INSIGHT

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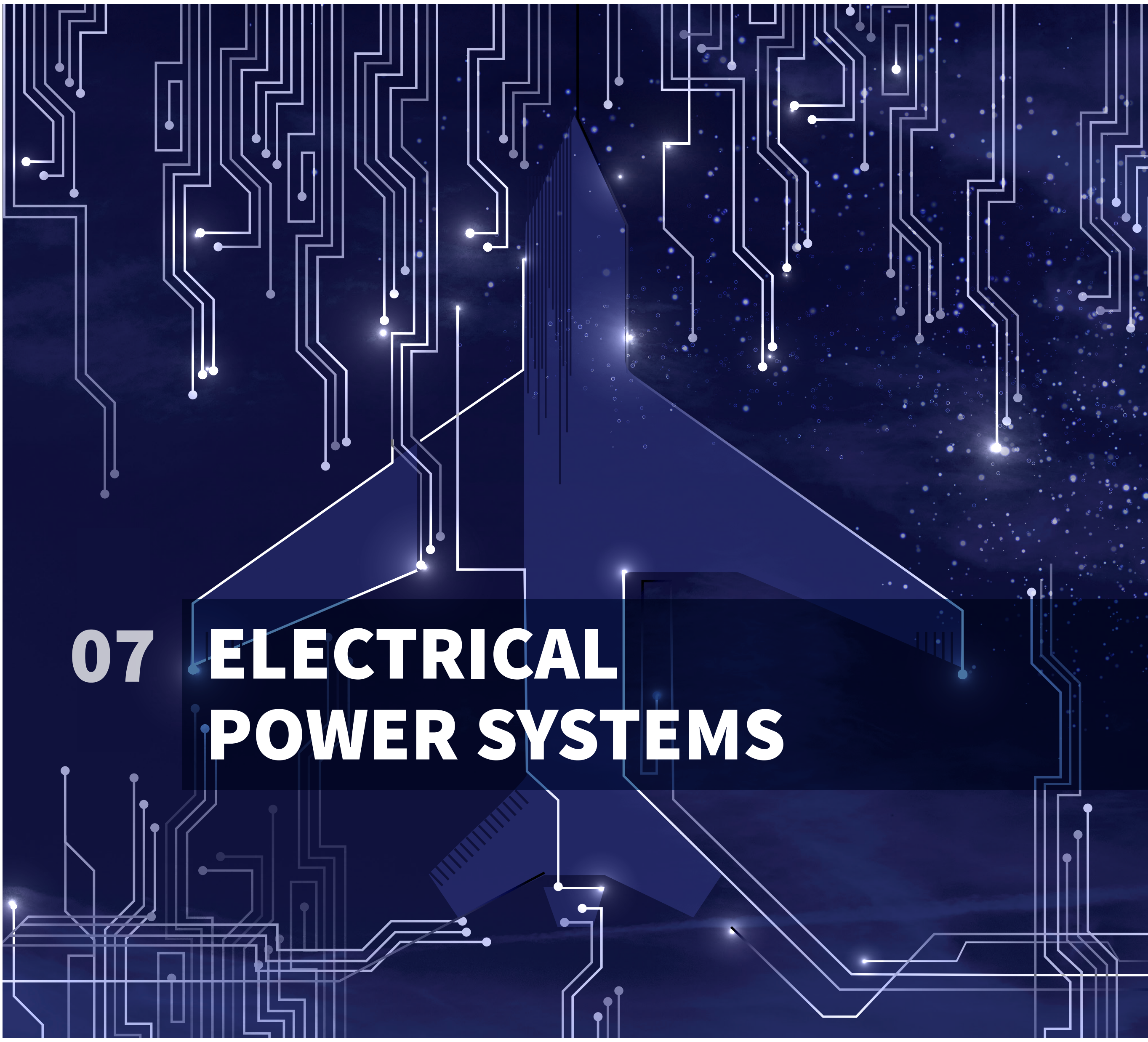
Introduction

This INSIGHT document is intended to enable wider consultation on electrical power systems in support of future updates to the Aerospace Technology Institute's technology strategy, Raising Ambition. This paper highlights the increasing importance of electrical power systems in current and future commercial aircraft and identifies new market sectors that are dependent on enhanced technologies for such systems. Four possible applications of advanced electrical power systems are considered, and the requirements derived from these market applications. An outline view of potential market opportunities is provided to support investment in electrical power systems in these sectors. Initial technology roadmaps have been established to explore technology development opportunities in electrical power systems for UK aerospace in advance of a future review of the ATI's Aerospace Technology Strategy.

The UK industry is well placed to take advantage of the more electric, or all electric aircraft and novel electric propulsion systems, with appropriate investment in technology development.

