

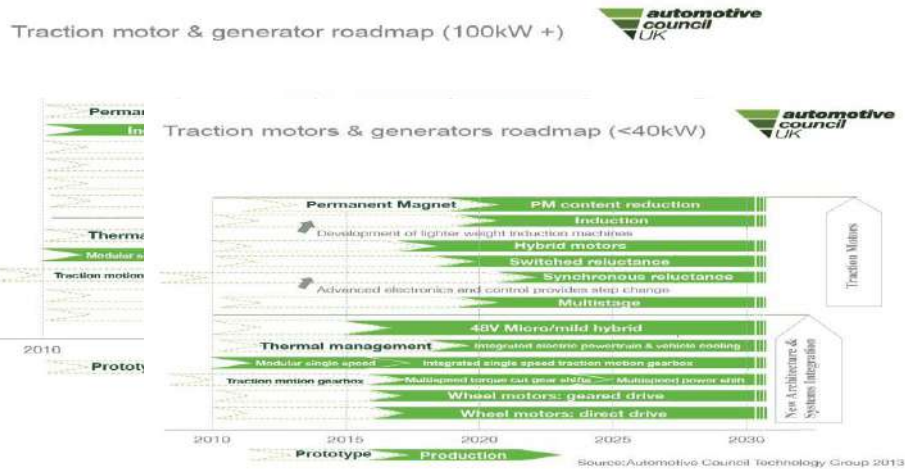


Electric Machines Roadmap



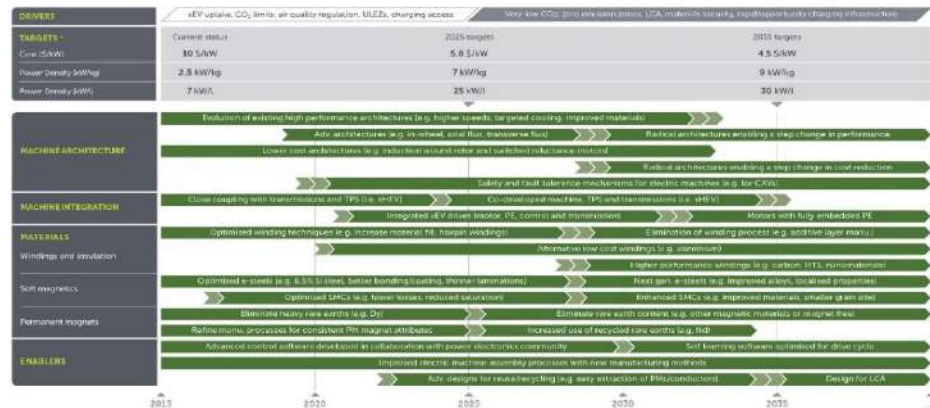
Updated by the Advanced Propulsion Centre in collaboration with and on behalf of the Automotive Council

Executive summary – Electric machines



TECHNOLOGY ROADMAP 2017: ELECTRIC MACHINES

Partnership developed by the Automotive Council and the Advanced Propulsion Centre

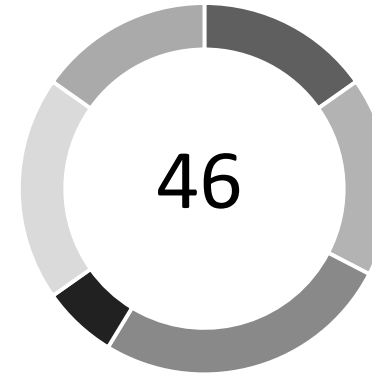


- **2013 roadmap focused on a number of different motor architectures** that could be applied for <40kW and >100kW electric machines.
- 2017 roadmap recognises that **e-machine development is broadly focussed on both increasing technical performance and reducing cost** in mass market products.
- **2017 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*

Electric Machine Steering Committee and Workshop Attendees

- Vehicle Manufacturer
- Supplier
- Technology Developer
- Engineering Service Provider
- Research
- Other



