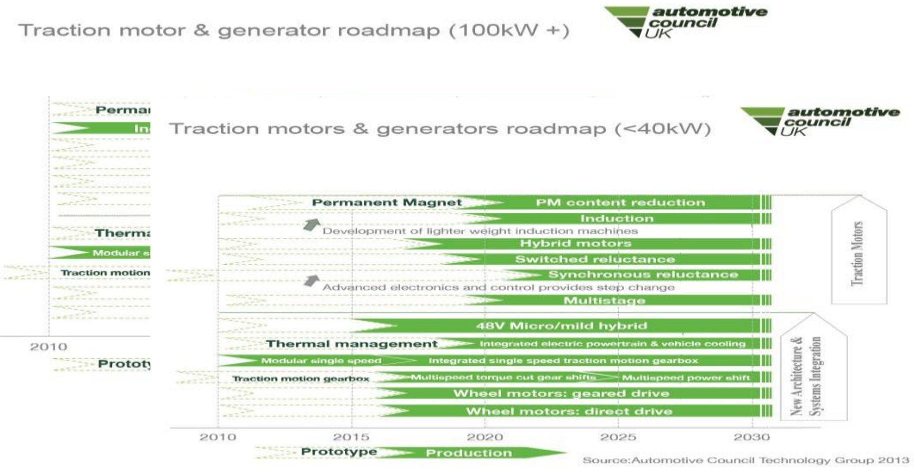
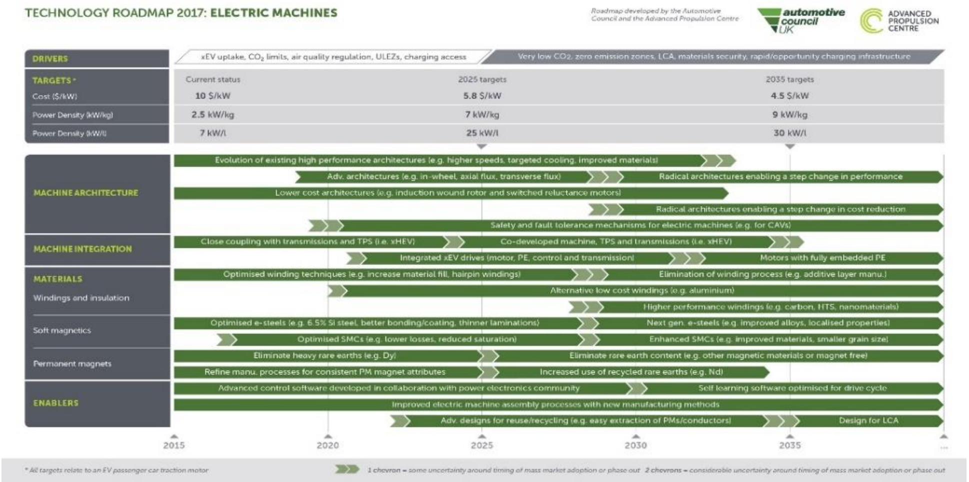
Electric Machines Roadmap

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

Executive summary – *Electric machines*



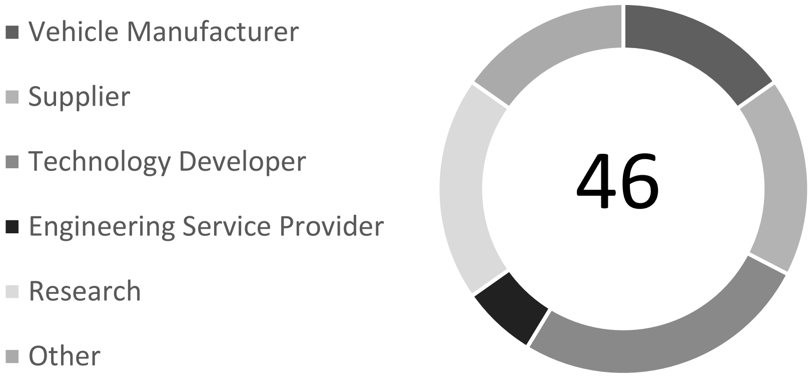


- **2013 roadmap focused on a number of different motor architectures** that could be applied for <40kW and >100kW electric machines.
- 2017 roadmap recognises that **e-machine development is broadly focussed on both increasing technical performance and reducing cost** in mass market products.
- **2017 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.
- **More emphasis has been placed on materials and manufacturing processes** reflecting their importance in delivering cost competitive and sustainable solutions.
- **A number of technology evolutions occur after 2025** which reflects the immaturity of the current e-machine automotive mass market and the need for targeted R&D on future applications.
- **The roadmap reflects greater alignment with the power electronics roadmap,** recognising that future product developments will lead to greater compatibility and integration.

