priorities and innovation for reaching net zero.
- Promote cross-sector collaboration and trade policies that benefit the automotive industry and broader industrial sectors.

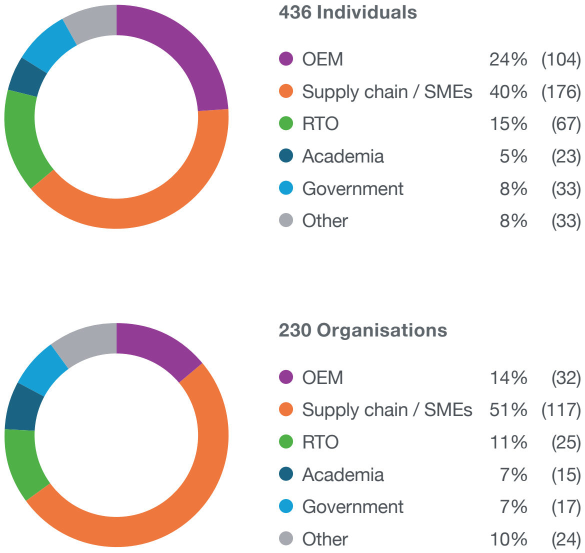
1.3 Building a consensus

This consensus roadmap has been developed through the facilitation of the Advanced Propulsion Centre UK (APC), with contributions from 436 individuals representing 230 organisations, which include government, industry and academia.

Collating the information required for the 2024 roadmaps has only been possible due to the breadth of contribution and valuable feedback from those who have fed into the process, which began in early 2023. The APC would like to thank everyone who gave their time and input across the various webinars, workshops, and surveys conducted.

As a result of this consultation across industry and academia the 2024 roadmaps build on previous versions and demonstrate the significant change that is happening across the automotive sector and its supporting industries.

Figure 1: Representation by individual and organisation



436 Individuals

● OEM	24%	(104)
● Supply chain / SMEs	40%	(176)
● RTO	15%	(67)
● Academia	5%	(23)
● Government	8%	(33)
● Other	8%	(33)

230 Organisations

● OEM	14%	(32)
● Supply chain / SMEs	51%	(117)
● RTO	11%	(25)
● Academia	7%	(15)
● Government	7%	(17)
● Other	10%	(24)

Mark Johnson
Professor of Advanced Power Conversion
University of Nottingham

I am delighted to introduce this third edition of the Automotive Council UK Power Electronics Roadmap. Our 2024 roadmap reflects the continuing global drive towards electrification, which has seen a dramatic acceleration in technology development accompanied by a deepening understanding of application requirements and the adoption of sustainability as a priority for the automotive industry.

In the build-up to the new roadmap, we engaged with a broad cross-section of the power electronics community, followed by surveys and a series of focused workshops. I am very grateful to all those who contributed.

Whilst the global power electronics sector has evolved rapidly since our 2020 roadmap, the primary technology thrusts remain semiconductors, components, sub-systems and life cycle. Wide bandgap semiconductors are now established across the automotive industry with Silicon Carbide MOSFETs being used extensively in higher voltage (500 V+) inverters and Gallium Nitride devices starting to be deployed within DC-DC converters and OBCs. Integration, both structural and functional, remains a key cost-down strategy; for example, by embedding power electronics into motors, axle systems and batteries, by combining multiple functions in one power electronics assembly or by combining components into compact sub-assemblies. Achieving sustainability in power electronics remains challenging with electronic assemblies proving difficult to recover and recycle. However, higher efficiency, reductions in material usage and improved durability can all help reduce life cycle impact while also contributing positively to reduced cost and the end-user experience.

Paul Jarvie
Business Development Manager, CSA Catapult
DER-IC Lead, South West & Wales

Power electronics play a key enabling role in the automotive sector, especially in the transition of the sector towards decarbonisation. Advances in areas such as wide bandgap semiconductors and advanced highly integrated packaging have allowed step-change in performance, especially at higher voltage levels. They are crucial components in battery electric vehicles, plug-in hybrids, and fuel cell electric vehicles. Up until quite recently they have played a somewhat quiet and hidden role within the automotive industry, also in the UK, renowned for innovative engineering in many fields including motorsport engineering. However, with the growing demand for electrification this is rapidly changing and extensive consultation with the industry for the Automotive Council's roadmap has teased out what enabling technology possibilities and opportunities to expect over the coming decade and beyond.

1.4 | Power Electronics – overview

Power electronics play a key role in the automotive transition to net zero. In the past few years it has become apparent that the technology developments of power electronics together with that of batteries will play a significant role in widening the availability across vehicle segments, as well as the affordability of electric vehicles, particularly battery electric vehicles (BEV).

Semiconductor materials

In an xEV power electronics are the enabling technology for conversion and control of electrical energy from batteries to traction, chargers to batteries, and within vehicles through DC-DC converters.

Semiconductors are at the heart of power electronics, over the past decade several new semiconductor materials have been introduced within the automotive sector, including Silicon Carbide (SiC), followed by Gallium Nitride (GaN).

Currently, SiC is taking centre stage but GaN is not far behind and other technological advancements in fusion technology are knocking on the door. Different semiconductor materials offer different performance benefits. The optimal choice will have to strike the right balance between power efficiency, material utilisation and cost. Currently, and over the next decade, the best usage of SiC and GaN overlap in ~20% of use-cases[1]. However, as technology develops, the overlap is likely to shrink, and specific and more affordable use-cases are likely to form, e.g. in the B- and C-segments.

Customisation and standardisation

Looking beyond semiconductors, one of the overarching themes within power electronics is customisation versus standardisation versus life cycle. This permeates everything, i.e. components and subsystems, packaging, design, and integration.

Ongoing research and development (R&D) within power electronics is enabling better packaging, thermal management, and increased efficiencies, but in many cases, they are still being customised for a particular original equipment manufacturer (OEM). Customised products are a necessity, partly because there are few standardised products. BEVs have not yet reached the mass-volume stage and penetrated the B- and C-segments. OEMs are therefore, to a large degree, competing in segments where customers want something special, requiring customised products, not end-product. At present, these partly or wholly customised solutions are generally not compatible with the longer perspective, i.e. life cycle perspective. Today's power electronics are difficult to reuse, disassemble and recycle. However, over the next decade certain levels of standardisation will take place which will widen the penetration of BEV models in the B-and C-segment.

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[1] https://www.edn.com/the-diverging-worlds-of-sic-and-gan-semiconductors/

This is a new section for the 2024 roadmaps and aims to provide a comprehensive context for issues and drivers that extend beyond vehicular systems and technologies.

Four overarching themes or micro-level drivers that influence all aspects of the technology roadmaps have been pinpointed. The drivers identified are multifaceted, ranging from global to local scales. Global drivers encompass changes and challenges that transcend national boundaries, often beyond the direct influence of UK suppliers. National drivers are those that are unique to the UK's socio-economic and regulatory environment, while local drivers affect specific regions or communities within the UK. The interplay between these cross-cutting themes and drivers impacts the evolution and development of forecasted technology solutions. These drivers interact with each other and with the technology roadmaps – expediting the advancement of certain technologies, while simultaneously necessitating change in others. In this section, we delve into four pivotal drivers that are reshaping the landscape of technology and innovation:

1. Policy and regulations: examining the influence of legislative frameworks on technological progress.
2. Energy and infrastructure: assessing the role of energy availability and infrastructural support in driving innovation.
3. Materials and manufacturing: understanding the impact of manufacturing capabilities and constraints on technology development.
4. Digitalisation: exploring the transformative power of digital technologies across the automotive sector.

2 | Cross-cutting themes

2.1 | Policy and regulations

PFAS

The regulation directly affecting power electronics is a proposed ban on the use of all per-and polyfluoroalkyl substances (PFAS), also known as fluorinated chemicals or 'forever chemicals', in the EU. The regulation proposal is currently under consultation (see Figure 2 on page 9). The proposal is pursuant to EU Regulation No 1907 / 2006 ('REACH') article 68.

PFAS are a large and diverse group of between 4,700 and 15,000 substances / synthetic chemicals (depending on how they are counted). PFAS are 'bad' because they do not degrade over time, with some forms of PFAS taking over 1,000 years to degrade. Instead, they seep out into the environment and are absorbed into water supplies, impacting wildlife and humans. Two of the most studied PFAS are already banned as they have been linked to at least six diseases and involuntary interference with the immune system, the hormonal system, and the reproductive system[2]. A further ~200 PFAS have been banned since February 2023.

A total ban would considerably affect the manufacturing process of semiconductors, as PFAS are an integral part of manufacturing, and also form part of the supply chain and manufacturing equipment. Different PFAS are used in separate phases of the manufacturing process, e.g. in photolithography, in the etching process, and in packaging. The usage is often very specific for the semiconductor sector and not currently easily exchanged for other chemicals[3].

The current suggestion includes a 13.5 year (18 months and 12 years) transition period specifically for the semiconductor sector. However, it is clear that the majority within industry participating in the consultation, believe this timeframe would be impossible to comply with. Semiconductor development cycles are often exceedingly long and complex, up to 25 years[3]. To incorporate new chemicals and materials would take approximately 15 years due to the qualification processes throughout the value chain.

The consultation period for the PFAS proposal ended in September 2023. At that time, the committee had received over 5,600 comments, many from semiconductor stakeholders. A decision is expected in 2025.

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[2] https://www.eea.europa.eu/publications/emerging-chemical-risks-in-europe
[3] https://www.eusemiconductors.eu/sites/default/files/20230713_ESIASummaryPaper-PFAS.pdf

CHIPs Act – US[4]

The US currently makes 12% of the world's semiconductors, a reduction from 37% in the 1990s. The recent semiconductor shortage is estimated to have had a negative impact on US economic growth by $1/4 trillion dollars in 2021. The US CHIPS and Science Act (September 2022) was introduced to aid investment in a national supply chain. The Act directs $280 billion over 10 years for scientific R&D and commercialisation. $52.7 billion is dedicated specifically for American semiconductor research, development, manufacturing, and workforce development with a further $24 billion worth of tax credits for chip production.

Chips Act – EU[5]

Approximately 8-10% of the world's semiconductors are being made in the EU, a drop from 30% in the 2000s. Similar to the US, the shortage of semiconductors during, and in the wake of, the COVID-19 pandemic alarmed the EU industry. The European Chips Act was proposed in February 2022 and published in September 2023 with the specific aim to get back to a level of 20% manufacturing world-share. It is defined by three pillars of action:

1. Establishment of the 'Chips for Europe Initiative', which will enable development and deployment of innovative next-generation semiconductors.
2. Support integrated production facilities and open EU foundries, packaging, test, and assembly.
3. Monitoring of the EU's semiconductor value chain to prevent and respond to semiconductor crises with ad-hoc emergency measures.

There is €43 billion of policy-driven investment available until 2030 via the European Chips Act.

Figure 2:
Planned dates for the PFAS restriction proposal[6]

	2023	2024	2025	2026 / 2027
EU[4]	March 22, 2023 – start of six-month consultation September 22, 2023 – end of six-month consultation, more than 5,600 comments were received	Opinion of Committees for Risk Assessment (RAC) and Social-economic Analysis (SEAC)	Commission decision and entry into force	Restriction becomes effective
UK	There is no equivalent ban proposal in the UK			
US	There are similar bans in around a dozen states in the USA, but there is no federal ban.			

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[4] https://www.mckinsey.com/industries/public-sector/our-insights/the-chips-and-science-act-heres-whats-in-it
[5] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en
[6] https://echa.europa.eu/documents/10162/2082415/2023-02-07_pfas+media+briefing_en.pdf/1661579d-353a-2fb0-1062-38fc3eb4bd78?t=1675849038730

There are many environmental initiatives (not legally binding) influencing the industry indirectly from material choice, design, manufacturing, and packaging. These initiatives are often aimed at using sustainable energy, recycling and reusing. For example, looking ahead, it is likely some power electronics will have a type of passport or similar in line with xEV batteries.

Global targets for vehicle sales

Worldwide, many regions are introducing legislation for zero-emission vehicles (see Figure 3 below). The definition varies from region to region with some designating zero emissions of any tailpipe emissions while others specify CO_2 only. In China, new energy vehicles (NEVs) include plug-in hybrid electric vehicles (PHEVs), BEVs and fuel cell electric vehicles (FCEVs).

Power electronics technology will continue to play a role in the transition to zero-emission vehicles and are crucial components in all NEVs. They all have inverters, DC-DC converters and onboard chargers (OBCs). FCEVs do not have an onboard charger with the battery instead charged via the fuel cell which uses hydrogen as its energy source. However, the inverters and converters work on the same principle for hydrogen as for electric vehicles.

As such, this global drive towards zero-emission vehicles creates a clear trajectory of growth for power electronics demand in the coming years. This substantial increase will require supply chains, worldwide, to scale-up at pace and, for materials, there will be increased pressure, specifically for SiC.