- 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



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



Drivers of change

- **CO₂ 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.**

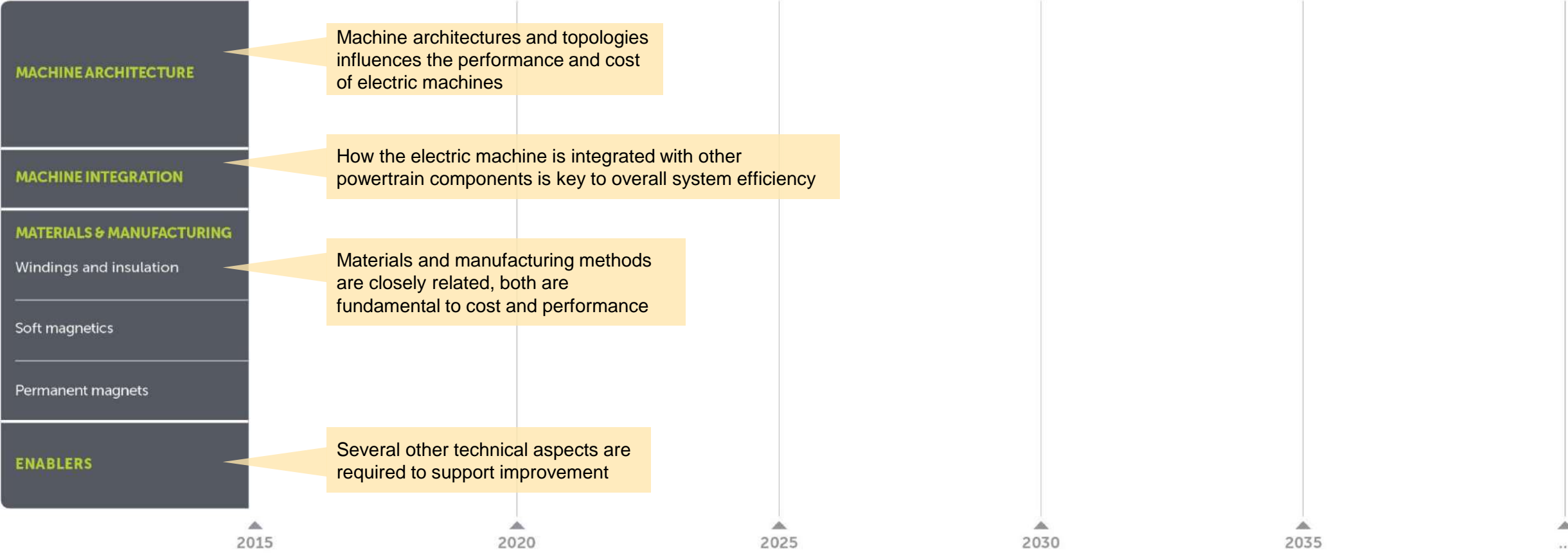
| Passenger Car Traction Motor ¹ | 2017 | 2025 | 2035 |
|-------------------------------------------|------|------|------|
| Cost (\$/kW) ² | 10 | 5.8 | 4.5 |
| Continuous power density (kW/kg) | 2.5 | 7 | 9 |
| Continuous power density (kW/l) | 7 | 25 | 30 |
| Drive cycle efficiency (%) ³ | 86.5 | 92.5 | 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