Update process: *The Electric Machine Roadmap was updated via a structured consensus-building process involving 46 experts*

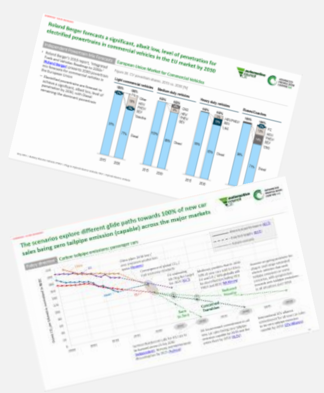
- A public workshop was held at the Advanced Propulsion Centre office in London, Stratford on the 25th January 2017
- The process was co-ordinated by the Advanced Propulsion Centre on behalf of Automotive Council
- The Advanced Propulsion Centre Electric Machine Spoke, supported by an expert Steering Group, helped to shape the roadmap before and after the workshop

Electric Machine Steering Committee and Workshop Attendees



Pre-Event Email — 1 day workshop with 40 attendees — Post-Event Email

Pre-event Common Assumptions Briefing



Collective Briefing Process

Breakout Sessions

Post-Event Debrief

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Technical targets: *Mass market adoption of ultra low emission vehicles underpins challenging cost and performance targets for electric machines*

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Drivers of change

- **CO_2 and air quality** objectives challenge the universal application of ICE powertrains
- **Electrification** features in product plans of almost every OEM across all sectors
- Electric machines feature in **all xEV formats** and larger ancillary machines used for steering and cooling
- Despite electric machines being used for over 100 years, **innovations are still needed in electric machines specifically designed for vehicle traction**
- **In order to meet mainstream automotive demands** increased reliability, lower overall systems cost using widely available materials and higher performance are required
- In response to these challenges significant innovation is needed. **Ambitious electric machine targets have been set which cannot be attained using existing designs.**

Passenger Car Traction Motor[1]	2017	2025	2035
Cost ($/kW)[2]	10	5.8	4.5
Continuous power density (kW/kg)	2.5	7	9
Continuous power density (kW/l)	7	25	30
Drive cycle efficiency (%)[3]	86.5	92.5	93
Truck and Bus Traction Motor[1]	**2017**	**2025**	**2035**
Cost ($/kW)[2]	60	15	12
Continuous power density (kW/kg)	1.5	2	2.5
Continuous power density (kW/l)	4.5	6	7
Drive cycle efficiency (%)[3]	83	88	90

1) All assume 350V / 450Amps @ 65degC inlet
2) Prices are 300% mark-up on material costs
3) Drive cycle based on WLTP

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Technology categories: *Parallel technical developments are required in electric machine architecture, integration, materials and supporting areas*

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
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MACHINE ARCHITECTURE

Machine architectures and topologies influences the performance and cost of electric machines

MACHINE INTEGRATION

How the electric machine is integrated with other powertrain components is key to overall system efficiency

