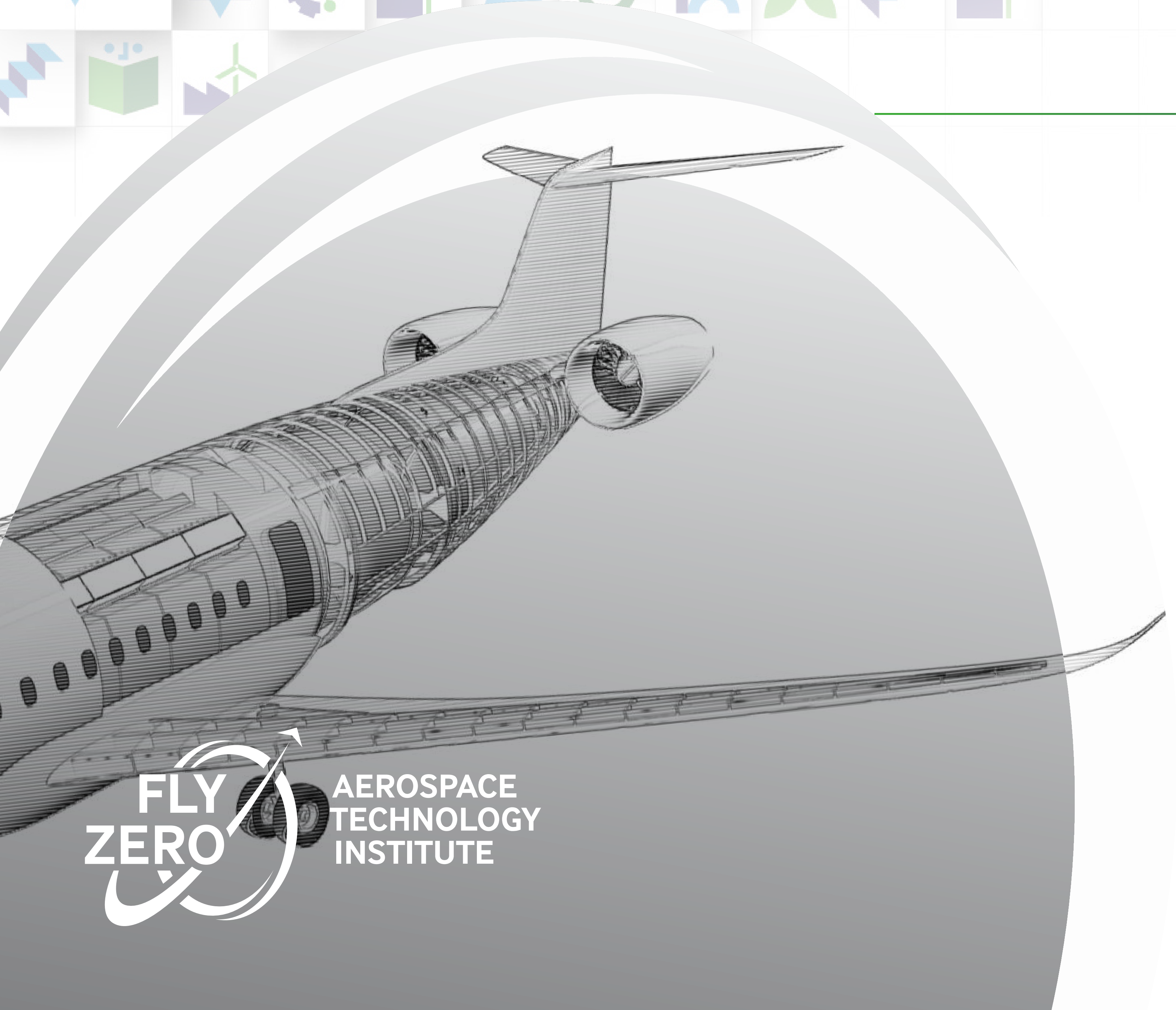


FLY ZERO
AEROSPACE TECHNOLOGY INSTITUTE

AERODYNAMIC STRUCTURES

Roadmap Report

FZO-AIR-COM-0016

Published March 2022

CONTENTS

KEY & LIST OF ABBREVIATIONS

Key

Technology Development	*Development required to bring roadmap technology to TRL6.*
Technology Mature	*Transition to further integration and production readiness.*
Essential Enabler	*Supporting activity or infrastructure to enable technology development*

List of Abbreviations

A/C – Aircraft
BLI – Boundary Layer Ingestion
CG – Centre of Gravity
CMC – Ceramic Matrix Composites
EMI – Electro-Magnetic Interference
HAR – High Aspect Ratio
HTP – Horizontal Tailplane
LE – Leading Edge
L.F.– Laminar Flow
LH_2 – Liquid Hydrogen
MDO – Multi-Disciplinary (MD) Optimisation
MRO – Maintenance, Repair & Overhaul
NDT – Non-Destructive Testing
Opt. – Optimisation
SFC – Specific Fuel Consumption
SMA – Shape Memory Alloys
SMPC – Shape Memory Polymer Composites
TE – Trailing Edge
UERF – Uncontained Engine Rotor Failure
VAN – Variable Area Nozzle
Volumetric energy density – available energy per unit volume
VTP – Vertical Tailplane

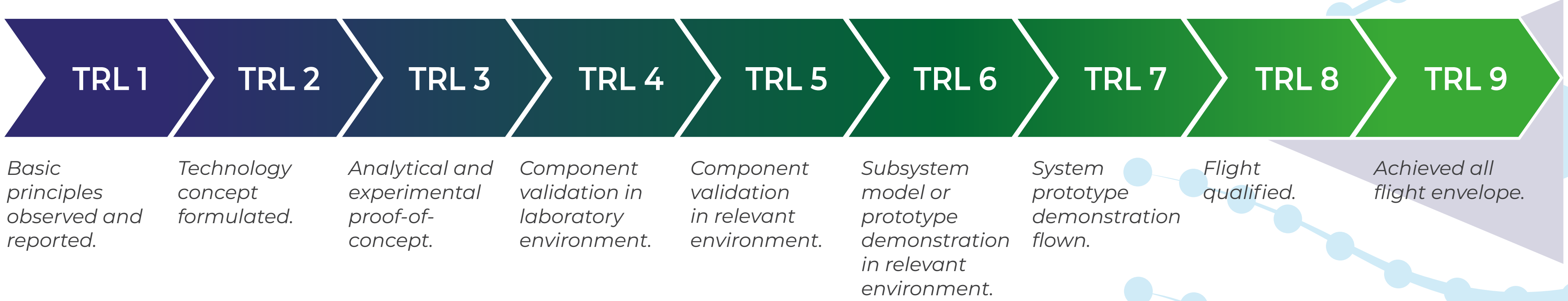


Figure 1 – Technology has been assessed against the NASA Technology Readiness Level (TRL) scale

OVERVIEW: AERODYNAMIC STRUCTURES

This Aerodynamic Structures Roadmap, encompassing aerodynamics, loads, aeroelastics, low-weight structural design, airframe optimisation, manufacturing, and assembly, presents a selection of high potential technologies that deliver aerodynamic performance improvements, fuel burn improvements and airframe weight reductions.

