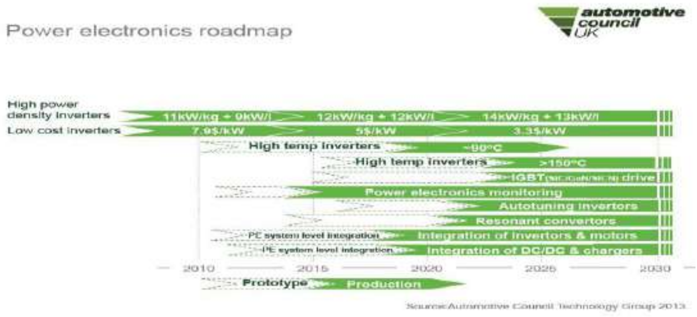
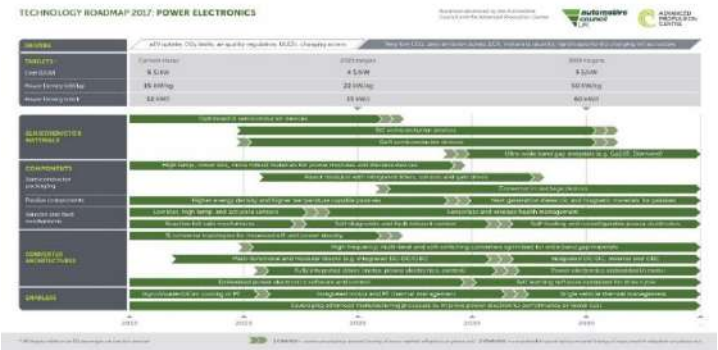
Power Electronics Roadmap

Updated by the Advanced Propulsion Centre in collaboration with and on behalf of the Automotive Council

Executive summary: *Power electronics*





- The 2013 roadmap was developed alongside the electric machine roadmap and **focused on progressing traction drive power electronics (automotive inverters).**
- The 2017 roadmap was developed separately from the electric machine roadmap resulting in **greater granularity with a focus on a broader set of power electronics challenges.**
- **2017 roadmap has been built using a targets-based approach**, informed by consensus amongst a wide range of industry and academic experts. Key targets are cost and power density.
- Step changes in 2035 performance targets reflect the **opportunities that can be realised through the optimisation and integration of wide and ultra wide band gap semiconductors** currently in development.
- **The 2017 roadmap provides a more detailed focus on supporting technologies and materials** (and their evolution) as earlier stage R&D is realised into future applications.

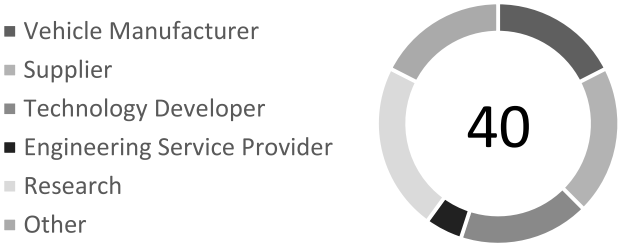
ADVANCED PROPULSION CENTRE UK

Update process: *The 2017 Power Electronics Roadmap was updated via a structured consensus-building process involving 40 experts*

automotive council UK

- A public workshop was held at the University of Nottingham on the 10th February 2017
- The process was co-ordinated by the Advanced Propulsion Centre on behalf of Automotive Council
- The Advanced Propulsion Centre Power Electronics Spoke, supported by an expert Steering Group, helped to shape the roadmap before and after the workshop

Power Electronics Steering Committee and Workshop Attendees



Pre-Event Email — 1 day workshop with 36 attendees — Post-Event Email

Pre-event Common Assumptions Briefing

Collective Briefing Process

Breakout Sessions

Post-Event Debrief

ADVANCED PROPULSION CENTRE UK

Technical targets: *Mass market adoption of ultra low emission vehicles drives challenging cost and performance targets for power electronics*