Figure 3:
Zero-emission vehicle sales commitments

	2025	2030	2035	2040
EU	• 15% CO_2 reduction across car fleet • 15% CO_2 reduction across HDV fleet	• 55% CO_2 reduction across car fleet (50% for LCV) • 45% CO_2 reduction across HDV fleet	• All new cars zero CO_2 emissions • HDV 65% fleet CO_2 reduction	• HDV 90% fleet CO_2 reduction
UK	• ZEV sales targets 22% cars and 10% vans	• ZEV sales targets 80% cars and 70% vans	• All sales ZEV for cars and vans • All HDV <26 tonnes ZEV	• All HDV ZEV
Rest of the world	• **Canada** 20% ZEV for light and heavy-duty sales (2026)	• **USA** 50% of vehicle sales to be electric • **China** NEV 60% of sales • **Japan** 20% BEV and PHEV passenger car sales • **India** 30% car sales ZEV, 70% commercial vehicles ad 80% two / three-wheelers • **Australia** 30% LDV sales to be ZEV	• **Canada** 100% ZEV for light- and heavy-duty sales • **Japan** 100% EV passenger car sales • **Australia** 100% LDV sales to be ZEV	• **China** 100% NEV for light- and heavy-duty sales

2.2 | Energy and infrastructure

This section focusses on the amount of energy used in the manufacturing process as well as the infrastructure of the electricity grid, which plays a huge part in the technology development of xEV and power electronics.

Energy

The heat resistance of SiC is one of the properties that make it particularly suitable for power electronics. The fundamental processes to make SiC powder and grow SiC ingots use a significant amount of energy. The Acheson and Physical Vapour Transport processes require furnace temperatures of up to 2,500ºC (compared to 1,200ºC for GaN) for several days[7]. The energy consumption exceeds 100,000 kWh per run and emits significant quantities of CO_2 in the process (in addition to the CO_2 emitted in relation to the energy consumption).

While there are alternative processes, these are still the main methods applied. The processes are difficult to change, although research does exist, demonstrating more energy-efficient processes which turn Si and SiC waste products into high-purity SiC. However, it does not solve the problem per se, leaving the industry with the option to use renewable energy as the most effective way of reducing its carbon footprint.

The demand for more green energy is likely to prompt more localisation of plants and, with manufacturing becoming more digitalised aided by machine learning (ML) and artificial intelligence (AI), the concept of self-sufficient production plants with their own microgrids is a distinct possibility.

Infrastructure

As the number of BEVs grows, there will be more focus on the (electricity) grid. There is a fear of balancing challenges due to the lack of standardisation, with vehicle-to-home (V2H) and vehicle-to-grid (V2G) becoming more common. The need for specific electricity grid codes to ensure the power electronics can stay safely connected to the grid, even when there is unbalance, is growing. There is work underway within the EU by ACER (European Union Agency for the Cooperation of Energy Regulators) to '…improve the Network Code on Requirements for Grid Connection of Generators and the Network Code on Demand Connection'[8]. Submission to the European Commission was made in December 2023.

The creation of microgrids, which can provide resilience, is already happening, reducing the risk of blackouts and other potential disruptions due to overload. Microgrids are small-scale power systems that can work independently from the main grid as they are connected with local battery storage, as well as wind and solar energy sources.

This new level of technologies and adoption of local renewable generation systems also creates opportunities for commercial plants to have their own microgrids.

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[7] https://www.britannica.com/science/silicon-carbide
[8] https://www.acer.europa.eu/document/acer-policy-paper-revision-network-code-requirements-grid-connection-generators-and-network-code-demand-connection

2.3 | Materials and manufacturing

This section focuses on semiconductors and their supply chain. It assesses the impact and exposure global events have had, exposing vulnerabilities and pressures as the industry looks to become less risk-averse and transition to net zero[9].

One of the biggest concerns regarding semiconductors is the (material) supply chain. Over the last five years, several 'unexpected factors' such as COVID-19 and geopolitical events have shaken up supply chains as well as exposed vulnerabilities and weaknesses, not only in individual companies supply chains, but in the wider value chain. This is because the semiconductor manufacturing process is intricate, comprising of several complex stages which all require a high level of expertise. This expertise demands a level of specialisation from the supply of raw materials, design, manufacture, assembly, and testing. It is important to note that this involves a large number of global companies and countries.

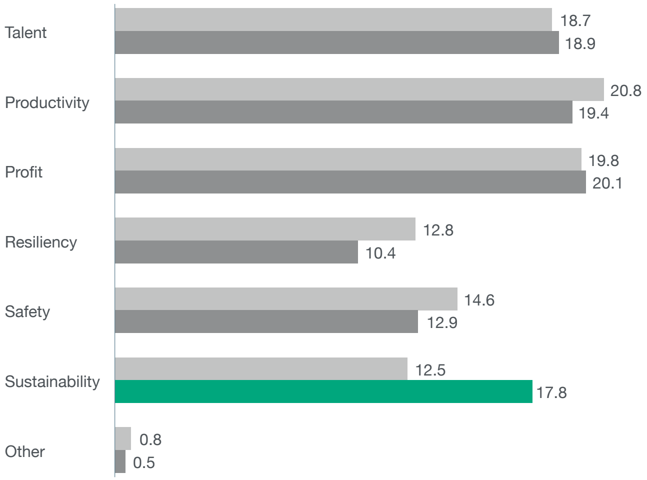
There is always some normal cyclic shortage and over-supply within the semiconductor industry, but the past few years has exposed how fragile the power electronics semiconductor supply chain is. The weaknesses are not just limited to raw materials, but apply to equipment such as tooling, technology knowledge, manufacturing, and talent. Additionally, there is the issue of energy supply, e.g. gas. Some countries have found a lack of control and access to several stages of the manufacturing processes more acutely challenging in recent years.

OEMs and Tier 1 suppliers are seeking to develop more vertical supply chains and partnerships with key technology suppliers. Additionally, in the wake of the semiconductor shortage, several countries and regions have set aside significant funds to strengthen and / or protect their own semiconductor industry (see 2.1 Policy and regulations).

Requirements to reach net-zero production and demonstrate sustainability across all areas is expected to put pressure on the entire supply chain, effectively forcing change further down the supply chain. In fact, a recent study by Bain and Co[10], states that 'sustainability is expected to climb as priority for (worldwide) manufacturers in the next two years' (see Figure 4).

It is likely that sustainability concerns will drive alternative material choices to enable on- or near-shoring, reduce energy consumption and reduce supply chain risk.

Figure 4: Share of manufacturing executives who identify these factors as their number one priority[10]



Note: Percentages are rounded
Source: Bain Factory of the Future Survey, December 2022

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[9] The future of semiconductor procurement – The changing semiconductor supply chain EY. https://www.ey.com/en_jp/supply-chain/the-future-of-semiconductor-procurement-in-response-of-changing-semiconductor-supply-chain
Chipping in to boost production: US and Europe move toward greater self-sufficiency and resilient supply chains https://www2.deloitte.com/xe/en/insights/industry/technology/semiconductor-manufacturing.html

[10] Factory of the Future: How Industry 4.0 and AI Can Transform Manufacturing https://www.bain.com/insights/factory-of-the-future-how-industry-4-0-and-ai-can-transform-manufacturing/

2.4 Digitalisation

This section focuses on digitalisation trends applicable to power electronics. Software-defined power electronics are focussed on algorithm-supported advanced control techniques, which optimise the [energy] conversion performance. Additionally, they monitor and predict the state-of-health of power electronic components and systems.

A software-defined vehicle is a key trend in digitalisation and this is being amplified by the emergence of dedicated BEV platforms designed from the ground up, supported by 'software-ready' architecture, e.g. a zonal electronic / electrical (E / E) architecture.

Predictive control[11]

Predictive control, particularly model predictive control (MPC), is an advanced control strategy widely used in power electronics. MPC uses a mathematical model of the system to predict future behaviour over a specified prediction horizon, which is the length of time for which system output is computed. This prediction is based on the current state and possible future control actions.

- DC-DC converters: MPC is used to optimise the performance of converters by minimising switching losses and improving efficiency.
- AC-DC rectifiers and inverters: integrated-MPCs helps achieve better power quality and dynamic response.

Enhanced sensor-less control

Advances in sensor-less control techniques, which estimate system states without direct measurement, are improving the performance and reliability of adaptive control algorithms. These methods are particularly useful in applications where installing sensors is impractical or costly.

Fault-tolerant control

Algorithms are being developed to ensure system reliability even in the presence of faults. These methods can detect and isolate faults ensuring that issues are addressed promptly and accurately, reconfigure control strategies and maintain system performance.

Real-time monitoring

Software enables real-time continuous monitoring of a vehicle's components through sensors and diagnostic tools. Continuous monitoring of the vehicle's operational health makes it possible to recommend maintenance actions based on the actual condition of components rather than on a fixed schedule.

Predictive maintenance

Advanced algorithms can predict the remaining useful life of components, allowing for pro-active maintenance. This minimises unforeseen breakdowns and prolongs the durability of vehicle components.

ML and AI

The development of all these is increasing at pace and enhanced by ML and AI, which are progressively being integrated into techniques and methods within the vehicle control and across the entire vehicle, with a projection of 90% of vehicles applying ML features by 2025[12].

Beyond ML and AI, the usage of digital twin technology is also growing. The concept of digital twin is well established throughout the automotive industry from design, manufacturing, operation, supply chain and assets. A digital twin creates a virtual model of any system which then runs in parallel with the physical system. It can simulate different operating conditions and predict system responses.

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[11] Advanced Control Techniques for Power Electronic Converter https://www.monolithicpower.com/en/learning/mpscholar/power-electronics/special-topics/advanced-control-techniques-for-power-electronic-converter

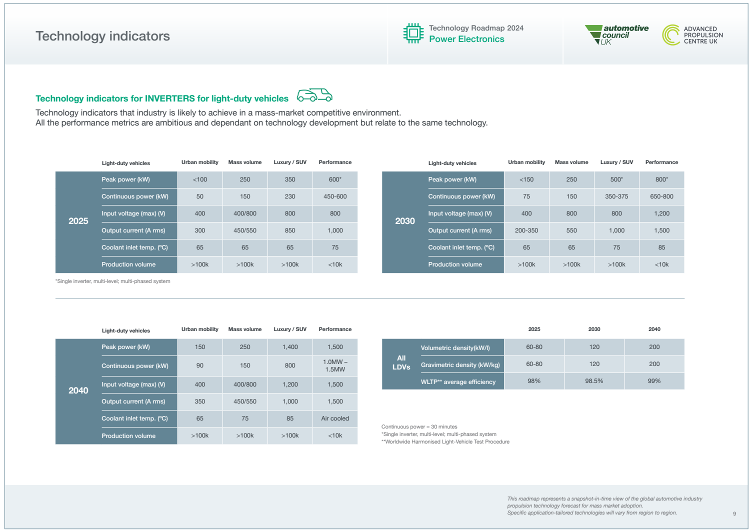
[12] 'Powertrain Software Study 2024' AESIN / APC analysis

3 | Narrative to roadmap

3.1 | Power Electronics – technology indicators

Propulsion systems are tailored to specific power and energy demands based on their use-cases and duty cycle, hence the technology indicators vary depending on vehicle category. The 2024 roadmap provides technology indicators that industry is likely to achieve in a mass-market, competitive environment.

Note: There are some differences between light-duty vehicles (LDV), heavy-duty vehicles (HDV) and non-road mobile machinery (NRMM) vehicles including off-highway vehicles.



Technology indicators

Technology Roadmap 2024
Power Electronics

automotive council UK
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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.*

9

Light-duty vehicle

In this roadmap the technology indicators are defined by the type of vehicle, for example:

- Urban mobility: Toyota C+Pod, Microlino Urban, Citroen Ami
- Mass-volume (brand): Toyota, Ford
- SUV / luxury (brand): JLR
- Performance cars (brand): McLaren, Aston Martin.

This is because the difference in the indicator measurement goals varies depending on the vehicle type.

Power

Continuous power is arguably the most important measurement, although peak power is more often cited. Continuous power is the power required for a vehicle to stably maintain over a period of time, usually measured for about 30 minutes, whereas peak power is measured for about 20 milliseconds.

The maximum voltage is the system input voltage and, in the case of a BEV, is the battery voltage. This is important as it dictates voltage requirements.

Density

In power density it is important to minimise mass / weight and free-up packaging space. Power density improvement is more limited in DC-DC converters and OBCs. This is because the converters are more complex, involving additional magnetic components and multiple conversion stages to realise galvanic isolation.

Efficiency

Inverters are typically being integrated with electric motors and transmissions. Efficiency targets are therefore represented as a worldwide harmonised light vehicle test procedure (WLTP) , the average efficiency number to reflect that the inverter must work efficiently as part of the vehicle powertrain. Given the more limited operating points, peak efficiencies are suitable for DC-DC converters and OBCs.

Inverter

For performance cars you would see at least 20% higher peak performance than the nearest other segment. However, in 2025 and 2030, the gap will still be much greater, and looking ahead to 2040 it is anticipated it will be close to a 20% difference. For performance cars, the aim is to match the continuous power as close as possible with the peak power.