MATERIALS & MANUFACTURING

- Windings and insulation
- Soft magnetics
- Permanent magnets

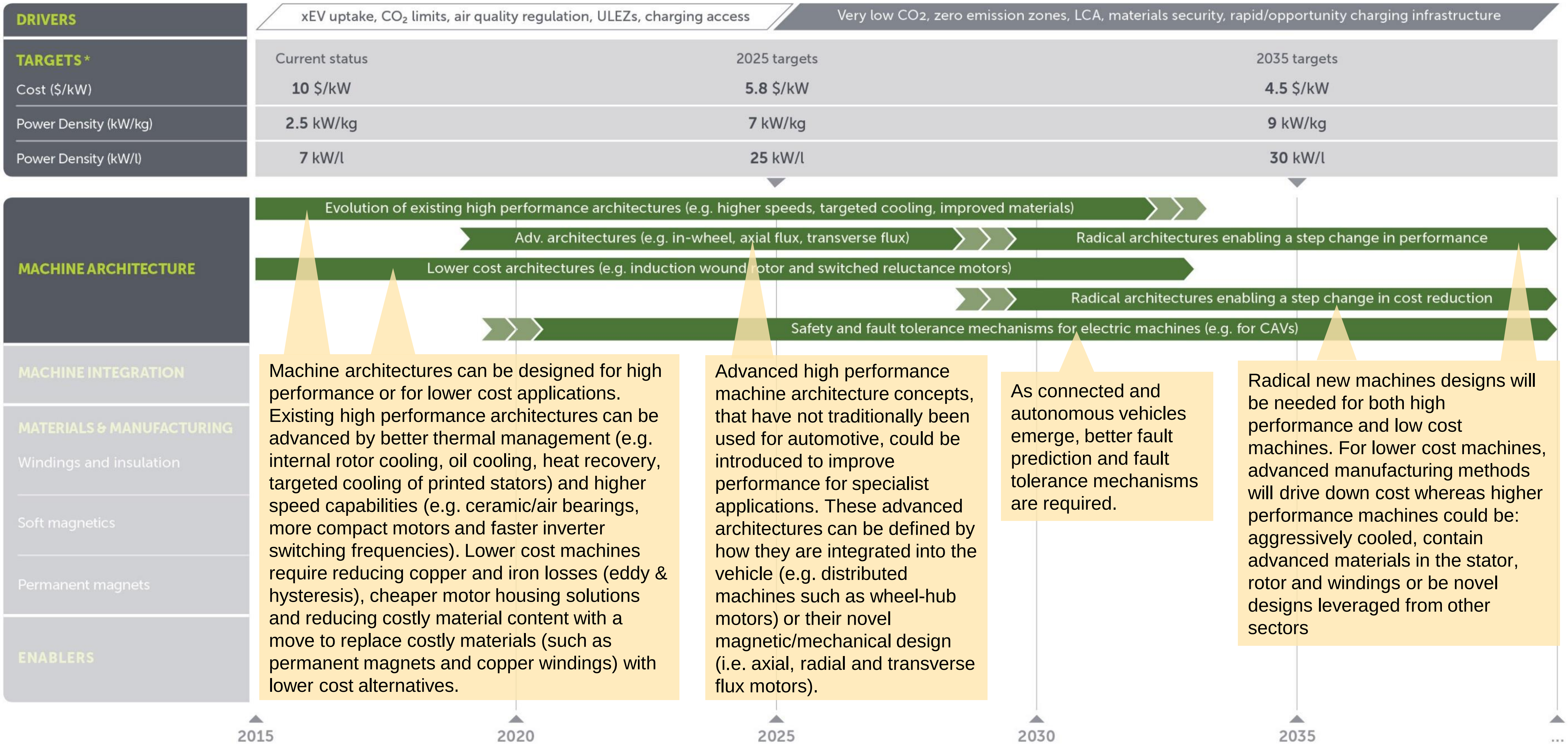
Materials and manufacturing methods are closely related, both are fundamental to cost and performance

ENABLERS

Several other technical aspects are required to support improvement

2015 | 2020 | 2025 | 2030 | 2035 | ...

Machine architecture: *Current machine architecture can be improved but new designs will be needed to meet longer term targets*



Machine integration: *Integrating an electric machine effectively into the vehicle powertrain is essential to overall system efficiency*