automotive council UK

Drivers of change

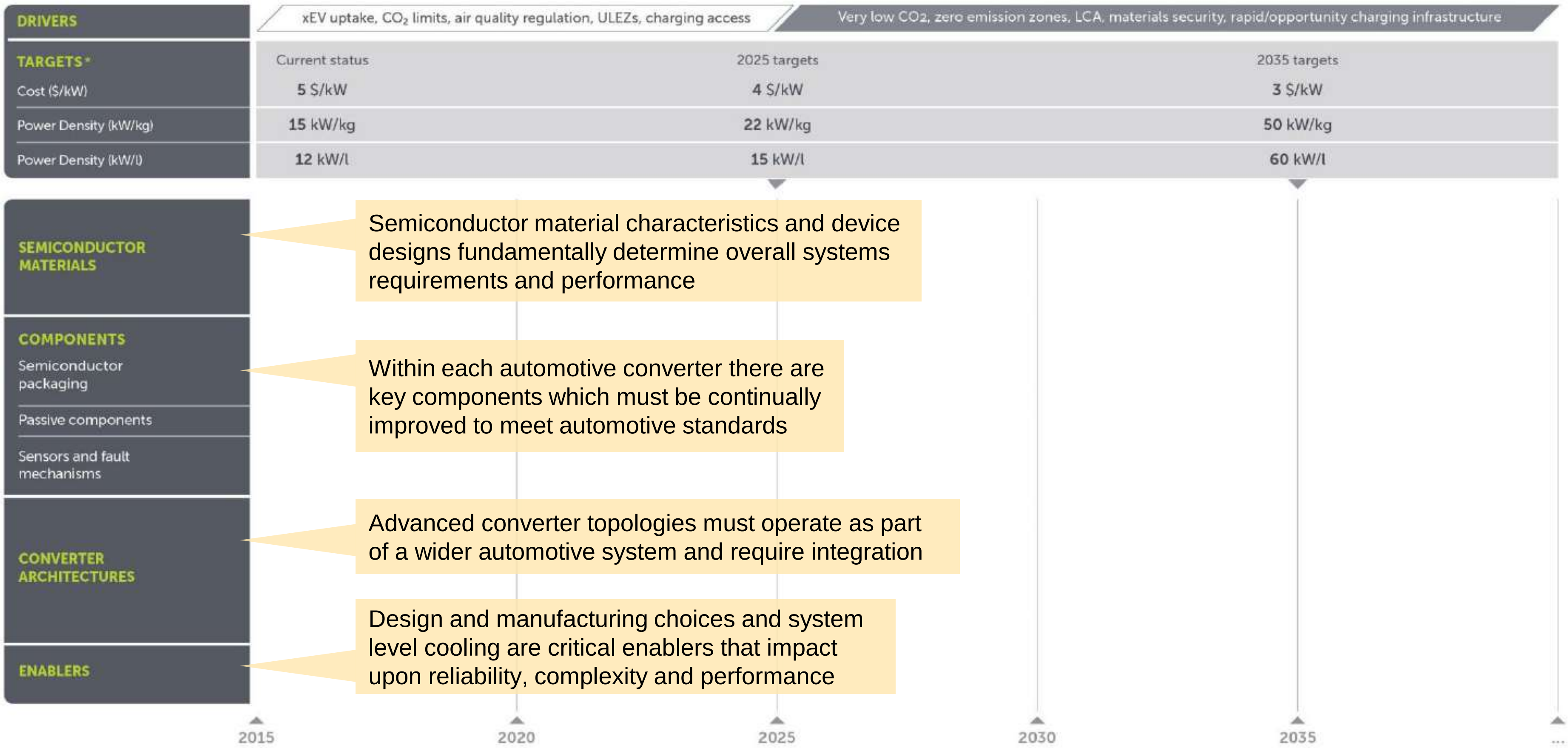
- **CO_2 and air quality** objectives challenge the universal application of TPS based powertrains
- **Electrification** features in product plans of almost every OEM across all sectors
- **Power electronics feature in all xEV formats** and are vital for BEV and PHEV in particular
- **Innovations are needed** in power electronics specifically designed for vehicle traction
- Improved characteristics such as **higher reliability, higher performance of semiconductor devices and lower system costs** are required to meet mainstream automotive demands
- In response to these challenges, **ambitious power electronics targets** have been set to drive innovation, as these targets cannot be attained with existing technology
- **Cost and power density targets should be read independently from one another**, different OEMs will prioritise different targets based on their product requirement

Inverter[1]	Low Cost Orientated	High Performance Orientated	2017	2025	2035
Cost ($/kW)	X		5	4	3
Power Density (kW/kg)		X	15	22	50
Power Density (kW/l)		X	12	15	60
Efficiency (%)	X	X	96	97	98
DC-DC Converter (2-port)[2]	**Low Cost Orientated**	**High Performance Orientated**	**2017**	**2025**	**2035**
Cost ($/kW)	X		15	10	6
Power Density (kW/kg)		X	8	15	50
Power Density (kW/l)		X	6	12	60
Efficiency (%)	X	X	97	98	99
Integrated Charger/DC-DC Converter[3]	**Low Cost Orientated**	**High Performance Orientated**	**2017**	**2025**	**2035**
Cost ($/kW)	X		30	15	8
Power Density (kW/kg)		X	3	6	12
Power Density (kW/l)		X	2	4	15
Efficiency (%)	X	X	94	96	97

