中国航空学会 Chinese Society of Aeronautics and Astronautics
IAGA INTERNATIONAL ASSOCIATION FOR GREEN AVIATION
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Techno-Economic Design Assessment of Hydrogen Fuel-Cell and Hybrid-Electric Propulsion for Regional Aircraft

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Layout of presentation

- DAF Research group @ University of Naples
- Motivation
- Design methodologies and tools for Hybrid and Full-Electric H2 aircraft
- Application case and TLAR
- Optimal solutions
- Results on environmental and economical consideration

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

- The University of Naples Federico II was founded by emperor of the Holy Roman Empire **Frederick II on 5 June 1224**.





Department of Industrial Engineering :

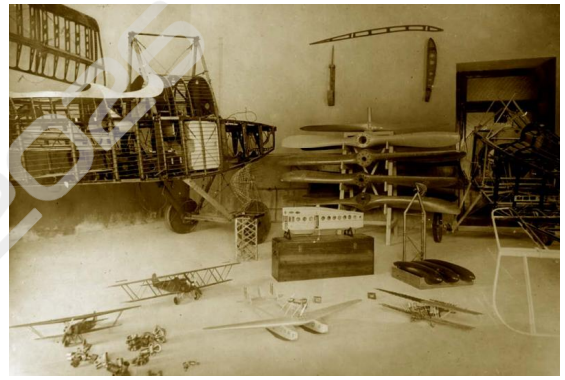
- About 150 Professors
- (Aerospace, Mechanical, Energy, Management, Naval)
- About 5 MSc Degree courses with 3000-4000 enrolled students per year

AEROSPACE Engineering is part of the Department with about 40 among Professors and Researchers

2026, 100 years of our Aerospace Engineering School !







DAF Research Group

DAF Research Group

- **F. Nicolosi – Full Professor - Coordinator**
- A. De Marco – Associate Professor
- P. Della Vecchia – Associate Professor
- S. Corcione – Assistant Professor
- M. Di Stasio – Assistant Professor
- D. Ciliberti – Post-Doc Researcher
- V. Cusati – Post-Doc researcher
- About 8-10 PhD students

Industrial Collaboration

LEONARDO
AIRBUS
QUALITY AIRCRAFT SINCE 1948 TECNAM
ATR
SAFRAN
MTU Aero Engines
CIRA Centro Italiano Ricerche Aerospaziali
Avio Aero a GE Aerospace company
Clean Sky 2
DLR
ONERA THE FRENCH AEROSPACE LAB
EASA European Aviation Safety Agency
CLEAN AVIATION

Our Spinoff

SMARTUP ENGINEERING

Recent research activities:

- Hydrogen aircraft design

EU projects : FAME (AIRBUS)
HEROPS (MTU)
HERO (AIRBUS)

- Hybrid/Electric A/C design
- Software and tools development
- Wind-Tunnel Tests (high AR wing)
- Wind-Tunnel Tests (DEP effects)
- E-V-ToL aircraft

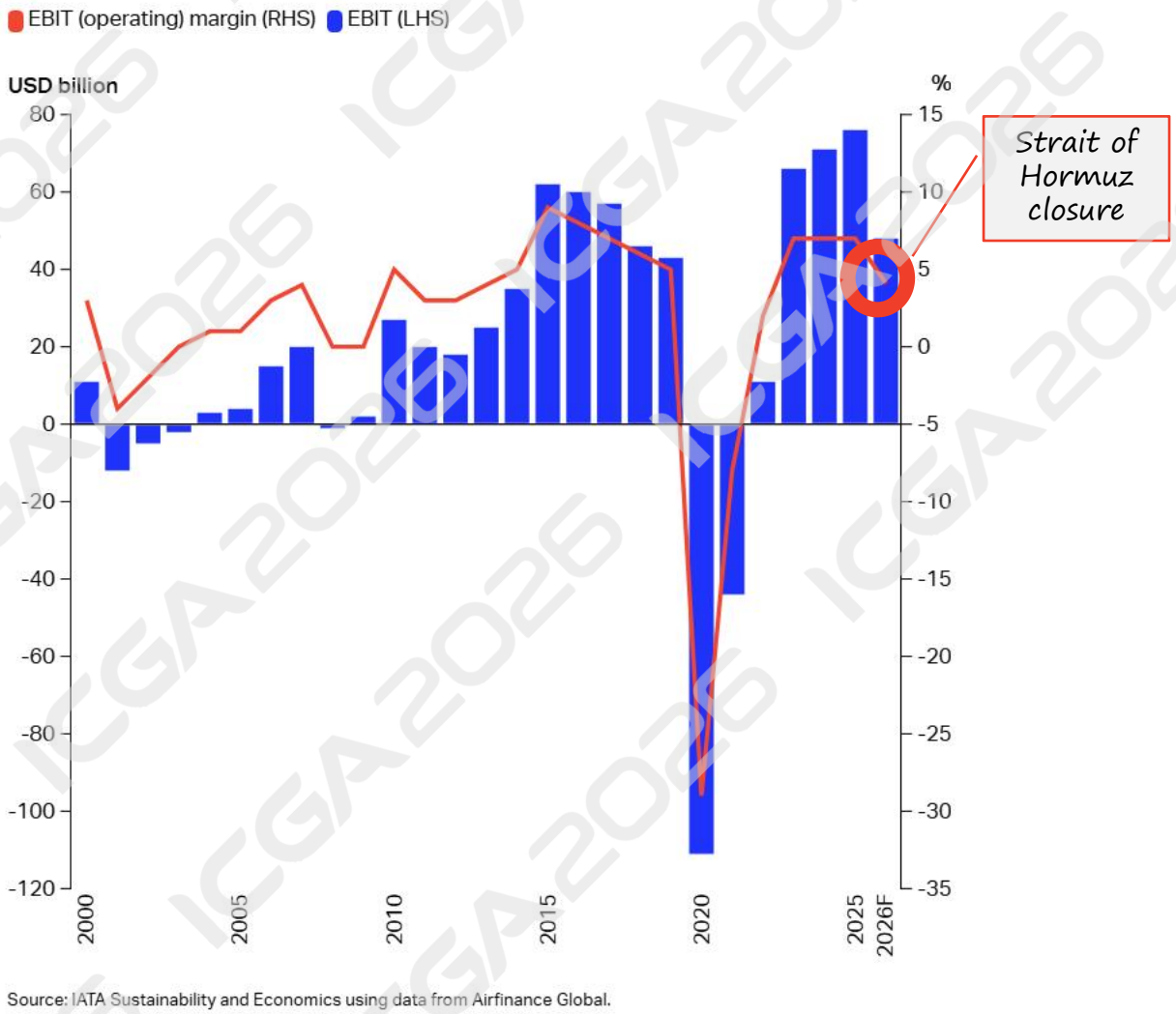
Distributed Electric Propulsion Tests





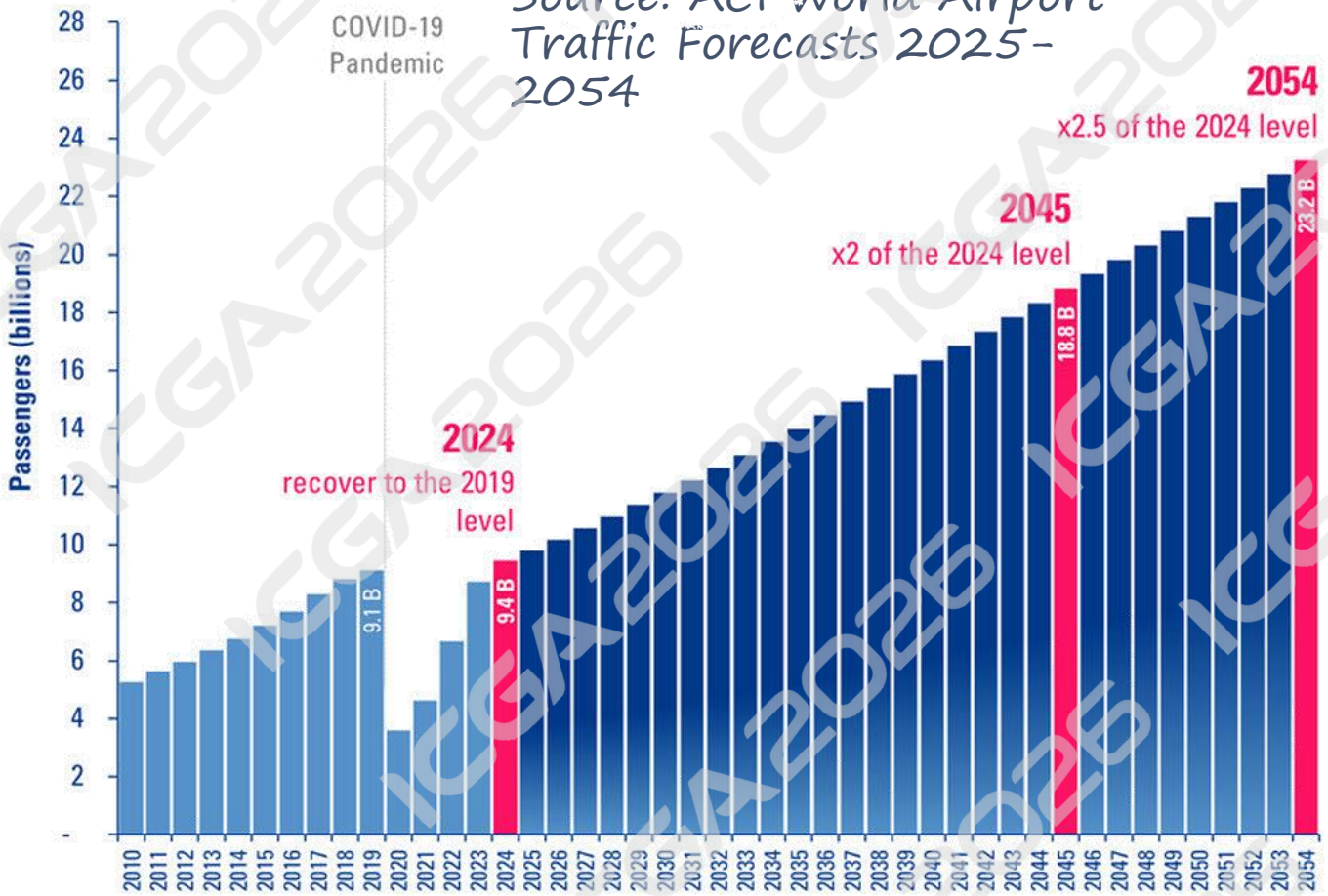
Motivation

- Global airline profitability is expected to remain positive in 2026, with **EBIT of about USD 48 billion** and an **EBIT margin of 4.1%**.
- This represents a marked decline from the **7.2% EBIT margin estimated for 2025**, following the strong post-COVID recovery in airline profitability.
- A broad return to industry-wide losses appears unlikely, although higher costs and slower demand growth are expected to put **increasing pressure on airline profitability**.

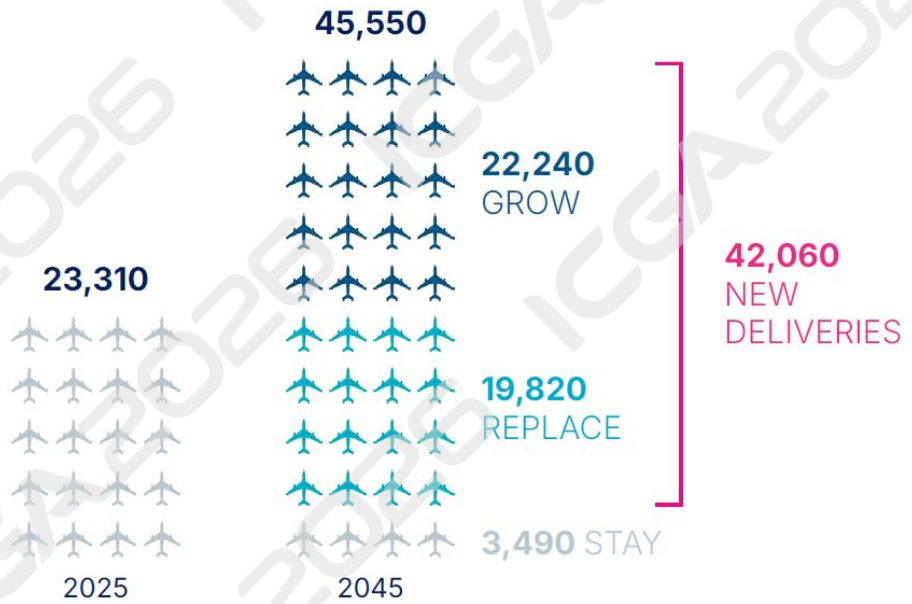


Long-Term Global Passenger Traffic Forecast
(2010 – 2054)