Aircraft performance improvements and weight savings are a means to reduce fuel burn, and consequently, operating costs and emissions. FlyZero concludes that liquid hydrogen fuelled aircraft are feasible, but aviation will continue to need such improvements for four reasons:

- To reduce volume and mass of hydrogen needed for a given mission
- To minimise operational costs and non-CO_2 emissions
- To limit demand for green energy for production of sustainable aviation fuel (SAF) and liquid hydrogen
- To limit CO_2 emissions of kerosene and SAF aircraft during transition to a liquid hydrogen fleet

FlyZero has identified critical Aerodynamic Structures technologies in six clusters of swimlanes that require immediate funding, research and development to maturity to enable zero-carbon aircraft of the future.

Figure 2 - Aerodynamic Structures roadmap clusters

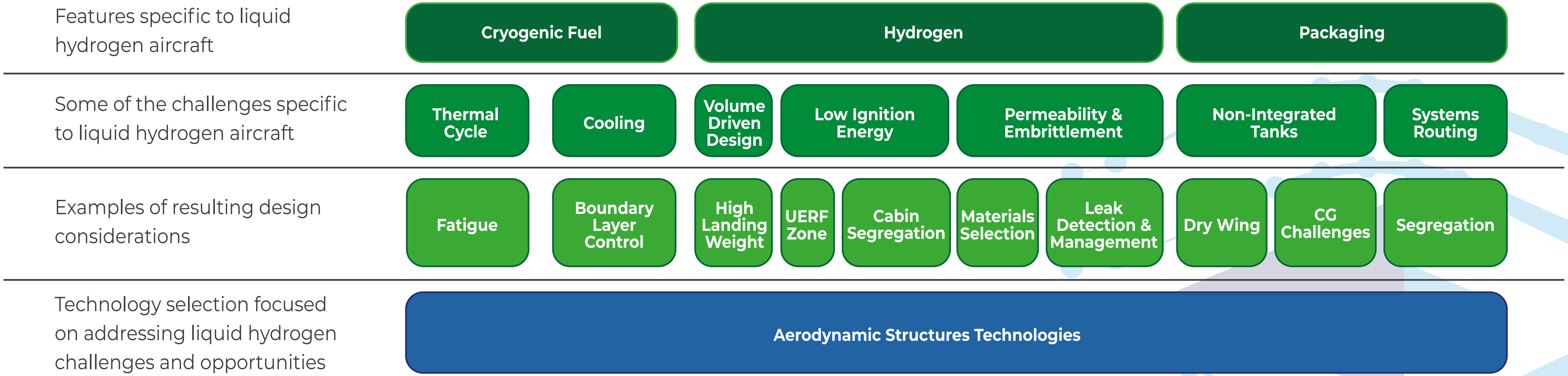
Note: Due to the large number of technologies identified, only a selection of high potential technologies are shown in this roadmap. A complete list with additional detail is provided in the FlyZero Aerodynamic Structures Technical Report.

Note: Direct Specific Fuel Consumption savings from propulsion system improvements are not covered as part of the Performance Improvements cluster of this roadmap.

KEY FINDINGS: AERODYNAMIC STRUCTURES

While some of the technologies in the Aerodynamic Structures Roadmap are unique to a liquid hydrogen aircraft, many are also applicable to kerosene and sustainable aviation fuelled aircraft. Therefore, these common technologies will have benefits regardless of the next generation aircraft fuel choice.

To focus the technology selection, features specific to liquid hydrogen were identified and the resulting design considerations explored. For example, cryogenic hydrogen results in spherical or cylindrical tanks not integrated in the wing structure. This, and the low volumetric energy density, may lead to a relatively wide diameter fuselage or external tanks, increasing airframe drag. Therefore, aerodynamic improvements such as laminar flow are selected for the roadmap.



AIRCRAFT CONFIGURATION & TECHNOLOGY SELECTION

Aircraft Configuration

Aerodynamic Structures technologies are inherently linked with aircraft configuration. Some novel configurations are included in the roadmap and others are discussed in the Aerodynamic Structures Technical Report.

Although many novel configurations are well researched, the challenge to design, build and certify them is recognised in the roadmap with longer timescales.

Technology Selection

The purpose of the roadmap is to accelerate technology development to TRL9 for aircraft entering into service in the 2030s. Technologies were selected based on maturity.

If a technology is already TRL9+ in 2022 it was not selected for the roadmap.

If a technology was not expected to reach TRL6 by 2030 it was not selected for the roadmap.

Technology maturity has been assessed against the NASA Technology Readiness Levels scale (TRL) to inform embodiment timescales.

TECHNOLOGY TARGETS

For the Aerodynamic Structures Roadmap, a set of ambitious but achievable aircraft improvement targets have been set which should be targeted by industry over the time periods shown in the table below.

	2025	2030	2035	2050
Weight Saving	20%	25%	30%	40%
Performance/SFC/CO_2 Emissions Improvements	10%	15%	20%	30%