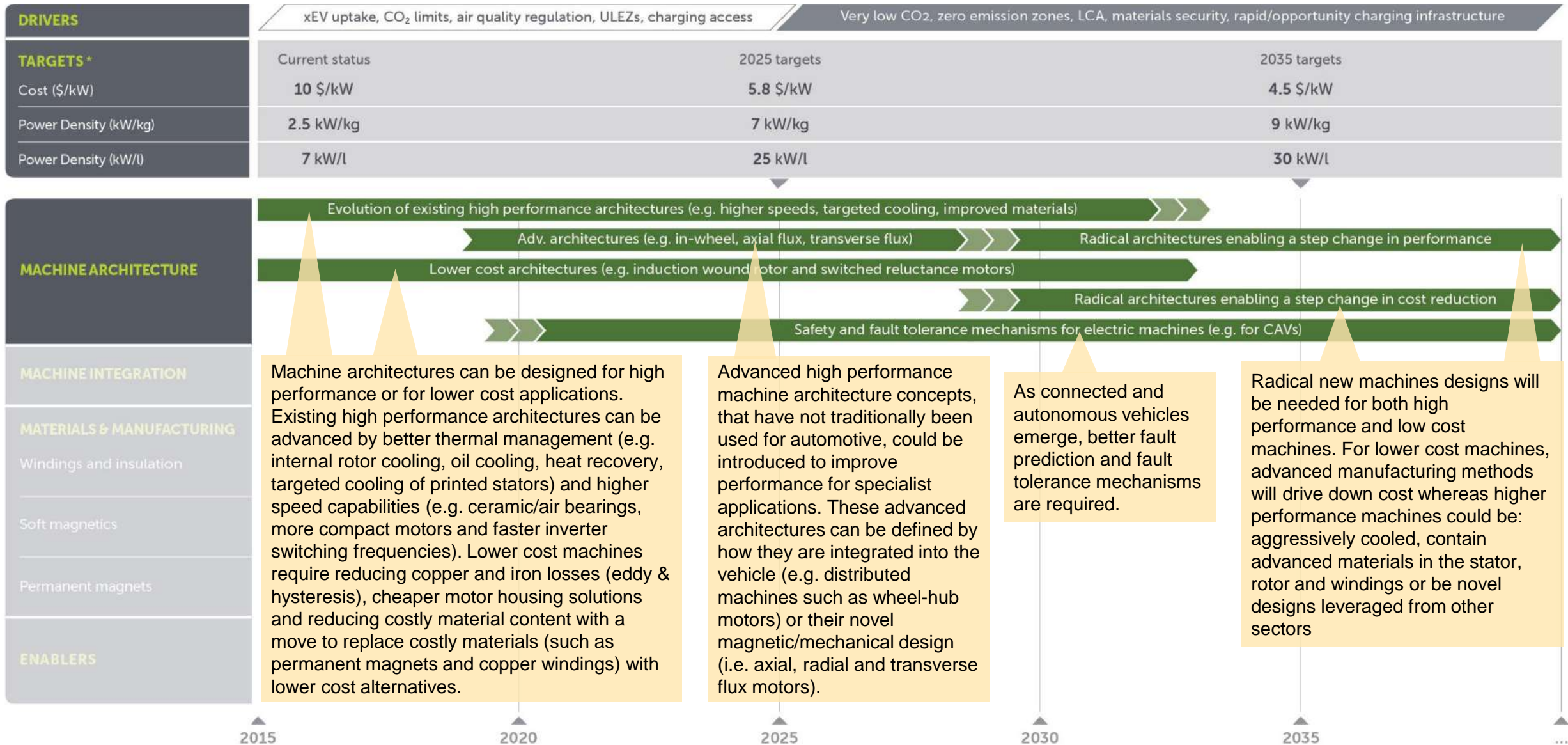


Technology categories: *Parallel technical developments are required in electric machine architecture, integration, materials and supporting areas*