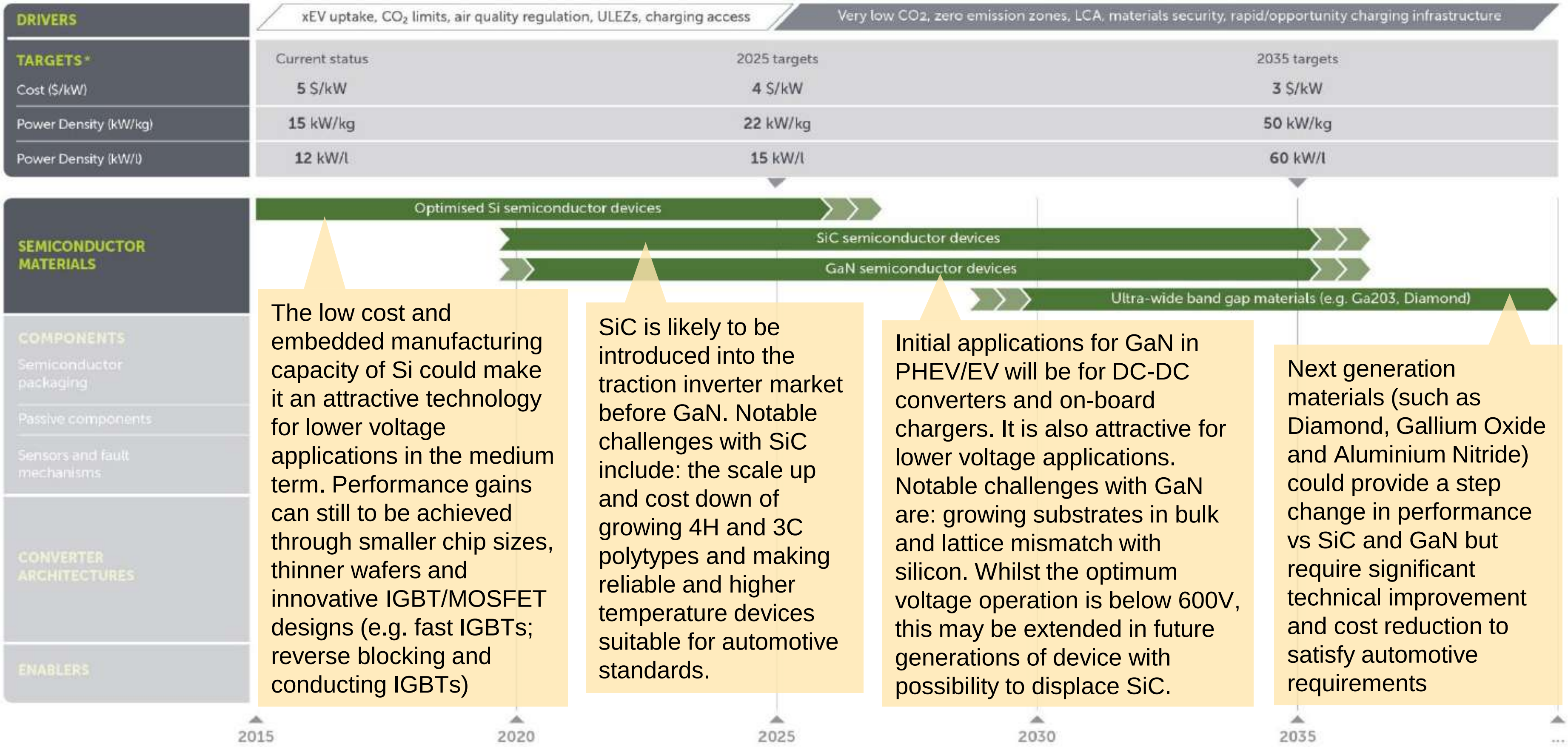
1) 3-phase with dc-link and controls
2) 2-port non isolated, bidirectional buck-boost
3) PFC front-end, isolated DC-DC with HV and LV battery outputs, bidirectional by 2030 (or earlier depending on V2G introduction)

ADVANCED PROPULSION CENTRE UK

Technology categories: *Parallel developments are needed in semiconductor materials, components, converter architectures and manufacture and design to meet challenging targets*



Semiconductor materials: *New wide band gap materials will begin to phase in which will provide a step change in performance compared to silicon*



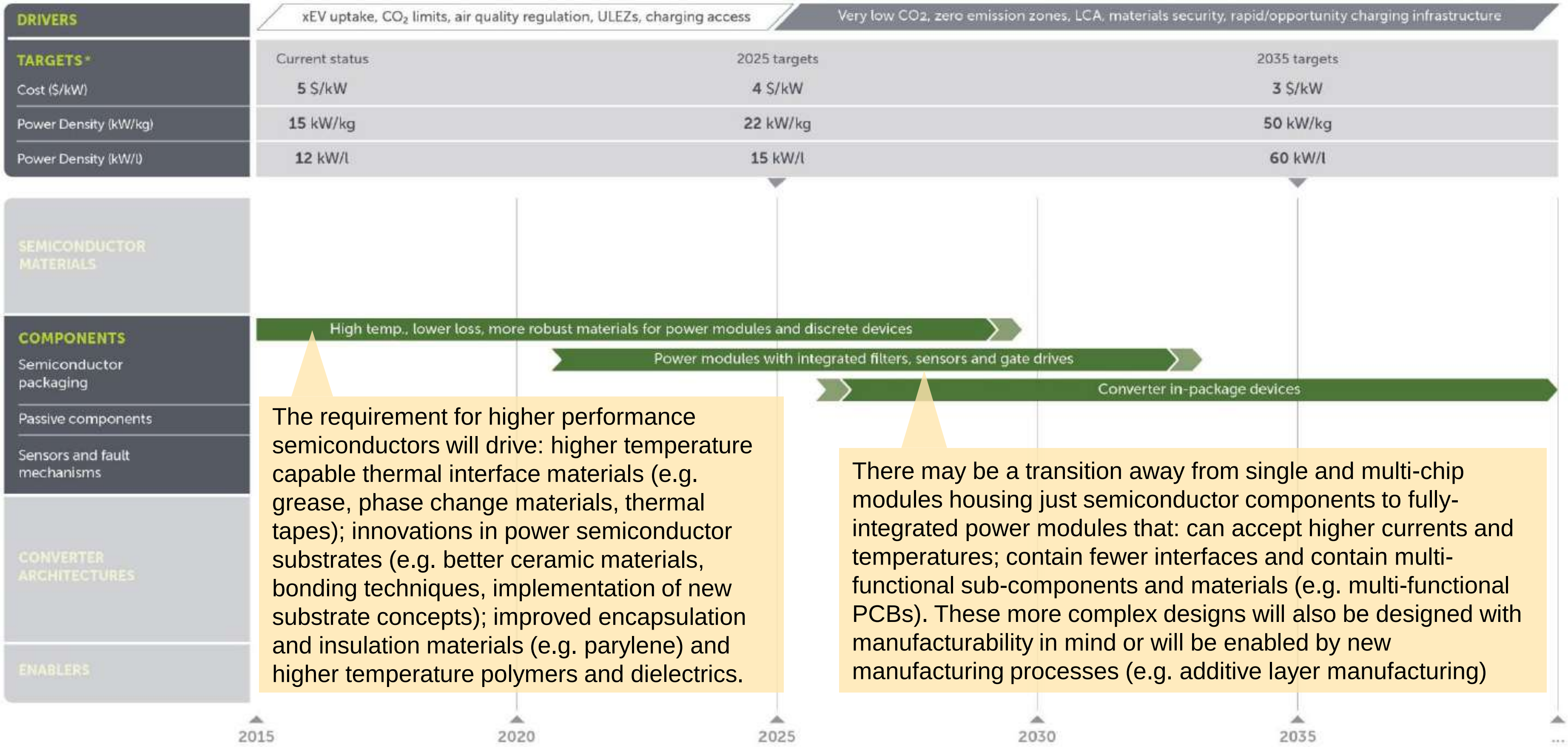
The low cost and embedded manufacturing capacity of Si could make it an attractive technology for lower voltage applications in the medium term. Performance gains can still to be achieved through smaller chip sizes, thinner wafers and innovative IGBT/MOSFET designs (e.g. fast IGBTs; reverse blocking and conducting IGBTs)

