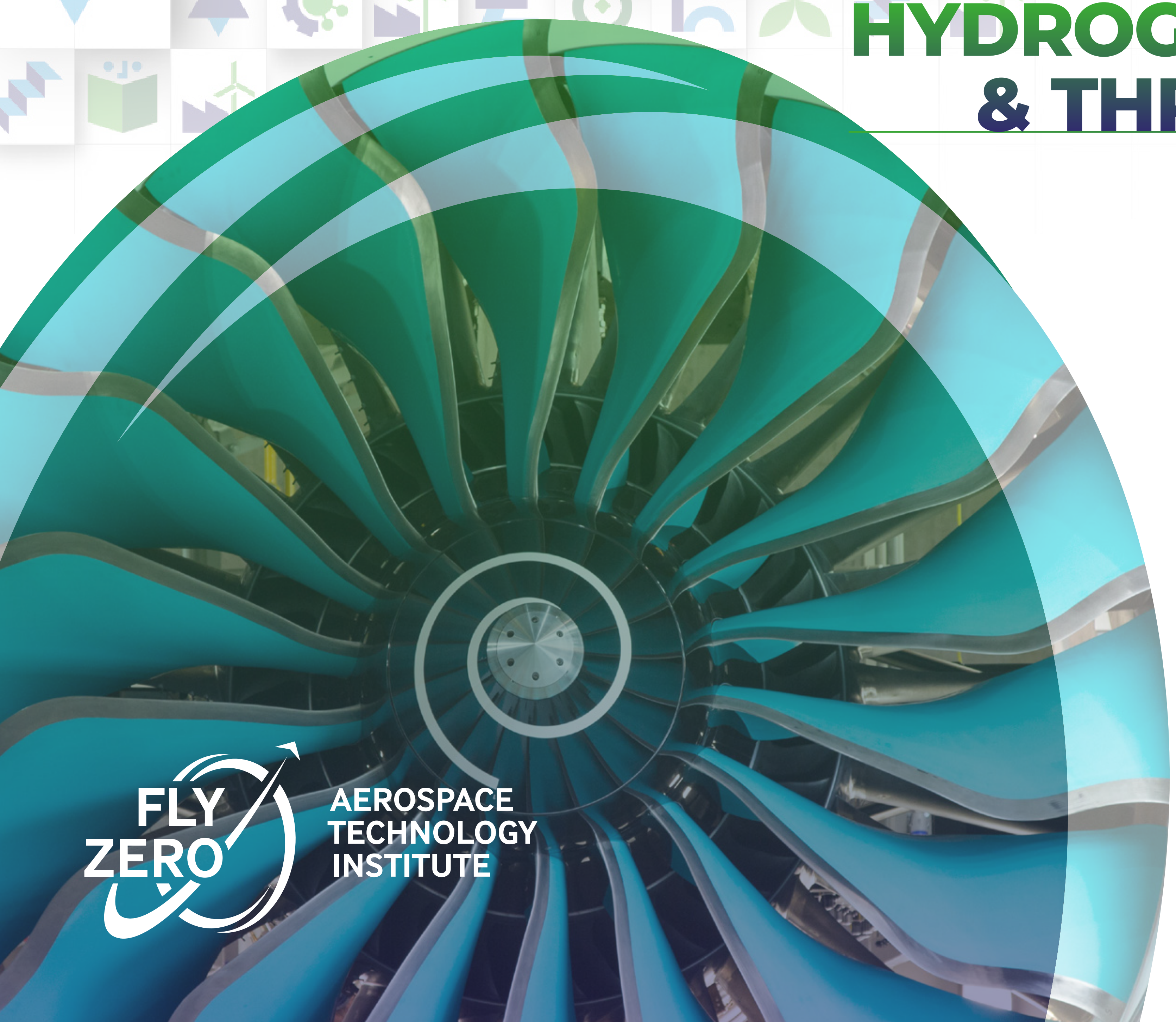
HYDROGEN GAS TURBINES & THRUST GENERATION

Roadmap Report



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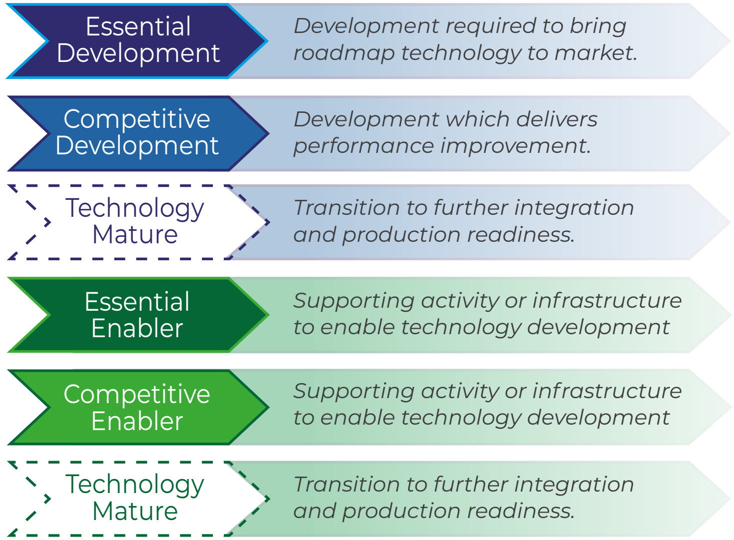
KEY & LIST OF ABBREVIATIONS

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

APU – Auxiliary power unit
CFD – Computational Fluid Dynamics
HP/HT – High Pressure/High Temperature
HPC – High Powered Computing
MTO – Maximum take off thrust
MCL – Maximum climb thrust
SPU – Supplementary power unit

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Basic principles observed and reported.	*Technology concept formulated.*	*Analytical and experimental proof-of-concept.*	*Component validation in laboratory environment.*	*Component validation in relevant environment.*	*Subsystem model or prototype demonstration in relevant environment.*	*System prototype demonstration flown.*	*Flight qualified.*	*Achieved all flight envelope.*

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

OVERVIEW: HYDROGEN GAS TURBINES & THRUST GENERATION

This companion report outlines the technologies necessary for zero-carbon emission propulsion covering the gas turbine, gas turbine combustor and thrust devices (e.g. propellers). The essential and competitive technologies have been derived for liquid hydrogen fuelled propulsion through a series of studies using concept aircraft. The essential technologies include the necessary developments to allow a hydrogen gas turbine to function and the competitive items deliver performance improvements. The technologies are focused on narrowbody and midsize aircraft sectors but are not exclusive to these sectors. It is expected that these technologies would scale to the regional sector and to larger civil applications.

The essential technologies focus on the fuel delivery system and the combustor, as without these the gas turbine would not function with hydrogen fuel:

- **Gas Turbine Roadmap** – delivering the essential technology to transition to hydrogen fuel.
- **Combustion Roadmap** – detailed roadmaps on sub-elements, component and functions of the combustor.
- **Thrust Generation Roadmap** – primarily focusses on propellers and high-speed propeller technology; ducted fans are covered in the gas turbine roadmap.

The technologies that have been excluded or discounted from the scope are:

- **Sustainable Aviation Fuel (SAF)** – out of scope as this is net carbon not zero carbon.
- **Intercooler and pre-cooler cycles** – complexity, increased weight and risk of high-pressure losses makes intercooling compressed air for aerospace gas turbine engines an uncompetitive technology.
- **Open rotor not covered in detail** – common technology to all applications and fuels, not a requirement for hydrogen-based aircraft.
- **Inter turbine combustion** – i.e. a second combustor, mid-turbine was discounted due to the additional combustor pressure drop and engine length.

Key challenges with hydrogen gas turbines:

- **Fuel conditioning and delivery to the combustor** is a key challenge as the fuel is very cold and compressible compared to conventional aviation fuels.
- **Designing a robust hydrogen combustor** in the next five to ten years is challenging compared to previous combustor technology timescales.
- **Delivering the test facilities and infrastructure** ahead of the technology development plan.
- **Understanding the atmospheric impact from burning hydrogen in aviation** is essential knowledge required in the early phase of this programme.

GAS TURBINE ROADMAP TECHNOLOGY INDICATORS*

	2025	2030	2035	2050
Energy consumption (MJ/kNs)	0.56	0.55	0.54	0.49
Total Efficiency (%) thermal x propulsive	41	42	43	47
Unit cost divided by power $/kW (System)	140	130	120	100
Time to first Shop Visit/overhaul (hours)	30,000	35,000		45,000
Power density (kW/kg)	6.5	6.5	6.8	7.6
Emissions (NO_x) relative to Legislation (CAEP 8)	80%	50%	30%	<10%
Noise A/C level db relative to Chapter 14	Ch 14	10db to 22db margin		>22db margin

Notes and Commentary

- **Energy consumption**: assuming hydrogen energy content at 118.353 MJ/kg
- **Efficiency**: total cruise efficiency
- **Unit cost divided by take-off power**: continued pursuit of cost reductions
- **Time on wing**: in hours
- **Power density**: small cores and larger fan systems with associated weight reductions and efficiency improvements
- **Emissions**: (NO_x) current aerospace legislative process is based around the landing and take-off (LTO) cycle. Climate science findings may recommend adoption of the energy industry gas turbine limits by 2050 (10 parts per million)
- **Noise (aircraft)**: target includes future proof margin

*Ref - Hydrogen Gas Turbines Technical Report

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It is predicted that a new aircraft entering into service in the 2030s will need to meet more stringent noise targets. The targets laid out in the table are expected to future-proof against new legislative targets from International Civil Aviation Organisation. (ref ICAO Annex 16, Volume 1, Chapter 14). Lighter take-off weights; slower, larger fans and rear mounted engines are some of the levers to deliver these targets.

Energy consumption will continue to be driven down primarily due to fuel costs rather than payload/range as with carbon fuels. Hydrogen offers the potential for larger fans and smaller core compared to carbon fuels. Hydrogen also offers cooling/heating opportunities.

Gas turbine efficiency will continue to develop and improve from core developments advancing the cycle temperatures, reduced losses and bypass ratio. Additions of water injection and hybridisation will also advance the design space.

Unit cost is expected to continue to be driven down through advanced manufacturing and intelligent designs. Hydrogen also offers a cooler cycle and opportunity to deliver efficiency without the same increase in cycle and material capability compared to carbon fuels.

On-wing life will need to be maintained and improved as it is a major part of the operating costs for an airline. A hydrogen gas turbine is 60K cooler than the kerosene equivalent which equates to two or three times the life for some components. This combined with technologies like water injection, hybridisation and cooled cooling air for the turbine components will all contribute towards improved time on wing.

Power density is first order important for aviation. Smaller cores and larger fans will drive efficiency improvements but the fan and nacelle mass must be reduced to compensate.

The technologies laid out for the combustor set a direction to deliver these NO_x improvements whilst managing the other risks and issues with combustor designs. Legislation from the Committee on Aviation Environmental Protection (CAEP) may move to even more stringent levels, including the cruise phase of flight and this roadmap anticipates these levels.

HYDROGEN GAS TURBINE ROADMAP

Technologies

Competitive Core

Competitive Core: hydrogen offers new opportunities compared to kerosene offering higher bypass ratio designs, smaller cores and higher pressure ratios. The use of a much lighter fuel does however change the exchange rate between efficiency and mass, driving different or higher priorities on certain technologies for a hydrogen gas turbine. The roadmap assumes the hydrogen gas turbine must be commercially competitive as well as zero-carbon emissions.

Fuel & Control System

Fuel & Control System: focuses on the fundamental areas of development within the fuel system and control system to enable hydrogen gas turbines to function. Heat exchanger cycle relates to the thermal management of the fuel. Liquid hydrogen fuelled gas turbines need to increase the temperature of the fuel delivered from the aircraft before it can be burnt in the combustor. This can be exploited further to create fuel burn benefits.

Enablers

Enablers: facilities and infrastructure necessary to enact the technology readiness roadmaps developed above. Timescales for these enablers are variable, some are pre-requisites to allow the programme to start whereas some will be needed when the concept is ready to fly or move into mass production.

HYDROGEN GAS TURBINE ROADMAP

Technologies

Optimised Cycle

Cycle Optimisation: the switch to hydrogen fuel offers developments in emissions reduction, better cruise efficiency and low-pressure shaft power offtake. These include thrust ratio optimisation and hybridisation of the gas turbine. The thrust ratios of a hydrogen aircraft are more aligned as the fuel mass is less penalising. The opportunity for boosting the gas turbine with electrical power from a fuel cell is also created with a hydrogen fuel source. Not considered essential technologies but are future-proof options to deliver fuel burn, emissions and cost savings.

Reduced Engine Weight

Engine Weight Reduction: larger, more efficient gas turbines trade well on kerosene aircraft as the fuel mass saved exceeds the additional mass of the engine. This trade is less compelling with a hydrogen aircraft as the fuel mass and tank weight is much lower. There is stronger emphasis on hydrogen gas turbines to reduce engine weight as the engine is developed to be more efficient.

