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ENABLEH2

PUBLIC REPORT

Technology and scenario evaluation studies and benchmarking report

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D1.4 – Technology and scenario evaluation studies and benchmarking

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1 Executive summary

A major objective of ENABLEH2 Work Package 1 has been to model potential designs for year-2050 (Y2050) aircraft fuelled by liquid hydrogen (LH_2) and to assess their likely energetic, economic, and environmental performance. A further objective has been to provide a comparison of transport modes. This deliverable reports on both of these objectives.

Exactly how first and second generation LH_2-powered aircraft will be configured remains uncertain. Storing LH_2 on an aircraft is quite challenging, but it has potential to improve the efficiency of advanced propulsion systems: enabling game-changing technologies such as Proton Exchange Membrane (PEM) fuel cells (aka Polymer Electrolyte Membrane fuel cells) and superconducting electrical transmission systems. To scope this wide design space, projected year-2050 technology concepts were modelled for Short/Medium-Range (SMR) and Long-Range (LR) aircraft, that represent most of the civil aviation market. In each case, a more conservative 'Lower Risk' design and a more aggressive 'Max Synergy' design was modelled. The two Max Synergy designs for LH_2 feature different combinations of technologies, but they share highly integrated airframes and propulsion systems and exploit the cryo-cooling capability that comes with LH_2. A further Max Synergy design for LNG was also modelled.

Comparisons were made with Y2020 and other Y2050 study aircraft having alternative fuels (Jet A-1, biofuel and LNG). For the given design missions, the sizes and weights of the Y2050 aircraft and their propulsion systems depended on the heating values of their fuels, and on the volumes of any cryogenic fuel tanks to be integrated within their fuselages. For the 'Lower Risk' Tube & Wing (T&W) aircraft fuelled by LH_2 or LNG, the fuel tanks were assumed to be located above the passenger cabins.

The resulting Y2050 SMR and LR aircraft fuelled with Jet A-1 are projected to have about 24% lower mission fuel burn and CO_2 emissions per available seat kilometer (ASK) relative to representative state-of-the-art aircraft currently in service. LNG is seen only to offer a modest reduction in mission level and life-cycle CO_2 relative to Jet A-1 in T&W aircraft because the LNG tanks increase the empty weight, fuselage volume and drag of the aircraft. However, the LNG-fuelled Blended Wing Body (BWB) aircraft shows a significant reduction in emissions relative to the advanced T&W design. Drop-in replacement biofuels reduce mission level CO_2 emissions only slightly, but they have the potential for very significant reductions in life-cycle emissions.

The Y2050 LH_2-fuelled aircraft are predicted to significantly reduce cruise NOx emissions relative to those fuelled by Jet A-1. The 'Cobalt Blue 2' aircraft concept has particularly low cruise NOx emissions because it derives most of its motive power at altitude from fuel cells.

Higher fuel costs and CO_2 emissions charges in Y2050 are found to be partly offset by improvements in aircraft and propulsion system efficiencies. In the preferred 'Heightened Environmental Awareness' (HEA) economics scenario the increases in operating cost per available seat-kilometer (CASK) are still modest, so rising disposable incomes over the next thirty years should keep air travel affordable with any of the proposed fuels.

Table 1 provides a top-level summary of the weight and performance of Y2050 aircraft with LH_2, LNG, Jet A-1 and biofuel, relative to state-of-the-art Y2020 aircraft with Jet A-1 fuel. It summarises best-case mission-level and life-cycle CO_2 emissions, mission-level energy use, and relative operating cost estimates. It also summarises best-case cruise NOx emissions assessments relative to Y2050 aircraft with Jet A-1 fuel.

Table 1: Overview of the weight savings and emissions reductions- A comparison between projected Y2050 aircraft and equivalent Y2020 baseline technology aircraft

Aircraft and Fuel	MTOW	OWE	Energy Use	Mission CO_2	Life cycle CO_2	Cruise NOx	CASK (HEA)
Typical 900 nmi missions for SMR aircraft							
SMR T&W 2050 Jet A-1	-21%	-22%	-24%	-24%	-24%	datum	+16%
SMR T&W 2050 Biofuel	-21%	-22%	-24%	-27%	-93%	-2%	+16%
SMR T&W 2050 LNG	-19%	-17%	-22%	-41%	-37%	-26%	+9%
SMR T&W 2050 LH_2	-19%	-3%	-9%	-100%	-97%	-52%	+12%
SMR Cobalt Blue 2 LH_2	+1%	+31%	-13%	-100%	-97%	-88%	+16%
Typical 3000 nmi missions for LR aircraft							
LR T&W 2050 Jet A-1	-12%	-8%	-23%	-22%	-22%	datum	+23%
LR T&W 2050 Biofuel	-13%	-7%	-22%	-23%	-92%	-1%	+23%
LR T&W 2050 LNG	-3%	+9%	-4%	-27%	-24%	+6%	+23%
LR T&W 2050 LH_2	-17%	+17%	-0%	-100%	-95%	-38%	+25%
LR BWB 2050 LH_2	-27%	+4%	-32%	-100%	-97%	-55%	+6%

To complement the aircraft studies, ENABLEH2 has examined the various options of hydrogen supply available to an airport and assessed their suitability. This report focuses on a specific geography to provide actual scenarios and includes a case-study for the supply of LH_2 to London's Heathrow Airport.

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2 Introduction

Utilizing a set of principles, methods, techniques, and tools the Technology Evaluation process within ENABLEH2 investigated and evaluated the potential of the key enabling technologies. This assessment has been undertaken at aircraft level from performance and environmental perspectives in line with the overall WP1 objective to quantify environmental and cost benefits of LH_2-fuelled technology concepts at block level. They are assessed relative to best-case scenario projections for Y2050 reference aircraft utilizing Jet A-1, drop-in biofuels, and LNG. To conduct these assessments, the research was structured into four primary tasks.

Research within this WP commenced with technology down-selection and top-level aircraft requirements (TLAR) setup (Task 1.1). The primary goal of this task was to down-select suitable LH_2 aircraft concepts for Short/Medium-Range (SMR) and Long-Range (LR) applications. As part of this process, 31 potential airframe architectures and 21 propulsion-system arrangements were analyzed in a two-step process. From these, two aircraft concepts were finally selected based on pre-set criteria, which related to operating cost, revenue, noise and safety. The aircraft concepts were assumed to benefit from synergistic and tightly coupled aero-propulsive systems and hence they were designated as Max Synergy aircraft concepts. The selected concepts used a Tube and Wing (T&W) design for SMR missions and a Blended Wing Body (BWB) design for LR missions.

The task involved selecting TLARs to provide a common technical basis, and setting modelling assumptions and plausible scenarios to provide a consistent basis for the propulsion system and aircraft-level impact analyses. This included specification of aircraft and engine technology levels, mission definitions and realistic long-term fuel cost scenarios. Three main fuel cost scenarios, namely baseline, progressive environmental awareness and heightened environmental awareness were defined to assess the market conditions under which new hydrogen-fuelled aircraft would be viable. Additional supplemental scenarios, which included low electricity costs, and higher and lower fossil fuel costs were also identified to provide a wider base for business risk assessments.

The next key task involved modelling the baseline/reference technologies and assessments (Task 1.2). The primary goal of this task was to model a set of reference SMR and LR aircraft technologies utilizing Jet A-1, drop-in biofuel and LNG fuels. Utilizing these analytical models, flight missions were simulated to undertake detailed performance and emission assessments, life-cycle CO_2 calculations, and preliminary cost estimates. The task therefore began with the selection of baseline Y2020 aircraft assumed for the study. These were based on conventional T&W aircraft, namely the Airbus A321NEO for SMR missions and the Airbus A350. The baseline technologies were assumed to be representative of aircraft with entry into service (EIS) in the year 2020 and fuelled by Jet A-1. Given these baseline configurations, the reference aircraft concepts were modelled with technology improvement factors representative of Y2050 EIS, whilst ensuring the aircraft achieved the required TLARs. An additional Y2050 LNG-fuelled BWB aircraft for LR missions was also modelled. To simulate representative performance of aircraft operating on biofuels and LNG, suitable modifications were made to the modelled fuel properties, the wing, and overall airframe design. Additionally, for the cases where LNG was assumed to be the fuel, the size and weight of integral cryogenic tanks and the drag increase were also calculated and included in the performance analysis.

Within the WP, a further task (Task 1.3) was dedicated towards modelling the integrated LH_2-fuelled aircraft and the associated technologies for the two Max Synergy concepts. The SMR aircraft concept, designated ‘Cobalt Blue 2’, was configured with an enlarged circular fuselage cross-section and a mid-height wing. The internal LH_2 tanks were accommodated in the wing roots and between the passenger cabin and cargo deck areas. The aircraft has a series partial hybrid electric propulsion system which includes a LH_2-fuelled tail-mounted single turbofan

and four ducted and boundary layer ingesting (BLI) electric fans, mounted at the trailing edges of the wings and powered by fuel cells.

The LR ‘max synergy’ aircraft concept is based on a BWB design, the NASA N3-X, but the fuselage and passenger cabin are extended in length to accommodate 414 passengers. The propulsion system is assumed to have a partial turbo-electric distributed configuration. It includes two turbofans buried in the wing roots for thrust and also power generation that in turn powers an array of fourteen BLI fans located above the fuselage.

Two Lower Risk technology LH_2-fuelled concept aircraft were also modelled. These designs were based on modifications to the conventional LR and SMR baseline aircraft, similar to the Y2050 reference T&W LNG aircraft designs.

The resulting aircraft evaluations within this WP were then compiled and analysed, to further contribute to this technology evaluation and benchmarking report.

This report begins with an overview of the project as an introduction. It then describes the TLARs and the concept aircraft down-selection process followed. The selected concepts are described together with an overview of the technology modelling process. The report then provides an analysis of the mission-level technology and scenario evaluations, which include performance assessments and comparisons of the LH_2 aircraft concepts with the reference aircraft using hydrocarbon-based fuels. The analysis also considers the life cycle CO_2 footprint and effects of fuel price and environmental taxation on the economics of the technologies.

As part of the evaluation of LH_2 aircraft technology, NOx and water vapour emissions are also assessed. Given that burning hydrogen will produce significantly larger amounts of water vapour, research has indicated that the future LH_2-fuelled aircraft could have higher potential to produce condensation trails (contrails) when compared to kerosene-fuelled aircraft. A brief analysis is presented and based on the available literature, a hypothesis on what may be expected when the fuel would change is also provided.

Finally this report includes a discussion comparing various transportation modes and methods that may be utilised to transport hydrogen from the source of production to airports, together with a case study.

3 Top level aircraft requirements

The technology evaluation process began with identifying 'top-level aircraft requirements' (TLAR) consistent with the requirements of comparable reference aircraft, a common standard for modelling the technology, and plausible scenarios to provide a consistent basis for the propulsion system and aircraft-level impact analyses. This included specification of aircraft and engine technology levels, detailed mission definitions, and plausible long-term fuel cost and emission taxation scenarios. To assess suitable market conditions under which hydrogen aircraft would be viable assets, three policy scenarios were considered. These included economic assumptions signifying business as usual, progressive environmental awareness, and heightened environmental awareness. To provide a wider base for assessing the business risks, additional supplemental scenarios were also identified, which included considerations of future costs of electricity, fossil fuels, and environmental taxation.

The TLARs enable a viable positioning of the Short/Medium-range (SMR) and Long-Range (LR) aircraft concepts in the foreseen year-2050 market segments. The SMR and LR aircraft mission requirements are based on current commercial aircraft operations and projected growth in the capacity of aircraft in the two classes. The two aircraft together may be taken to be broadly representative of the commercial aviation fleet. At this stage, to simplify the concept selections, single aircraft designs were proposed, though the relative ease of producing 'shrink and stretch' versions of each aircraft concept was a factor considered in assessing their merits.

Table 2 lists the SMR and LR aircraft missions and design requirements. The SMR aircraft may be considered successors to the Airbus A320 while the LR aircraft may be considered successors to the Airbus A350 or the Boeing 777-9X.

Table 2: SMR and LR aircraft missions and design requirements

Requirements	SMR	LR
General Requirements		
Range	3000 nmi	7500 nmi
Pax	200 (single class)	414 (two-class)
Operational Stage length	900 nmi	3000 nmi
Economic Load Factor	85%	85%
Typical Passenger Weight (economic mission)	105 kg	115 kg
Passenger Weight for Max Payload	125 kg	166 kg
Operational Stage-length Payload Assumption	85%	85%
Technology Freeze EIS-year	2050	2050
Take-off and Landing		
TOFL (MTOW, SL, ISA)	2438 m (8000 ft)	3048 m (10000 ft)
Hot and High Denver (DEN)	Max PAX DEN ISA+20ºC	Max Pax DEN ISA+20ºC
TTC (from 1500 ft, ISA)	25 min	25 min
App Speed (MLW, SL, ISA)	< 135 KCAS	< 140 KCAS

Requirements	SMR	LR
LFL (MLW, ISA) if different from MTOW	1737 m (5700 ft)	1768 m (5800 ft)
Cabin Pressure Max Altitude	6000 ft	6000 ft
Cruise		
Initial Cruise Altitude (ISA+10°C)	at least FL350	at least FL330
Design Cruise Mach Number	at least M 0.75	at least 0.82
Max Cruise Altitude	FL410	FL410
Operations		
Airport Compatibility Limits	Code C	Code E (with folding wingtip option)
COC reduction target vs best SOA	15%	15%
Turn-around Target Time	30 min	180 min
Design Number of Cycles	60,000	20,000
Emissions and Noise		
External Noise Target (vs 2000)	-35 dB vs chapter 14	-35 dB vs chapter 14
LTO NOx Emission Reduction Target (vs 2000)	-75%	-75%
Cruise NOx Target Reduction Target (vs 2000)	-90%	-90%
ETOPS/LROPS/EDTO Capability	180 min	unlimited

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4 Aircraft down-selection process and selected concepts

4.1 Down-selection process

Transitioning to hydrogen-fuelled aircraft poses significant technical and integration challenges. These range from design of suitable aircraft and integration of specialized systems on board to facilitate storage of the cryogenic fuel, to modifications at airports and at air transportation system level to cater for future operational requirements.

Future aircraft fuelled with hydrogen will be fundamentally different in terms of overall design, so a technology down-selection process was adopted to identify credible candidates among the many possible.

The technology evaluation activities within ENABLEH2 considered many of these challenges, but were primarily focused on identifying, modelling, and evaluating suitable aircraft concepts that could efficiently use LH_2 as fuel, while synergistically exploiting its unique properties. The overall objective was to quantify, for typical defined missions, the environmental emissions reduction potential and cost benefits of the LH_2-fuelled aircraft concepts. These were compared with best-case scenario projections for reference aircraft utilizing Jet A-1, drop-in biofuels, and LNG, under various fuel price and emission taxation scenarios.

As in previous studies, a fast and simple method of identifying the most promising advanced airframe and propulsion system configurations for SMR and LR applications was needed. The concept selection methodology applied within the project used Morphological Analysis (MA), Quality Function Deployment (QFD) and pairwise comparison. Following agreement on the methodology and the relative weightings to be applied to the selection criteria, the concept selection was undertaken in two phases, similar to the process proposed by Mistree et al. [1] and to the Cryoplane concept selection study reported by Sefain [2].

In the ENABLEH2 project wide ranges of potential airframe architectures and propulsion system arrangements were analysed. The first phase assessed potential airframe configurations and propulsion systems. Based on this preliminary assessment, the second phase assessed a short-list of potential aircraft and propulsion system combinations to identify the suitable SMR and LR configurations.

MA was used to generate configurations for the first phase of the selection. As indicated in Table 3, the criteria against which scores were tabulated included factors relating to: cost per available seat kilometre (CASK), noise, and the revenue-earning potential of the aircraft, which included the anticipated passenger perception of safety. The relative cost of engineering equivalent levels of safety however was assessed separately. It should be noted that all scoring and the weightings are essentially qualitative. While they attempt to be proportionate, the scores are relative and are only used to compare one conceptual design with another. Many more factors might ideally be considered to produce a detailed quantitative estimate of overall noise or CASK, for example, but this was considered beyond the scope of the project.

Following agreement within the consortium on the list of assessment criteria and their weightings, the concept selection was initiated. The first part made a qualitative assessment of airframe architectures and propulsion systems, separately considering lists of concepts both for SMR and LR aircraft. This involved assessing 31 airframe arrangements and 21 propulsion systems for the two applications.

Table 3: Consideration criteria

Criteria					
Top Level Categories	CASK				
	Revenue				
	Noise				
	Breakdown of CASK				
CASK	Non-fuel Costs				
	Fuel Burn Related Costs				
	Breakdown of Fuel Burn				
	Fuel Burn	Thrust and Drag Requirement			
		Propulsion System SFC			
		Breakdown of Thrust Requirement			
		Thrust	L/D		
			Operating Weight Empty		
CASK	Fuel Burn	Thrust & Drag Requirement	L/D	Aspect Ratio and winglets	
				Surface Area	
				Fuselage Fineness Ratio	
				Trim Drag to maintain pitch, stability	
			OWE	Airframe structural efficiency	
				Total propulsion system weight	
				Wing Bending Moment relief	
				CoG Location	
				Fuel Tanks Capacity and Efficiency	
				Undercarriage length	
		SFC		Propulsive efficiency	
				Core thermal efficiency	
				Transfer efficiency	
				Nacelle Drag	
				Benefit from BLI systems	
	Non-fuel Costs			Shrink and Stretch Capability	
				Complexity	
				Maintainability	
Revenue				Comfort	
				Aesthetics	
				Safety Perception	
				Cargo capacity	
Noise				Ducted Fans or Open Rotors	
				Noise Shielding	
				Inlet distortion related noise	
				Airframe noise	
Safety				Engine Location	
				Fuel tank location	
				Ditching Capability	
				Systems Redundancy	
				Fuelling Capability	
				Emergency Egress	
				Crew access to all areas	
				Stability & Control	

In the second phase, shortlisted combinations of airframe and propulsion system concepts from the first phase were assessed via Quality Function Deployment (QFD) and the use of pairwise comparison. Ideally the pairwise comparisons would compare every option against every other option for each application. But even after down-selecting only a small number of candidate aircraft configurations for the second phase, the time required to do that presented

an unreasonable challenge to those making the assessments. Thus it was agreed to define preferred baseline SMR and baseline LR concepts at each phase of the selection process and to make all the pairwise comparisons only against these baseline concepts. The baseline concepts scored zero for each criterion, with the alternative concepts scoring positively or negatively relative to the baseline. In keeping with QFD practice, preferred scores were set to +9, +3, +1, 0, -1, -3 or -9, to be able to give sufficient emphasis to strongly positive or negative factors.

4.2 Final concepts assessments

Nine design concepts were shortlisted for the second/final phase of the selection process and the relative safety assessments were made independently of the CASK, noise, and revenue related criteria for all of the shortlisted options.

4.2.1 SMR baseline and alternative concepts

For the SMR application Cranfield University (CU), Chalmers University and Safran proposed alternative concepts including open rotor and double-fuselage designs. Figure 1 shows the five proposed architectures for the SMR concepts assessment. In (a) of Figure 1 the Cobalt Blue 2 (CB2) concept from Safran is depicted, which will be elaborated upon in the following section. Schematic (b) of Figure 1 shows the ‘CU1’ single-hull concept with a ‘T’ tail and aft-fuselage pusher open rotor with a third electrically driven BLI open rotor on the fuselage centreline. A larger fuselage diameter and a Boeing 767 (or Airbus A300) type twin-aisle seating arrangement (with seat configuration assumed to be 2-3-2) is considered necessary to avoid an excessively-long 200 passenger aircraft. All the hydrogen systems are located aft of the passenger cabin, minimising the risks from impact damage etc. However, the loss of bending moment relief from not having wing mounted engines and the need for pressurised and insulated LH_2 tanks and aft fuselage reinforcement make these relatively heavy aircraft. The open rotor noise sources are not shielded, and external noise is considered a major drawback for the CU1 concept.

Concept (c) (Figure 1), namely ‘Chalmers1’, is based on an earlier Cryoplane study configuration with one LH_2 tank in the tail and others located above the passenger cabin. It has a conventional under-wing turbofan engine installation and consequently has relatively long fuel lines running through or around the passenger cabin. With tanks above the cabin, the tail-tank could be quite small in this SMR aircraft, so a single-aisle fuselage with 3-3 seating may still be possible.

The schematic (d) of the same figure shows the ‘CU2’ double-fuselage concept with aft-fuselage mounted turbofans and BLI open rotors to reenergise the fuselage boundary layers. Both fuselages accommodate passengers and fuel tanks with cargo containers beneath the passenger decks. The fuselages are based on the Airbus A319 with shortened passenger cabins and hydrogen tanks in place of the last few seat rows. All the hydrogen systems are aft of the passenger cabins. The open rotors are powered by electrical generators on the turbofans. Fuel can be cross-fed via a manifold in the ‘pi’ empennage and power can be cross-fed to the opposite open rotor to reduce asymmetric thrust in the event of a turbofan engine failure. An alternative version of the same concept, ‘Chalmers2’, is shown in (e) of Figure 1. It is assumed to have simpler and less-expensive single-rotation turboprops and laminar-flow wings. The design could have the potential to reduce fuel burn, but potentially might not meet the cruise speed dictated by the TLAR.

The **Cobalt Blue 2** (concept proposed by Safran) was finally selected as the *Max Synergy option* for the SMR application.

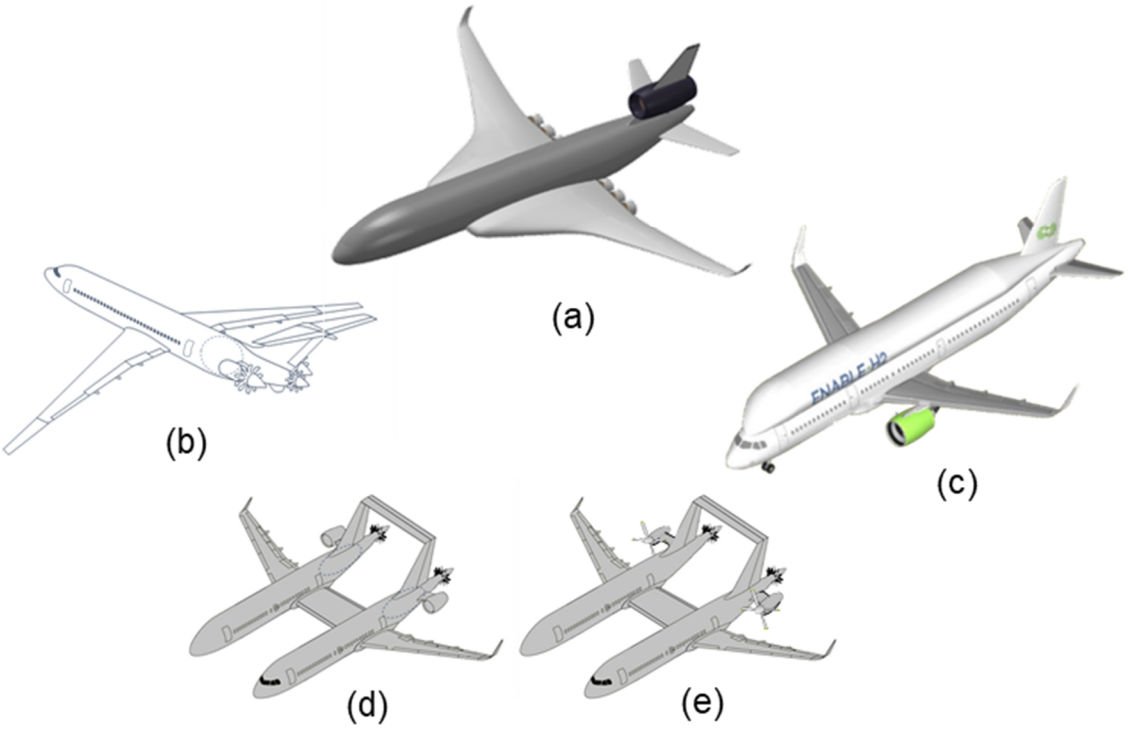

Figure 1: Five proposed architectures for the SMR concepts assessment

Cobalt Blue 2

The CB2 (Figure 2) is an innovative concept for SMR commercial transport aircraft capable of competing with the class of aircraft such as the Airbus A320/A321 NEO and Boeing 737 Max in Europe and North America. CB2 is designed around a LH_2-fuelled propulsion system and incorporates capabilities such as electric taxiing which enables engine-off transit around the airfield, leading to a reduction in both noise and emissions on the ground. A number of other novel systems are incorporated into the design, namely: aero-propulsion augmentation devices (APADs) which form a series of articulated ducted fans installed on each of the inner wings and capable of enhancing aircraft thrust in different phases of flight; 'minipods' at the end of each wing, which fulfil a similar function to a ram air turbine on a conventional aircraft; a state of the art Flight Control System (FCS) using fly-by-wire technology to reduce pilot workload; a virtual co-pilot function, enabling operation of CB2 by a single pilot; and enhanced passenger focused features including improved access for disabled passengers and modern entertainment requirements incorporated by design within the cabin.