SiC is likely to be introduced into the traction inverter market before GaN. Notable challenges with SiC include: the scale up and cost down of growing 4H and 3C polytypes and making reliable and higher temperature devices suitable for automotive standards.

Initial applications for GaN in PHEV/EV will be for DC-DC converters and on-board chargers. It is also attractive for lower voltage applications. Notable challenges with GaN are: growing substrates in bulk and lattice mismatch with silicon. Whilst the optimum voltage operation is below 600V, this may be extended in future generations of device with possibility to displace SiC.

Next generation materials (such as Diamond, Gallium Oxide and Aluminium Nitride) could provide a step change in performance vs SiC and GaN but require significant technical improvement and cost reduction to satisfy automotive requirements

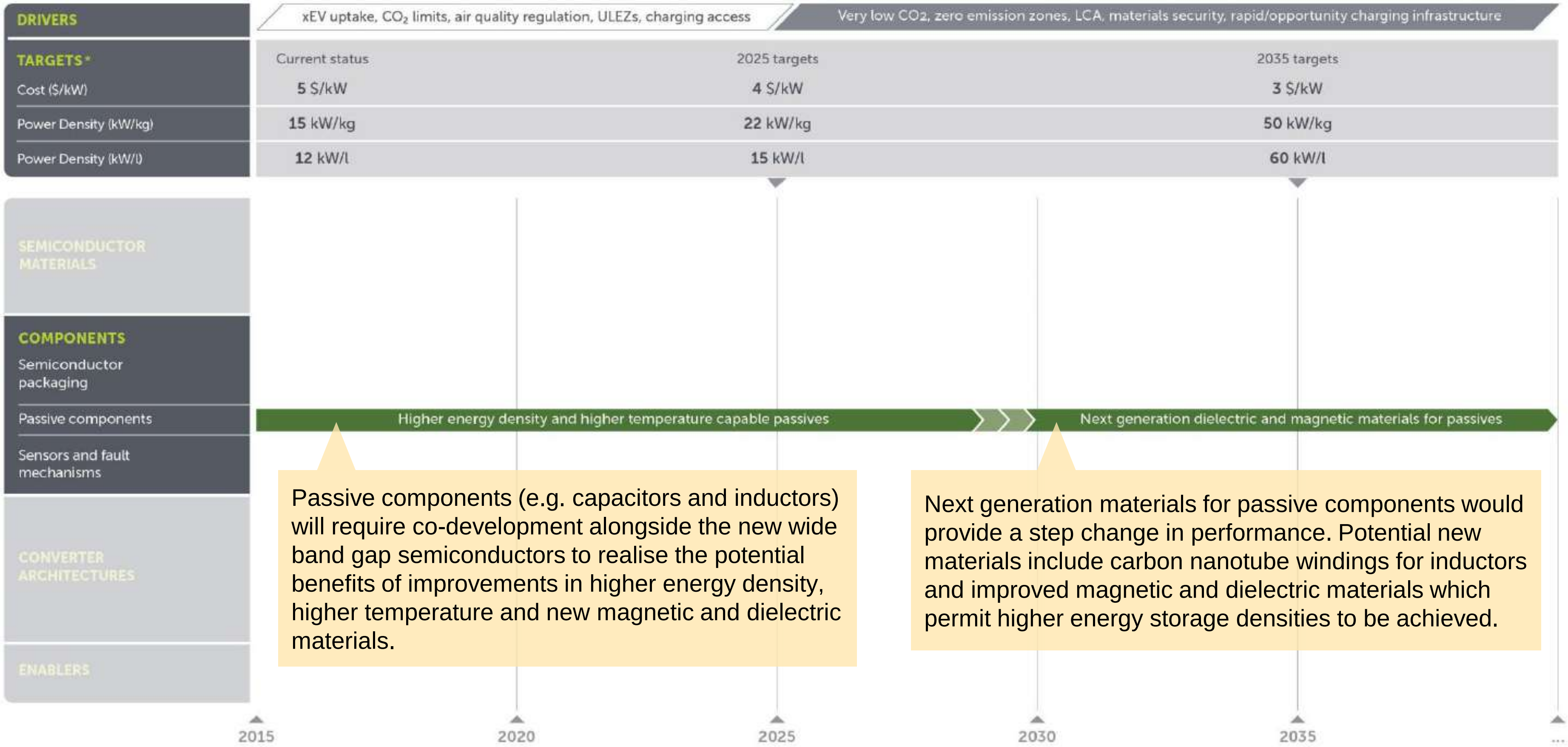
Components: *Improvements in semiconductor packaging technology can be achieved through new materials and closer integration of filters, sensors and gate drives*



The requirement for higher performance semiconductors will drive: higher temperature capable thermal interface materials (e.g. grease, phase change materials, thermal tapes); innovations in power semiconductor substrates (e.g. better ceramic materials, bonding techniques, implementation of new substrate concepts); improved encapsulation and insulation materials (e.g. parylene) and higher temperature polymers and dielectrics.