Low Pressure System Developments

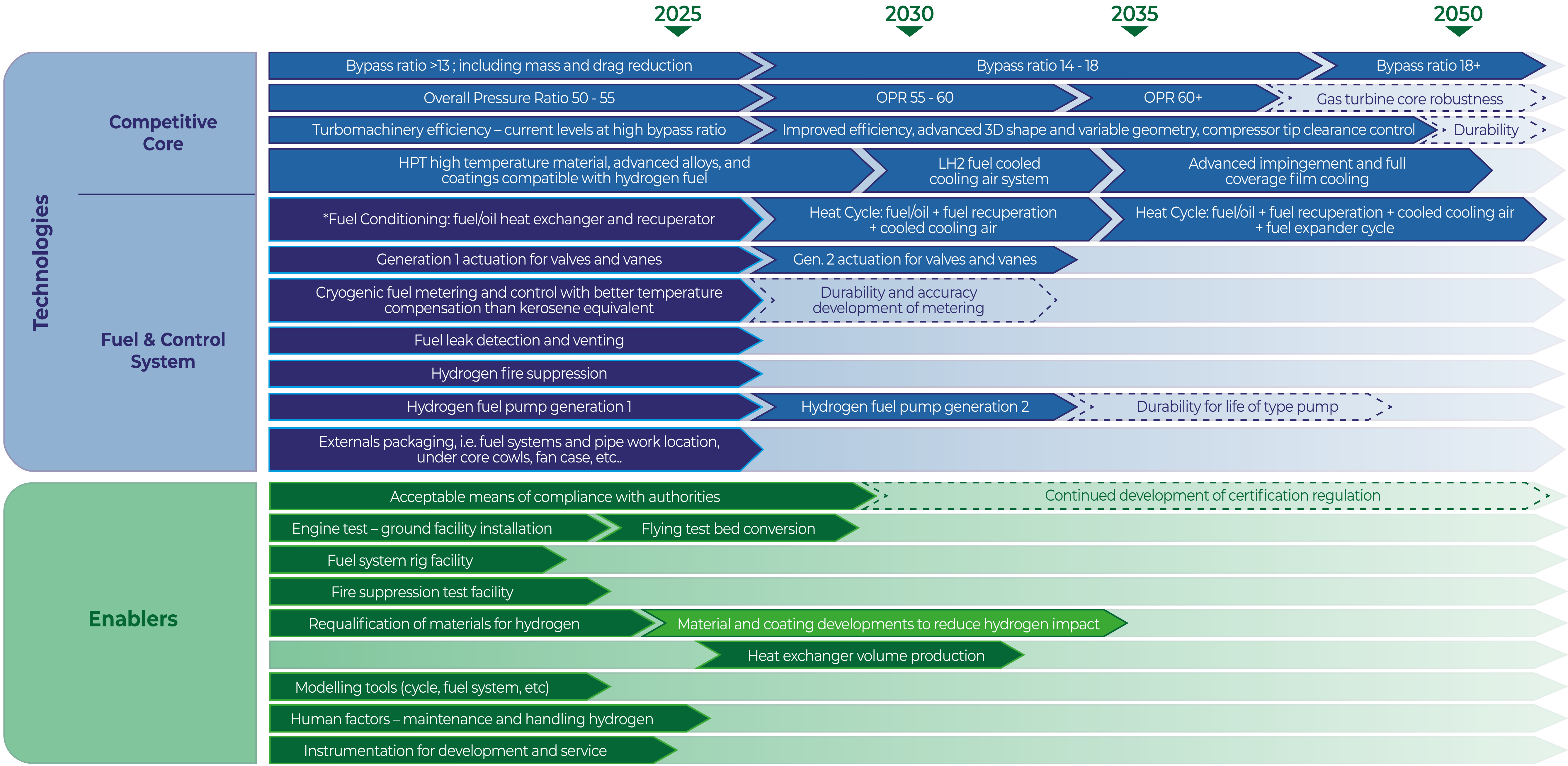
Low Pressure System Developments: covers the fan system, fan inlet, exhaust nozzle, power gearbox and the development of the higher bypass ratio gas turbine. The optimum bypass ratio of a hydrogen gas turbine is likely to be different to that of a kerosene equivalent placing a different set of priorities on the technologies.

Sustainability/ Life Cycle Impact

Sustainability / Life Cycle Impact: developing an understanding of the atmospheric impact of the gas turbine focusing on emissions like NO_x, water, contrails and particulates is key. It also highlights the noise reduction challenge and the continued development to improve the sustainability of the gas turbine.

HYDROGEN GAS TURBINE ROADMAP

Key
- Essential Development
- Competitive Development
- Technology Mature
- Essential Enabler
- Competitive Enabler
- Technology Mature



2025 **2030** **2035** **2050**

Technologies

Competitive Core

- Bypass ratio >13 ; including mass and drag reduction → Bypass ratio 14 - 18 → Bypass ratio 18+
- Overall Pressure Ratio 50 - 55 → OPR 55 - 60 → OPR 60+ → Gas turbine core robustness
- Turbomachinery efficiency – current levels at high bypass ratio → Improved efficiency, advanced 3D shape and variable geometry, compressor tip clearance control → Durability
- HPT high temperature material, advanced alloys, and coatings compatible with hydrogen fuel → LH2 fuel cooled cooling air system → Advanced impingement and full coverage film cooling

Fuel & Control System

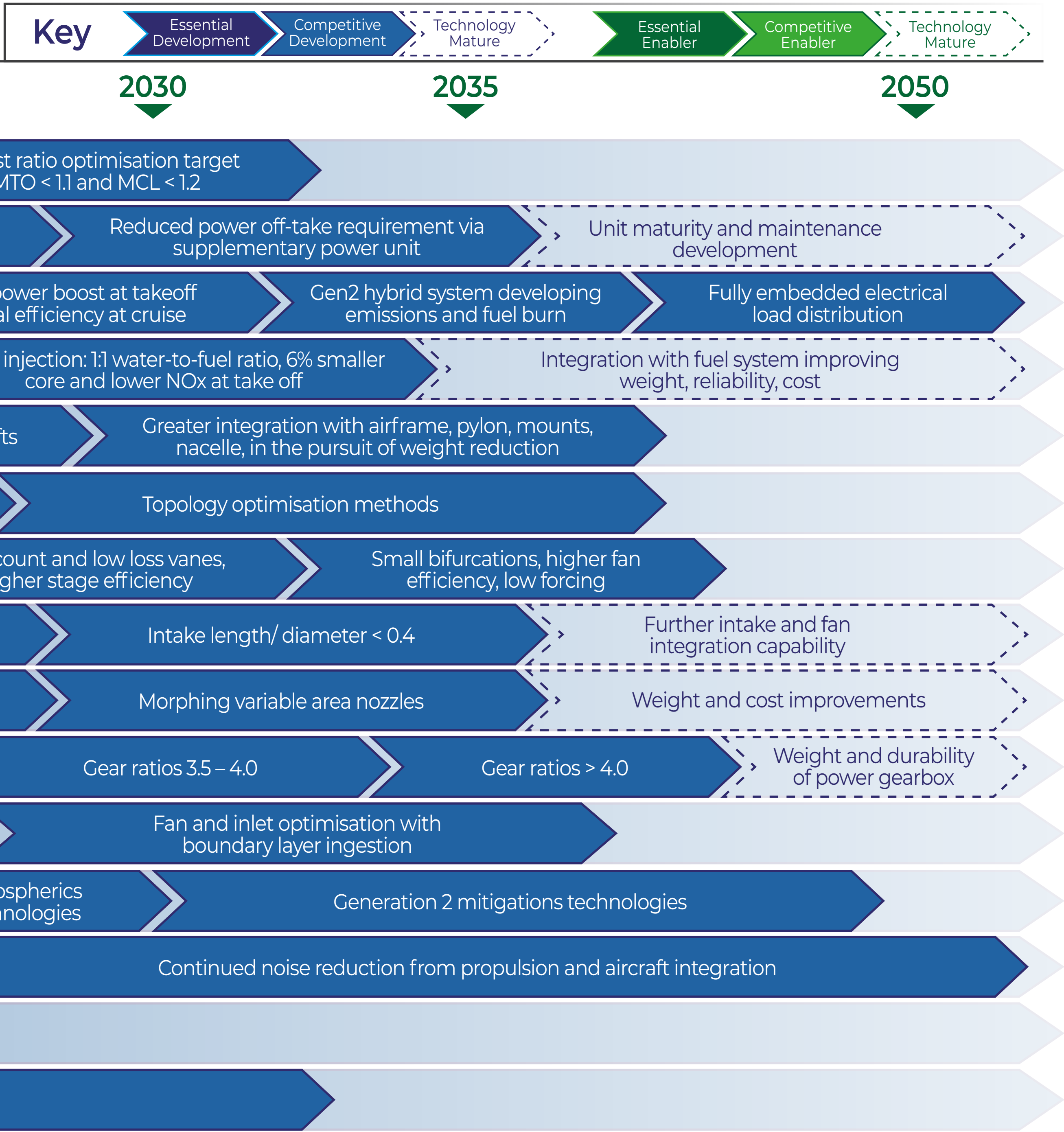
- *Fuel Conditioning: fuel/oil heat exchanger and recuperator → Heat Cycle: fuel/oil + fuel recuperation + cooled cooling air → Heat Cycle: fuel/oil + fuel recuperation + cooled cooling air + fuel expander cycle
- Generation 1 actuation for valves and vanes → Gen. 2 actuation for valves and vanes
- Cryogenic fuel metering and control with better temperature compensation than kerosene equivalent → Durability and accuracy development of metering
- Fuel leak detection and venting
- Hydrogen fire suppression
- Hydrogen fuel pump generation 1 → Hydrogen fuel pump generation 2 → Durability for life of type pump
- Externals packaging, i.e. fuel systems and pipe work location, under core cowls, fan case, etc..

Enablers

- Acceptable means of compliance with authorities → Continued development of certification regulation
- Engine test – ground facility installation → Flying test bed conversion
- Fuel system rig facility
- Fire suppression test facility
- Requalification of materials for hydrogen → Material and coating developments to reduce hydrogen impact
- Heat exchanger volume production
- Modelling tools (cycle, fuel system, etc)
- Human factors – maintenance and handling hydrogen
- Instrumentation for development and service

**Ref - Thermal Management Roadmap Report*

HYDROGEN GAS TURBINE ROADMAP



Key: Essential Development; Competitive Development; Technology Mature; Essential Enabler; Competitive Enabler; Technology Mature

2025 **2030** **2035** **2050**

Technologies

Optimised Cycle

- Low specific thrust vs engine weight and drag optimisation at aircraft level → Thrust ratio optimisation target MTO < 1.1 and MCL < 1.2
- Power off-take from low pressure shaft → Reduced power off-take requirement via supplementary power unit → Unit maturity and maintenance development
- Hybridisation: LP shaft power boost at takeoff creating higher thermal efficiency at cruise → Gen2 hybrid system developing emissions and fuel burn → Fully embedded electrical load distribution
- Water injection: 1:1 water-to-fuel ratio, 6% smaller core and lower NOx at take off → Integration with fuel system improving weight, reliability, cost

Reduced Engine Weight

- Low weight fan system; blade, case, vanes, containment, structures, shafts → Greater integration with airframe, pylon, mounts, nacelle, in the pursuit of weight reduction
- Reduced core casings and structure weight through additive manufacturing and 3D printing → Topology optimisation methods