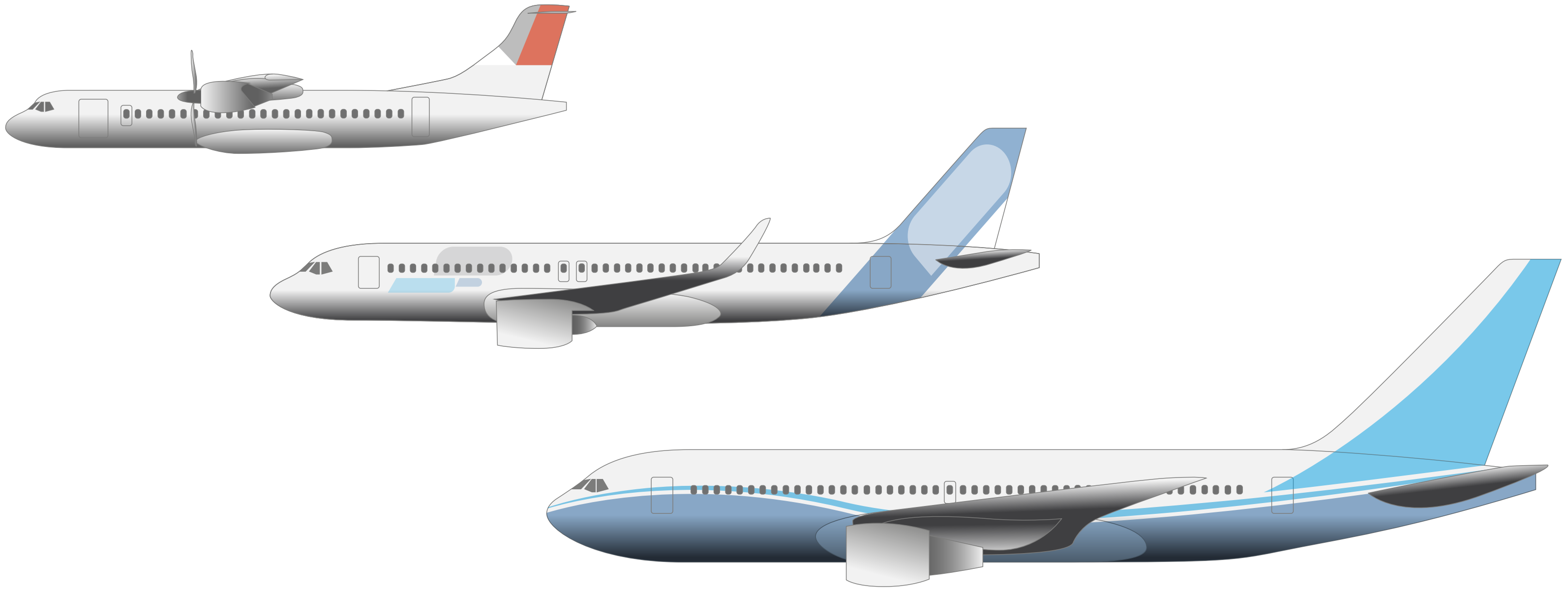
Figure 3 - Percentage improvement targets compared with reference ATR72-600 (below top), Airbus A320neo (below middle) or Boeing 767-200ER (below bottom) aircraft

These targets are improvements over reference aircraft in three sectors: Regional, Narrowbody & Midsize.

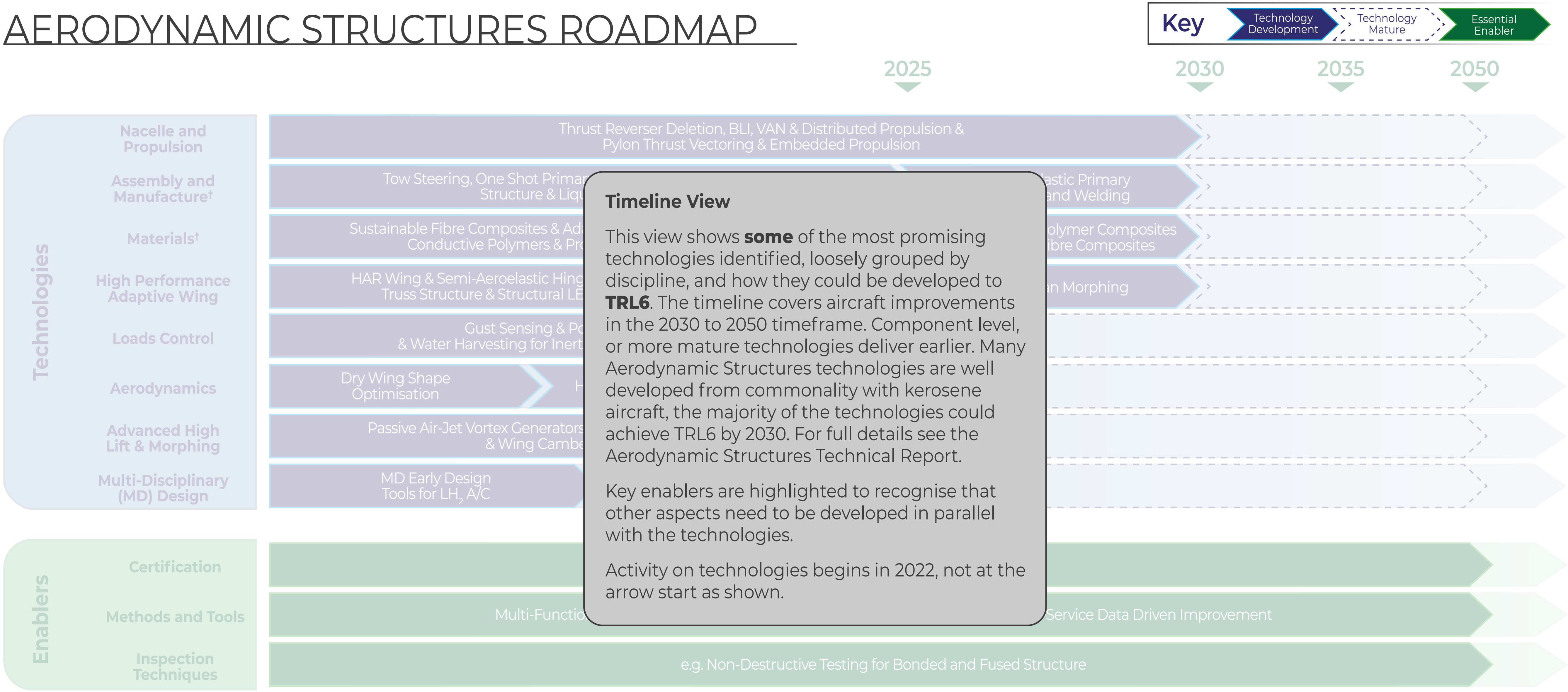
Target values have been selected based on reviews of other technology roadmaps, literature, and key stakeholder consultations.

Not all of the technologies presented within the roadmap will be implemented in aircraft of the future, but all of them should be targeted for research and development as they represent an opportunity to take a step towards achieving these targets.

In the context of reducing aircraft emissions and enabling early adoption of zero-carbon aircraft these targets should be pursued at pace.



AERODYNAMIC STRUCTURES ROADMAP



Timeline View

This view shows **some** of the most promising technologies identified, loosely grouped by discipline, and how they could be developed to **TRL6**. The timeline covers aircraft improvements in the 2030 to 2050 timeframe. Component level, or more mature technologies deliver earlier. Many Aerodynamic Structures technologies are well developed from commonality with kerosene aircraft, the majority of the technologies could achieve TRL6 by 2030. For full details see the Aerodynamic Structures Technical Report.