There may be a transition away from single and multi-chip modules housing just semiconductor components to fully-integrated power modules that: can accept higher currents and temperatures; contain fewer interfaces and contain multi-functional sub-components and materials (e.g. multi-functional PCBs). These more complex designs will also be designed with manufacturability in mind or will be enabled by new manufacturing processes (e.g. additive layer manufacturing)

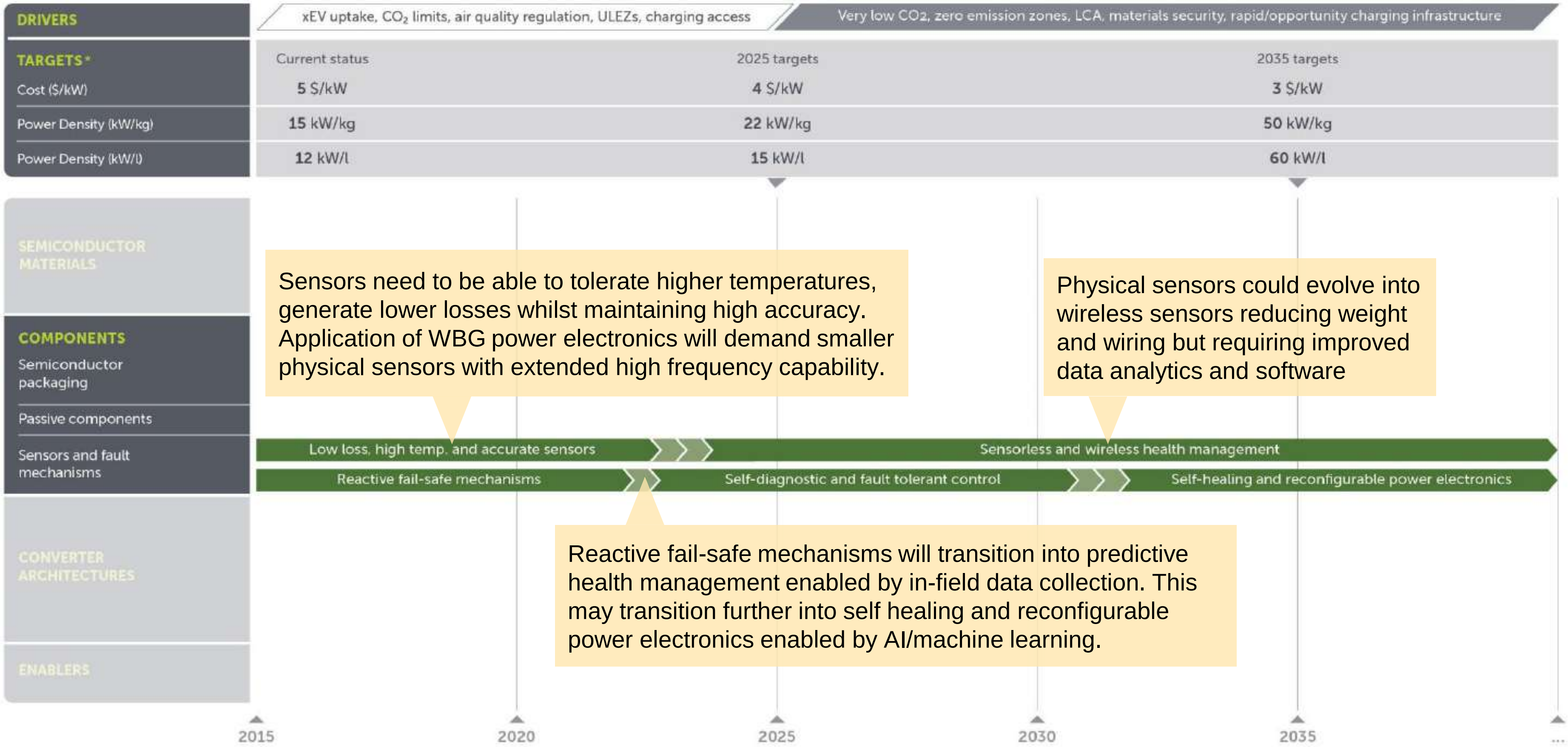
Components: *Increasing the energy density and thermal properties of passive components can improve overall system efficiency*



