ELECTRICAL PROPULSION SYSTEMS

Roadmap Report

FZO-PPN-COM-0030

Published March 2022

CONTENTS

KEY & LIST OF ABBREVIATIONS

Key

Essential Development	*Development required to bring roadmap technology to market.*
Competitive Development	*Development which delivers performance improvement.*
Technology Mature	*Transition to further integration and production readiness.*
Essential Enabler	*Supporting activity or infrastructure to enable technology development*
Competitive Enabler	*Supporting activity or infrastructure to enable technology development*
Technology Mature	*Transition to further integration and production readiness.*

List of Abbreviations

CNT – Carbon Nanotube
EMI – Electro-Magnetic Interference
HMM – Hard Magnetic Material
LH_2 – Liquid Hydrogen
MDO – Multi-Disciplinary (MD) Optimisation
NPC – Neutral Point Clamped
PEEK – Polyether Ether Ketone
PEM – Proton Exchange Membrane
PM – Permanent Magnet
SMM – Soft Magnetic Material
SPM – Surface Mount Permanent Magnet
TMS – Thermal Management System

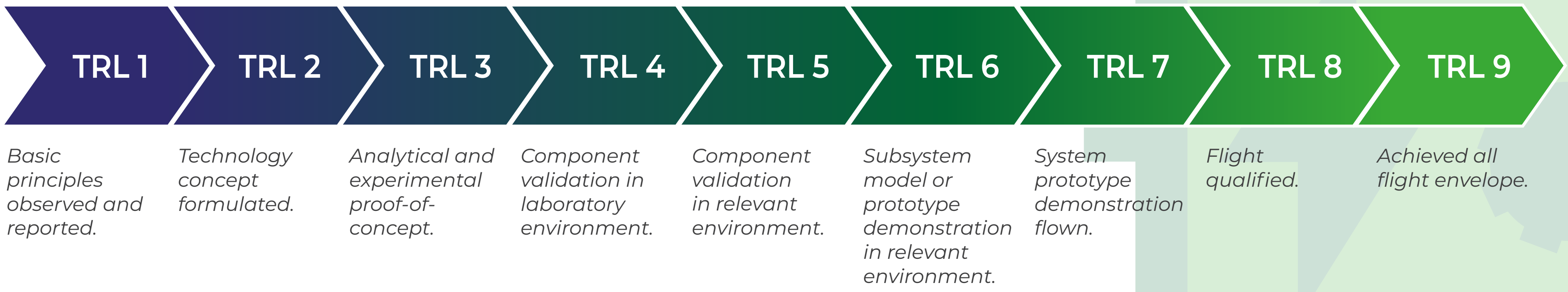


Figure 1 – Technology has been assessed against the NASA Technology Readiness Level (TRL) scale

OVERVIEW: ELECTRICAL PROPULSION SYSTEMS

This roadmap and accompanying report recommends technologies to make electrical propulsion viable for zero emission flight.

FlyZero has identified liquid H_2 (LH_2) as the most viable energy source for a zero emission aircraft. The FlyZero team assessed a hydrogen fuel cell powered electrical propulsions system, identifying that the power density of the system would be the primary parameter to optimise. Initial assessment showed that an electrical propulsion system would be significantly heavier than a gas turbine equivalent; however, it was an unexplored area with significant potential for improvement.

The electrical propulsion system considered within FlyZero uses proton exchange membrane (PEM) fuel cells as the power source, electric motor driven propeller and all the associated conversion and distribution systems. For the scope of FlyZero, electric propulsion was evaluated on a regional concept due to the weight challenges mentioned above. However, as the technology is developed it can be utilised on bigger platforms.

An advantage of distributed propulsion and modularity of electrical propulsion system is the possibility of novel airframe design and reduction in propulsion requirement due to the in-built redundancy of the architecture.

Battery electric was considered in the initial phase of the project, however with a relatively poor energy density of batteries it was discounted as a viable solution to make an impact on the market segments FlyZero is targeting. However it is still a viable solution for the advanced air mobility market.

It was also estimated that an electrical propulsion system provides a superior fuel burn efficiency than an equivalent LH_2 gas turbine turboprop which might play a big role in the operating cost of a LH_2 powered fleet. Our current estimates show electrical propulsion system efficiency to be ~55-60% compared to a LH_2 gas turbine engine of ~44% (fuel-to-shaft).

This report covers the system level assessments, technology indicators and proposed development roadmaps for electrical propulsion system. Certain components such as fuel cell and associated balance of plant are covered in detail in their own roadmap report due to the level of importance.

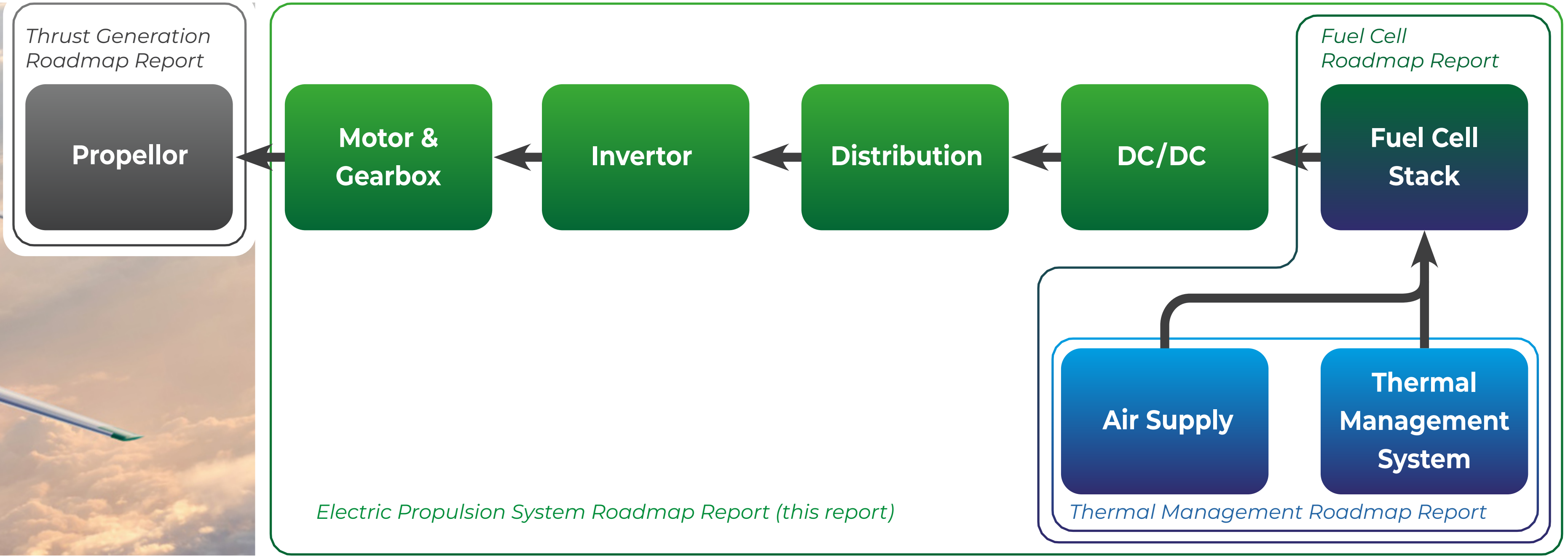
OVERVIEW: ELECTRICAL PROPULSION SYSTEMS

An electrical propulsion system was evaluated for the FlyZero regional concept shown below. This concept showcases distributed propulsion with six motor driven propellers. The propulsion architecture is shown below from propeller to the fuel cell modules.