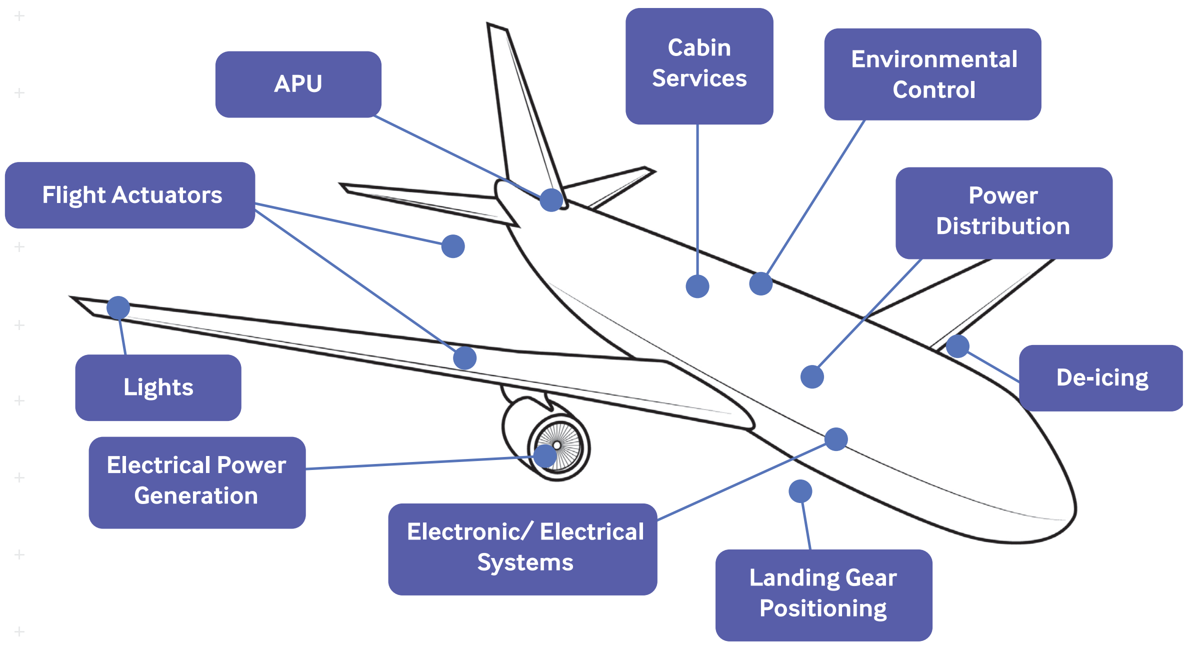


07 ELECTRICAL POWER SYSTEMS

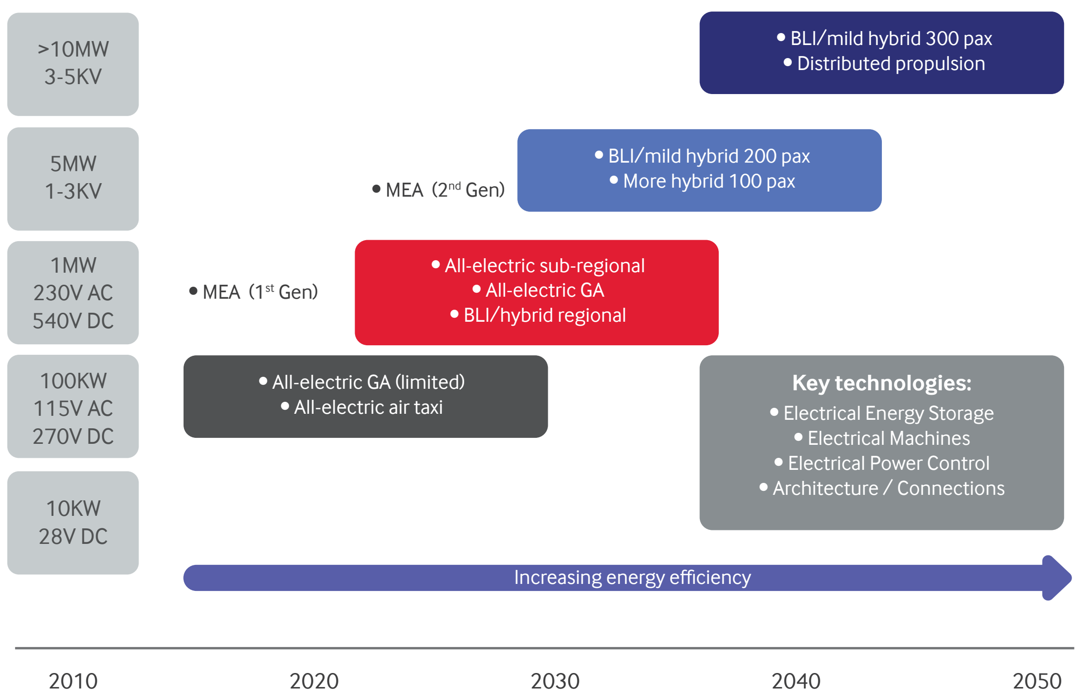
ELECTRICAL POWER SYSTEMS

Aircraft electrical power systems are self-contained networks of components that generate, transmit, distribute, store and use electrical energy. They are made up of electrical generators, power electronics, energy storage devices and actuators, as well as the power distribution and control networks that enable operation of these individual components. These systems power avionics, flight controls, environmental subsystems, anti-icing devices, communications (internal and external), lights, and a myriad of other key functional elements of the aircraft. All of these parts must have high reliability and be as light and as small as possible to deliver the highest operational efficiency. Electrical power systems will increase in importance as more subsystems are electrified to improve overall aircraft efficiency and reduce emissions. This, in due course, will put electrical power systems at the heart of electric propulsion options in future aircraft designs.

A conceptual schematic of typical aircraft elements can be seen below:



The UK supply chain delivers electrical power system products for most current aircraft platforms. To maintain competitiveness, continued technology advances are required in the electrical power system components to improve size, weight, power and cost. The trend to higher power can be seen below (timing subject to viability):



Electric Power Demands

DRIVING ELECTRIFICATION

Commercial aerospace has transformed society in the past decades, enabling cost-effective and safe transport around the world. This has been driven by the development, delivery and operation of both fixed- and rotary-wing aircraft over several generations, enabled by evolutionary and radical advances in technology. Sustained growth in air transport has been maintained, with air passenger traffic growing at 4.5% compound annual growth rate in recent times, with similar levels predicted for the future.

Continued expansion of air transport will impact the environment, and growth may become limited through national and international regulation unless mitigating actions are taken. Aircraft affect the climate (through CO_2 emissions and contrail formation), local air quality (NO_x, unburned hydrocarbons and particulate emissions) and community noise. Aerospace companies are investing heavily in research and technologies to drive down these effects (supported through the UK Aerospace Research and Technology Programme). For many of these developments, the increased use of electrical power (electrification) is attractive, as it permits new opportunities for aircraft optimisation to help reduce the environmental impact. These include the potential for improved power system efficiency, reduced weight and volume, and additional functionality of sub-systems. As systems are electrified and aircraft level design is optimised, it introduces the potential to improve overall reliability, total cost and maintainability, and safety can be further enhanced. In more radical aircraft concepts, electrical power would be used to provide propulsive thrust. The shift to electrification will significantly disrupt incumbent supply chains and facilitate access to new market entrants.

It is unlikely that the European Commission's Flightpath 2050 environmental targets will be achieved without consideration of new disruptive technologies. These include hybrid and electric propulsion for new aircraft. The advent of novel electrification technologies (e.g. high voltage, megawatt class) in electrical power systems is widely seen as potentially enabling the future launch of new aircraft platforms with advanced hybrid or all electric propulsion. Additionally, the use of electrical power to drive the production of propulsive thrust can give much higher flexibility in the distribution of energy storage, energy conversion and thrust elements of the propulsion system, potentially enabling broader whole aircraft benefits such as higher fuel efficiency and lower noise.

At a high level, electrification in aerospace can be characterised as two concurrent technology trends: an evolutionary trend towards all-electric and more-electric configurations, reducing the demand for conventional hydraulic and pneumatic systems, and a disruptive trend transitioning towards hybrid or full-electric propulsion. As aircraft and technologies evolve, moving from secondary electrical power systems towards the development of primary electrical power systems, a step-change in the amount of power transmitted electrically around the aircraft is required. Higher power electrical machines of high power density and low weight will be required, and efficient high power density electrical energy storage is likely to be a key enabler for low environmental impact air travel.

Electrification of aircraft systems creates new market sectors as well as enabling significant efficiency improvements in established aircraft types (see table: applications of electrification on page 5). These new markets include all electric urban air transport and low, or zero emission sub-regional air transport to exploit small airports. More electric regional and medium range airliners (the more electric aircraft) will be developed to improve fuel efficiency and reduce environmental impact.

This paper examines electrical power system opportunities for future air platforms, both conventional and disruptive. It considers market issues, evolutionary and revolutionary developments, evaluates the technologies required to deliver evolved and future architectures, and some of the key challenges to be addressed. The paper establishes an initial set of roadmaps that explore technology development opportunities in electrical power systems for UK aerospace, in advance of a future review of the ATI's technology strategy, Raising Ambition.

THE MORE ELECTRIC AIRCRAFT

The more electric aircraft (MEA) takes advantage of projected advances in electrical systems and machine technology to enhance operational efficiency through reductions in size, weight and power consumption of aircraft systems. These technologies enable the replacement of pneumatic and hydraulic systems by more efficient and lighter electrical subsystems, permitting more efficient bleed-less engines and simplified architectures. Additional advantages accrue from improved monitoring and reliability, and simplified maintenance processes.

The more electric aircraft offers:

- Improved power system efficiency
- Improved weight and volume of subsystems
- Improved reliability
- Improved maintainability
- New capabilities and system level optimisation
- Cost effective rapid technology insertion

The above will lead to lower fuel consumption, lower emissions and reduced total cost. For this to happen, advances in electrical technologies, system design and integration are required. Key aircraft subsystems are shown in the following illustration, which allocates them to four specific technology areas. These technologies will require significant investment in specific topics to enable the exploitation of the more electric aircraft, as highlighted in the associate technology roadmaps.