Low Pressure System Developments

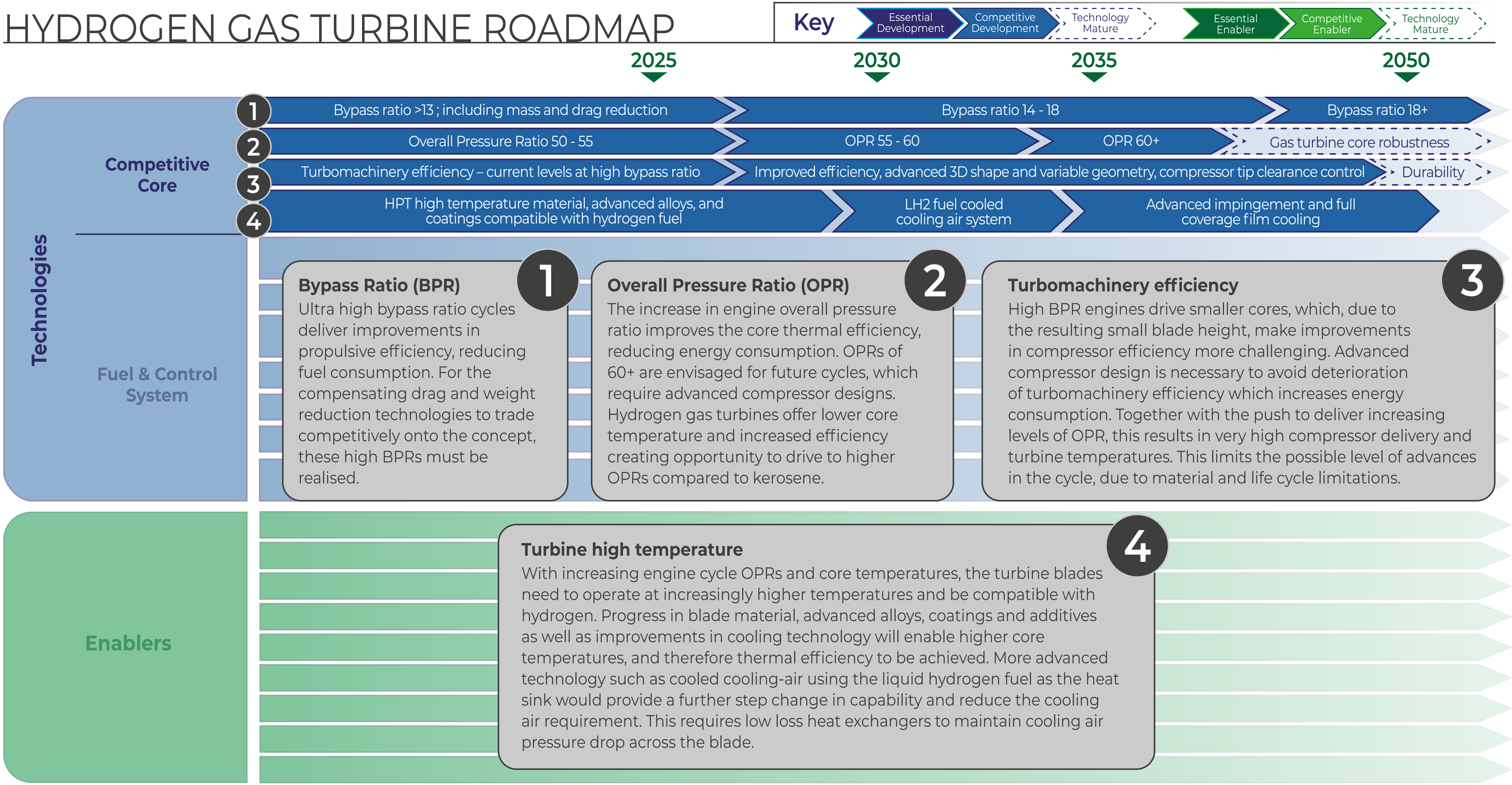
- Highly swept, low speed, low pressure ratio fan → Low count and low loss vanes, higher stage efficiency → Small bifurcations, higher fan efficiency, low forcing
- Intake length/ diameter = 0.4 → Intake length/ diameter < 0.4 → Further intake and fan integration capability
- Advanced exhaust system design → Morphing variable area nozzles → Weight and cost improvements
- Power Gearbox gear ratio ~3.0 and mass reduction → Gear ratios 3.5 – 4.0 → Gear ratios > 4.0 → Weight and durability of power gearbox
- Fan and inlet optimisation with boundary layer ingestion

Sustainability/ Life Cycle Impact

- *Improve estimates of atmospheric impacts of hydrogen combustion → Further development of atmospherics impacts and mitigations technologies → Generation 2 mitigations technologies
- Propulsion noise reduction → Continued noise reduction from propulsion and aircraft integration
- **Increased component life where platinum group metals are used
- Reduced input material during production

*Ref - Sustainability Technical Report
**Ref - Advanced Materials

HYDROGEN GAS TURBINE ROADMAP



1

Bypass Ratio (BPR)

Ultra high bypass ratio cycles deliver improvements in propulsive efficiency, reducing fuel consumption. For the compensating drag and weight reduction technologies to trade competitively onto the concept, these high BPRs must be realised.

2

Overall Pressure Ratio (OPR)

The increase in engine overall pressure ratio improves the core thermal efficiency, reducing energy consumption. OPRs of 60+ are envisaged for future cycles, which require advanced compressor designs. Hydrogen gas turbines offer lower core temperature and increased efficiency creating opportunity to drive to higher OPRs compared to kerosene.

3

Turbomachinery efficiency

High BPR engines drive smaller cores, which, due to the resulting small blade height, make improvements in compressor efficiency more challenging. Advanced compressor design is necessary to avoid deterioration of turbomachinery efficiency which increases energy consumption. Together with the push to deliver increasing levels of OPR, this results in very high compressor delivery and turbine temperatures. This limits the possible level of advances in the cycle, due to material and life cycle limitations.

4

Turbine high temperature

With increasing engine cycle OPRs and core temperatures, the turbine blades need to operate at increasingly higher temperatures and be compatible with hydrogen. Progress in blade material, advanced alloys, coatings and additives as well as improvements in cooling technology will enable higher core temperatures, and therefore thermal efficiency to be achieved. More advanced technology such as cooled cooling-air using the liquid hydrogen fuel as the heat sink would provide a further step change in capability and reduce the cooling air requirement. This requires low loss heat exchangers to maintain cooling air pressure drop across the blade.

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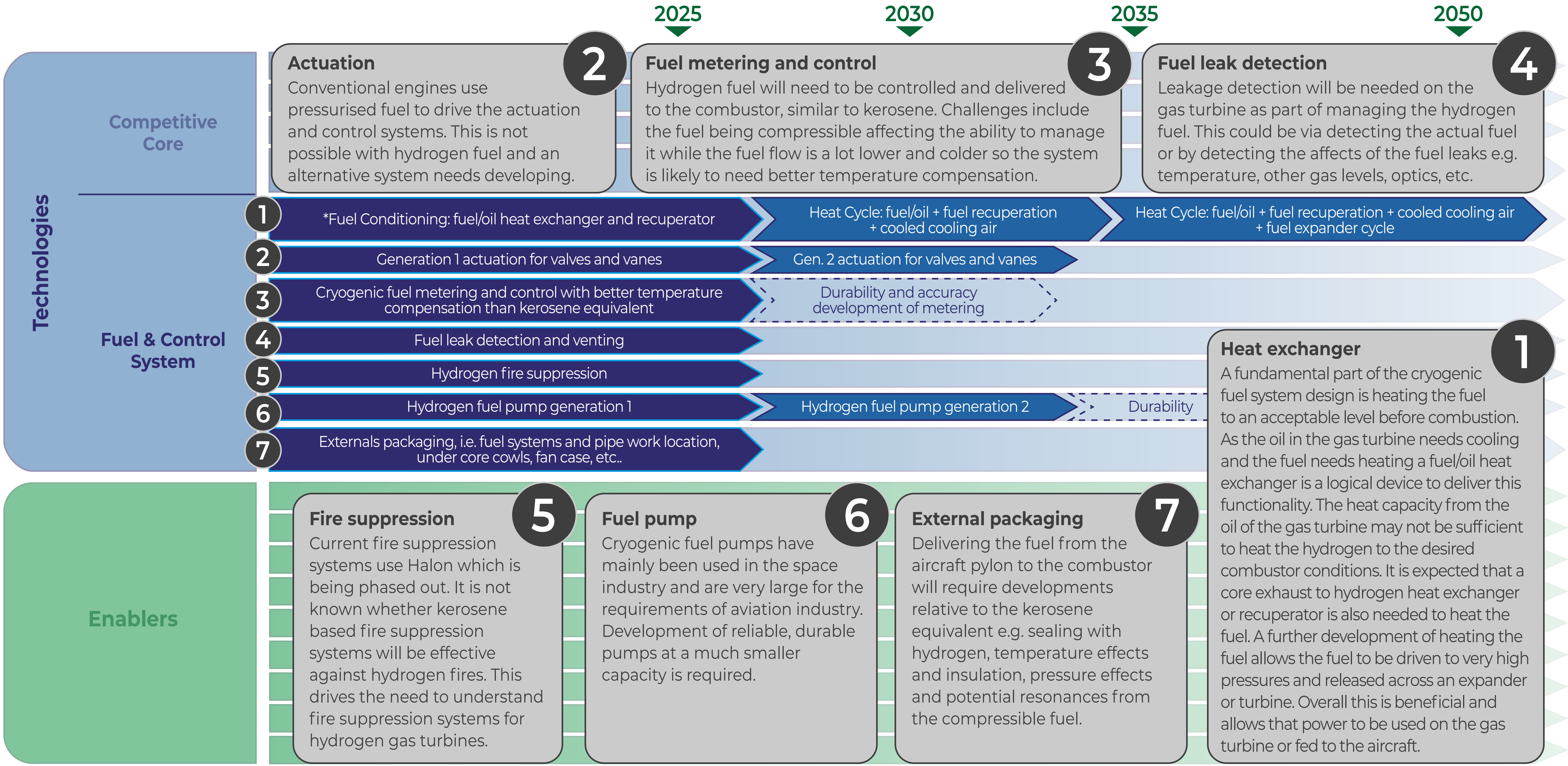

Actuation ②
Conventional engines use pressurised fuel to drive the actuation and control systems. This is not possible with hydrogen fuel and an alternative system needs developing.

Fuel metering and control ③
Hydrogen fuel will need to be controlled and delivered to the combustor, similar to kerosene. Challenges include the fuel being compressible affecting the ability to manage it while the fuel flow is a lot lower and colder so the system is likely to need better temperature compensation.

Fuel leak detection ④
Leakage detection will be needed on the gas turbine as part of managing the hydrogen fuel. This could be via detecting the actual fuel or by detecting the affects of the fuel leaks e.g. temperature, other gas levels, optics, etc.

1. *Fuel Conditioning: fuel/oil heat exchanger and recuperator → Heat Cycle: fuel/oil + fuel recuperation + cooled cooling air → Heat Cycle: fuel/oil + fuel recuperation + cooled cooling air + fuel expander cycle
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4. Fuel leak detection and venting
5. Hydrogen fire suppression
6. Hydrogen fuel pump generation 1 → Hydrogen fuel pump generation 2 → Durability
7. Externals packaging, i.e. fuel systems and pipe work location, under core cowls, fan case, etc..

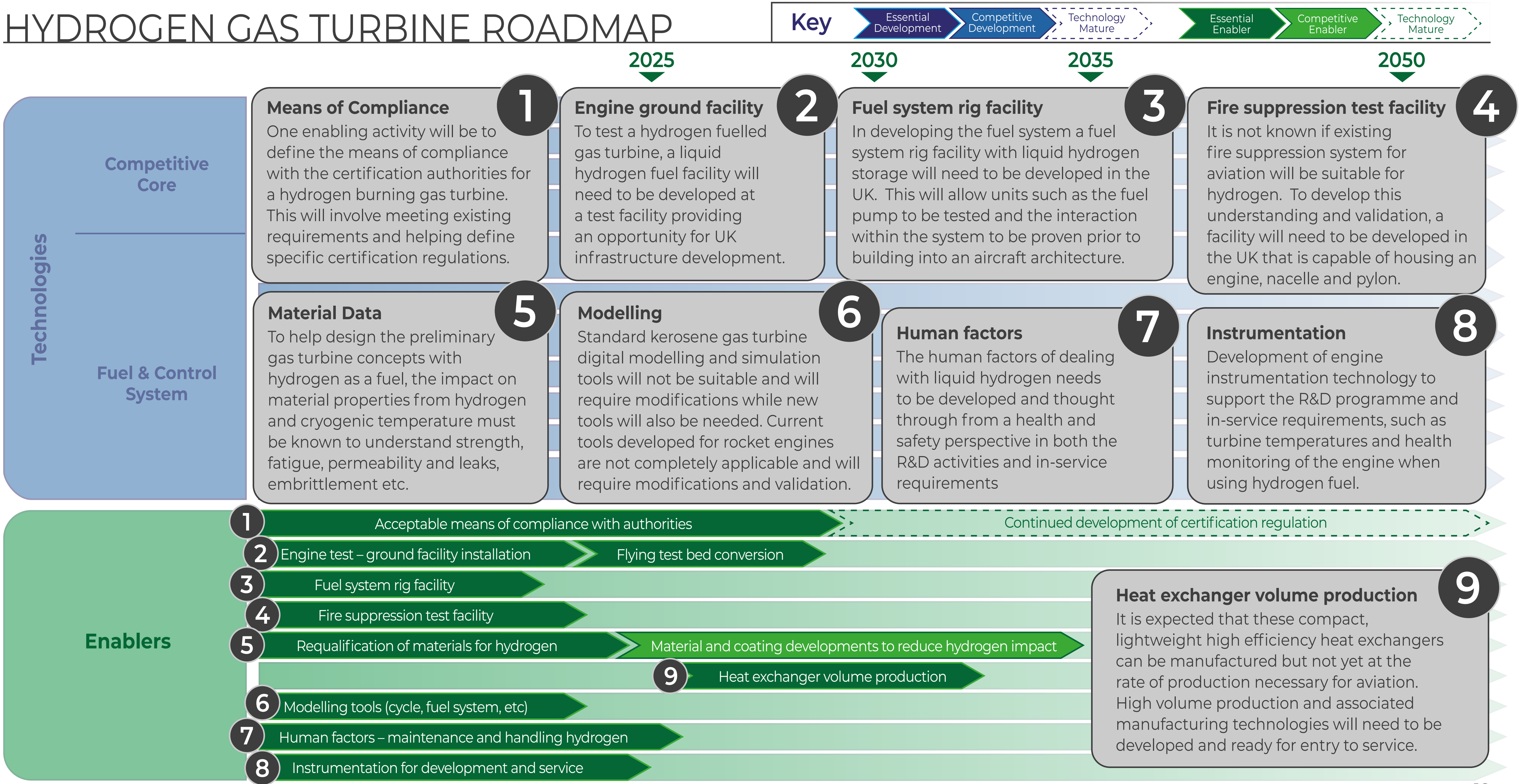
Heat exchanger ①
A fundamental part of the cryogenic fuel system design is heating the fuel to an acceptable level before combustion. As the oil in the gas turbine needs cooling and the fuel needs heating a fuel/oil heat exchanger is a logical device to deliver this functionality. The heat capacity from the oil of the gas turbine may not be sufficient to heat the hydrogen to the desired combustor conditions. It is expected that a core exhaust to hydrogen heat exchanger or recuperator is also needed to heat the fuel. A further development of heating the fuel allows the fuel to be driven to very high pressures and released across an expander or turbine. Overall this is beneficial and allows that power to be used on the gas turbine or fed to the aircraft.