To maximise the advantage of distributed propulsion six independent electrical channels were chosen. Due to the modularity of electrical propulsion systems, splitting components into multiple channels did not incur a significant weight penalty. Instead it provided enhanced availability at the aircraft level. The additional redundancy also allowed for reducing the power requirements for single engine failure condition.

Although the regional concept required ~0.75 MW shaft power per propeller, the assessments performed by the team were scaled from 0.5 MW to 4 MW to understand scalability. No significant variation in system level power density or efficiency was observed within this range. To transmit power, 1 kV to 3 kV voltage levels were deemed essential. Below these levels the transmission became prohibitive due to resistive losses and the mass of the cables.

As well as improving the gravimetric power density of the system, thermal management was identified as a key area of optimisation. As the thermal management system (TMS) contributes a sizable proportion of the overall mass, improvement of efficiency of each of the components will be essential to improve the system performance.

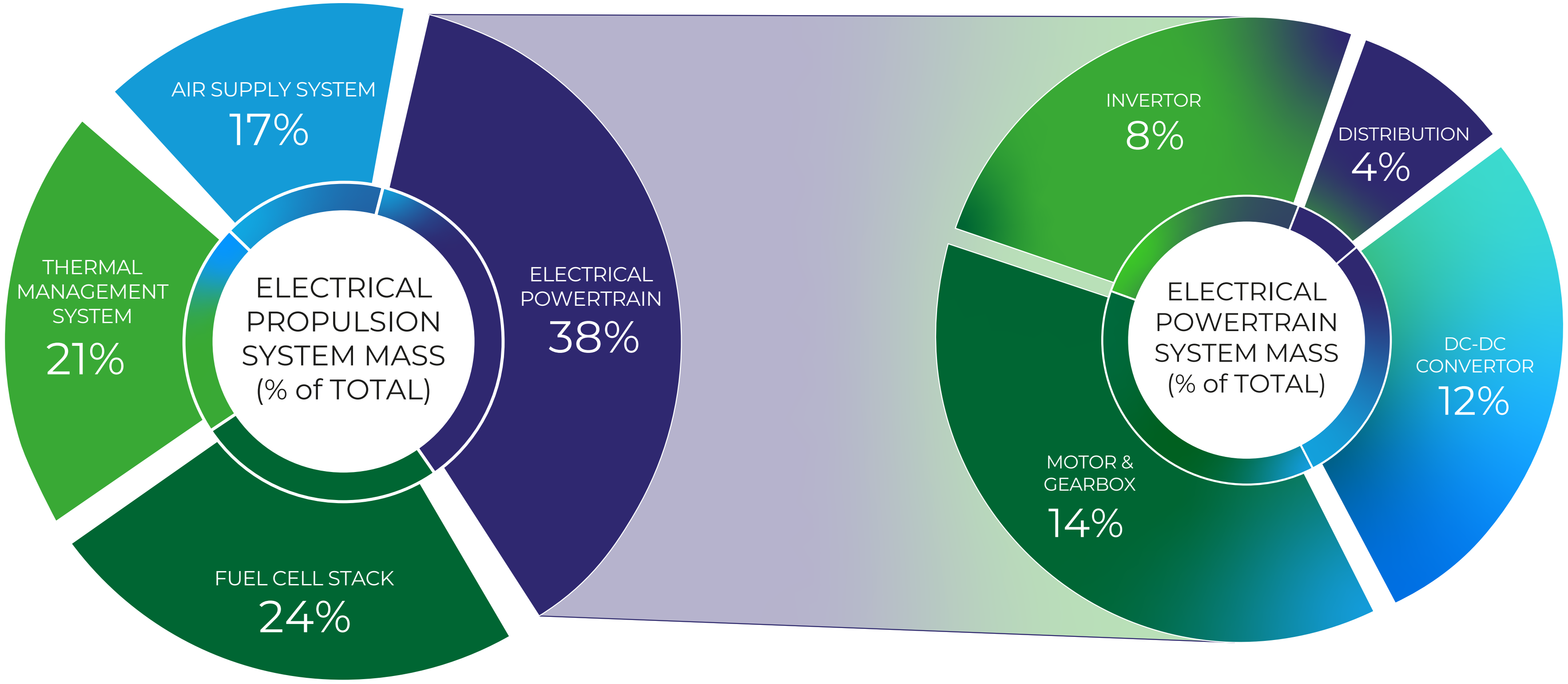


Note *for the remainder of the report the references to electrical propulsion system refers to all the components shown in the architecture above except the propeller.*

MASS BREAKDOWN

The chart below shows the mass breakdown for the entire electrical propulsion system. It shows that the TMS is a big proportion of the overall system. This indicated that an improvement in overall system efficiency is paramount to reducing the mass of the system. The biggest user of the TMS is the fuel cell module. A method of improving the efficiency of fuel cells is to oversize them, therefore utilise them below the rated power. Though this improves the efficiency of the fuel cell module it increases the mass of the fuel cell. A study undertaken by FlyZero indicated that oversizing the fuel cell module by 25% actually provides a net reduction of mass at the electrical propulsion system level. The reduction in TMS mass due to increased efficiency of the fuel cell would be greater than the increase in fuel cell mass.

Furthermore, this improved efficiency would improve the fuel burn, hence reducing the fuel mass for a particular mission. However this wasn't analysed in depth within FlyZero.