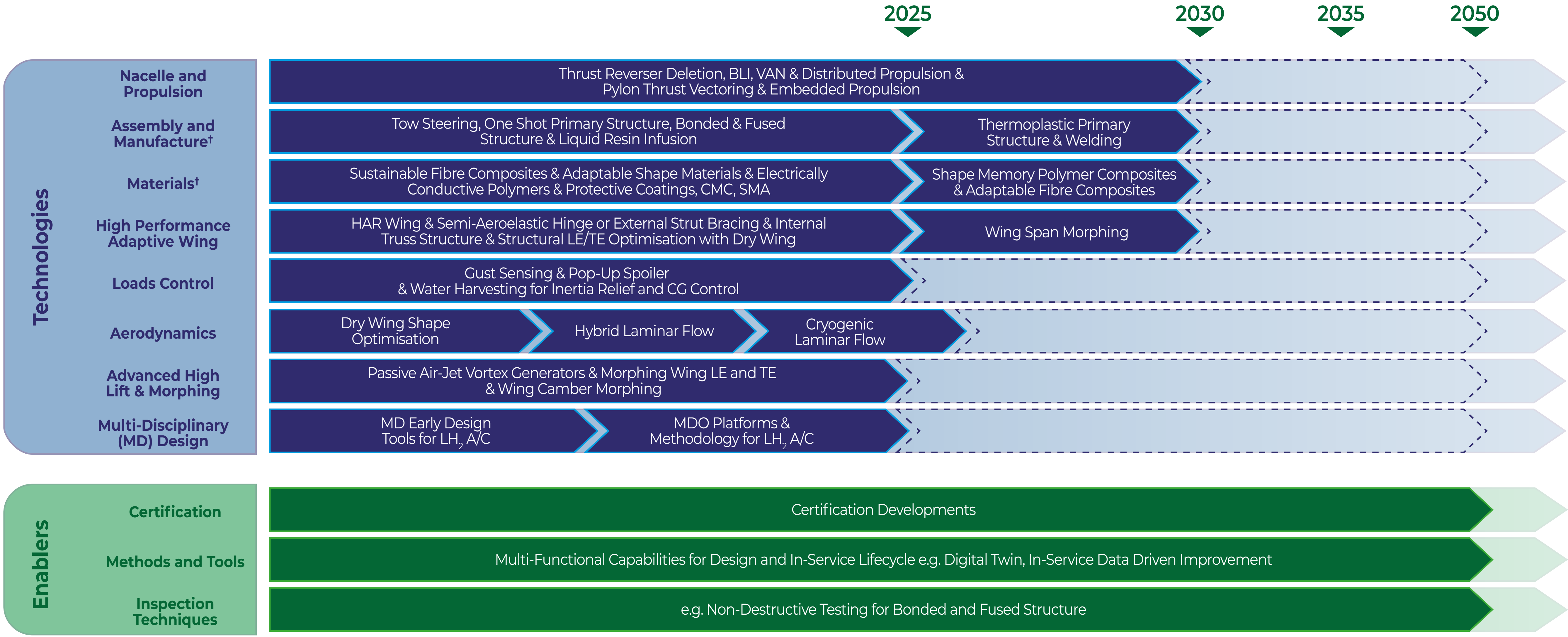
Key enablers are highlighted to recognise that other aspects need to be developed in parallel with the technologies.

Activity on technologies begins in 2022, not at the arrow start as shown.

† The focus in this roadmap for the materials and manufacturing clusters has been on composites given their high potential for weight saving however metallics are still a primary choice for airframe structures and technology development in this area should continue apace.

AERODYNAMIC STRUCTURES ROADMAP

Key: Technology Development | Technology Mature | Essential Enabler



† The focus in this roadmap for the materials and manufacturing clusters has been on composites given their high potential for weight saving however metallics are still a primary choice for airframe structures and technology development in this area should continue apace.

TECHNOLOGY ASSESSMENT

A Technology Assessment for cost, weight and performance has been performed based on literature reviews, academia & industry engagement, and engineering judgement to show the potential estimated benefits of technologies at the swim lane level.

Technology indicators show likely trends to be achieved at aircraft level by 2030-2050, but these may change as technology is further developed and matures. Technology indicators may change depending on the application of the technology on aircraft or advances in key enablers.

The definition of each technology indicator is presented below.

Cost

Cost refers to Non-Recurring Cost (NRC) related to the manufacture of the aircraft or components.

Buy-to-Fly Ratio or recurring costs are not covered by this indicator.

Cost indicators reflect today’s cost to enable technology deployment, but costs should reduce with maturity and the introduction of more advances in materials and manufacturing technologies.

Weight

Weight refers to total airframe weight, not whole aircraft weight reduction.

The technology weight indicator trend reflects that while some technologies may be heavy or lighter individually, their integration on to an aircraft may result in an overall weight increase or reduction by addition to or replacement of other technologies.

Performance

Performance refers to aircraft level operational performance.

This includes operational costs, lift to drag ratio & fuel efficiency of the aircraft.

It does not include any performance gains due to weight reduction improvements.

TECHNOLOGY ASSESSMENT

		Cost	Weight	Performance	% Benefit
Advanced and Novel/ Adaptable Materials	Ceramic Matrix Composites	-	+	+	...ction (in ...tallic to ...ersion) ...ent
	Shape Memory Alloys	[illegible]	0	++	
	Shape Memory Polymer Composites	[illegible]	[illegible]	[illegible]	
	Adaptable Fibre Composites	[illegible]	[illegible]	[illegible]	
	Electrically Conductive Polymers	[illegible]	[illegible]	[illegible]	
Laminar Flow	Natural Laminar Flow	[illegible]	[illegible]	[illegible]	...vement
	Hybrid/ Natural Laminar Nacelle Technol...	[illegible]	[illegible]	[illegible]	
	Hybrid Laminar Flow	[illegible]	[illegible]	[illegible]	
	Cryogenic Laminar Flow	[illegible]	[illegible]	[illegible]	
Lift to Drag Ratio Improvement	Riblets (Non-Mechanically Fastened)	[illegible]	[illegible]	[illegible]	...vement
	Dry Wing Shape Optimisation	[illegible]	[illegible]	[illegible]	
Advanced Moveables and High Lift	Passive Air-Jet Vortex Generators	[illegible]	[illegible]	[illegible]	1-3% SFC improvement
	Coanda Blowing	0	+	+	
	Multi-Functional Trailing Edge	0	0	+	

Technology Assessment View

This view shows the expected percentage benefit of **some** of the most promising technologies identified. A colour scale gives a qualitative assessment of each technology against the technology indicators.