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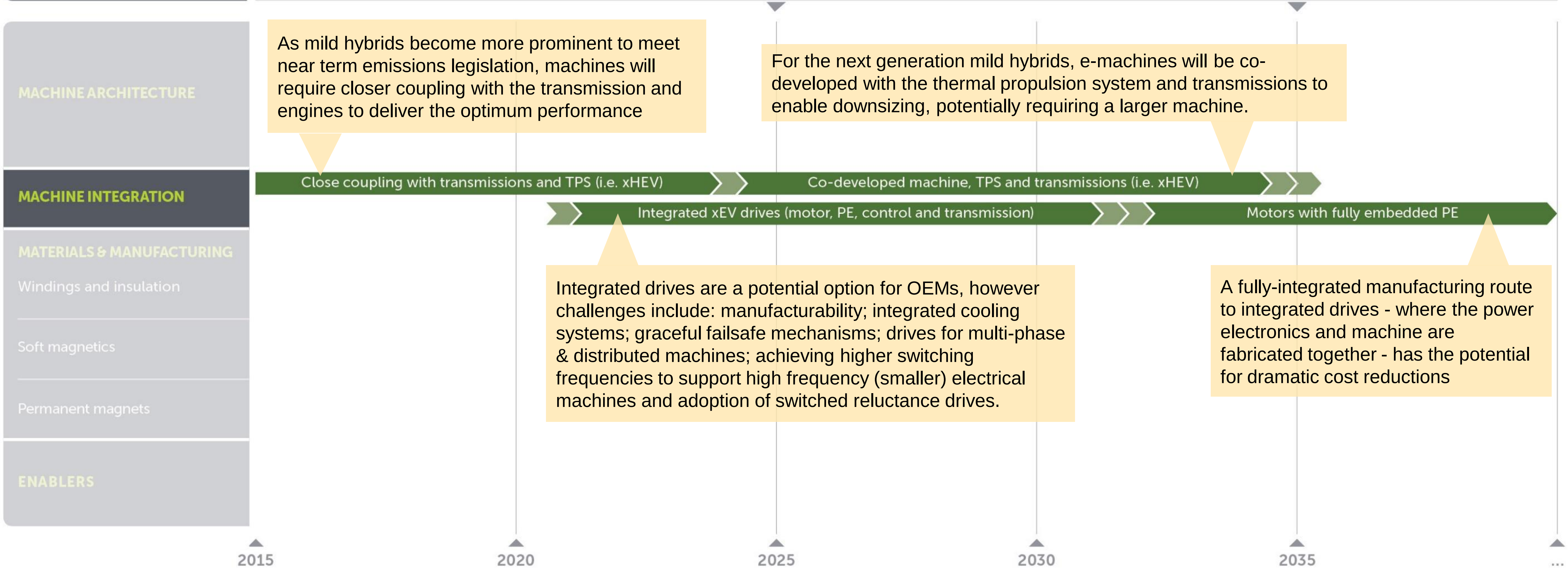

Materials and manufacturing: *New processes and materials for windings can significantly improve performance or lower cost*

DRIVERS

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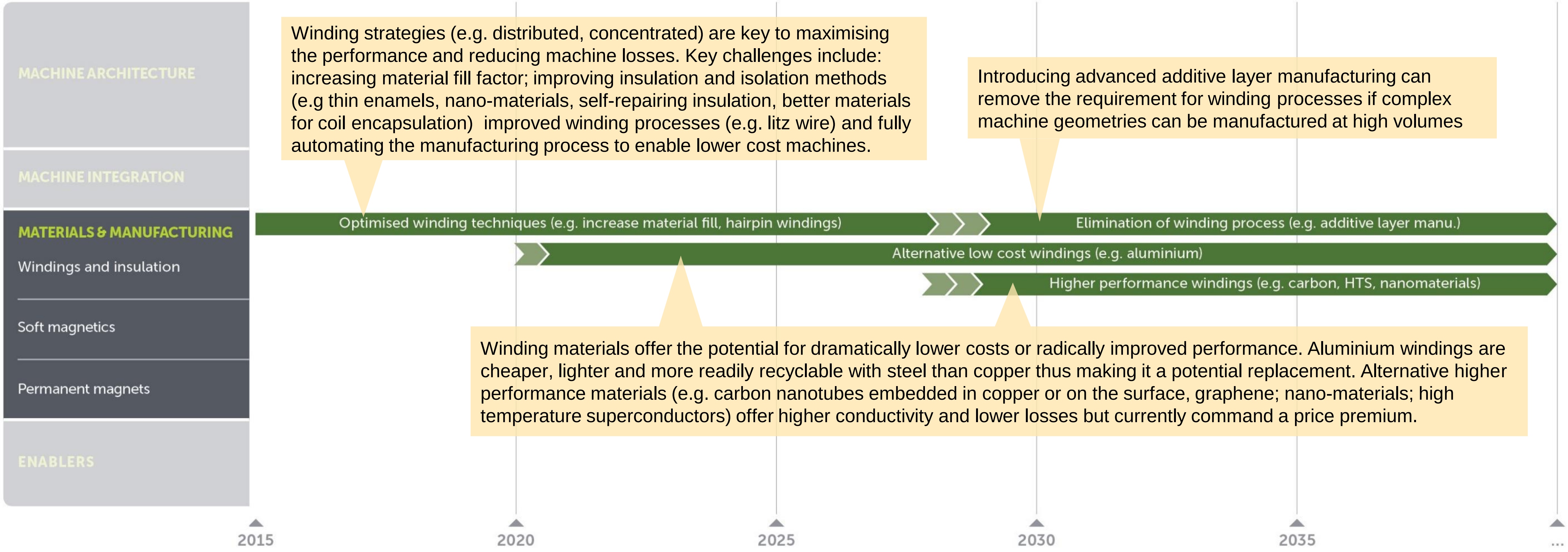