Figure 2: The Cobalt Blue 2 concept

Aircraft features and innovations

Wings and tail

The wings, as seen in Figure 2 are shaped to store much of the hydrogen required to fly the design mission. More specifically, as tanks are fitted in the wing roots, the section is thicker and larger than a classic wing, and two extra spars have been added. To reduce the drag due to friction, generated by this increase in wing wetted surface area, boundary layer ingestion (BLI) fans, also called APADs, are positioned at the wing root trailing edges. To comply with the airport compatibility code C, the wingspan is set to 35.5 m. The chords are sized to meet the reference wing area compatible with the design wing loading of 380 kg/m².

Powertrain

CB2 is powered by two individual systems, a single hydrogen-fuelled turbofan engine installed at the tailfin of the aircraft and four APADs mounted at the trailing edge of the wing roots that are powered by fuel cells and batteries. The turbofan is sized to provide around 45% of the Take-Off thrust. The rest is provided by APADs. The aircraft can therefore be considered as twin-engined. In cruise, the turbofan is throttled down to 30% of its max cruise thrust (to guarantee no flameout) while deferring to the more efficient fuel cell propulsion system.

The APADs have ducted fans rotated by superconducting electric motors. They are mounted on an actuation device, which can change their position to ensure an optimal aerodynamic integration, depending on the flight phase. The DC electrical power produced by the fuel cells is transferred to DC-AC inverters installed at wing trailing edges via superconducting cables.

The APADs are powered by a hybrid electric power system comprising fuel cell stacks and batteries. The fuel cells are sized to provide sufficient thrust in cruise and the batteries are sized to provide 20% of the maximum fuel cell power to ensure correct functioning of the hybrid system in all situations. The technology selected for the fuel cells is the proton exchange membrane (PEM) fuel cell, which is the most widespread type and already in commercial use in the automotive industry, and a high target efficiency of 70% at cell level has been assumed for 2050 EIS.

Fuel tanks, distribution, and heat management system

The Cobalt Blue 2 features two types of LH_2 tanks. The tanks are sized to have sufficient capacity to store the fuel necessary to complete the design mission, including reserve fuel. Common fuel pumps are used for the fuel cells and the turbofan engine. All the flow is directed towards the fuel cells where it is heated to ambient temperature. It is then split into the fuel cell and turbofan fuel flows.

The aircraft's heat management system serves two purposes: it heats the cryogenic hydrogen to the required operating temperature and removes the high amount of heat generated by the fuel cells. The heat produced by the fuel cells is removed in two ways. First, the cryogenic hydrogen fuel flow directed to the fuel cell and the turbofan engine is used as a cold source for an Organic Rankine Cycle (ORC) machine, which uses the fuel cell as its hot source. The machine produces electrical power to run the air compressor providing air to the fuel cell. This machine has two benefits. It generates additional electricity, improving the fuel cell system efficiency. It also increases the heat sink potential of the fuel, as some part of the heat generated by the fuel cell is converted into electricity instead of being directly transferred to the cold fuel. After exiting the condenser of the ORC machine, the hydrogen is introduced inside the fuel cell where it reaches the fuel cell working temperature while further cooling it.

The turbofan does not feature any thermal management system for hydrogen as the fuel cells produce sufficient heat to heat the fuel flows for both the fuel cells and the turbofan engine. The fuel cells are divided into two stacks per wing, i.e., four fuel cell stacks. In case of the loss of one stack, the other stacks can still provide sufficient heat to the whole fuel flow. Using the hydrogen to help cool the fuel cells means the active thermal management system can be throttled down, as it consumes power, generates some drag, and does not heat the hydrogen.

To maintain superconducting temperatures, the fans feature a cryogenic cooling system with a helium loop, the temperature of which can possibly be lowered by a refrigerating cycle. The cooler for this helium loop is installed at the trailing edge of the wing, close to the APAD actuation mechanism interface. The helium is cooled in the cooler by the cryogenic hydrogen coming from LH_2 tanks and afterwards is conveyed to the fuel cells.

Additional cooling loops transfer the remaining heat of the fuel cell to the wing leading edges to ensure anti-icing and to the fuselage crown where heat rejections cause minimal drag and could possibly give a friction drag reduction aft of the laminar to turbulent transition. The heat is dissipated to the atmosphere through surface heat exchangers.

Fuselage and cabin

The top-level requirements stipulate that the aircraft is required to carry 200 passengers. The fuselage has an ovoid section with 4.47 m maximum external width and external height of 5.03 m and the passenger cabin features 2+2+2 (twin aisle) seats abreast. Considering aerospace industry practice, the materials preferred in the aircraft are mostly composites and aluminium alloys.

4.2.2 LR Concepts

For the LR application four designs from CU and GKN/Chalmers were selected and scored. Schematic (b) of Figure 3 shows the Cranfield LR concept CU-A. This has a horizontal double-bubble fuselage cross-section and two underwing engines. It has a structural partition in the passenger cabin, dividing the 12-abreast economy seating into two halves with each of the two aisles having three seats on each side. This enables the LH_2 tanks to be located at the forward and aft ends of the fuselage while maintaining access between the cockpit and the passenger cabin. The structurally efficient double-bubble arrangement has lower drag than a circular fuselage of the same width and gives a broader wingspan for the same wing root

bending moment. Also, compared with a BWB airframe, it is more-easily shortened or lengthened to create a family of aircraft.

The GKN1 concept, presented in (c) of the same figure, is similar to Chalmers1 SMR concept, but with larger tanks above the passenger cabin. Unlike earlier NASA and Cryoplane LR aircraft designs there is only a single passenger deck with seating like the Boeing 777-9X. This has two aisles and a 3-4-3 seating arrangement in the economy section. There is potential for some area-ruling of the fuselage cross-section between the two tanks, which are separated to minimise exposure to debris from potential uncontained engine failures.

The last concept, shown in (d) of Figure 3, is the GKN/Chalmers LR2 which has two external wing-mounted pods each containing two LH_2 tanks. The wing bending moment relief provided by the mass of these pods added to that of the under-wing engines can facilitate an increased the wingspan with folding wingtips extended. For structural simplicity and maximum ground-clearance the tanks may be mounted above the wings. The concept was assessed without any BLI systems though these might be added to the rear of the fuselage and the external pods containing the fuel tanks. (A possible variant would move the engines to the sides of the aft fuselage. This would enable the pods to be shortened and the tanks within them merged, but it would increase the length of the fuel pipes).

The ENABLEH2 (EH2) BWB proposed from CU, shown in (a) of Figure 3, was finally selected as the Max Synergy option for application on LR missions. It is based on NASA's N3-X airframe but with increased fuselage volumes to accommodate both a higher number of passengers as well as providing extra under-floor volume for the LH_2 tanks.

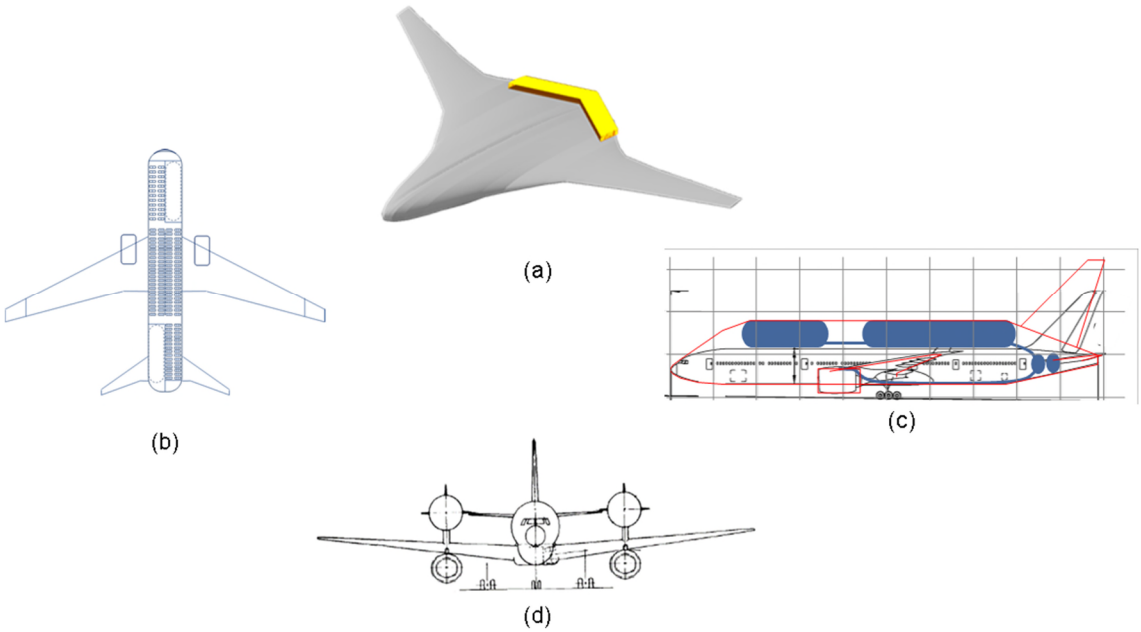

Figure 3: LR application four designs from CU and GKN/Chalmers

EH2 BWB

The EH2 BWB (as shown in Figure 4) is an LH_2-powered blended-wing body (BWB) aircraft for LR transport. The BWB airframe concept for passenger use originated in the 1990s as discussed in reference [3] but has not seen practical application to date. Contrary to a T&W design, the fuselage of a BWB airframe generates a small amount of lift and provides improved

aerodynamic performance. In addition, the internal volume of the fuselage allows enough space to efficiently install LH_2 tanks. The aircraft is powered by a turbo-electric distributed propulsion system (TeDP), where most of the thrust is produced by ducted fans that are powered by two turbofan engines. The passenger cabin is designed to carry 414 passengers in a two-class configuration and the aircraft has a design range of 7500 nmi.

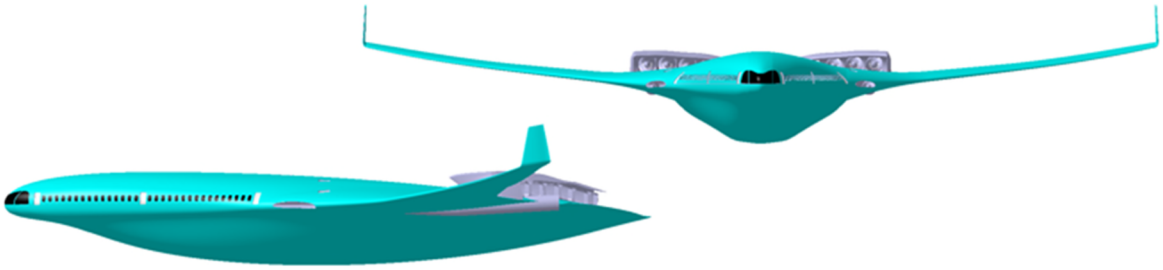

Figure 4: The EH2 BWB concept

Aircraft features and innovations

Airframe geometry

The airframe is based on the geometry of NASA's N3-X aircraft [4] but the fuselage was scaled to accommodate more passengers and the large LH_2 tanks needed to to meet the design mission range.

The passenger cabin is designed based on a multi-bay layout [5]. Contrary to conventional tube and wing aircraft, the passenger cabin of a BWB covers a trapezoidal area towards the front of the aircraft and is divided into four separate bays. Each bay features a seating arrangement of 6-abreast for economy and 4-abreast for business-class, which is considered to be an efficient compromise between passenger comfort and spacing economy. To accommodate both the passenger cabin as well as the LH_2 tanks installed in the underbelly volume, the fuselage section (roughly determined by the width of the passenger cabin) is increased by 17.5% in length and depth compared to the N3-X providing a maximum length and depth of the fuselage of 49.5 m and 6.6 m respectively. Spanwise, the 65 m wingspan is maintained unchanged to meet the airport compatibility code E. The wings are equipped with winglets that have moving surfaces to assist vertical stabilisation.

Powertrain

The propulsion system chosen for this application is based on a turboelectric distributed propulsion configuration and comprises two turbofan engines that provide electrical power to 12 remotely installed ducted fans. The system is designed to enable significant reduction in fuel burn, which is a consequence of the fans ingesting the boundary layer developed over the fuselage. This helps in improving the aerodynamic characteristics of the airframe. The design also allows for higher equivalent bypass ratios to be achieved. Given the location, the fans are not restricted in size as much as in a conventional turbofan, and hence allow for more flexibility in terms of their design and sizing. The propulsion system has the following characteristics:

- The 12 remote fans are installed above the aft fuselage section, ingest the boundary layer developed over the fuselage, and produce 90% of the thrust.
- The turbofan engines are embedded in the wing roots and provide all the power required for the remote fans at all stages of the flight. As the fan array may not exceed a 20 m span,

the remaining thrust is provided by the bypass and core streams of the turbofans. The fans on the turbofan engine are assumed to be low by-pass ratio and are directly driven by the low-power turbine (LPT). The turbofans have a three-spool design.

- The power transmission between the main engines and the fans is achieved through a synchronous AC superconducting system of generators, motors and cables. This technology allows for high transmission efficiency and high power to weight ratios compared to conventionally conducting machines. The generators and the motors are connected via the high-power cables and are directly coupled with the turbines and remote fans respectively, without the use of gearboxes. For higher efficiency and lower weight, inverters are not used and so the LPT–generator and motor–fans rotate with a fixed transmission speed ratio.
- To moderate the fan performance and avoid fan surging at off-design, variable nozzle area is considered for all the fans to give optimum fan operation throughout the flight.
- To avoid complete loss of the thrust generating devices as well as to avoid asymmetric thrust in the event of an engine shut down, each engine powers every other fan with separate transmission lines.

Fuel tanks, distribution, and heat management system

In order to better utilise the volume under the passenger cabin for maximum fuel capacity, six tanks of different sizes are proposed. The tanks are cylindrical with hemispherical cap ends. They have single-skin walls from aluminium alloy Al 2219 together with polyvinylchloride rigid closed-cell foam insulation. They are sized in pairs, having different external diameter and length constraints depending on their location, due to the fuselage's spanwise depth variation.

The four tanks that are closest to the centreline of the aircraft are the biggest and are sized to contain the block fuel required for the design mission. They are designed based on an innovative feature where during cruise both Gaseous Hydrogen (GH_2) and LH_2 are extracted from the tanks for engine feed with a ratio that maintains steady pressure inside the tanks. This avoids excessive pressure rise during the long cruise segment and leads to lighter and more compact designs. In addition to this, these tanks are oversized to compensate for the unusable LH_2 that evaporates throughout the mission (in the order of 3-3.5% of the initial mass stored) and occupies the remaining tank volume as fuel is consumed in the engines.

The two tanks the furthest from the centreline of the aircraft are the smallest and contain the reserve fuel. They are designed to withstand the pressure rise throughout the flight and for 12 hours afterwards while on the ground without any further fuel extraction. Assuming no means might be available to moderate the pressure, thicker insulation is chosen to minimise the heat input and the consequent pressure rise. However, in practice some GH_2 would normally be extracted during an extended ground stop and used in fuel cells or an APU, thus avoiding the need to vent unburned GH_2 overboard after 12 hours or so.

The cold hydrogen extracted from the tanks is first used to cool the superconducting electrical transmission system which requires cryogenic temperatures to efficiently operate. However, this rejected heat alone is not sufficient to adequately pre-heat the hydrogen before combustion. The remaining heat is added to the fuel through a heat exchanger installed in the core exhaust of each turbofan engine.

4.2.3 Lower risk aircraft

The lower risk aircraft, both for the SMR and LR application, represent ENABLEH2 vision of how 2050 LH_2-powered aircraft may be designed using well established technologies. They both feature a conventional T&W architecture and underwing mounted turbofans. The low risk concept aircraft for SMR and the LR application are presented in schematic (a) and (b) of Figure 5.

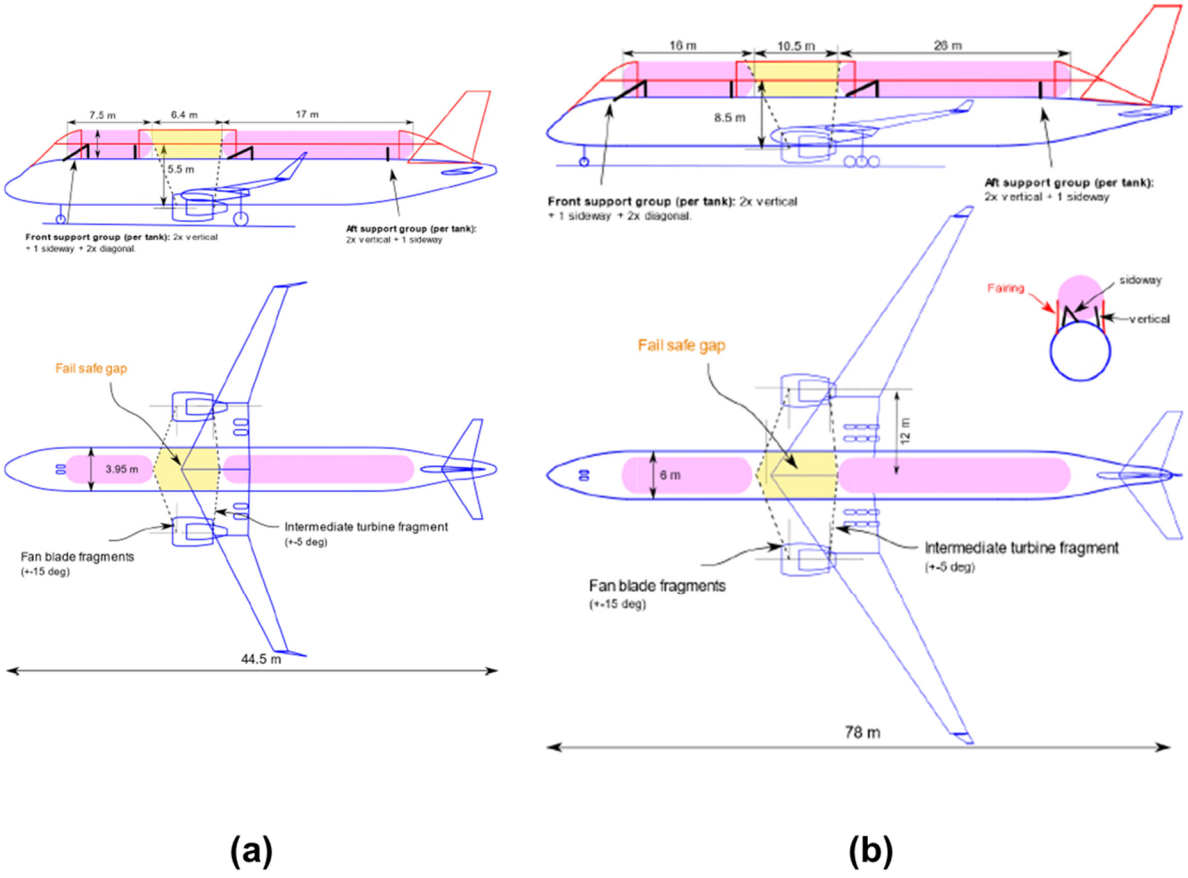

Figure 5: (a) SMR and (b) LR lower risk concepts

Airframe geometry

The fuselage is extended above the passenger cabin to accommodate the LH_2 tanks. A fairing is only used to provide a smooth transition between the fuselage and tanks, to reduce interference drag, to cover the fail-safe gap (where tanks would potentially be exposed to high-energy debris from a failed turbomachinery component) as well as to reduce any additional pressure drag.

The SMR aircraft wing-span is restricted to 36 m according to the aircraft compatibility code C and the fuselage has a length of 44.5 m. The LR aircraft has a wingspan of 70.5 m and features folding wing tips to comply with the 65 m wingspan limit, similar to a Boeing 777-9X. The fuselage is 78 m in length.

Propulsion system

The engine concepts for the SMR and LR aircraft are based on a recuperative cycle, where a two-pass cross-over tubular heat exchanger is placed at the turbine exhaust to pre-heat the LH_2 before combustion. A schematic of the engine is presented in Figure 6.

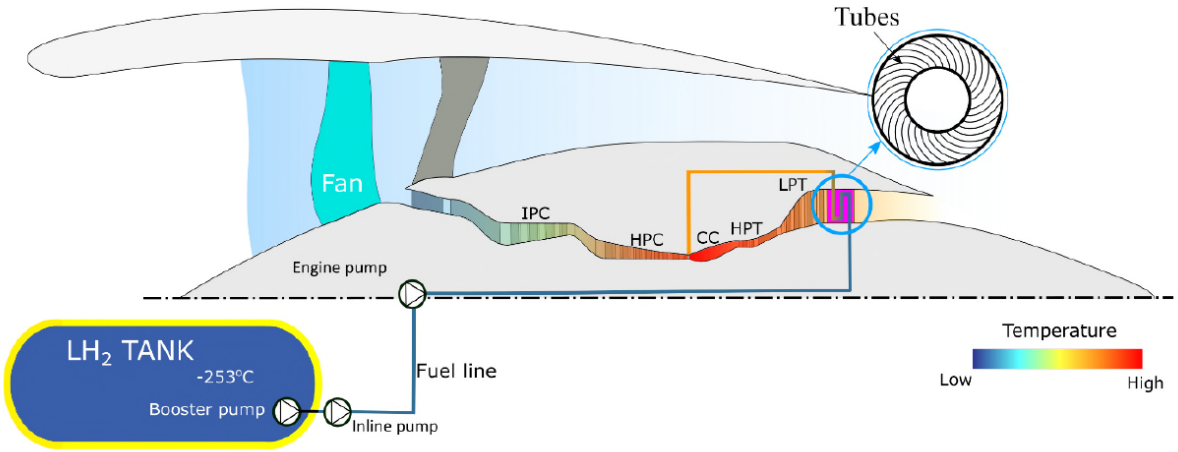

Figure 6: Lower risk concept recuperative turbofan

Fuel tanks

To save weight and reduce exposed areas, a two-tank layout with inner partitions (two per tank) was favoured over a four-tank layout. Both tanks are cylindrical with hemispherical cap ends and their insulation comprises polyvinylchloride rigid closed cell insulation. 2% of mission fuel is permitted to boil-off for the total duration of the design mission. For this amount of boil-off the tank should be able to retain most of the evaporated fuel in the specified design mission.

5 Modelling methodologies

5.1 Aircraft modelling

To simulate the performance of the proposed aircraft concepts, two tools were used: Orion, an in-house code developed within Cranfield University, and Pacelab, a commercial software. The former was used for the analysis of the LR maximum synergy concepts and the latter for all the other concepts.

Although the two tools have different capabilities, in terms of aircraft performance, they incorporate similar physics-based methods. The user initially determines the geometry, characteristic weights of the aircraft and the flight envelope, which would include the altitude and speed of the aircraft across the different phases of the mission. Based on these inputs, established methods based on existing literature are then used to estimate the drag of various integrated components (fuselage, wings, empennage, propulsion system etc.) for each specified point in flight. To calculate performance of the aircraft through the mission, the models utilise a point mass approximation [6]. In addition, for every segment, and based on drag estimation, the propulsion system fuel flow demand and thrust are provided either via predefined performance tables or through integrated propulsion system simulation software. More details about the propulsion system performance modelling are provided in the next section. For each segment, the aircraft weight is adjusted to account for the fuel burned in the previous one, and the overall block fuel is then calculated as the cumulative sum of fuel consumed in all segments. Based on the specific diversion and hold profiles, reserve fuel is also assumed with an additional quantity included for contingency. Block fuel and reserves cumulatively indicate the on-board fuel carried. Additional outputs also include the block time and emissions (CO_2, H_2O and NOx). Depending on the mission to be investigated and a specified initial input (predefined range, a take-off weight, or a given trajectory based on waypoints), the tools can be configured accordingly to undertake simulations.

Aircraft weight estimation

For the weight estimation of tube and wing configurations Pacelab has built in capabilities that are based on empirical correlations proposed by Raymer [7], Torenbeek [8] and Roskam [9]. The weight is estimated separately for all the components of the aircraft based on user-defined geometry, aircraft type, number of passengers etc. The correlations are limited to conventional airframes and cannot be used for a blended-wing-body airframe weight, such as that of the LR max synergy concept. Instead, the weight estimation for the BWB was based on the method developed by NASA [10] and integrated in the Flight Optimisation System (FLOPS). Contrary to the other methods, the correlations used for the wing and fuselage sections were derived from finite element analysis studies. In addition, this method allows for the sizing of the complex geometry of a BWB passenger cabin. Validation of the tool can be found in references [11] [12].