DC-DC converter

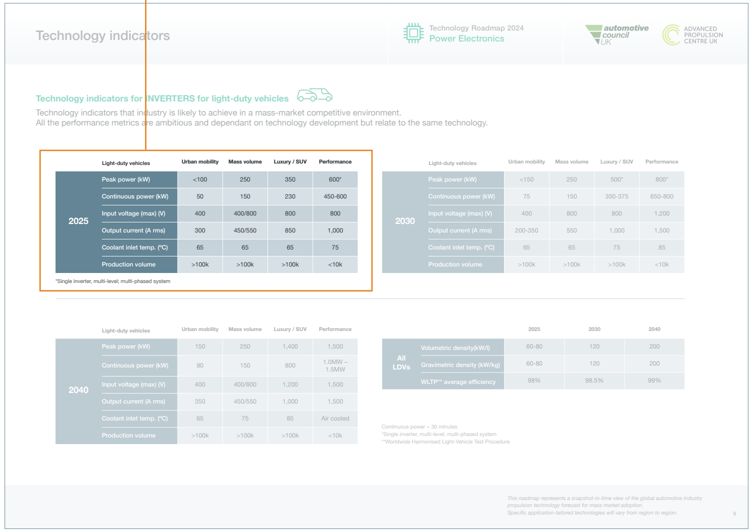
In all segments there are limited technology changes expected.

On-board charger

For OBCs, the direction is straight forward and equal across segments, not counting urban mobility: 2025 (7 kW/11 kW), 2030 (11 kW/22 kW), and 2040 (22 kW). Volumetric is a particularly important measure / metric for mass-volume cars because of packaging and how much space can be made available.

	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



Technology indicators

Technology Roadmap 2024
Power Electronics

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.

9

Heavy-duty vehicle

Note: the tech indicator measurements are different for HDV than for LDV.

The common weight classification, i.e. gross vehicle weight (GVW), for HDVs are 7.5 t - 26 t and 26 t - 44 t in the UK and EU respectively. However, because the electrification increases the unladen weight and removes some of the valuable payload, zero-emission HDVs are allowed 2t on top of the regulated GVW (since 2019). This is thought to be an insufficient compensation and a new EU rule is proposing an additional 2t, which is currently going through the revision and ratification process (currently there is no corresponding proposal in the UK). Early indicators point to approval by all member countries. Therefore, by 2030 the weight classification should be increased.

Inverter

For HDVs, the focus is more on peak torque than peak performance. The latter is only used for starting-off, as a HDV spends most of its time at full load, i.e. if laden at the traffic lights, the HDV will push peak performance when taking-off.

Today, a large (26 t - 44 t) HDV vehicle typically uses more than one motor, hence the requirement for multiple inverters. After 2035, some HDVs are likely to use two different motors; one for the motorway for 'operational running' and one for up-hill driving or taking-off from stand-still. The aim of this 'two-system' approach is to negate the need for costly 1,200 V devices across the entire vehicle.

DC-DC converter

The attributes do not change much depending on the type of HDV. What does change is the number and type of systems and how many powerlines the converter supports.

The nominal input voltage will therefore be varied between 28 V, 48 V and, in some cases, 750 V. However, the overall goalposts for converters are not looking to change much over the timeframe.

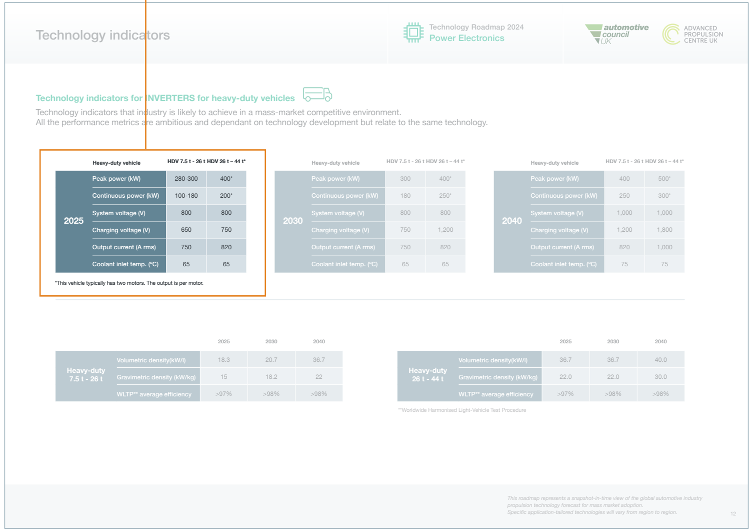
The industry will settle on an input voltage and the infrastructure that links into it, so it will not change much after that. The exact voltage the industry will settle on will depend on a number of factors that feed in to this and will need to be suitable for passenger cars, the charging infrastructure, the electric grid network, homes, policy and regulations, etc.

Onboard charger

HDVs between 7.5 t and 26 t have 22 kW onboard chargers and this is not likely to change within the period set out in the roadmap. For HDVs 26 t - 44 t, there is no technology indicator as they will not have an OBC, they will only DC-charge.

	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. (ºC)	65	65

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



Technology indicators

Technology Roadmap 2024
Power Electronics

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. (ºC)	65	65

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

	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. (ºC)	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. (ºC)	75	75

		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

*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.*

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NRMMs

NRMMs are used very differently. The largest variables beside size and power, are the type of site they are operating on, how often they change sites and how intensively they are being used. These variables typically drive the choice of powertrain. Examples of NRMMs are forklifts, excavators, telehandlers, dumpers, bulldozers, sweepers, port tractors and cranes.

There is no weight or established classification for NRMMs, but they are generally grouped according to mobility / use-case, utilisation levels or power rating. To simplify, mobile NRMMs with a power rating between 37 kW and 560 kW are being developed. For clarity, this does not include hand-held / hand-moved machines, such as, lawnmowers, chainsaws or cement mixers. They could be used <50% or >50% (relative to an eight hour day, 365 days a year). The NRMMs covered here already need to meet emission standards set by regulatory authorities in the EU, USA and Japan (not yet fully harmonised).

Small NRMMs, those under 5 t, are fully electric, while the larger ones 8 t - 14 t and 15 t - 44 t are hybrids. NRMMs using alternative fuels or hydrogen fuel cells are not included in this roadmap (see Internal Combustion Engines Roadmap and Hydrogen Fuel Cell System and Hydrogen Storage Roadmap respectively).

Currently, the fully electric machinery connects and charges directly from the mains. Hybrid NRMMs are not plug-in hybrids but mild or full hybrids, i.e. they do not need to be charged and they do not generally solely use the electric motor, it is used to boost the machinery:

- hybrid NRMMs are currently commercially available for the majority of power ratings and utilisation cases
- fully electric NRMMs (those under 5 t) with <50% utilisation are expected to become widely available by 2025-2030
- medium-sized NRMMs (8 t - 14 t) are unlikely to be fully electric before 2035
- larger NRMMs, both in size and power rating, will have limited commercial availability as electric after 2030.

Note: the technology indicator measurements are different for NRMMs than for HDVs and LDVs.

In order for heavier >8 t NRMMs to transition to BEV, PHEV and HEV, the converters ideally need to be more powerful than what the roadmap indicates in 2040 (4-5 kW). The reason is twofold: the burdensome need for cooling; and the lack of standardisation of operation voltage increase the need for a more powerful converter.

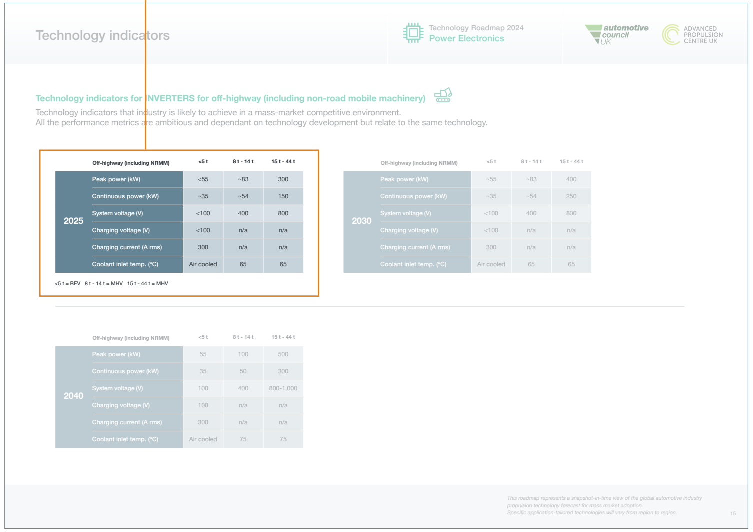
Figure 5: Powertrain availability matrix by machinery type

Machinery category	Power rating (max)	Utilisation level	Hybrid	BEV
< 5 t	< 37 kW	Low (<50%)	Currently	2025- 2030 (TRL 6-7)
8 t 14 t	37-129 kW	Low (<50%)	After 2030 (TRL 6-7)	2035-2040 (TRL1-3)
15 t 44 t	130-560 kW	Low (<50%)	Currently	After 2030 (TRL 4-5)
8 t 14 t	37-129 kW	High (>50%)	After 2030 (TRL 6-7)	2035-2040 (TRL1-3)
15 t 44 t	130-560 kW	High (>50%)	Currently	After 2030 (TRL 4-5)
15 t 44 t	> 560 kW	High (>50%)	Currently	After 2030 (TRL 4-5)

Table source: ERM, Industrial Non-Road Mobile Machinery Decarbonisation Options: Techno-Economic Feasibility Study

	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. (°C)	Air cooled	65	65

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



Technology indicators

Technology Roadmap 2024
Power Electronics

automotive council UK
ADVANCED PROPULSION CENTRE UK

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. (°C)	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
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. (°C)	Air cooled	65	65

	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. (°C)	Air cooled	75	75

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.

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3.2 | Power Electronics – technology themes

Roadmap technology themes

The next few pages of this report will look in-depth at each section of the Power Electronics Executive Roadmap document so it is recommended you have the document to hand. However, for ease of reference, the relevant page of the roadmap is pictured

- Semiconductors
  - Materials
  - Wafer size
  - High power / Low power
  - Device innovation
- Components
  - Packaging
  - Actives, passives and PCBs
  - Electro-mechanical
- Subsystems
  - Design
  - Control
  - Integration
- Life cycle
  - Life cycle impact
  - Material recovery

Semiconductors

Materials: Electrical properties of a semiconductor can vary depending on the selected materials. Ideally, the chosen material should be an excellent conductor as well as being an insulator. Silicon (Si) is the most used material for semiconductors. However, compound materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) have emerged as more promising materials for some applications as they can withstand much higher heat then Si. Additionally, several variations of engineered substrates, for instance aluminium with diamond and sapphire, are emerging and providing future options.

Wafer size: Wafer size is a key parameter in the semiconductor manufacturing, not least from a cost perspective, as larger sizes mean more dies and less edge waste. Due to the properties of the different wafer materials such as hardness, wafer sizes will have different time trajectory depending on material type. The roadmap does not show what size will dominate but what technologies based on different materials will co-exist.

High power / Low power: The emergence of new materials has pushed on the overall shift by OEMs towards 800 V batteries. Devices specifically designed for low and high power respectively will facilitate a more targeted match / usage of devices and power electronics.

Device innovation: The choice of material allows for the opportunity to use devices more suited for the purpose and operating voltage, making power electronics more cost-effective.

Components

Packaging: Semiconductor packaging is paramount because it protects the semiconductor die from physical damage, contamination, light and moisture. Advanced semiconductor packaging focuses on combining multiple semiconductor chips into one single package, creating a single device with superior performance, better power efficiency and compact designs.

Active, passive and printed circuit boards (PCBs):
Active components transform and inject power into a circuit while passive components utilise power or energy in a circuit. The drive to miniaturise, improve efficiency, and increase functionality is constant, specifically moving towards advanced modelling and design of magnetic components (inductors, transformers, chokes).

Electro-mechanical: This section refers to the mechanical and electrical interfaces with other systems, especially solutions which increase switching frequencies.

Subsystems

Design: Emphasis is on advanced / alternative converter architectures (device-topology combinations), e.g. multi-level topologies and hybrid use of power devices, as cost-effective and high-performance options.

Control: Control and monitoring are driven by digitalisation. Software-defined control architectures and systems are becoming commonplace.