Architecture & Interconnect

- Whole Aircraft
- Propulsion
- Systems
- Protection
- Connectors
- Insulation

Electrical Energy Storage

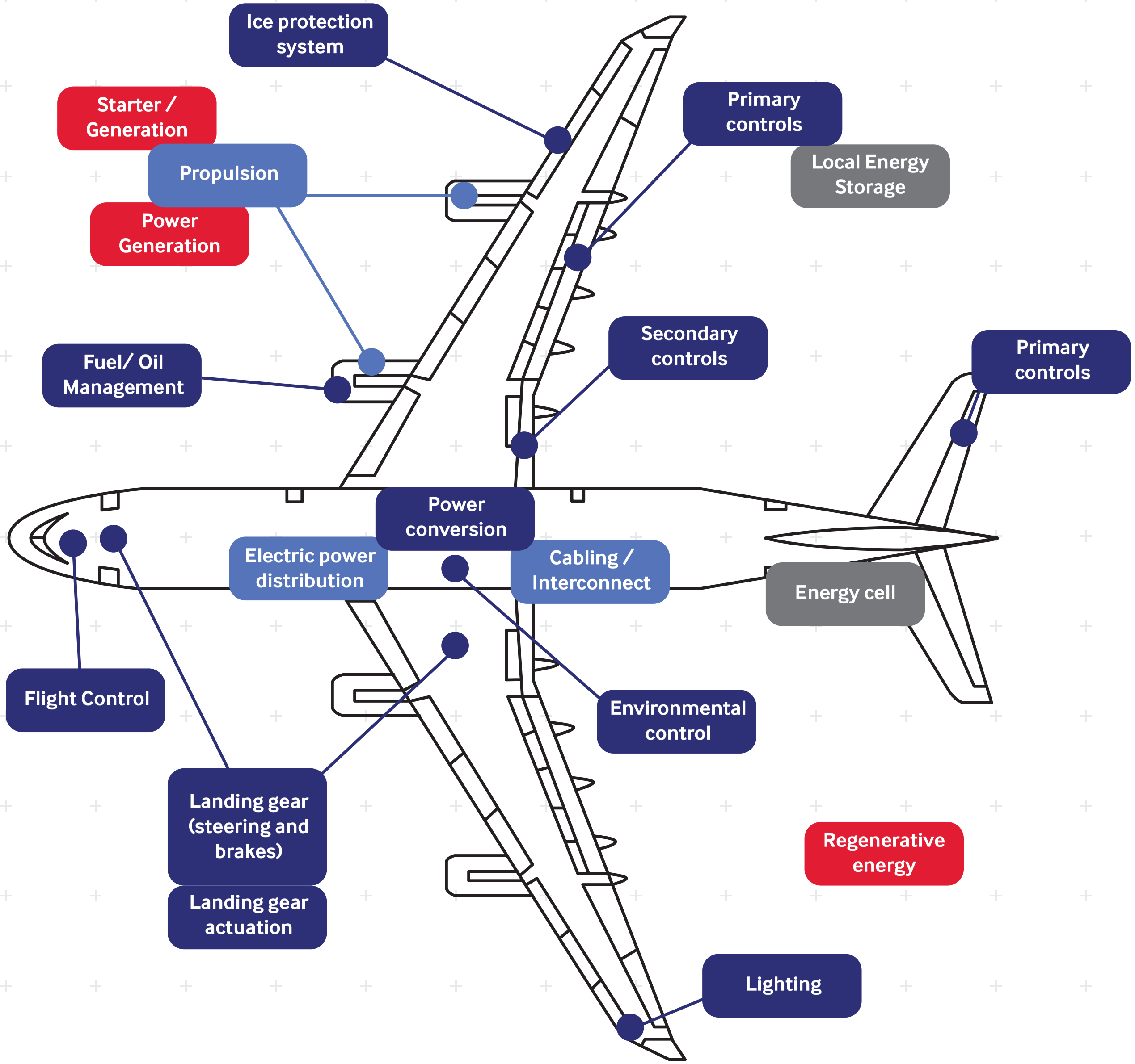
- Energy Storage
- Energy Generation
- Energy Management
- Infrastructure

Electrical Machines

- Motors
- Generators
- Topologies
- Transformers
- Drivers
- Actuators

Power Electronics

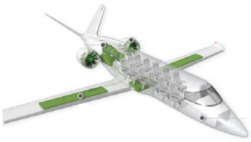
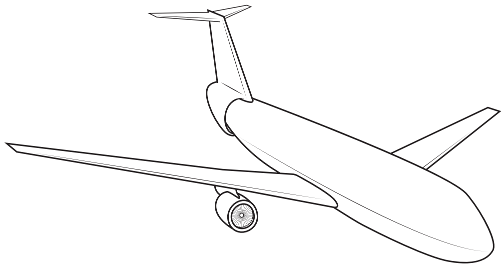
- Power Conversion
- Control
- Monitoring
- Switching



The More Electric Aircraft

On an ultimate more electric aircraft, all systems except propulsion would be electrically powered, potentially with local electrical energy storage. This concept would permit a rebalancing of energy use in the aircraft, and would allow optimisation at different flight stages, exploiting potential advantages of electrical aircraft systems. Current pneumatic systems that will evolve to electrical operation include cockpit and cabin environmental control, anti- and de-icing systems, and various ancillaries such as engine starting (parts of this have already been implemented on the Boeing 787). Reductions in weight, improved engine efficiency and system independence are key deliverables from this transition. Hydraulic systems will be more challenging to replace and may move to local electro-hydraulic operation to eliminate the heavy, unreliable centralised hydraulic systems (parts of this have already been implemented on the A380). Improvements in electrical machine power density, power switching and distribution will be key enablers in this change, as indicated in the table of technology challenges for the aircraft systems to be upgraded. These advances would also assist rotary winged aircraft in exploiting electrical technologies in areas such as electric tail rotors, lighter actuators and ancillaries.

APPLICATIONS OF ELECTRIFICATION

Category	Urban Air Transport (new market)	Sub-regional small commercial air transport (new)	Midsize commercial air transport (existing market)	Large air transport (existing market)
				
Power requirement	150-200kW	2MW propulsive	22MW propulsive	60MW propulsive
Energy requirement	100-200 kWh*	12 MWh	55 MWh	390 MWh
Non-propulsive energy requirement	5-10 kWh	0.1-0.3 MWh	1-6 MWh	8-30 MWh
Number of passengers	1-5	9-20	120-200	240-500
Range	30 miles + limited divert	300 miles + divert	800 miles + divert	3000 miles + divert
All-up weight	1t	2-10t	~100t	~250t
Recharge/refuel time	2-10 mins	15-30 mins	20-60 mins	< 2 hours
More electric architecture	-	-	Evolved	Evolved
Hybrid	-	Hybrid parallel	Evolved + transient assist - attractive	Evolved + transient assist - possible
Advanced hybrid or electric	All-electric with energy storage	serial	serial – perhaps possible	serial - difficult
Operating altitude	Tens of metres	Low commercial	Commercial	Commercial
Operating speed (max)	<150mph	300-400mph	600mph	600mph
Value of autonomy	Essential	Medium	Medium	Medium/high
Regulatory hurdles	Very high	High	Medium	Possibly high
VTOL	Yes	Unlikely	No	No

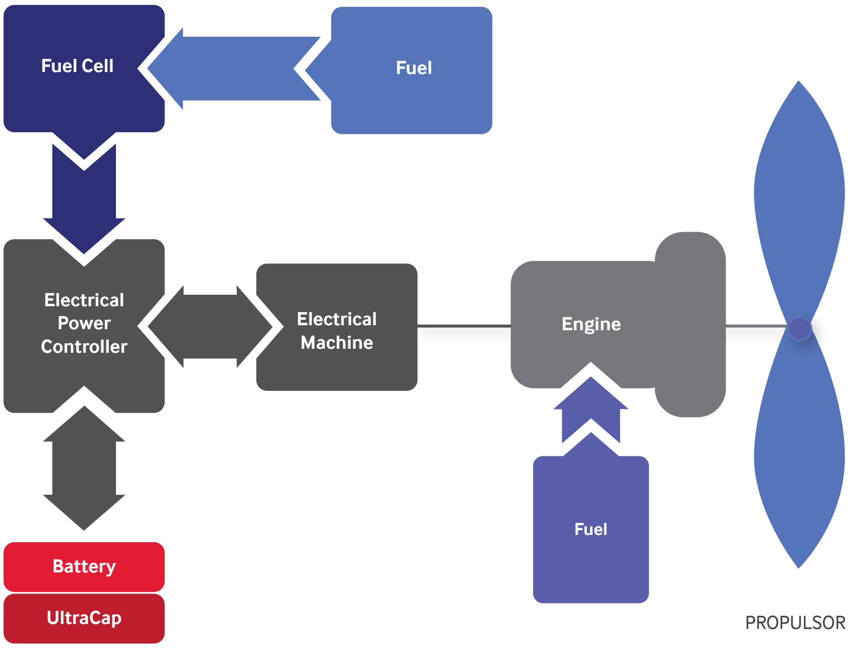
**** Current helicopters require 550kWh for nominal 100 mile trip, no divert allowance***

HYBRID OR ELECTRIC PROPULSION

Hybrid electric propulsion systems are being considered for future larger commercial aircraft. These combine gas turbine or internal combustion engines with electrical power generation and storage systems, and typically drive either a fan or a propeller. All electric propulsion systems rely wholly on electrical power, either generated in a fuel cell, or from storage in a battery or capacitor system.