5.2 Propulsion system modelling

The propulsion system modelling was carried out using two simulation tools, GESTPAN and PROOSIS. GESTPAN is a Chalmers University in-house modelling tool [13]. The GESTPAN code is a FORTRAN 90 implementation, supporting both steady-state and transient modelling of conventional and novel propulsion and power generation systems by freely connecting mathematical models of various components constituting the systems. GESTPAN was used for the sizing and performance simulation of the turbofan engines that feature in both the low-risk aircraft and the max synergy SMR concepts.

PROOSIS is an object-oriented propulsion system simulation software created for commercial use. It features a dedicated library for turbomachinery, namely TURBO, which includes a large variety of components that can be combined to create several customised gas turbine configurations. As PROOSIS also allows for the creation of new components to simulate advanced hybrid systems, it was used to model the turbo-electric distributed propulsion system of the max synergy LR concept. A list of published research where the software has been used can be found in reference [14].

To simulate the performance of a gas turbine using hydrogen, two areas of focus have been considered and relevant changes in the tools have been made. The first step was to include thermodynamic tables for relevant properties such as enthalpy, entropy, specific heat and specific heat ratio of the hydrogen combustion products. The second step was to model pure hydrogen properties for the fuel and heat management system. This requires thermodynamic information about the fuel's performance over a very large range, extending from cryogenic conditions to the high temperatures expected at the entry to the combustor. In this context the software REFPROP [15] was used, either by integrating it within the tools, or via tabulation of the fuel properties.

Both these features were necessary to model the heat transfer between the fuel supply and the main engine. In the models created, hydrogen preheating is achieved via a heat exchanger assumed to be installed at the exhaust of the low-pressure turbine. This made on-design and off-design point simulations of the system substantially more complex than those of a conventional turbofan. The two flows merge in the main combustor after having substantial amounts of heat exchanged prior to their merging. The heat transferred to the hydrogen is of a magnitude that influences the thermodynamic state of the combustion products and affects the sizing of the main gas path. Preheating the fuel from a cryogenic condition of around 25 K possibly all the way up to 400-500 K requires about up to 6 MJ/kg, i.e. about 5% of the heat released upon combustion. An example of the discussed configuration applied for a geared turbofan as modelled in PROOSIS is presented in Figure 7 below.

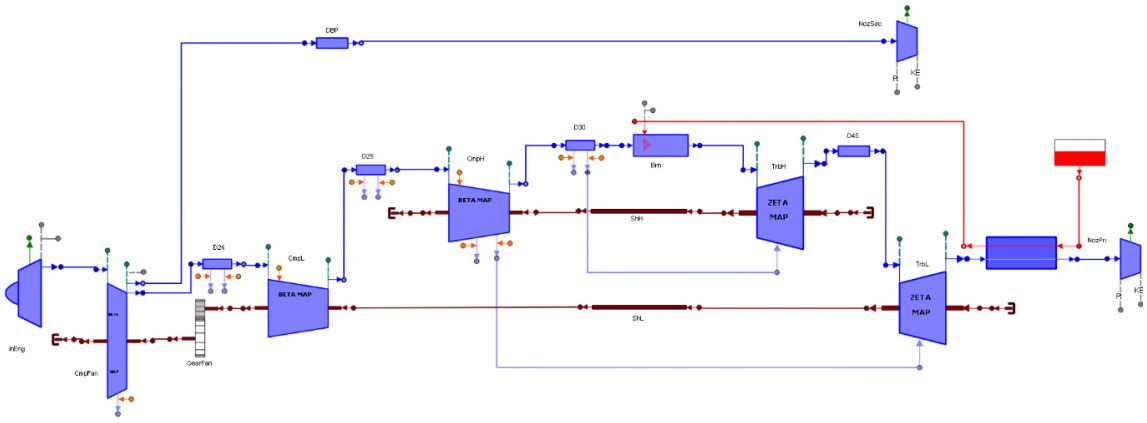

Figure 7: Schematic of a geared turbofan as modelled in PROOSIS

5.3 Tank sizing

For all the LH_2 and LNG aircraft concepts, foam insulated tanks have been assumed. They comprise insulation that limits the heat leak from the environment and a wall structure to withstand the differential pressures developed over time. Polyvinylchloride rigid closed-cell foam was chosen over vacuum and multi-layer insulation for its low density and low cost, as

well as ease of implementation. Although it comes with the challenge of higher heat ingress compared to the other options, it provides the lightest solution for the intended applications.

Aluminium alloy walls are assumed to be integrated inside the outer foam layer to protect and seal the insulation from the cryogenic fuel and protect it from hydrogen permeation and embrittlement. Aluminium alloys are commonly selected for their properties under cryogenic conditions. Composite materials are a potentially lighter option, but since they are generally prone to hydrogen permeation, a protective liner should additionally be used.

The tanks are cylindrical with hemispherical cap ends and have either high integration with the airframe, or none, depending on the concept they are applied to. Spherical tanks may offer better surface to volume characteristics than cylindrical tanks for the same content capacity and withstand the same pressure loads with thinner walls, but are volumetrically less efficient. For aircraft applications, the main driver is to store as much fuel as possible by simultaneously occupying the least space and saving weight.

As the tank walls need to be sized for a maximum allowable operating pressure, a mission-level approach was adopted, since the conditions that determine the pressure variation constantly change. The internal pressure is affected, inter alia, by effects such as heat ingress from the environment surrounding the tanks, the rate engine fuel is withdrawn from the tank and the tank's LH_2 fill-level. For a given geometry and insulation thickness, the pressure accumulation is determined for the whole flight envelope and the wall is sized accordingly. For example, a thinner layer of insulation will allow more rapid heat ingress and pressure increase. Consequently, the wall needs to be thicker and heavier to avoid the need to vent gas. Conversely better insulation will restrict the heat input and the pressure rise, allowing thinner and lighter walls but with more insulating materials. In a study conducted in the context of ENABLEH2, the trade-off between insulation and wall thicknesses demonstrated there is an optimum combination that leads to the lightest overall solution for a given amount of LH_2 stored. Additional parameters that significantly affect the tank sizing are: ground hold times before departure, the initial filling pressure, and the additional volume needed to account for LH_2 expansion and evaporation throughout the mission. Some fuel inevitably evaporates to occupy the remaining space as LH_2 is drawn from the tank and this vapour is assumed to be unusable by the engines. A detailed discussion of the methodology used to size the tank is included in reference [16].

5.4 Cryogenic fuel system modelling

The ENABLEH2 study aircraft that use Jet A-1 or drop-in-replacement fuels are assumed to retain conventional fuel systems. The Y2050 SMR aircraft using Jet A-1 and biofuel are assumed to be more fuel-efficient than the Y2020 aircraft, and hence do not need an Auxiliary Container Tank (ACT) in the fuselage to meet the design payload–range target, so all their fuel is contained in the wings. However, the Y2050 aircraft that use LNG or LH_2 need very different fuel systems to handle the cryofuels safely and efficiently, and also to vaporise them before supplying them to engine combustors or to fuel cells.

Within the scope of activities in WP1, the optimum overall configurations for LH_2 aircraft fuel systems have been studied. Lower Risk aircraft with LH_2 can use the cryofuel as a heat sink to provide oil cooling on the engines and potentially also for intercooling. However, to raise the fuel's temperature appropriately for inlet to the combustor, it is likely that the hydrogen will be warmed by the LP turbine exhaust gas or use another pre-heating device. This can significantly improve fuel economy by increasing the effective heating value of the fuel. Good turbine exhaust heat exchanger designs are needed to minimise pressure loss in the core exhaust duct and to ensure safety in the event of any potential hydrogen leakages.

To provide required levels of redundancy, the aircraft under investigation need two separate fuel tanks to feed the two gas turbines (or to feed one gas turbine and fuel cells in the case of the Cobalt Blue 2 concept). The two halves of the fuel system are normally isolated, so that no single failure can result in a total loss of fuel supply to the engines (or engine and fuel cells). A cross-feed valve is only opened when it necessary for one side of the fuel system to supply fuel to the other side, as might be the case during refuelling or in a one engine inoperative (OEI) diversion scenario.

LR aircraft generally need more than two tanks, so that fuel can be moved about to maintain the aircraft's centre of gravity within acceptable limits. Low pressure (LP) or 'backing' pumps are needed to be able to transfer LH_2 and to defuel the aircraft when needed. Relying on the pressure of the fuel in the tank is unlikely to be acceptable. Since the availability of helium is limited, it cannot routinely be used to pressurise aircraft fuel tanks. This means the LH_2 in the tanks will be close to boiling point, so if its pressure is not increased by a pump, it is liable to boil in the supply lines. The resulting two-phase flow could then cause pressure and mass flow fluctuations downstream. The LP pumps would be electrically driven and ideally located inside the fuel tanks. A minimum of two pumps for each tank is needed to provide redundancy.

To off-load fuel, or to transfer it between tanks, a pressure increase of one or two bar may be sufficient. However, consideration should be given to providing higher-pressure pumps inside the tanks to send hydrogen to the engines at supercritical pressure (above 14 bar). A small buffer tank may also be incorporated to provide a reserve of supercritical-pressure hydrogen to help to maintain continuity of supply in the event of turbulence. The buffer tank could be located inside the main tank. A supercritical pressure in the supply lines would guarantee single-phase flow and avoid potential cavitation problems at entry to the engine's high-pressure pump. A further option would be to have a pump to compress the cold ullage gas and add it to the supply line. Having this option would enable the tank pressure to be controlled during long flights where heat ingress might otherwise warm the contents excessively. This works because extracting gas from the storage tank has a greater cooling effect than extracting the liquid. Managing the pressure inside the tanks is important to avoid needing to vent gas overboard during a flight or a regular stop-over.

The fuel system design requirements are more complex for the 'max synergy' aircraft: i.e. the SMR Cobalt Blue 2 concept from Safran, which has fuel cells as well as a turbofan engine, and the BWB aircraft concept from CU, which has superconducting turbo-electric distributed propulsion (TeDP). These aircraft concepts are described in sections 5.2.1 and 5.2.2.

The LH_2 BWB aircraft has low bypass ratio turbofans buried at the wing roots, but most of the power from the LP turbines is consumed by superconducting electrical generators and transmitted to a bank of ducted fans above the centrebody. These fans provide most of the thrust. The fan motors are also assumed to be superconducting and cooled by very cold hydrogen circulated along with the superconducting electric cables that connect them to the generators. In this way it may not be necessary to also have a closed-circuit cooling system using helium as proposed for the Cobalt Blue 2 aircraft. Otherwise the systems are similar.

The on-engine thermal management of GH_2 and LH_2 has been researched in ENABLEH2 WP2. This work is described in the final public deliverable D2.4 'Final Report on Heat Management Systems'.

5.5 Emissions modelling

5.5.1 Methodology for CO_2

Emissions of CO_2 are directly related to the fuel consumption and the chemical composition of the fuel. Complete combustion is assumed for hydrogen and hydrocarbon fuels, so the

combustion products are just water and carbon dioxide. The mass of the combustion products is therefore based on the atomic weights of carbon, hydrogen, and oxygen. These are conventionally taken to be 12.011, 1.008 and 15.999 respectively. In addition to kerosene, the following hydrocarbon-based fuels were also considered in the technology evaluation process:

Sustainable Alternative Jet Fuel (SAJF)

The term Sustainable Alternative Jet Fuel (SAJF) essentially covers biofuels, fuel from waste, and synthetic fuels including 'electrofuels' which are synthesised from hydrogen produced by the electrolysis of water and from CO_2 extracted from the air or sea water. Various production trials have been made and research continues, but currently few processes are economically viable even with subsidies. Today the majority of biofuel for aviation is produced from vegetable oils. Hydrotreated Vegetable Oil (HVO) provides biodiesel, but further processing is required for aviation use, giving a product containing Hydro-processed Esters and Fatty Acids (HEFA). When provided as a 'drop-in-replacement' fuel for aviation such a biofuel is commonly known as Biojet, Sustainable Jet Fuel (SJF), Renewable Jet Fuel (RJF) or biomass-sourced Synthetic Paraffinic Kerosene (bio-SPK).

In terms of lifecycle CO_2 emissions, the Air Transport Action Group (ATAG) have indicated that biofuels have the potential to reduce the carbon footprint by 80% at 100% Concentration, or 40% for the 50:50 blend. However, the savings will depend on the feedstocks and processes used and the accounting practices adopted. Some studies also claim that biofuels may not deliver real life-cycle CO_2 or total greenhouse gas (GHG) emissions reductions at all, and many commentators have highlighted negative environmental impacts. The use of food crops and the cultivation of corn (sweetcorn) to produce ethanol or biodiesel is particularly contentious. Life-cycle studies account for the energy used on farms, the production of fertilizer, transportation and processing. Some also consider the impact on soils, pre-existing vegetation, and water use. However, most studies agree that current biofuels and their by-products (such as cattle-feed) at least have slightly higher energy content than the fossil fuels used to produce them.

Liquified Natural Gas

Liquified Natural Gas was initially considered to be one of fuels that could have the potential to be used in commercial aviation, The fuel (along with LH_2) has been successfully flight tested by the Russians in the 1980s on a TU155, which was used as an alternative fuel testbed. Within ENABLEH2, the initial consideration was that, if natural gas was carried in a liquid form (as LNG), then it could be used to primarily build experience and act as an ideal technology transition fuel to LH_2,. Other considerations included its (historically) lower cost and its properties as a "cleaner" fuel, with a lower propensity to form soot. However, LNG does not have significantly higher potential to reduce CO_2 emissions when compared with kerosene and so eventually it was not considered to be a prime candidate as a future aviation fuel.

Natural gas is mostly methane, but it also contains higher hydrocarbons and other gases. It is normally refined before it is used, with some processing undertaken at the well-head and further processing undertaken before it is distributed or liquefied. For gas destined to become LNG this processing includes condensate removal (which separates out most of the higher hydrocarbons such as pentane, oils and waxes), dehydration, and the removal of CO_2, H_2S and mercury. The composition of the consumable fuel is then closer to 100% methane, but it can still contain significant amounts of nitrogen, ethane, propane and butane, which all affect its heating value. There is no universal quality specification for LNG and no existing specification for LNG as an aviation fuel. The LHV for LNG is typically in the range 49.0 to 49.9 MJ/kg, but the LHV for LNG can possibly be as low as 45 MJ/kg. This compares with 50.0 MJ/kg for pure methane. However, it seems likely that a minimum heating value of around 49.0 MJ/kg at standard temperature would be specified for aviation. If it is ever used, it is

anticipated that the LNG will be gasified or raised to supercritical pressure before it is burned. It will also be preheated by being used to cool various engine systems prior to injection.

Comparing conventional cycle engines, the SFC at a thrust will be about ~14% higher for Jet A-1 than for LNG. For LNG the CO_2 emissions are about 2.75 times the fuel mass flow, so for engines with the same thrust and overall efficiency the CO_2 emissions are reduced by about 23.3%. In practice the savings at mission-level will not be this high due to the increased volume and weight of the pressurised LNG tanks, and any required increase in fuselage volume resulting in additional airframe weight and drag. As with other fuels, additional CO_2 will be generated in processing and transporting the fuel. From the perspective of global warming, methane 'slip' is a further concern as methane is a potent greenhouse gas with 20–30 times the warming potential of CO_2. No assessment is made of methane slip from LNG fuel.

Based on internal discussion, consultation with experts within partner organisations in ENABLEH2 and a literature search in public domain the following information (Table 4) was compiled. It was used to calculate the mission level and life-cycle CO_2 footprint of the various technologies investigated in the technology evaluation process:

Table 4: Key assumptions for various hydrocarbon-based fuels used for the technology evaluation

Fuel	Description	Year	LHV (MJ/kg)	Density (kg/ L)	$EICO_2$ (kg CO_2/ kg fuel)	$EICO_2$ LCA (kg CO_2/ kg fuel)	Comments
Typical Jet A-1			43.15	0.80	3.15	3.84	
Alternative	HEFA, Vegetable Oil, 50% blending ratio	2025	43.6	0.78	3.12	2.68	60% reduction GES, 50% blend
Alternative	HEFA, Algae, 100% blending ratio	2030	44	0.75	3.12	0.76	80% reduction GES, 100% blend
Alternative	FT, Lignocellulosic, 100% blending ratio	2030	44	0.75	3.12	0.57	85% reduction GES
Alternative	PtL, FT ex renewable electricity, 100% blending ratio	2050	44	0.75	3.12	0.38	90% reduction, fully renewable electricity
LNG	Pure Methane		50	0.42	2.74	3.45	
LNG	Aero LNG		49.6	0.42	2.75	3.53	96% Methane

5.5.2 Methodology for EINOx

Assuming 100% combustion efficiency, the emissions indices for H_2O and CO_2, are directly related to the fuel's chemical composition. The emissions indices for NOx (EINOx), however, depend on many factors, including the fuel, the combustor design, and conditions within the combustor. All the Y2050 gas turbines are assumed to have advanced lean-burn combustors that would tend to produce lower NOx emissions than Y2000 or Y2020 engines, but because the Y2050 engines are expected to operate at higher pressures and temperatures than Y2000 engines, their NOx emissions indices are not dissimilar. The levels of NOx generated per ASK in 2050 are however lower than in Y2000 because improvements in airframe and propulsion system technology will reduce fuel burn.

The EINOx figures quoted within this report are estimated separately for each flight phase according to correlations against engine cycle parameters for the combustor. The NOx masses generated in each flight phase are then summed to give total mission-level NOx. Three different correlations have been used: one for Jet A-1 and biofuels or SAF, one for 'aero' LNG, and one for hydrogen micromix combustion.

There is considerable uncertainty about the most-likely NOx emissions of year-2050 advanced combustors for all the possible aviation fuels. For engines fuelled with Jet A-1, the simple NASA correlation for NOx emissions was selected for the ULTIMATE project (following an extensive review of alternative correlations) and provided estimates for both Landing and Take-off (LTO) certification cases and on-route assessments. This correlation is considered generally applicable to advanced lean-burn combustors, such as Lean Direct Injection (LDI) designs, that are expected to be used in future engines, so it is used also in this study.

This preferred NASA correlation was attributed to S. Jones and the Advanced Subsonic Technology Project (AST) by Antoine and Kroo [17], but also to Bill Haller and the NASA-industry Advanced Subsonic Engine (ASE) study by Lukachko and Waitz [18]. It was one of several correlations used by Alexiou et al. in the NEWAC project [5 20]. It has been described as applicable to dual-annular staged combustors, but it has also been applied to studies of lean premixed prevaporized (LPP) combustors. It is reproduced here as equation Eq.1 with the units converted so that the compressor delivery temperature T3 and combustor exit temperature T4 are (K) and the pressure P3 is (kPa). The index EINOx is expressed in grams per kilogram of fuel.

$$EINO_X = 0.007549 \times T_4 \left(\frac{P_3}{3027} \right)^{0.37} e^{\frac{1.8T_3 - 1471}{345}} \qquad \text{Eq.1}$$

Because this equation provides a continuous function, it is not expected to be very accurate where fuel staging switches different nozzles on and off. It may also tend to underestimate NOx emissions at idle, where only the pilot nozzles are operating, but operation at idle only makes a small contribution to overall NOx emissions so that deficiency is not very significant.

A humidity correction is also applied to account for the increase in NOx emissions in the drier air at higher altitudes (since the effects of humidity on engine performance are not usually explicitly modelled). Typically, this results in a 12.5% increase at the top of climb and cruise conditions. Humidity increases *EINOx* by e^H where *H* is the humidity correction factor which is calculated according to equation Eq. 2, where ω is the specific humidity (kg_{H2O}/kg_{air}).

$$H = -19(\omega - 0.006344) \qquad \text{Eq.2}$$

The figure of 0.006344 corresponds to the specific humidity ω on an ISA day at sea-level that has 60% relative humidity (RH), which is typical for ground-level emissions testing. If the actual sea-level RH is 60% then *H* is zero the factor e^H is unity. For completely dry air e^H is 1.127 and for saturated air on an ISA day at sea-level, e^H is about 0.923. A representative correction factor for cruise altitudes is 1.125. The effects of humidity can thus be quite significant, with higher specific humidity reducing NOx emissions.

Some assessments have been made for the NOx emissions with various biofuels and biofuel blends with kerosene, but the differences are relatively small and subject to significant uncertainties. The same equations as for Jet A-1 are used therefore for drop-in replacement biofuels and synthetic fuels (SAF). Where the biofuel has a higher heating value than Jet A-1, then for the same emissions index there will be a slight reduction in the predicted mass of NOx due to the reduced fuel mass flow, but this might be outweighed by an increased emissions index due to the higher combustor temperature [19].

The hydrogen content of LNG is typically 24.5%, which is significantly higher than the 14–15% typical of Jet A-1 and drop-in replacement biofuels. This means there is much more water vapour in the combustor exit flow.

The NOx emissions of an engine burning methane or natural gas in a premixed or partially premixed combustor can be very low, so much so that in practical designs with a pilot burner taking up to 10% of the airflow, the NOx emissions from a richer-burning pilot burner may predominate. This was noted by Lauer et al. [20]. However, it is not obvious what design of combustor would be used in LNG-fuelled aero engines. One possibility is a micromix combustor, somewhat similar to that proposed for the hydrogen-fuelled engines, but natural gas has narrower combustion limits than hydrogen, longer autoignition delay times and lower flame speeds, increasing the risk of lean blow-out and problems with altitude relight. Therefore, micromix combustors for LNG-powered aero engines are likely to require more fuel staging, with only a sub-set of the injectors fuelled at low power conditions. This would detract from the simplicity of the design, but the micromix arrangement still seems an attractive option as it should be more compact than the typical pilot-stabilized pre-mixed Dry Low Emissions (DLE) designs used in existing industrial gas turbines.

If the residence time and relationship between flame temperature and T_4 in the LNG combustor would be comparable to that of the advanced Jet A-1 combustor, then the NOx emissions should also be comparable. However, given industrial engine experience and considerations of relight performance, it is more likely that aero engine combustors for gasified LNG would have lower NOx emissions than advanced combustors burning liquid hydrocarbons. This is because they would not suffer from the additional time delay for vaporization of the fuel under altitude relight conditions, so they could be designed with smaller combustor volumes and shorter residence times, reducing thermal NOx generation at higher power conditions. It seems reasonable therefore to suppose that a combustor design optimised for altitude relight and combustion efficiency could achieve a 25% reduction in NOx, resulting in equation Eq. 3.

$$EINO_X = 0.005662 \times T_4 \left(\frac{LHV_{LNG}}{43.15} \right) \times \left(\frac{P_3}{3027} \right)^{0.37} e^{\frac{1.8T_3 - 1471}{345}} \qquad \text{Eq.3}$$

In the current study ‘aero’ LNG is taken to have LHV equal to 49.6 MJ/kg. The above equation is also assumed to apply to combustion with air having specific humidity equal to air with relative humidity of 60% on an ISA day at sea level, so the humidity correction of Eq. 2 still applies.

Performance models generating input parameters for the correlations ideally take account of the actual temperature of the fuel as it enters the combustor and for any heat taken out of the engine cycle to preheat the fuel. This is particularly important for the cryogenic fuels.

Micromix combustors are assumed for all the LH_2-fuelled engines and a new correlation for EINOx for such combustors has been generated in the ENABLEH2 project. It is backed-up by extensive numerical studies undertaken in Work Package 3 and is presented as Eq.4

$$EINOx = 0.0864 \times {P_3}^{0.4} \times e^{\frac{T_3}{191}} \times \Phi^{1.95} \qquad \text{Eq.4}$$

where Φ is the equivalence ratio, calculated assuming 10% of the incoming air is used for cooling and the stoichiometric fuel air ratio for hydrogen is 0.029.

In this case the correlation is for dry air, so the correction factors applied for typical 60% humidity at sea level ISA and at cruise altitude are 0.8873 and 0.9982 respectively.

6 Mission-level technology evaluations

The year 2050 best-case-scenario projections for the performance of future commercial aircraft were assessed within the project. This inevitably involves engineering judgement and economic forecasting, which introduce uncertainty. The analysis included the assessment of performance, weight, fuel burn, NOx emissions and operating costs of various aircraft operated on hydrocarbon-based fuels. These were then compared with figures for the LH_2 designs for SMR and LR aircraft. The overall compiled results of the SMR and LR aircraft concepts are as included in Tables (5 and 6).

Significant fuel burn reductions are projected for aircraft entering service in 2050, relative to current state of the art airliners, whether they be fuelled with Jet A-1, Biofuel or LNG. The Y2050 SMR and LR aircraft fuelled with Jet A-1 are both projected to have about 24% lower mission fuel burn and CO_2 emissions per available seat kilometer (ASK) relative to representative state-of-the-art aircraft currently in service. Drop-in replacement biofuels only reduce mission-level CO_2 emissions by a few per cent, but they have the potential for very significant reductions in life cycle emissions. For Y2050, reductions of up to 90% have been predicted for synthetic electrofuels.