Source: ACI World Airport Traffic Forecasts 2025-2054



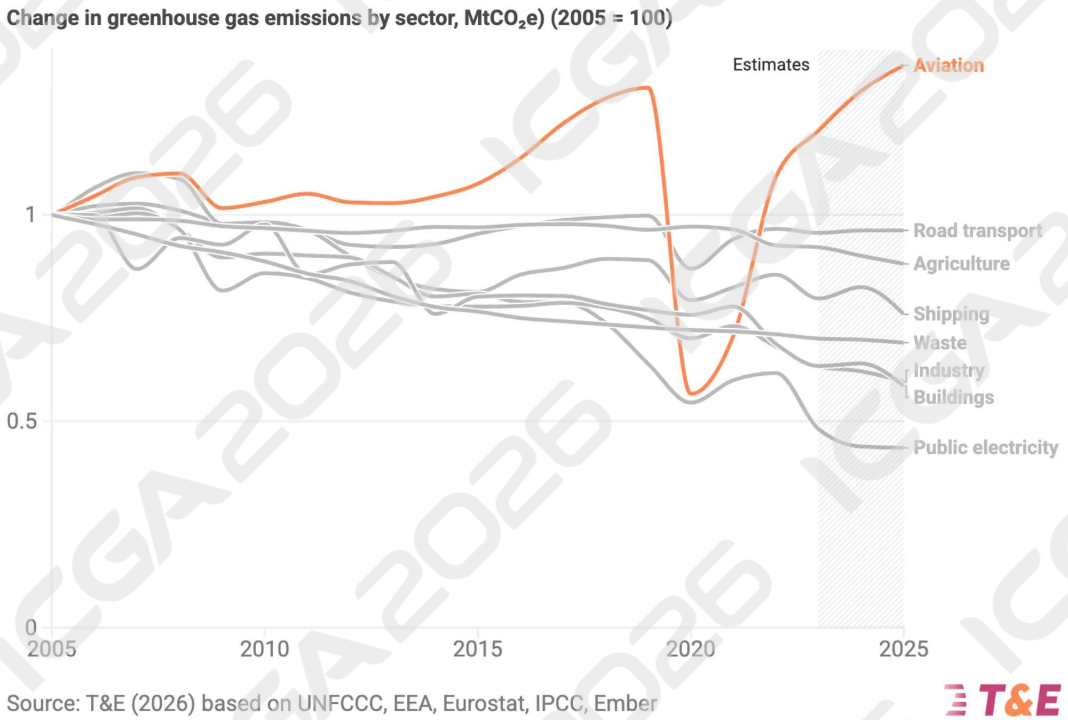
A big opportunity for aviation industry



Source: Airbus Global Market Forecast 2026-2045

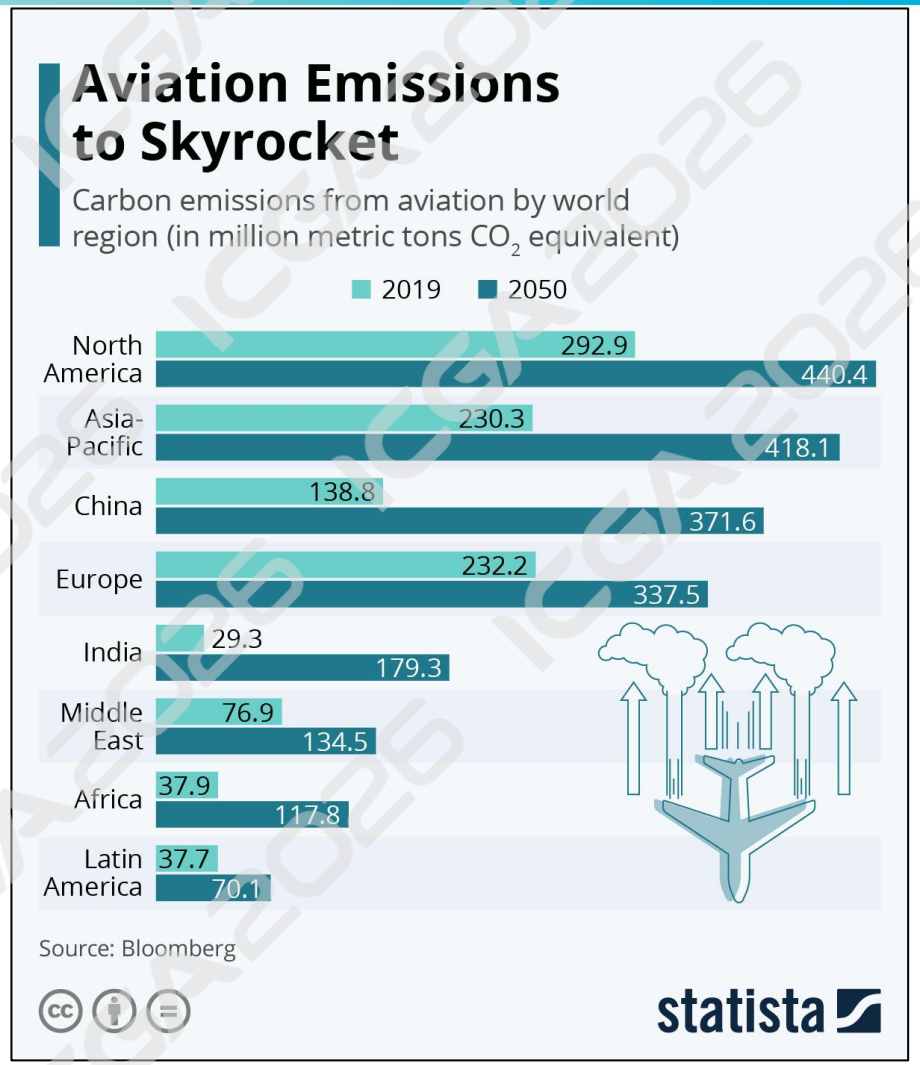
Ageing fleets and increased passenger demand will lead to increased emissions !

Aviation emissions have risen by more than 30% since 2005, while emissions from other sectors have been reduc



Source: T&E (2026) based on UNFCCC, EEA, Eurostat, IPCC, Ember

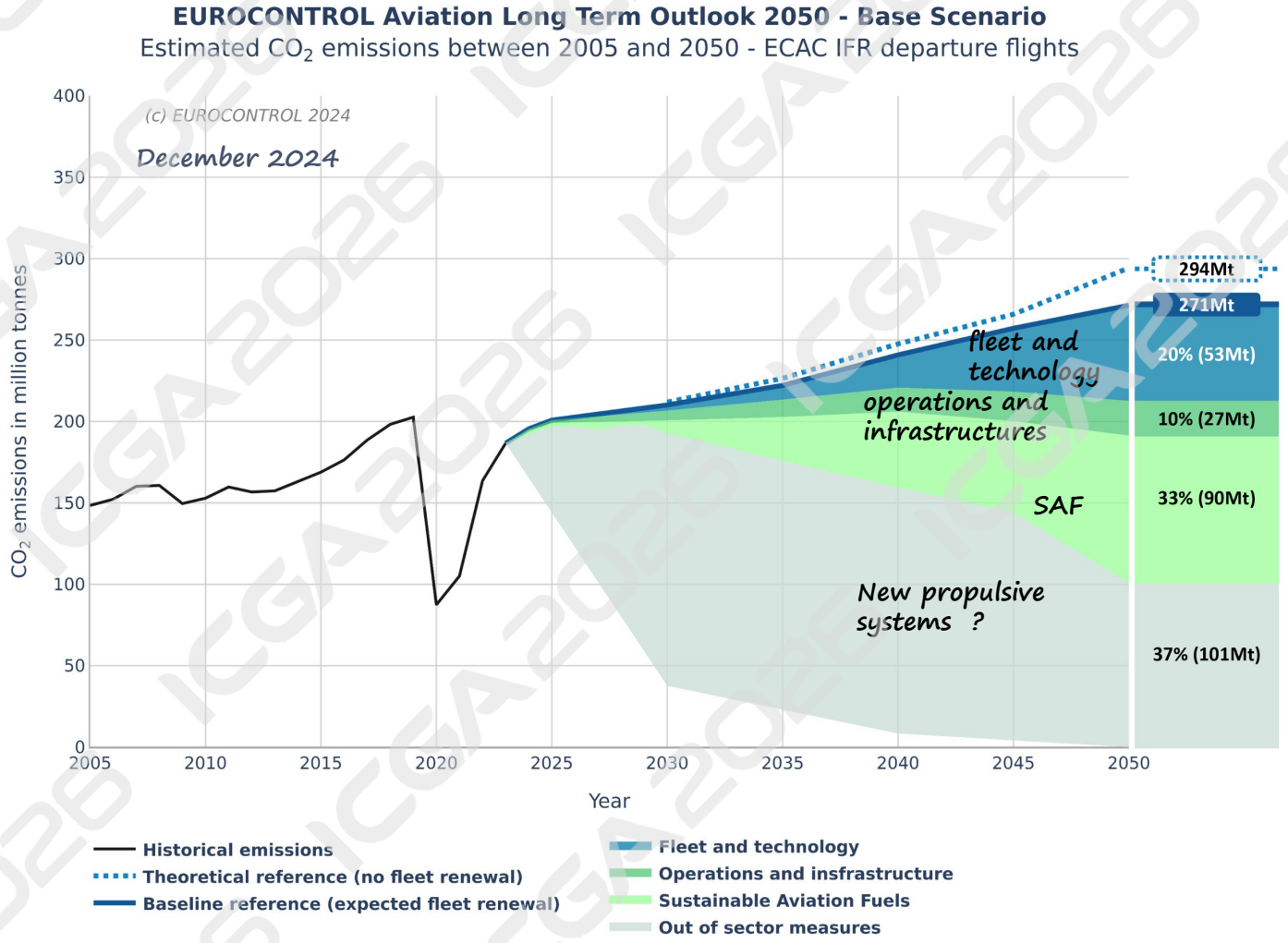
T&E



To get to the net-zero target, the key sustainability factors identified would require savings:

- 53 Mt (**20%** of the total carbon emissions in 2050) from fleet and technology
- 27 Mt (**10%**) from operations and infrastructures (incl. innovation in ATM)
- 90 Mt (**33%**) from Sustainability Aviation Fuels (SAF).

And the remaining gap to net-zero (101 Mt or **37%**) would have to be covered by out-of-sector measures ….