TECHNOLOGY INDICATORS

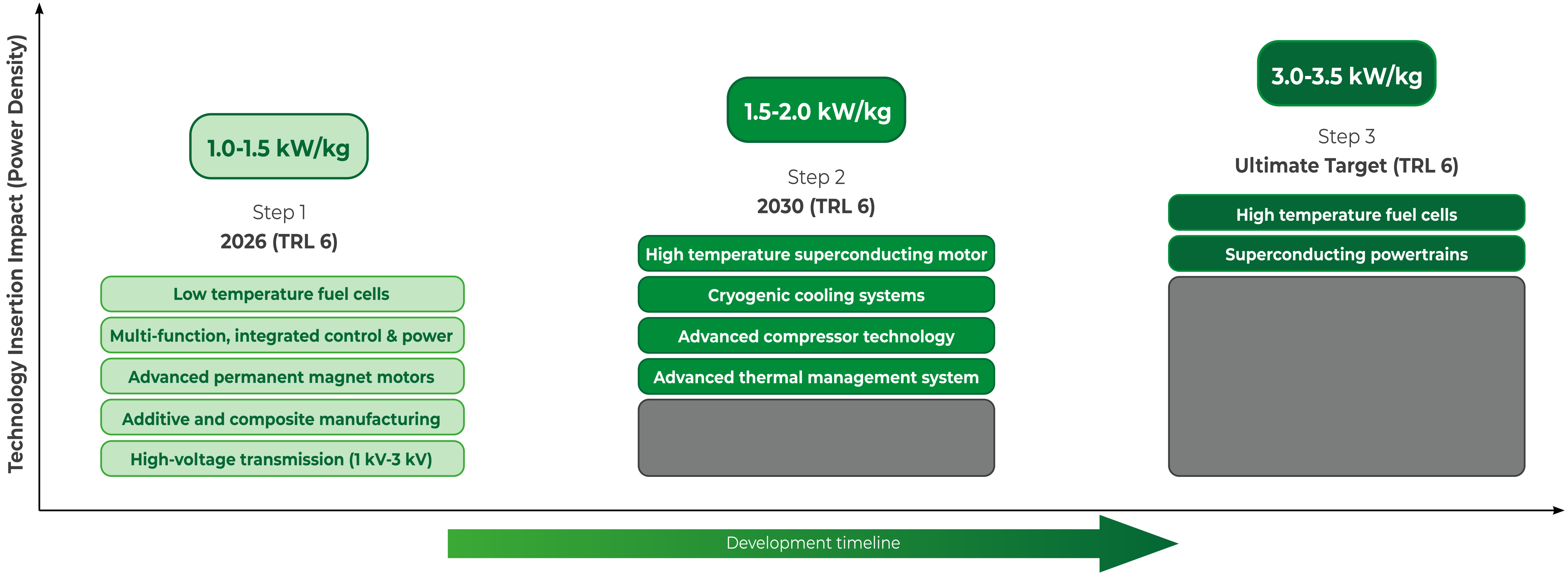
		2026	2030	Ultimate Target 2050
Electric motor	Power Density (kW/kg)	13	23	25
Power electronics (Inverter)	Power Density (kW/kg)	22	40	60
Power electronics (DC-DC)	Power Density (kW/kg)	15	40	60
Fuel cell stack	Power Density (kW/kg)	7	9	16
Thermal management system*	Power Density (kW/kg)	6	7	20
Air-supply system*	Power Density (kW/kg)	1	1	3
Electrical propulsion system	Power Density (kW/kg)	1.0-1.5	1.5-2.0	3.0-3.5

**For thermal management system and air supply system the power used to calculate power density refers to amount of heat dissipated, and compression power required to support the system.*

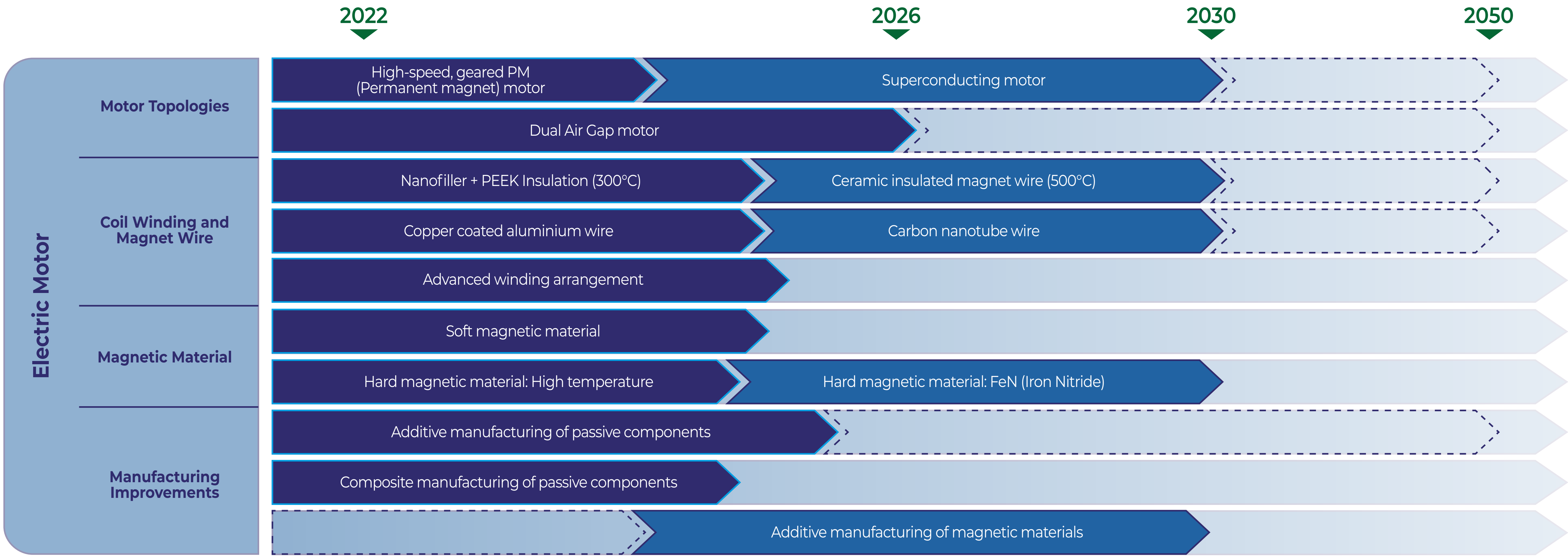
TECHNOLOGY STAIRCASE

The chart below shows the development of essential technologies, their potential insertion at specific points in time and the overall impact this could have on electrical propulsion system power density. The power density numbers need to be considered with opportunities of novel airframe designs, which are possible due to the flexibility of the electrical propulsion system. Though FlyZero hasn't explored designs such as blended wing body or wing mounted pods, it is a strong recommendation to evaluate these in conjunction with an electrical propulsion system.