Liquefied natural gas (LNG) generally only offers a modest reduction in mission-level and life-cycle CO_2 reductions relative to Jet A-1. This is because the LNG tanks increase the empty weight, fuselage volume and drag of the aircraft, such that the benefit of the fuel's lower carbon content and higher heating value are largely offset, particularly for the LR tube and wing aircraft. However, the LR BWB aircraft (with any fuel) shows a significant reduction in emissions relative to the advanced tube and wing designs. This is because the BWB aircraft has higher lift/drag ratio and a more efficient boundary layer ingesting propulsion system in comparison to the tube and wing aircraft. The LNG variant is less penalised than the LH_2 one by needing large fuel tanks, because the basic BWB design already has high internal volume.

The mission-level NOx emissions per ASK tend to be lower for the LR aircraft because they spend a smaller proportion of their time in take-off and climb where NOx production is highest. Note estimates for the landing and take-off (LTO) cycle NOx emissions that are measured in engine certification tests, and mission-level estimates for the Y2020 baseline aircraft, are outside the scope of the current study. The quantitative results for the Y2050 aircraft are of course highly dependent on the assumptions made regarding the pace of improvements in aircraft and propulsion system technologies over the next 30 years.

The four LH_2-powered aircraft, which include conventional and aggressive concepts to cover both SMR and LR market segments, were designed within the project. As described earlier, all aircraft met the top-level requirements. As expected, empty weight is higher for LH_2 aircraft when compared with hydrocarbon-fuelled aircraft, but fuel mass is significantly reduced (by around 70%) owing to the very high energy density of hydrogen. This, in combination with the lightweight tank technology selected for 2050 entry into service, favours longer range designs and operation close to maximum design range, where greater improvements can be observed. However, tanks which would be less efficient in terms of weight (as anticipated for near-term LH_2 aircraft in some other studies) would severely penalize the LR aircraft because their tank weights are proportionately greater than those for the SMR aircraft.

The Lower Risk LH_2 aircraft (EIS 2050) entail mass and drag penalties due to their larger fuel tanks, which make them less energy-efficient relative to hydrocarbon powered aircraft of the same generation. However, they are still on par with or more efficient than current aircraft. The introduction of more aggressive technologies and integration concepts enables significant improvements in terms of aerodynamics and propulsion efficiency, which in turn reduce fuel mass and fuel tank volume. This leads to lower energy requirements making an LH_2 SMR

aircraft a plausible candidate, and an LH_2 LR aircraft an attractive solution for a sustainable aviation. The compiled results for Mission-level technology evaluations are included in the following tables (Table 5 and Table 6).

Table 5: Mission-level technology evaluations (Short/Medium Range)

Short/Medium-Range Aircraft							
		Y2020	**Y2050**				
Designation	**-**	**T&W Jet A-1**	**T&W Jet A-1**	**T&W Biofuel**	**T&W LNG**	**Lower Risk LH_2**	**Cobalt Blue 2 LH_2**
Max PAX Design Range							
Max PAX Design Range	nmi (km)	3000 (5556)					
Max PAX Design Payload	t (PAX)	21.0 (200)					
Block Fuel (ISA)	t	14.8	11.3	11.0	10.0	4.9	4.5
Δ Block Fuel	-	datum	-24%	-26%	-32%	-67%	-70%
Block Fuel per ASK	kg/ASK	0.0133	0.0102	0.0099	0.0090	0.0043	0.0040
Block Energy	GJ	639	488	484	496	588	539
Δ Block Energy	-	datum	-24%	-24%	-22%	-8%	-16%
Block Energy per ASK	MJ/ASK	0.575	0.439	0.436	0.446	0.529	0.485
Operational Stage Length							
Stage Length	nmi (km)	900 (1667)					
Payload (PAX)	t (PAX)	21.0 (200)					
Block Fuel (ISA)	t	4.7	3.6	3.5	3.2	1.5	1.5
Δ Block Fuel	-	datum	-24%	-26%	-32%	67%	-70%
Block Fuel per ASK	kg/ASK	0.0140	0.0107	0.0104	0.0095	0.0046	0.0044
Block Energy	GJ	202	154	153	158	183	175
Δ Block Energy	-	datum	-24%	-24%	-22%	-9%	-13%
Block Energy per ASK	MJ/ASK	0.606	0.461	0.458	0.473	0.551	0.525

Table 6: Mission-level technology evaluations (Long Range)

Long-Range Aircraft								
		Y2020	**Y2050**					
Designation	**-**	**T&W Jet A-1**	**T&W Jet A-1**	**T&W Biofuel**	**T&W LNG**	**BWB LNG**	**Lower Risk LH_2**	**BWB LH_2**
Max PAX Design Range								
Max PAX Design Range	nmi (km)	7500 (13890)						
Max PAX Design Payload	t (PAX)	47.6 (414)						
Block Fuel (ISA)	t	113.6	86.0	84.8	92.6	49.5	38.2	24.9
Δ Block Fuel	-	datum	-24%	-25%	-18%	-56%	-66%	-78%
Block Fuel per ASK	kg/ASK	0.0198	0.0150	0.0147	0.0161	0.0086	0.0066	0.0043
Block Energy	GJ	4902	3712	3715	4595	2455	4584	2983
Δ Block Energy	-	datum	-24%	-24%	-6%	-50%	-6%	-39%
Block Energy per ASK	MJ/ASK	0.852	0.646	0.649	0.799	0.427	0.797	0.519
Operational Stage Length								
Stage Length	nmi (km)	3000 (5556)						
Payload	t (PAX)	47.6 (414)						
Block Fuel (ISA)	t	41.2	31.8	31.5	34.3	19.5	14.9	10.0
Δ Block Fuel	-	datum	-23%	-23%	-17%	-53%	-64%	-76%
Block Fuel per ASK	kg/ASK	0.0179	0.0138	0.0137	0.0149	0.0085	0.0065	0.0044
Block Energy	GJ	1778	1372	1387	1701	969	1784	1203
Δ Block Energy	-	datum	-23%	-22%	-4%	-45%	-0%	-32%
Block Energy per ASK	MJ/ASK	0.773	0.597	0.603	0.739	0.421	0.776	0.523

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7 Emissions, operating cost, and contrails

7.1 Life cycle CO_2 emissions

A major incentive for switching to new fuels, SAF, methane, or hydrogen, is to reduce life cycle carbon emissions from civil aviation to combat global warming. However, none of these options will eliminate lifecycle CO_2 emissions completely as the fuel production cycle and the manufacturing of the aircraft will also need to be considered. If considered from a mission perspective, improving the energy efficiency of future aircraft continues to be vital. In ENABLEH2 the down-selected aircraft and propulsion system concepts for use with have been studied in sufficient detail to make comparisons between them. Life cycle analysis accounts for CO_2 absorbed and released during the production and distribution of the fuel in addition to that emitted by the aircraft in operation.

There is a distinction to be made between fuels like hydrogen or ammonia that provide zero CO_2 emissions at mission-level and fuels that capture carbon from the environment. If direct air capture of CO_2 is used to produce SAF then the carbon is extracted before the fuel is used, but construction of the plant and the generation of the energy needed to extract the carbon will result in some CO_2 emissions before that. For biofuels the timeframe of carbon emissions depends on the feedstock. If additional cultivation is put in place before the fuel is produced then there may be a temporary reduction of CO_2 in the atmosphere, but if a pre-existing source of biocarbon is used then there will be a temporary increase of CO_2 in the atmosphere before net zero is achieved. In worst-case scenarios, such as clearing forests to grow energy crops, the increase in atmospheric CO_2 may persist for many decades before net zero is achieved. The current study does not address these factors.

Carbon emissions are assessed and compared relative to the available passenger kilometres flown in each aircraft. This provides a fair basis for comparison, but it does not completely assess the emissions associated with those journeys. The CO_2 emissions per passenger trip will be higher if the aircraft are operated with load factors less than 100% and if the air traffic management is inefficient and results in longer routings being taken. There will also be CO_2 emissions associated with airport operations and passenger travel to and from the airports. These additional factors are not assessed here, nor are the environmental impacts of the CO_2 emissions, but they are being assessed in other EU projects such as MINIMAL.

The mission-level CO_2 emissions are easily calculated as the emissions indices for different fuels are directly related to their chemical composition. However, all fuels require energy input for their extraction or manufacture and distribution. Therefore, the life-cycle emissions indices are more uncertain and rely on assumptions made regarding the efficiency with which the fuels are extracted, or manufactured, and distributed to airports and associated CO_2 emissions.

The life-cycle CO_2 emissions assessments for the ENABLEH2 study aircraft are given in Table 7 for the SMR aircraft and Table 8 for the LR aircraft. The tables also list the emissions indices assumed for Jet A-1, ‘aero’ LNG, and SAF. The index of 380 g/kg for 100% SAF in year 2050 is considered a best-case figure. For comparison purposes the same index is quoted for LH_2 but that index could be a lot higher or lower depending on the efficiency of production of green or blue hydrogen in year 2050 and associated carbon emissions. In a best-case scenario, where the hydrogen is produced from biomethane and the CO_2 is captured and sequestrated, the life-cycle emissions index for LH_2 could even be negative. Mission-level and life-cycle CO_2 emissions are quoted for maximum design range and for more typical shorter flights. The life cycle emissions per ASK for the typical range flights are probably the more relevant figures considering fleet-wide operation.

Table 7: Life cycle CO_2 emissions from SMR Aircraft with 200 Passengers in Single-Class Seating

EIS	Type	Fuel	Range		Block Fuel	Mission-level CO_2 Emissions				Life Cycle CO_2 Emissions			
Year	-	-	nmi	km	kg	EI g/kg	kg CO_2	g/ASK	relative	EI g/kg	kg CO_2	g/ASK	relative
2020	T&W	Jet A-1	3000	5556	14800	3150	46620	42.0	datum	3840	56832	51.1	datum
			900	1667	4680	3150	14733	44.2	datum	3840	17971	53.9	datum
2050	T&W	Jet A-1	3000	5556	11300	3150	35595	32.0	76%	3840	43392	39.0	76%
			900	1667	3560	3150	11200	33.6	76%	3840	13667	41.0	76%
		Biofuel	3000	5556	11000	3120	34320	30.9	74%	380	4180	3.8	7%
			900	1667	3470	3120	10800	32.4	73%	380	1319	4.0	7%
		LNG	3000	5556	10000	2750	27500	24.7	59%	3530	35300	31.8	62%
			900	1667	3180	2750	8733	26.2	59%	3530	11233	33.7	63%
		LH_2	3000	5556	4900	Zero				380	1862	1.7	3%
			900	1667	1530					380	581	1.7	3%
	CB2	LH_2	3000	5556	4491	Zero				380	1707	1.5	3%
			900	1667	1459					380	554	1.7	3%

Table 8: Life cycle CO_2 emissions from LR Aircraft with 414 Passengers in Two-Class Seating

EIS	Type	Fuel	Range		Block Fuel	Mission-level CO_2 Emissions				Life Cycle CO_2 Emissions			
Year	-	-	nmi	km	kg	EI g/kg	kg CO_2	g/ASK	relative	EI g/kg	kg CO_2	g/ASK	relative
2020	T&W	Jet A-1	7500	13890	113600	3150	357840	62.2	datum	3840	436224	75.9	datum
			3000	5556	41200	3150	129960	56.5	datum	3840	158208	68.8	datum
2050	T&W	Jet A-1	7500	13890	86035	3150	271010	47.1	76%	3840	330374	57.5	76%
			3000	5556	31801	3150	101438	44.1	78%	3840	123520	53.7	78%
		Biofuel	7500	13890	84814	3120	264620	46.0	74%	380	32229	5.6	7%
			3000	5556	31527	3120	99598	43.3	77%	380	11980	5.3	8%
		LNG	7500	13890	92643	2750	254768	44.3	71%	3530	327030	56.9	75%
			3000	5556	34285	2750	95458	41.5	73%	3530	121026	52.6	76%
		LH_2	7500	13890	38200	Zero				380	14516	2.5	5%
			3000	5556	14865					380	5649	2.5	5%
	BWB	LNG	7500	13890	49500	2750	136000	23.7	38%	3530	174735	30.4	40%
			3000	5556	19538	2750	54514	23.7	42%	3530	68969	30.0	44%
		LH_2	7500	13890	24856	Zero				380	9445	1.6	3%
			3000	5556	10027					380	3810	1.7	3%

7.2 H_2O and NOx emissions

NOx and H_2O emissions from aviation have the biggest impacts on climate after CO_2 provided the combination of the fuel and combustor technology minimises soot and sulphur particle emissions. Unlike CO_2, the altitudes at which NOx and H_2O emissions occur are very relevant to their GWP. These species have indirect as well as direct effects on global warming – for NOx this is via the interaction with ozone and for H_2O this is via contrail formation and induced cloudiness. Apart from the health impact of NOx emissions around airports, the emission of NOx and H_2O at high altitudes is most relevant in relation to their GWP. When aircraft fly in the stratosphere, the emitted water vapour can persist for much longer and so have a bigger impact on radiative forcing. The H_2O emissions assessments for the ENABLEH2 study aircraft are given in Table 9 for the SMR aircraft and in Table 10 for the LR aircraft. These tables also show the energy content of the fuels used and the H_2O emissions indices for Jet A-1, biofuel (SAF), 'aero' LNG, and LH_2.

The LH_2-fuelled Cobalt Blue 2 is the only aircraft in the study to use fuel cells to provide motive power. The fuel cells produce zero NOx, giving it an advantage. As the aircraft has a hybrid propulsion system, including a turbofan engine, it still generates some NOx, but this is minimised in the cruise phase by throttling-back the turbofan to a low power level of about 30% of its maximum cruise rating, such that around 85% of the thrust is generated by the four fuel-cell-powered APAD propulsion systems. In this way the overall system meets the target of a 90% reduction in NOx emissions at cruise. But the take-off and climb phases contribute more to the total mission-level NOx emissions than the cruise phase because this aircraft is not operated over very long distances. NOx emissions during climb could also be reduced by throttling-back the turbofan in this flight phase, though this might increase the times taken to reach cruise altitude. In the current assessment the turbofan engine has been assumed to contribute an average of 45% to the net thrust during the take-off and climb phases. Note 'Cobalt Blue 2' NOx emission indices, tabulated below, relate to the whole of its propulsion system fuel flow including the fuel cells powering the APADs.

Table 9: H_2O emissions from SMR Aircraft with 200 Passengers in Single-Class Seating

EIS	Type	Fuel	Range		Block Fuel	Mission-level Energy Use			Mission-level H_2O Emissions			
Year	-	-	nmi	km	kg	GJ	kJ/ASK	relative	EI g/kg	kg H_2O	g/ASK	relative
2020	T&W	Jet A-1	3000	5556	14800	639	575	datum	1250	18500	16.6	datum
			900	1667	4680	202	606	datum	1250	5850	17.5	datum
2050	T&W	Jet A-1	3000	5556	11300	488	439	76%	1250	14125	12.7	76%
			900	1667	3560	154	461	76%	1250	4450	13.3	76%
		Biofuel	3000	5556	11000	484	436	76%	1280	14080	12.7	76%
			900	1667	3470	153	458	76%	1280	4442	13.3	76%
		LNG	3000	5556	10000	496	446	78%	2182	21818	19.6	118%
			900	1667	3180	158	473	78%	2182	6938	20.8	119%
		LH_2	3000	5556	4900	588	529	92%	8945	43831	39.4	237%
			900	1667	1530	184	551	91%	8945	13686	41.1	234%
	CB2	LH_2	3000	5556	4491	539	485	84%	8945	40172	36.2	217%
			900	1667	1459	175	525	87%	8945	13051	39.2	223%

Table 10: H_2O emissions from LR Aircraft with 414 Passengers in Two-Class Seating

EIS	Type	Fuel	Range		Block Fuel	Mission-level Energy Use			Mission-level H_2O Emissions			
Year	-	-	nmi	km	kg	GJ	kJ/ASK	relative	EI g/kg	kg H_2O	g/ASK	relative
2020	T&W	Jet A-1	7500	13890	113600	4902	852	datum	1250	142000	24.7	datum
			3000	5556	41200	1778	773	datum	1250	51500	22.4	datum
2050	T&W	Jet A-1	7500	13890	86035	3712	646	76%	1250	107544	18.7	76%
			3000	5556	31801	1372	597	77%	1250	39751	17.3	77%
		Biofuel	7500	13890	84814	3732	649	76%	1280	108562	18.9	76%
			3000	5556	31527	1387	603	78%	1280	40355	17.5	78%
		LNG	7500	13890	92643	4595	799	94%	2182	202130	35.2	142%
			3000	5556	34285	1701	739	96%	2182	74804	32.5	145%
		LH_2	7500	13890	38200	4584	797	94%	8945	341699	59.4	241%
			3000	5556	14865	1784	776	100%	8945	132967	57.8	258%
	BWB	LNG	7500	13890	49500	2455	427	50%	2182	108000	18.8	76%
			3000	5556	19538	969	421	55%	2182	42628	18.5	83%
		LH_2	7500	13890	24856	2983	519	61%	8945	222337	38.7	157%
			3000	5556	10027	1203	523	68%	8945	89692	39.0	174%

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The Lower Risk LH_2-fuelled Y2050 SMR aircraft also achieves low overall mission-level NOx emissions by having a less-aggressive performance cycle for its turbofan engines, but it cannot match the ultra-low cruise NOx emissions achieved by the Cobalt Blue 2 design.

NOx emissions assessments for the ENABLEH2 study aircraft are given in Table 11 for the SMR aircraft and in Table 12 for the LR aircraft. These tables also list the emissions indices for the different aircraft and fuels. For the mission-level assessments these are the average figures over the whole flight. For the cruise NOx emissions figures these are for the fuel burned in the cruise phase only, but the g/ASK figures are for the total ASK for the flight, not just the cruise phase.

Table 11: NOx emissions from SMR Aircraft with 200 Passengers in Single-Class Seating

EIS	Type	Fuel	Range		Block Fuel	Mission-level NOx Emissions				Cruise NOx Emissions			
Year	-	-	nmi	km	kg	EI g/kg	kg NOx	g/ASK	relative	EI g/kg	kg NOx	g/ASK	relative
2050	T&W	Jet A-1	3000	5556	11300	9.9	112	0.101	datum	9.7	94.9	0.085	datum
			900	1667	3560	10.7	38	0.114	datum	9.7	20.4	0.061	datum
		Biofuel	3000	5556	11000	10.1	111	0.098	97%	8.7	93.3	0.084	98%
			900	1667	3470	10.7	37	0.111	97%	8.7	20.0	0.060	98%
		LNG	3000	5556	10000	8.3	83	0.075	74%	8.1	70.3	0.063	74%
			900	1667	3180	9.0	29	0.086	75%	8.1	15.1	0.045	74%
		LH_2	3000	5556	4900	10.6	52	0.047	46%	10.1	42.3	0.038	45%
			900	1667	1530	12.0	18	0.055	48%	10.1	9.7	0.029	48%
	CB2	LH_2	3000	5556	4491	NA				2.7	10.4	0.009	11%
			900	1667	1459					2.7	2.4	0.007	12%

Table 12: NOx emissions from LR Aircraft with 414 Passengers in Two-Class Seating

EIS	Type	Fuel	Range		Block Fuel	Mission-level NOx Emissions				Cruise NOx Emissions			
Year	-	-	nmi	km	kg	EI g/kg	kg NOx	g/ASK	relative	EI g/kg	kg NOx	g/ASK	relative
2050	T&W	Jet A-1	7500	13890	86035	16.1	1388	0.241	datum	15.7	1263	0.220	datum
			3000	5556	31801	16.5	525	0.228	datum	15.7	434	0.188	datum
		Biofuel	7500	13890	84814	16.1	1369	0.238	99%	15.7	1247	0.217	99%
			3000	5556	31527	16.5	520	0.226	99%	15.7	430	0.187	99%
		LNG	7500	13890	92643	15.6	1447	0.252	104%	15.2	1326	0.231	105%
			3000	5556	34285	15.9	545	0.237	104%	15.2	458	0.199	106%
		LH_2	7500	13890	38200	20.9	794	0.138	57%	20.4	736	0.128	58%
			3000	5556	14865	21.5	320	0.139	61%	20.4	268	0.117	62%
	BWB	LH_2	7500	13890	24856	23.0	572	0.100	41%	22.0	514	0.089	41%
			3000	5556	10027	23.9	240	0.104	46%	22.0	193	0.084	45%

7.3 Cost and scenarios evaluations

Economic projections for operating costs are even more uncertain, particularly considering the costs of new fuels and the price of carbon credits to offset the remaining life-cycle emissions (CO_2 or $CO_{2\text{-equivalent}}$). In this study no cost penalties have been applied for the global warming effects of NOx or methane emissions, water vapour or contrails, but these additional factors could be significant if not mitigated by other actions, such as reducing cruise altitude when necessary to avoid flying through ice supersaturated regions. For the reported analyses the authors have relied on specialist opinion within their own organizations and engineering

judgement to provide assessments considered to be the 'best cases' for the different aircraft and fuels in Y2050.

The CASK estimates in Y2050 USD account for the cost reductions from improved aircraft technology, but they also account for long-term average inflation of 2% p.a. Currently annual inflation rates are significantly higher than this, but the ENABLEH2 study assumes this is a temporary state-of-affairs, so the original methodology has been retained. To avoid confusion the estimated Y2050 costs have been converted back to Y2020 USD in the following tables.

The Heightened Environmental Awareness (HEA) fuel costs scenario from deliverable D1.1 now appears the most realistic. It assumes a level of emissions charges, in whatever form in 2050 to be just sufficient to offset the higher cost of biofuel relative to the untaxed fossil fuel kerosene (Jet A-1). LNG, being historically less expensive than kerosene, and producing slightly less CO_2, is still predicted to offer a potential cost advantage both for the SMR aircraft and the LR BWB aircraft. However, this cryogenic fuel presents many of the same technical challenges as LH_2 without the benefit of eliminating all mission-level CO_2 emissions, so it is now considered unlikely to be widely adopted.

Anticipated real-terms manufacturing cost reductions and operational improvements would make air travel in 2050 less expensive when converted back to Y2020 USD, but in the HEA scenario air travel becomes more expensive in real terms because of the increased cost of hydrocarbon fuels, including charges to offset CO_2 emissions. Nevertheless, rising incomes from resumed economic growth and improved productivity should still keep air travel very affordable in 2050. The ENABLEH2 studies indicate that a transition to LH_2 fuel can make air travel even more affordable and sustainable in the long term. Table 13 and Table 14 summarise the operating cost assessments for the SMR and LR aircraft respectively.

Table 13: Operating cost assessments for SMR Aircraft with 200 Passengers in Single-Class Seating

EIS	Type	Fuel	MTOW	OWE	Range		Block Fuel	CASK (Y2020)	Fuel % of CASK
Year	-	-	tonnes	tonnes	nmi	km	kg	USD/ASK	-
2020	T&W	Jet A-1	97.0	53.1	900	1667	4680	0.058	15%
2050	T&W	Jet A-1	77.1	41.4	900	1667	3560	0.067	29%
		Biofuel	76.7	41.3	900	1667	3470	0.067	29%
		LNG	78.3	44.1	900	1667	3180	0.063	24%
		LH_2	78.6	51.3	900	1667	1530	0.065	25%
	CB2	LH_2	97.6	69.5	900	1667	1459	0.067	23%

Table 14: Operating cost assessments for LR Aircraft with 414 Passengers in Two-Class Seating

EIS	Type	Fuel	MTOW	OWE	Range		Block Fuel	CASK (Y2020)	Fuel % of CASK
Year	-	-	tonnes	tonnes	nmi	km	kg	USD/ASK	-
2020	T&W	Jet A-1	339.5	166.4	3000	5556	41200	0.062	18%
2050	T&W	Jet A-1	293.7	152.3	3000	5556	31801	0.076	34%
		Biofuel	296.8	154.8	3000	5556	31527	0.076	34%
		LNG	330.9	181.0	3000	5556	34285	0.076	32%
		LH_2	281.0	194.3	3000	5556	14865	0.077	30%
	BWB	LNG	269.8	165.5	3000	5556	19538	0.065	21%
		LH_2	248.6	173.5	3000	5556	10027	0.066	24%

7.4 Contrails

Aircraft flying at cruise altitudes are known to contribute to global cloudiness through the formation of persistent contrails. Persistent contrails, essentially thin line-shaped ice clouds, are formed due to mixing of the warm water vapor emitted from the engine with ambient air at low temperatures. This may then lead to local liquid saturation, followed by the condensation and subsequent freezing of water on ambient aerosols and engine exhaust particles (essentially soot). Contrails are created at high altitudes (above ~8 km), where the ambient conditions favour their formation. Contrails that last for more than ten minutes are referred to as persistent or long-lived contrails and those that exist for shorter periods of time are referred to as non-persistent or short-lived contrails [21]. Persistent contrails may also tend to spread and hence cover a large area, while no longer retaining their linear shape. Once they grow wider, they are referred to as contrail cirrus clouds. Persistent contrails and contrail cirrus clouds are known to cause an energy imbalance in the atmosphere between the incoming solar radiation and the outgoing infrared radiation, which can be quantified using metrics such as Radiative Forcing (RF) or Effective Radiative Forcing (ERF), both expressed in $\mathrm{mW\,m^{-2}}$. A positive RF indicates that heat is trapped in the atmosphere and will contribute to global warming [21]. As per current estimates the RF attributed to Contrail Cirrus is estimated to be 111.4 $\mathrm{mW\,m^{-2}}$ albeit, with a large uncertainty (33-189 $\mathrm{mW\,m^{-2}}$) and confidence levels indicated as low [22]. While the uncertainty in the estimation has significantly reduced over the years (±70%), the effect is still considered to be much higher than CO_2, which has an estimated RF of 34.3 $\mathrm{mW\,m^{-2}}$, with a significantly lower uncertainty and high confidence level in the estimation (31-38 $\mathrm{mW\,m^{-2}}$).