Hydrogen propelled aircraft

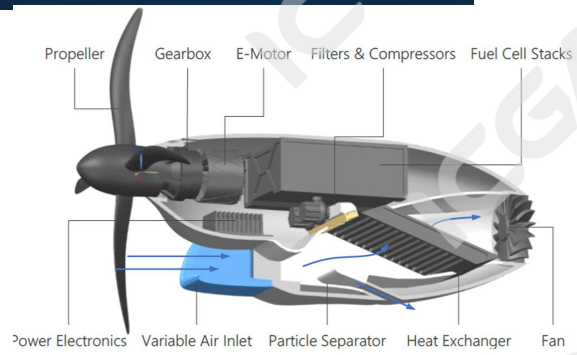


Two Complementaries Propulsion Pathways

- *Hydrogen combustion*
- *Hydrogen fuel-cell electric prop*

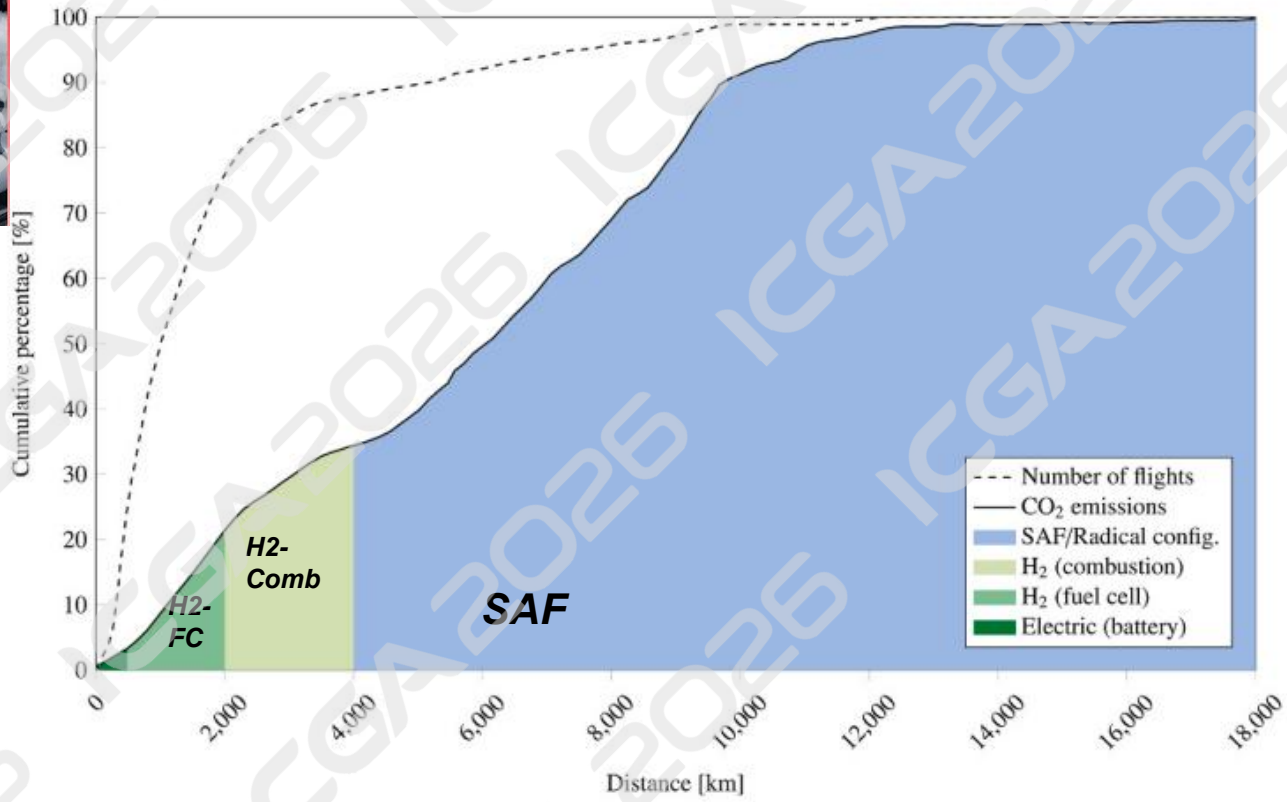


Regional Scale





different aircraft classes and missions require different solutions…

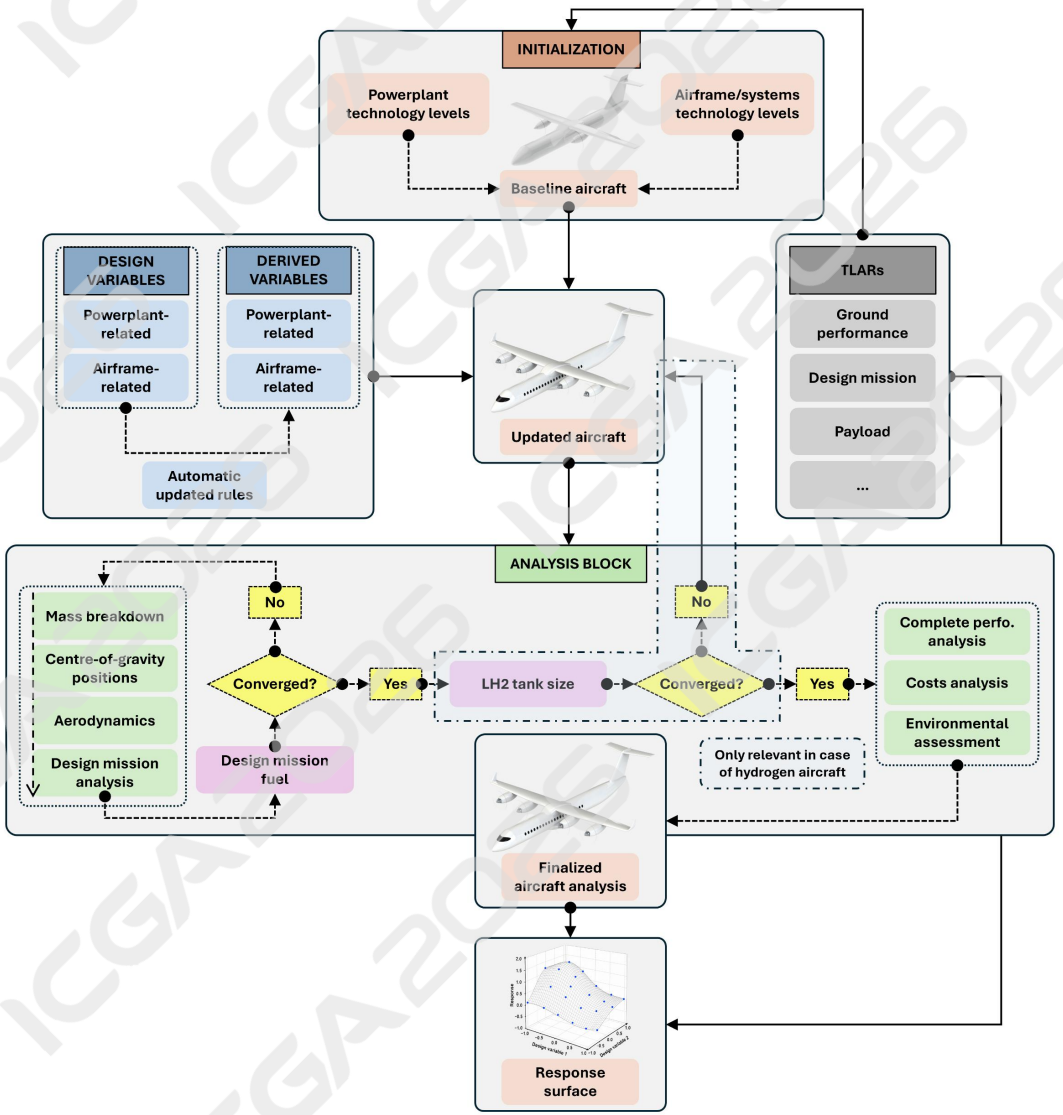


Design methodologies and tools for Hybrid and Full-Electric H2 aircraft

- **Classical estimation of weight and aerodynamic for the airframe**
- **Bottom-up powerplant**
  Mass, losses, usable power
- **Detailed modelling of powertrain components**
  Fuel cell, Electric motor, Cables, power electronics, LH2 tank and line, Thermal Management System.
  Modelling of conventional turboprop engine

Two convergence loops
Fuel / MTOM and LH_2 integration
Feasible optimum
Minimum mission fuel



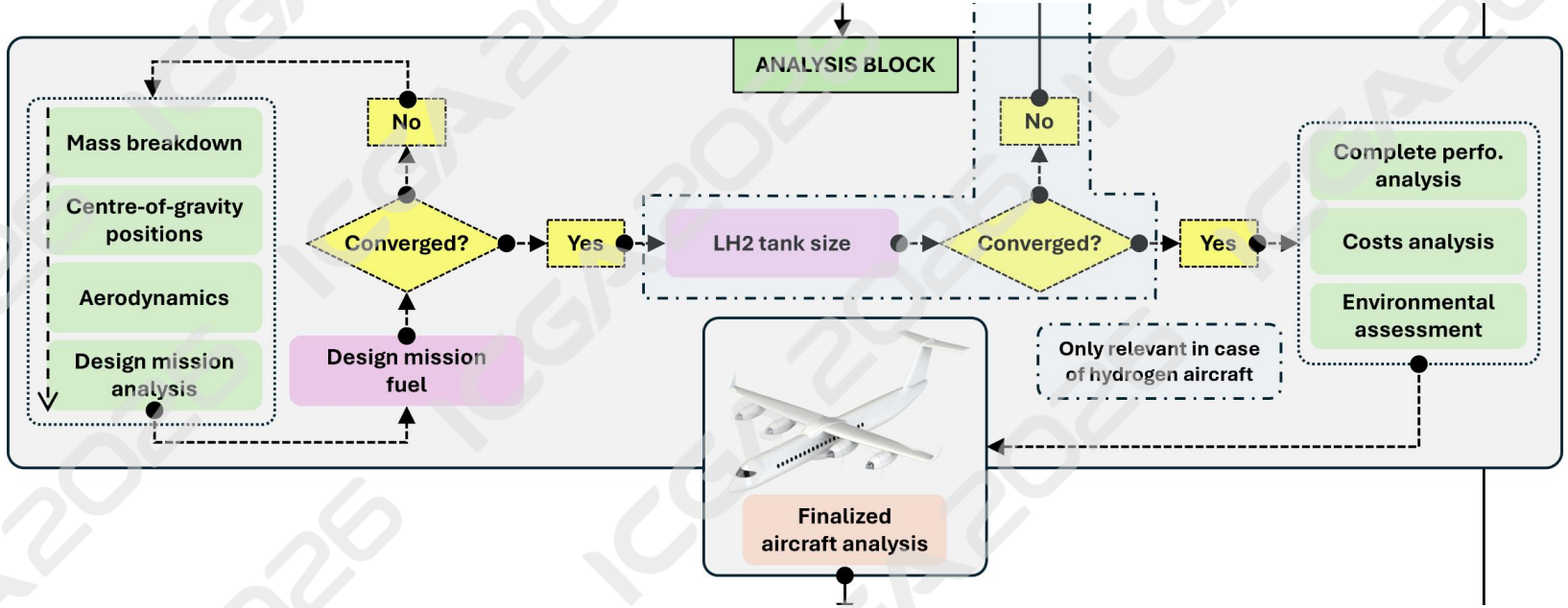


Coupled aircraft and hydrogen-storage sizing

HEART conceptual design workflow

Inner loop: aircraft mass and mission fuel

Outer loop: hydrogen tank sizing and fuselage integration

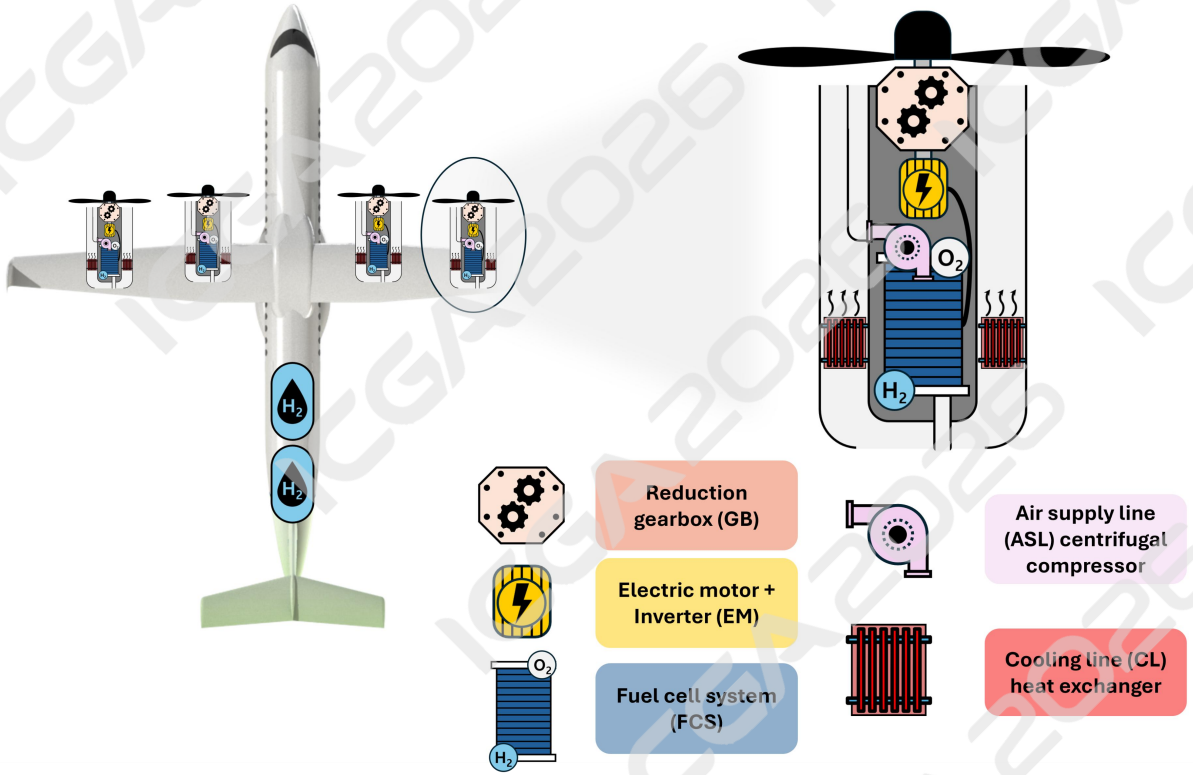


Component Technological level (EIS 2040)