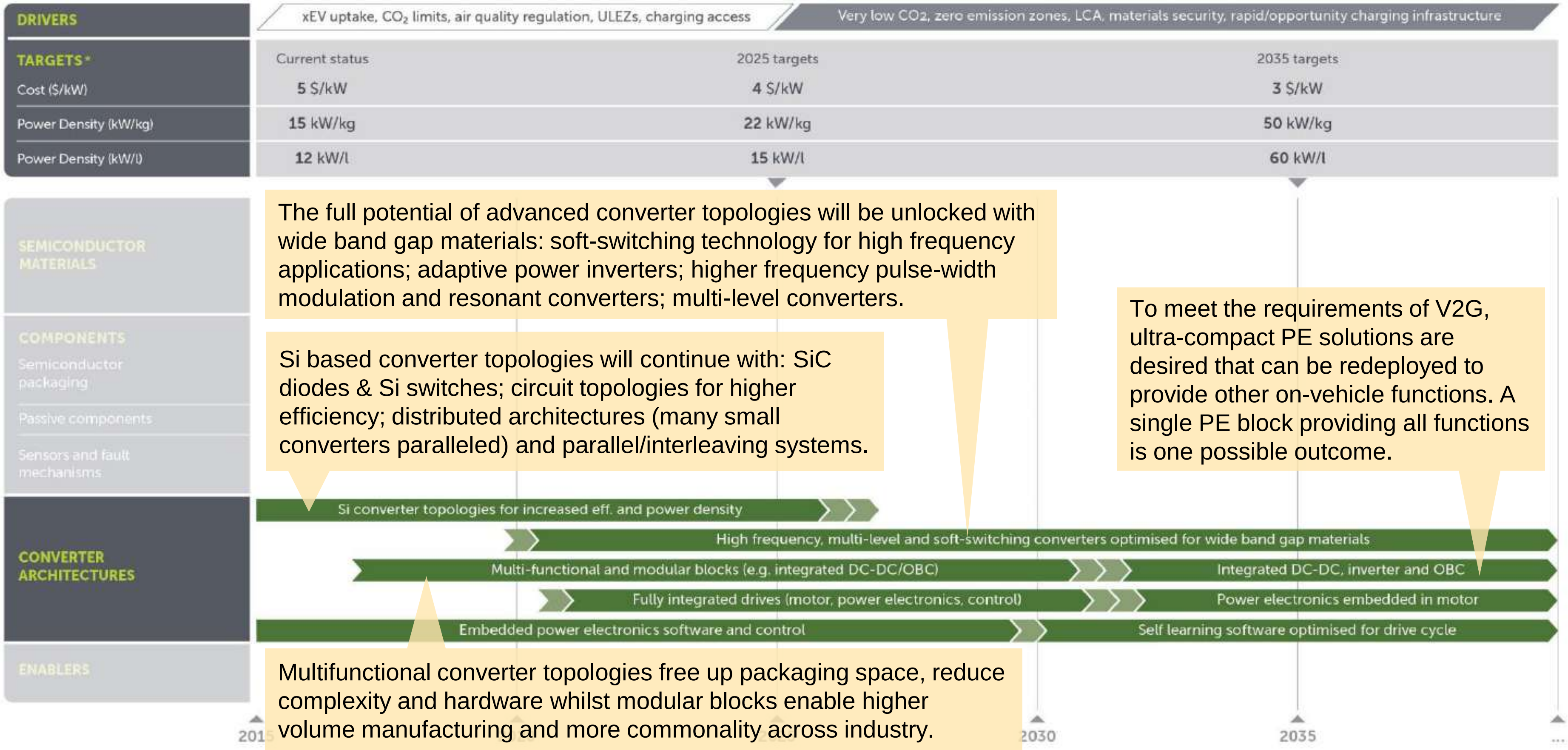
Passive components (e.g. capacitors and inductors) will require co-development alongside the new wide band gap semiconductors to realise the potential benefits of improvements in higher energy density, higher temperature and new magnetic and dielectric materials.

Next generation materials for passive components would provide a step change in performance. Potential new materials include carbon nanotube windings for inductors and improved magnetic and dielectric materials which permit higher energy storage densities to be achieved.

Components: *Lower loss, improved accuracy and higher temperature capable sensors alongside more sophisticated fault tolerance mechanisms are critical for safe and efficient converters*



Converter architectures: *Advanced converter architectures are needed for future automotive applications with a need to integrate the power electronics into the vehicle system*