7.4.1 Contrail prediction and the Schmidt Appleman criteria

Within ENABLEH2, establishing the RF of the proposed technologies through contrail formation was considered beyond the scope of technology evaluation. However, based on the performance of the aircraft concepts at cruise, the potential of these technologies to produce persistent contrails was assessed using the Schmidt and Appleman criterion [23]

Based on this criterion, a thermodynamic model is used to predict the threshold temperature for contrail formation. This depends on the ambient relative humidity (RH), temperature (T) and the parameter G, which may be calculated using the following equation (Eq.5):

$$G = \frac{c_p\, p}{\epsilon} \frac{EI_{H2O}}{(1-\eta)Q} \qquad \text{Eq.5}$$

In the equation $c_p$is the specific heat capacity of air; *p* is the ambient pressure; EI_{H2O} is the water emission index (EI) of the fuel, or quantity of water produced per unit of fuel burned; ϵ is the molar mass ratio of water and air (0.622); η is the engine overall propulsion efficiency (which is a function of the true air speed and performance characteristics of the aircraft) and Q is the fuel heat value. The water emission index is an important parameter in the equation. For kerosene this parameter is ~1.26, which means the combustion of 1 kg of kerosene will produce ~1.26 kg of water, and when H_2 is burned in the gas turbine, the EI is ~9.0. However, it should be noted that Jet A-1 (43.15 MJ/kg) and H_2 (120 MJ/kg) have different lower heating values.

The contrail formation process is best represented on the water phase diagram [23], which plots the partial pressure of water vapour against temperature. The mixing process of the exhaust vapour with the ambient air is represented as a straight line (referred to as the mixing line) with parameter *G* defining its slope. In order to assess contrails, depending on the ambient conditions (temperature and relative humidity) at a required altitude and the magnitude of parameter *G*, the position of the theoretical / notional mixing line can be calculated, and consequently the contrail formation threshold temperature. According to the

formation process of contrails, liquefaction of water vapour is necessary for contrail formation. Therefore, if the slope is such that the mixing line intersects the water saturation curve, the vapour will condense into liquid form, and if the ambient temperature is lower than the threshold temperature, contrails will form.

If the conditions are such that vapour does not condense into liquid while mixing with ambient air, then contrails will not form. Once contrails form, if the ambient conditions are such that at the temperature, the prevailing vapour pressure is lower than the corresponding saturation vapour pressure with respect to ice (below the sublimation curve), the contrail is expected to be non-persistent. In this condition, ice crystals will sublimate soon after forming (ice sub-saturation condition). If, however, at the temperature, the vapour pressure is lower than vapour condensation pressure relative to water, but greater than vapour condensation pressure relative to ice, contrails forming will be persistent as the region will be considered as an Ice Super-Saturated Region (ISSR).

7.4.2 Transition to blends, pure synthetic fuel and biofuels

From the perspective of the performance of the propulsion system, the transition to pure synthetic and biofuels will influence the formation of contrails. These fuels are expected to contain no sulphur or aromatic species. This therefore could lead to reductions in soot and aqueous particles which are critical to heterogenous nucleation and ice particle formation. This, in turn, could have an impact on the number of ice crystals being formed because of fewer nucleation sites being available, the size of the ice particles, and in turn the optical thickness of the contrail. However, kerosene blends created using these fuels are expected to have only a moderate reduction in soot particle emissions and hence they are unlikely to hugely influence Aviation Induced Cloudiness (AIC) effects.

These expectations have recently been corroborated by work undertaken by DLR and partners through their flight test campaigns [24]. Within the campaigns, exhaust and contrail characteristics of an Airbus A320 burning low aromatic sustainable aviation fuel blends were measured and compared against results from kerosene-fuelled flights. The study provided evidence that burning low aromatic sustainable aviation fuels could result in a 50 to 70% reduction in soot and ice number concentrations and an increase in ice crystal size. This in turn was indicated to have less energy deposition in the atmosphere and hence could be attributed to less warming [24]

7.4.3 Utilising hydrogen fuel

Exhaust and contrail characteristics of engines fuelled with hydrogen have not been experimentally measured in flight, however based on theoretical research undertaken and the effects of lower soot content as seen in synthetic fuels, a hypothesis of what could be expected is suggested in literature.

When compared with kerosene, hydrogen has nearly three times the specific combustion heat and results in significantly higher quantities of water vapour in the exhaust (nearly 2.6 times for the same combustion heat). If the Schmidt and Appleman criterion were to be applied, this would result in the mixing line having a greater slope and hence much higher threshold temperature for contrail formation. Based on this, contrails could then be expected to form at temperatures typically 10 K higher, and consequently at lower altitudes.

Combustion of hydrogen produces no soot or sulphur emissions. Hence for heterogenous nucleation to take place and for the condensation of water to occur, the process would need to necessarily rely on the presence of ambient aerosols, which are usually several orders of magnitude lower when compared to soot particles in the exhaust. The lower number of nucleation sites would lead to the formation of fewer, but larger, droplets and consequently larger ice particles. These ice particles could be expected to exhibit a smaller optical thickness.

They could also be expected to descend to lower altitudes more rapidly and sediment earlier in comparison. While this could result in hydrogen-fuelled aircraft producing more persistent contrails and spreading to larger areas before evaporating, these contrails could have shorter lifetimes and lower optical thickness, and hence have lower overall environmental impact.

7.4.4 ENABLEH2 technologies and contrails

As part of the Technology Evaluation tasks within ENABLEH2, the conceptualized hydrogen-fuelled technologies were compared with some of the baseline technologies. Based on this analysis, the following observations are presented on the potential of technologies to produce persistent contrails:

- Except for the turbofan of the SMR Max Synergy concept, overall propulsion efficiencies of all the aircraft considered in the 2050 timeframe range between 40-50%. Hence, compared to technology with an EIS Y2020, these propulsion systems will extract more heat for propulsion. This will result in cooler exhausts and therefore will be expected to be more supersaturated for similar water vapour emissions. The turbofan of the SMR Max Synergy concept (when considered without the distributed fans) was found to have 30% efficiency.
- The H_2-fuelled aircraft do not produce any soot. Heterogenous nucleation process for contrail formation would need to rely on prevailing atmospheric aerosols. These as indicated earlier will be orders of magnitude lower than soot particles and hence could be expected to have a significant impact on ice crystal number, size, shorter durations of persistence and lower optical density.
- At the appropriate environmental conditions at cruise (low temperatures and RH above 59-60%), all aircraft have the potential of forming persistent contrails.
- The ENABLEH2 LH_2 concept aircraft investigated include the low risk and max synergy concepts for SMR and only the low-risk concept for LR application. The contrail parameter G for concept aircraft was found to 2.1-2.4 times that of kerosene or biofuel-fuelled concepts and 1.4-1.9 times that of the LNG-fuelled concept. This results in higher threshold temperatures (~8-9 and 3.3-4.5 degrees higher for kerosene/biofuels and LNG respectively) and hence these technologies will have the potential to form contrails at lower altitudes. These could range from 4000-4650 ft and 1700-3500 ft lower, when compared with baseline kerosene/ biofuel technologies and LNG-fuelled concepts respectively. This difference between LNG and kerosene-fuelled concepts is attributed to LNG having a higher LHV and EI and additionally the propulsion system having a slightly lower SFC.
- The parameter G was not calculated for the fuel cell powered distributed fans on the SMR max synergy aircraft (CB2), however the fuel cells powered propulsion system will be expected to produce a significantly large amount of overall thrust (>~85%). For every kg of H_2 consumed by a fuel cell, ~9kg of water will be produced and the water production rate will be proportional to the output power. The water in the exhaust will be at much lower temperatures (333-353 K) when compared with the water vapour at the exhaust of a gas turbine [25] [26]. Based on expected water emissions from fuel cells, Girens [26] has theoretically investigated the potential of contrail formation and suggested a variant of the Schmidt-Appleman theory.
- The research indicates that the calculated contrail factor G will be significantly larger than for Jet A-1. As expected, and similar to the hydrogen fuelled gas turbine, contrails from a fuel cell-based propulsion system could occur in the lower stratosphere and would be unavoidable in upper troposphere and stratosphere. However, similar to vapour emissions from hydrogen-fuelled gas turbines, in the absence of soot and given the significantly lower number of nucleation sites (primarily atmospheric aerosols), they will be expected to remain persistent for significantly shorter periods of time, would be optically thinner and have shorter lifetimes, when compared with persistent contrails formed by kerosene fuelled gas turbine propulsion systems [26].

7.4.5 Contrails from H_2-fuelled aircraft – recommendations for further research

During the technology evaluation process, reviewed literature provided a theoretical basis and thermodynamic perspective for a hypothesis to be formed, however significant further research is required. From the perspective of modifying trajectories of H_2 aircraft to avoid contrails, the studies undertaken in ENABLEH2 utilised a contrail prediction model based on the Schmidt Appleman criterion to analyse the contrail formation potential of hydrogen fuelled aircraft. As the criterion implicitly assumes the presence of soot particles in the exhaust, the assumption was made that in the absence of soot particles, ambient aerosols which are orders of magnitude lower, would facilitate heterogenous nucleation. This is expected to have a significant impact on size and number of ice particles being formed, their optical density and persistence characteristics. Given the significantly larger amount of water vapour produced by the hydrogen fuelled ENABLEH2 aircraft concepts assessed and when compared with kerosene fuelled aircraft, the contrail formation threshold temperatures were found to be higher, and hence contrails are expected to form at lower altitudes. Recommendations for further research include:

- Improved numerical modelling and validation through research/experimental flight testing to improve prediction models. Specifically, assessments of the effect of the absence of soot and its consequent effect on the size and number of ice particles being formed, their optical density and persistence characteristics needs to be undertaken.
- Mission level assessments of contrail avoidance trajectories. This should include quantitative assessments of the fuel burn penalty incurred by a hydrogen fuelled aircraft to avoid (ISSR) regions conducive to formation of persistent contrails.
- Given the significantly higher threshold temperatures, feasibility assessments of modified trajectories (to avoid ISS regions) from an ATM perspective.
- H_2 fuelled aircraft may have differently shaped airframes and fuselage structures (Double-bubble, BWB etc.) and hence the analysis of the fluid dynamical effects the wake (of the aircraft) will have on the evolution and formation of contrails.
- Contrails from H_2 fuelled aircraft are expected to remain persistent for significantly shorter periods of time, will be optically thinner and have shorter lifetimes and hence the climate impact of a hydrogen fuelled aircraft fleet needs to be assessed.
- The thrust at cruise for future aircraft, especially for SMR aircraft where thrust could be provided from disparate systems. Such designs are exemplified by the Cobalt Blue 2 concept aircraft that combine turbofans with fuel cell powered distributed fans.
- A better understanding of the following is required:

    - *Feasibility of collection and temporary storage of water:* As suggested in reference [25], water produced by the fuel cell at cruise altitude could either be released immediately or stored temporarily. Temporary storage of the water could enable jettisoning at a specific location/altitude which would be non-conducive to persistent contrail formation. The implications of such a collection and storage system on mission level performance needs to be better assessed.
    - *The state of the water when released:* This would largely depend on the altitude (and corresponding pressure) at which it is released. However, if water droplets, even a few micrometers in radius were to exist and be released at cruise, in supercooled conditions they could freeze in the absence of any ice nuclei through homogeneous ice nucleation, which essentially requires temperatures ≤ −39 °C (> ~FL300 @ ISA).
    - *The location of the exhaust for the release of the water from the aircraft*: This would influence how the released water would interact with the wake of the aircraft and the exhaust of the gas turbine, if the aircraft were to have more than one type of propulsion system generating thrust. The point of release could influence the overall mixing process with the wake and consequent formation of contrails.

8 Transport modes – a comparison

The largest consumer of hydrogen will be civil aviation, and typically, more than half the hydrogen produced will need to be stored as a cryogenic liquid to use for propulsion. It is opined that fuel cells will be useful in a fraction of land transport (much will be electric), small ships and aircraft. Hydrogen-fuelled gas turbines will be primarily used on large ships (via combined cycle gas turbines), medium to large airplanes and land-based power generation applications. This section considers the various options available to the aviation industry to access hydrogen at scale. During the ENABLEH2 project, the options and interest in hydrogen has extended enormously. It is now seen as the energy vector of choice by many heavy-duty mobility applications and hard to abate energy uses. Given the EU's Fit-for-55 goals [27] and the more recent REPowerEU [28] package, the EU has made hydrogen a central pillar of its future energy policy to achieve its net zero goals.

8.1 Hydrogen supply pathways

Given this context, ENABLEH2 has examined the various options of hydrogen supply open to an airport and assessed their suitability. High level technology and market status is initially outlined. The report focuses on a specific geography to provide actual scenarios. The case study of Heathrow Airport, London is explored. As the seventh largest airport hub in the world, it will require both scaled up supply and supply security. This report provides insights on how this can be achieved using expected supply chain pathways and compares the various elements which comprise their overall CO_2 footprint.

In keeping with the theme of ENABLEH2, the requirement for hydrogen liquefaction is central – both in terms of the technical emphasis on energy density and the need for geographical location near the airport. As liquid hydrogen (LH_2) pipelines are currently technologically unfeasible over long distances due to the need to cryogenically cool the pipeline – a feat which is expensive and untested over long distances – co-location of a liquefaction plant(s) at an airport allows for the most logical production and distribution scenario available today. Due to the expected demand for LH_2 by an airport the size of Heathrow, trucking over extended distances would require too many vehicles and journeys to make the scenario economically feasible. For smaller regional airports, however, this could be considered. Figure 8 provides a schematic depicting typical hydrogen supply pathways.

8.1.1 Hydrogen global trends

To understand the language of the hydrogen energy sector, one needs to understand the environmental impact of the various production processes for hydrogen itself. The community has divided the different production pathways into a series of bands which are characterized by different colours (Figure 9). There are three main 'colours' of hydrogen you will regularly hear about today – grey, blue and green. Grey hydrogen is hydrogen created with from fossil fuel derived processes, most commonly steam methane reformation, and has one of the highest carbon footprints. Blue hydrogen is also created from fossil-fuel derived processes but, in this case, the carbon emissions are captured and stored, and, in the best scenarios, used and locked-in in other processes such as cement production. Whereas green hydrogen is made from renewable energy, typically through the electrolysis of water, thus meaning it has no associated carbon emissions.

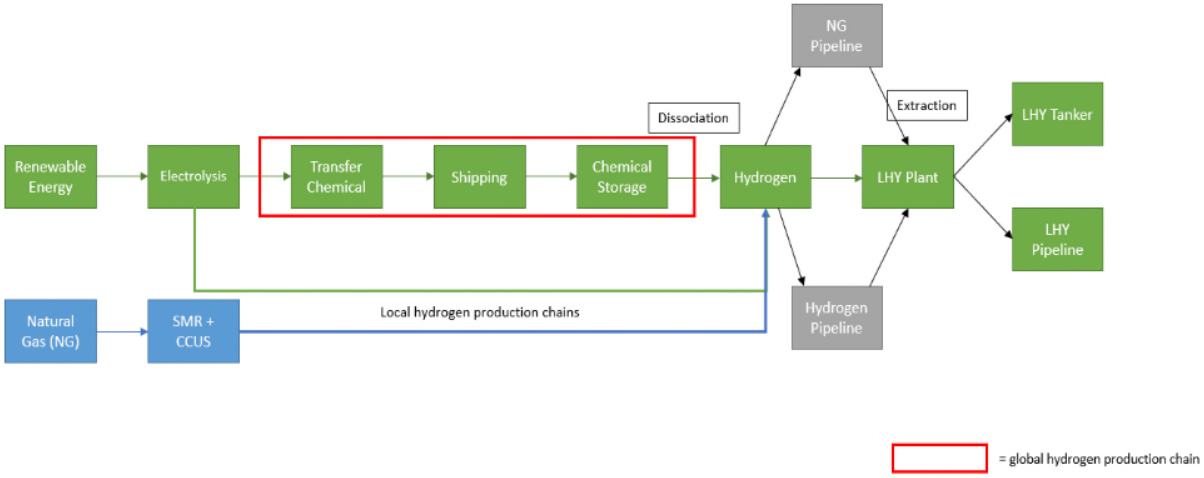


Figure 8: Hydrogen supply pathways

The goal of major European economies is to move away from the use of grey hydrogen and towards these two alternatives as a way to avoid CO_2 emissions, particularly for their industrial processes. Blue hydrogen production will be favoured by countries that have access to geological features that can be used to store and sequester carbon dioxide, such as the UK and Norway with their access to exhausted oil formations in the North Sea. Whereas green hydrogen will be produced by those with overwhelming renewable resources, primarily wind and solar, such as Spain and Portugal.

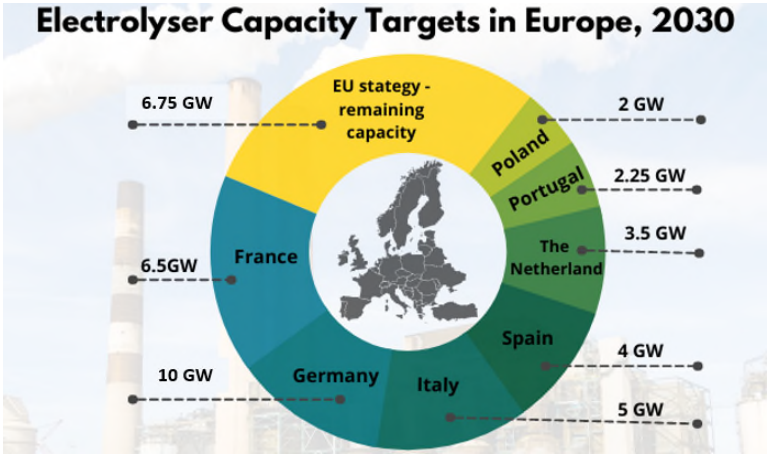
Many countries have put in place hydrogen strategies which aim to chart the development of hydrogen production and applications in the near term. These strategies will provide impetus for public funding support and will be kept under review.

Source: EnergyVoice, The colours of hydrogen: what does 2022 have in store?, December 2021

Figure 9: The Hydrogen Rainbow

8.1.2 Electrolysis

The EU electrolysis capacity pipeline is really starting to gather pace towards the EU target of 40 GW [29] of capacity now proposed by 2030 (Figure 10) including an exponentially rapid acceleration of project announcements in the last 12 months. According to the IEA, Europe is leading the way with planned electrolyser developments, with 40% of those expected globally in the continent [30].



Source :Prospero Graphic

Figure 10: Electrolyser capacity targets set for 2030

For Europe, the production capacity increase was initially based around two principal scenarios:

– Areas in which renewable resources are readily available, leading to the production of the lowest cost green hydrogen possible – primarily through the deployment of solar and on-shore and off-shore wind technologies.
– Areas of high hydrogen demand, such as in Netherlands and Germany who not only lead the EU in hydrogen consumption but are also key early movers in enabling a European green hydrogen economy.

However, the size of the demand required by the latter of these scenarios is so overwhelming that the development of a European-, or even globally-, wide electrolysis network will occur over the next decade in order to satisfy their needs, simultaneously providing a suitable scale-up opportunity for the sector. Whilst, the EU is leading the way in this field, both in terms of size and innovation, currently there remains 11.75 GW required in the medium-term to 2030.

Innovation in the electrolysis sector has been a key focus for the European hydrogen sector for some time, simultaneously driving increases in efficiency and the size of these systems in order to achieve large-scale emission savings across the continent. This has led to the evolution of several electrolyser technologies, each with their own unique set of advantages and disadvantages. As the most mature of the options, alkaline electrolysis, which has been used for well over 100 years, has until recently, been the go-to electrolysis technology due to its reliability and scale. That is until Proton Electrolyte Membrane (PEM) electrolysers entered the scene, which, due to their increased efficiencies and operability, have gained significant momentum. Come 2025, the majority of projects installed will feature PEM electrolysers – a change that materialised in just five years – whereas alkaline dominated in 2020.

Despite the technological expertise that the EU possesses, there are still a number of pinch points occurring in the project and supply chain of these technologies. Electrolyser companies are building capacity through the creation of ‘Giga-Watt’ scale production facilities to deliver

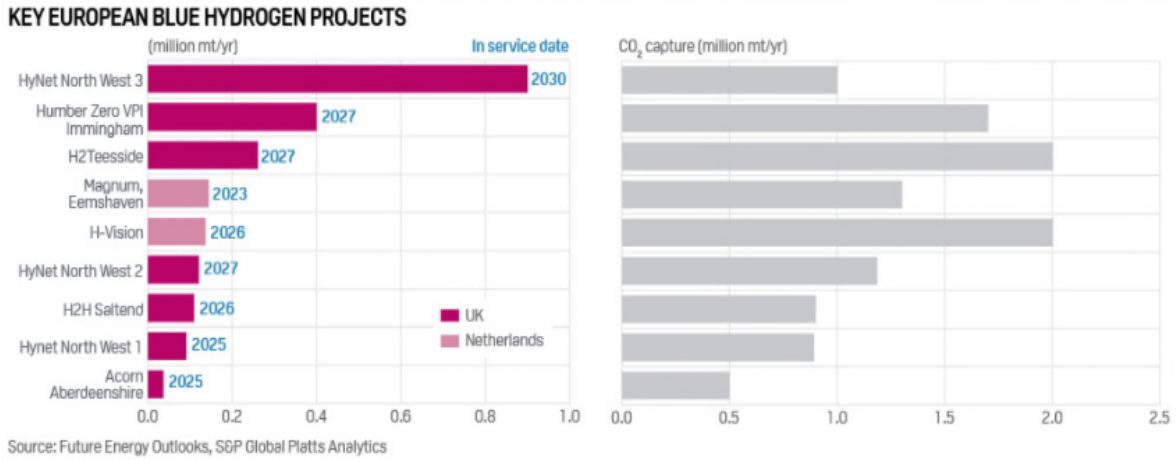
this demand expansion. In project terms, there is an order of magnitude scale-up of electrolysers being planned. Investment in these facilities is proving challenging from traditional financial institutions perspective due to the enhanced risks involved. So, with the extra impetus provided from the COVID-19 pandemic and the need to reduce energy imports, as well as commitments made at COP-26, the development of associated renewable and hydrogen investment funds has emerged in the last 12 months as a key financial mechanism, for not only an increase in emissions reduction, but also growth of economies in the wake of the pandemic.

8.1.3 Methane reforming with carbon capture utilisation and storage

The European Commission has placed much less emphasis on blue hydrogen production than on green. This route is seen as a potential interim solution for 'buying-time' – significantly reducing emissions through the use of large-scale Carbon Capture Utilisation and Storage (CCUS) opportunities whilst waiting for green hydrogen technologies to significantly reduce in cost.

However, it is worth noting that given the recent global developments, countries are starting to recognise the pace at which they must act in order to achieve net-zero targets. For instance, Germany's new coalition government has revised the country's hydrogen targets, not only doubling previous green hydrogen ambitions (now 10 GW of electrolysis capacity by 2030 [31]), but also taking a technologically neutral approach – allowing blue hydrogen, and other alternatives, to play more of a role in the scale up of their hydrogen economy.

Some European countries are already investigating the large-scale possibilities of the blue alternative, namely the UK, Netherlands, and Norway. With their historic fossil-based energy reserves, these countries have suitable geological structures which can be used to store the emitted CO_2. For example, Equinor of Norway have announced that they see a role for blue hydrogen beyond 2050 with the company claiming they can potentially supply 10% of Europe's low carbon hydrogen across three to five of their 'industrial hydrogen production hubs' by 2035 [32]. In the UK, the government are targeting 5 GW of low-carbon hydrogen by 2030, which includes both green and blue hydrogen, in what they dub a 'twin-track approach'. Several blue hydrogen projects (Figure 11) are underway to help achieve this goal with considerable government support in the form of a £1bn CCUS fund.