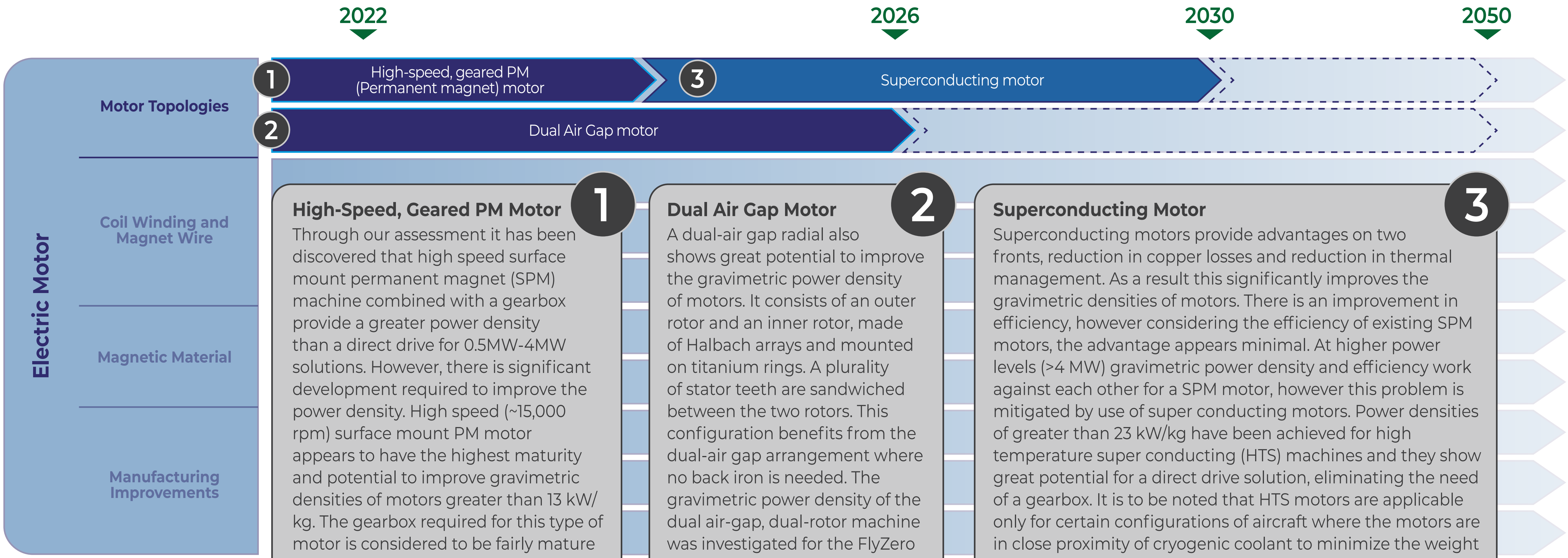
The ultimate target refers to a step change in high temperature fuel cell technology and implementation of superconducting powertrain. However, there is significant uncertainty on the development timeline for these technologies.



ELECTRIC MOTOR ROADMAP



ELECTRIC MOTOR ROADMAP



1 High-Speed, Geared PM Motor

Through our assessment it has been discovered that high speed surface mount permanent magnet (SPM) machine combined with a gearbox provide a greater power density than a direct drive for 0.5MW-4MW solutions. However, there is significant development required to improve the power density. High speed (~15,000 rpm) surface mount PM motor appears to have the highest maturity and potential to improve gravimetric densities of motors greater than 13 kW/kg. The gearbox required for this type of motor is considered to be fairly mature technology, however there is effort required to develop these high-power high-speed motors and integrating with a gearbox optimised for gravimetric power density.

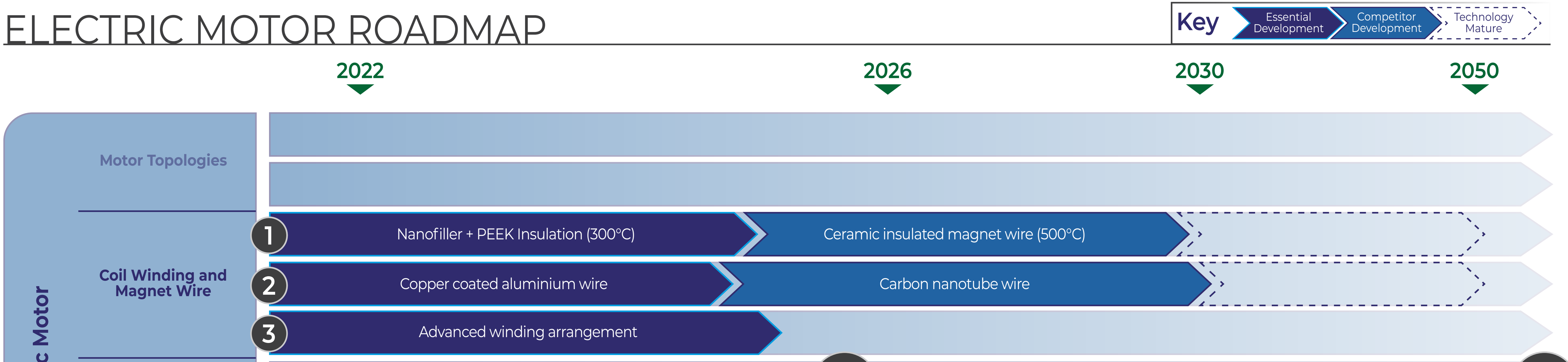
2 Dual Air Gap Motor

A dual-air gap radial also shows great potential to improve the gravimetric power density of motors. It consists of an outer rotor and an inner rotor, made of Halbach arrays and mounted on titanium rings. A plurality of stator teeth are sandwiched between the two rotors. This configuration benefits from the dual-air gap arrangement where no back iron is needed. The gravimetric power density of the dual air-gap, dual-rotor machine was investigated for the FlyZero configuration and improvements over 30% were predicted compared to the conventional SPM topology.

3 Superconducting Motor

Superconducting motors provide advantages on two fronts, reduction in copper losses and reduction in thermal management. As a result this significantly improves the gravimetric densities of motors. There is an improvement in efficiency, however considering the efficiency of existing SPM motors, the advantage appears minimal. At higher power levels (>4 MW) gravimetric power density and efficiency work against each other for a SPM motor, however this problem is mitigated by use of super conducting motors. Power densities of greater than 23 kW/kg have been achieved for high temperature super conducting (HTS) machines and they show great potential for a direct drive solution, eliminating the need of a gearbox. It is to be noted that HTS motors are applicable only for certain configurations of aircraft where the motors are in close proximity of cryogenic coolant to minimize the weight penalty of cryogenic cooling systems, and its benefits are only materialised at higher levels of shaft power (>4MW). In case of FlyZero concept aircrafts the LH_2 fuel could double us as a cryogenic coolant.

ELECTRIC MOTOR ROADMAP



1 Nanofiller + PEEK Insulation (300°C)

Often the operating temperatures of motors are governed by the insulation on the magnet wires. Higher operating temperatures allow for greater current and more efficient thermal management, consequentially improving the gravimetric power density. By adding thin nickel plating and nanofillers to the polyimide matrix, magnet wires rated to 280°C have been achieved.