LH2 tank gravimetric index

≈ 40%

Hydrogen fuel-cell architecture

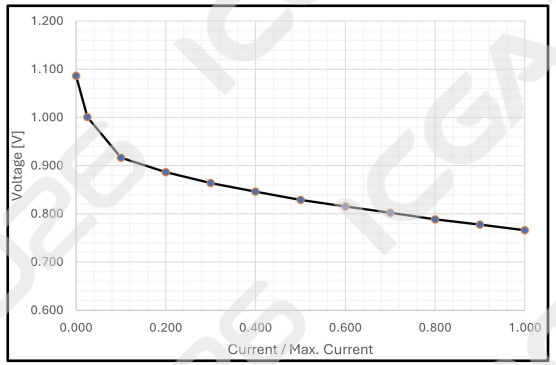


Variable	Value
Hydrogen tank	
Hydrogen gravimetric energy density (LHV)	33.3 kWh/kg
Tank technology	Cryogenic
Capability	240 min @ISA+40°C w/o venting
Insulation	Vacuum + multi-layer insulation
Number of tanks	2
Fuel cell system (FCS)	
Gravimetric power density	2.0 kW/kg
Volumetric power density	2.0 kW/L
Efficiency @max. power	55.0%
Efficiency @min. power	65.0%
Nominal voltage	800 V
FCS air supply line (ASL) and cooling line (CL)	
ASL gravimetric power density	7.1 kW/kg
CL gravimetric power density	3.0 kW/kg
FCS-generated heat % removed through the exhaust	10.0%
ASL+CL FCS power extraction @SL, ISA	8.0%
ASL+CL FCS power extraction @8500 m, ISA	19.0%
Power line (PL)	
Electric motor and power electronics	15.0 kW/kg
Electric motor efficiency	98.0%
Inverter efficiency	98.0%
Cables efficiency	99.5%
Reduction gearbox efficiency	99.0%

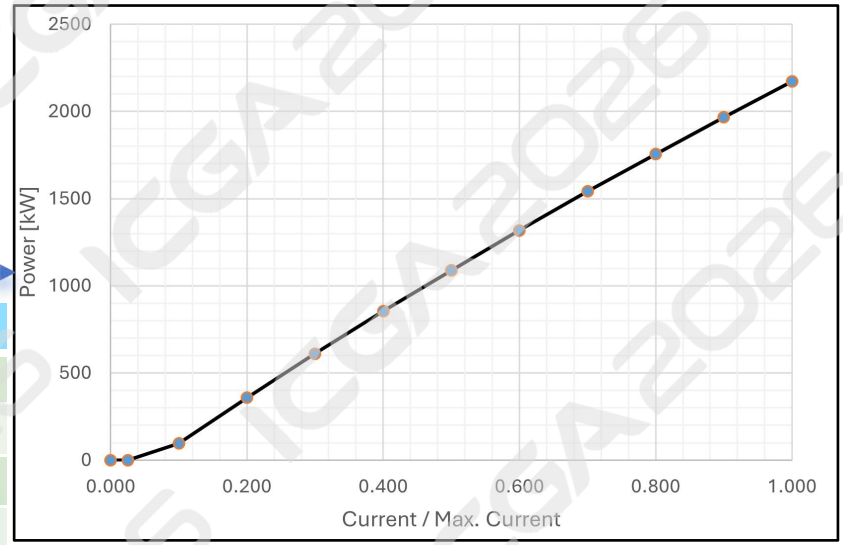
Design methodologies and tools for Hybrid and Full-Electric H2 aircraft

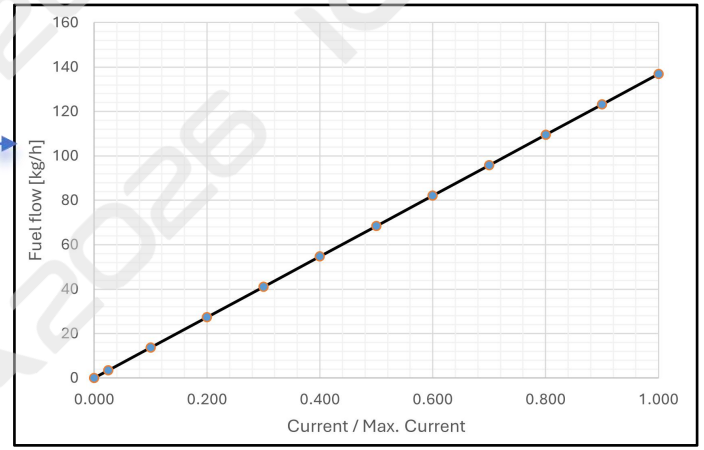
Fuel cell system (FCS) + Cooling line (CL) + Air Supply Line (ASL)

Input parameters
Fuel cell max. current density
Fuel cell active area
Fuel cell polarization curve
FCS sizing power
FCS nominal voltage
FCS gravimetric power density
FCS volumetric power density
CL power density
CL cooling capability per cooling power
ASL power extraction
ASL gravimetric power density
(Non-propulsive) power off-takes



Output
FCS output power [1]
FCS fuel flow
FCS total mass [2]
FCS length
FCS cross-section size
Number of parallel stacks
Number of stack's cells in series





1. Including CL, ASL and non-propulsive off-takes.
2. Including CL and ASL masses.

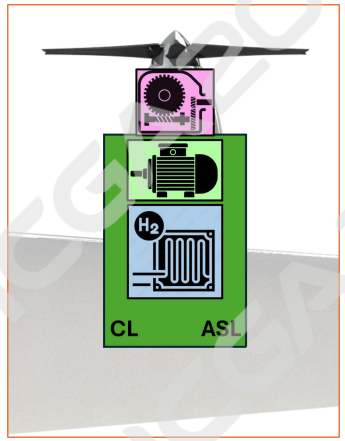
Estimated adopting the simulation-based approach described by Winnefeld.

LH2 tank

Input parameters	
Max. outer diameter	Total thickness
Gravimetric index	LH2 density
Head-to-length ratio	Total LH2 mass

Output
LH2 tank mass
LH2 tank total length
LH2 tank internal volume

Design methodologies and tools for Hybrid and Full-Electric H2 aircraft



FCS + CL + ASL – Performance

- Fuel cell module target power provided as an input.
- Fuel cell default polarization curve calibrated to match target 55% efficiency @max. current intensity.
- Air supply line power extraction accounted.
- Cooling line power extraction accounted.

$$P_{\mathrm{H2,\,Cell}} = \frac{I_{\mathrm{Cell}} \cdot SE_{\mathrm{H2}} \cdot mm_{\mathrm{H2}}}{N_e \cdot F} \qquad P_{\mathrm{Cell}} = V_{\mathrm{Cell}} \cdot I_{\mathrm{Cell}}$$

$$\eta_{\mathrm{FC}} = \frac{V_{\mathrm{Cell}} \cdot N_e \cdot F}{SE_{\mathrm{H2}} \cdot mm_{\mathrm{H2}}} = \frac{V_{\mathrm{Cell}}}{V_{\mathrm{Ref.}}} \qquad FF_{\mathrm{FC}} = \frac{I_{\mathrm{Cell}} \cdot mm_{\mathrm{H2}}}{N_e \cdot F} \cdot N_{\mathrm{Cell}} \cdot \frac{1}{\eta_{\mathrm{Utilization}}}$$

Fuel cell

Power Fraction	Voltage	Output Power	Fuel Flow	SFC	Oxygen Flow	Air Flow	Waste Water Flow	Efficiency
-	V	W	kg/h	kg/kWh	kg/h	kg/h	kg/h	-
0.000	1.086	0.0	0.00000	0.0000	0.00000	0.00000	0.00000	0.000
0.025	1.001	10.8	0.00045	0.0417	0.00358	0.01541	0.00362	0.719
0.100	0.917	39.5	0.00180	0.0456	0.01430	0.06166	0.01449	0.658
0.200	0.887	76.5	0.00360	0.0471	0.02860	0.12332	0.02899	0.637
0.300	0.864	111.8	0.00541	0.0484	0.04290	0.18497	0.04348	0.620
0.400	0.846	145.9	0.00721	0.0494	0.05721	0.24663	0.05797	0.607
0.500	0.829	178.7	0.00901	0.0504	0.07151	0.30829	0.07247	0.595
0.600	0.815	210.9	0.01081	0.0513	0.08581	0.36995	0.08696	0.585
0.700	0.802	242.1	0.01261	0.0521	0.10011	0.43161	0.10145	0.576
0.800	0.789	272.1	0.01442	0.0530	0.11441	0.49327	0.11595	0.566
0.900	0.778	301.8	0.01622	0.0537	0.12871	0.55492	0.13044	0.558
1.000	0.766	330.5	0.01802	0.0545	0.14302	0.61658	0.14493	0.550

Fuel cell system

Power Fraction	Voltage	Output Power	Fuel Flow	SFC	Oxygen Flow	Air Flow	Waste Water Flow	Efficiency
-	V	kW	kg/h	kg/kWh	kg/h	kg/h	kg/h	-
0.000	1031	0.00	0.00	0.0000	0.0	0.0	0.0	0.000
0.025	950	81.94	3.42	0.0417	27.1	117.0	27.5	0.719
0.100	870	300.16	13.68	0.0456	108.6	468.1	110.0	0.658
0.200	841	580.58	27.36	0.0471	217.2	936.2	220.1	0.637
0.300	820	848.46	41.04	0.0484	325.7	1404.3	330.1	0.620
0.400	803	1107.89	54.73	0.0494	434.3	1872.4	440.1	0.607
0.500	787	1356.86	68.41	0.0504	542.9	2340.5	550.2	0.595
0.600	774	1601.19	82.09	0.0513	651.5	2808.7	660.2	0.585
0.700	761	1838.19	95.77	0.0521	760.0	3276.8	770.2	0.576
0.800	748	2065.56	109.45	0.0530	868.6	3744.9	880.3	0.566
0.900	738	2291.39	123.13	0.0537	977.2	4213.0	990.3	0.558
1.000	727	2508.79	136.82	0.0545	1085.8	4681.1	1100.3	0.550

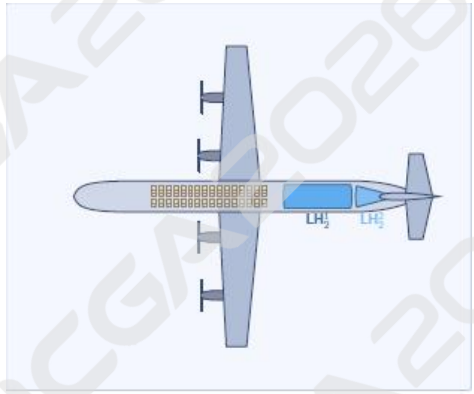
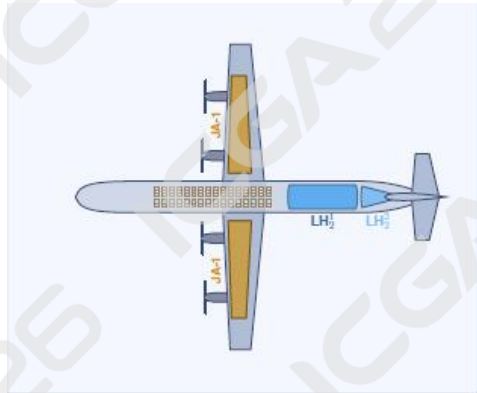
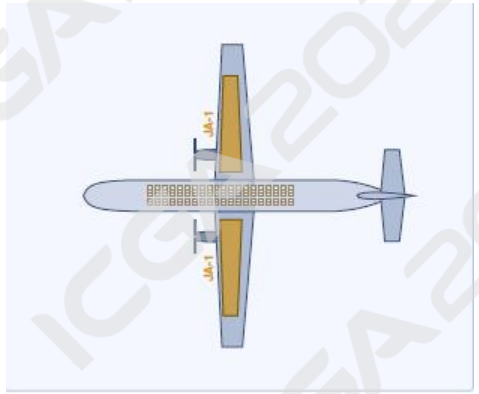
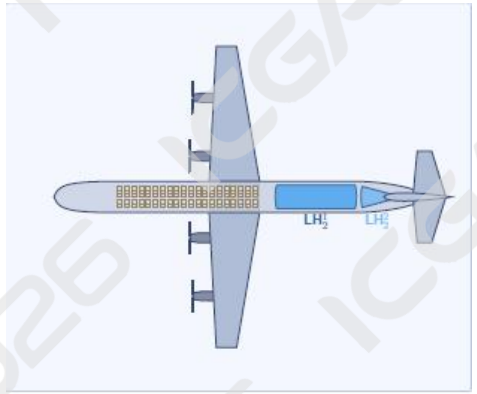
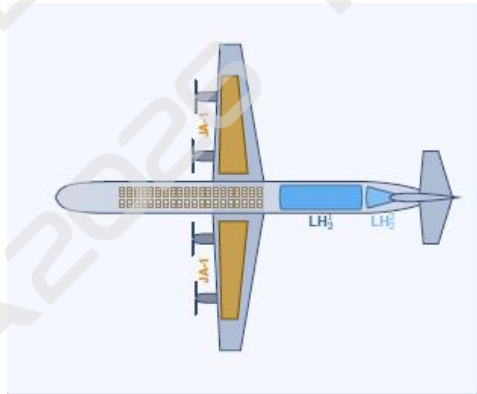
FC+ ASL + CL (ground)