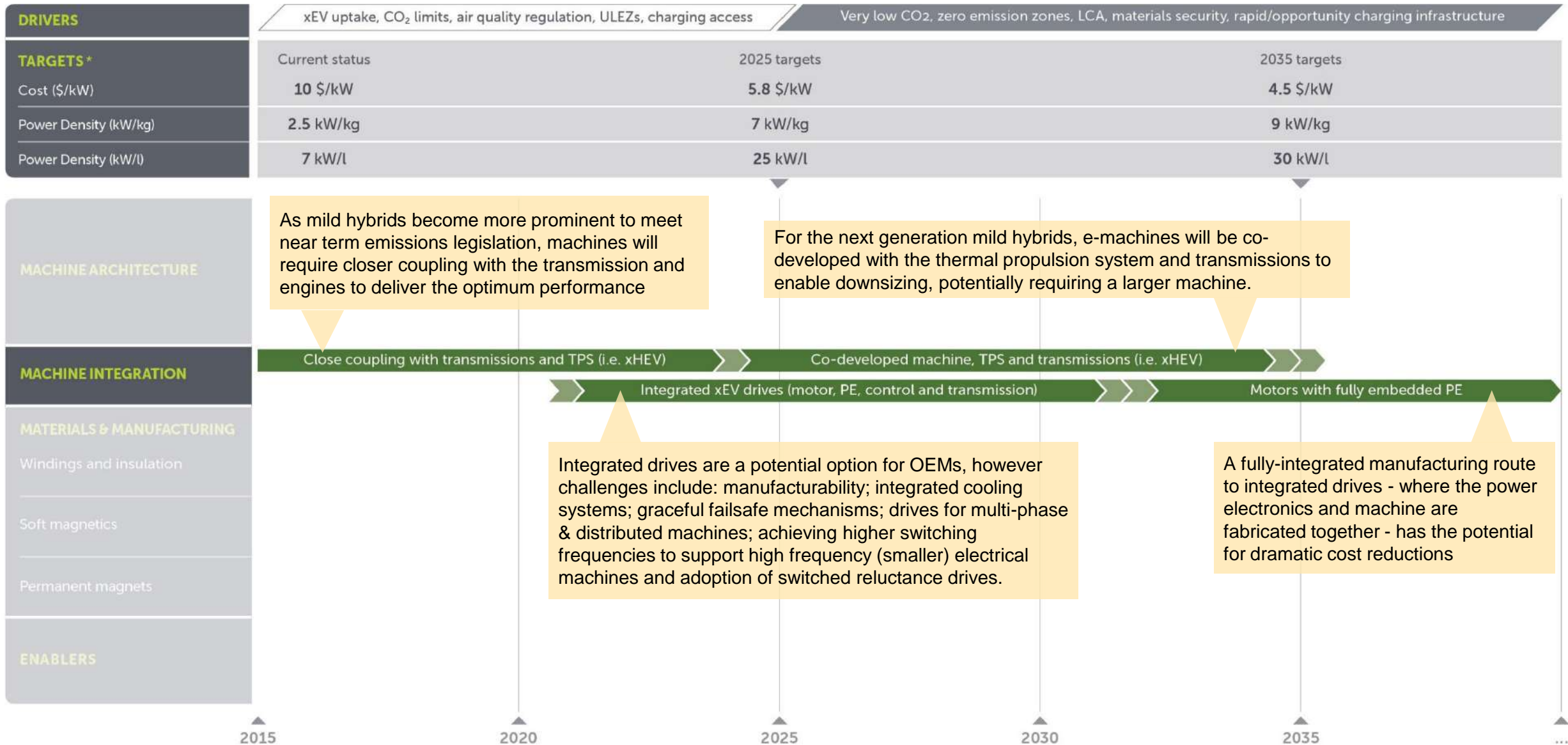
| DRIVERS | xEV uptake, CO ₂ limits, air quality regulation, ULEZs, charging access | | Very low CO ₂ , zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure | |
|-----------------------|------------------------------------------------------------------------------------|--------------|--------------------------------------------------------------------------------------------------------------------|--|
| TARGETS* | Current status | 2025 targets | 2035 targets | |
| Cost (\$/kW) | 10 \$/kW | 5.8 \$/kW | 4.5 \$/kW | |
| Power Density (kW/kg) | 2.5 kW/kg | 7 kW/kg | 9 kW/kg | |
| Power Density (kW/l) | 7 kW/l | 25 kW/l | 30 kW/l | |