For full details see the Aerodynamic Structures Technical Report.

Combining the percentage benefit with the colour scale provides a view of the potential for each technology.

All the technologies merit further work but some may offer improvements at lower cost, or may offer more significant benefits.

Key

--	Negative trend - high
-	Negative trend - medium
0	No change/ marginal change
+	Positive trend - medium benefit
++	Positive trend - high benefit
n/a	Not applicable

TECHNOLOGY ASSESSMENT

		Cost	Weight	Performance	% Benefit
Advanced and Novel/ Adaptable Materials	Ceramic Matrix Composites	-	+	+	1-5% weight reduction (in addition to metallic to composite conversion) improvement
	Shape Memory Alloys	-	0	++	
	Shape Memory Polymer Composites	-	0	++	
	Adaptable Fibre Composites	-	+	++	
	Electrically Conductive Polymers	0	+	n/a	
Laminar Flow	Natural Laminar Flow	-	0	++	10% SFC improvement
	Hybrid/Natural Laminar Nacelle Technology	-	0	+	
	Hybrid Laminar Flow	--	-	++	
	Cryogenic Laminar Flow	-	-	++	
Lift to Drag Ratio Improvement	Riblets (Non-Mechanically Fastened)	-	0	+	3-5% SFC improvement
	Dry Wing Shape Optimisation	0	0	++	
Advanced Moveables and High Lift	Passive Air-Jet Vortex Generators	0	+	+	1-3% SFC improvement
	Coanda Blowing	0	+	+	
	Multi-Functional Trailing Edge	0	0	+	

Key

--	Negative trend - high
-	Negative trend - medium
0	No change/ marginal change
+	Positive trend - medium benefit
++	Positive trend - high benefit
n/a	Not applicable

TECHNOLOGY ASSESSMENT

		Cost	Weight	Performance	% Benefit
Morphing Structures	Wing Camber Morphing	-	-	+	2-8% SFC improvement
	Adaptive Wing Tip	-	-	+	
	Wing Span Morphing	--	-	+	
	Morphing Nacelle Inlets	-	0	+	
	Control Surface Morphing (on HTP/VTP)	0	-	+	
Loads and Aeroelastic Control	Semi-Aeroelastic Hinge	-	++	++	1-5% SFC improvement
	Gust Sensing Devices	-	+	n/a	
	Aeroelastic Tailoring (Tow Steered)	-	++	+	
Novel Structural Design	Truss Internal Wing Structure	-	++	n/a	5% SFC improvement
	Folding Wing Tip	-	-	+	
	Topology Optimisation/Generative Design	0	++	0	
Novel Wing Architectures	Wing External Strut Bracing	--	+	++	5-10% SFC improvement

Key

--	Negative trend - high
-	Negative trend - medium
0	No change/ marginal change
+	Positive trend - medium benefit
++	Positive trend - high benefit
n/a	Not applicable

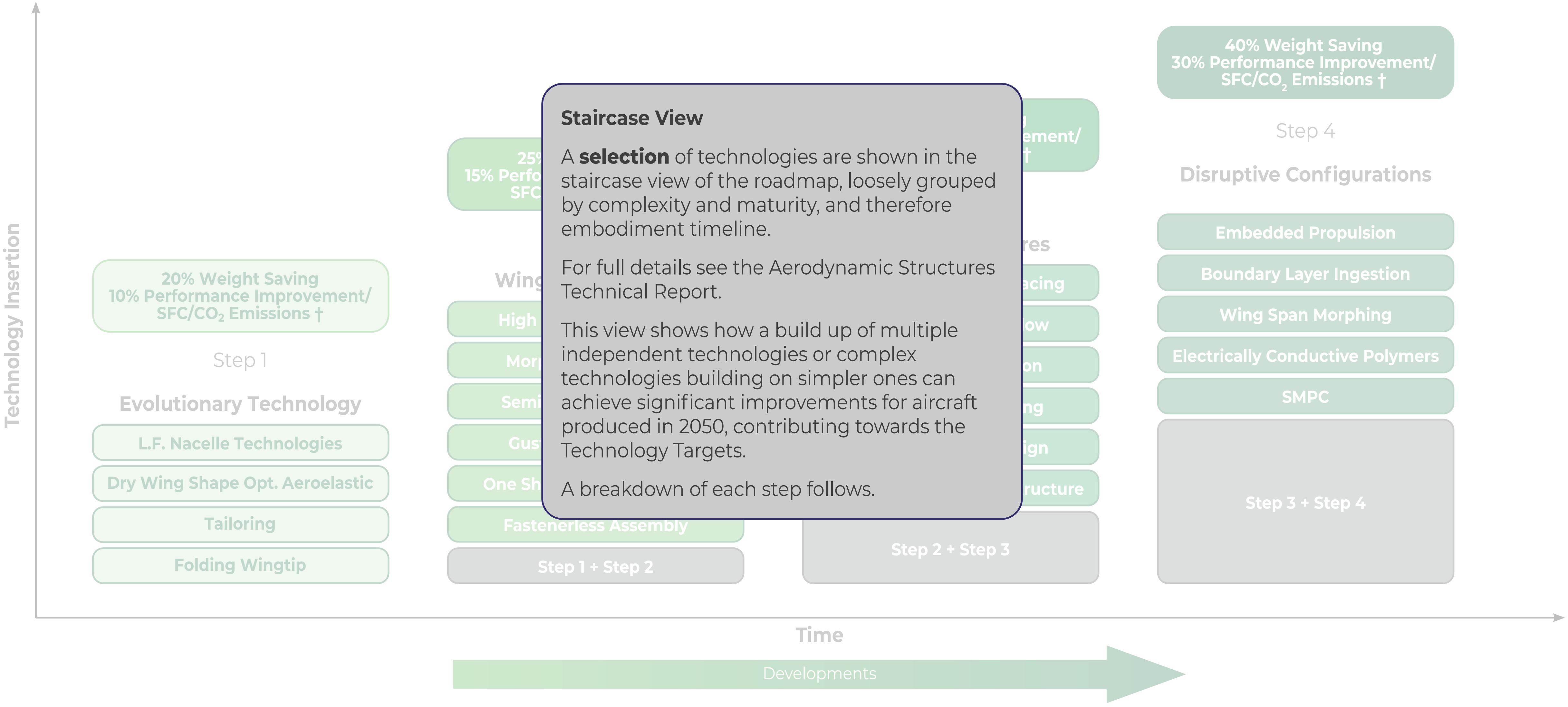
TECHNOLOGY ASSESSMENT

		Cost	Weight	Performance	% Benefit
Novel Nacelle and Pylon Design	Distributed Propulsion	0	0	+	5% SFC improvement
	Nacelle Technologies - Thrust Reverser Deletion, BLI and VAN	+	+	+	
	Embedded Propulsion	--	+	+	
	Moveable Pylon for Thrust Vectoring	-	0	+	
Additive Manufacturing	Additive Manufacturing (Metallic)	+	++	+	10-20% weight reduction
	Additive Manufacturing (Composite)	-	+	+	
Manufacturing and Assembly Process	Liquid Resin Infusion	++	+	+	5-10% weight reduction
	Bonded & Fused Primary Structure with NDT	++	++	+	
	One Shot Primary Structure	+	+	0	
	Thermoplastic Primary Structure	++	++	+	
Multi-Disciplinary (MD) Design	Platform Development	-	++	++	1-3% SFC improvement
	Methodology Development	++	++	++	