Power Fraction	Voltage	Output Power	Fuel Flow	SFC	Oxygen Flow	Air Flow	Waste Water Flow	Efficiency
-	V	kW	kg/h	kg/kWh	kg/h	kg/h	kg/h	-
0.000	1031	0.00	0.00	0.0000	0.0	0.0	0.0	0.000
0.025	950	0.00	3.42	0.0000	27.1	117.0	27.5	0.000
0.100	870	145.39	13.68	0.0941	108.6	468.1	110.0	0.319
0.200	841	408.99	27.36	0.0669	217.2	936.2	220.1	0.448
0.300	820	660.80	41.04	0.0621	325.7	1404.3	330.1	0.483
0.400	803	904.66	54.73	0.0605	434.3	1872.4	440.1	0.496
0.500	787	1138.70	68.41	0.0601	542.9	2340.5	550.2	0.499
0.600	774	1368.36	82.09	0.0600	651.5	2808.7	660.2	0.500
0.700	761	1591.14	95.77	0.0602	760.0	3276.8	770.2	0.498
0.800	748	1804.88	109.45	0.0606	868.6	3744.9	880.3	0.495
0.900	738	2017.15	123.13	0.0610	977.2	4213.0	990.3	0.491
1.000	727	2221.51	136.82	0.0616	1085.8	4681.1	1100.3	0.487

FC+ ASL+ CL (flight)

Power Fraction	Voltage	Output Power	Fuel Flow	SFC	Oxygen Flow	Air Flow	Waste Water Flow	Efficiency
-	V	kW	kg/h	kg/kWh	kg/h	kg/h	kg/h	-
0.000	1031	0.00	0.00	0.0000	0.0	0.0	0.0	0.000
0.025	950	18.41	3.42	0.1858	27.1	117.0	27.5	0.162
0.100	870	223.54	13.68	0.0612	108.6	468.1	110.0	0.490
0.200	841	487.14	27.36	0.0562	217.2	936.2	220.1	0.534
0.300	820	738.94	41.04	0.0555	325.7	1404.3	330.1	0.540
0.400	803	982.81	54.73	0.0557	434.3	1872.4	440.1	0.539
0.500	787	1216.84	68.41	0.0562	542.9	2340.5	550.2	0.534
0.600	774	1446.51	82.09	0.0568	651.5	2808.7	660.2	0.529
0.700	761	1669.29	95.77	0.0574	760.0	3276.8	770.2	0.523
0.800	748	1883.02	109.45	0.0581	868.6	3744.9	880.3	0.516
0.900	738	2095.30	123.13	0.0588	977.2	4213.0	990.3	0.511
1.000	727	2299.65	136.82	0.0595	1085.8	4681.1	1100.3	0.504

Aircraft configurations explored, with EIS 2040

	K Conventional	H Fuel-cell electric	KH Hybrid-electric
80 pax			
100 pax			

Design requirements and optimisation

Requirement	Value
Design range	500 nm
Typical Range	250 nm
Passenger payload	80 or 100 at 110 kg
Wing span	< 36 m (ICAO C)
TOFL and LFL	≤ 1350 m
Approach speed	≤ 120 kn CAS
Cruise capability	M 0.50 at 25,000 ft
Static stability margin	≥ 5% MAC
MTOM limits for K/H	40 / 45 t for 80 / 100 pax

Optimisation objective

Minimum total block fuel mass
Kerosene + hydrogen for KH

Design variables

K: wing area, AR, GT power
H: wing area, AR, FC power
KH: wing area, AR, GT and FC power

Wing area driven by ground performance requirements and aircraft weight

Subsequent comparison
Mission energy and DOC

Main Technology assumptions for 2040

Component	Assumption
Gas turbine engine	10 kW/kg , SFC in line with PW127-like (ATR engine)
Fuel-cell system	1.2 kW/kg and 50% efficiency at rated power (FC stack 2.0 kW/kg and 55% eff)
Electric motor	15 kW/kg and 98% efficiency
Inverter	15 kW/kg and 98% efficiency, 800 V bus
Propeller	12.5 kW/kg
Reduction gearbox	11.1 kW/kg and 97% mechanical efficiency
LH_2 storage	MLI + Vacuum, Structural wall aluminium 2219 liners, fixed venting pressure 2 bar

Backup: investigated design-space ranges

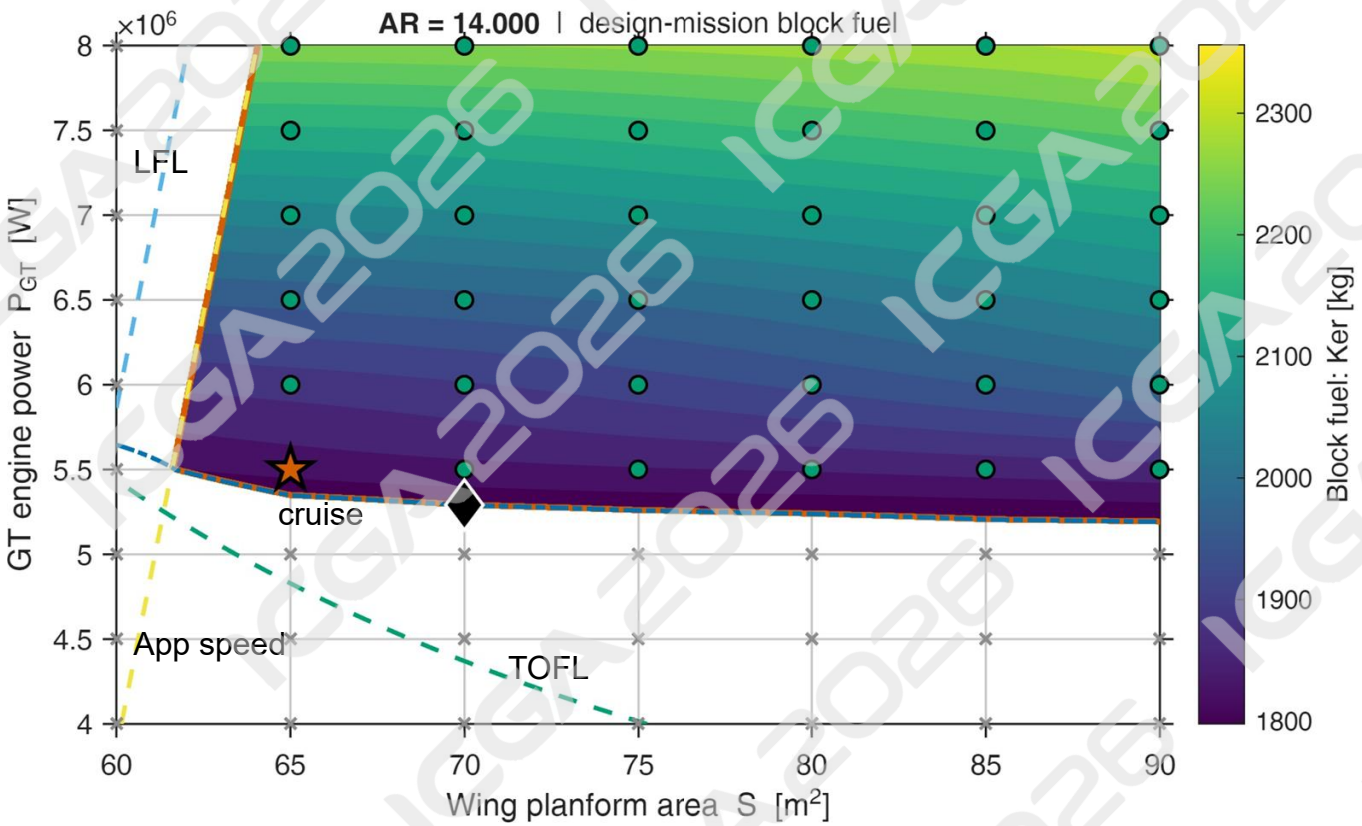
Variable	K80	K100	H80	H100	KH80	KH100
Wing area (m²)	60–90	65–95	80–105	85–105	80–100	85–105
Aspect ratio	12–14	12–14	12–14	12–14	12–14	12–14
GT power (MW)	4–8	4.5–8.5	None	None	1–4	1.5–4.5
Gross FC power (MW)	None	None	6–10	7–11	4–7	5–8
Tank vent pressure (bar)	None	None	2	2	2	2

Power values refer to total installation across all propulsion units

Hybridization (% of electric power vs total power)

min	max
47%	89%

Conventional aircraft design landscape: 80 passengers



Wing area 65.0 m²

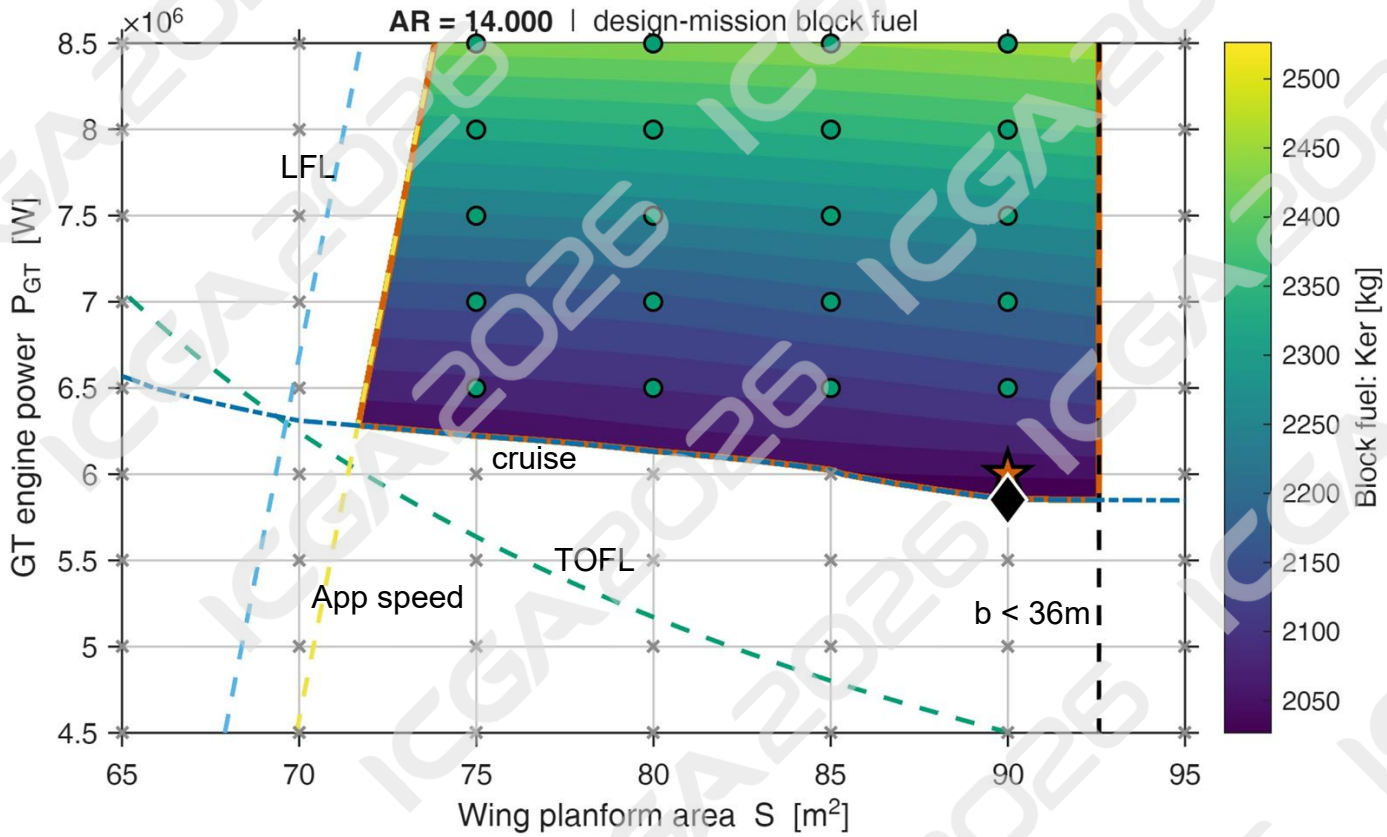
GT power 5.5 MW

(2 turboprop engine 2.75 MW each)

AR 14.0. The selected solution lies near the cruise-power boundary. Span ≈ 30.2 m.