Winding strategies (e.g. distributed, concentrated) are key to maximising the performance and reducing machine losses. Key challenges include: increasing material fill factor; improving insulation and isolation methods (e.g thin enamels, nano-materials, self-repairing insulation, better materials for coil encapsulation) improved winding processes (e.g. litz wire) and fully automating the manufacturing process to enable lower cost machines.

Introducing advanced additive layer manufacturing can remove the requirement for winding processes if complex machine geometries can be manufactured at high volumes

Winding materials offer the potential for dramatically lower costs or radically improved performance. Aluminium windings are cheaper, lighter and more readily recyclable with steel than copper thus making it a potential replacement. Alternative higher performance materials (e.g. carbon nanotubes embedded in copper or on the surface, graphene; nano-materials; high temperature superconductors) offer higher conductivity and lower losses but currently command a price premium.

Materials and manufacturing: *Improvements in the material properties of electrical steels and soft magnetic composites can deliver cost and performance improvements*

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

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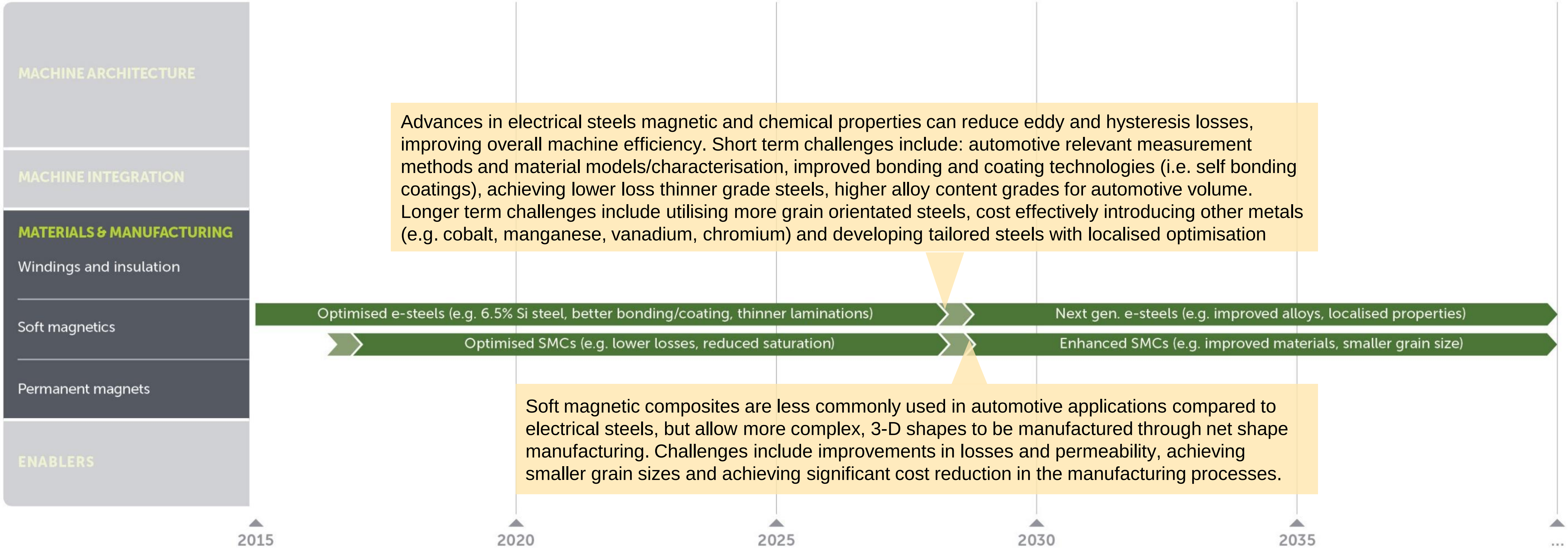