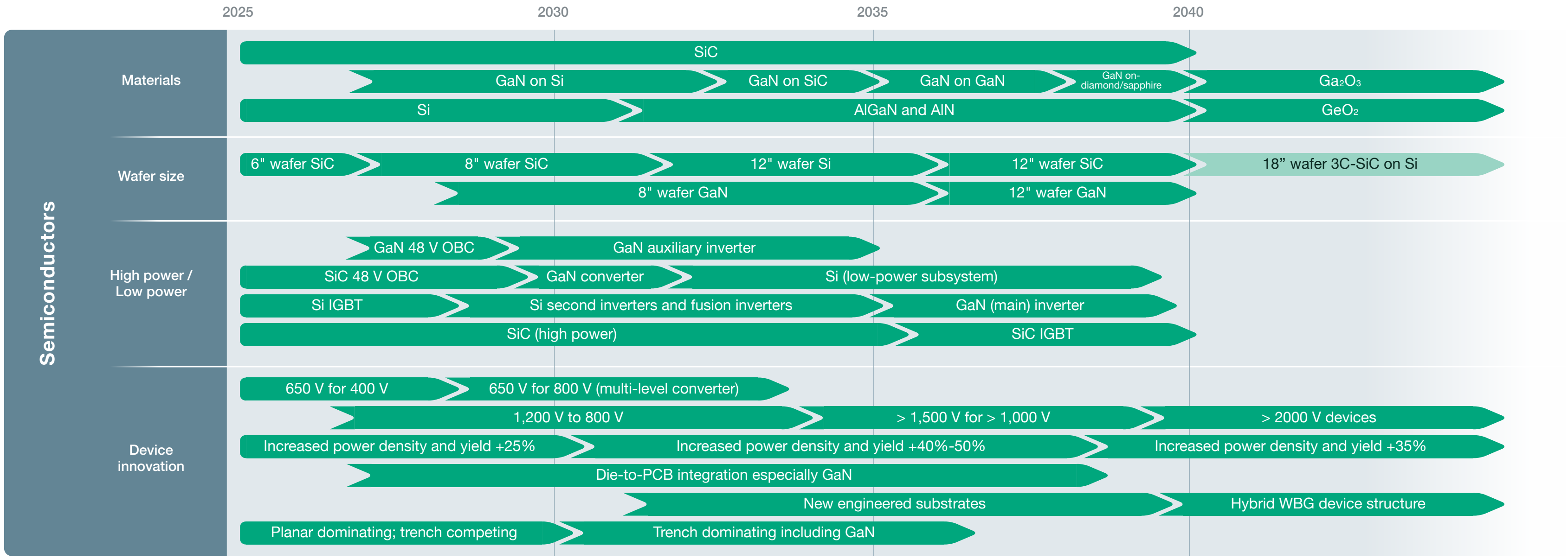
Integration: Integration refers to both physical integration of two or more components but also computing integration. There is a lot of development, although cost is not decreasing significantly yet at a component level. System-level costs are reducing, which is mainly caused by the reduction in copper use and ease of assembly at vehicle level enabled by higher efficiencies.

Life cycle

Life cycle impact (LCI): This looks at changes in technology and manufacturing methods driven by reducing the impact over the product lifetime. This includes the effect on the environment, ecosystem, and human health.

There are still many improvements, especially regarding energy consumption, which can be made in the manufacturing stages of semiconductors.

Material recovery: This topic covers recovery, recycling and reuse of materials. Currently, high-value materials are mainly recycled and reused. However, the large trends within power electronics, customisation and integration are rendering material recycling and reuse difficult to implement.



Semiconductors – Materials

Silicon (Si)

Si is the staple material in all semiconductors. The emergence of SiC and wide bandgap semiconductors in the late 2010s is beginning to change this. However, it will not become obsolete in the automotive sector. It is established and highly reliable and is widely thought to have several use-cases post-2035, although this could change if the price of SiC becomes comparable.

Use-cases include:

1. For high-volume passenger vehicles, Si will still be used in low-power subsystems
2. Budget to mid-end vehicles / urban utility cars will use Si inverters
3. Heavy-goods vehicles (HGVs) and commercial vehicles will continue to use Si until volumes have reached critical mass, i.e. SiC is affordable.

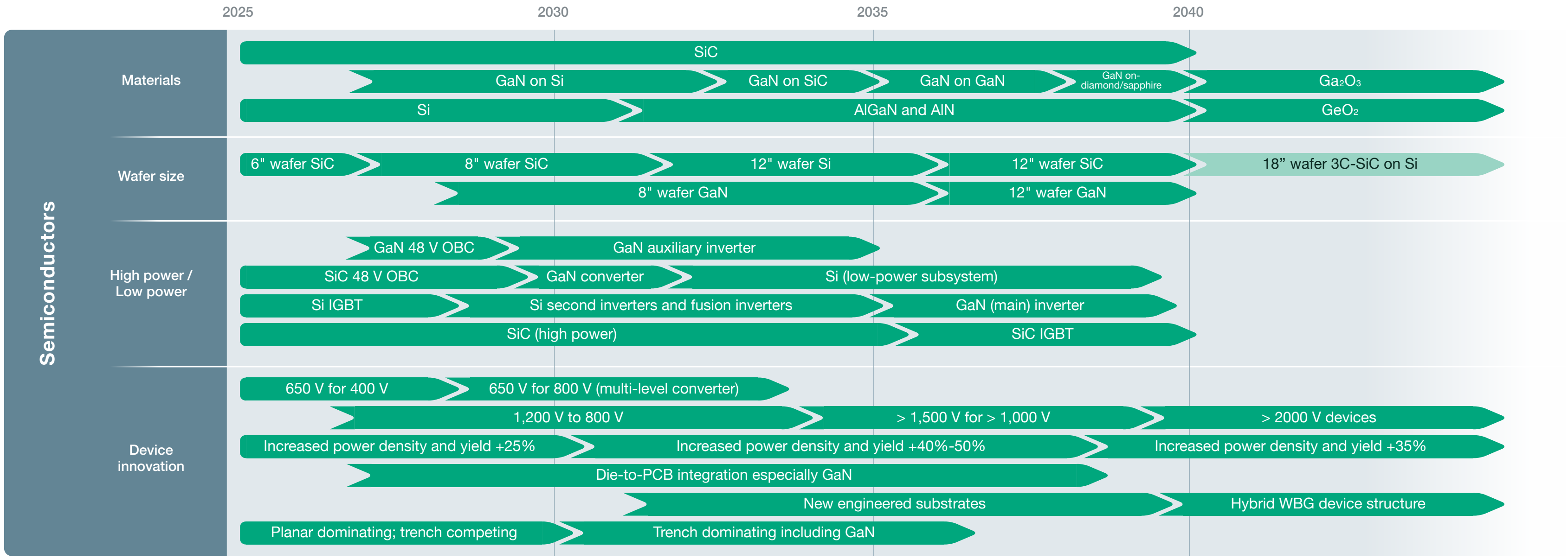
Silicon Carbide (SiC)

The are three main characteristics that makes SiC so desirable (compared to Si):

1. High thermal conductivity
2. High switching frequency (wide bandgap)
3. High breakdown voltage

SiC was first used in OBCs in the early 2010s and today a large majority of premium BEVs are, or will be, using SiC-based power electronics.

With the steady trend of 800 V batteries on the horizon for the majority of OEMs before 2030, SiC is becoming the preferred material within power electronics. Despite the significant decrease in its price, SiC costs have not decreased at the pace hoped for.



Semiconductors – Materials (continued)

Gallium Nitride (GaN)

GaN is a compound material with similar attributes to SiC:

1. High thermal conductivity
2. High switching frequency (more so than SiC)
3. High breakdown voltage

However, GaN cannot withstand the high temperature that SiC can and has a lower breakdown voltage.

GaN is already widely used within the consumer electronics industry, in optoelectronics, such as LEDs in mobile phones, TVs, and computer screens. GaN is also used within the automotive industry in lighting, connectivity, ADAS and infotainment, but not yet (in production) in power electronics.

GaN is on the horizon to enter the automotive market (for power electronics). Because of the perceived cost-savings, development is being pushed quite aggressively and GaN will emerge quickly. GaN is seen as a frontier technology within power electronics.

It is worth noting that there is division between those who ‘believe’ in GaN and those who will ‘stick’ with SiC. SiC and GaN are often pitted against each other, but that picture is beginning to change. Where the two technologies overlap in (application) suitability, the industry now seems to accept the overlap. See Figure 6 for a comparison of the physical attributes of Si, SiC and GaN.

Figure 6: Comparison of physical attributes for Si, SiC and Gan

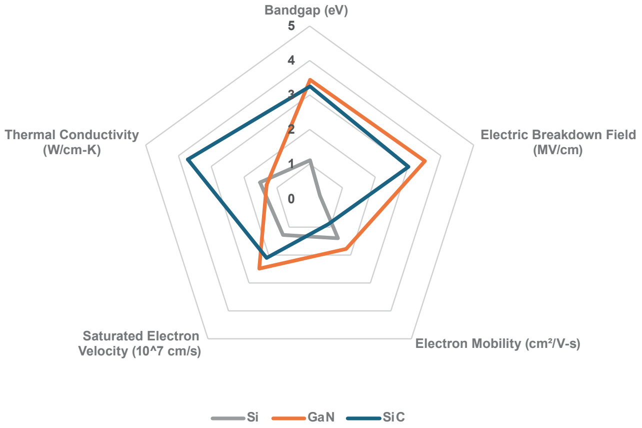
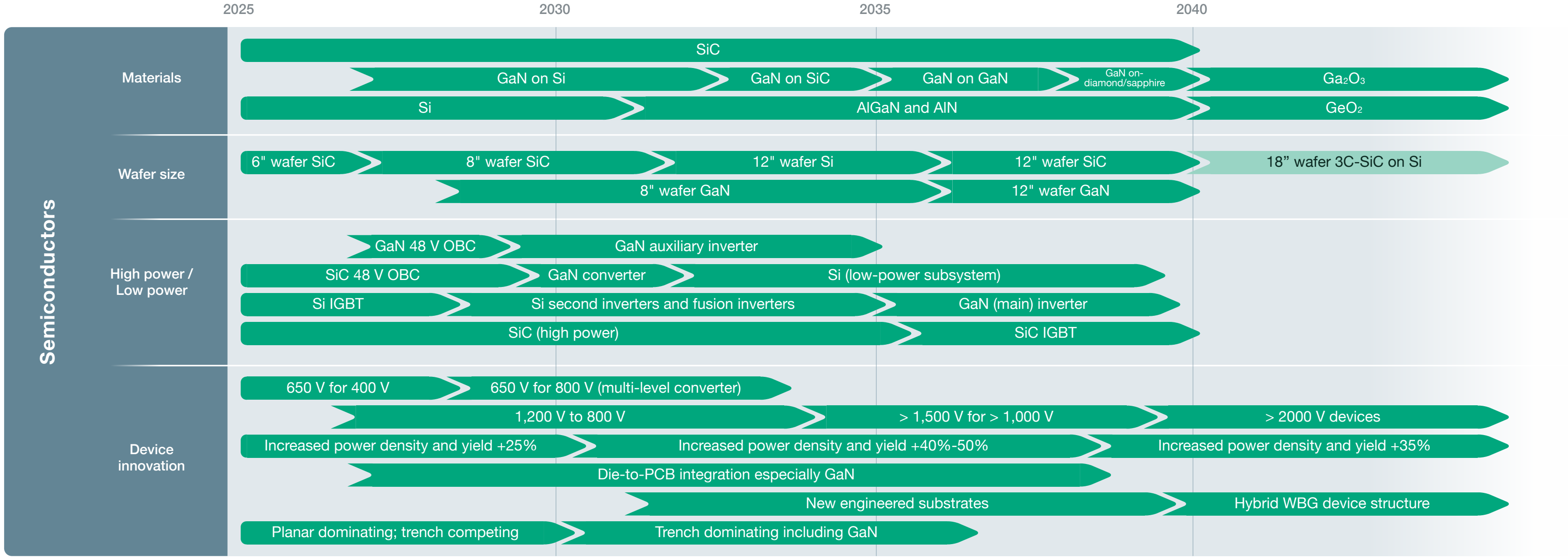


Diagram source: APC adaptation of ‘Understand practical GaN and SiC differences for EV onboard chargers’ – Avnet and ‘WBG Devices, Circuits and Applications’ – E. Shelton, P. Palmer, A. Mantooth, B. Zahnstecher, G. Haynes



Semiconductors – Materials (continued)

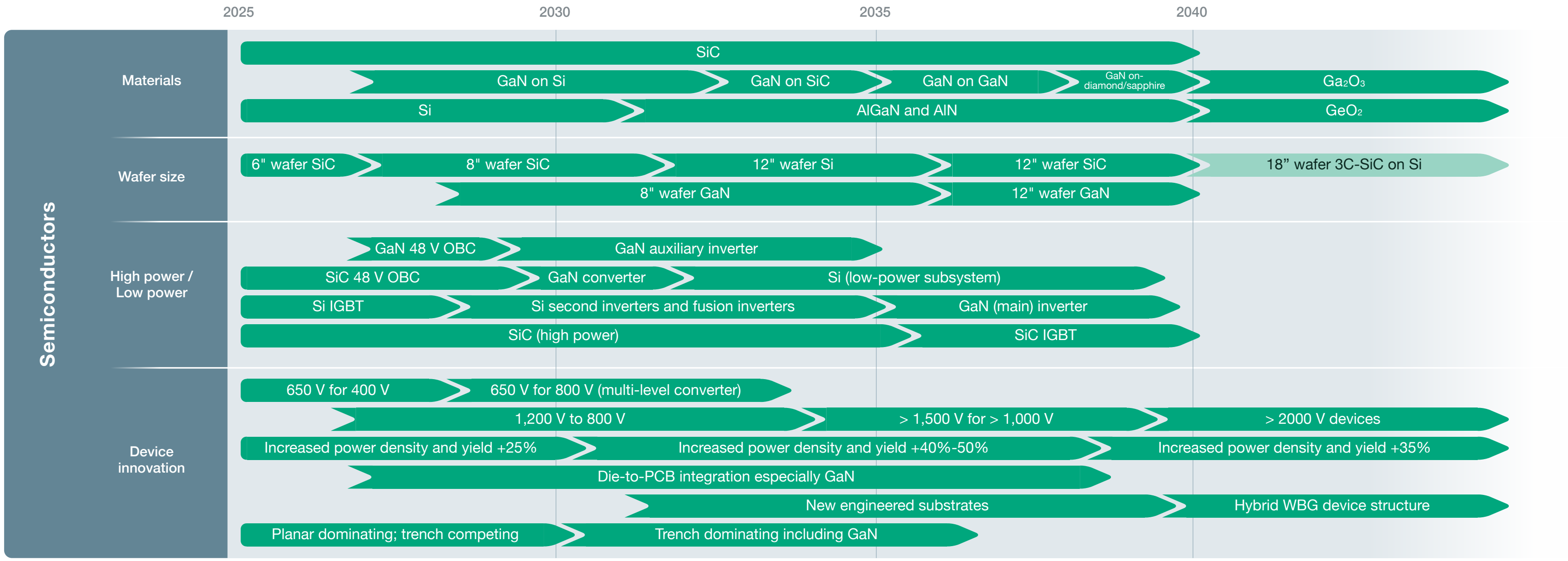
Engineered substrates

The continuous development efforts of GaN includes several different engineered substrates, where the main object is to boost the low thermal conductivity of GaN (low in comparison to SiC) and increase the operating voltage.