- Feasible boundary
- Span 36 m
- MTOM 40 t
- TOFL 1350 m
- LFL 1350 m
- Approach 120 kn
- Static margin 5% MAC
- Cruise 25,000 ft, M 0.50

Conventional aircraft design landscape: 100 passengers



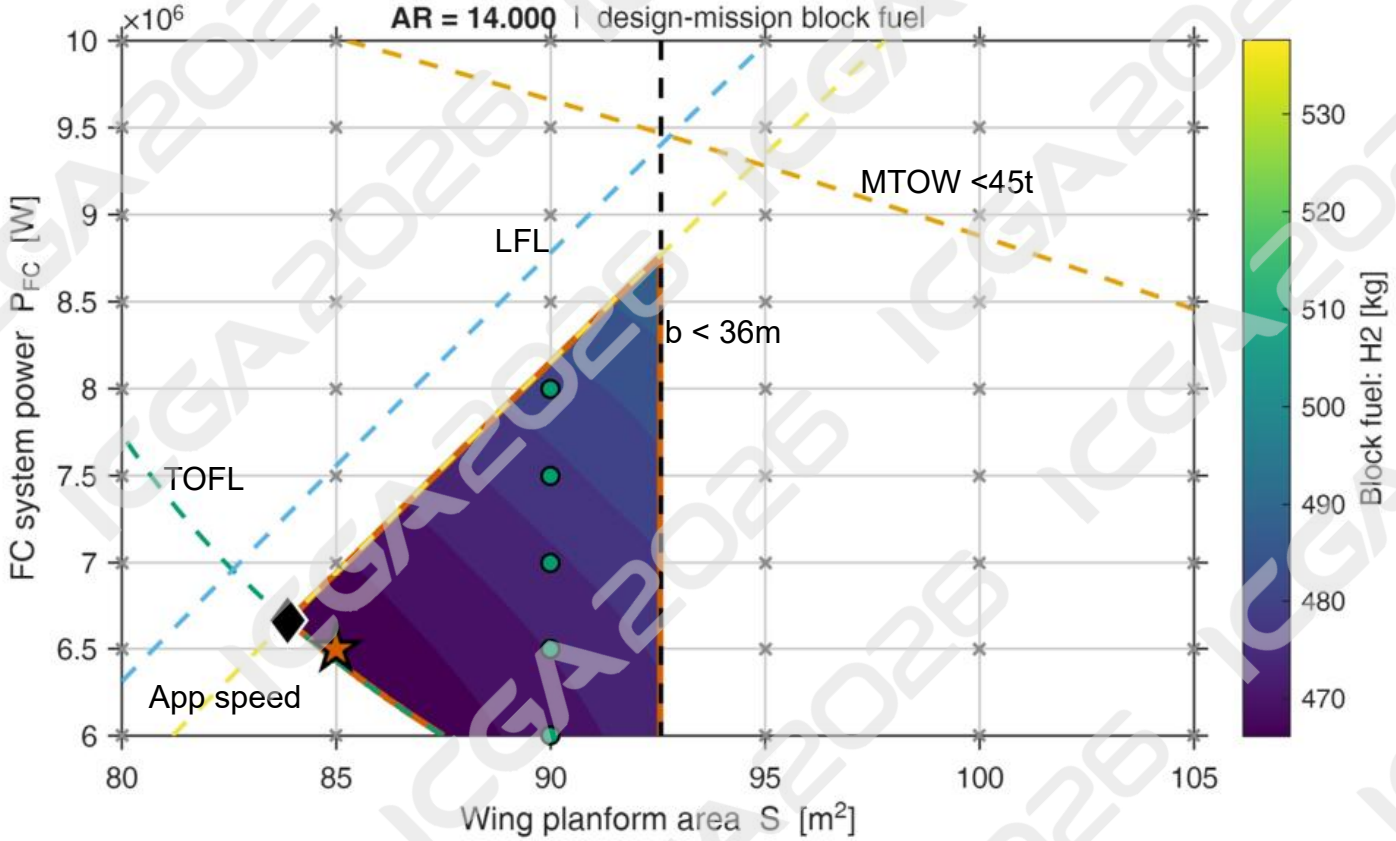
Wing area 87.5 m²

GT power 6.0 MW

AR 14.0. The continuous solution refines the discrete optimum. Span ≈ 35.0 m.

- Feasible boundary
- Span 36 m
- MTOM 45 t
- TOFL 1350 m
- LFL 1350 m
- Approach 120 kn
- Static margin 5% MAC
- Cruise 25,000 ft, M 0.50

Fuel-cell aircraft design landscape: 80 passengers



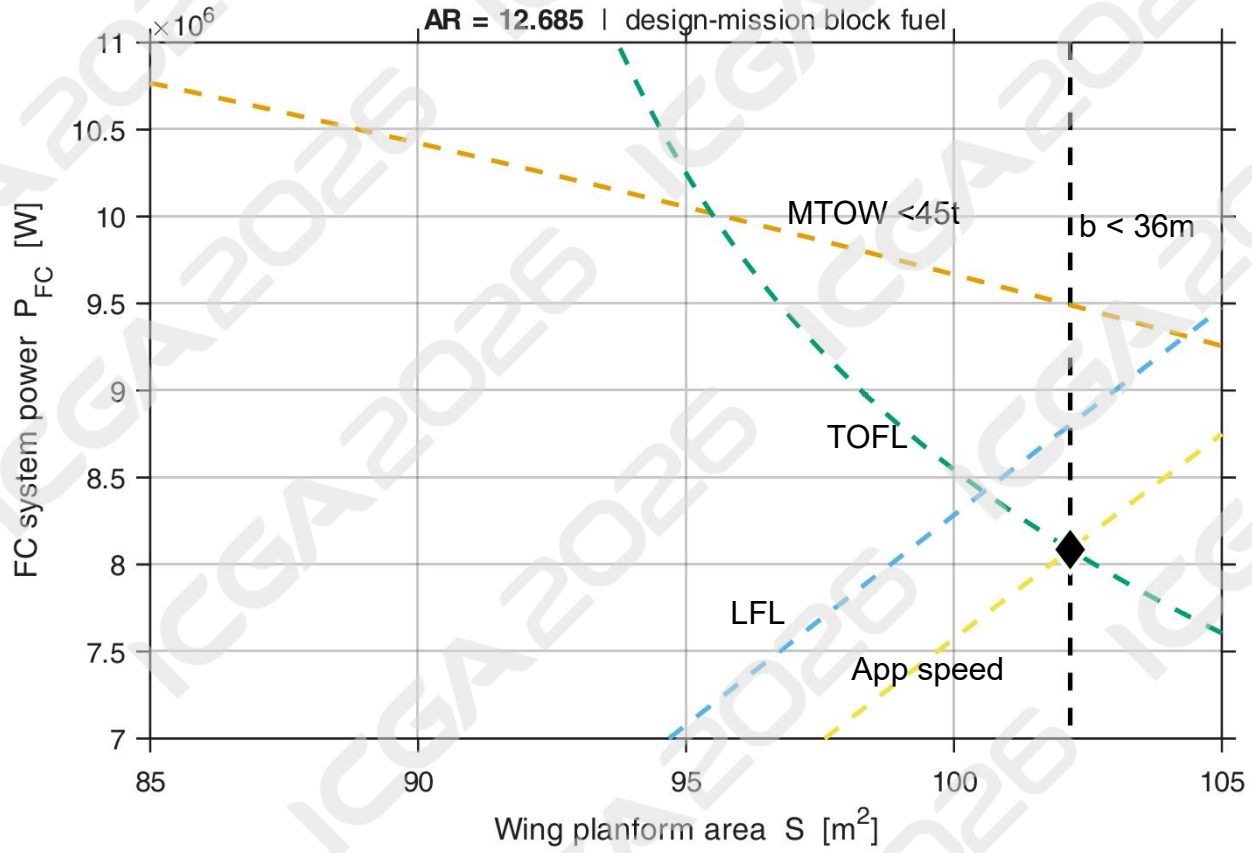
Wing area 83.9 m²

Gross FC power 6.7 MW

AR 14.0. Take-off and approach-speed limits shape the optimum. TOFL 1350 m.

- Feasible boundary
- Span 36 m
- MTOM 40 t
- TOFL 1350 m
- LFL 1350 m
- Approach 120 kn
- Static margin 5% MAC
- Cruise 25,000 ft, M 0.50

Fuel-cell aircraft design landscape: 100 passengers



Wing area 102.2 m²

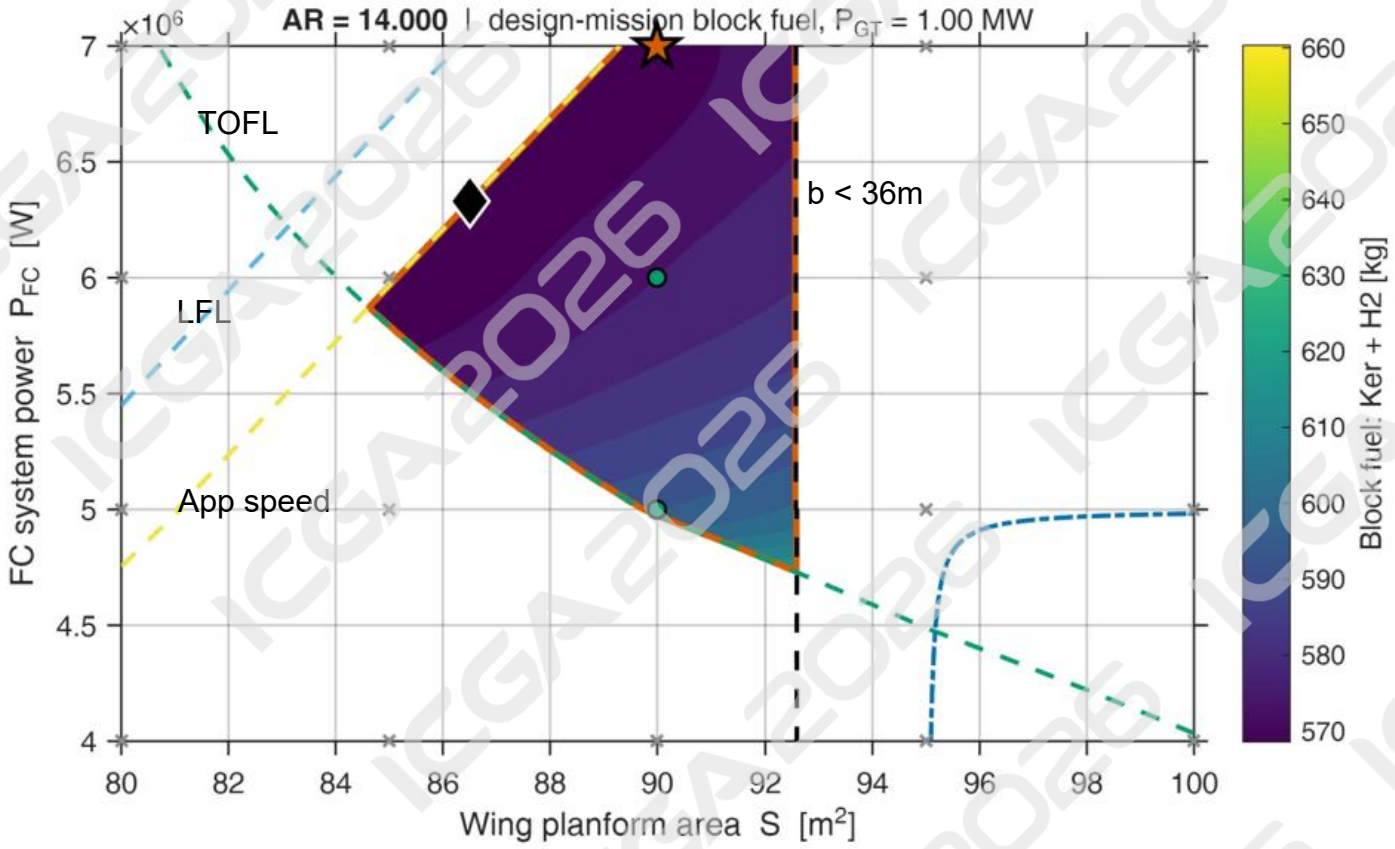
Gross FC power 8.1 MW

AR 12.685. The reported optimum lies near the take-off, approach and span limits.