Fire suppression ⑤
Current fire suppression systems use Halon which is being phased out. It is not known whether kerosene based fire suppression systems will be effective against hydrogen fires. This drives the need to understand fire suppression systems for hydrogen gas turbines.

Fuel pump ⑥
Cryogenic fuel pumps have mainly been used in the space industry and are very large for the requirements of aviation industry. Development of reliable, durable pumps at a much smaller capacity is required.

External packaging ⑦
Delivering the fuel from the aircraft pylon to the combustor will require developments relative to the kerosene equivalent e.g. sealing with hydrogen, temperature effects and insulation, pressure effects and potential resonances from the compressible fuel.

HYDROGEN GAS TURBINE ROADMAP



1 Means of Compliance
One enabling activity will be to define the means of compliance with the certification authorities for a hydrogen burning gas turbine. This will involve meeting existing requirements and helping define specific certification regulations.

2 Engine ground facility
To test a hydrogen fuelled gas turbine, a liquid hydrogen fuel facility will need to be developed at a test facility providing an opportunity for UK infrastructure development.

3 Fuel system rig facility
In developing the fuel system a fuel system rig facility with liquid hydrogen storage will need to be developed in the UK. This will allow units such as the fuel pump to be tested and the interaction within the system to be proven prior to building into an aircraft architecture.

4 Fire suppression test facility
It is not known if existing fire suppression system for aviation will be suitable for hydrogen. To develop this understanding and validation, a facility will need to be developed in the UK that is capable of housing an engine, nacelle and pylon.

5 Material Data
To help design the preliminary gas turbine concepts with hydrogen as a fuel, the impact on material properties from hydrogen and cryogenic temperature must be known to understand strength, fatigue, permeability and leaks, embrittlement etc.

6 Modelling
Standard kerosene gas turbine digital modelling and simulation tools will not be suitable and will require modifications while new tools will also be needed. Current tools developed for rocket engines are not completely applicable and will require modifications and validation.

7 Human factors
The human factors of dealing with liquid hydrogen needs to be developed and thought through from a health and safety perspective in both the R&D activities and in-service requirements

8 Instrumentation
Development of engine instrumentation technology to support the R&D programme and in-service requirements, such as turbine temperatures and health monitoring of the engine when using hydrogen fuel.

Enablers

1 Acceptable means of compliance with authorities → Continued development of certification regulation

2 Engine test – ground facility installation → Flying test bed conversion

3 Fuel system rig facility

4 Fire suppression test facility

5 Requalification of materials for hydrogen → Material and coating developments to reduce hydrogen impact

9 Heat exchanger volume production

6 Modelling tools (cycle, fuel system, etc)

7 Human factors – maintenance and handling hydrogen

8 Instrumentation for development and service

9 Heat exchanger volume production
It is expected that these compact, lightweight high efficiency heat exchangers can be manufactured but not yet at the rate of production necessary for aviation. High volume production and associated manufacturing technologies will need to be developed and ready for entry to service.

HYDROGEN GAS TURBINE ROADMAP

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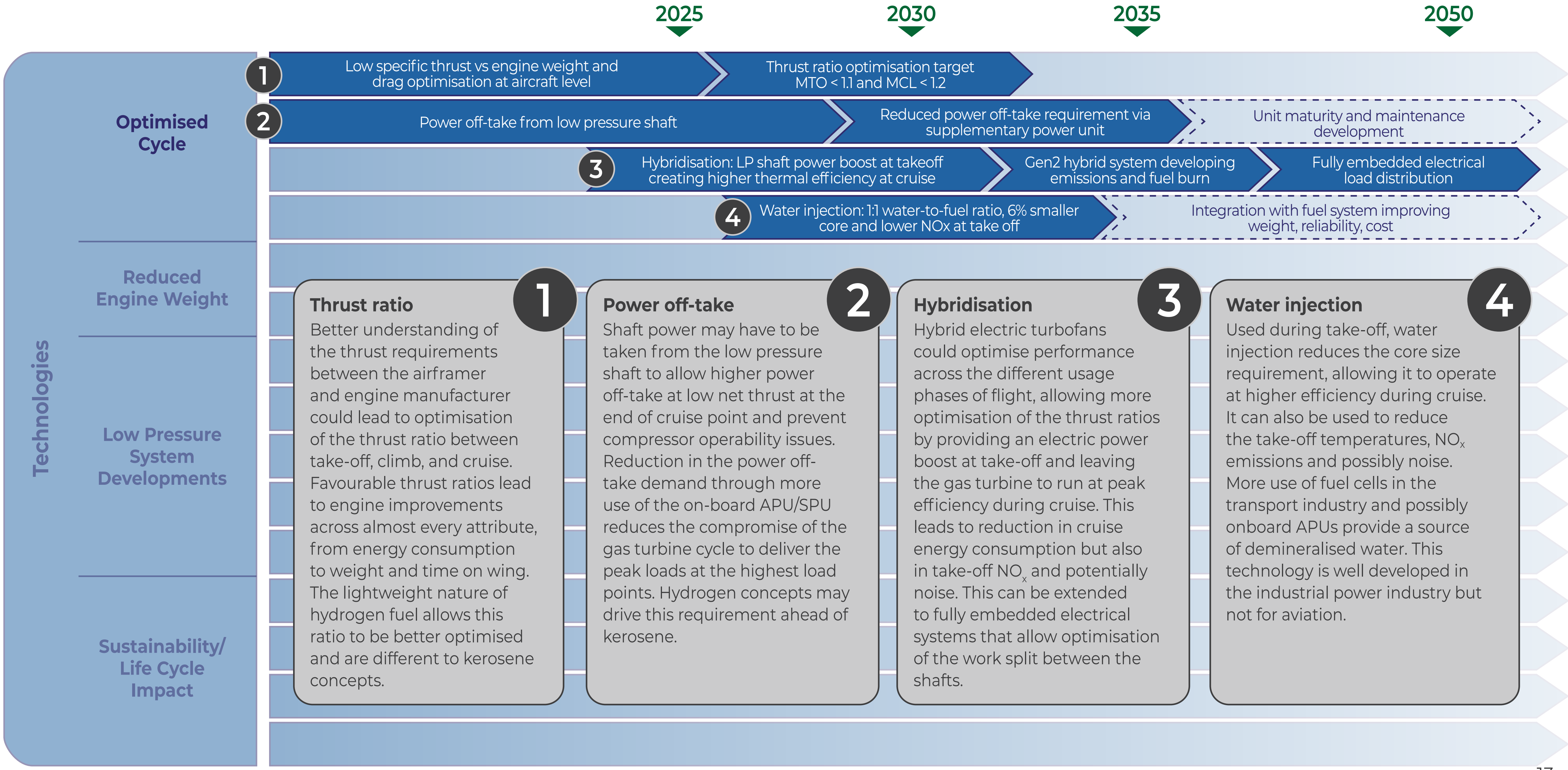


Optimised Cycle

① Low specific thrust vs engine weight and drag optimisation at aircraft level → Thrust ratio optimisation target MTO < 1.1 and MCL < 1.2

② Power off-take from low pressure shaft → Reduced power off-take requirement via supplementary power unit → Unit maturity and maintenance development

③ Hybridisation: LP shaft power boost at takeoff creating higher thermal efficiency at cruise → Gen2 hybrid system developing emissions and fuel burn → Fully embedded electrical load distribution

④ Water injection: 1:1 water-to-fuel ratio, 6% smaller core and lower NOx at take off → Integration with fuel system improving weight, reliability, cost

Reduced Engine Weight

Low Pressure System Developments

Sustainability/ Life Cycle Impact

1 Thrust ratio

Better understanding of the thrust requirements between the airframer and engine manufacturer could lead to optimisation of the thrust ratio between take-off, climb, and cruise. Favourable thrust ratios lead to engine improvements across almost every attribute, from energy consumption to weight and time on wing. The lightweight nature of hydrogen fuel allows this ratio to be better optimised and are different to kerosene concepts.

2 Power off-take

Shaft power may have to be taken from the low pressure shaft to allow higher power off-take at low net thrust at the end of cruise point and prevent compressor operability issues. Reduction in the power off-take demand through more use of the on-board APU/SPU reduces the compromise of the gas turbine cycle to deliver the peak loads at the highest load points. Hydrogen concepts may drive this requirement ahead of kerosene.

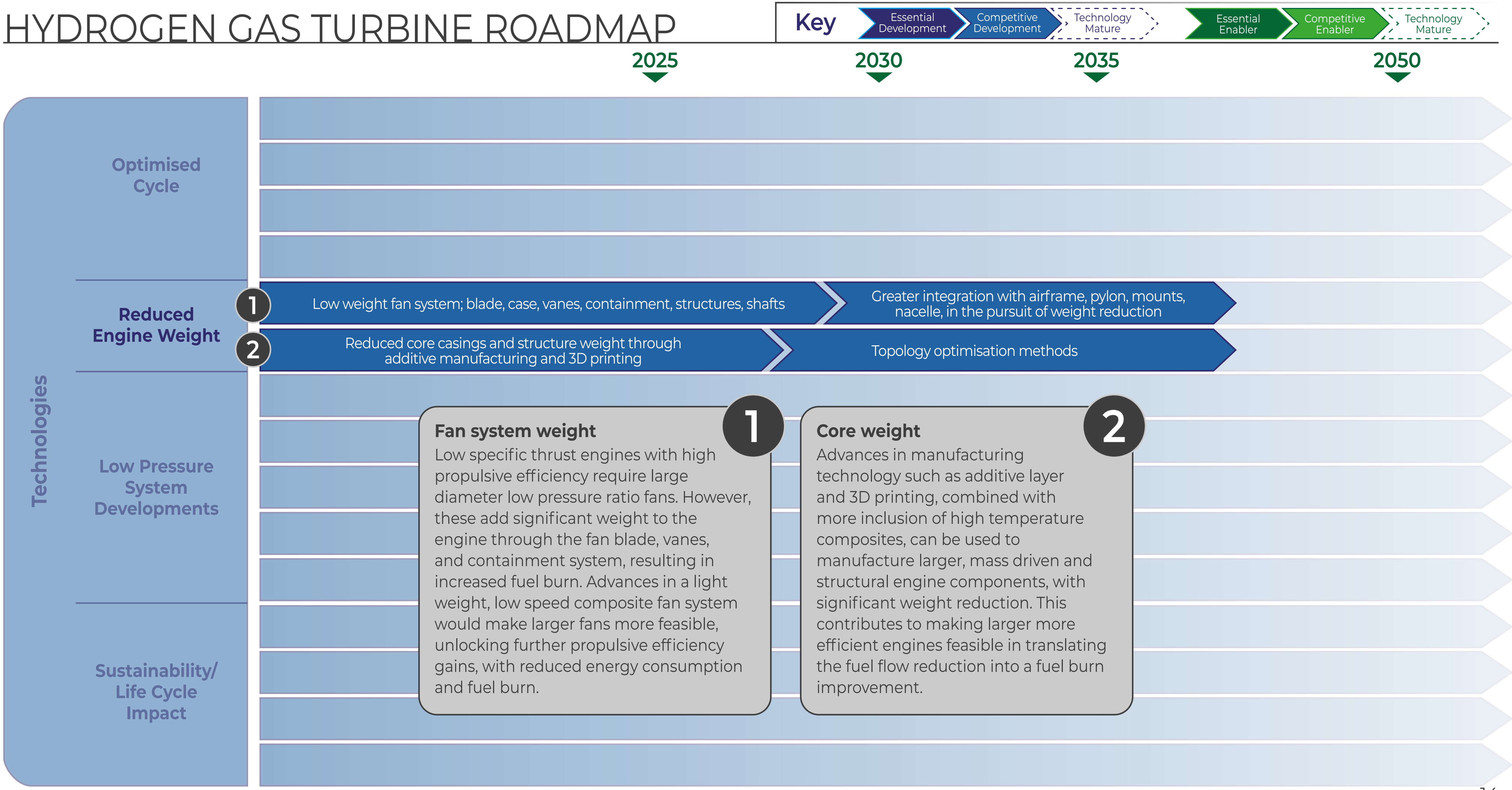
3 Hybridisation

Hybrid electric turbofans could optimise performance across the different usage phases of flight, allowing more optimisation of the thrust ratios by providing an electric power boost at take-off and leaving the gas turbine to run at peak efficiency during cruise. This leads to reduction in cruise energy consumption but also in take-off NO_x and potentially noise. This can be extended to fully embedded electrical systems that allow optimisation of the work split between the shafts.