Currently, GaN is grown on Si which means it inherits the limitation of Si. The ultimate goal will be GaN as there will be no cause for mismatch between the epitaxial growth and the substrate. This is introduced on the roadmap just before 2035.

Aluminium nitride (AlN) and aluminium gallium nitride (AlGaN) are other materials which have performance advantages but not necessarily cost benefits on their side. First adopters would be those with specific performance requirements. The same applies for materials such as gallium oxide (Ga_2O_3) and germanium oxide (GeO_2).

There are other variants being worked on; GaN-on-diamond, GaN-on-sapphire, and GaN-on-Qromis. All three have shown encouraging results, but are unlikely to emerge before 2035.

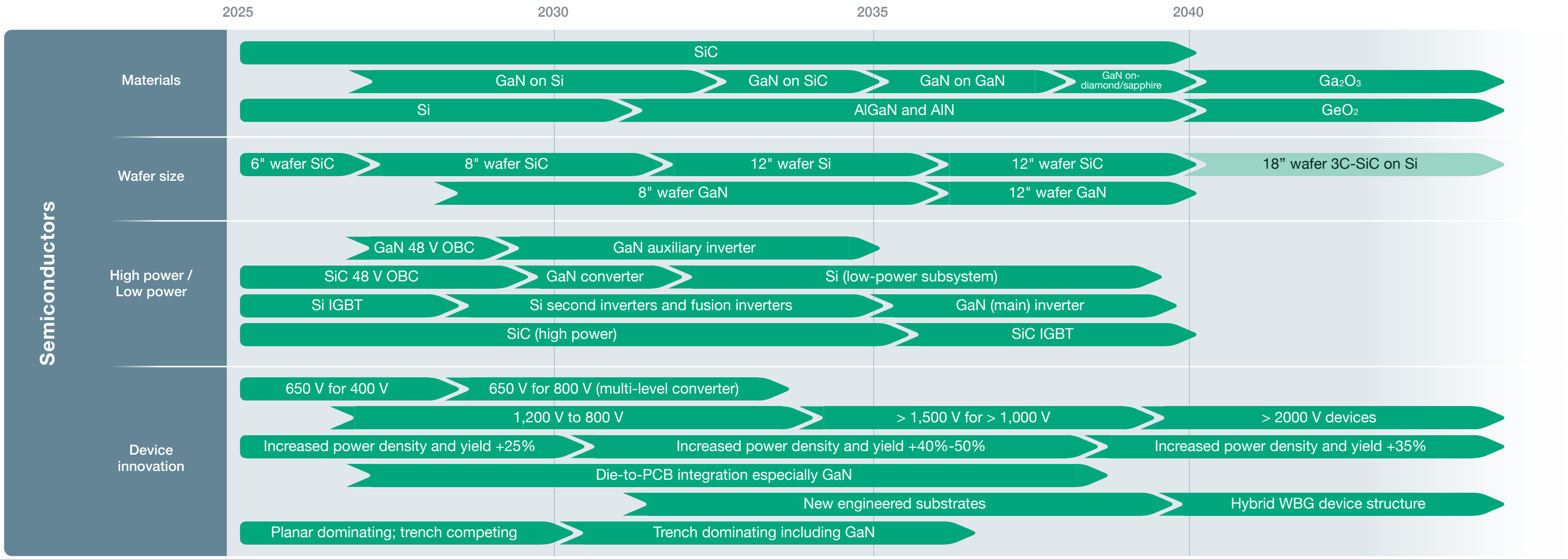


Semiconductors – Wafer size

There is ongoing development of larger wafers due to the cost savings this would deliver, but the transition from 6” to 8” for SiC has been slower than anticipated. The required thinness is difficult to achieve and there have been various problems with splitting wafers, warp, high defect rates and shape difficulties. However, the big foundries and vertical integrators are only approximately one to two years away from commercialising 8” SiC wafers.

It is anticipated that 8" GaN will emerge just before 8" SiC. A 12" option is currently deemed to only work for Si and GaN. It is fragile to shape and, although likely to emerge, this is unlikely to happen before 2030. There is not enough market drive for 15" options, but 18" options are possible on 3C-SiC on Si or GaN on Si if these become mature enough.

All SiC fabrication lines will not have < 90 nm (or even < 240 nm) node fabrication needed for integrated circuits (IC). Power devices currently only require 1 µm feature sizes and these will need different fabs as well as potentially different supply chain investments.



Semiconductors – High power / Low power

A different usage for Si, SiC and GaN is likely to be observed. There is a sweetspot for each material in terms of power and voltage (for voltage, see section 3.2.4): Si up to 20 kW, SiC from ~100 kW up to 300 kW and GaN between 20 kW up to 100 kW. There is a span where SiC and GaN are overlapping and the material choice could be determined by factors including budget and need. Regardless, Si will continue to be used.

Low power

Si will not disappear. In the long-run, it is likely to be used for specific use-cases such as for low-power subsystems, and in low- to mid-voltage inverters for budget electric vehicles (EVs).

GaN will initially be used in OBCs, expected to emerge before 2030.

SiC is also expected to be used in OBCs, even though there is no immediate need.

GaN will also be used for auxiliary inverters as well as for DC-DC converters.

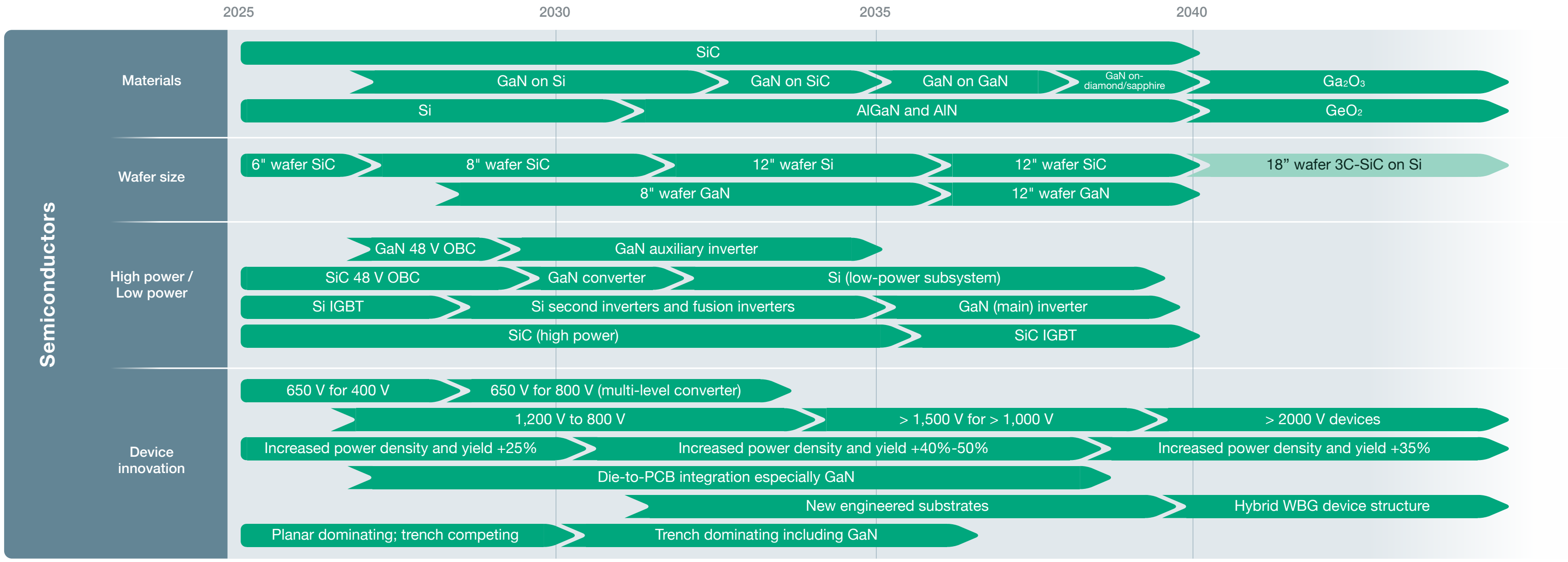
High power

Si will not disappear from high-power applications overnight. The use of Si insulated-gate bipolar transistors (IGBTs) will occur for the foreseeable future. It will remain the first choice for entry level BEVs. Si IGBT will also be seen in second inverters (dual eAxle) and in fusion inverters, which will be seen more and more moving towards 2030.

SiC will continue to dominate for high-voltage applications. The majority of inverters of new BEVs being launched will feature SiC up until 2030-2035. However, depending on how SiC cost and demand develops, SiC power electronics might be limited to only high-end and performance vehicles with increased high-power demands and needs.

Currently, GaN is not used for all high-voltage electronics but limited to medium- to high-voltage applications.

There is some scepticism regarding if and how prominently GaN will be used for inverters. It is unlikely to happen in any volume until after 2035.



Semiconductors – Device innovation

Operating voltage

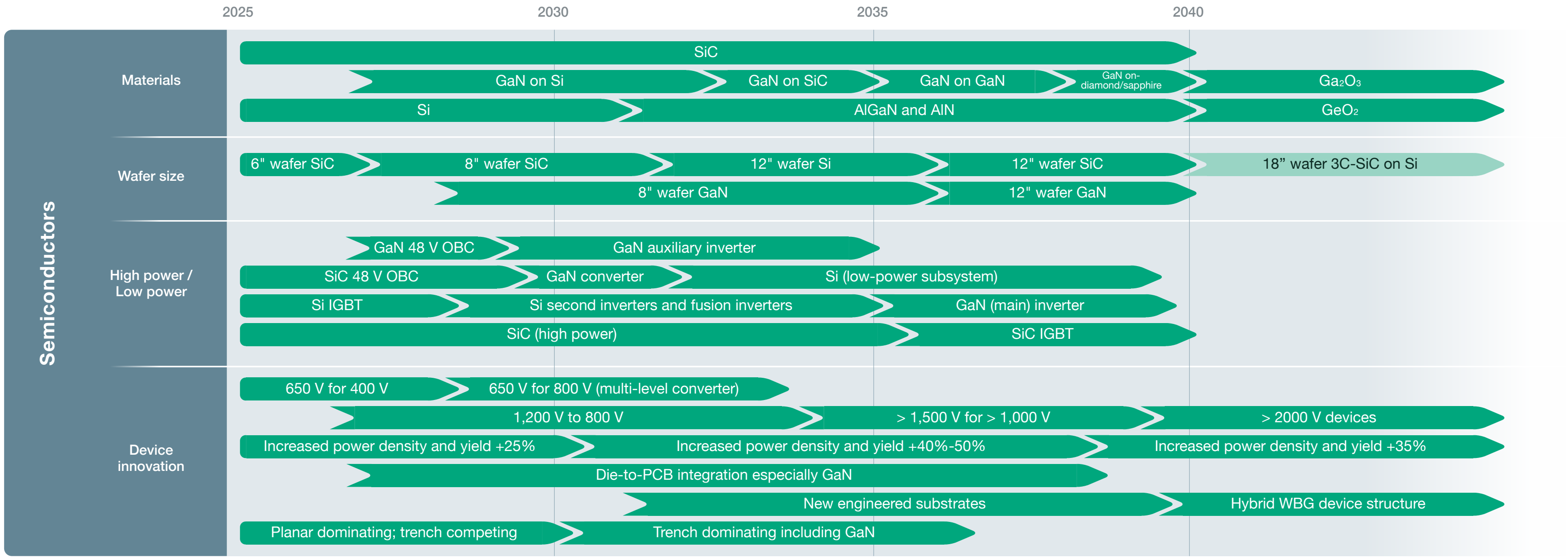
Si: 40 V – 50 V
GaN: 50 V – 900 V (optimal performance ~650 V)
SiC: 650 V – 1,200 V

Operating voltage drives choices in technology trends:

- 650 V devices for 400 V; is dominated by a thinner substrate
- 650 V devices with multi-level converters for 800 V system from about 2028
- 1,200 V devices for 800 V systems; is dominated by epitaxis around 2026-27, this is mainly due to lack of supplies rather than technology
- 1,500 V and 1,700 V devices for 1,000 V systems from about 2034
- 2,300 V new device from 2040 onwards
- less than 650 V use GaN and Si (rather than SiC) because of material cost

Power density

Power density is increasing every 10 years or so, roughly doubling in size.