A parallel hybrid approach exploits a source of stored electrical energy to power an electrical motor and deliver propulsion thrust, either complementing or as an alternative to a conventional turbo-shaft or internal combustion (IC) engine that uses conventional fuel. Additional electric energy can be used for acceleration, and in times of high power demand, and bi-directional flow of power is possible between the electrical machine and a battery.

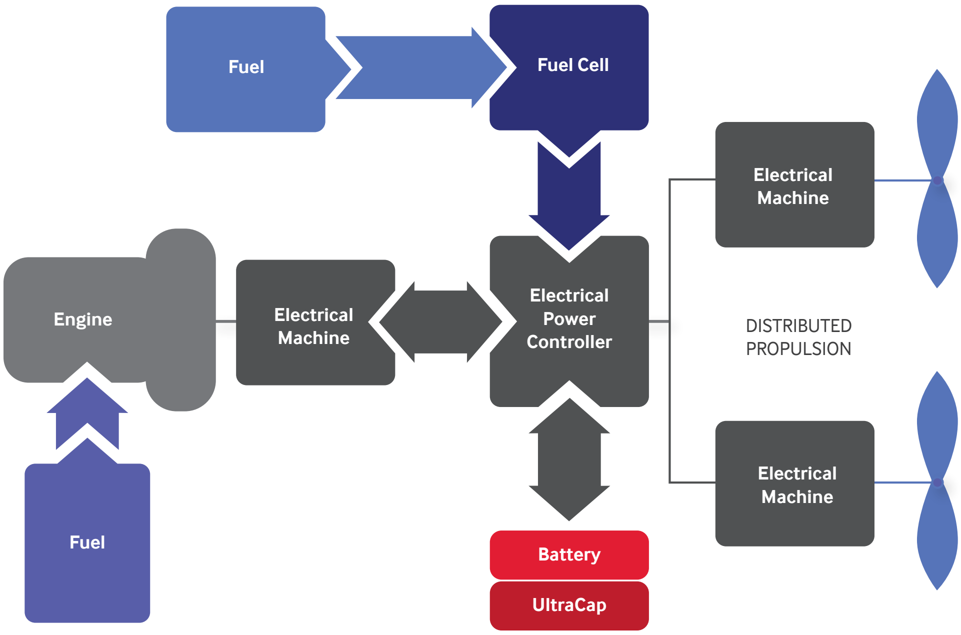
Electric assistance consists of incorporating an electric motor/generator within the gas turbine housing to form a mild-hybrid system, minimising changes to other mechanical parts of the engine. This makes it a promising and economical short- to medium-term solution for the reduction of CO2 emissions, and could be an extension of planned development for the small regional and larger passenger aircraft.



Parallel Hybrid Propulsion

This configuration allows independent operation and optimisation of the engine and electrical system, and independent design of the power share between the two systems. It constrains aircraft design in that the engine position is determined by the propulsor, and the engine may not be operating at its optimal design conditions in some flight sectors. Key technology challenges are in improving the efficiency of electrical machines, power electronics, the power density of electrical energy storage, and in protection and fault tolerance (see technology challenges in the electrification of aircraft table).

In a series hybrid propulsion configuration, the energy of a turbo-shaft or IC engine is transformed into electric energy via a generator that drives the propulsion system. This can be localised, or delivered by multiple, distributed fans with the fans driven by electric motors. The turbo-shaft engine is also used to generate electricity which can then be used directly to power the electrical motor(s) that delivers propulsion, or to recharge the electrical energy storage system (if battery based). When peak propulsive power is required, or when the engine is not needed, the electrical power is delivered from the energy storage system. The ability to generate electricity from fuel during flight can be used to reduce the required electrical energy storage, thus allowing optimisation at system level, and achieving extended ranges at lower overall weights.



Series Hybrid Propulsion

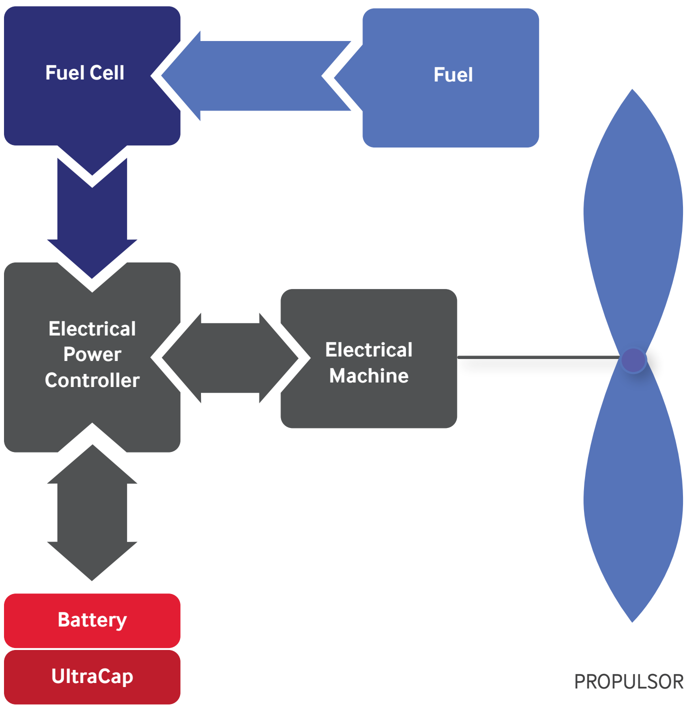
This configuration permits operation of the engine at its optimal conditions and at a higher effective bypass ratio, enabling optimisation of the distributed propulsion system. However, it is likely to be heavier and less efficient overall.

This solution can be applied to the three cases under consideration, offering different advantages and limitations in each situation. depending on the mission profile.

Efficient electrical energy storage technology is key to this concept, as indicated in the technology challenge table below. Power electronics are also of great importance, as efficiency needs to be very high to minimise thermal losses and associated cooling systems.

The engine is eliminated in an all electric propulsion system, as shown below. This permits emission-free flight, which is especially attractive in areas of high population density, such as cities. However, the forecast energy storage density of batteries does not permit the use of pure electric propulsion in aircraft requiring ranges beyond local applications, thus excluding the medium and longer range sectors for the time being. Batteries may be combined with ultra-capacitors to provide peak power demands as necessary. Fuel cells may offer greater potential, but are still heavy and unproven in such applications.

This development will be driven by market demand and potential regulatory and environmental considerations rather than reduced cost - some applications are already technologically close to viability, such as urban air transport. Others require significant development in the areas indicated below, showing common themes in energy storage (critical), efficient electrical machines, and power electronics across the application sectors.



ElectricPropulsion

TECHNOLOGY CHALLENGES IN THE ELECTRIFICATION OF AIRCRAFT

The table below considers the four main technology areas and indicates the level of challenge associated with each of the four cases.