Source: Hydrogen fever in EU puts 2024 target of 6-GW electrolyser capacity in reach. July 2021.

Figure 11: Notable blue Hydrogen developments in Europe

Despite CCUS' increased maturity when compared to electrolysis, there are still a number of challenges the production pathway needs to overcome in order to truly rival grey hydrogen production.

– CCUS technology is available 'at-scale' today, however, the capture rates being achieved need to be increased to maximise emission savings – the percentage of CO_2 captured in comparison to the total CO_2 produced. Currently, these capture rates stand at roughly 90% for new deployments, however, according to the IEA there are no physical limitations inhibiting the establishment of capture rates >90%, it will just take more time, research and investment to realize these improvements.
– The production of blue hydrogen is highly dependent on natural gas prices, which, with great fluctuations recently, can have a large effect on the levelized cost of hydrogen produced.
– Furthermore, with the use of fossil-based feedstocks, blue hydrogen production costs are left liable to increases in carbon taxes too – making this option less attractive to investors. However, it is highly unlikely that these factors will scare the financial community permanently from blue hydrogen investments, given the bankability of its mature production methods.
– Finally, there is little opportunity for cost reduction potential relating to CCUS and steam methane reforming in comparison to the green hydrogen pathway. Both these technologies are considered to be relatively mature and the major advancements available, such as capture rates as previously mentioned, are unlikely to result in large cost savings. Whereas electrolysis has a number of research areas which will result in price decreases – such as electrolyser cell and stack costs, and balance of plant scale-up savings.

However, if this infrastructure is to become a mass-deployed solution, then the advent of a European hydrogen certification system will be necessary to quantify the carbon-quality of the hydrogen injected into the network, to accurately address carbon emission savings. This will require the establishment of common metrics and an industry-wide life-cycle assessment approach, as has been developed by the CertifHy [33] project, which, in the case of fossil-fuel feedstocks, will need to take CO_2 capture into account.

8.1.4 Hydrogen pipeline infrastructure

Although seen to be one of the most difficult sectors to decarbonise, reducing emissions from heat is one of the key long-term drivers for hydrogen as an energy carrier. The potential hydrogen demand from this sector has been projected to dwarf the amounts required for mobility including aviation. Existing power grids are not capable of transporting additional intermittent renewable energy without robust reinforcement, and with Europe trying to reduce their reliance on natural gas, green hydrogen pipelines have gained considerable momentum in the past few years to enable decarbonisation to continue at pace. This will have a knock-on effect for the wider hydrogen sector – pipelines will offer a suitable, cost-efficient opportunity to store and transport hydrogen to a variety of applications, including key transport hubs such as along Trans-European Transport Network (TEN-T) networks and at airports.

Trial projects testing concepts and technology, have already shown promise across a number of European countries. In the UK, the HyDeploy [34] project has been trialling 20% hydrogen mixed with natural gas on Keele university's campus (30 faculty buildings and 100 domestic properties). A follow up project is already running where many homes will be connected to the mixed gas supply. Similarly, in Leeds, the H21 project [35] has positively assessed the techno-economic viability of converting the gas grid in the North of England to 100% hydrogen. Other industrial cluster hydrogen supply projects have followed. New hydrogen extraction technologies are being trialed, by Linde and HyET [36] amongst others, to allow these mixed

gas systems to be used as 100% hydrogen supply systems. As these trials have proven successful, focus has migrated to shaping policy surrounding the transition strategy and safety codes that need to be in place to enable a widespread deployment of such technology.

Elsewhere in Europe, Gasunie and other natural gas transmission system operators (TSOs) have been considering where hydrogen can be utilised within the gas energy mix. Initially, they focused their research on both the need and mechanisms for the storage of sufficient quantities of hydrogen within the TSO2020 project [37]. Within the HEAVENN project [38], this activity has been taken further with the cavern storage solution being trialed. Across Europe these principles are being tested from supply to application right through to the public. As an example, also within HEAVENN, the municipality of Hoogeveen is looking at building new hydrogen energy homes, as well as retrofitting some existing natural gas supplied housing with pure hydrogen. There are further studies underway to repeat and expand on the experience gained within these initial demonstrations across wider European regions.

From an overarching perspective, in July 2020, several European gas TSOs came together to produce a vision document for the European gas sector to tackle its role in the energy transition – The European Hydrogen Backbone [39]. Hydrogen can enable a reduction in emissions throughout Europe by offsetting the use of natural gas whilst maintaining a similar framework to what is used today. The plans utilise existing gas pipelines to blend hydrogen in higher percentages, potentially up to 100% hydrogen with only minor modifications. The costs associated with this opportunity are relatively low in comparison to other alternatives too – repurposed old pipelines are predicted to require roughly 1/3 of the capital vs building specialised hydrogen analogues. This vision document focuses on linking demand sites, such as industrial clusters, with areas of peak hydrogen generation to establish an initial demand for hydrogen and then focusing on building up regional areas around these key hubs. An updated hydrogen backbone report was released in April 2022, which was the result of additional TSOs becoming aware of the potential for hydrogen and at the same time the EU positioned its Fit-For-55 [40] and REPowerEU initiatives. Now the vision covers 28 interconnected countries, likely ensuring hydrogen has solidified its future heating role as well as creating a mechanism for widescale hydrogen transmission. The paper concluded that the cost of such a continent-wide network would cost €80–143 billion with completion possible by 2040, and an annual demand in excess of 1,640 TWh expected.

The EU has recognised the key role such a hydrogen network could play in moving hydrogen from primary production locations to specific demand centres. Given the size of demand heating poses, and the relative ease with which pipelines could be transitioned, this solution could be deployed across the continent, as well as further afield towards Northern Africa and the Middle East, as is being explored.

These pipelines will be crucial to enabling the wider roll-out of low- and zero-carbon hydrogen as they enable dislocation of production and hydrogen applications via cost-efficient storage and distribution. Further variations on this concept are also being explored, such as Gasunie's hydrogen ring for the Netherlands. The ring, which would connect the country's main industrial clusters and run close to major transport routes, hubs – including Schipol – and cities, will distribute 97-98% purity hydrogen to customers whilst also behaving as an energy storage mechanism for hydrogen produced from renewable energy.

Should this hydrogen be required for fuel cell use, further purification will be required, however, its use for heat and industrial processes is not likely to require this upgrading. This concept has been futureproofed to allow for considerable industrial scale-up as further activities are undertaken by the linked clusters. However instead of a purely industrial focus, the ring is likely to scale-up to include alternative sectors such as aviation – which in the case of Schipol would represent a very proximal addition to the current Amsterdam cluster. Adding Schipol

would represent a reasonably modest increase in terms of volume in the short-to-medium term, in comparison to the large demand required by industrial hubs, with a reasonable proportion of flights being switched to other lower-emission alternatives (i.e. SAFs) therefore not materially impacting the supply capcity of the network. The only downside to this pipeline network is the need to implement hydrogen purification or blend splitting infrastructure to enable fuel cell applications. Airports will be able to couple such a pipeline connection with other necessary infrastructure, such as liquefaction, as described in the following sections, to meet their needs for liquid hydrogen as a fuel.

8.1.5 Hydrogen liquefaction plants

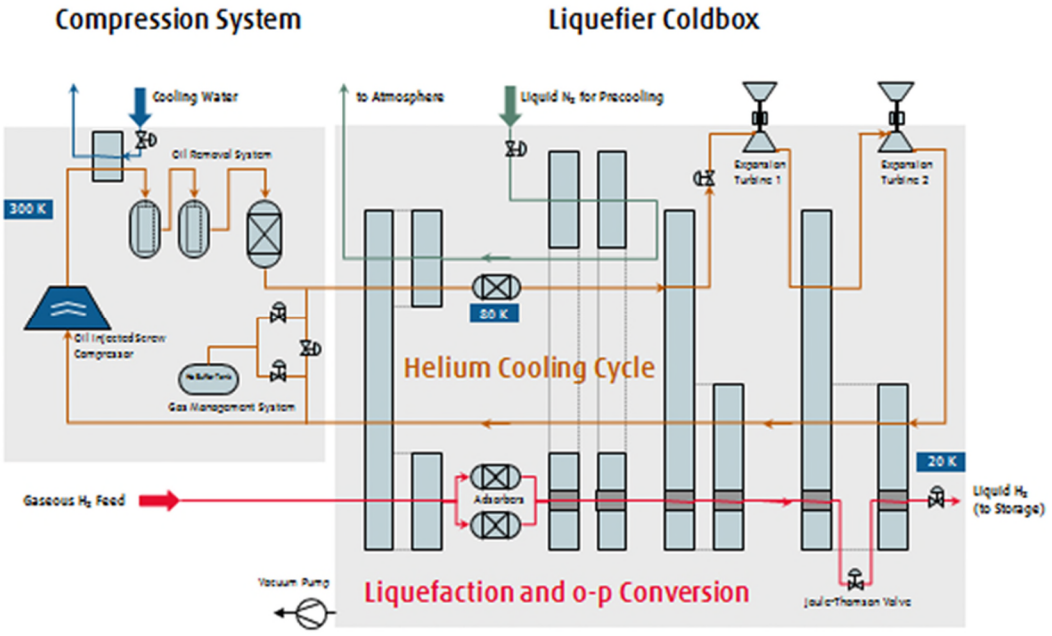
In order for hydrogen to suitably cover the needs of the aviation industry, it will need to be converted into its liquid form to provide a sufficient power-to-weight density to fuel aircraft. The most efficient and cost-effective way to produce hydrogen remain gaseous, and thus, to adequately service the needs of the aviation industry, large liquefaction plants to produce the amount of liquid hydrogen (LH_2) will be required. Feasibly, these plants could be based anywhere that had enough space and cooling water – whether that be the airport or elsewhere nearby with the LH_2 distributed to the airfield via a short pipeline network.

LH_2 has been used as a flight fuel since the early days of the NASA space programme. This technology race enabled industrial gas companies to develop stable large-scale processes which aligned to NASA's demand. These companies saw advantages in using LH_2's increased density to reduce transportation costs for their other hydrogen businesses so multiple LH_2 plants were developed across the US in optimised locations for the customer demand. In Europe, shorter transport distances due to increased gaseous hydrogen source density, meant that LH_2 plants did not achieve the same impact, with only three relatively small plants being deployed until recently.

Green LH_2 has received very little consideration within a European geography aside from specific applications in industry. However, with the realisation that hydrogen can be effectively used to decarbonise heavy duty vehicles, and more specifically aircraft, interest in LH_2 has been increasing. It offers roughly double the energy density of 500 bar gaseous hydrogen, thus increasing the efficacy of zero-emission heavy-duty transport by increasing range whilst decreasing the fuel's effect on payloads – which is where batteries fall down.

A hydrogen liquefier essentially consists of two process systems – compression and a cold box (Figure 12). There are different configurations for the cooling cycle. Cold is introduced via the use of liquid helium and nitrogen and via expanders which serve to cool the hydrogen gas flow. The system is not excessively large in footprint terms, readily accommodated within large scale hydrogen production facilities.

Hydrogen gas is provided from any production method suitable for clean scaled operation. Today industry favours steam methane reforming due to historic lower costs. The liquefaction elements can be placed remotely from the hydrogen production source and connected by gaseous pipeline. This is one of the anticipated methods which could offer airports local liquefaction. The interconnection of planned hydrogen pipeline networks to various remote hydrogen sources increases overall supply security. Multiple liquefaction trains deliver the equivalent redundancy locally for LH_2 production as volumes grow.



Source: Brayton Cycle

Figure 12: Hydrogen liquefaction system

This large-scale hydrogen infrastructure is currently in its infancy, however, as can be seen from the potential Schiphol connections highlighted previously, plans are being developed. The likely timeline for hydrogen pipeline delivery should be expected to be longer than that of the delivery of LH_2 infrastructure. However, this will be dependent on available space around the airport and ease of permitting.

Currently, some of the largest LH_2 production systems worldwide are based in Asia, with facilities reaching 13,000 tonnes/annum set to come online by early 2023 [41]. These production plants can produce 30-50 tonnes LH_2 per day, with some newly announced plants reaching 100 tonnes LH_2 per day courtesy of industrial gas companies. These plants will not be large enough to satisfy the growing demand for LH_2 from both aviation and the heavy-duty mobility market. In fact, the heavy-duty hydrogen trucks are at the head of the queue in terms of hydrogen sector momentum today, and so are likely to require a secure hydrogen supply much more quickly than aviation does – in the region of 100's tonnes LH_2 per day in the medium-term. According to the recent Clean Sky 2 report, the initial steps of hydrogen deployment within aviation will see a requirement for 5 and 10 tonnes LH_2 per day by 2035 and 2040 respectively for their varying decarbonisation scenarios; representing 5,000 and 40,000 tonnes LH_2/annum for regional and international airports respectively [42].

For low- and zero-carbon hydrogen, this is not currently possible worldwide today, let alone in Europe. However, with the REPowerEU hydrogen production plans, momentum is accelerating and by the middle of the next decade multiple large scale hydrogen production projects with interconnecting pipeline infrastructure will be online. The aviation industry needs to engage in planning its needs and infrastructure well in advance, likely starting today. Aviation will need to develop airport-centric supply scenarios and these will need significant vision and development, as currently seen in airports such as in Paris. There will be significant increase in optimisation and demand for LH_2 technology companies across the mobility sector. Stepping into the hydrogen supply planning debate early will enable airport infrastructure to become recognised in the same way that seaports have emerged as key energy transition hubs. Creating supply not just for airside mobility but for all airport mobility and beyond into the surrounding region.

8.2 Hydrogen supply to an airport

8.2.1 Hydrogen production

This study primarily considered two types of hydrogen production green hydrogen, and low-carbon hydrogen, defined as follows:

– Green (renewable and low-carbon) – hydrogen that has no associated carbon emissions during the production process, often utilising renewable energy (e.g. wind/solar/hydro) or some allowed biomass based feedstocks as defined by the second European Renewable Energy Directive (RED II). CertifHy, the European hydrogen Guarantees of Origin scheme, defines this as renewably produced hydrogen with emissions that are at least 60% lower than the fossil-feedstock carbon intensity benchmark (91g CO_{2eq}/MJ H_2 [33]).
– Low-carbon (non-renewable and low-carbon) – hydrogen that originates from non-renewable, nuclear or fossil-energy sources often deploying CCUS technologies. To be classified as low-carbon, CertifHy also requires this methodology to have at least 60% lower emissions than the fossil-feedstock carbon intensity benchmark.

Green hydrogen is most commonly produced via electrolysis using renewable electricity. Electrolysers, the equipment which carries out this process, come in many varieties but operate on the same basic principle – they split water into its constituent elements, oxygen and hydrogen, through the introduction of an electrical current. ALK and PEM electrolysers are the two most advanced technologies available in today's market – with the former having been operated for over 100 years and the latter rapidly gaining market traction thanks to increased investment for scaled up manufacturing, particularly in Europe. Table 15 provides an indication of the expected increases in efficiency from electrolysis technologies in the next 30 years. Almost all GHG emissions associated with green power-to-hydrogen pathways are CAPEX-related and the emissions are expected to reduce over time as efficiencies increase.

Table 15: Expected increases in efficiency from electrolysis technologies in the next 30 years

	Alkaline (ALK)		Polymer Electrolyte Membrane (PEM)	
Year	***Efficiency (LHV)***	***Stack lifetime (1000 h)***	***Efficiency (LHV)***	***Stack lifetime (1000 h)***
2020	63-70%	50-90	56-70%	30-90
2030	63-72%	72.5-110	61-72%	60-90
2050	70-80%	100-150	67-80%	100-150

Source: Guidehouse and Tractebel Impact. Hydrogen Generation in Europe. July 2020.

However, in comparison, the manufacturing of fossil-based hydrogen (e.g. from steam methane reforming) involves large operational GHG emissions. For instance, according to a report by the Hydrogen Council [43], hydrogen production utilising solar, wind and hydro renewable energy resources will only emit 0.3-1 kg GHG/kg H_2 by 2030, considerably less than the conventional steam methane reforming route over the same time (11 kg GHG/kg H_2).

Currently most small electrolysis systems are connected to the grid. They are deployed in demonstration projects where operational run hours are important to generate data for OEMs, funders and project developers. Hydrogen applications traditionally need continuous, reliable production which, at a small scale, is difficult to achieve in the face of renewable intermittency. Currently, this is more GHG emitting than fossil-based pathways, such as steam methane reforming, due to the cleanliness of global energy matrices and their reliance on fossil fuels, but as electricity production sources are further decarbonised in the race to cut emissions, this will become a viable route of producing low-carbon or green hydrogen depending on their carbon intensity.

The scaled-up electrolysers of tomorrow will be renewables connected and coupled with suitable network storage solutions offered by line packing, salt caverns and use of other molecules. These systems will offer world-scale hydrogen production with intermittency removed by the storage solutions deployed. The use of electrolysis as an energy demand balance can also offer the electrical system enhanced robustness to facilitate increased access to renewables. This is only possible assuming the cost of electrolysis reduces exponentially as forecast. Most studies are predicting rapid cost reduction as production scales to meet new project demand. The rate of reduction is particularly interesting when assessing the commerciality of blue hydrogen pathways.

Blue hydrogen pathways offer considerable carbon emission savings at scale, with capture rates of 90% reducing GHG emissions by roughly 65%. If these capture rates can improve to 98% they can achieve savings of 90% when deployed with autothermal reforming technologies. However, blue pathways require geological structures to store the CO_2. These are not always available. In addition, whilst the building blocks of CCUS are relatively mature their deployment as a single system, at scale in typically marine environments, is less developed. As with electrolysis there are examples which need adaptation and wider application.

In addition, whilst steam methane reforming and CCUS technologies are cheap and available at scale, their use of fossil-based feedstocks, particularly natural gas, leaves them heavily-liable to potential changes in commodity prices – such as the extreme spiking in natural gas prices that has been experienced in recent years. Furthermore, both their feedstocks and the cost of their product, could be affected by carbon taxes across the world, as communities look to install policy measures that incentivise decarbonisation.

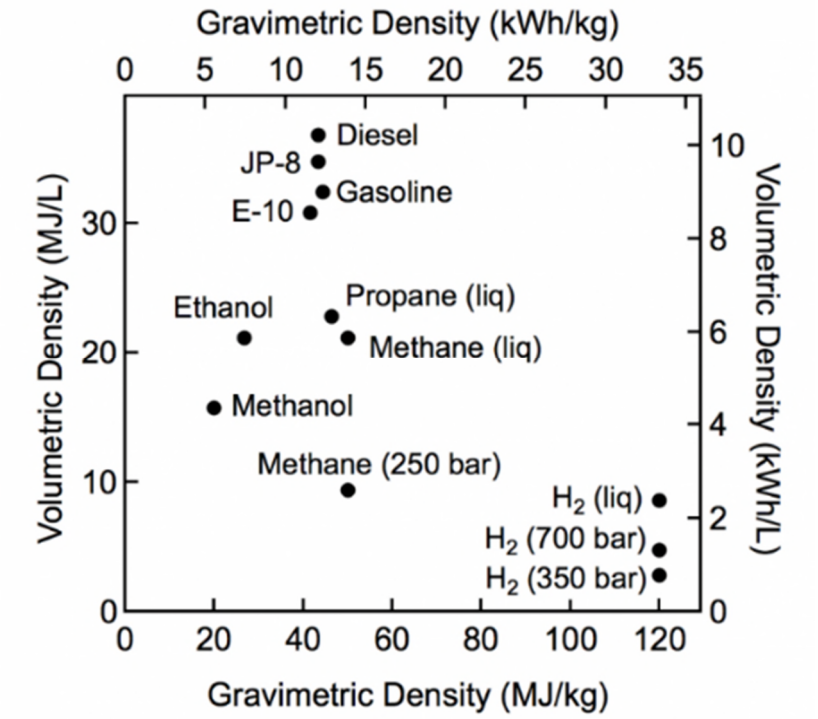
Therefore, blue hydrogen is an efficient carbon-emission-saving hydrogen production pathway, however, its longevity as a *cost*-efficient pathway in the long-term is yet to be seen, especially if the expected electrolysis cost reduction curve is achieved. Most believe, where storage is available, such as in and around the North Sea, blue hydrogen will play a significant role in enabling the scale-up of green hydrogen by ‘buying time’ for fully renewable supply chains to scale. Therefore, blue hydrogen facilities are likely to see geographically-led deployment in the near term with developers and investors watching the UK and European regulatory landscape.

8.2.2 Regional transmission of hydrogen

Whilst hydrogen is a very energetically dense molecule, much more so than that of conventional fossil fuels such as diesel or gasoline, hydrogen has very poor volumetric density due to its low molecular weight – making it difficult to store in manageable, high-pressure containers without high capital and operational costs, especially in its gaseous form. Due to this, many international projects are choosing to convert hydrogen into different forms to make it easier-to-handle and more cost-efficient to transport over long distances. Figure 13 provides an overview of hydrogen's gravimetric and volumetric density in comparison to other fuels. These options include:

Ammonia – Certain chemicals can behave as a hydrogen carrier and release hydrogen when it is required. Ammonia has a number of suitable characteristics that make it ideal for such a role. Not only does ammonia have a high hydrogen storage density (17.7% gravimetrically and 123 kg/m^3 in its liquid phase when stored at 10 bar) but it is also a regularly handled and traded material worldwide, due to its importance in fertiliser production. Therefore, by transforming into ammonia, hydrogen can access regularly used, and regulated, frameworks in order to enable transfer of large amounts of hydrogen across borders – without any carbon atoms entering the supply chain. In addition, Ammonia is also being developed as a marine

fuel with engines being adapted and first systems being demonstrated. This would allow ammonia to enhance hydrogen's ability to decarbonise hard-to-abate energy needs.



Source: Office of Energy Efficiency & Renewable Energy. Hydrogen Storage.

Figure 13: Hydrogen's gravimetric and volumetric density in comparison to other fuels

However, one of the largest challenges facing the use of ammonia, when a final hydrogen molecule is required, is its dehydrogenation process – in order to obtain full dissociation (of the nitrogen and hydrogen in ammonia molecules) temperatures in excess of 650°C [44] must be used, with available catalysts being very expensive for use in large-scale scenarios, and alternatives requiring even more strenuous operating conditions (>900°C for nickel catalysts). These systems exist for metals industries today but not at scale or purity, so technical development and scaling is required.

However, this has not stopped the development of global energy projects investigating the use of ammonia as an energy and hydrogen transfer mechanism. These projects, which have been developed with the goal to save carbon emissions, have been extremely popular in Australia and the Middle East as a means of transitioning from their fossil-dominated positions to a more sustainable alternative. One such example is in NEOM – the planned zero-emission megacity based in Saudi Arabia – where Air Products and ACWA Power have signed an exclusive $5bn deal to produce 1.2 million tons of green ammonia, from green hydrogen, per year, set to be on stream by 2025. Air Products will be the exclusive distributor of this product and intends to transport it around the world, where it will dissociate back into green hydrogen for sale into the transport market. Both the conversion and dissociation of hydrogen to and from ammonia has associated energy and efficiency losses, in its creation and distribution, and thus this pathway is likely only suitable for large scale processes that can cope with such losses without significantly impacting production quantities and margins. Table 16 provides indicative costs associated with the transformation of Hydrogen.

Table 16: Costs associated with the transformation of hydrogen

Conversion process	Unit	Min	Max	Comment	Source
H_2 to Ammonia	€ (2019)/ MWh_{H2}	27	27	Approximate number, small variations can arise due to cost of electricity in different countries	IRENA, 20219
H_2 to LH_2	€ (2019)/ MWh_{H2}	38	74	Cost contribution to the LCOH with liquid delivery. Cost for a liquefier with a capacity of 27000 $kWhH_2$/ day. Lower bound: Capital costs only, upper bound including additional recurring costs (e.g. electricity)	DOE, 2019
Ammonia	€ (2019)/ MWh_{H2}	34	34	Based on decentralized configuration for reconversion to hydrogen	IEA,2019

Source: Guidehouse and Tractebel Impact. Hydrogen Generation in Europe. July 2020

Other conversion/storage molecules are available, such as methanol or LOHCs (Liquid Organic Hydrogen Carriers), though they are yet to see the same amount of market momentum that ammonia is experiencing currently. This is likely due to the fact that ammonia is more commonly used worldwide when compared to methanol, whilst LOHCs are lower in their Technology Readiness Level (TRL) and currently require more CAPEX to establish.

Liquid Hydrogen – LH_2 is a much denser form of hydrogen than compressed gaseous hydrogen, and as a result liquid tankers can deliver significantly more hydrogen when compared to their gaseous analogues. In the US, where long distribution distances are frequent, LH_2 has been used as the primary delivery method between production sources and customers for many years.