To improve the insulation temperature further for magnet wires, ceramic coatings provide extremely high temperature tolerance of up to 500°C. Ceramics have been used in high temperature environments, but its use in magnet wire coating is challenging due to its brittleness. This currently prohibits thin ceramic insulation application for tightly packed magnet wire application. However the technology is promising, provided development is progressed. This would significantly improve the gravimetric power densities of motor.

2 Copper Coated Aluminium Wire

Another branch of magnet wire development is to improve the conducting wire material itself. Copper-coated aluminium wire combines the benefits of copper's high conductivity with aluminium's low mass-density to achieve a hybrid solution, with electrically insulating layer at the surface. Such wires have recently become available in commercial market, however its application on motors has been limited. The method appears to provide great advantage in improving power densities with accelerated time scales due the high level of maturity and availability.

To improve the conductive property of the wire further than traditional copper or aluminium materials, carbon nanotubes (CNT) provide a step change in conductivity. Magnet wires made out of CNT provide significant improvement in conductivity at a very low density, thus improving the overall power densities of motor. The current technology readiness level (TRL) levels of this technology is fairly lower however it is an area of great potential.

3 Advanced Winding Arrangement

The method of packing coils in a motor also have a big impact on its performance. Randomly wound coils have a very low packing density for copper (40%). This results in higher proportion of insulation material hence lowering the overall thermal conductivity. To improve this two promising technologies are recommended, preformed coils and transposed coil packing. These allow much higher packing density (>70%) providing an improvement in thermal conductivity and overall mass of the motor.

ELECTRIC MOTOR ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

2022 | 2026 | 2030 | 2050

Electric Motor

Motor Topologies

Coil Winding and Magnet Wire

Magnetic Material

1 Soft magnetic material

2 Hard magnetic material: High temperature → Hard magnetic material: FeN (Iron Nitride)

Manufacturing Improvements

1 Soft magnetic material

Soft magnetic materials (SMM) are used to direct the flux created by the coil windings. They result in iron losses for the motor. It is crucial to reduce these losses to materialise the advantage of higher frequency operation. High performance machines in the automotive industry are moving towards the use of 0.2mm-SiFe, such as the grade NO20 which reduces the core losses by 40% at 1kHz fundamental frequency.

Further reduction can be achieved by increasing the amount of silicon. If further weight savings are required by the application, CoFe grades may be used which have a higher saturation flux density. The improved performance of CoFe comes at a significant cost premium, with the cost per kg being roughly around ten times that of SiFe. However that might be acceptable for zero emissions aviation application.

2 Hard magnetic material: High temperature

Hard magnetic material (HMM) used in motors are also temperature constrained. Commonly available HMM have a lower operating temperature (~180°C). With advancement of high temperature material, such as samarium cobalt, operating temperature (500°C) can be achieved.

Another area of great potential is shown in development of FeN magnets. FeN magnets have the potential to improve the energy density by 40% compared to SoCo HMM and an additional advantage is they are rare-earth free, which elevates a significant concern on sourcing materials for manufacturing.

ELECTRIC MOTOR ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

2022 | 2026 | 2030 | 2050

Electric Motor

- Motor Topologies
- Coil Winding and Magnet Wire
- Magnetic Material
- Manufacturing Improvements

1

Additive & Composite Manufacturing of Passive Components

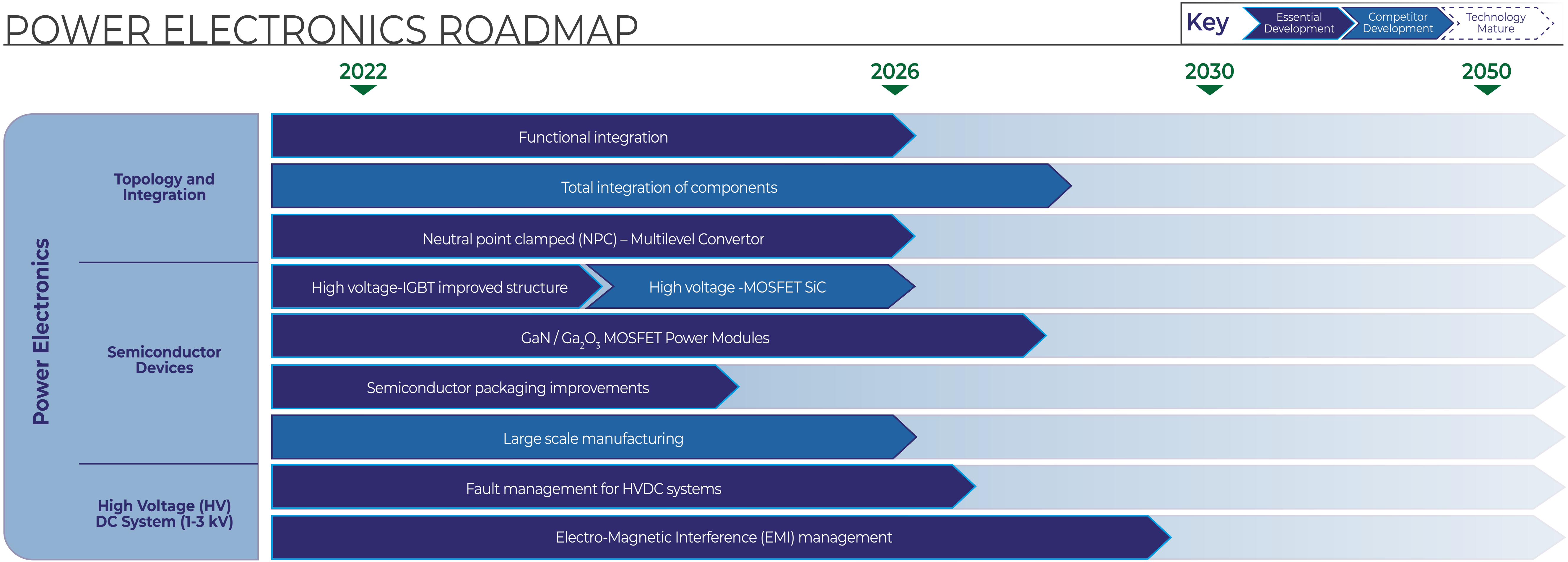
For an electric motor almost 50% of the mass is attributed to passive components. These components have been manufactured using traditional techniques, but using additive and composite manufacturing the mass of these passive components can be reduced significantly. Assessment has shown a reduction of more than 30%. Additive and composite manufacturing has been used actively in aerospace on safety critical structures and is considered proven and mature technology. However, its application on motor design has been limited. This has been identified as the single most mature technology to provide benefits as early as 2024.

To leverage the additive technology further, it can be applied to creating magnetic material of desired shapes and sizes. This could help reduce the mass of magnets required to achieve the same flux density. This technology is still very new and significant work is required to develop method to 3D print with the desired magnetic properties.