4 Water injection

Used during take-off, water injection reduces the core size requirement, allowing it to operate at higher efficiency during cruise. It can also be used to reduce the take-off temperatures, NO_x emissions and possibly noise. More use of fuel cells in the transport industry and possibly onboard APUs provide a source of demineralised water. This technology is well developed in the industrial power industry but not for aviation.

HYDROGEN GAS TURBINE ROADMAP



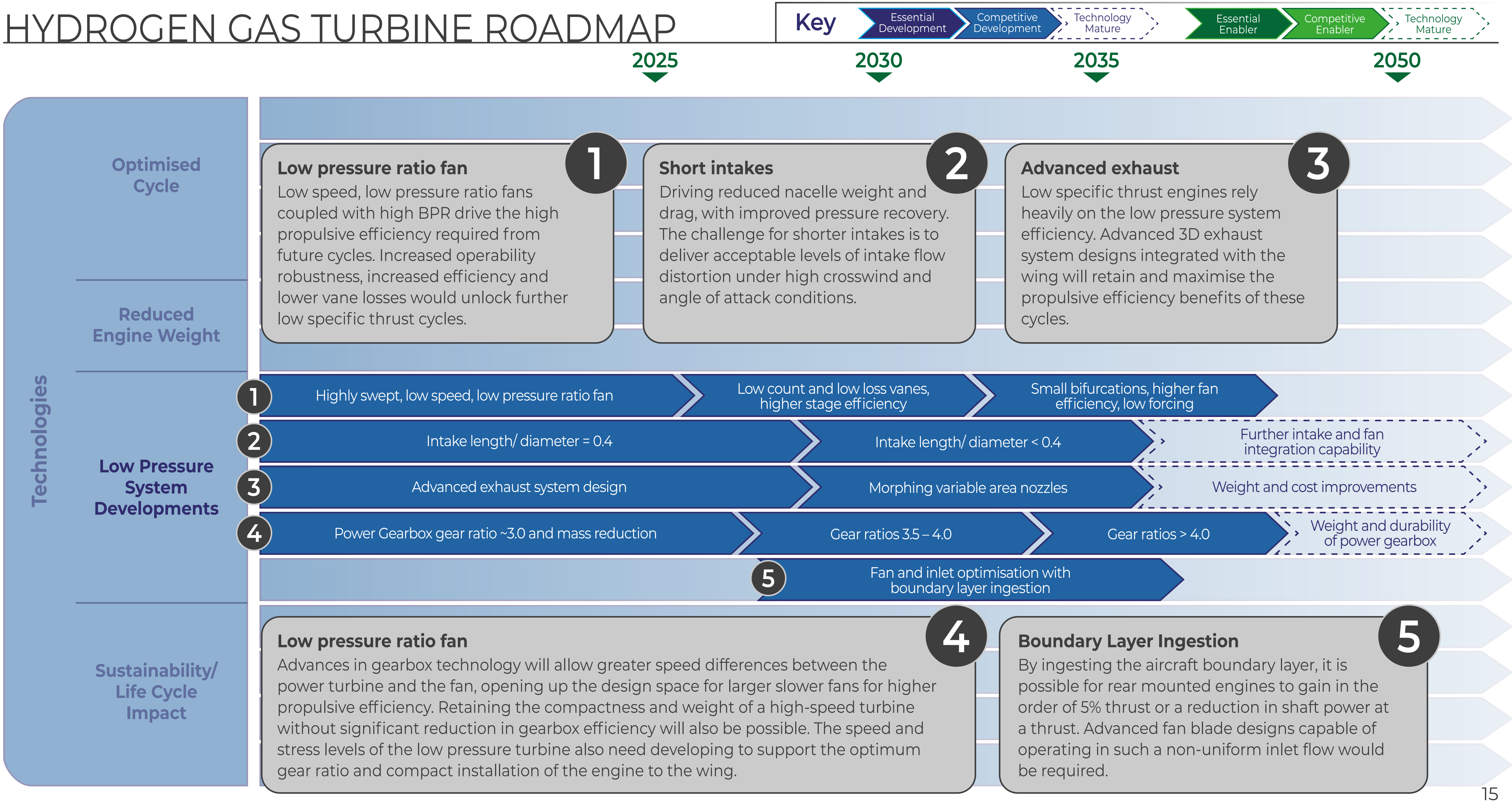
Fan system weight 1

Low specific thrust engines with high propulsive efficiency require large diameter low pressure ratio fans. However, these add significant weight to the engine through the fan blade, vanes, and containment system, resulting in increased fuel burn. Advances in a light weight, low speed composite fan system would make larger fans more feasible, unlocking further propulsive efficiency gains, with reduced energy consumption and fuel burn.

Core weight 2

Advances in manufacturing technology such as additive layer and 3D printing, combined with more inclusion of high temperature composites, can be used to manufacture larger, mass driven and structural engine components, with significant weight reduction. This contributes to making larger more efficient engines feasible in translating the fuel flow reduction into a fuel burn improvement.

HYDROGEN GAS TURBINE ROADMAP



Key

Essential Development

Competitive Development

Technology Mature

Essential Enabler

Competitive Enabler

Technology Mature

2025 **2030** **2035** **2050**

Technologies

Optimised Cycle

Reduced Engine Weight

Low Pressure System Developments

Sustainability/ Life Cycle Impact

1 Low pressure ratio fan

Low speed, low pressure ratio fans coupled with high BPR drive the high propulsive efficiency required from future cycles. Increased operability robustness, increased efficiency and lower vane losses would unlock further low specific thrust cycles.

2 Short intakes

Driving reduced nacelle weight and drag, with improved pressure recovery. The challenge for shorter intakes is to deliver acceptable levels of intake flow distortion under high crosswind and angle of attack conditions.

3 Advanced exhaust

Low specific thrust engines rely heavily on the low pressure system efficiency. Advanced 3D exhaust system designs integrated with the wing will retain and maximise the propulsive efficiency benefits of these cycles.

1. Highly swept, low speed, low pressure ratio fan → Low count and low loss vanes, higher stage efficiency → Small bifurcations, higher fan efficiency, low forcing
2. Intake length/ diameter = 0.4 → Intake length/ diameter < 0.4 → Further intake and fan integration capability
3. Advanced exhaust system design → Morphing variable area nozzles → Weight and cost improvements
4. Power Gearbox gear ratio ~3.0 and mass reduction → Gear ratios 3.5 – 4.0 → Gear ratios > 4.0 → Weight and durability of power gearbox
5. Fan and inlet optimisation with boundary layer ingestion

4 Low pressure ratio fan

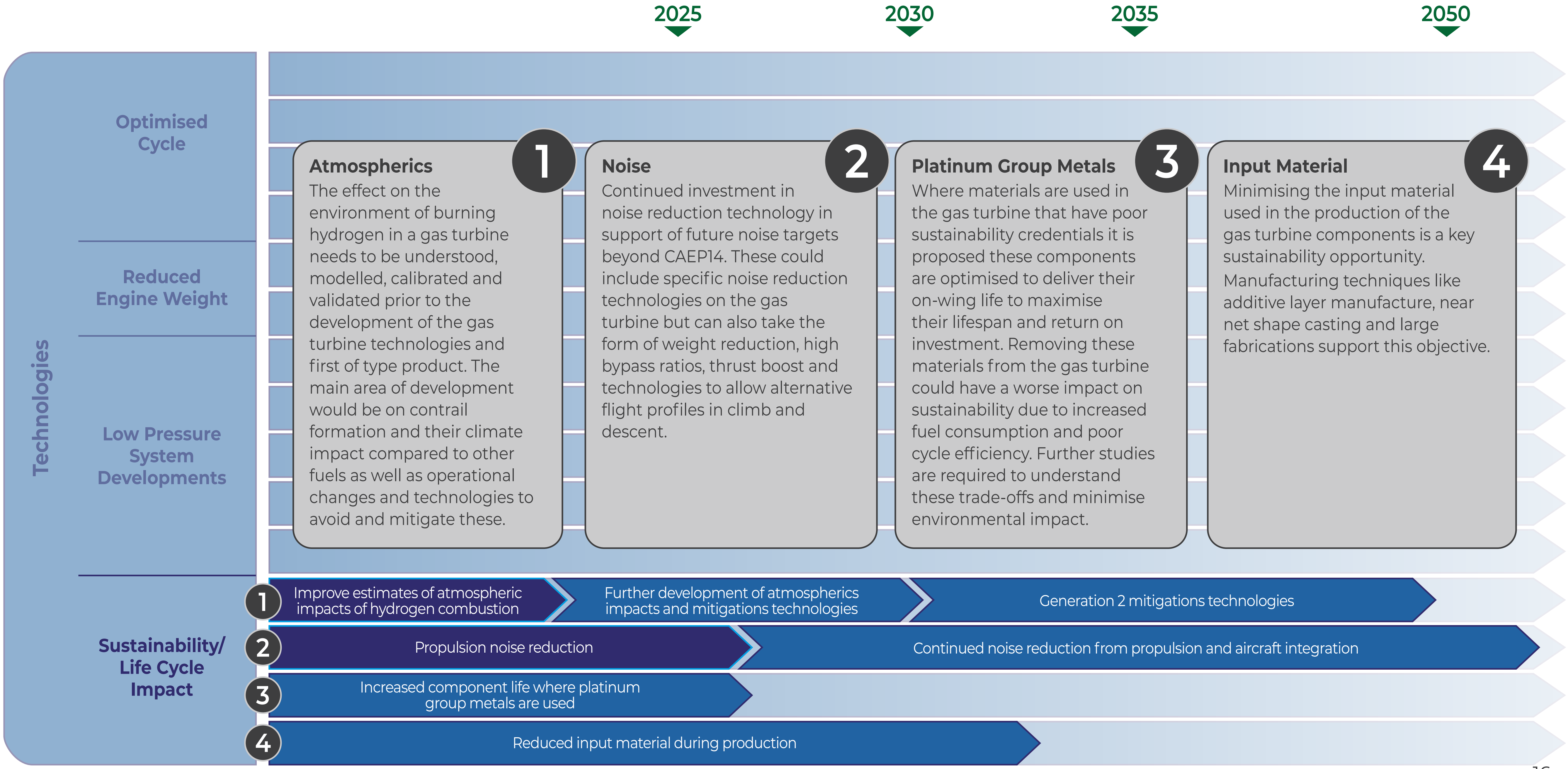
Advances in gearbox technology will allow greater speed differences between the power turbine and the fan, opening up the design space for larger slower fans for higher propulsive efficiency. Retaining the compactness and weight of a high-speed turbine without significant reduction in gearbox efficiency will also be possible. The speed and stress levels of the low pressure turbine also need developing to support the optimum gear ratio and compact installation of the engine to the wing.

5 Boundary Layer Ingestion

By ingesting the aircraft boundary layer, it is possible for rear mounted engines to gain in the order of 5% thrust or a reduction in shaft power at a thrust. Advanced fan blade designs capable of operating in such a non-uniform inlet flow would be required.

HYDROGEN GAS TURBINE ROADMAP

Key: Essential Development | Competitive Development | Technology Mature | Essential Enabler | Competitive Enabler | Technology Mature



1 Atmospherics

The effect on the environment of burning hydrogen in a gas turbine needs to be understood, modelled, calibrated and validated prior to the development of the gas turbine technologies and first of type product. The main area of development would be on contrail formation and their climate impact compared to other fuels as well as operational changes and technologies to avoid and mitigate these.

2 Noise

Continued investment in noise reduction technology in support of future noise targets beyond CAEP14. These could include specific noise reduction technologies on the gas turbine but can also take the form of weight reduction, high bypass ratios, thrust boost and technologies to allow alternative flight profiles in climb and descent.

3 Platinum Group Metals

Where materials are used in the gas turbine that have poor sustainability credentials it is proposed these components are optimised to deliver their on-wing life to maximise their lifespan and return on investment. Removing these materials from the gas turbine could have a worse impact on sustainability due to increased fuel consumption and poor cycle efficiency. Further studies are required to understand these trade-offs and minimise environmental impact.

4 Input Material

Minimising the input material used in the production of the gas turbine components is a key sustainability opportunity.

Manufacturing techniques like additive layer manufacture, near net shape casting and large fabrications support this objective.