Source: Marine Currents

Figure 14: The Suiso Frontier: Kawasaki Heavy Industry's LH_2 transportation vessel

Recent innovations in road tankers, particularly surrounding the weight of vessels and valving, has raised payloads to 4-5 tonnes/load. The parallel development of LH_2 trucks by companies like Daimler, has seen an increase in momentum surrounding the use of LH_2 for high-demand mobility applications due to the larger fuel volume needs (e.g. at motorway service stations).

Similar to ammonia, countries are exploring the use of LH_2 as a versatile energy carrier across the globe. 2021 saw the launch of a Japanese-Australian venture to produce hydrogen from brown coal and transport it to Japan as LH_2 via ship (Figure 14). This LH_2 marine tanker [45] undertook its maiden voyage on December 24, 2021 and has since been filled with LH_2 from the port of Hastings in Victoria, Australia. The tanker has the capability to store roughly 75 tonnes of LH_2 and will regularly complete the route from Australia to Japan as it serves a AUS$362 million pilot project capable of producing 225,000 tonnes of LH_2/year. If liquid hydrogen is deemed to be one of the preferential methods of hydrogen usage for the transport sector in the coming years, then LH_2 may become an ideal way of transporting hydrogen to reduce the need for costly molecule conversion and dissociation facilities as LH_2 systems and storage become more widespread.

8.2.3 Hydrogen transmission from local production/import facility

Once the hydrogen molecule is produced in country, or is delivered and dissociated from whatever global transmission molecule has been used to reach a local port, the hydrogen needs to be moved to the airport. As previously mentioned, the two most likely distribution methods of hydrogen to airport sites will either be performed by LH_2 road tankers or rail-cars, a pipeline network, or a combination of both (Figure 8). Liquefaction can either occur at the production site/port or close to the airport with molecules transmitted there by pipeline. This will be defined by the airport demand and geographic proximity to the supply node.

Pipelines – Pipelines are one of premier methods of hydrogen distribution available to the sector today. They offer reliable high-throughput transmission whilst having considerably lower operational costs than alternatives – the European Hydrogen Backbone predicts that the cost of distribution will be €0.11-0.21 per kg per 1000 km through their continent-wide network.

The trade-off however is that the installation of new pipelines involves large capital costs with long lead times due to the planning, permitting and installation required. In some instances, this work can be circumvented by utilising existing natural gas infrastructure where possible – whether that be refurbished dedicated hydrogen pipelines or blending hydrogen into suitable existing networks.

Blending hydrogen into natural gas networks is an available technology that is being used as both an application and distribution mechanism currently across Europe. However, to acquire pure hydrogen from a blended pipeline, as would be required for the aviation industry and other fuel cell applications, an extra separation step will have to be added to isolate hydrogen from the natural gas mix. Whilst blending is reaching maturity, this separation process is relatively new. The initial industrial scale demonstration by Linde utilising Evonik technology is underway in Germany. The technology can take hydrogen blended between 5-60%, isolate it and purify it to PEM fuel cell grade quality (99.9999%).

In both cases, the hydrogen will be transported in its gaseous form and so for use in aviation it will have then have to be liquefied.

LH_2 tankers – As previously discussed, LH_2 tankers are an optimum distribution method for small-to-medium-scale airports particularly in the next decade as the slow ramp-up towards zero-emission fuels occurred. The Clean Sky 2 view that 5000 tonnes H_2/yr would be required to swap 10% of a regional airport's fuel supply to LH_2, requires just four deliveries per day. This is a manageable and realistic scale of delivery, especially if airports have access to fleets of transport vehicles to regularly make these fuel transfers. The most ideal scenario would see fuel-cell trucks satisfy these deliveries, refuelling with the same hydrogen they are delivering to create a zero-emission pathway for the last link in this supply chain.

Looking at large scale airports, 25 LH_2 deliveries per day are anticipated by 2030/35. This could be considered to be a manageable requirement, especially with a large fleet of tankers. However, as demand increases towards 2050, different liquefaction and distribution mechanisms will become necessary as the economics of trucking will not be deemed feasible. The volume concerned would possibly necessitate local, liquefaction at the airport. Due to this, many large airports may circumvent trucking hydrogen to site and instead 'futureproof' their distribution mechanisms with pipeline infrastructure instead. This could therefore lead to a cross over in the short-to-medium term, when the demand associated with large airports will migrate to local liquefaction, adding impetus to pipeline development.

Liquid hydrogen pipelines are too costly due to their requirement for continuous cooling and pressurisation, instead solutions have been deployed in which gaseous hydrogen pipelines directly feed large-scale liquefaction facilities. These facilities could be based proximally to airports, which can then directly feed airport bunker systems. This arrangement would allow airports more security in supply of fuels by presenting airports with the opportunity to own or form long-term partnerships with liquefaction facilities rather than being reliant on supply form a national, or continental network of pipelines.

8.2.4 Airside LH_2 distribution

Once LH_2 is locally available at the airport it needs to be distributed to the application. Smaller volumes and those required during fleet ramp up can be provided by LH_2 tankers, however, the most efficient method to achieve larger volume transfers would be by LH_2 pipeline. This technology has not yet been used across medium or long distances – mainly because its deployment has been limited as LH_2 tanker and barge distribution has met all industry/space needs cost-effectively to date. It should be expected that both these distribution methods will be widely used at airports, however, to ensure most effective large scale LH_2 use, wider cryogenic pipeline technology will need to be deployed.

LH_2 trucks to airplanes

As airports start to consider the necessity to switch their fuels from carbon-intensive ones to low- or zero-emission alternatives, the refuelling solutions that provide the most variability will be the most successful in the short-to-medium term. Whilst LH_2 pipelines could provide a reliability and volume unrivalled by any other fuel transportation method, the required capital cost and scope of work to implement such a technology is difficult to justify in the short-term whilst LH_2-use at airports remains low. With the Clean Sky 2 initial 2035 prediction of just four tanker loads per day for regional airports and 25 for larger airports, LH_2 distribution by road will be a much more cost-effective interim model which allows for flexible delivery patterns from multiple producers, adding redundancy during a scale-up phase for the sector.

These tankers could deliver LH_2 to both the airport site for other mobility applications and airside for direct refuelling of the aircraft. They present an ideal opportunity to transport smaller amounts of hydrogen from source-to-tank, either decanting their fuel into mobile refuelling platforms or via dedicated refuelling hoses fitted to the distribution tankers themselves.

LH_2 pipelines to fill hubs

Generally, modern-day airports utilise large tank farms to store their fuel. These tank farms connect to underground bunkering systems via hydrant pipelines that in turn feed a number of refuelling sites on the airport site, in hangars or on runways, to quickly and efficiently fuel multiple vehicles. For instance, Manchester Airport is serviced by a refinery based in Cheshire which can pump several million litres down a 30-mile pipeline [46] in roughly 4-6 hours – doing the same job of over 70 road tankers, but much more reliably and in much less time. To cut carbon emissions in the short term, the airport is now looking to deploy a similar framework to

secure a feed of SAF. If the plan goes ahead, the £600 million facility will make around 100 million litres of SAF per year and directly feed the airport via pipeline.

As demand for LH_2 refuelling grows, there is the potential to deploy a similar refuelling solution by implementing analogous infrastructure or, where possible, transforming existing infrastructure to enable LH_2 capability. However, this could be extremely capital intensive. Existing hydrant pipelines would require replacement with super-insulated pipelines suitable for LH_2 transfer to keep the hydrogen below -253°C. The technology is well known and proven within industry for short transfers. Once installed and kept cold, i.e. at LH_2 temperature, the systems are highly effective. Losses and heat build-up within the LH_2 across the transfer will need careful management, but should be achievable with good design.

Deploying LH_2 to set refuelling points across an airport is feasible. The rigidity of the vacuum insulation applied to LH_2 pipelines makes them heavy and difficult to handle/use for regular interconnection with something like an aircraft. As discussed, LH_2 heavy duty road transport demand is likely to ramp up rapidly in the short term. The EU has mandated, as part of its alternative fuels infrastructure regulation, the need to have LH_2 refuelling stations every 450 km along key goods transport corridors across Europe. This will foster the wider development of LH_2 technology. In addition, the regular, repeated refuelling connection for LH_2 for trucks will enable robust, safe, scaled up designs to be available to the aviation sector by the time mass-rollout is expected.

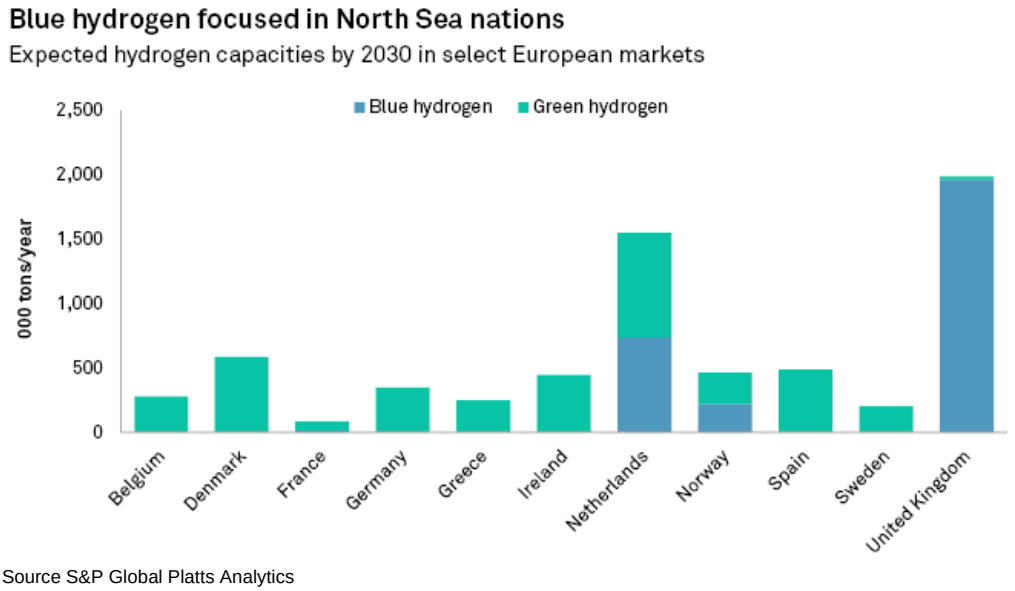
8.3 Case Study: Liquid hydrogen supply to Heathrow

This section presents the GHG emissions associated with the establishment of a potential hydrogen supply chain for Heathrow Airport. Within this example supply chain, multiple hydrogen production and distribution pathways featuring both domestic and international opportunities were assessed.

This assessment was based on the following principles:

- Firstly, the hydrogen that will be supplied to Heathrow will most likely be produced via renewable energy coupled with electrolysis, or conventional blue hydrogen production routes of steam methane reforming with CCUS capabilities. These two pathways are currently the most mature, and whilst there are more emission-saving pathways available, they are unlikely to be able to address the necessary scale required by an international airport.
- Furthermore, as blue hydrogen is only being favoured by European countries that border the North Sea (Figure 15), there is less momentum surrounding the international trading of blue hydrogen than green hydrogen. Within the project only domestic blue hydrogen production pathways were assessed. Whereas, with much impetus around the world to create green hydrogen value chains for export to lucrative markets, as well as in the UK, both international and domestic production pathways for green hydrogen were considered.
- There are several possible distribution mechanisms these international hydrogen value chains could employ – such as pipelines or shipping. The pipelines are seen as an immediate answer for the movement of hydrogen within Europe, but when it comes to importing hydrogen from further afield (e.g. Saudi Arabia or Australia), these pipelines will not be suitable. Instead, it is more likely that shipping will be the preferred mode of transportation between these countries and the UK – the scenario was based on the conversion of hydrogen to ammonia for shipping as most large-scale deployments are expected to utilise this procedure to maximise the amount of hydrogen distributed, as is already being investigated around the world.

- As presented within this study, it was envisaged that hydrogen will be liquefied in order to present the necessary energy density to fuel aircraft. Either, this will happen at a location independent of the airport with LH_2 trucked via tanker, or alternatively, a liquefaction plant would be based proximal to the airport, with the final distribution occurring by LH_2 transfer pipeline to an airport fuel bunker system.



Source S&P Global Platts Analytics

Figure 15: Expected hydrogen capacities in Europe by 2030

8.3.1 Production Emissions

As one of the largest airports in the world in terms of passenger throughput, Heathrow Airport will require vast amounts of renewable fuels in order to achieve net-zero. Not all of this will come directly from hydrogen, with a large proportion likely, at least into the medium term, to be satisfied by the use of Sustainable Aviation Fuels, though hydrogen is expected to play a significant role just given the number of aircraft already under development and planned for future testing.

As discussed, hydrogen via blue and green production pathways is likely to prove the most suitable, unless there are considerable market shifts in the next 5-10 years with regards to turquoise (methane pyrolysis) and pink (nuclear) hydrogen. Blue hydrogen understandably has larger GHG emissions with the majority being caused by upstream emissions from creating and transporting the natural gas (e.g. methane leakage) and the high temperatures and energy requirements of the hydrogen production process. However, with the ability to be deployed at scale, and with considerable momentum within the UK, blue hydrogen is still a very viable way of producing hydrogen whilst considerably cutting emissions. GHG emissions are likely to remain fairly constant for blue hydrogen production, with higher capture rates the only real opportunity to improve upon these figures – but even then, these will only capture 98% of the emissions produced. For Heathrow, this blue hydrogen could be supplied from a number of UK locations, primarily based around key industrial hubs such as Humberside, Teesside and the North West with transportation in the form of pipelines. Both Humberside and the North West options are roughly 215 miles from Heathrow airport.

Electrolytic hydrogen however presents a difficult challenge. Whilst electrolysers will produce green hydrogen when operated with renewable energy – whether that be solar, wind or hydro – at several initial deployment sites in the UK, electrolysers will be connected to the grid to

ensure continuous production and prevent the equipment from incurring high maintenance costs and accelerated degradation in performance. This grid electricity, currently, is fairly carbon-intensive – 181 g CO_2/kWh on average [47] with a total renewable penetration of 43% [48] – meaning any grid electricity that has to be used will considerably increase the emissions associated with electrolytic hydrogen production. One way to tackle this issue is to deploy a diverse mix of renewable energy sources, therefore increasing the capacity factor for operating an electrolyser on zero-emission electricity. One paper, investigating a 3 MW electrolysis deployment at a 15 MW wind farm in Ireland, found that instead of just utilising curtailed wind, a 3 MW electrical battery and further dedicated wind and PV could increase the electrolyser's capacity factor from 27% to 51% - decreasing the levelised cost of hydrogen (LCOH) produced by almost €4/kg despite the additional capital costs. Table 17 provides an indicative ratio of CO_{2eq} emissions produced for every kg of H_2 as expected in the years 2030 and 2050.

Table 17: Hydrogen Production Associated Emissions

Hydrogen Type	GHG Emissions 2030 (kg CO_{2eq} / kg H_2)	GHG Emissions 2050 (kg CO_{2eq} / kg H_2)
Electrolytic	0.3 - 11.1	0.3 - 3.1
Low carbon	1.2 - 3.9	0.8 - 3.9

Green hydrogen production is expected to occur in most places within the UK, but larger deployments, similar in size required by large transport or industry-scale applications, are likely to be based on the coast due to the ability to deploy offshore wind. Given their position as critical energy handling points, locations such as the Rotterdam port are receiving considerable interest in Europe as key geographic locations. In the context of this project, Southampton was selected as the production location for domestic green hydrogen production due to its port activity and proximal location to Heathrow (~65 miles).

For the international hydrogen chain, this location was also selected as the import terminal for a global hydrogen shipping route coming from Saudi Arabia in the form of ammonia. Saudi Arabia was selected due to the amount of available data on activities being carried out within the region, but this data can be easily translated to alternative scenarios due to the study's normalised approach.

8.3.2 Imported Hydrogen

The international value chain requires several steps which are not present for domestic hydrogen supply. These include conversion to a transfer molecule, shipping this transfer molecule across borders, and dissociation of the hydrogen back into its pure form on arrival at the final destination country. Although there are some losses in efficiencies when converting the hydrogen, shipping in the form of ammonia is much more cost efficient over long distances, even more so than pipelines in some scenarios.

As previously discussed, in the scenario considered for this study, green hydrogen produced is assumed to be converted into ammonia and shipped overseas from Saudi Arabia to Europe, including the UK. Currently, ammonia production is an incredibly energy intensive industry, requiring around 1.8% of global energy output each year whilst producing ~500 million tonnes of CO_2, an equal proportion of the world's emissions. However, it's worth noting that roughly 90% of all ammonia emissions are from production of grey hydrogen, therefore, by changing to blue or green hydrogen considerable emission saving will be achieved. Using blue hydrogen can significantly cut emissions within this process is utilitised, but green hydrogen, produced

from 100% renewable electricity, when coupled with electrolysis, has no direct emissions whatsoever, when using direct air capture of nitrogen.

However, whilst there are no direct emissions in the ammonia production process, there are emissions within the hydrogen production process from upstream sources that have to be factored into this green ammonia process. Once produced, this hydrogen will be shipped as ammonia from Saudi Arabia to Southampton, a journey of 7,000-8,000 km.

On average the carbon footprint of cargo ships in the United Kingdom is between 13.08 and 16.14 g CO_{2eq} per tonne of shipped goods per kilometre travelled, depending on the cargo. If the figure for general cargo – 13.23 [49] is considered, this would equate to an average of 99.2 kg CO_{2eq} per tonne for shipping ammonia over 7500 km. Large ships may carry up to 60,000 tonnes [50], but hydrogen constitutes only 17.6% of the mass of ammonia, so only 10,560 tonnes would be hydrogen. This means the emissions *per unit of hydrogen* would be significantly higher, at 564 kg CO_{2eq} per tonne of hydrogen shipped. This is comparable with the emissions from ammonia dissociation (aka cracking). Table 18 provides expected GHG emissions (in kg CO_{2eq} per tonne transported) together with expected efficiency losses.

Table 18: Hydrogen transportation through shipping – expected emissions and efficiency loss

Shipping processes	GHG Emissions 2030 ratio: kg CO_{2eq} / tonne	Efficiency loss
Green Ammonia Production	Dependent on production source*	7-18%*
Ammonia shipped (per km)	0.0132	
Hydrogen content (per km)	0.075	
Ammonia shipped utilizing ammonia-powered vessel	NA	~20%
Ammonia dissociation (cracking)	460**	15% loss of hydrogen

**To overcome the efficiency losses of the ammonia production process, 7-18% more hydrogen feedstock must be used to obtain desired volume. Therefore, this must be taken into account for each kg of hydrogen relative to its own production carbon intensity.*

***Transformation processes, such as ammonia cracking or hydrogen liquefaction, are energy intensive. To calculate emissions factors of these processes, the energy required to obtain tonne of hydrogen has been multiplied by the expected carbon intensity of the UK's electricity grid in 2030 (51g_{CO2e}/kWh). It is possible that these processes could be completely emission free if dedicated renewable energy supplies, or renewable PPAs are present. Reductions in emissions are expected post-2030 in-line with increasing proportion of renewable electricity within the UK's grid.*

There is a large push from both the ammonia and shipping sectors to establish the use of green ammonia as a fuel for seagoing vessels to provide marine transport with a suitable pathway to approach net-zero. There are a number of market players investigating the potential of these vehicles, such as the consortium of Mitsubishi Shipbuilding Co., Namura Shipbuilding and Mitsui O.S.K Lines jointly developing a large ammonia-fueled ammonia carrier [51] – with the first large carrier to be commissioned by 2026. Although these vessels will utilise a proportion of the payload they carry in order to fuel themselves, they will also achieve near-zero-emission sea travel and therefore greatly reduce the emissions seen, not just within energy transportation, but also in goods distribution and passenger transport – including reducing CO_2, NOx, SOx, and soot.

8.3.3 Ammonia Cracking

Once delivered to the port, this ammonia will have to be dissociated back into its constituent elements in order to re-obtain hydrogen – a process called cracking. This is a relatively energy intensive process currently requiring high temperatures and expensive metal catalysts. A paper published in 2017 [52] found that whilst the net energy required to crack ammonia was 0.28-0.30 MWh per tonne, due to efficiency losses of hydrogen encountered in this process –

the actual energy total was closer to 1.41 MWh per tonne (with an assumed ammonia cracker efficiency of 76%). This equates to 1.55 kWh/kg NH_3 or, 8.96 kWh/kg H_2 when considering the amount of hydrogen obtained from each kg of ammonia. Note that scaled-up ammonia cracking requires long-term demonstration to develop a true understanding of its emissions.

8.3.4 Liquefaction

Once a pure hydrogen stream is available liquefaction is a necessary to increase the energy density to be suitable for use by aviation vehicles. A study published in January of 2022 found that this process, at an industrial scale typically consumed around 10-15.5 kWh of energy per kg of hydrogen liquefied – representing a 19.0-23.6% energy efficiency. Assuming the average carbon intensity of the UK grid of 181 g CO_{2eq} / kWh, this represents a very large emission cost of over 2 kg CO_{2eq} per kg of hydrogen liquefied, however the carbon intensity of this process will decrease as the grid becomes more decarbonised (51 g CO_{2eq} / kWh is expected by 2030), or if it is fed by directly connected renewables. Table 19 provides an indication of the expected emissions and energy efficiency from the hydrogen liquefaction process.

New methods of liquefaction are being explored, but are currently in the early stages of their development. This frequently uses a pre refrigerated substance to provide additional cooling i.e. LNG or CO_2. By utilising CO_2 as a refrigerant [53], the energy consumption required could be dramatically reduced to 7.63 kWh/kg, whilst other studies, including the US Department of Energy, predict this could fall as low as 6 kWh/kg [54]. Figure 16 provides flow charts depicting the process followed in two varying liquefaction methods.

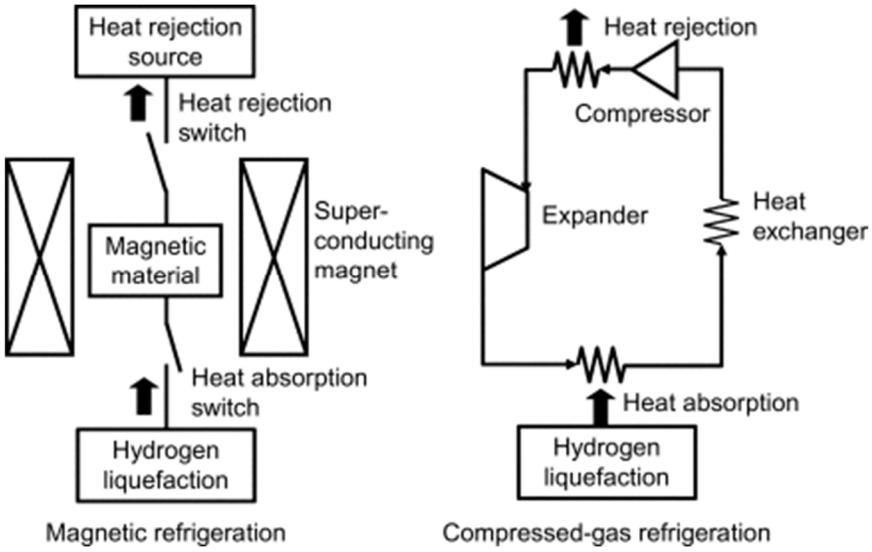


Figure 16: Two liquefaction methods - magnetic refrigeration and compressed-gas refrigeration

Liquefaction facilities could be based in one of two places. Next to the cracking facilities in the port of Southampton, minimizing the required transport and distribution of hydrogen between facilities by directly feeding hydrogen from one to the other via pipeline, or adjacent to the airport thereby shortening the distance LH_2 needs to be distributed by local to the demand.

Table 19: Hydrogen liquefaction – expected emissions and energy efficiency

Liquefaction Method	GHG Emissions Y2030 ratio: (kg CO_{2eq} / kg H_2)	Energy efficiency
Current industrial scale	0.51 – 0.79	30-35%
Innovative solutions	0.31 – 0.39	50%

8.3.5 Distribution

There are several options available when considering hydrogen distribution over a short distance. If liquefied at the port:

- Hydrogen can be trucked via LH_2 tankers from the port to Heathrow where it is decanted into a storage system based either at the airfield or just offsite. This distribution mechanism produces emissions from the vehicle transporting the LH_2 tanker from Southampton to Heathrow.
- Hydrogen could theoretically be distributed via liquid hydrogen pipeline directly from the liquefaction plant to the airport. However, the cost of this sort of infrastructure, not to mention the safety implications, would be far too great to make this deployment option viable currently.

If liquified at Heathrow:

- Hydrogen could be trucked via tube trailers from the port to Heathrow. However, the number of trucks involved vs the demand would make this unviable. It is included just as a comparator in this analysis.
- Hydrogen can be piped via dedicated, or blended, pipelines from the port's dissociation terminal to Heathrow at which point the hydrogen undergoes the liquefaction step before being transferred to a fuel bunkering or storage system via LH_2 truck or pipe.