Materials and manufacturing: *Permanent magnet electric machines can be high cost so effective use of rare earth materials is needed*

DRIVERS

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MACHINE ARCHITECTURE

MACHINE INTEGRATION

MATERIALS & MANUFACTURING

Windings and insulation

Soft magnetics

Permanent magnets

- Eliminate heavy rare earths (e.g. Dy) → Eliminate rare earth content (e.g. other magnetic materials or magnet free)
- Refine manu. processes for consistent PM magnet attributes → Increased use of recycled rare earths (e.g. Nd)

Heavy rare earth materials such as Dysprosium are added to improve the temperature resistance of Neodymium but are expensive and strongly concentrated in China. There is a desire that these should be eliminated to reduce costs and supply risks.

Light rare earth magnets (e.g. Neodymium) are a significant cost to current electric machines. Architectures that do not use magnets (i.e. induction and switched reluctance) or alternative magnetic materials (i.e. ferrite magnets) are potential solutions.

New manufacturing processes are required to: allow thinner laminations to reduce eddy current losses; produce PMs with improved strength, durability and high temperature capability; manufacture new materials with improved electrical resistivity

Utilising recycled permanent magnets that maintain performance characteristics will enable a closed-loop supply chain for rare earths improving the cost and environmental performance of permanent magnet machines.

ENABLERS

2015 2020 2025 2030 2035 ...

Enablers: *A number of supporting innovations are essential to meet the performance and cost targets*

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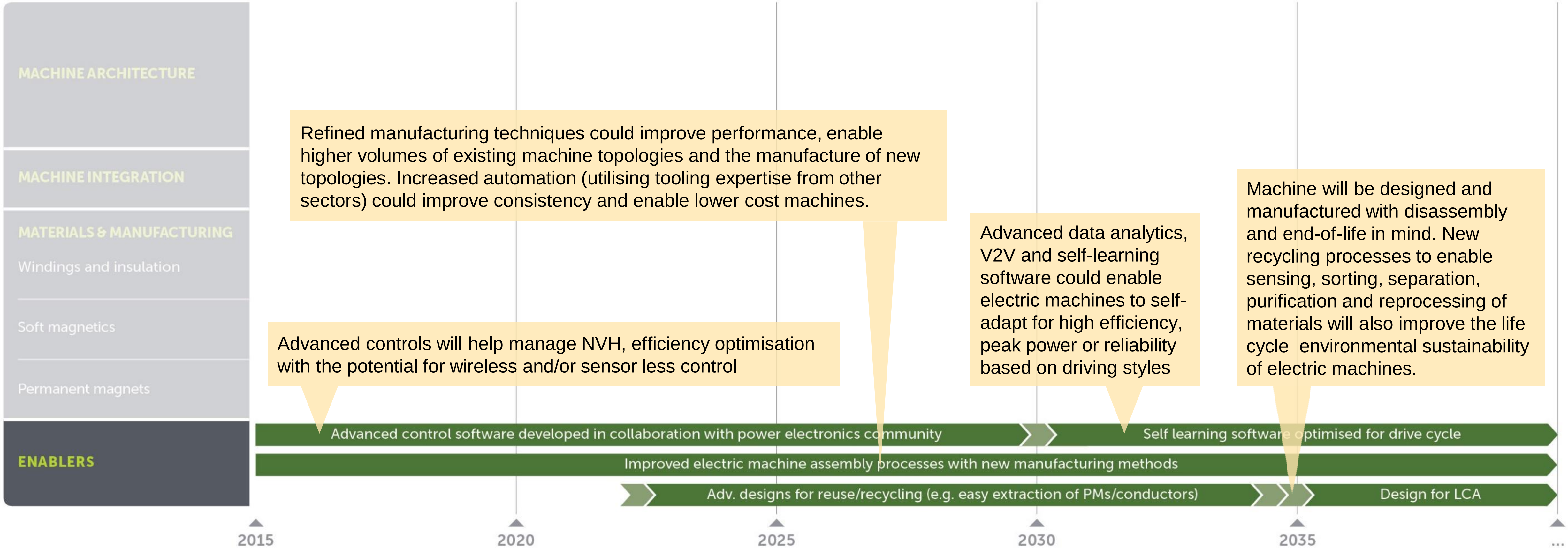