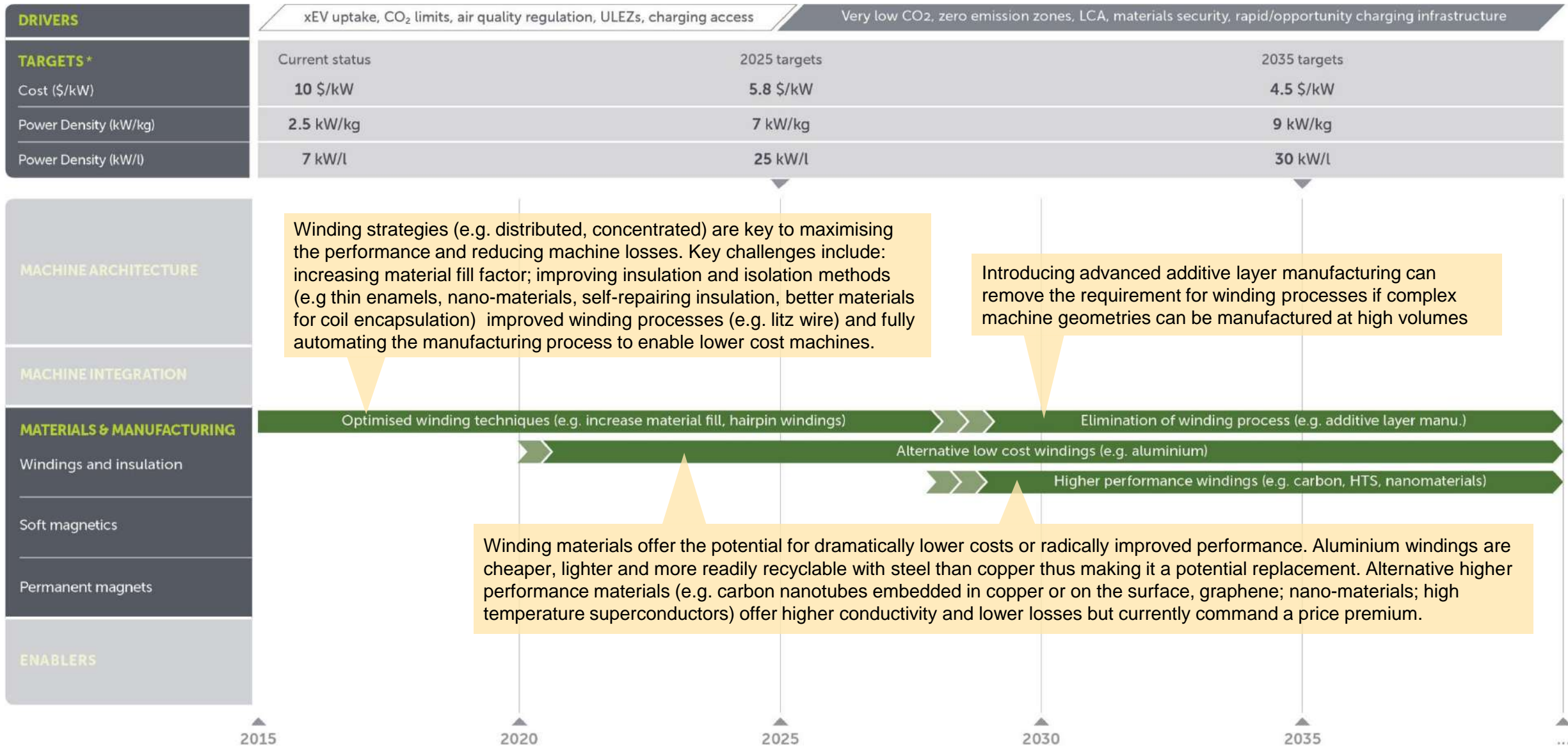
Machine architecture: *Current machine architecture can be improved but new designs will be needed to meet longer term targets*