Aircraft subsystem to be upgraded	Architecture and interconnect	Energy generation and storage	Electrical machines	Power electronics
Technology challenges in MEA subsystems				
Environmental control	Grey		Blue	Grey
Electric anti-icing			Grey	Grey
Starter / generator		Grey	Blue	Blue
Electro-mechanical actuation	Blue	Grey	Blue	Grey
More electric engine	Grey		Blue	Blue
Power distribution & protection	Blue	Blue		Blue
Fuel cells for non-critical power	Grey	Blue		Grey
Overall system power demands	Grey	Blue		Blue
Technology challenges in parallel hybrid propulsion subsystems (in addition to MEA)				
High-power motor / generator	Grey		Red	Blue
Power sharing control				Red
Battery		Red		Blue
Power distribution & protection	Blue	Blue		Blue
Overall system power demands	Blue	Red		Blue
Technology challenges in series hybrid propulsion subsystems (in addition to MEA)				
High-power generator			Blue	Blue
Power sharing control	Blue			Red
Battery		Red		Blue
Fuel cell		Red		Blue
Propulsion motors (distributed)	Blue		Red	Blue
Power distribution & protection	Blue	Blue		Red
Overall system power demands	Blue	Red		Red
Technology challenges in electric propulsion subsystems (in addition to MEA)				
Battery		Red		Blue
Fuel cell		Red		Blue
Propulsion motors (distributed)	Blue		Red	Red
Power distribution & protection	Blue	Blue		Red
Overall system power demands	Blue	Red		Red

Key: **Red** - major challenge; **Blue** - significant challenge; **Grey** - work required but risk manageable; **White** - N/A

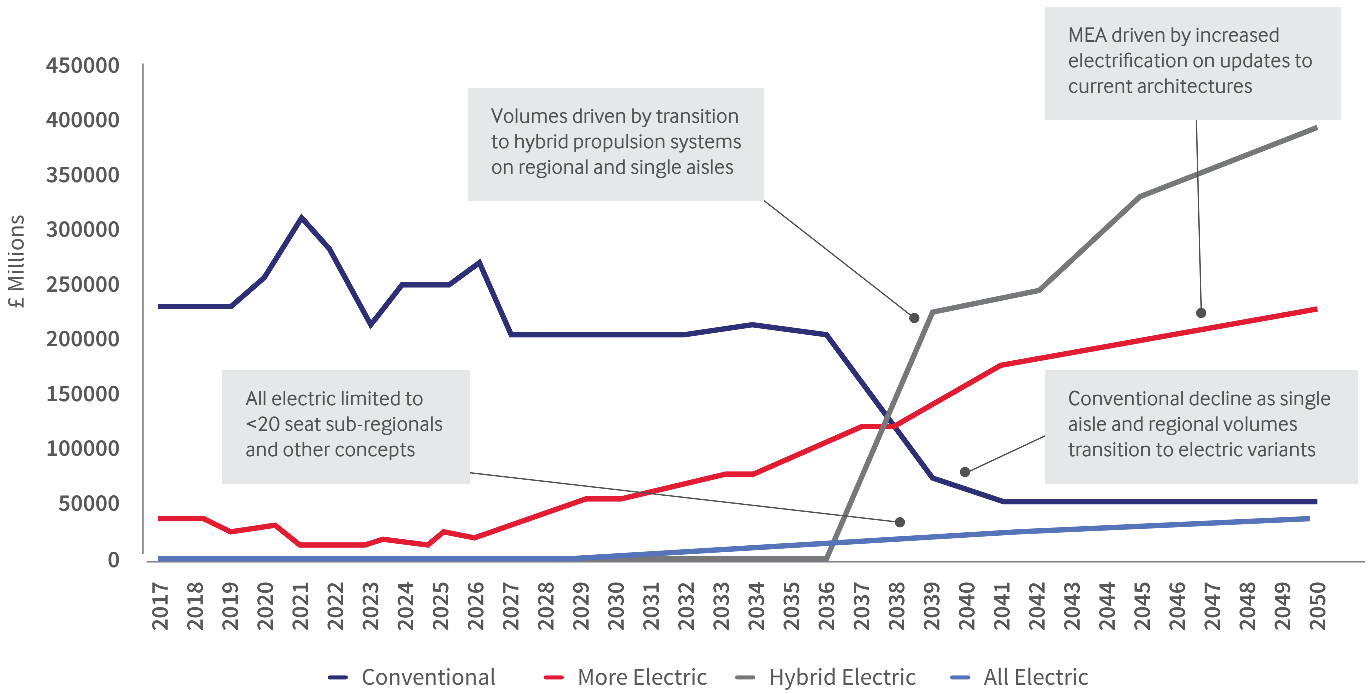
MARKET OPPORTUNITIES

Technology development for electrification is applicable across a range of market segments, including military applications (where dual use technology is feasible), hybrid rotorcraft and tilt rotor (engine starting and increasing safety), business jet (performance optimisation) and cargo aircraft (efficiency optimisation), as well as the mainstream passenger airliners and new local sectors. In the large commercial air transport sector, electrification supports two very distinct applications: the continued increase in electrification of current conventional architectures trend (the MEA), and the introduction of various levels of electric propulsion supporting potential new market applications ranging from hybrid electric regional (>20 seats) and single aisle aircraft (with range limitations) to all electric sub-regionals (<20 seats) and other new concepts such as electric vertical take-off and landing (VTOL) for applications in urban air transport etc.

Market adoption and application of potential hybrid and all electric architectures rely on the development and availability of qualified and mature technologies that can address the size, weight, power and safety requirements that are specific to the aerospace sector. There are also broader issues such as regulations and ground infrastructure required to support these architectures that need to be addressed. This broader picture will determine the pace of technology adoption and market evolution. Several entry-into-service scenarios could be considered to determine when these technologies will enter the market.

The ATI is modelling the various possible developments in the market for new aircraft deliveries. This scenario does not include rotorcraft or business jets. Under the most conservative scenario the market and the Primes might retain conventional technology in narrow body and wide body segments with hybrid and all electric applications limited to regional and sub-regional platforms. This would see a majority of the market value retained by conventional architectures with limited electrification in future upgrades of these platforms.

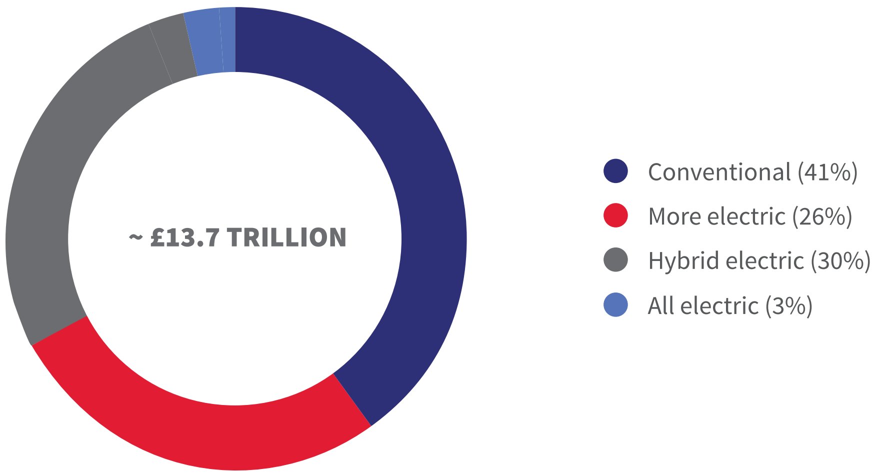
Revenues by platform type (global) - new aircraft deliveries