Having taken into account concurrent results from the European Automobile Manufacturers Association [55] and the International Council on Clean Transportation [56] – type 10-RD and 10-LH_2 trailers, the sort that readily transport hydrogen today, emit a baseline of 83.6 g/t-km and 58.45 g/t-km respectively. 10-LH_2 trailers are the predominant trailer of choice in this size category, making up 9.7% of all vehicles (Q3-4 2019), with 10-RD vehicles making up just 0.1% - therefore the average vehicle is 58.71 g/t-km. Typically, liquid tankers and gaseous tube trailers are 40 tonnes in weight as this is a standardized size, however, the amount of hydrogen that each stores varies wildly. Tube trailers typically carry somewhere between 500 – 1,000 kg, with reports saying that, with new innovations, they could reach 1,200 kg in payload weight. Whereas LH_2 tankers can carry much more between 2,500 – 4,500 kg. Of course, with the advent of new zero-emission vehicles, both hydrogen and electric, the emissions associated with this segment of the value chain can be negated. Given the current manufacturing capabilities for such vehicles, as well as associated infrastructure, this is likely to become a viable opportunity in the next 10 years.

When LH_2 is stored or transported, it experiences boil-off, which also needs to be considered. This is a process where LH_2 is vaporized into its gaseous state resulting in energy and hydrogen loss due to the requirement to remove this hydrogen from the vessel to prevent pressure build-up. However, this only occurs where the hydrogen is stored for extended periods i.e. beyond a day or transported over longer distances. 0.2 to 0.5% of vessel contents per day stored, if not used, would be typical. In both instances this is not due to occur for airport applications.

Piped gaseous hydrogen assumes a small emissions factor as a result of the energy required to operate the necessary compression systems. These systems are assumed to run on grid electricity which in 2030 will have an expected carbon intensity of 51 g CO_{2eq} / kWh. Table 20 quantifies the expected emissions and energy loss for different hydrogen distribution methods.

Table 20: Hydrogen distribution methods – expected emissions and energy loss

Distribution Method	GHG Emissions: (kg CO_{2eq} / kg H_2)	Energy loss
Trucked LH_2 per km	0.00052 - 0.00094	
Trucked gaseous hydrogen per km	0.0023 - 0.0047	
Piped gaseous hydrogen	0.12*	6-8%*

**Piped gaseous hydrogen assumes a small emissions factor as a result of the energy required to operate the necessary compression systems. These are assumed to run on grid with an expected carbon intensity of 51g CO_{2eq} per kWh in 2030, but then further reductions should follow in-line with the UK's zero-emission grid goals.*

Pipelines, are a very efficient form of gaseous hydrogen transportation, connecting production facilities directly to customers through robust infrastructure with extremely high throughputs. Hydrogen can be transported via dedicated or blended pipelines, with the only need for external energy being the operation of compression systems to maintain the pipeline's pressure. Whilst there can be some leakage in pipeline systems, the low GHG intensity of hydrogen means that this would have a minimal effect on the overall intensity of delivered hydrogen. Furthermore, although there are emissions associated with the construction and deployment of pipelines themselves, this report focuses on the operation of these systems and thus will only assess emissions associated with distribution of hydrogen.

Dedicated hydrogen pipelines circumvent this issue, and in this case, as the hydrogen is not trying to substitute for the use of natural gas, its reduced energy density is not an issue – for example, in applications for heating an increased flow-rate of hydrogen is required to address the energy difference between hydrogen and natural gas. Given these pipelines only transport hydrogen, although expensive to implement, their use has no associated CO_2 emissions, although the energy required to compress hydrogen for pipelines will result in an energy loss of between 6-8%, according the BNEF data presented in Table 20.

Blended hydrogen separation

When hydrogen is blended into a natural gas pipeline there is one final required step – extraction. During this step the hydrogen is removed from the pipeline and purified to sufficient quality of use for its application – in this case, fuel cell grade quality. Currently there are very few of these facilities, with Linde's Dormagen plant the first to be deployed at scale – thus data on this topic are very scarce currently and it is hard to draw conclusions surrounding the emissions/energy needs of these technologies.

8.3.6 Supply chain summaries

Table 21 summarises the emissions from the considered pathways.

Table 21: Pathway emissions: processes and methods

Hydrogen Production	
Hydrogen Type	**Y2030 GHG emissions (kg CO_{2eq} / kg H_2)**
Electrolytic	0.3 - 11.1
Blue	1.2 - 3.9
International Ammonia Chain	
Process	**GHG Emissions (kg CO_{2eq})**
Green NH_3 production (per tonne H_2 transformed)	Dependent on production process
Ammonia shipped (per tonne-km)	0.0132
Hydrogen content shipped (per tonne-km)	0.075
Ammonia cracking procedure (per tonne H_2 obtained)	460

Liquefaction	
Liquefaction Method	**GHG Emissions (kg CO_{2eq} / kg H_2)**
Current industrial scale	0.51 – 0.79
Innovative solutions	0.31 – 0.39
Distribution	
Distribution Method	**GHG Emissions (kg CO_{2eq})**
Trucked LH_2 (per tonne-km)	0.52 - 0.94
Trucked Gaseous H_2 (per tonne-km)	2.3 – 4.7
Piped Gaseous H_2 per tonne	120

8.4 Key conclusions

The carbon intensity analysis carried out in the previous section of this report has been used to produce a set of supply pathway scenarios for 2030. These scenarios showcase how different types of hydrogen production, conversion, and distribution affect the carbon intensity of hydrogen supplied to Heathrow Airport's airside. In each, it is assumed hydrogen will be delivered to Heathrow's airside in liquid phase to be directly fuelled into aircraft. These scenarios are:

1. **Blue trucked** – Blue hydrogen that is both produced and liquefied in the northeast of England, which is then trucked 215 miles, or 346 km, in LH_2 tankers to Heathrow.
2. **Blue piped** – Blue hydrogen that is produced in the northeast of England and piped to a facility proximal to Heathrow, at which point it is liquefied and distributed 10 miles to the airside via LH_2 tankers.
3. **Green trucked** – Green hydrogen that is both produced and liquefied in the northeast of England, and then trucked to Heathrow in LH_2 tankers.
4. **Green piped** – Green hydrogen that is produced in the northeast of England and then piped to a facility proximal to Heathrow, at which point it is liquefied and distributed to the airside via LH_2 tankers.
5. **NH_3 shipped and piped** – Green hydrogen that is converted to ammonia and shipped from Saudi Arabia to Southampton (~7500 km). Ammonia is reconverted to hydrogen and piped to a facility proximal to Heathrow, at which point it is liquefied and distributed to the airside via LH_2 tankers.
6. **NH_3 Shipped and trucked -** Green hydrogen that is converted to ammonia and shipped from Saudi Arabia to Southampton. Ammonia is reconverted to hydrogen and liquefied at Southampton before being distributed 65 miles, or 105 km, to Heathrow airside via LH_2 tankers.

Emissions for each scenario described above have been calculated utilising available median data (Table 22).

As expected, supply pathways which featured blue hydrogen production were far more emitting than those featuring green hydrogen production – between 56-68% greater total emissions – due, almost entirely to the difference in steam methane reforming and CCUS technologies, compared to electrolysis.

International supply pathways can be competitive on a carbon emissions-basis with domestically produced product. Hydrogen that is converted into ammonia for international distribution is considerably less emitting than domestic blue hydrogen supply pathways per kilogram of hydrogen, due to the economies of scale achieved.

Table 22: Scenario analysis and expected carbon emissions

Emissions ratios: kg_{CO2eq} / kg_{H2}	Blue H_2 trucked	Blue H_2 piped	Green H_2 trucked	Green H_2 piped	NH_3 shipped and piped	NH_3 shipped and trucked
Production	2.55	2.55	0.75	0.75	0.75	0.75
Conversion	0	0	0	0	0.09	0.09
Shipping	0	0	0	0	0.56	0.56
Dissociation	0	0	0	0	0.46	0.46
Liquefaction	0.65	0.65	0.65	0.65	0.65	0.65
Distribution	0.25	0.13	0.25	0.13	0.13	0.09
TOTAL	**3.45**	**3.33**	**1.65**	**1.53**	**2.65**	**2.60**

Despite the addition of conversion, dissociation, and shipping steps, international pathways are only 0.95 – 1.12 kg CO_{2eq} /kg H_2 more emitting than domestic green hydrogen supply pathways. Thus, with a number of ideal renewable locations considering power-to-X solutions for energy export (e.g. Saudi Arabia, north Africa, and Oceania), international pathways open up access to large-scale, low-cost product that is comparable with locally produced hydrogen. Furthermore, the overall emissions intensity of international pathways is also expected to reduce with advancing technologies, particularly for ammonia dissociation, through to 2050.

The distribution method has an overall effect on the emissions of the hydrogen supplied. The use of pipelines is advantageous over longer distances, as seen in the scenarios above. However, when considered over small distances, the energy consumption associated with compression technologies results in greater emissions than the use of conventional liquid hydrogen tankers. Emissions from distribution pathways are expected to continue to decrease after 2030 as zero-emission tractors, powered by both hydrogen and batteries, enter service in line with the UK government's mandate that all new HGVs sold in UK should be zero-emission by 2040.

Emissions from liquefaction, conversion, dissociation, and distribution via pipeline, are expected to exhibit a steady decline as the carbon intensity of the grids that power these processes continues to decrease. This is particularly important for the liquefaction process which currently is responsible for between 19–43% of emissions of all scenarios, and for ammonia dissociation which accounts for roughly 18% of the emissions from international pathway scenarios.

Hydrogen production will need significant amounts of fresh water for electrolysis. In order to conserve existing fresh water supplies, it is important to consider alternative methods of generating fresh water where necessary. These include large-scale desalination plants, that could be supplied with sea water that would then be converted to fresh water using reverse osmosis or flash desalination. Sea water would also be very useful for cooling electrolysers and liquefaction plants.

A summary of the overall analysis of the carbon intensity of systems based on the above scenarios is presented graphically in Figure 17.

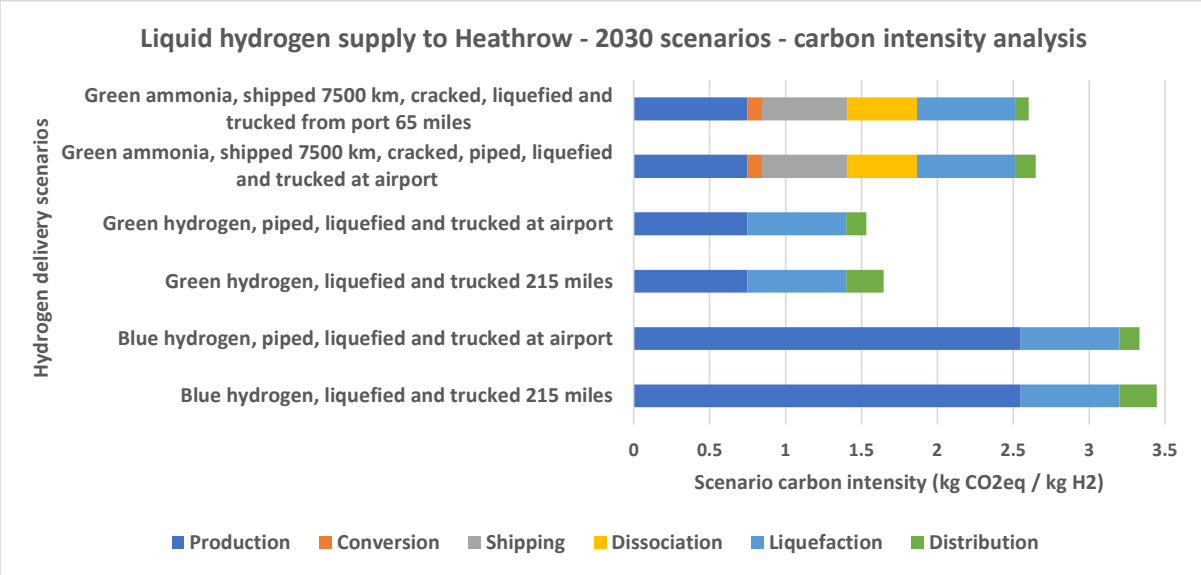


Figure 17: Overall analysis - carbon intensity based on the assumed scenarios

9 Conclusions

Several developments over the last few years have changed the outlook with regard to hydrogen-fuelled aviation. This is no-longer considered highly speculative. Several prototype hydrogen fuel cell-powered experimental aircraft have flown recently including DLR's HY4 and ZeroAvia's retrofitted Piper Matrix M-class aircraft. Cranfield Aerospace Solutions and Airbus UpNext plan to have aircraft flying in 2023.

Airbus is receiving significant French government and EU funding to research larger LH_2-fuelled regional and narrowbody aircraft concepts and plans flight demonstration of hydrogen aircraft technologies and engines. The UK ATI's FlyZero project came out strongly in favour of LH_2 as the preferred fuel for sustainable aviation and Rolls-Royce has launched hydrogen demonstrator test programmes running AE2100 and Pearl 15 engines. ENABLEH2 originally targeted 2050 as the year when hydrogen-fuelled commercial aircraft production might ramp up. Considering subsequent developments, it now seems credible that this could start up to a decade earlier.

Studies undertaken in ENABLEH2 Work Package 1 confirmed the potential environmental benefits and indicated that commercial aircraft using liquid hydrogen (LH_2) can be competitive. These studies present best-case-scenario projections for the performance of aircraft operating with alternative fuels in year 2050. This inevitably involves engineering judgement and economic forecasting, with attendant uncertainties. The figures presented here are subject to revision as more information becomes available.

For more detailed studies, ten representative aircraft concepts were down-selected in a two-step process from larger sets of Y2050 candidate airframes and propulsion systems. The selected designs include Short/Medium-Range (SMR) and Long-Range (LR) aircraft, four different fuels (Jet A-1, biofuel, LNG and LH_2) for both 'Lower Risk' and 'Max Synergy' airframe and propulsion-system architectures. The aircraft have been assessed for performance, weight, emissions and relative operating costs, and compared with Y2020 state-of-the-art SMR and LR aircraft sized to meet the same top-level aircraft requirements.

Previous studies of hydrogen-fuelled aircraft have considered various placements for the bulky hydrogen tanks. NASA studies in the 1970s and the European Cryoplane project around Y2000 mostly assumed relatively conventional airframes with LH_2 tanks placed in the fuselage. More recent studies considered unconventional airframes including Blended Wing Body (BWB) aircraft that offer relatively large internal volumes for fuel tanks and higher lift/drag ratios. The latter study aircraft have also been integrated with advanced turbo-electric distributed propulsion systems with multiple ducted fans configured for boundary-layer ingestion to improve propulsive efficiency. ENABLEH2 studies include three 'Max Synergy' aircraft that feature advanced propulsion systems that use the LH_2 or LNG as a heat sink for highly-efficient and power-dense superconducting electrical equipment. The Lower Risk LH_2 designs are more conventional 'Tube & Wing' (T&W) aircraft with tanks located above their passenger cabins.

Three fuel cost scenarios were originally defined in 2019 to consider the potential market conditions under which hydrogen-fuelled aircraft could become viable. These were "baseline, progressive environmental awareness and heightened environmental awareness (HEA). Three supplemental scenarios for low electricity cost, high fossil fuel cost and low fossil fuel cost were also proposed to provide a wider base of business risk for fuel choice. However, given subsequent developments, the HEA scenario is now considered the most realistic. The operating cost assessments are still based on projections made before the COVID-19 pandemic and the conflict in Ukraine, so the current high inflation rates are considered a temporary phenomenon. LNG is considered the lowest cost option in the near term, but the

cost of liquefied green hydrogen is projected to fall rapidly over the study period in comparison with alternative fuels.

The ENABLEH2 studies have sized the SMR aircraft for 200 passengers in single-class seating and for 3000 nmi design range. The LR aircraft are sized for 7500 nmi design range and for 414 passengers in two-class seating. However, as aircraft are normally operated on shorter routes, the SMR aircraft is also assessed over a 900 nmi mission and the LR aircraft is assessed over a 3000 nmi mission. These missions may be considered representative of operations by the whole commercial aircraft fleet.

The quantitative results for the Y2050 aircraft are highly dependent on the assumptions made regarding the pace of improvements in aircraft and propulsion system technologies over the next 30 years. Economic projections for operating costs are even more uncertain, particularly for the costs of the different fuels and the price of carbon credits to offset the remaining CO_2 or CO_2-equivalent life-cycle emissions. No cost penalties have been applied in these studies for the global warming effects of NOx or methane emissions, water vapour, or contrails, but these additional factors could be significant.

The Y2050 SMR and LR aircraft fuelled with Jet A-1 are both projected to have about 24% lower mission fuel burn and CO_2 emissions per available seat kilometre (ASK) relative to representative state-of-the-art aircraft currently in service. Drop-in replacement biofuels only reduce mission-level CO_2 emissions by a few per cent, but they have the potential for very significant reductions in life cycle emissions. For Y2050, reductions of up to 90% have been predicted for synthetic electrofuels.

LNG generally only offers a modest reduction in mission-level and life-cycle CO_2 reductions relative to Jet A-1. This is because the LNG tanks increase the empty weight, fuselage volume and drag of the aircraft, such that the benefit of the fuel's lower carbon content and higher heating value are largely offset. This however applies particularly for the LR tube and wing aircraft. The LNG-fuelled BWB aircraft shows a significant reduction in emissions relative to the advanced T&W designs. This is because the BWB aircraft has higher lift/drag ratio and a more efficient boundary layer ingesting propulsion system in comparison to the T&W aircraft. The LNG BWB variant is less penalised by needing large fuel tanks, because the basic design already has higher internal volume. Liquefied bio-gas is an attractive option, but it is not expected to become widely available, so it has not been assessed in these studies.

Mission-level NOx emissions per available seat–kilometre (ASK) tend to be lower for longer flights as the take-off and climb phases (where NOx emission rates are highest) are relatively less significant in comparison with shorter flights.

For the HEA fuel costs scenario, the assumed level of emissions charges (in whatever form) in 2050 are considered just sufficient to offset the higher cost of biofuel relative to the untaxed fossil fuel kerosene (Jet A-1). Untaxed LNG, currently being less expensive than kerosene, and producing less CO_2, is still shown to offer a potential cost advantage for the SMR aircraft and for the LR BWB aircraft.

The original cost per available seat–kilometre (CASK) estimates in Y2050 USD account for the cost reductions from improved aircraft technology, but they also account for inflation at 2% per annum. The cost reductions should make air travel in 2050 less expensive when converted back to Y2020 USD, but in the HEA scenario air travel becomes more expensive in real terms because of the increased cost of fuel including charges to offset CO_2 emissions. Nevertheless, rising incomes from resumed economic growth and improved productivity should still allow air travel to remain affordable in 2050.

As anticipated, empty weight is higher for LH_2 T&W aircraft than for the hydrocarbon-fuelled aircraft, but fuel mass is reduced by around 70% because of the high energy density of LH_2. This, taken in combination with the lightweight tank technology selected for 2050 entry into service, favours longer-range designs and operation close to maximum design range, where greater improvements can be observed. However, less mass-efficient tanks with worse gravimetric efficiencies (anticipated for near-term LH_2 aircraft in some other studies) would penalize the LR aircraft more than the SMR aircraft, because the LR aircraft tank weights are proportionately greater.

The Y2050 Lower Risk LH_2 aircraft suffer mass and drag penalties due to their larger and heavier fuel tanks, which make them less energy-efficient relative to the Y2050 hydrocarbon-powered aircraft. However, they are still roughly on par with current aircraft for mission-level energy-efficiency. The introduction of more aggressive technologies and integration concepts in the BWB designs enables significant improvements in terms of aerodynamics and propulsion efficiency. These in turn reduce fuel mass and tank volumes. This leads to lower energy requirements, making the LH_2 LR BWB a more attractive solution.

The most innovative Max Synergy SMR study aircraft is the ‘Cobalt Blue 2’ concept from Safran. This combines gas turbine and fuel cell electric propulsion. By throttling-back the single turbofan engine at cruise to 30% of max cruise thrust, its NOx emissions are greatly reduced. Most of the thrust is then generated by the APADs powered by the fuel cells which do not emit NOx. In this way the aircraft reduces cruise-phase NOx emissions per ASK by around 90% relative to current aircraft. However, the overall design mission NOx emissions would not reduce significantly as most of the NOx would be generated at take-off and climb. Ideally the turbofan would be throttled-back at climb as well as at cruise.

Increased water vapour emissions, contrails and contrail induced cloudiness are of concern when the fuel is hydrogen. Contrail formation with different fuels has been discussed. Studies in ENABLEH2 have used a contrail prediction model based on the Schmidt Appleman criterion. As the criterion implicitly assumes the presence of soot particles in the exhaust, the assumption was made that in the absence of soot particles, ambient aerosols, which are orders of magnitude less abundant, would facilitate heterogenous nucleation. This is expected to reduce the number of ice particles being formed and their optical density. However, the greater amount of water vapour produced by the hydrogen fuelled aircraft, relative to kerosene fuelled aircraft raises the contrail formation threshold temperature. While persistent contrails are expected to form over a wider range of altitudes, they would also be expected to dissipate faster.

Finally, this deliverable describes potential LH_2 production and supply pathways to airports and new airport operations relating to LH_2-fuelled aircraft.

The outlook for hydrogen-fuelled aviation seems bright, but significant research, development and infrastructure investments will be needed to introduce it on a global scale. An accompanying ENABLEH2 public deliverable (D5.2) *Roadmap for the Introduction and Transition to Liquid Hydrogen for Civil Aviation* addresses these issues and identifies 13 ongoing research strands necessary to realize this vision.

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11 Notation

AIC	Aviation-Induced Cloudiness
ALK	Alkaline
APAD	Aero-Propulsion Augmentation Device
APU	Auxiliary Power Unit
ASE	Advanced Subsonic Engine
ASK	Available Seat kilometre
ATAG	Air Transport Action Group
BIO	Biofuel
Bio-SPK	Biomass-sourced Synthetic Paraffinic Kerosene
BLI	Boundary Layer Ingestion
BNEF	Bloomberg New Energy Finance
BWB	Blended Wing Body (aircraft)
CAPEX	Capital Expenditure
CASK	Cost per Available Seat kilometre
CB2	Cobalt Blue 2 (aircraft concept)
CCUS	Carbon Capture Utilisation and Storage
CO2eq	CO2-equivalent Global Warming Potential
COC	Cash Operating Cost
CU	Cranfield University
dB	Decibels
DC	Direct Current
DEN	Denver Airport
EDTO	Extended Diversion Time Operations
EI	Emission Index
EIS	Entry into Service
ERF	Effective Radiative Forcing
ETOPS	Extended-range Twin Operations
FAR	Fuel Air Ratio
FCS	Flight Control System
FL	Flight Level
FL	Flight Level

FT	Fischer–Tropsch
GH2	Hydrogen Gas
GHG	Greenhouse gas
GWP	Global Warming Potential
HEA	Heightened Environmental Awareness (scenario)
HEFA	Hydro-processed Esters and Fatty Acids
HGV	Heavy Goods Vehicle
ISA	International Standard Atmosphere
ISSR	Ice Super-Saturated Region
KCAS	Knots Calibrated Air Speed
LCOH	Levelised Cost Of Hydrogen
LFL	Landing Field Length
LH2	Liquid Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPP	Lean Premixed Prevaporized
LPT	Low Pressure Turbine
LR	Long Range
LROPS	Long-Range Operations
LTO	Landing and Take-Off (cycle)
MA	Morphological Analysis
MJ	Mega Joules
MLW	Maximum Landing Weight
MTOW	Maximum Take-Off Weight
NA	Not Available or Not Applicable
nmi	Nautical Miles
NOx	Oxides of Nitrogen
OEI	One Engine Inoperative
ORC	Organic Rankine Cycle
OWE	Operating Weight Empty

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PAX	Passengers (with luggage)
PEM	Proton Exchange Membrane or Polymer Electrolyte Membrane
PPA	Power Purchase Agreement
PRJ	Projections (technologies 2050)
PtL	Power to Liquid
QFD	Quality Function Deployment
RF	Radiative Forcing
RJF	Renewable Jet Fuel
SAF	Sustainable Aviation Fuel
SAJF	Sustainable Alternative Jet Fuel
SFC	Specific Fuel Consumption
SJF	Sustainable Jet Fuel
SL	Sea Level
SMR	Short/Medium Range
SOA	State of the Art
T&W	Tube and Wing (aircraft)
TeDP	Turbo-electric Distributed Propulsion
TEN-T	Trans-European Transport Network
TLAR	Top-Level Aircraft Requirements
TOFL	Take-off Field Length
TSO	Transmission System Operator
TTC	Time to Climb
USD	US Dollars

ENABLEH2

Public Report

Technology and scenario evaluation studies and benchmarking

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