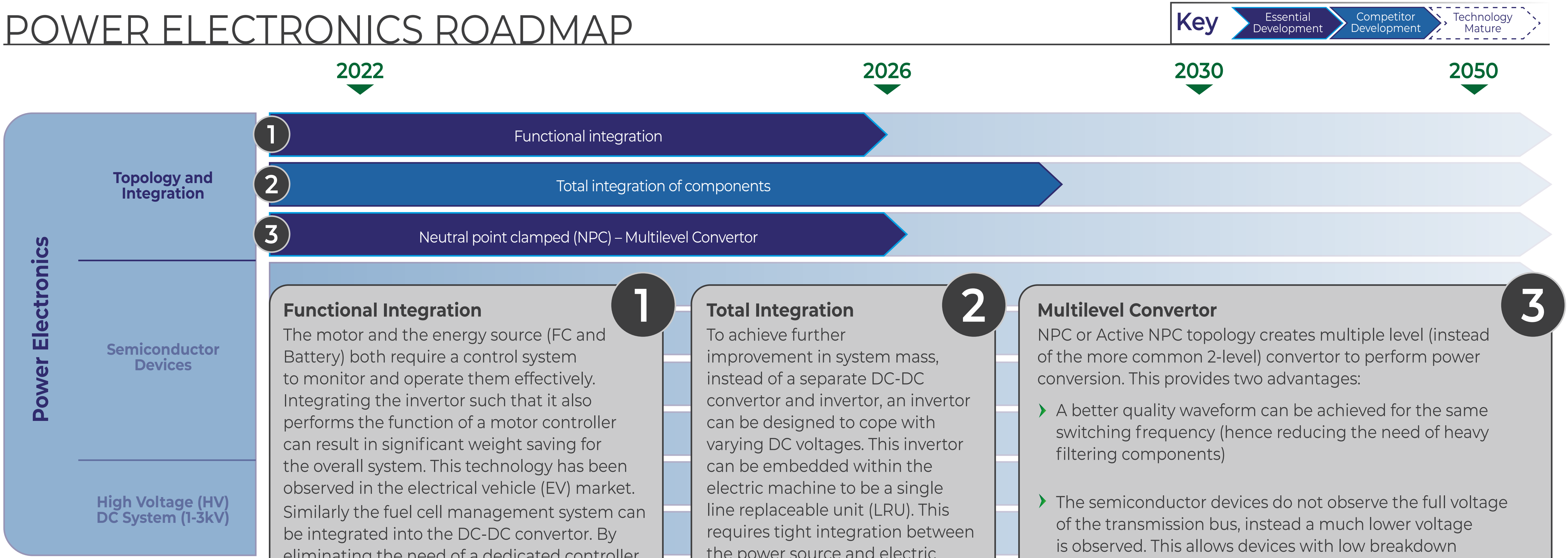
Manufacturing Improvements:

- Additive manufacturing of passive components
- 1 Composite manufacturing of passive components
- Additive manufacturing of magnetic materials

POWER ELECTRONICS ROADMAP



POWER ELECTRONICS ROADMAP



1 Functional Integration

The motor and the energy source (FC and Battery) both require a control system to monitor and operate them effectively. Integrating the invertor such that it also performs the function of a motor controller can result in significant weight saving for the overall system. This technology has been observed in the electrical vehicle (EV) market. Similarly the fuel cell management system can be integrated into the DC-DC convertor. By eliminating the need of a dedicated controller a reduction in system mass can be achieved.

2 Total Integration

To achieve further improvement in system mass, instead of a separate DC-DC convertor and invertor, an invertor can be designed to cope with varying DC voltages. This invertor can be embedded within the electric machine to be a single line replaceable unit (LRU). This requires tight integration between the power source and electric machine, but it does improve the specific power density of the system by an order of magnitude.

3 Multilevel Convertor

NPC or Active NPC topology creates multiple level (instead of the more common 2-level) convertor to perform power conversion. This provides two advantages:

- A better quality waveform can be achieved for the same switching frequency (hence reducing the need of heavy filtering components)
- The semiconductor devices do not observe the full voltage of the transmission bus, instead a much lower voltage is observed. This allows devices with low breakdown voltages to be used, hence reducing the cost significantly and eliminating the need to wait for custom devices to be manufactured.

POWER ELECTRONICS ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

2022 | 2026 | 2030 | 2050

Power Electronics

Topology and Integration

Semiconductor Devices

High Voltage (HV) DC System (1-3kV)

1 High voltage-IGBT improved structure → High voltage -MOSFET SiC

2 GaN / Ga_2O_3 MOSFET Power Modules

3 Semiconductor packaging improvements

Large scale manufacturing

1 High Voltage IGBT

Based on the assessment within FlyZero it has become clear that multi-megawatt propulsion systems are required to commercialise electrical aircraft. As a result there is a need to use voltage levels within 1-3 kV range. To achieve this efficiently in the short term there is a need for development of high voltage SiC semiconductor devices for aerospace application.

2 MOSFET Power Modules

GaN and Ga_2O_3 devices have shown great potential in the High frequency operation. In particular GaN has shown significant improvement in efficiency and heat dissipation when cooled to 75K, which might be achievable with cryogenic coolant now available on board. Ga devices can be used in conjunction with superconducting motors to have a common cooling system and lower operating voltage. On the other hand, it can also be used on the proposed high voltage system when using a multilevel convertor topology. The voltage limitations of existing Gallium devices can be overcome by use of multilevel convertor topologies.

3 Packaging & Manufacturing

One of the main constraints which prevents power density optimisation through high frequency operation is high power module package design. This involves integration of various technologies of different materials at each layer of packaging. The technologies for die attachment, encapsulation, substrate material and interconnections are critical to maintain high frequency switching operation with minimum voltage overshoot and uniform current sharing across the semiconductor chips. Until recently the development has been primarily focused on Si devices, however further development is required to improve the packaging for SiC and GaN. Some of these developments will be covered by the automotive sector with the progress of EVs, however further development is needed to optimise the packaging for the performance level and operating environment required for aerospace application.

Though SiC and GaN/Ga_2O_3 have been manufactured and tested, reliable bulk manufacturing is still lagging behind. This makes their implementation prohibitively expensive. Further co-ordination with device manufactures is required to create a viable commercial strategy.

POWER ELECTRONICS ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

2022 | 2026 | 2030 | 2050

Power Electronics

- Topology and Integration
- Semiconductor Devices
- High Voltage (HV) DC System (1-3kV)

1 Fault management for HVDC systems

HV electrical power systems have a challenge mitigating faults such as arcing and partial discharge. To manage these faults one of the most critical technologies would be development of detection and isolation of such events.