1. Improve estimates of atmospheric impacts of hydrogen combustion → Further development of atmospherics impacts and mitigations technologies → Generation 2 mitigations technologies
2. Propulsion noise reduction → Continued noise reduction from propulsion and aircraft integration
3. Increased component life where platinum group metals are used
4. Reduced input material during production

HYDROGEN COMBUSTION ROADMAP

Key
- Essential Development
- Competitive Development
- Technology Mature
- Essential Enabler
- Competitive Enabler
- Technology Mature

Technologies

Hydrogen capable combustion simulation tools

Hydrogen capable combustion simulation tools: aerospace combustor design is heavily dependent on a variety of computational fluid dynamic (CFD) tools. These tools cover one to three dimensions analysing aerodynamics, acoustics, mixing, chemistry and heat transfer.

Gaseous delivery system

Fuel delivery system: a hydrogen fuel delivery system will be transporting lower mass flows, low density and a wide range of hydrogen temperatures.

Hydrogen Combustor

Combustor: the combustor must contain the flame in a safe and reliable manner. The concept recommended by FlyZero is significantly different to current aerospace approaches meaning significant development will be required to mature the technology. However, it also lends itself to additive manufacture which should realise cost reductions relative to conventional kerosene fuelled designs.

Hydrogen/Air mixer

Fuel/air mixer: this swim lane refers to the part of the combustor assembly where the fuel is introduced and mixed with a large proportion of the air delivered from the compressor system. The mixing must be complete within a fraction of a millisecond to achieve acceptable emissions.

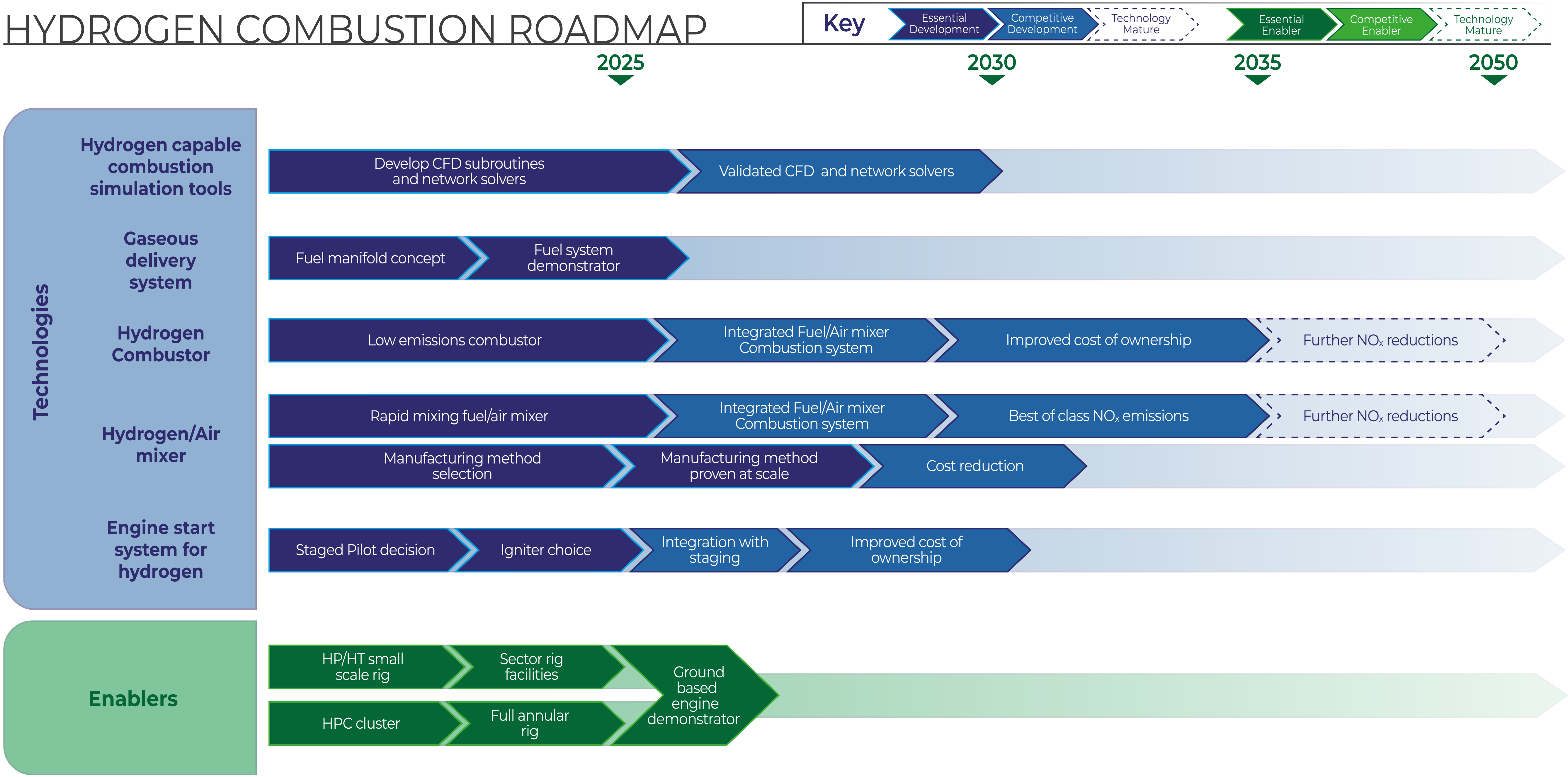
Engine start system for hydrogen

Engine start system: starting a gas turbine reliably is a key customer deliverable. Hydrogen presents a very different challenge compared to kerosene due to low temperatures from the cryogenic fuel delivery.

Enablers

Enablers: the swim lanes above will require a range of infrastructures such as test facilities in order to perform the design and development task.

HYDROGEN COMBUSTION ROADMAP



Key
- Essential Development
- Competitive Development
- Technology Mature
- Essential Enabler
- Competitive Enabler
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2025 · 2030 · 2035 · 2050

Technologies

Hydrogen capable combustion simulation tools
- Develop CFD subroutines and network solvers
- Validated CFD and network solvers

Gaseous delivery system
- Fuel manifold concept
- Fuel system demonstrator

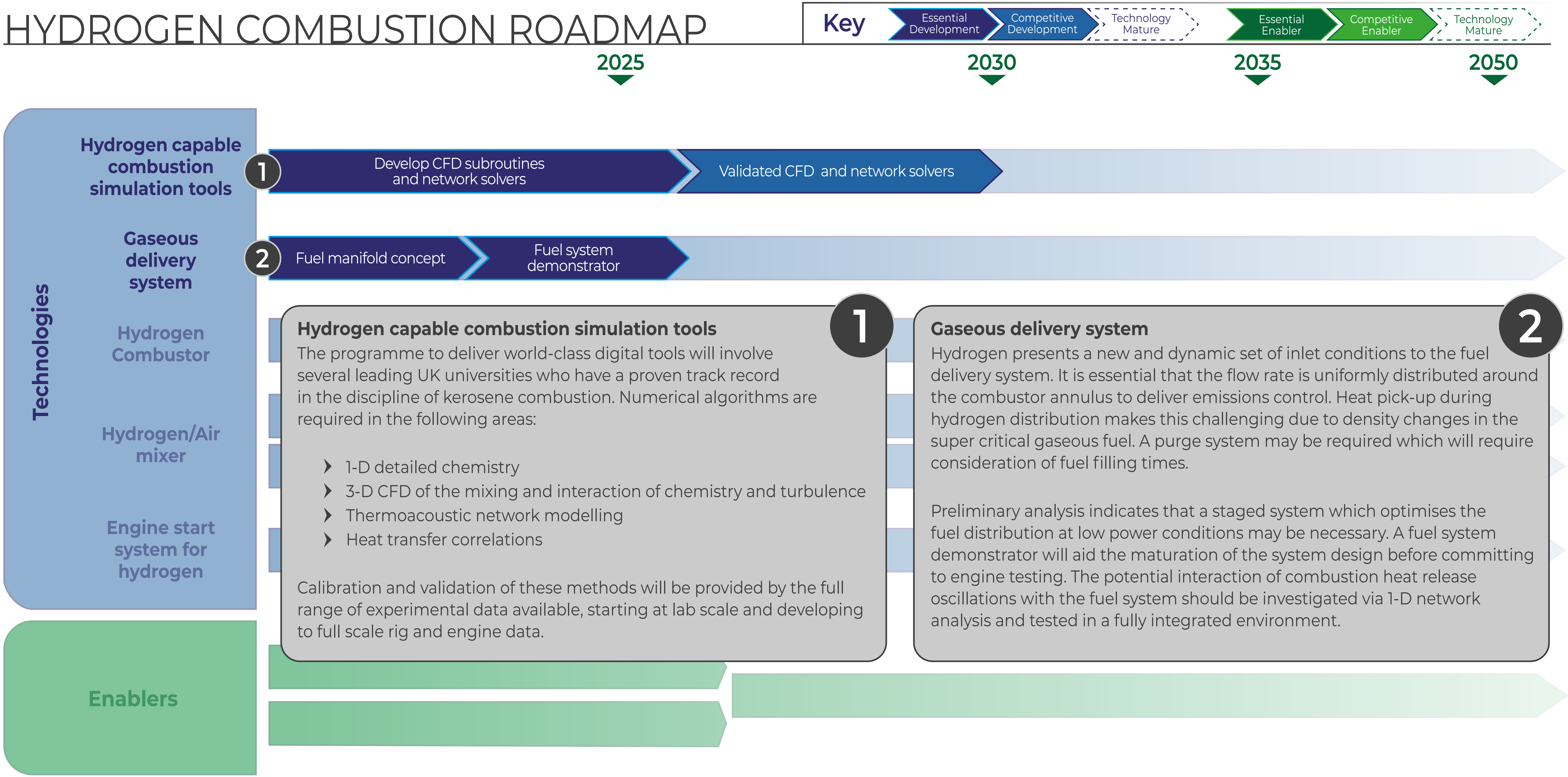
Hydrogen Combustor
- Low emissions combustor
- Integrated Fuel/Air mixer Combustion system
- Improved cost of ownership
- Further NO_x reductions

Hydrogen/Air mixer
- Rapid mixing fuel/air mixer
- Integrated Fuel/Air mixer Combustion system
- Best of class NO_x emissions
- Further NO_x reductions
- Manufacturing method selection
- Manufacturing method proven at scale
- Cost reduction

Engine start system for hydrogen
- Staged Pilot decision
- Igniter choice
- Integration with staging
- Improved cost of ownership

Enablers
- HP/HT small scale rig
- Sector rig facilities
- HPC cluster
- Full annular rig
- Ground based engine demonstrator

HYDROGEN COMBUSTION ROADMAP



1 Hydrogen capable combustion simulation tools

The programme to deliver world-class digital tools will involve several leading UK universities who have a proven track record in the discipline of kerosene combustion. Numerical algorithms are required in the following areas:

- 1-D detailed chemistry
- 3-D CFD of the mixing and interaction of chemistry and turbulence
- Thermoacoustic network modelling
- Heat transfer correlations

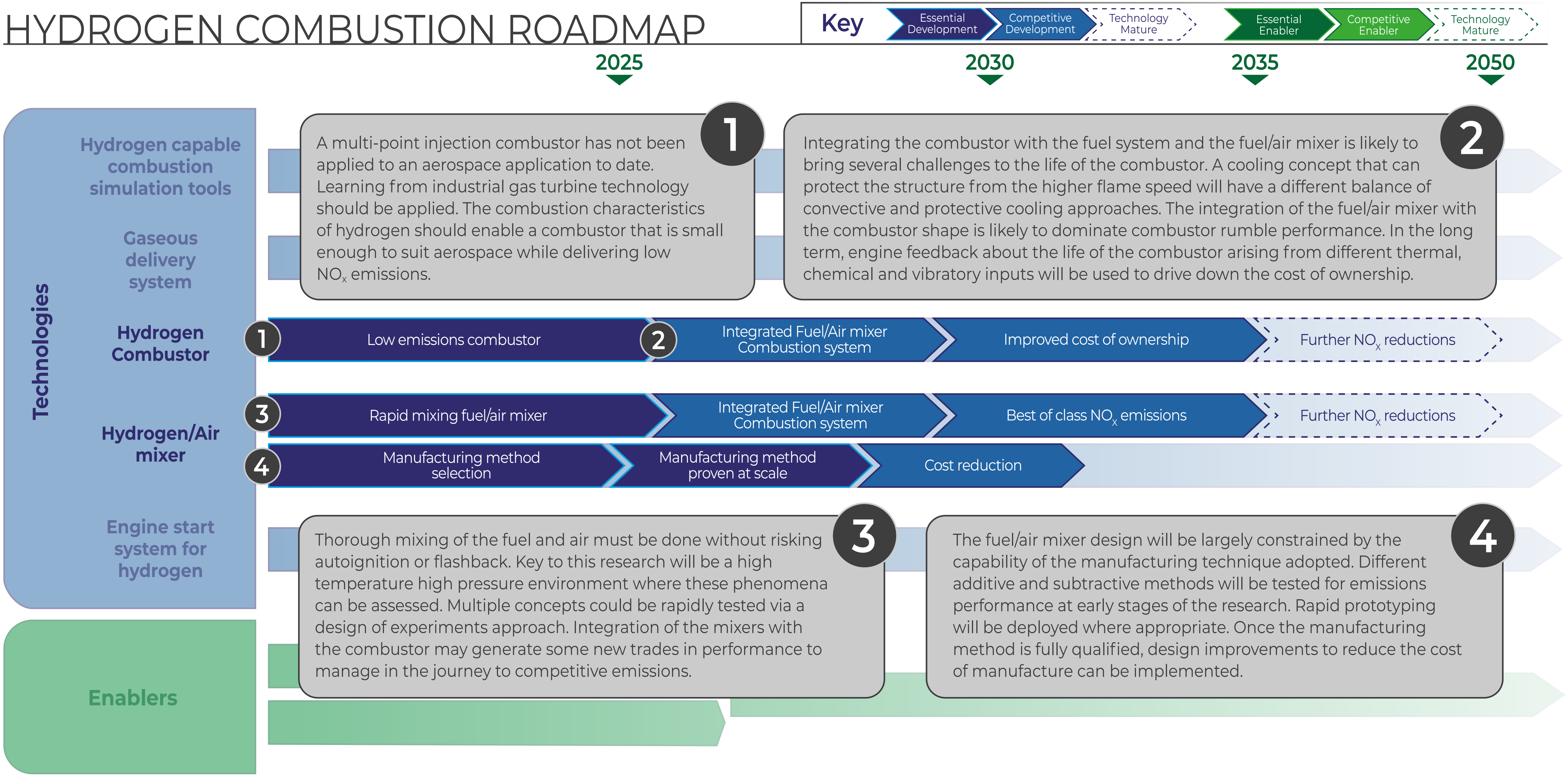
Calibration and validation of these methods will be provided by the full range of experimental data available, starting at lab scale and developing to full scale rig and engine data.