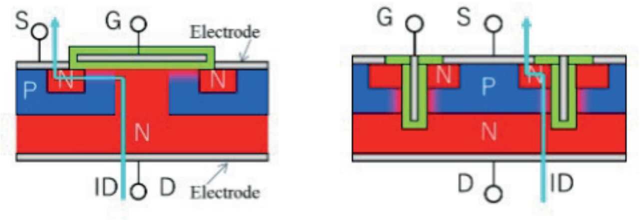
Semiconductors – Device innovation (continued)

Planar vs. Trench (SiC)

There is a clear trend towards trench (architecture), although manufacturing process is longer and more complex than planar, and the end-product more sensitive to yields. There is not a consensus within industry and trench is still deemed less reliable by some. Up until late 2023, there was a clear division between the five major Western foundries with three still pursuing planar, the fourth shortly releasing Gen 5 planar, while the fifth has swayed and has recently announced that its first trench is due for release in 2024.

The main drive is performance benefits, although the base foundation is always cost, albeit on occasions, indirectly. According to Rohm[13], the first to launch a SiC trench metal–oxide–semiconductor field-effect transistor (MOSFET), the advantages of the trench design include; 1) lower ON resistance, 2) smaller parasitic capacitance, and 3) improved switching performance. However, one drawback is reduced short-circuit tolerance due to the lower ON resistance (see Figure 7).

Figure 7: Planar and trench structure



Planar (gate) structure
Trench (gate) structure

Diagram source: https://www.shindengen.com/products/semi/column/basic/mosfet/planar_type_and_trench_type.html

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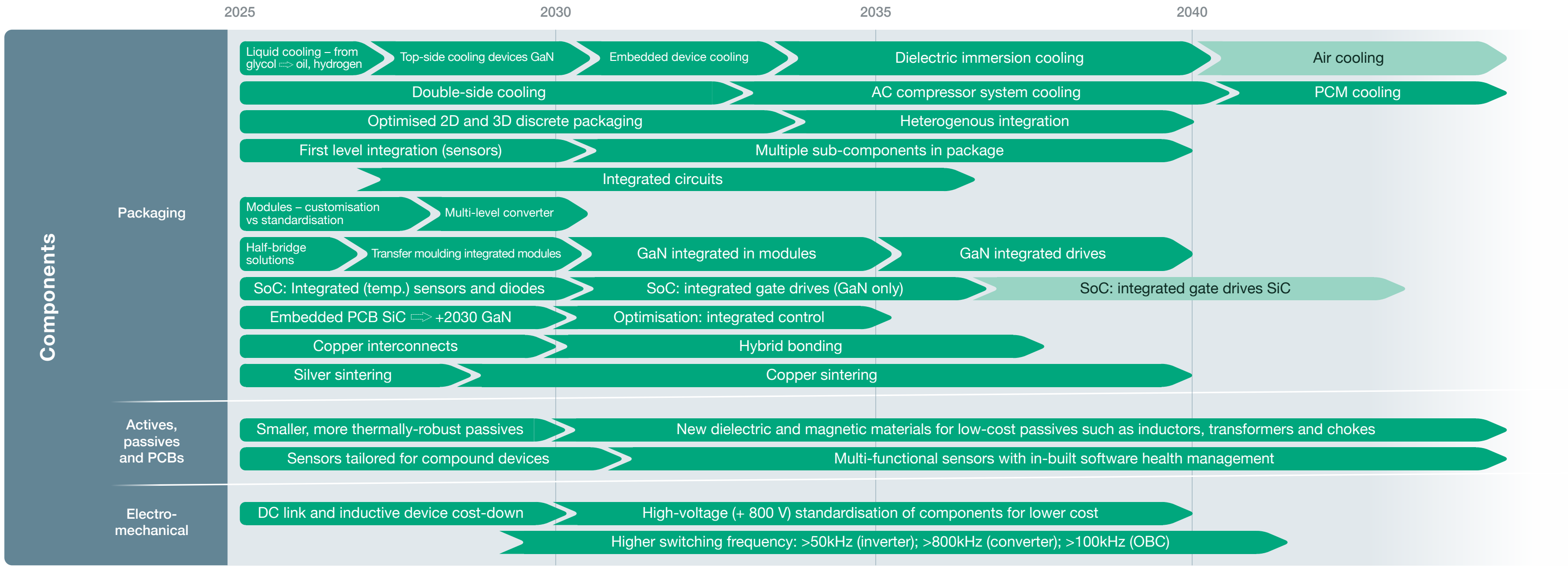
[13] https://www.rohm.com/products/faq-search/faqId/500



Components – Packaging

Packaging of the semiconductors has a key role for the efficacy and sustainability of the power electronics. The packaging ensures optimal thermal management, dissipates heat, and prevents moisture and contaminants from infiltrating devices – preventing corrosive processes and electrical failures. The perfect packaging combines the right material, advanced bonding and joining technologies with very good thermal management.

There are a few themes within packaging which aim to reach the perfect combination: different cooling methods, integration, 3D packaging and new bonding material.

There is much scope to reduce packaging costs and this is expected to become more refined from about 2030 onwards. However, there currently is (comparatively) little innovation within packaging in general, as much of the cost reduction is focussed around materials, particularly for SiC.

Cooling[14]

Thermal management within power electronics is critical. Up until now, it has involved advanced heat sinks, liquid cooling and thinking about different phase-changing materials. This is still the case with some variations. Product development exists using other types of liquid rather than the typical glycol, which is currently favoured, and instead cools with oil or hydrogen.

Top-side cooling device is already used for SiC. It is expected to see this also applied for GaN once GaN devices emerge in full. With top-side cooling, the thermal path is more direct, through a drain, which is exposed at the surface or directly connected to the heatsink. This allows for up to 95% of the heat to be dissipated directly to the heatsink, improving thermal performance by up to 70%.

Double-sided cooling is already in production within the VW Group, for example. It is quite a costly and complex design where the wire bonding is replaced by lead frames.

Direct liquid cooling, or immersion cooling, simply means submerging the object needing to cooled, in liquid. Compared to air cooling, it is more efficient as it also comes into contact with the object's surface, lowering the operating temperature. Dielectric immersive cooling is already gaining traction in the computer world and Tesla has adopted the technology, but no other OEM has so far followed suit[15]. It is designed with the battery in mind, but it also makes the heatsink for power electronics redundant.

The AC compressor is already helping cool the battery in an xEV. However, as technology and vehicles evolve, the AC compressor has the potential to become a thermal management system responsible for cooling the vehicle's entire heating system and subsequent thermal efficiency.

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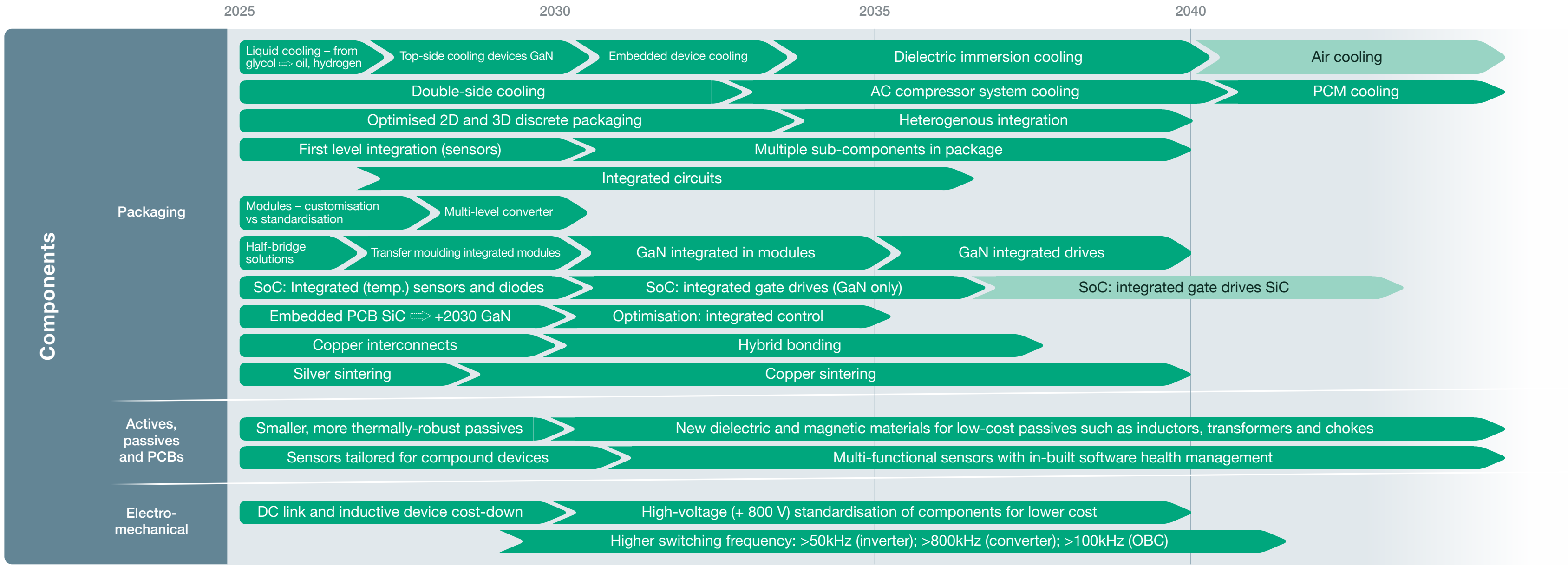
[14] https://www.emobility-engineering.com/immersive-cooling/
[15] Tesla Semi and Tesla CyberTruck will be using immersion cooling



Components – Packaging (continued)

Phase changing materials (PCMs) provide passive thermal protection without an additional power supply. They can release trapped heat into their surroundings when no heat is transferred internally, making them reversible heat absorbers. PCMs are increasingly used for thermal management in power electronics. However, only as a compliment to the heatsink, in effect 'transporting' the heat to the heatsink. There is ongoing research which aims to replace the heatsink and use PCM for the whole BEV powertrain system, i.e. including the battery. This is currently seen as a promising design beyond 2040.

Chipset

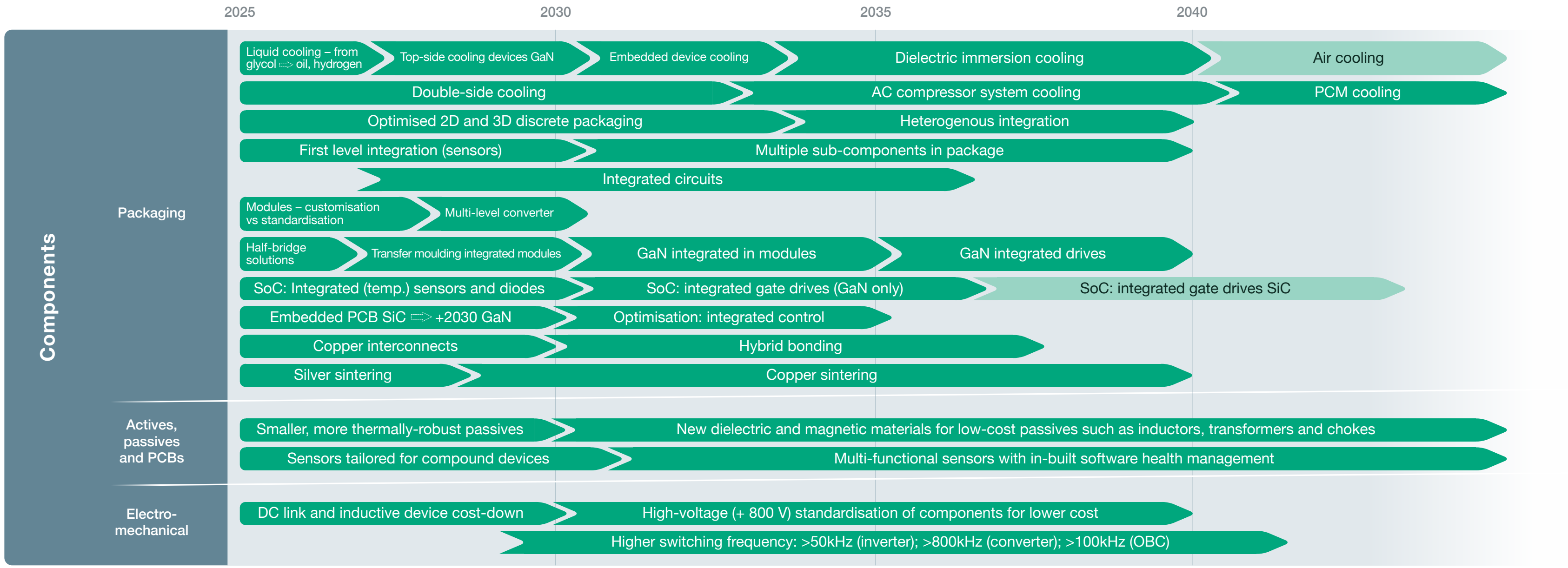
The overall trend for chipsets is integration. This could be integration of functions, components or semiconductors being integrated into modules. Additionally, there is a continuing battle between customisation and standardisation. For modules, the trend is firmly being pulled towards custom packages by OEMs, whereas standardisation is being driven by cost, but also by recycling and reusability purposes.