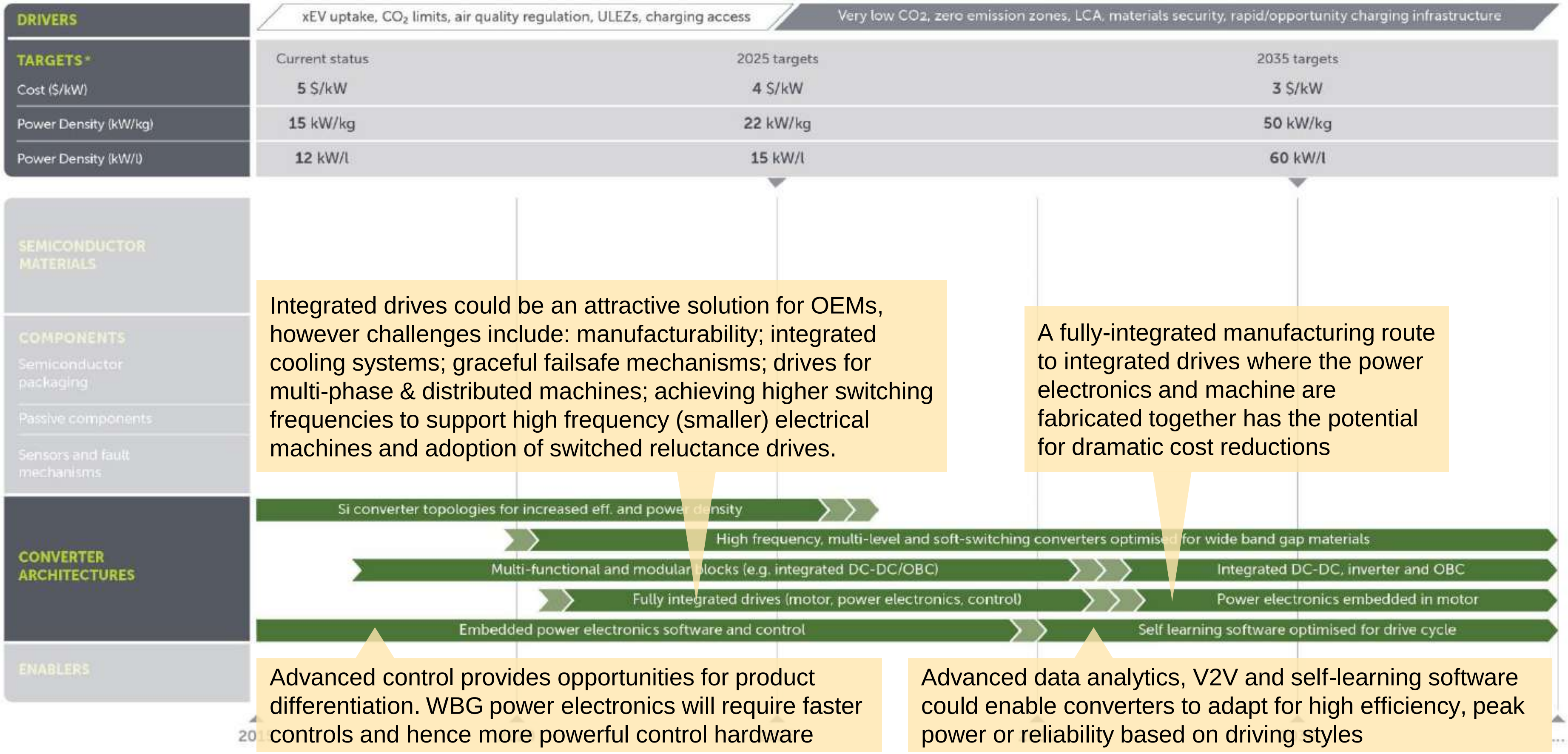
The full potential of advanced converter topologies will be unlocked with wide band gap materials: soft-switching technology for high frequency applications; adaptive power inverters; higher frequency pulse-width modulation and resonant converters; multi-level converters.

Si based converter topologies will continue with: SiC diodes & Si switches; circuit topologies for higher efficiency; distributed architectures (many small converters paralleled) and parallel/interleaving systems.

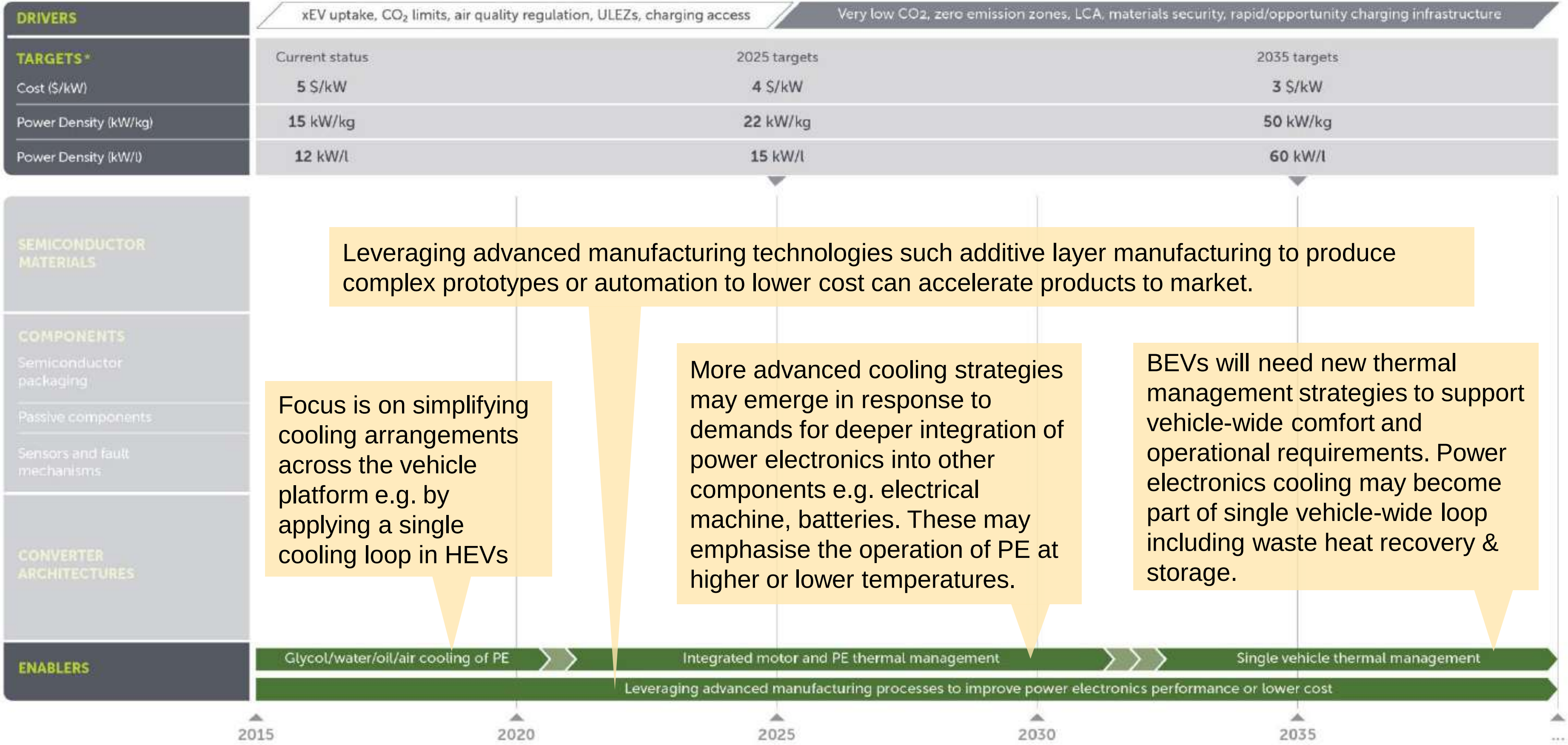
To meet the requirements of V2G, ultra-compact PE solutions are desired that can be redeployed to provide other on-vehicle functions. A single PE block providing all functions is one possible outcome.