Source map shows no coloured feasible area at this AR

- Span 36 m
- MTOM 45 t
- TOFL 1350 m
- LFL 1350 m
- Approach 120 kn
- Static margin 5% MAC
- Cruise 25,000 ft, M 0.50

Hybrid aircraft design landscape: 80 passengers



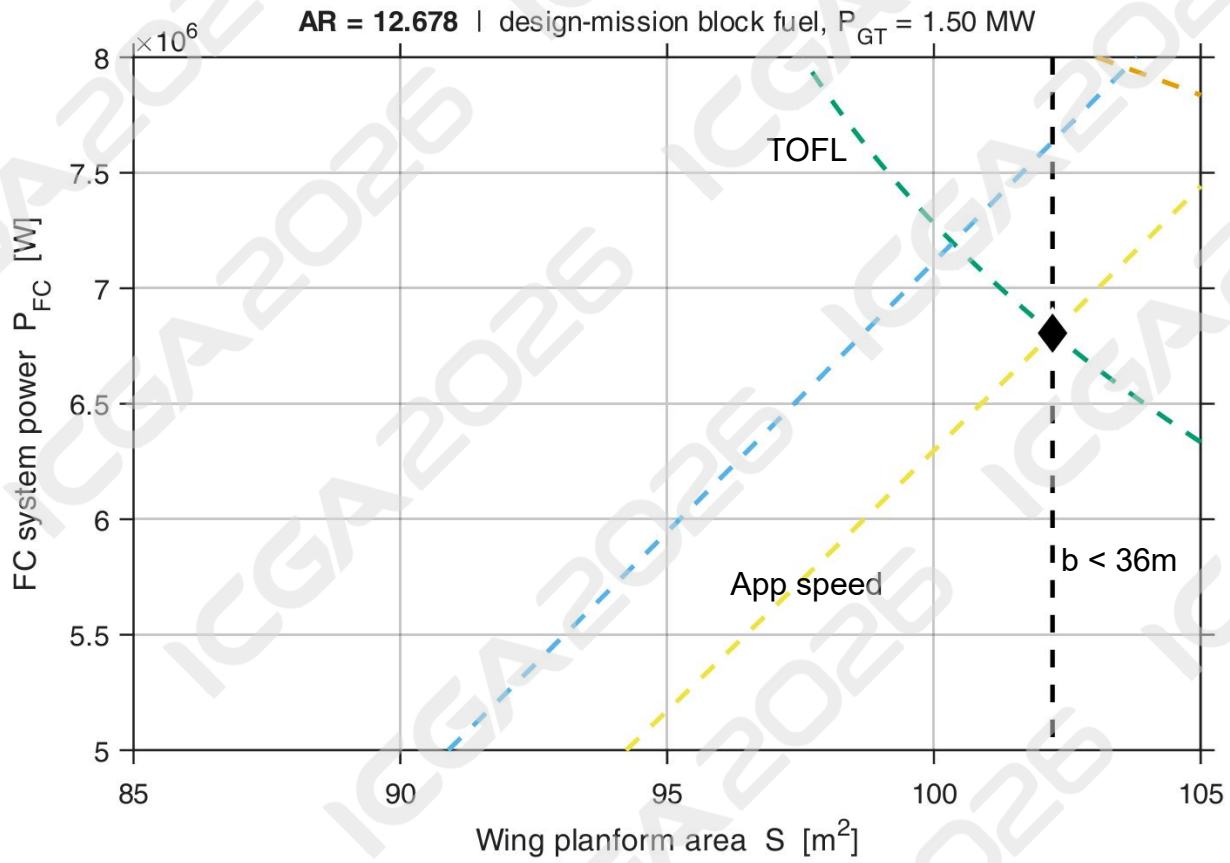
Wing area 86.5 m²

GT 1.0 MW and gross FC 6.3 MW

AR 14.0. Hybridization 86.3%. TOFL 1300 m, with GT power at its lower explored bound.

- Feasible boundary
- Span 36 m
- MTOM 40 t
- TOFL 1350 m
- LFL 1350 m
- Approach 120 kn
- Static margin 5% MAC
- Cruise 25,000 ft, M 0.50

Hybrid aircraft design landscape: 100 passengers



Wing area 102.2 m²

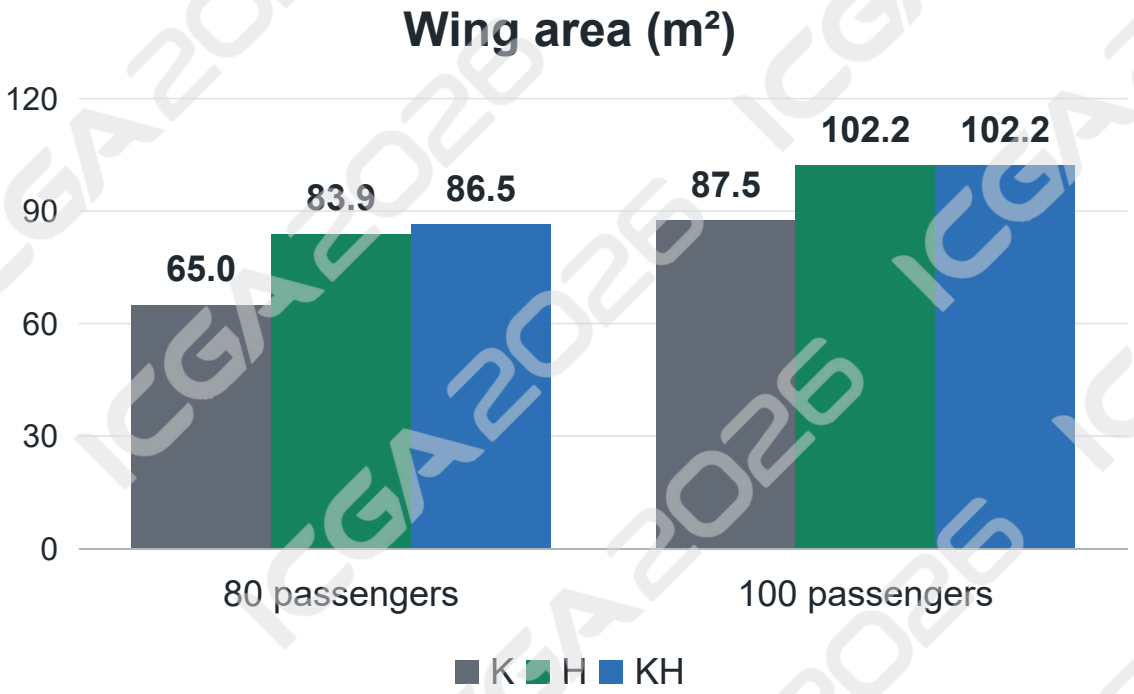
GT 1.5 MW and gross FC 6.8 MW

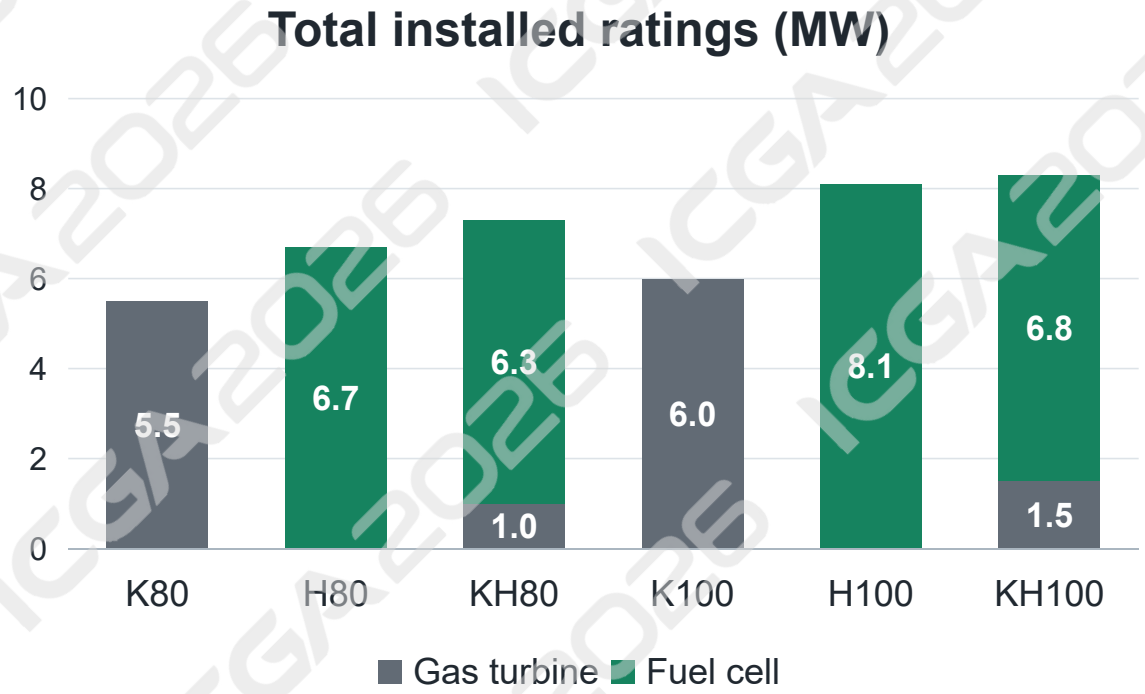
AR 12.678. Hybridization 81.9%. The reported optimum retains the 36 m span limit.

Source map shows no coloured feasible area at this AR

- Span 36 m
- MTOM 45 t
- TOFL 1350 m
- LFL 1350 m
- Approach 120 kn
- Static margin 5% MAC
- Cruise 25,000 ft, M 0.50

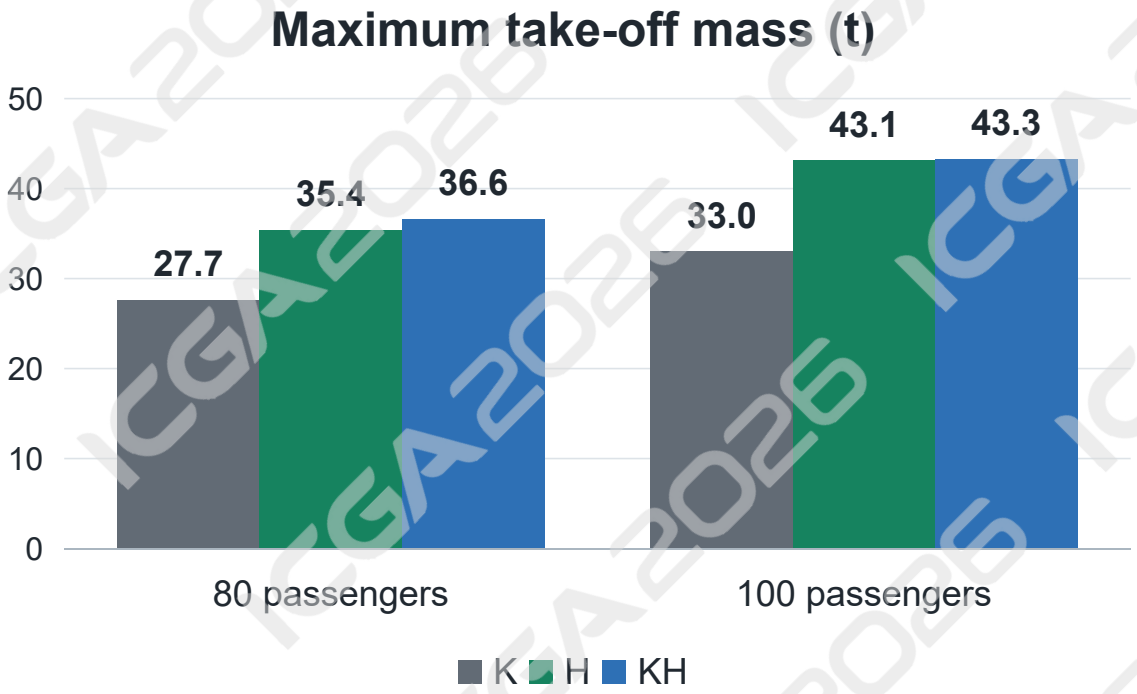
Wing area and total installed power ratings