2D / 2.5D and 3D packaging involves stacking several layers of components, enabling shorter interconnects, and improved electrical performance. This in turn has meant high-packaging density and high-energy efficiency. Heterogeneous integration is the next logical step, this is not new but not yet widely used. Here, multiple dies (a host of functions) are integrated in the same package. Functions that perhaps used to be further apart on the circuit board or on the box level. 2D and 3D is a mode, an enabler, and the output is heterogenous integration. Without advanced 2D to 3D packaging, heterogenous integration will not occur.

Integrated sensors are becoming more common and are highly desirable. Having the current and the temperature sensor integrated within the same chip enables direct measurement and fast feedback of current temperature and any changes.

It is expected that we will see much more usage of multi-level topologies integrated in the module, as these can mix different voltages and achieve higher power density. There is interest in higher voltage, i.e. 1,000 V and 1,100 V, even 1,500 V for passenger cars. In the next few years, the usage of 3-4 multi-level convertors can enable the use of 650 V devices. Instead of using a standard converter, i.e. 0 V to 800 V, three levels exist: 0 V; 400 V and 800 V or four levels: 0 V; 200 V; 500 V and 800 V. There is even research using 15 levels where the centrepoint can be balanced, which makes it operational even if one level is lost. Multi-level converters are a potential enabler for wider usage of GaN.

Half-bridges are already used and are expected to be used more widely over the next few years. Half-bridge modules increase the current per module, enabling higher frequencies.



Components – Packaging (continued)

Resin transfer moulded (RTM) module for SiC, refers to the manufacturing process where the power module is encapsulated and sealed by a dielectric epoxy resin, protecting the components from heat, high voltage, and humidity. As a result, the power module becomes very robust, power-efficient and reliable.

System-on-Chip (SoC): This has a dedicated line on the technology roadmap to demonstrate a clear direction is predicted. Integration starts (already) predominately with temperature sensors and diodes. Gate drives prove more difficult to integrate, but there are ideas within gate-drive technology. The consensus is that integrated drives for GaN devices will exist in the next decade and, highly likely, also for SiC towards 2040. Optimisation of SiC could move faster, but it is being hampered as there is a need to balance benefits versus costs.

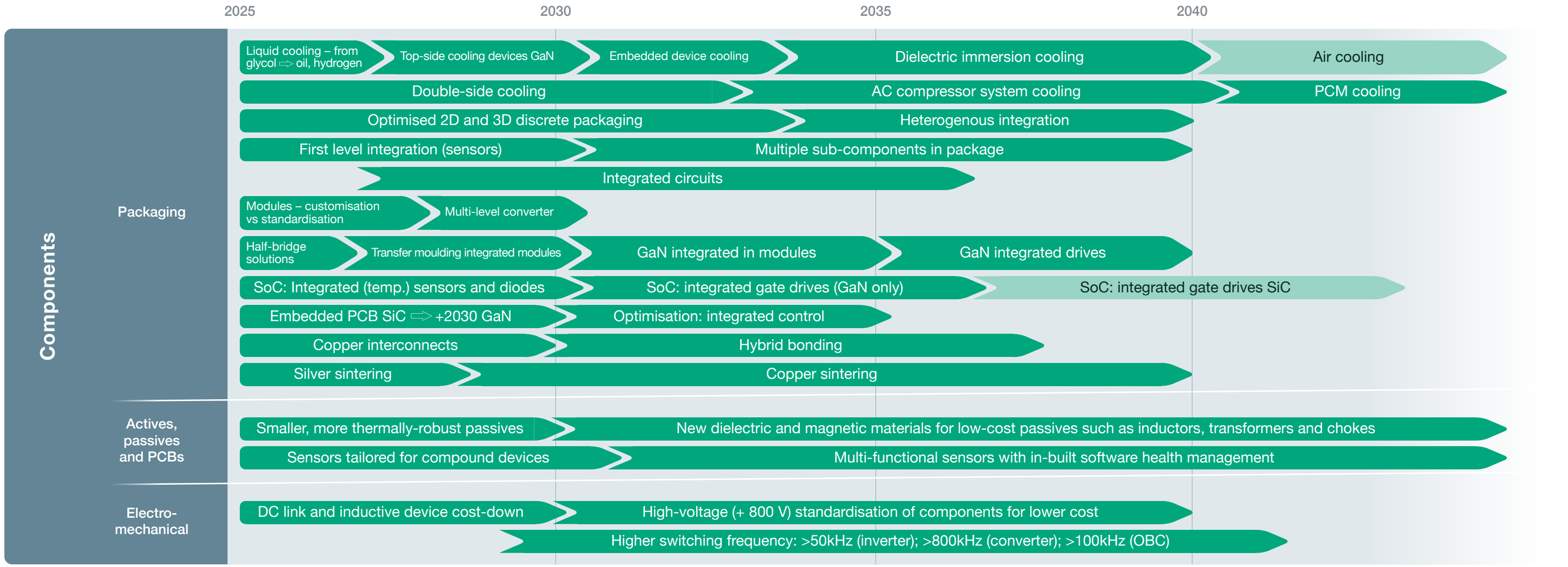
Embedded PCB: The die is directly integrated into PCB, which reduces thermal resistance and parasitic inductance, offering overall improved reliability. This is already happening with SiC and is likely to achieve mass-production volumes in the next few years. It is less certain if this will also happen to GaN, but could potentially over the next decade, i.e. 2030+.

Bonding

The semiconductor industry is moving from aluminium to copper interconnects because copper (Cu) has a lower diffusivity rate. Compared to soldered chips with aluminium bonding wire, a 50-fold higher number of cycles is achieved before faults occur.

With the continued development in packaging and with the introduction of 3D packing and heterogenous integration, further adoption of hybrid bonding will also take place. Hybrid bonding uses embedded metal pads in the bond interface (Cu-Cu bonding) allowing face-to-face connection to the wafers.

The next step, which is already underway, is to replace interconnects with sintering. Silver-sintering paste is currently the most widely used material. It helps maximise thermal performance, margin, and heat-management flexibility. The true benefit of silver sintering has only become apparent with SiC, and for cost reasons, as well as better thermal resistance and electro-migration resistance, it is anticipated that silver will be replaced by copper before 2030.



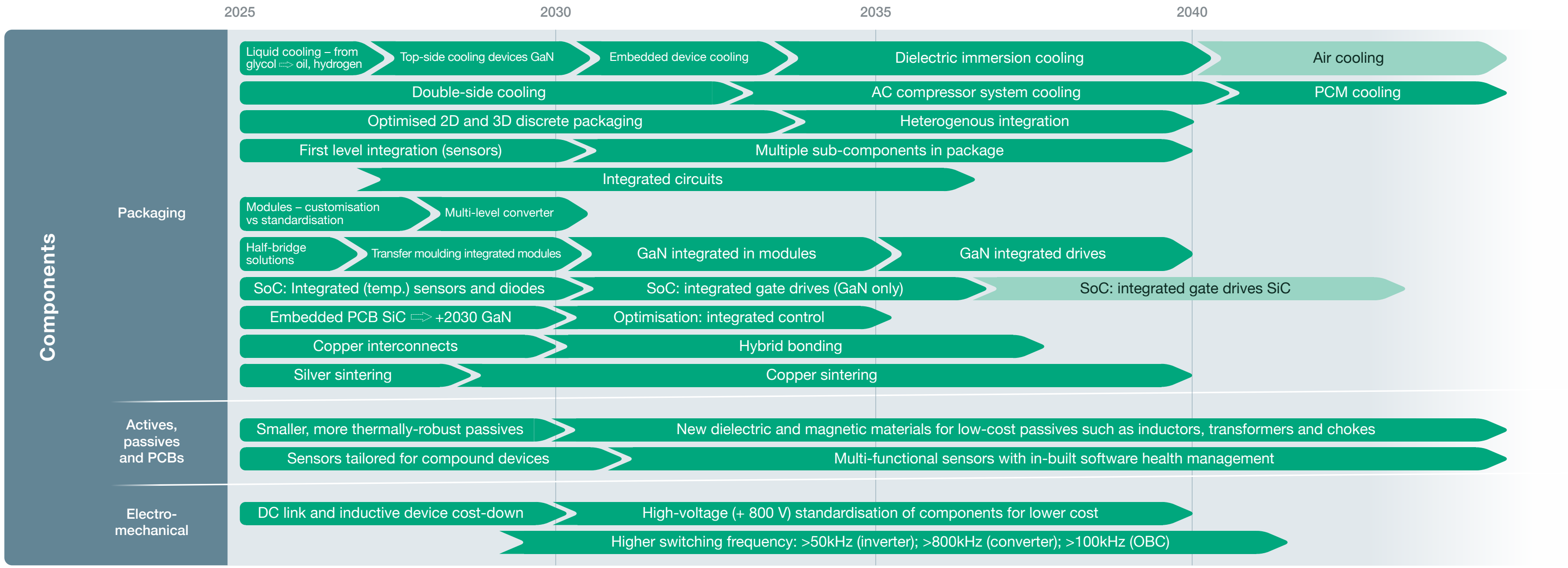
Components – Actives, passives and PCBs

Active components provide active influence such as amplifying, rectifying, or converting supplied electric energy. These would be diodes, transistors, sensors and ICs.

Passive components provide passive functions such as consuming, storing, or releasing supplied electric energy. These are inductors, capacitators, and resistors.

The main goal here is size-reduction for integration. There is much research, advanced modelling and design of magnetic components (inductors, transformers, chokes), which promotes size reduction.

Sensors are hugely important and, up until recently, those used were standard off-the-shelf products. However, we are now seeing an increased focus on customised sensors, specifically for wide bandgap (WBG) semiconductor devices, which are more thermally robust. In the next decade, we will see the production of smarter, more targeted sensors with enhanced software and AI. The application of software and ML will play a significant role in health management of key components, starting with the battery, followed by power electronics, and then likely the inverter after 2030.



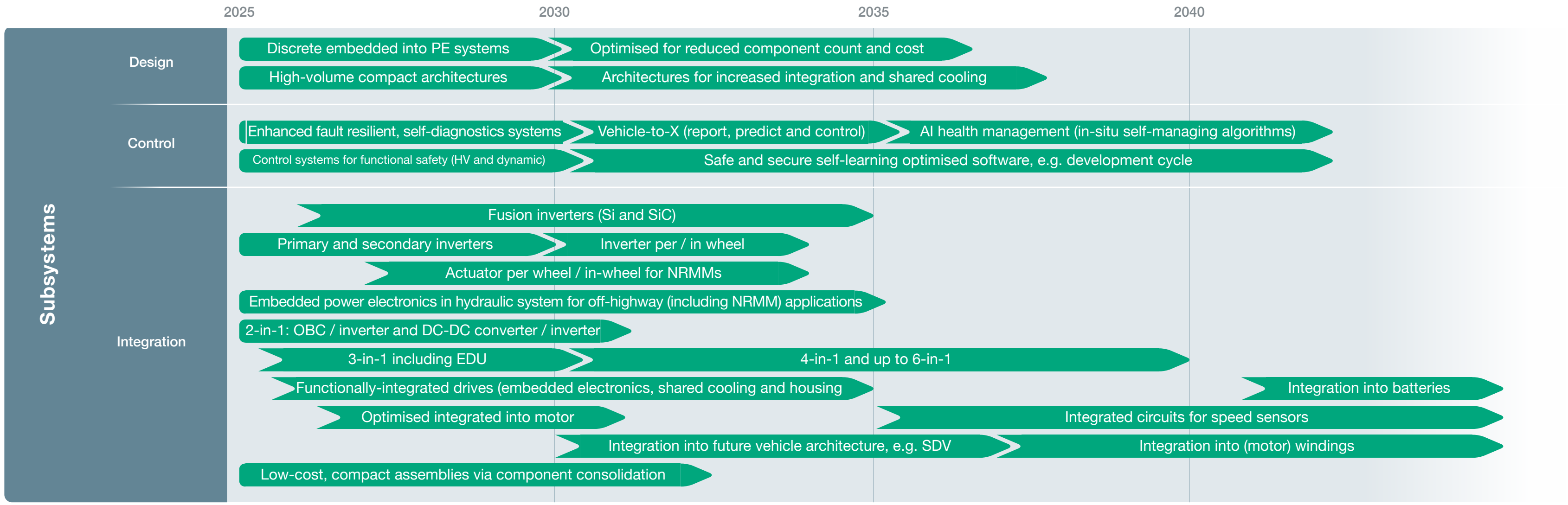
Components – Electro-mechanical

Half-bridge modules enable higher switching frequencies, which in turn enables smaller passive components offering smaller packaging and end-products. For example, the OBC could be integrated within the DC-DC converter (already happening). The whole industry will benefit from this space-saving exercise creating more space in the back seat and / or boot areas of a vehicle.