Multifunctional converter topologies free up packaging space, reduce complexity and hardware whilst modular blocks enable higher volume manufacturing and more commonality across industry.

Converter architectures: *Integrated drives offer an integrated solution with the supporting software and control critical for the efficiency and performance of advanced converter architectures*



Enablers: *Integrated thermal management strategies and advanced manufacturing technologies are all critical enablers for improved power electronics*



Leveraging advanced manufacturing technologies such additive layer manufacturing to produce complex prototypes or automation to lower cost can accelerate products to market.

Focus is on simplifying cooling arrangements across the vehicle platform e.g. by applying a single cooling loop in HEVs

More advanced cooling strategies may emerge in response to demands for deeper integration of power electronics into other components e.g. electrical machine, batteries. These may emphasise the operation of PE at higher or lower temperatures.

BEVs will need new thermal management strategies to support vehicle-wide comfort and operational requirements. Power electronics cooling may become part of single vehicle-wide loop including waste heat recovery & storage.

TECHNOLOGY ROADMAP 2017: POWER ELECTRONICS

Roadmap developed by the Automotive Council and the Advanced Propulsion Centre

automotive council UK

ADVANCED PROPULSION CENTRE UK

DRIVERS

- xEV uptake, CO_2 limits, air quality regulation, ULEZs, charging access
- Very low CO2, zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure

TARGETS*	Current status	2025 targets	2035 targets
Cost ($/kW)	5 $/kW	4 $/kW	3 $/kW
Power Density (kW/kg)	15 kW/kg	22 kW/kg	50 kW/kg
Power Density (kW/l)	12 kW/l	15 kW/l	60 kW/l

SEMICONDUCTOR MATERIALS

- Optimised Si semiconductor devices
- SiC semiconductor devices
- GaN semiconductor devices
- Ultra-wide band gap materials (e.g. Ga203, Diamond)

COMPONENTS

Semiconductor packaging

- High temp., lower loss, more robust materials for power modules and discrete devices
- Power modules with integrated filters, sensors and gate drives
- Converter in-package devices

Passive components

- Higher energy density and higher temperature capable passives
- Next generation dielectric and magnetic materials for passives

Sensors and fault mechanisms

- Low loss, high temp. and accurate sensors
- Sensorless and wireless health management
- Reactive fail-safe mechanisms
- Self-diagnostic and fault tolerant control
- Self-healing and reconfigurable power electronics

CONVERTER ARCHITECTURES

- Si converter topologies for increased eff. and power density
- High frequency, multi-level and soft-switching converters optimised for wide band gap materials
- Multi-functional and modular blocks (e.g. integrated DC-DC/OBC)
- Integrated DC-DC, inverter and OBC
- Fully integrated drives (motor, power electronics, control)
- Power electronics embedded in motor
- Embedded power electronics software and control
- Self learning software optimised for drive cycle

ENABLERS

- Glycol/water/oil/air cooling of PE
- Integrated motor and PE thermal management
- Single vehicle thermal management
- Leveraging advanced manufacturing processes to improve power electronics performance or lower cost

2015 2020 2025 2030 2035 ...

All targets relate to an EV passenger car traction inverter

1 chevron = some uncertainty around timing of mass market adoption or phase out 2 chevrons = considerable uncertainty around timing of mass market adoption or phase out

Glossary: *Explanation of acronyms and terms not described in the roadmap due to space constraints*

- **Band gap -** *A band gap is the energy needed to excite electrons from a material's valence band into the conduction band. Materials with larger band gaps (SiC and GaN) allow them to withstand higher voltages and temperatures than silicon.*

- **Converters –** *Converters refer to a system which transforms one form of electrical energy into another form of electrical energy. In automotive applications there are:* ***Inverters*** *(convert DC into AC) which are coupled to the electric motors;* ***DC-DC converters*** *which transforms fixed DC input voltage to a controllable DC output voltage for lower power ancillaries; and there are* ***on-board chargers (OBC's)*** *that transform alternating current from the electrical grid (mains AC) to direct current (DC) suitable for recharging the battery pack.*

- **Ga_2O_3 (Gallium oxide) –** *Gallium Oxide is an "ultra-wide band gap" material. Currently at the fundamental research stage, it has a higher band gap than GaN and SiC.*

- **GaN (Gallium nitride) –** *Gallium Nitride is a wide band gap material and a potential replacement for silicon.*

- **LCA (Life cycle analysis)** – *Identifying the total environmental impact of a given product.*

- **Si (Silicon) –** *Since its first use in the 1950's, silicon has become the most common semiconductor material as its abundancy has made it cheap.*

- **SiC (Silicon carbide) –** *Silicon Carbide is a wide band gap material and a potential replacement for silicon.*

- **V2X (Vehicle-to-X)** – *Vehicle-to-X refers to an intelligent transport system where all vehicles and infrastructure systems are interconnected with each other.*

ADVANCED PROPULSION CENTRE UK