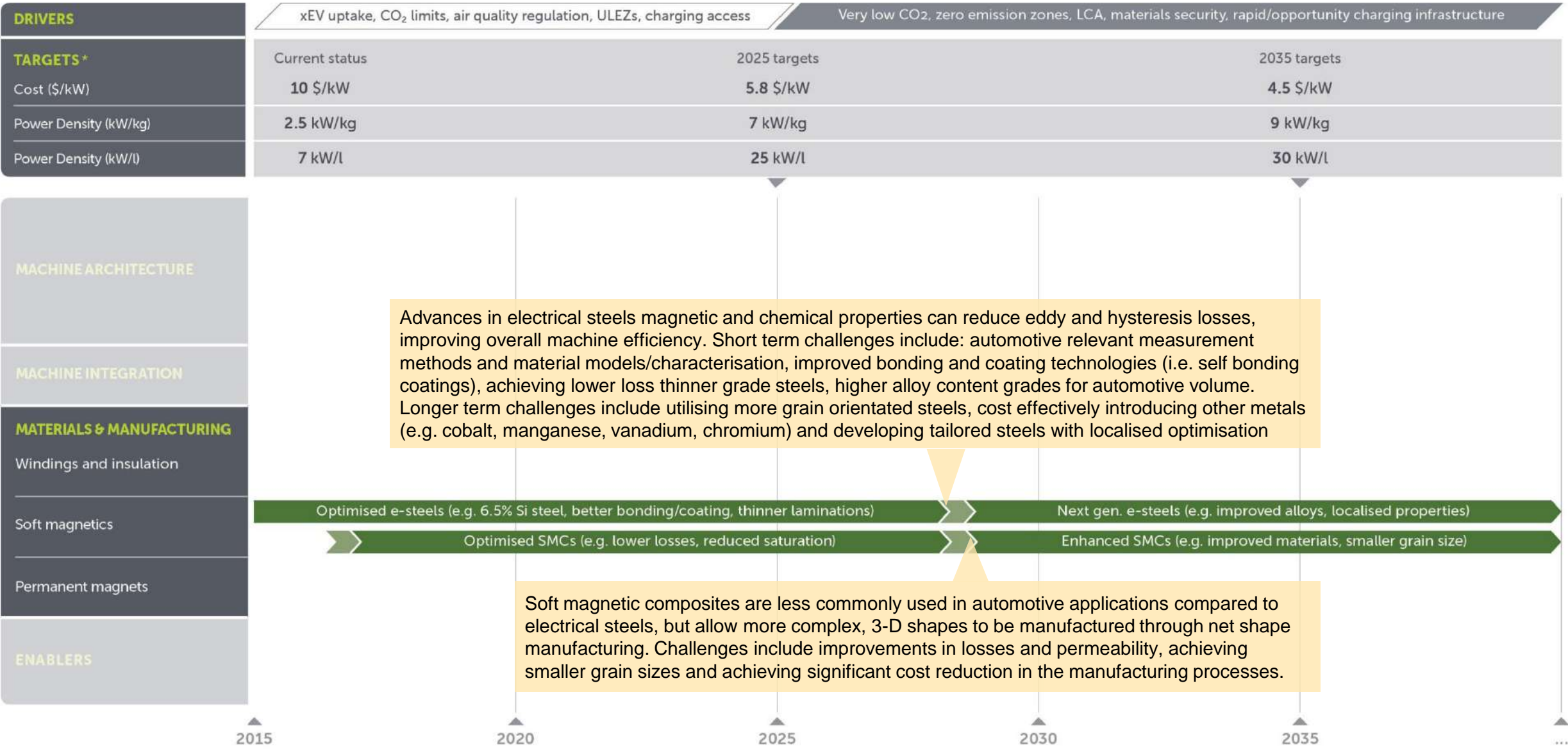
Machine integration: Integrating an electric machine effectively into the vehicle powertrain is essential to overall system efficiency