A significant amount of work has been done on researching these detection technologies; however the advancement of semiconductor devices, particularly in the increase in switching frequency does, make the detection more challenging. Applying technologies such as travelling wave detection or detection impedance measurement will be crucial to realise a HVDC system for an electrical propulsion system.

2 Electro-Magnetic Interference (EMI) management

With high frequency switching and high power levels managing the EMI is another hurdle that needs to be overcome. The current standards for electrical distribution on aircraft were developed for much lower levels of power. These standards appear to be conservative, however at the point of conception simulation tools to understand EMI weren't available.

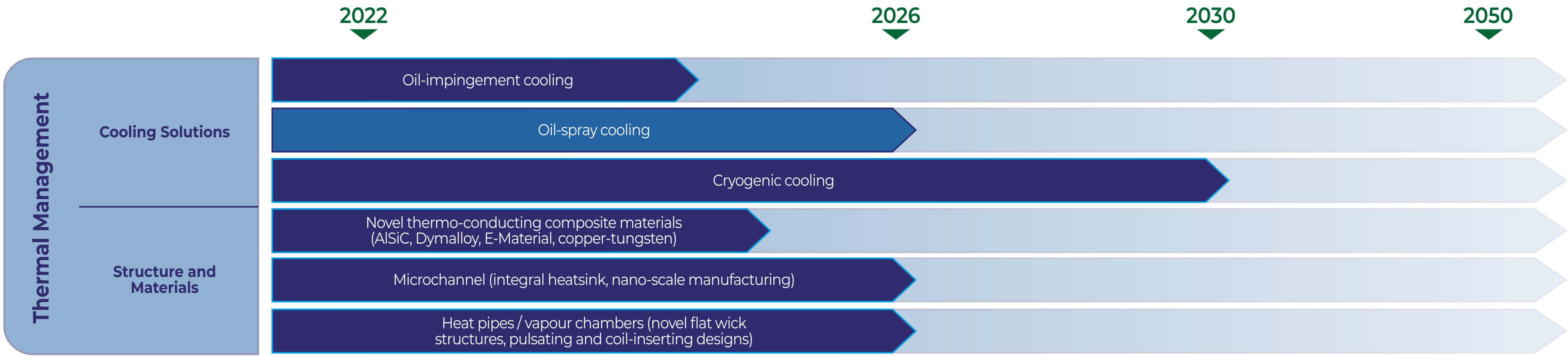
It is important to recognise the need to develop simulation tools that help us understand the susceptibility and emissions of HV systems. The outputs of these assessments will assist in updating the standards that are suitable for HV electrical systems suitable for electrical propulsion systems.

High Voltage (HV) DC System (1-3kV):

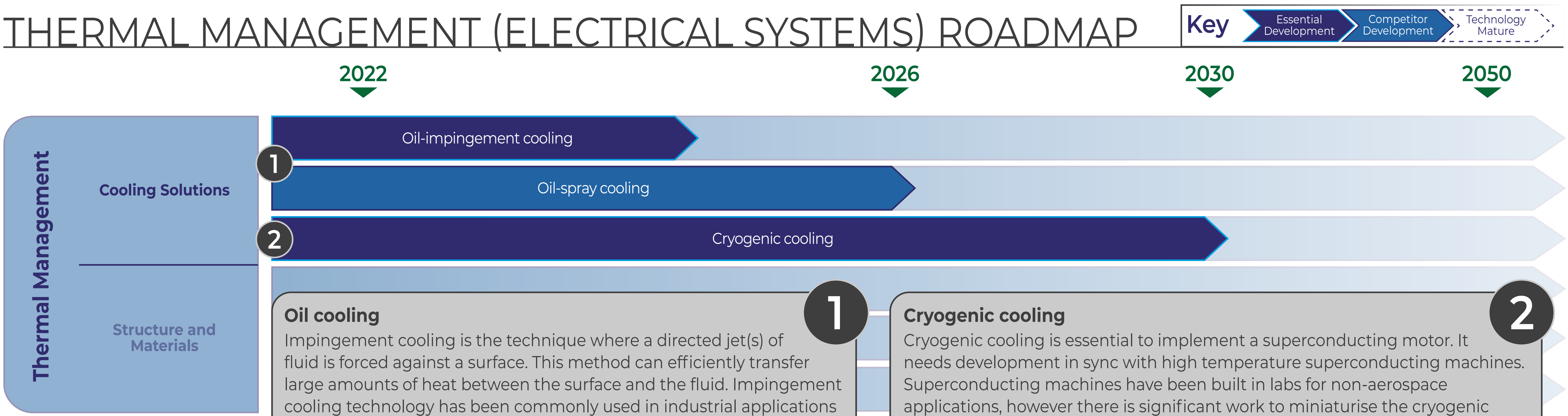
1. Fault management for HVDC systems
2. Electro-Magnetic Interference (EMI) management

THERMAL MANAGEMENT (ELECTRICAL SYSTEMS) ROADMAP

Key: Essential Development | Competitor Development | Technology Mature



THERMAL MANAGEMENT (ELECTRICAL SYSTEMS) ROADMAP



1 Oil cooling

Impingement cooling is the technique where a directed jet(s) of fluid is forced against a surface. This method can efficiently transfer large amounts of heat between the surface and the fluid. Impingement cooling technology has been commonly used in industrial applications using gas. Using oil-impingement provides a huge improvement in heat transfer for electric motors and allows for higher current density.

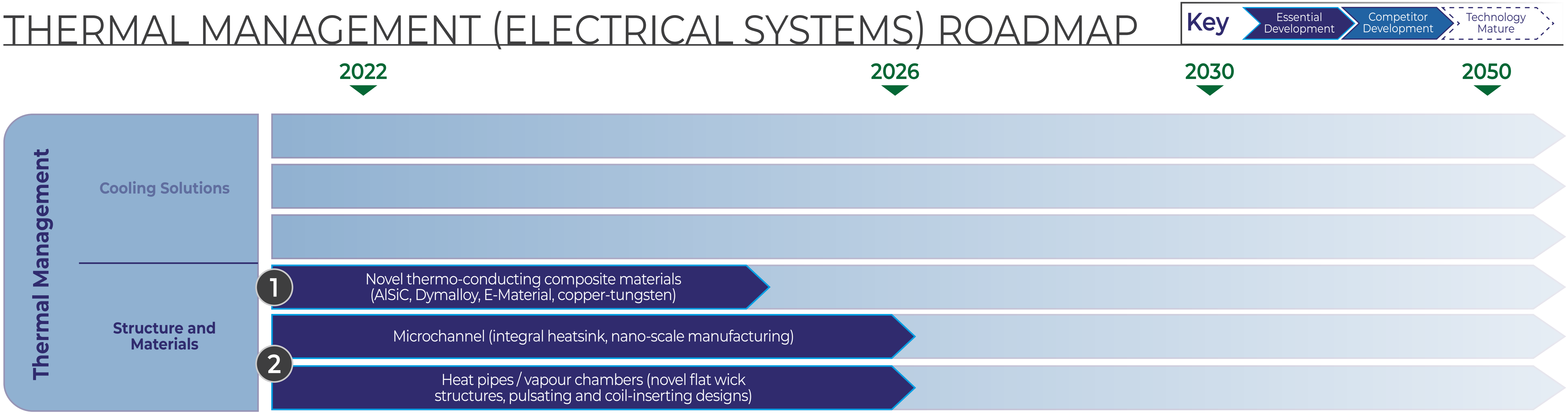
Oil-spray is another promising technology that shows potential to improve the thermal performance beyond the oil-impingement technique. The technique works by spraying oil droplets on a surface to be cooled. Both of these technologies can be applied to motor and power convertors (DC-DC and invertor).