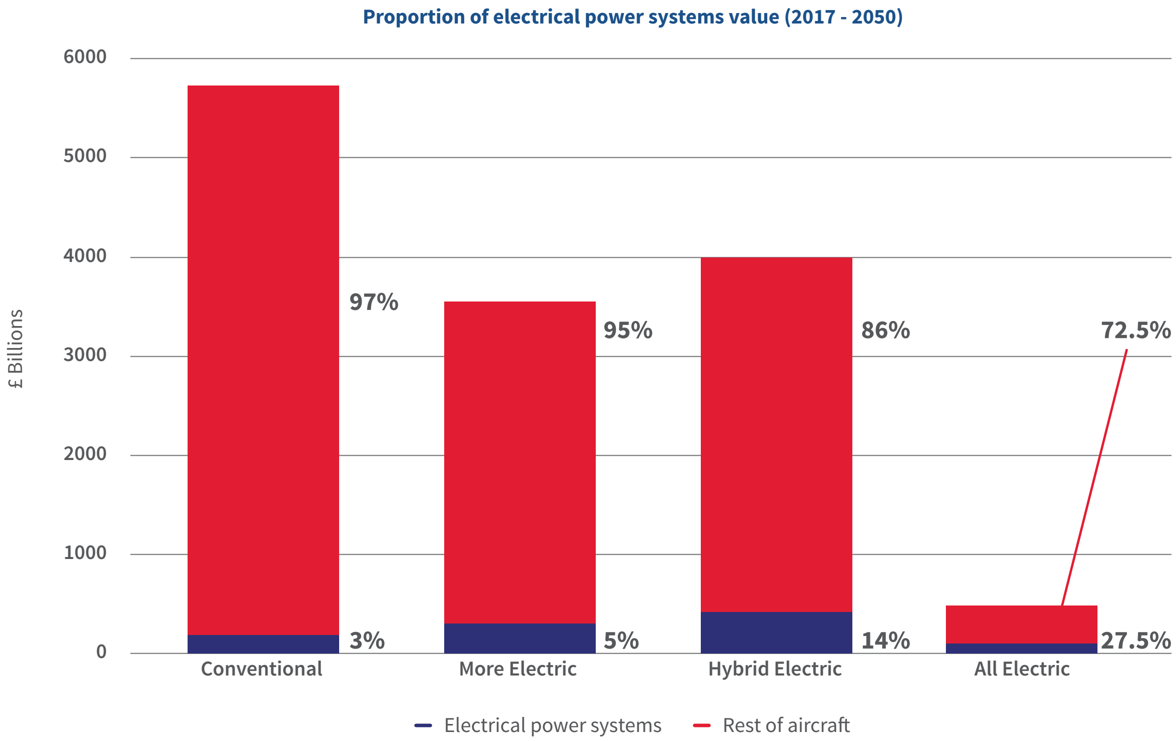
Another scenario (represented in the graph above) considers the possible introduction of a hybrid electric regional aircraft with over 20 seats and a sub-20 seat all electric regional aircraft around 2030. The scenario also considers the introduction of hybrid electric narrow body platforms between 2035 and 2040, and potential hybrid electric widebodies beyond 2040. It assumes that no new clean sheet conventional aircraft will be introduced in this period. These platforms are enabled by availability of relevant new technologies. UK industry needs to ensure that it is ready should this scenario develop.

[1] All financial numbers in this section are taken from initial ATI analysis of the given scenario

The Institute's initial analysis indicates that, under this scenario, conventional platforms would still retain the largest cumulative market value at over £5.6 trillion, however gradually declining in volume and value through to 2050. This is closely followed by £3.5 trillion worth of more electric aircraft growing on an upward trend. It is important to note that the evolution of more-electric aircraft architectures is not limited by the same scale of challenges as with hybrid or all electric architectures, thereby offering more definite market opportunities. The biggest gains under such a scenario would be for hybrid electric aircraft that could be delivered during this period, worth ~£4 trillion. This substantial growth will be driven by the transition of volumes from conventional regionals and single aisles to hybrid electric variants. Technology availability could also see the introduction of all electric, less than 20 seat sub-regionals, which could open new regional air travel routes and these aircraft could be worth over £400 billion within this forecast period.



It is important to note that even under this scenario, conventional platforms would still retain the largest cumulative market value at over £5.6 trillion, however gradually declining in volume and value through to 2050. There is also significant value associated with system-level opportunities, especially as the value of electrical power systems increases to enable the transition to more electric and subsequent hybrid and all electric architectures.



Electrical power systems content through the forecast period to 2050 is expected to be worth an estimated £162 billion on conventional aircraft, £192 billion on more electric aircraft, £578 billion on hybrid electric and circa £127 billion on all electric aircraft platforms.

REVOLUTIONARY CONCEPTS

The combination of electrification and autonomy may enable new mobility concepts, such as autonomous electric VTOLs for application in areas such as urban air transport. There have been several launches of development projects for 1-4 passenger electrically operated VTOL carriers with limited range capabilities. These vehicles would compete with traditional taxis and hence will have to be cheap and accessible. With noise and emissions being key issues in urban environments, these platforms will rely on electrical propulsion systems to gain acceptance and adoption.

TECHNOLOGY ROADMAPS

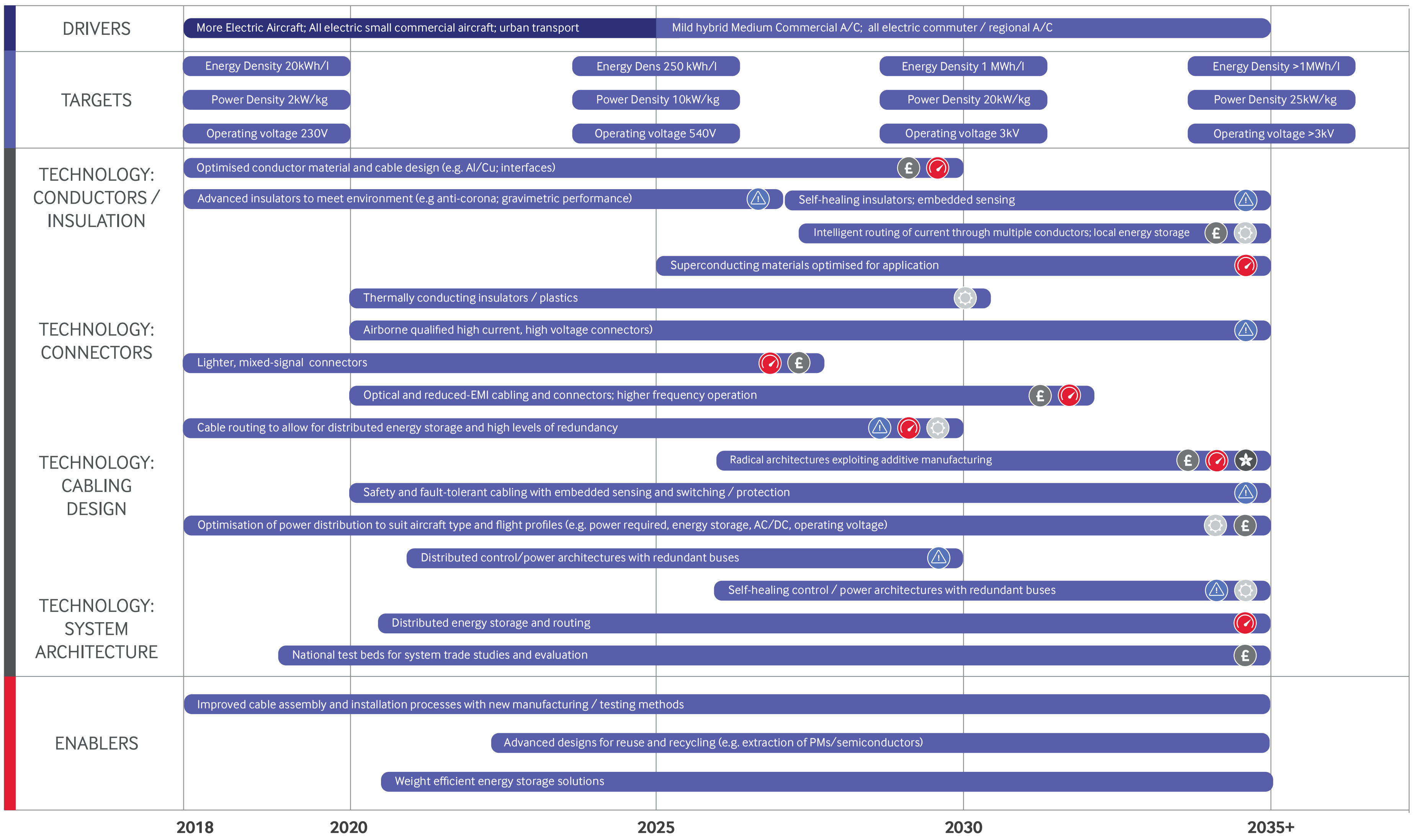
Consideration of the technology challenges to be faced in electrifying the key subsystems for the various use cases highlights four areas of prime interest:

- Architecture and interconnect: the overall design of the aircraft's electrical power system to handle the higher power levels, to permit the use of higher voltage distribution and offer protection at these levels
- Electrical energy storage: means of storing sufficient electrical energy in weight and volume efficient devices that are cost effective and offer the required lifetimes and charge or discharge rates
- Electrical machines: light and power-dense electrical machines that can generate the required electrical power levels, and that can deliver the mechanical or propulsive thrust that will be required via actuators,
- Power electronics: very low loss, light, high temperature electronic devices and circuits to condition, route and control the high levels of electrical power that will be required

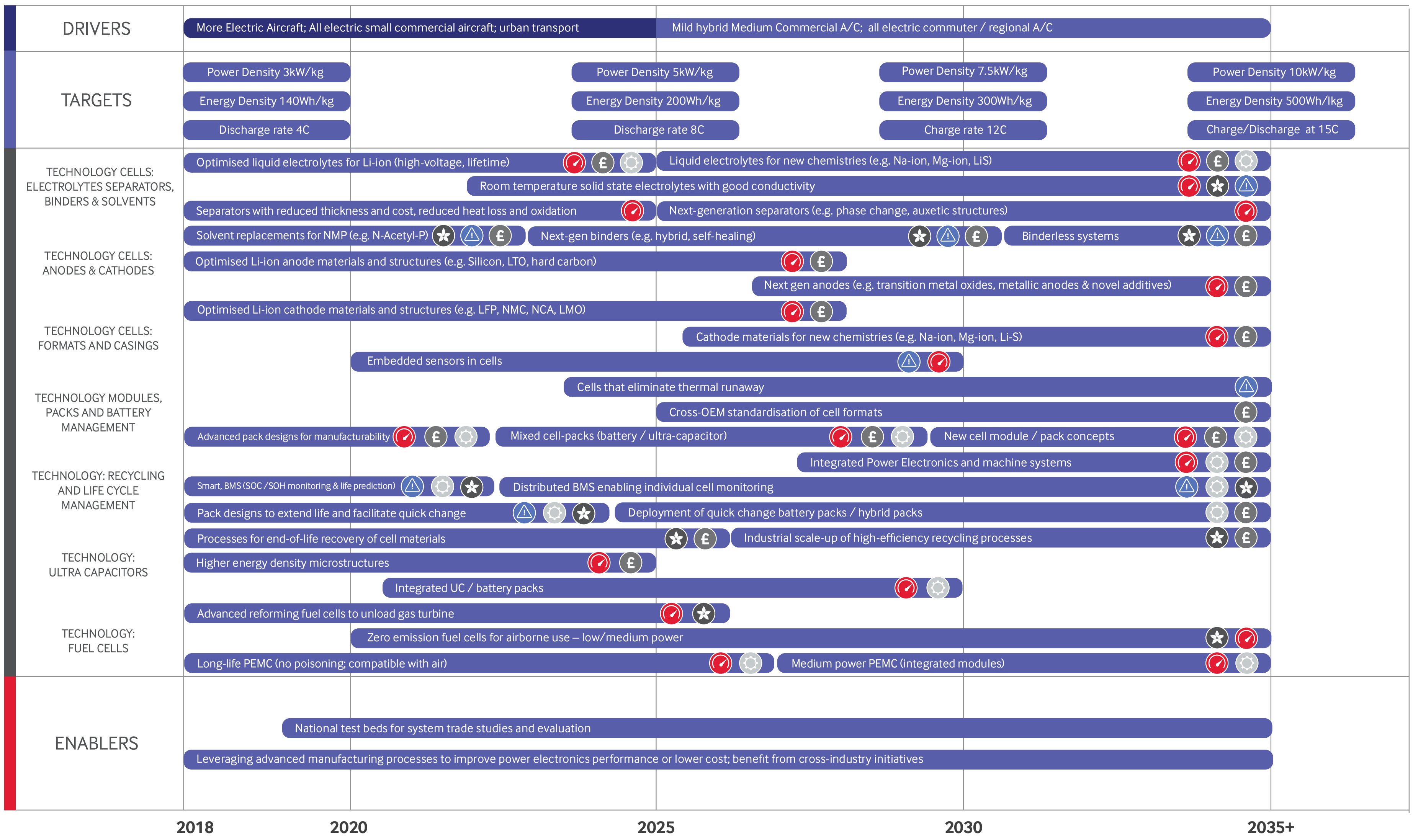
The technology roadmaps represent the Institute's view of core technologies that will need to be developed, and a possible timescale for this work. In the roadmaps, the main drivers reflect the market opportunities. Explicit targets for each challenge area are proposed, and a number of key technologies to achieve these targets are listed below. Specific programme areas are itemised for each technology, with the implementation timescale, and the relationship of these to the ATI whole aircraft attributes indicated symbolically. Comment is invited on these technology roadmaps as they will guide future investment decisions in this area – please email comments to the ATI via **info@ati.org.uk** with a subject title of: EPS INSIGHT.

These programmes will need to be supported by appropriate infrastructure, especially research and test facilities. These facilities need to support systems delivering, or exceeding the anticipated targets of maximum power, specific power, and energy density to permit system level integration and testing with realistic thermal management and environments. National facilities providing such high power capabilities are not currently available to interested parties in a collaborative environment - specific requirements need to be agreed and funding needs clarified.

Technology Road Map 2018: Architecture & Interconnect



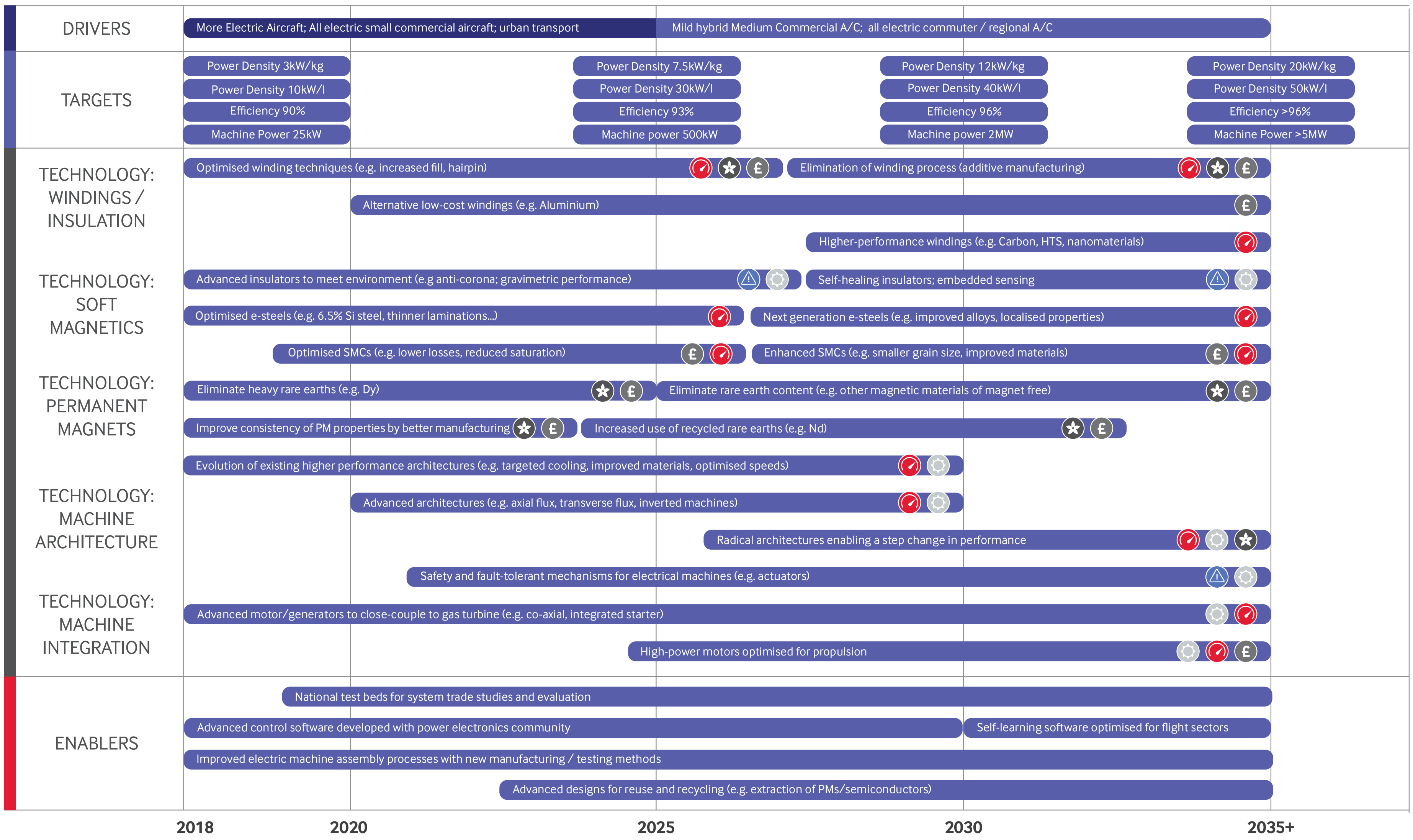
Whole Aircraft Attributes:



Technology Road Map 2018: Electrical Energy Storage

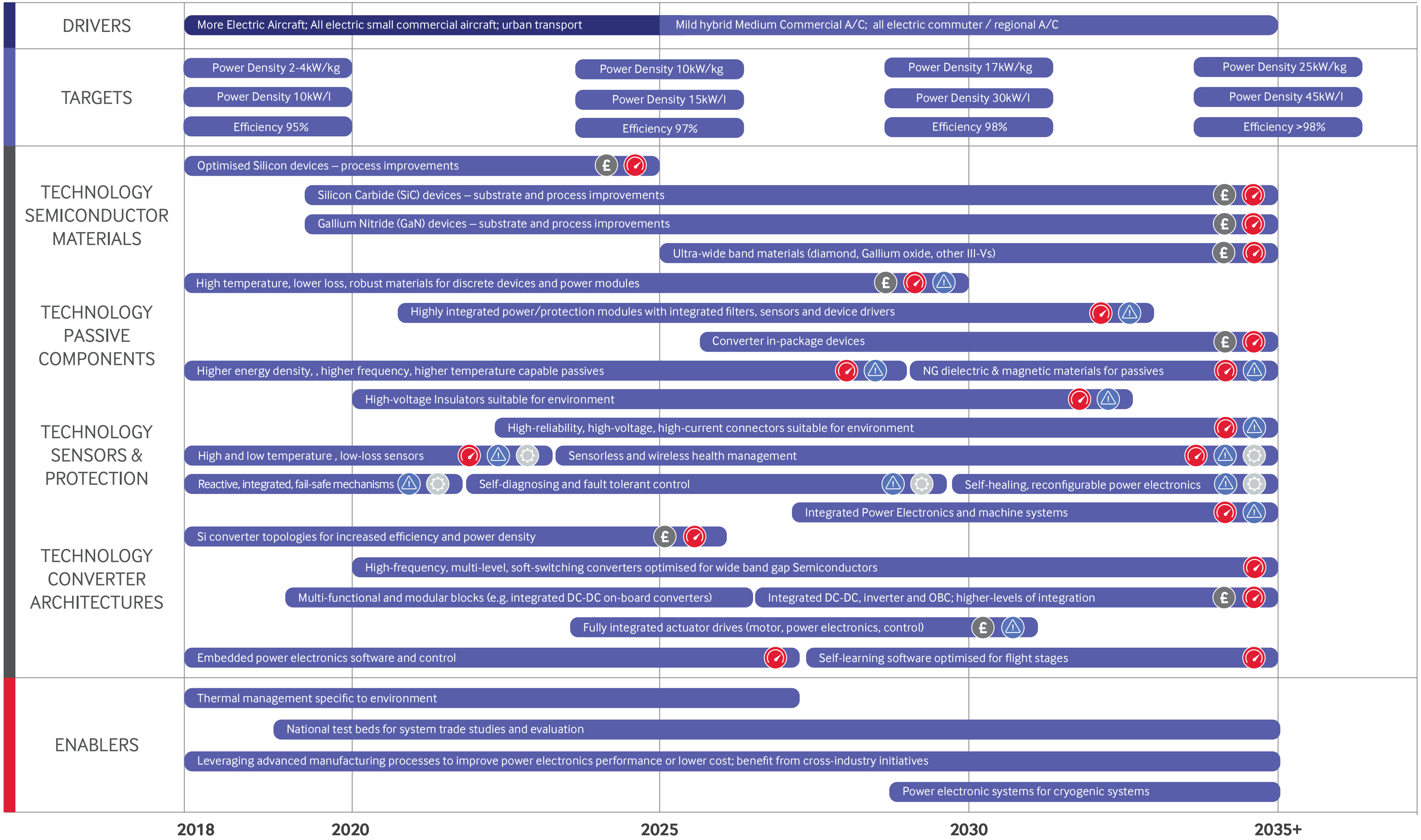
Whole Aircraft Attributes:

Cost: | Operational needs & flexibility: | Fuel efficiency: | Passenger experience: | Safety: | Environment:



Technology Road Map 2018: Electrical Machines

Whole Aircraft Attributes:



Technology Road Map 2018: Power Electronics

CONCLUSIONS

The key conclusions from this paper are:

- Electrification in aerospace can be characterised as two concurrent technology trends: an evolutionary trend towards all electric and more electric configurations, reducing the demand for conventional hydraulic and pneumatic systems; and a disruptive trend transitioning towards hybrid or full electric propulsion
- Electrification will change the market for UK industry in aircraft subsystems, offering both a competitive threat and a significant opportunity for the UK supply chain
- Electrification will create new accessible market sectors for the UK electrical power systems supply chain
- Significant investment in electrical power systems research and technology (as identified in the technology roadmaps) is required if the UK is to maximise its market capture
- Technology requirements for national infrastructure to support UK industry in integrating and testing the new complex and higher power electrical systems should be developed and possible funding needs clarified

The UK industry is well placed to take advantage of developments in more electric or all electric aircraft, and in novel electric propulsion systems. Initial technology roadmaps are presented for the four key elements that have been identified through analysis of the needs of projected aircraft electrification, and priority areas, including infrastructure investments, are highlighted. These are:

- Architecture and interconnects
- Electrical energy storage
- Electrical machines
- Power electronics

National facilities to permit the integration and testing of electrical power systems and components at the higher power levels that will be required in the future is proposed as a key enabler for these developments.

The UK supply chain and wider aerospace sector is invited to comment on this paper, and to consider projects that tackle the key challenges and position the UK at the forefront of the electrification of commercial aircraft. Please email responses to the ATI via **info@ati.org.uk** with a subject title of: EPS INSIGHT.

The Institute will continue to convene industry, research technology organisations and academia to develop and deliver electrical power systems technology to maximise UK economic value.

WHO WE ARE

The **Aerospace Technology Institute** (ATI) is the objective convenor and voice of the UK's aerospace technology community. The Institute defines the national aerospace technology strategy that is used to focus the delivery of a £3.9 billion joint government-industry funded aerospace technology programme.

DISCLAIMER

The Aerospace Technology Institute (ATI) believes the content of this report to be correct as at the date of writing. The opinions contained in this report, except where specifically attributed, are those of ATI, based upon the information that was available to us at the time of writing. We are always pleased to receive updated information and opposing opinions about any of the contents. All statements in this report (other than statements of historical facts) that address future market developments, government actions and events, may be deemed 'forward-looking statements'. Although ATI believes that the outcomes expressed in such forward-looking statements are based on reasonable assumptions, such statements are not guarantees of future performance: actual results or developments may differ materially, e.g. due to the emergence of new technologies and applications, changes to regulations, and unforeseen general economic, market or business conditions.

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