As a result, we will see a push towards higher frequencies power electronics in the next couple of years (pre-2030):

- > 50 kHz for the inverter (which means the motor can be designed differently for high speed)
- > 800k Hz converters
- > 100 kHz OBC

With higher switching frequencies comes higher switching losses. Without solutions to reduce the losses, the real switching increase could be limited. There are some solutions today which can improve the switching losses, for example the right gate drive. The gate resistor and capacitor values must be optimised to achieve faster and more efficient switching. Other solutions include choosing SiC or GaN, effective thermal management and AI-powered soft-switching.

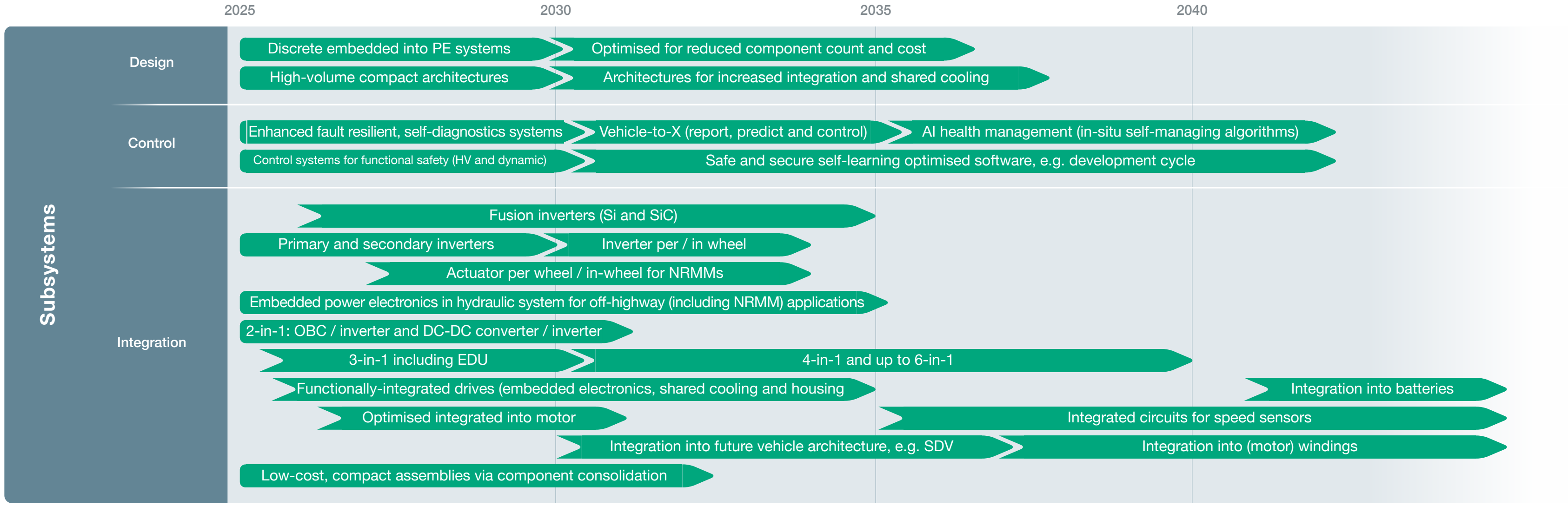


Subsystems – Design

Key design trends include architectures that enable hybrid use of power devices and increasing integration of other components, along with shared cooling. This aligns with a trend of reducing component counts and reducing costs for power devices.

Subsystems – Control

The main theme here is digitalisation, with a real emphasis on the state-of-health of components and systems within the vehicle. It could simply be monitoring and reporting. However, with the development of more intelligent software, the trend is moving towards in-situ health management and failure management, not only for technicians, but also specifically for end-users.



Subsystems – Integration

Integration is considered as a mega-trend within power electronics, like customisation. It is not just the physical integration where two or more components can be boxed together (mechanical) or partly merged (electronic), but also the computing / working integration where (new) components need to work in harmony.

At the micro-components level, integration is a constant driver. For example, integrated circuits for speed sensors are expected to be seen after 2035. A lot of the larger drivetrain components being integrated have already been observed, and this is a continuing focus. There is an emphasis on improvements such as shared housing and cooling of the 2-in-1 and 3-in-1 power electronics, with the motor with the emergence of optimised solutions in ~2026. After 2030, the focus will shift towards ‘working integration’ – the seamless integration into new platforms and future vehicle architectures, such as software-defined vehicle architecture. Towards the second half of the roadmap timings, more physical integration will be discussed again, for example, the integration into motor windings and batteries.

One of the drawbacks of integration is the more there is, the less opportunity there is for service and repair, reuse and / or recycling of a system, part, or component.

Inverters

A large degree of innovation with inverters has been identified; both in terms of configuration and use, e.g. primary and secondary inverters as well as in-wheel inverters with different combinations of Si IGBTs and SIC MOSFETs. Fusion inverters, use both IGBTs and MOSFETs simultaneously, where SiC is used for acceleration and deceleration, and Si for recuperation.

X-in-1

As referenced earlier, one of the future key trends is integration; both in electronics and mechanics. X-in-1 is where at least two components are built into one box, for example an inverter boxed together with the OBC or the DC-DC converter.

The configuration building momentum right now is the x-in-1 known as eAxle, where the motor, transmission and power electronics are packed together, sitting between the driving wheels (front for forward-wheel drive (FWD), rear for rear-wheel drive (RWD) and one on each wheel axle for four-wheel drive (4WD) and all-wheel drive (AWD)). With the promise of significant size reductions, we are seeing more development beyond 3-in-1. 4-in-1* and even 6-in-1[16] are already available, albeit not currently deployed en masse.

A parallel trend is the reduction of the number of boxes, i.e. ‘a box, in a box, in a box’, to one single integration, removing the aluminium casting inside the box to one shared housing.

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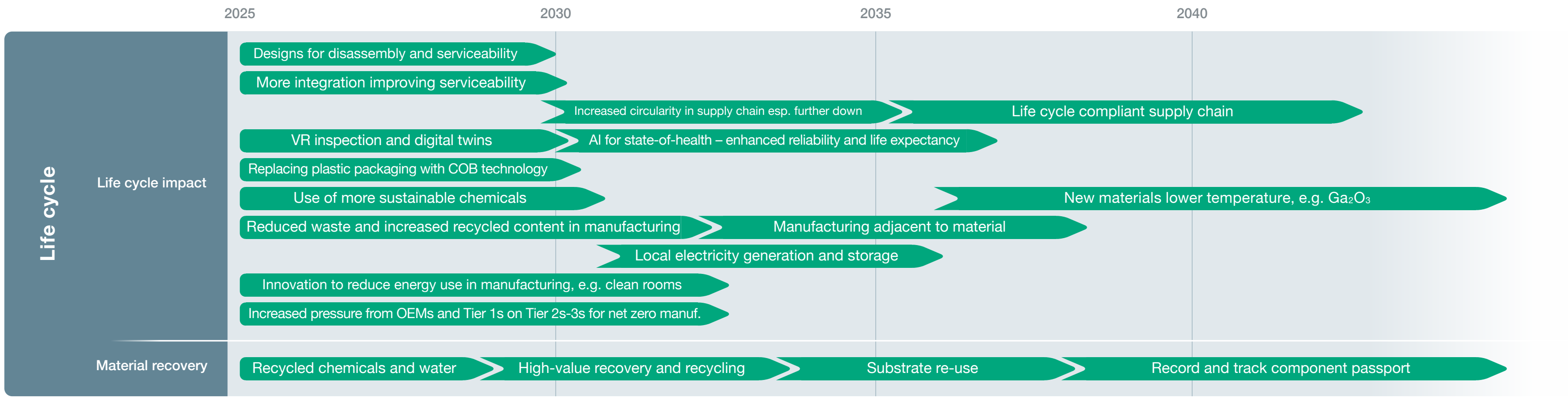
[16] e.g. 4-in-1: motor, transmission, inverter, and thermal mgt. 5-in-1: motor, inverter, reducer, electric generator, and increaser 6-in-1: DC-DC converter, OBC, power distribution unit (PDU), motor, inverter, and gearbox.

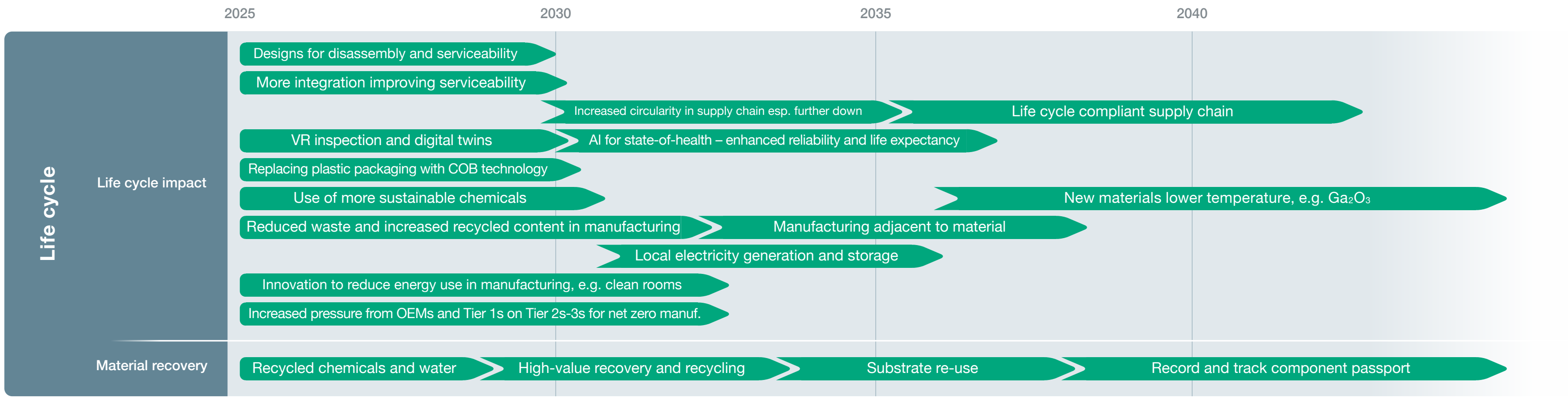


Life cycle – Life cycle impact

Overall, semiconductor manufacturing is heavy on energy. A clean room (used for when wafers are manufactured to semiconductor chips) has extremely strict requirements regarding temperature, humidity and cleanliness requiring 24/7 air-conditioning and air-filtering systems. This applies for all semiconductors. However, depending on the material, the raw material stages can be equally energy intensive, as mentioned previously in 2.2; SiC is more energy-intensive than Si and GaN to produce.

The pressure to achieve net zero throughout the entire life cycle of a product is increasing. There is an effort to reduce carbon footprint, energy consumption, and the use of non-sustainable chemicals and plastics, etc.

The responsibility to facilitate recovery / reuse / recycle of vehicle (parts) used to lie with ‘recyclers’. Nowadays, the circular economy and design thinking is emerging at the design and development stage. Currently, the increase of circularity in the supply chain is estimated to be +5% to 15% over the coming years, up to 2030.



Life cycle – Material recovery

Material recovery from power electronics is currently difficult to achieve. Systems and components are neither designed to be reused or recycled and semiconductors are not designed to be disassembled at all. There are currently no regulations or legislations demanding the reuse or recycle of semiconductor parts to push the development of recycling.

With the current two main drivers within power electronics – integration and customisation – there is little room for reuse and recycle due to the fact that it is almost impossible to recover, recycle or reuse components and / or material.

As such, it is easier to recycle or reuse by-products and waste products from the manufacturing process, such as water and chemicals.

There is advanced research taking place, within the industry, to facilitate more reuse and recycling. For example, researchers at the Fraunhofer Institute for Ceramic Technologies and Systems IKTS are developing a process called RECOSiC©[17]. This recycles the SiC waste and by-products produced in the conventional Acheson process, and turns the recycled materials into high-quality SiC, using less energy and creating less pollution. Another example was discovered by chance in the US. A method where Si waste product, together with low-cost natural gas, can be converted into high-purity SiC powder while producing hydrogen (H_2) as a clean by-product[18].

It is likely regulation will emerge moving forward, but what it will entail is difficult to foresee currently. It is likely that a form of passport will be established for all or some power electronics. However, with no clear definitions and exact process, there is uncertainty around how effective it would be.

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[17] https://www.fraunhofer.de/en/press/research-news/2023/june-2023/energy-efficient-and-low-in-emissions-silicon-carbide-recycling-with-recosic.html
[18] https://www.aiche.org/resources/publications/cep/2022/october/catalyzing-commercialization-novel-low-cost-sustainable-process-produce-silicon-carbide

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
SoC	System-on-Chip
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

System-Level Roadmaps

- Mobility of People
- Mobility of Goods

Technology Roadmaps

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- Electrical Energy Storage
- Lightweight Vehicle and Powertrain Structures
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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.

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