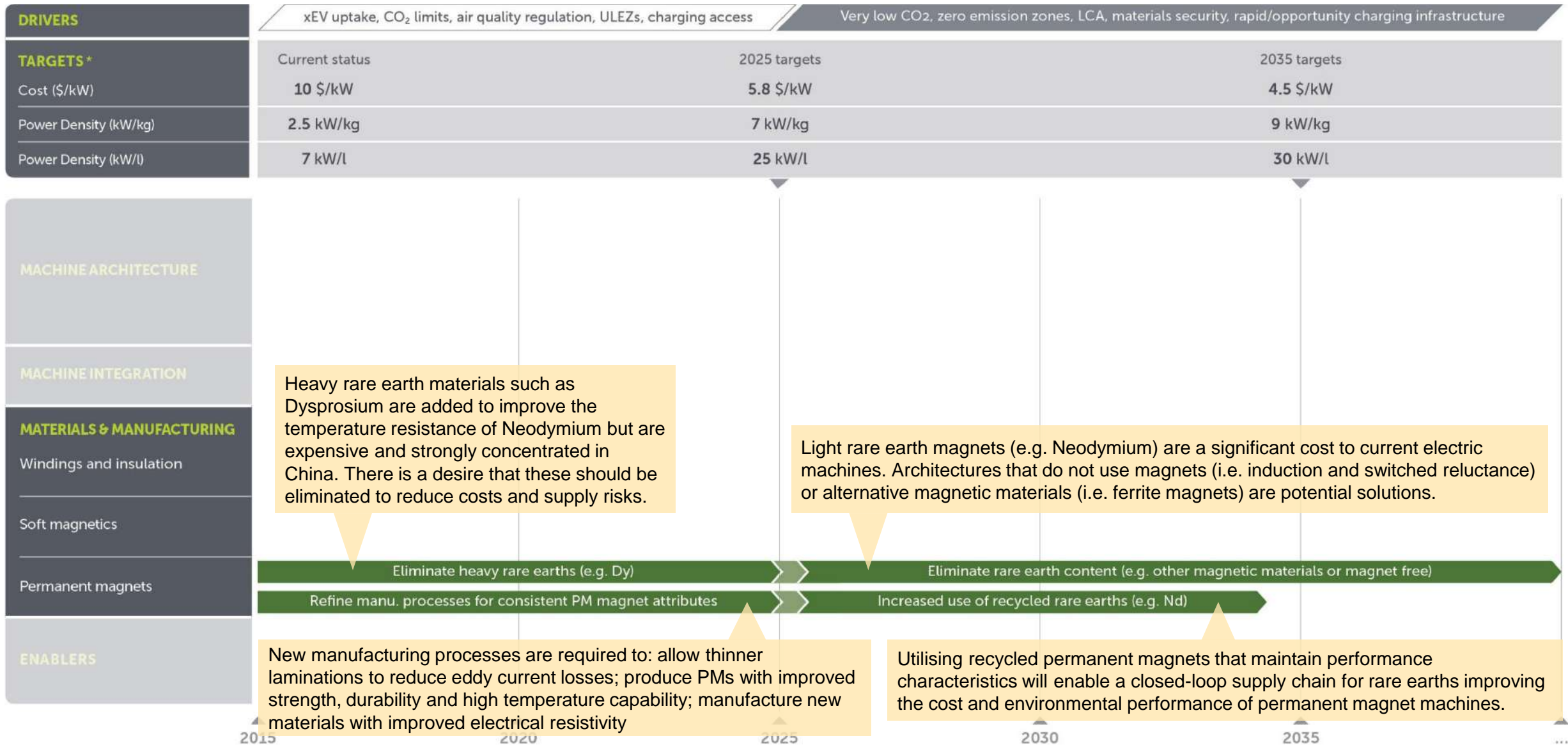
Materials and manufacturing: *New processes and materials for windings can significantly improve performance or lower cost*