2 Gaseous delivery system

Hydrogen presents a new and dynamic set of inlet conditions to the fuel delivery system. It is essential that the flow rate is uniformly distributed around the combustor annulus to deliver emissions control. Heat pick-up during hydrogen distribution makes this challenging due to density changes in the super critical gaseous fuel. A purge system may be required which will require consideration of fuel filling times.

Preliminary analysis indicates that a staged system which optimises the fuel distribution at low power conditions may be necessary. A fuel system demonstrator will aid the maturation of the system design before committing to engine testing. The potential interaction of combustion heat release oscillations with the fuel system should be investigated via 1-D network analysis and tested in a fully integrated environment.

HYDROGEN COMBUSTION ROADMAP



Key
Essential Development
Competitive Development
Technology Mature
Essential Enabler
Competitive Enabler
Technology Mature

2025
2030
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2050

Technologies

Hydrogen capable combustion simulation tools

Gaseous delivery system

Hydrogen Combustor
① Low emissions combustor
② Integrated Fuel/Air mixer Combustion system
Improved cost of ownership
Further NO_x reductions

Hydrogen/Air mixer
③ Rapid mixing fuel/air mixer
Integrated Fuel/Air mixer Combustion system
Best of class NO_x emissions
Further NO_x reductions

④ Manufacturing method selection
Manufacturing method proven at scale
Cost reduction

Engine start system for hydrogen

Enablers

1

A multi-point injection combustor has not been applied to an aerospace application to date. Learning from industrial gas turbine technology should be applied. The combustion characteristics of hydrogen should enable a combustor that is small enough to suit aerospace while delivering low NO_x emissions.

2

Integrating the combustor with the fuel system and the fuel/air mixer is likely to bring several challenges to the life of the combustor. A cooling concept that can protect the structure from the higher flame speed will have a different balance of convective and protective cooling approaches. The integration of the fuel/air mixer with the combustor shape is likely to dominate combustor rumble performance. In the long term, engine feedback about the life of the combustor arising from different thermal, chemical and vibratory inputs will be used to drive down the cost of ownership.

3

Thorough mixing of the fuel and air must be done without risking autoignition or flashback. Key to this research will be a high temperature high pressure environment where these phenomena can be assessed. Multiple concepts could be rapidly tested via a design of experiments approach. Integration of the mixers with the combustor may generate some new trades in performance to manage in the journey to competitive emissions.

4

The fuel/air mixer design will be largely constrained by the capability of the manufacturing technique adopted. Different additive and subtractive methods will be tested for emissions performance at early stages of the research. Rapid prototyping will be deployed where appropriate. Once the manufacturing method is fully qualified, design improvements to reduce the cost of manufacture can be implemented.

HYDROGEN COMBUSTION ROADMAP

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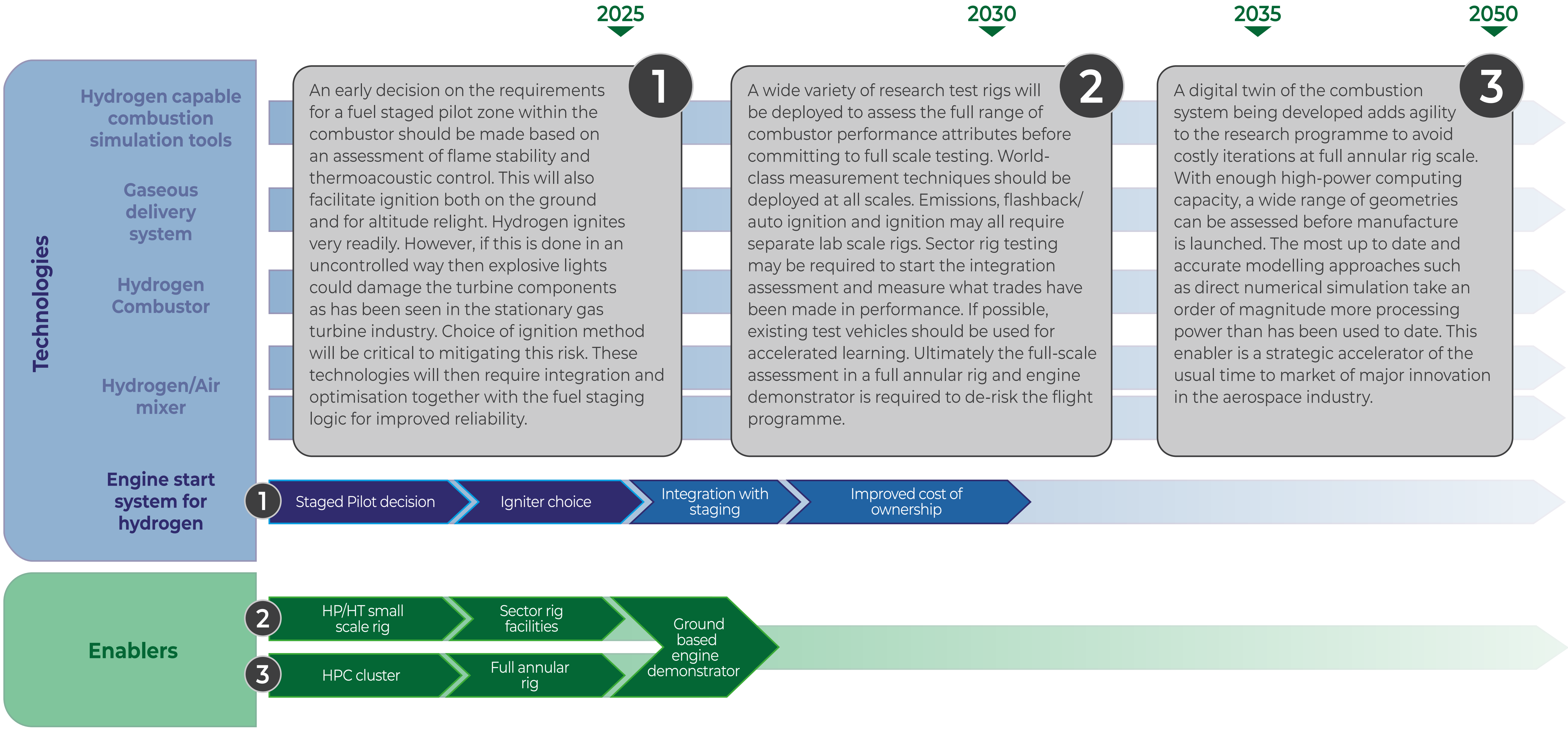


2025 | 2030 | 2035 | 2050

Technologies

Hydrogen capable combustion simulation tools

Gaseous delivery system

Hydrogen Combustor

Hydrogen/Air mixer

① An early decision on the requirements for a fuel staged pilot zone within the combustor should be made based on an assessment of flame stability and thermoacoustic control. This will also facilitate ignition both on the ground and for altitude relight. Hydrogen ignites very readily. However, if this is done in an uncontrolled way then explosive lights could damage the turbine components as has been seen in the stationary gas turbine industry. Choice of ignition method will be critical to mitigating this risk. These technologies will then require integration and optimisation together with the fuel staging logic for improved reliability.

② A wide variety of research test rigs will be deployed to assess the full range of combustor performance attributes before committing to full scale testing. World-class measurement techniques should be deployed at all scales. Emissions, flashback/auto ignition and ignition may all require separate lab scale rigs. Sector rig testing may be required to start the integration assessment and measure what trades have been made in performance. If possible, existing test vehicles should be used for accelerated learning. Ultimately the full-scale assessment in a full annular rig and engine demonstrator is required to de-risk the flight programme.

③ A digital twin of the combustion system being developed adds agility to the research programme to avoid costly iterations at full annular rig scale. With enough high-power computing capacity, a wide range of geometries can be assessed before manufacture is launched. The most up to date and accurate modelling approaches such as direct numerical simulation take an order of magnitude more processing power than has been used to date. This enabler is a strategic accelerator of the usual time to market of major innovation in the aerospace industry.

Engine start system for hydrogen

① Staged Pilot decision → Igniter choice → Integration with staging → Improved cost of ownership

Enablers

② HP/HT small scale rig → Sector rig facilities → Ground based engine demonstrator

③ HPC cluster → Full annular rig → Ground based engine demonstrator

THRUST GENERATION ROADMAP

Key
- Essential Development
- Competitive Development
- Technology Mature
- Essential Enabler
- Competitive Enabler
- Technology Mature

Technologies

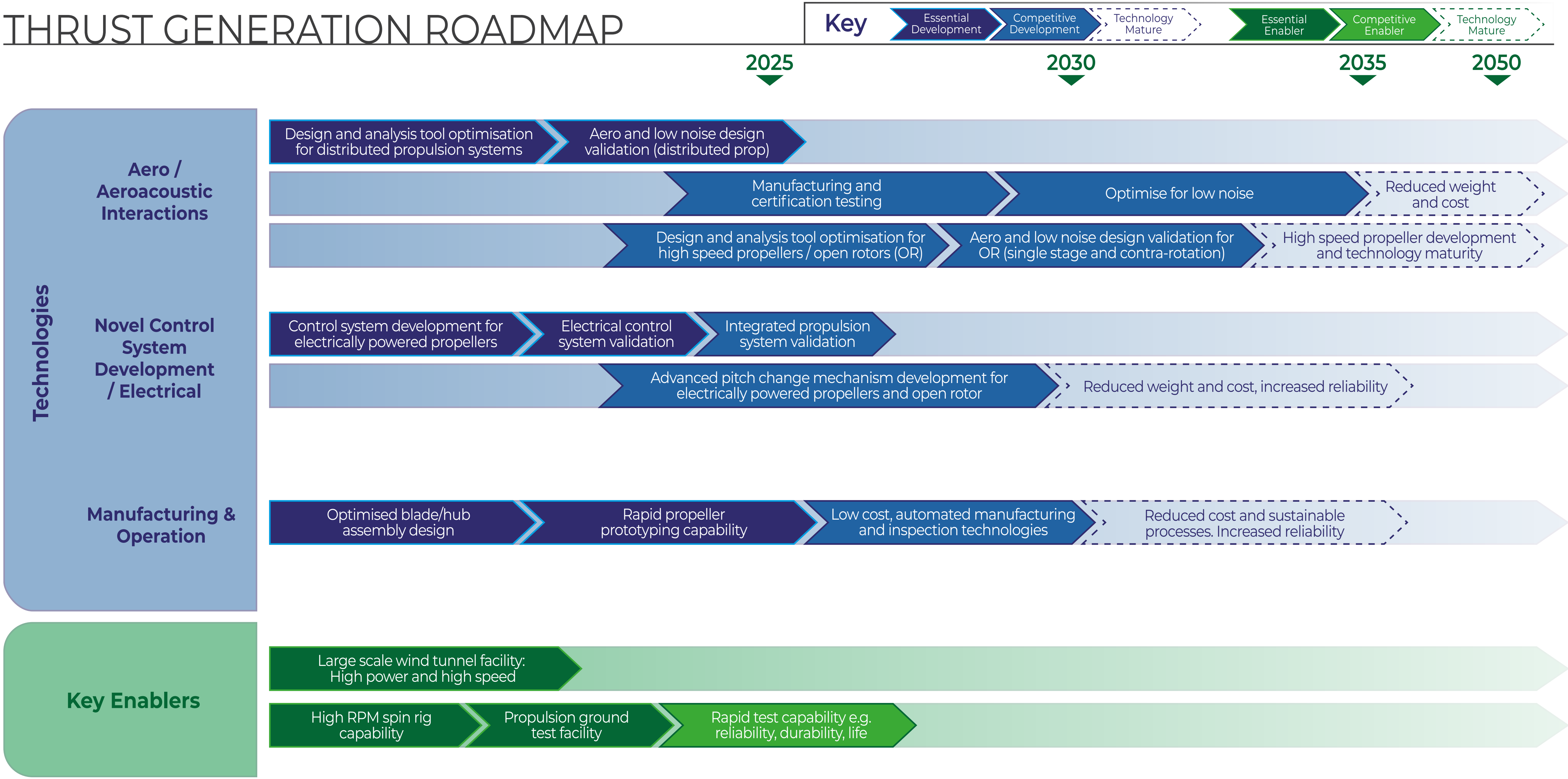
Aero / Aeroacoustic Interactions ← Develop aerodynamic and aeroacoustic understanding of distributed propulsion through analytical modelling and testing.