Key

--	Negative trend - high
-	Negative trend - medium
0	No change/ marginal change
+	Positive trend - medium benefit
++	Positive trend - high benefit
n/a	Not applicable

TECHNOLOGY STAIRCASE



Staircase View

A **selection** of technologies are shown in the staircase view of the roadmap, loosely grouped by complexity and maturity, and therefore embodiment timeline.

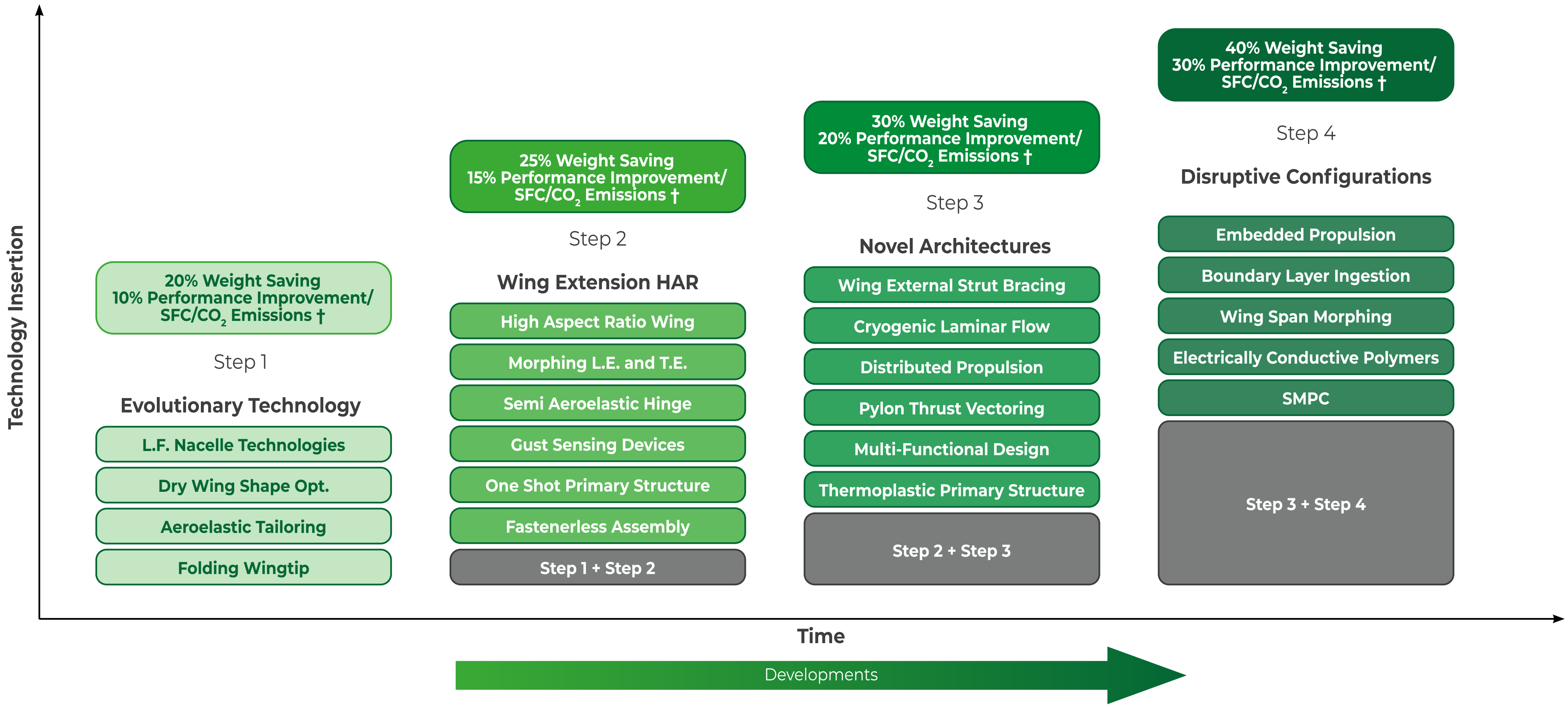
For full details see the Aerodynamic Structures Technical Report.

This view shows how a build up of multiple independent technologies or complex technologies building on simpler ones can achieve significant improvements for aircraft produced in 2050, contributing towards the Technology Targets.

A breakdown of each step follows.

† Potential total gains are a combination of technologies which is not limited to those shown here nor the sum of all