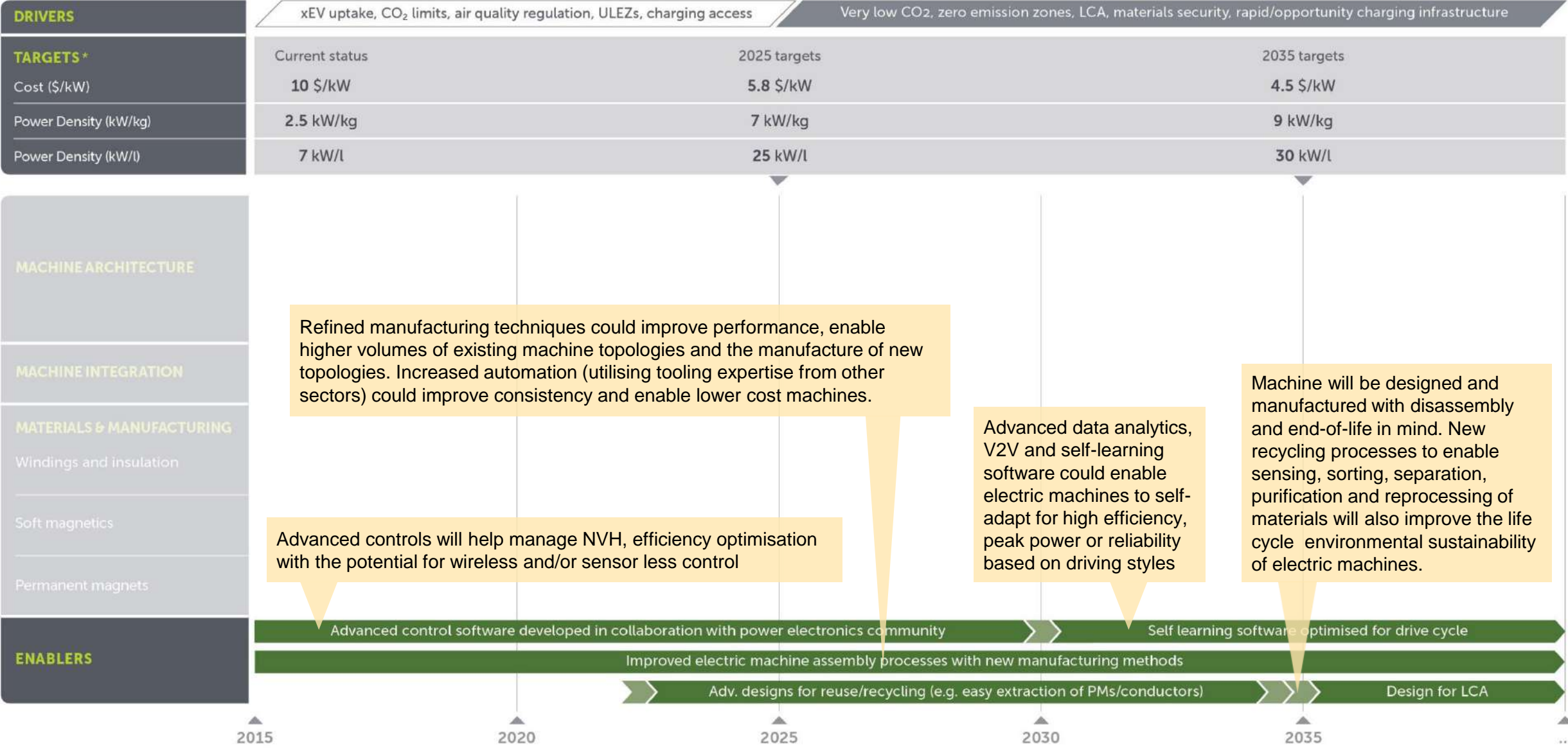
Materials and manufacturing: Improvements in the material properties of electrical steels and soft magnetic composites can deliver cost and performance improvements



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



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



TECHNOLOGY ROADMAP 2017: ELECTRIC MACHINES

Roadmap developed by the Automotive Council and the Advanced Propulsion Centre



* 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*



- **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 -240°C and -70°C) 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.*