Novel Control System Development / Electrical ← Propeller control system for electrical propulsion to meet certification and safety standards.

Manufacturing & Operation ← Areas of development required to achieve manufacturing readiness for the novel designs highlighted within the above swim lanes.

Key Enablers ← Facilities and infrastructure necessary to enact the TRL roadmap developed above.

THRUST GENERATION ROADMAP



Key

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- Essential Enabler
- Competitive Enabler
- Technology Mature

2025

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Technologies

Aero / Aeroacoustic Interactions

- Design and analysis tool optimisation for distributed propulsion systems
- Aero and low noise design validation (distributed prop)

- Manufacturing and certification testing
- Optimise for low noise
- Reduced weight and cost

- Design and analysis tool optimisation for high speed propellers / open rotors (OR)
- Aero and low noise design validation for OR (single stage and contra-rotation)
- High speed propeller development and technology maturity

Novel Control System Development / Electrical

- Control system development for electrically powered propellers
- Electrical control system validation
- Integrated propulsion system validation

- Advanced pitch change mechanism development for electrically powered propellers and open rotor
- Reduced weight and cost, increased reliability

Manufacturing & Operation

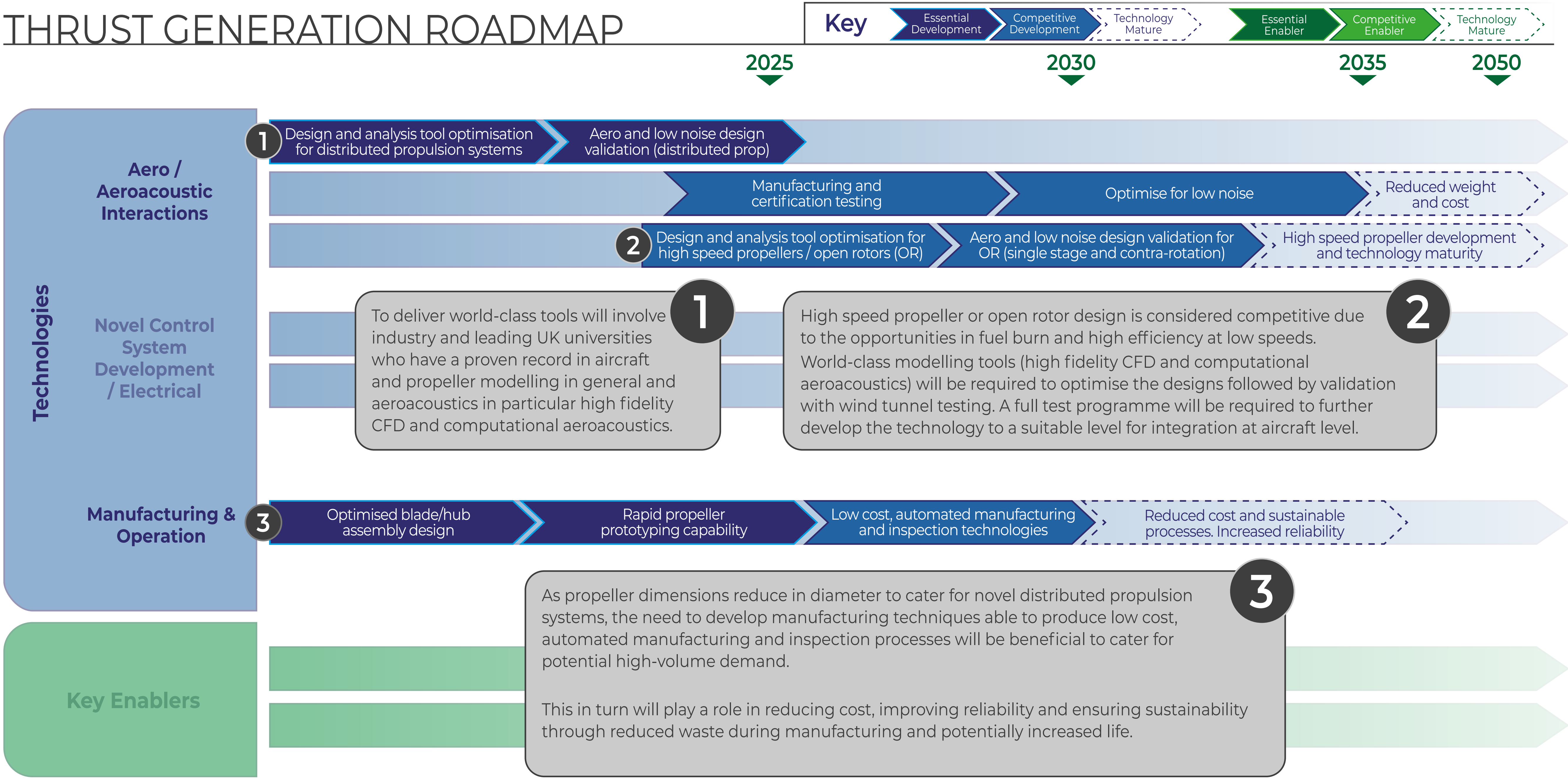
- Optimised blade/hub assembly design
- Rapid propeller prototyping capability
- Low cost, automated manufacturing and inspection technologies
- Reduced cost and sustainable processes. Increased reliability

Key Enablers

- Large scale wind tunnel facility: High power and high speed

- High RPM spin rig capability
- Propulsion ground test facility
- Rapid test capability e.g. reliability, durability, life

THRUST GENERATION ROADMAP



1

To deliver world-class tools will involve industry and leading UK universities who have a proven record in aircraft and propeller modelling in general and aeroacoustics in particular high fidelity CFD and computational aeroacoustics.

2

High speed propeller or open rotor design is considered competitive due to the opportunities in fuel burn and high efficiency at low speeds. World-class modelling tools (high fidelity CFD and computational aeroacoustics) will be required to optimise the designs followed by validation with wind tunnel testing. A full test programme will be required to further develop the technology to a suitable level for integration at aircraft level.

3

As propeller dimensions reduce in diameter to cater for novel distributed propulsion systems, the need to develop manufacturing techniques able to produce low cost, automated manufacturing and inspection processes will be beneficial to cater for potential high-volume demand.

This in turn will play a role in reducing cost, improving reliability and ensuring sustainability through reduced waste during manufacturing and potentially increased life.

THRUST GENERATION ROADMAP

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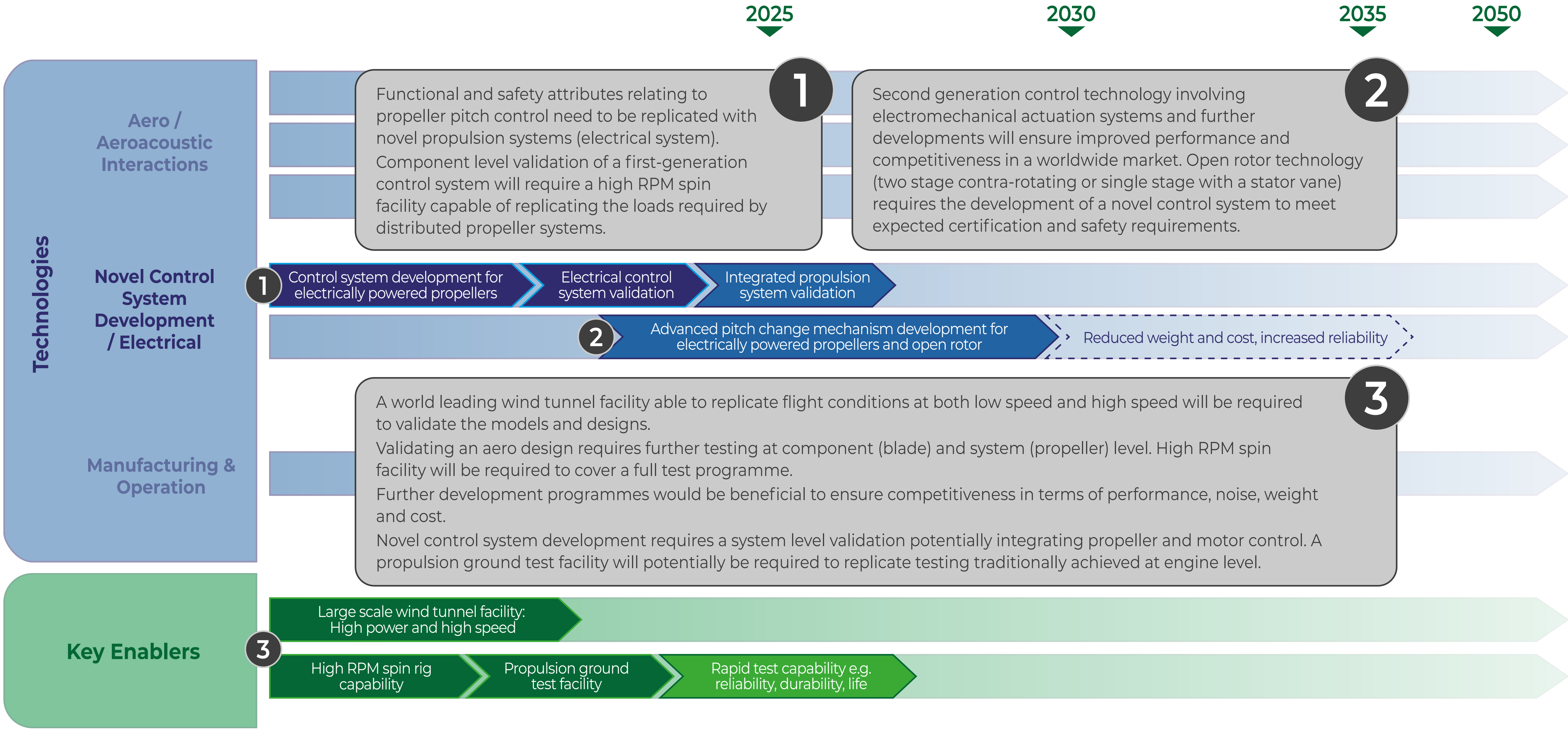

2025 | 2030 | 2035 | 2050

Technologies

Aero / Aeroacoustic Interactions

① Functional and safety attributes relating to propeller pitch control need to be replicated with novel propulsion systems (electrical system).

Component level validation of a first-generation control system will require a high RPM spin facility capable of replicating the loads required by distributed propeller systems.

② Second generation control technology involving electromechanical actuation systems and further developments will ensure improved performance and competitiveness in a worldwide market. Open rotor technology (two stage contra-rotating or single stage with a stator vane) requires the development of a novel control system to meet expected certification and safety requirements.

Novel Control System Development / Electrical

① Control system development for electrically powered propellers → Electrical control system validation → Integrated propulsion system validation

② Advanced pitch change mechanism development for electrically powered propellers and open rotor → Reduced weight and cost, increased reliability

Manufacturing & Operation

③ A world leading wind tunnel facility able to replicate flight conditions at both low speed and high speed will be required to validate the models and designs.

Validating an aero design requires further testing at component (blade) and system (propeller) level. High RPM spin facility will be required to cover a full test programme.

Further development programmes would be beneficial to ensure competitiveness in terms of performance, noise, weight and cost.

Novel control system development requires a system level validation potentially integrating propeller and motor control. A propulsion ground test facility will potentially be required to replicate testing traditionally achieved at engine level.

Key Enablers

③ Large scale wind tunnel facility: High power and high speed

High RPM spin rig capability → Propulsion ground test facility → Rapid test capability e.g. reliability, durability, life

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

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

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

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

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

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**

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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

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HYDROGEN GAS TURBINES & THRUST GENERATION

Roadmap Report

FLY ZERO

AEROSPACE
TECHNOLOGY
INSTITUTE