TECHNOLOGY STAIRCASE



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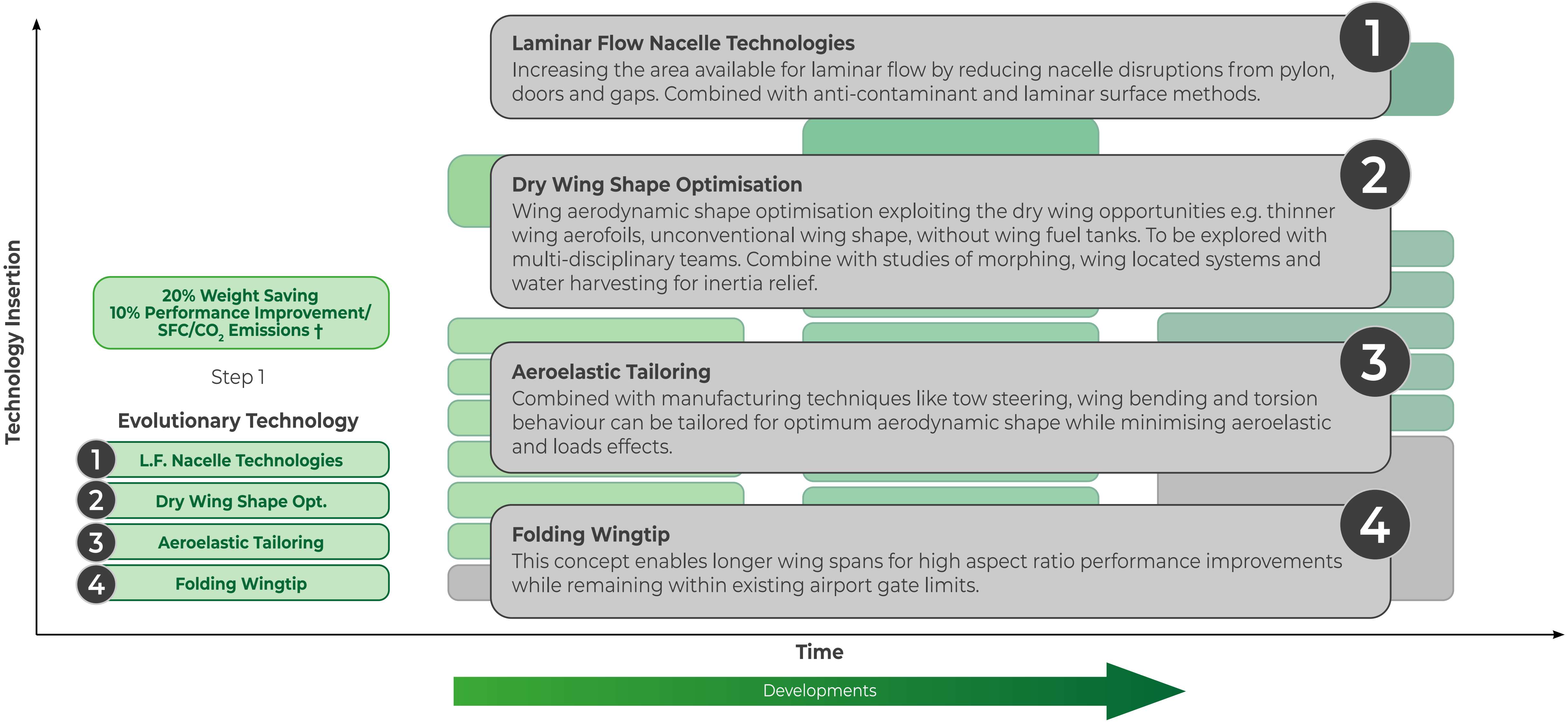
TECHNOLOGY STAIRCASE - STEP 1



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TECHNOLOGY STAIRCASE - STEP 2

1 High Aspect Ratio (HAR) Wing

High aspect ratio wings offer improved induced drag. Combine with semi-aeroelastic hinge to manage loads and achieve span limits for airport gates.

2 Morphing Leading and Trailing Edge

Morphing enables a wing to be optimised for more than just the cruise design point reducing drag and fuel burn. Dry wings may enable more volume for leading and trailing edge morphing mechanisms.

3 Semi-Aeroelastic Hinge

An upgrade from folding wingtip, semi-aeroelastic hinge is used on ground and in flight. The aircraft remains within gate limits, gust loads in flight are reduced and the rolling moment inertia of HAR is managed.

25% Weight Saving
15% Performance Improvement/ SFC/CO_2 Emissions †

Step 2

Wing Extension HAR

1. High Aspect Ratio Wing
2. Morphing L.E. and T.E.
3. Semi Aeroelastic Hinge
4. Gust Sensing Devices
5. One Shot Primary Structure
6. Fastenerless Assembly

Step 1 + Step 2

4 Gust Sensing Devices

Gust sensing devices such as LiDAR can allow an aircraft to predict when gusts and turbulence will occur so that control surfaces can be deployed to reduce the loads.

5 One Shot Primary Structure

Technologies that would allow for more integrated structures, to the point where large scale components (wings, fuselage etc) could potentially be manufactured in one operation.

6 Fastenerless Assembly

Joining of components and sub assemblies to form primary structures using bonded and fused joints.