2 Cryogenic cooling

Cryogenic cooling is essential to implement a superconducting motor. It needs development in sync with high temperature superconducting machines. Superconducting machines have been built in labs for non-aerospace applications, however there is significant work to miniaturise the cryogenic system used for these land-based solutions. Novel technologies such as metal as an insulator and direct cooling needs to be researched. Despite the low TRL of the current technology high-temperature superconducting machines and associated cryogenic cooling systems are predicted to provide a step change in power density of the electrical propulsion system.

Once this technology is developed for a superconducting motor, it can also be applied to the power convertors. Gallium devices show improved performance at cryogenic temperatures.

THERMAL MANAGEMENT (ELECTRICAL SYSTEMS) ROADMAP



1 Novel thermo-conducting composite materials

The main area of the power electronics liquid cooling system development involves usage of novel materials and structures for cold plates, heat pipes and liquid cooling techniques.

In the short-term development period, new composite thermo-conducting materials should become available - for example, AlSiC, Dymalloy, E-Material, copper-tungsten, etc. These increase thermal conductivities and help reduce overall cooling system requirements.

2 Microchannel, Heat Pipes & Vapour Chambers

During the mid-term development period, more advanced material manufacturing technologies will be available. These will allow more precise shapes of cooling system components. This would improve heat dissipation and can be further improved with the design of micro-channels within the cold plates, as well as micro-fins within the baseplates. Also, heat pipe shapes can be optimised in wick forms, as well as fitted oscillation or pulsation to increase an overall liquid flow without involvement of moving parts.

RELATED FLYZERO FURTHER READING

The ATI FlyZero project developed its technology roadmaps through a combination of broad industry consultation and assessment of technologies by experts. Technology assessment was carried out both by the FlyZero team and by approximately 50 industrial and academic organisations that partnered with FlyZero to support delivery. During the project, FlyZero developed three concept aircraft and used this exercise to gain a deep understanding of requirements and challenges for systems and technologies, which have been reflected in the roadmaps. Further detail of these technologies and developments can be found in the following reports, available to download from **ati.org.uk**:

FlyZero

Zero-Carbon Emission Aircraft Concepts
Report
Ref. FZO-AIN-REP-0007

Technology Roadmaps
Report
Ref. FZO-IST-MAP-0012

Workforce to Deliver Liquid Hydrogen Powered Aircraft
Report
Ref. FZO-IST-PPL-0053

Hydrogen Aircraft

Aerodynamic Structures
Technical Report
Ref. FZO-AIR-REP-014
Roadmap
Ref. FZO-AIR-MAP-0015
Roadmap Report
Ref. FZO-AIR-COM-0016
Capability Report
Ref. FZO-AIR-CAP-0066

Electrical Propulsion System
Technical Report
Ref. FZO-PPN-REP-0028
Roadmap
Ref. FZO-PPN-MAP-0029
Roadmap Report
Ref. FZO-PPN-COM-0030
Capability Report
Ref. FZO-PPN-CAP-0070

Thermal Management
Technical Report
Ref. FZO-PPN-REP-017
Roadmap
Ref. FZO-PPN-MAP-0018
Roadmap Report
Ref. FZO-PPN-COM-0019
Capability Report
Ref. FZO-PPN-CAP-0067

Fuel Cells
Technical Report
Ref. FZO-PPN-REP-0031
Roadmap
Ref. FZO-PPN-MAP-0032
Roadmap Report
Ref. FZO-PPN-COM-0033
Capability Report
Ref. FZO-PPN-CAP-0071

Hydrogen Gas Turbines & Thrust Generation
Gas Turbine Technical Report
Ref. FZO-PPN-REP-020
Thrust Devices Technical Report
Ref. FZO-PPN-REP-021
Roadmap
Ref. FZO-PPN-MAP-0022
Roadmap Report
Ref. FZO-PPN-COM-0023
Capability Report
Ref. FZO-PPN-CAP-0068

Cryogenic Hydrogen Fuel System & Storage
Fuel System Technical Report
Ref. FZO-PPN-REP-024
Fuel Storage Technical Report
Ref. FZO-PPN-REP-025
Roadmap
Ref. FZO-PPN-MAP-0026
Roadmap Report
Ref. FZO-PPN-COM-0027
Capability Report
Ref. FZO-PPN-CAP-0069

Cross-Cutting

Aircraft Systems
Ref. FZO-AIR-POS-0013

Airports, Airlines, Airspace - Operations & Hydrogen Infrastructure
Ref. FZO-CST-POS-0035

Advanced Materials
Ref. FZO-IST-POS-0036

Lifecycle Impact
Ref. FZO-STY-POS-0034

Sustainable Cabin Design
Ref. FZO-AIR-POS-0039

Compressed Design and Validation - Culture and Digital Tools
Ref. FZO-IST-POS-0038

Advanced Manufacturing
Ref. FZO-IST-POS-0037

ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions and recommendations of the project.

This report forms part of a suite of FlyZero outputs which will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology and skills for years to come. To discover more and download the FlyZero reports, visit **ati.org.uk**

ACKNOWLEDGEMENTS

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FlyZero would like to acknowledge the support and expertise provided by the following individuals or organisations noting the conclusions shared in this report are those of the FlyZero project*: University of Nottingham, Woodford Engineering Consultancy (WEC).*

FlyZero contributing companies: *Airbus, Belcan, Capgemini, easyJet, Eaton, GE Aviation, GKN Aerospace, High Value Manufacturing Catapult (MTC), Mott MacDonald, NATS, Reaction Engines, Rolls-Royce, Spirit AeroSystems.*

These roadmaps have been developed with a view to accelerate zero-carbon technology development and maximise the potential future value for the UK. They are unconstrained by the availability of funding.

Department for Business, Energy & Industrial Strategy

FlyZero was funded by the Department for Business, Energy and Industrial Strategy.

ELECTRICAL PROPULSION SYSTEMS

Roadmap Report

FLY ZERO

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