TECHNOLOGY ROADMAP 2017: ELECTRIC MACHINES

Roadmap developed by the Automotive Council and the Advanced Propulsion Centre

automotive council UK

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	2015 → 2025	2025 → …
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MACHINE ARCHITECTURE

- Evolution of existing high performance architectures (e.g. higher speeds, targeted cooling, improved materials)
- Adv. architectures (e.g. in-wheel, axial flux, transverse flux) → Radical architectures enabling a step change in performance
- Lower cost architectures (e.g. induction wound rotor and switched reluctance motors)
- Radical architectures enabling a step change in cost reduction
- Safety and fault tolerance mechanisms for electric machines (e.g. for CAVs)

MACHINE INTEGRATION

- Close coupling with transmissions and TPS (i.e. xHEV) → Co-developed machine, TPS and transmissions (i.e. xHEV)
- Integrated xEV drives (motor, PE, control and transmission) → Motors with fully embedded PE

MATERIALS & MANUFACTURING

Windings and insulation

- Optimised winding techniques (e.g. increase material fill, hairpin windings) → Elimination of winding process (e.g. additive layer manu.)
- Alternative low cost windings (e.g. aluminium)
- Higher performance windings (e.g. carbon, HTS, nanomaterials)

Soft magnetics

- Optimised e-steels (e.g. 6.5% Si steel, better bonding/coating, thinner laminations) → Next gen. e-steels (e.g. improved alloys, localised properties)
- Optimised SMCs (e.g. lower losses, reduced saturation) → Enhanced SMCs (e.g. improved materials, smaller grain size)

Permanent magnets

- Eliminate heavy rare earths (e.g. Dy) → Eliminate rare earth content (e.g. other magnetic materials or magnet free)
- Refine manu. processes for consistent PM magnet attributes → Increased use of recycled rare earths (e.g. Nd)

ENABLERS

- Advanced control software developed in collaboration with power electronics community → Self learning software optimised for drive cycle
- Improved electric machine assembly processes with new manufacturing methods
- Adv. designs for reuse/recycling (e.g. easy extraction of PMs/conductors) → Design for LCA

2015 2020 2025 2030 2035 …

** All targets relate to an EV passenger car traction motor with continuous power targets*

***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*

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- **CAVs (Connected and autonomous vehicles) –** *Connected and autonomous vehicles is an umbrella term to capture the varying levels of autonomy and technologies relating to self-driving vehicles.*

- **Dy (Dysprosium) –** *Dysprosium is a heavy rare earth material that is used alongside Neodymium. Dy has been essential in making it possible to use NdFeB magnets in high power density applications such as vehicle traction*

- **HTS (High temperature superconductors) –** *Developmental conductor materials that are extremely conductive compared to copper but require low temperatures (between -240ºC and -70ºC) in order to conduct efficiently.*

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

- **Nd (Neodymium) –** *Neodymium is a light rare earth material that is widely used as a rare earth material in automotive electric machines. In order to make a usable magnet, Neodymium is usually alloyed with Iron and Boron to create NdFeB magnets.*

- **SMCs (Soft magnetic composites) –** *Soft magnetic composites (SMC's) are an alternative to electrical steels. They are made of iron powder particles coated with an electrically insulating layer and they can be moulded into complex shape under high pressure in a die.*

- **TPS (Thermal propulsion systems) –** *Thermal propulsion system is the Automotive Council's new term for internal combustion engines. It is a device that integrates an engine or fuel cell with thermal and / or electrical systems to manage power delivery to the wheels and recover waste energy to improved performance and efficiency. The key feature of a TPS is that the primary energy is stored chemically (rather than electrochemically like in a battery)*

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

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