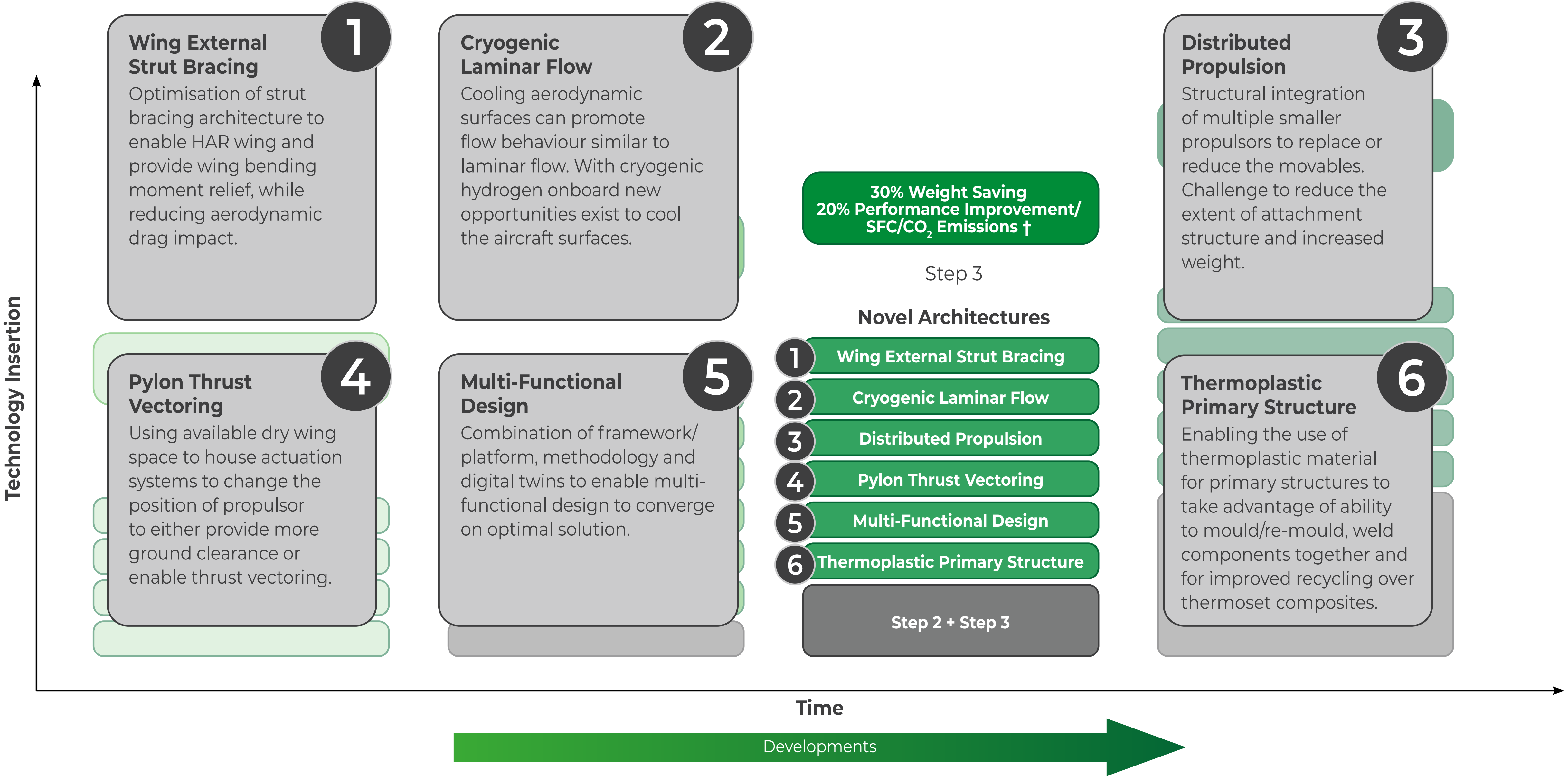
Technology Insertion

Time

Developments

† Potential total gains are a combination of technologies which is not limited to those shown here nor the sum of all

TECHNOLOGY STAIRCASE - STEP 3



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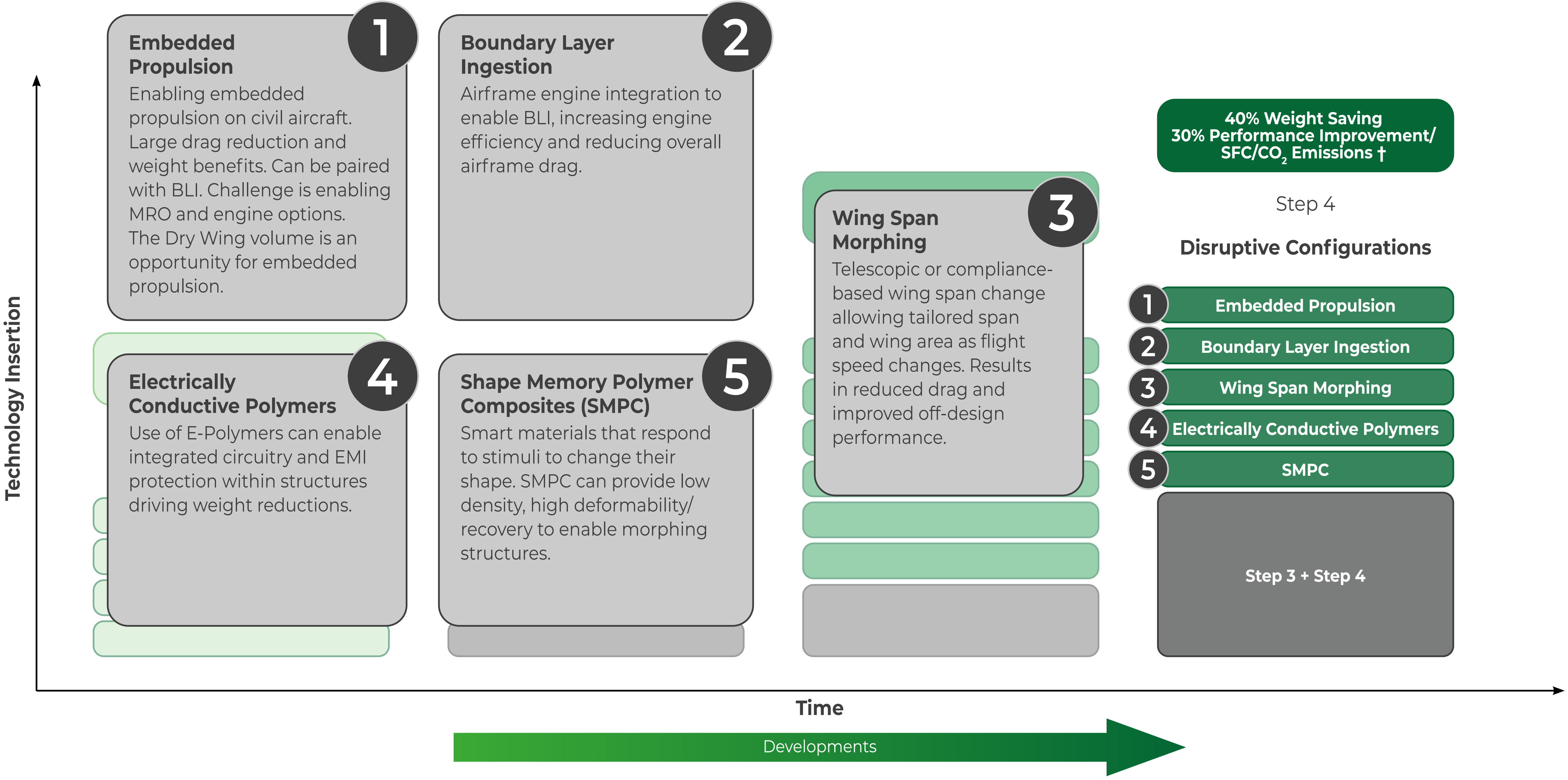
TECHNOLOGY STAIRCASE - STEP 4



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CONCLUSION: AERODYNAMIC STRUCTURES

The Aerodynamic Structures Roadmap, encompassing aerodynamics, loads, aeroelastics, low-weight structural design, airframe optimisation, manufacturing, and assembly, presents a selection of high potential technologies that deliver aerodynamic performance improvements, fuel burn improvements and airframe weight reductions.

The Aerodynamic Structures Technical Report includes all the identified technologies with potential to deliver meaningful airframe improvements in the ambitious timescales of commercial entry into service in the 2030s, meriting investment and development.

Research continuously discovers new ideas and technologies. New technologies that contribute to significant aerodynamic performance improvements, fuel burn improvements or airframe weight savings by 2030 should also be proposed for investment and accelerated development.

One of the key messages from FlyZero is that understanding and development of these key technologies must be accelerated to deliver a viable zero-carbon aircraft product in the 2030s.

Figure 4 - Aerodynamic Structures roadmap clusters

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**

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FlyZero contributing companies

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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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Front cover image © ATI

AERODYNAMIC STRUCTURES

Roadmap Report

FLY ZERO AEROSPACE TECHNOLOGY INSTITUTE