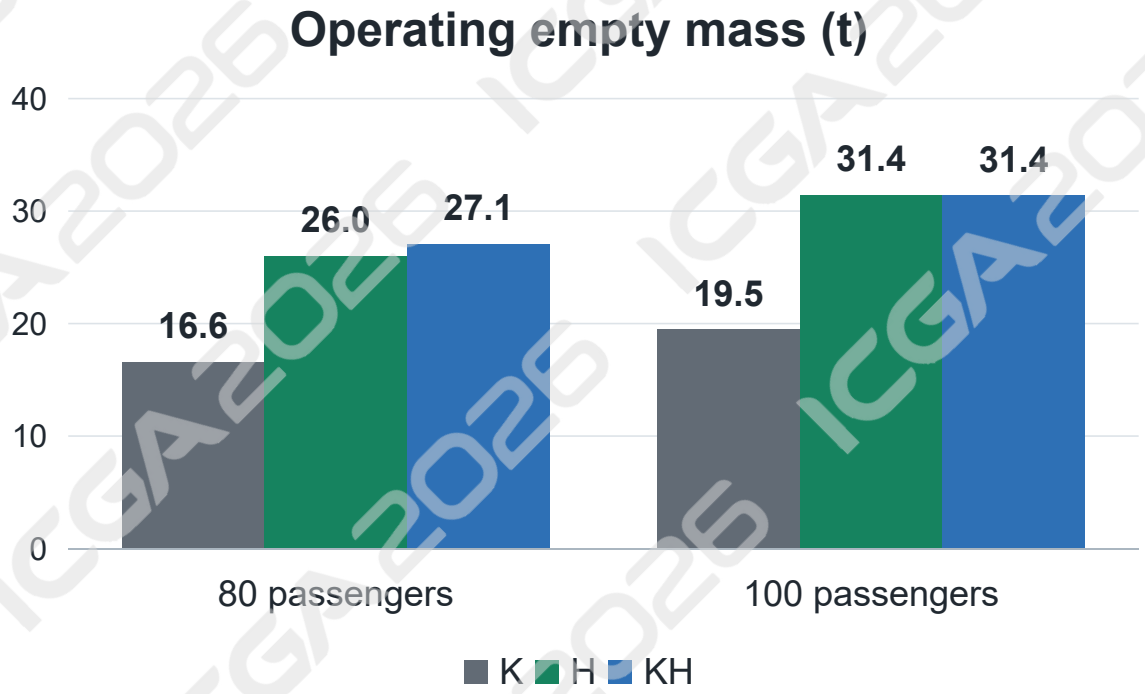




H100 and KH100 select 102.2 m² under the span constraint

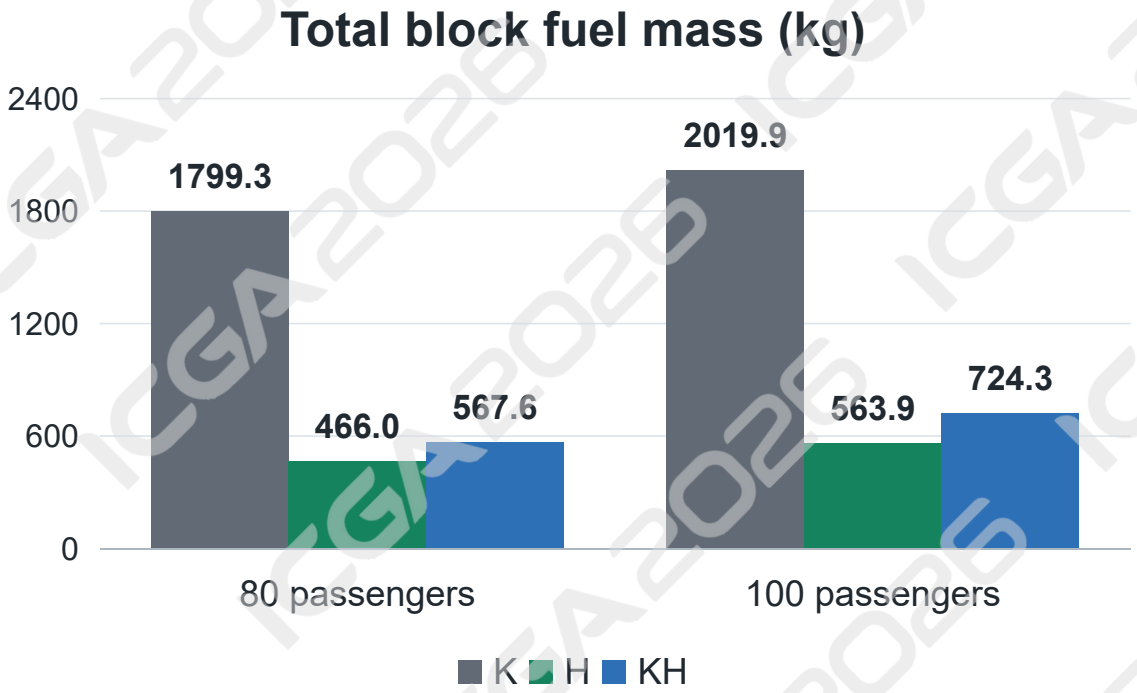
Aircraft mass penalties

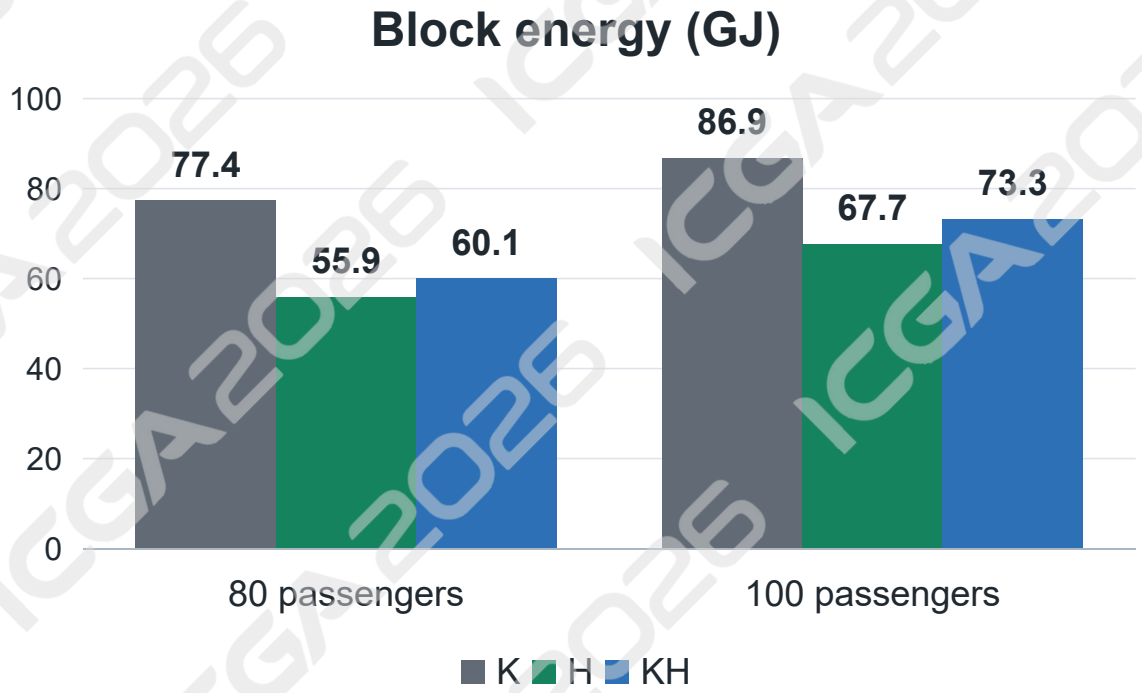




Full-electric MTOM increases by 28.1% at 80 passengers and 30.7% at 100 passengers

Design-mission fuel mass and energy





Energy reductions vs K **H: 27.7% / 22.1%** **KH: 22.4% / 15.6%**

80 pax 100 pax 80 pax 100 pax

Direct operating cost assumptions

250 nm typical mission

Scenario	Kerosene price	Hydrogen price
H_2 -unfavourable	0.51	3.00
Baseline	1.06	2.13
H_2 -favourable	1.95	1.35

Prices in equivalent 2020 USD/kg

6 flights/day 30 min turnaround 20-year depreciation

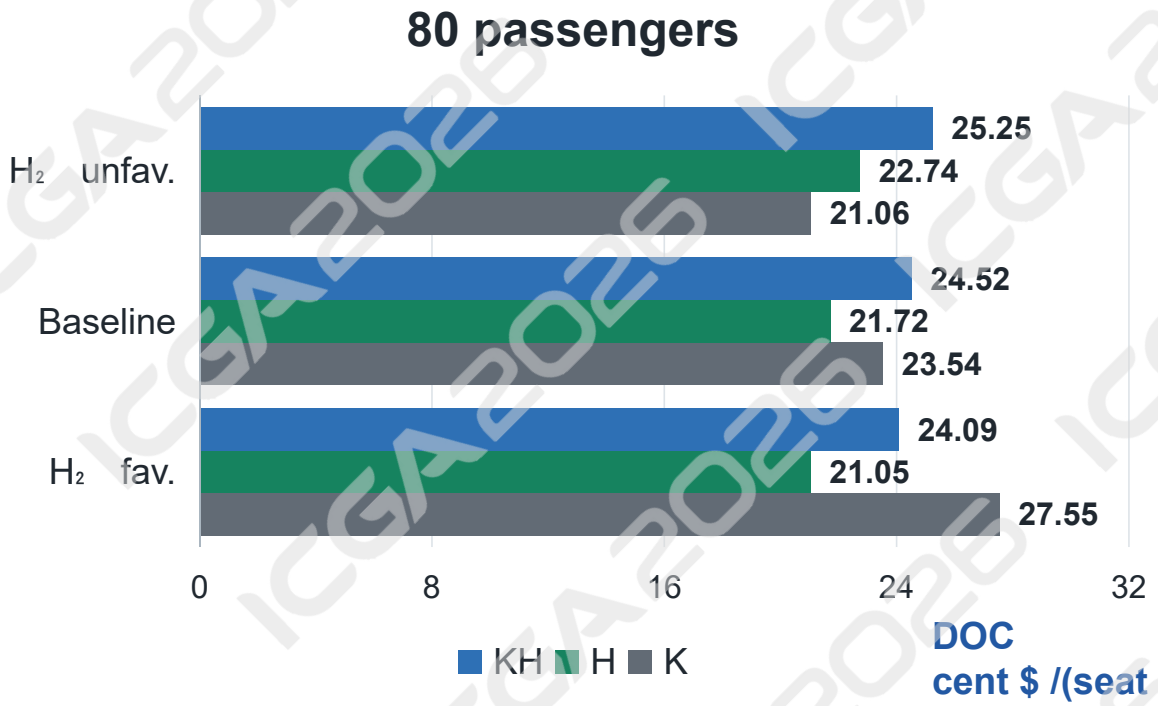
- Capital and mission costs
- Additional FC, electrical and LH_2 systems
- Fixed aircraft across price scenarios

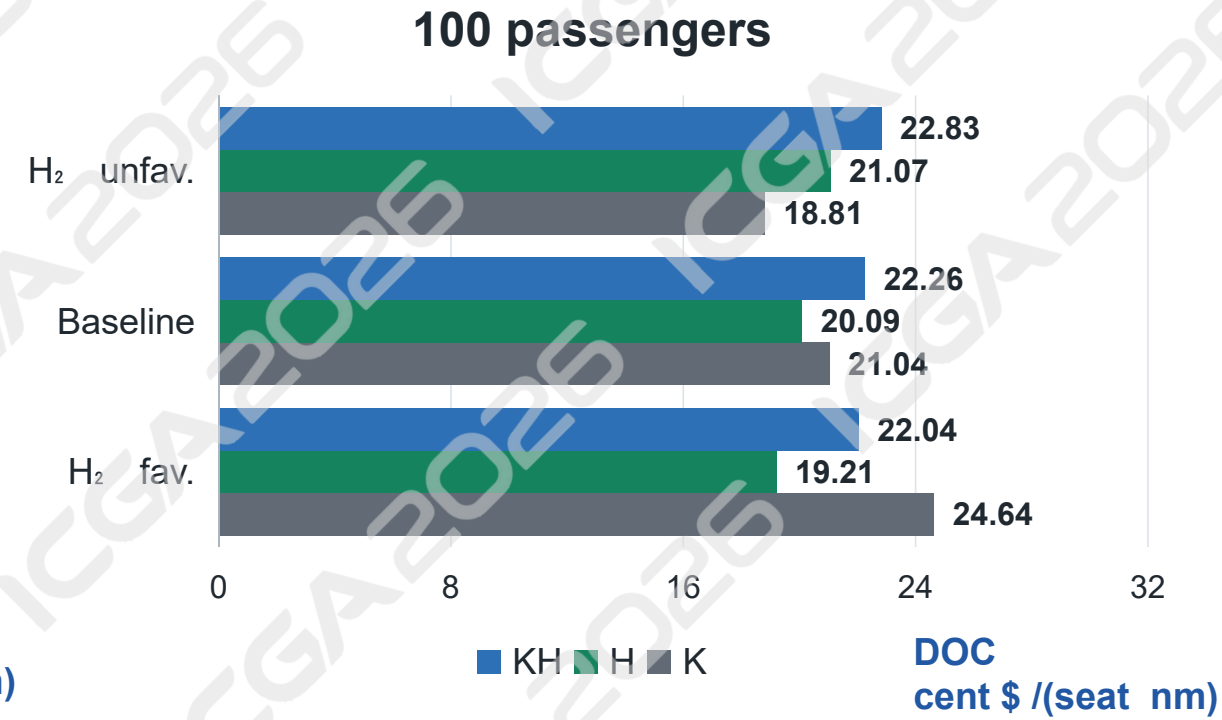
- Propulsive unit cost and maintenance are different for the 6 configurations.

- Component cost estimated through Genesis project

Component	price	unit
Fuel-cell system	356.4	USD/kW
Electric motor	60	USD/kW
Power electronic	260	USD/kW
Hydrogen storage system	119	USD/kg

Fuel prices change the DOC ranking





Lowest DOC: K with H_2 -unfavourable prices, H at baseline and H_2 -favourable prices

Baseline H savings vs K: 7.7% at 80 passengers and 4.5% at 100 passengers

Backup: percentage changes relative to conventional

Configuration	MTOM	Block energy	DOC baseline	DOC H_2 unfav.	DOC H_2 fav.
H80	+28.1%	-27.7%	-7.7%	+8.0%	-23.6%
KH80	+32.4%	-22.4%	+4.2%	+19.9%	-12.6%
H100	+30.7%	-22.1%	-4.5%	+12.0%	-22.0%
KH100	+31.2%	-15.6%	+5.8%	+21.4%	-10.6%

Energy: 500 nm design mission. DOC: 250 nm typical mission.
All comparisons use the same passenger capacity.

Conclusions

Aircraft integration

Hydrogen storage and propulsion increase aircraft size and mass.
Take-off, approach speed and span constraints shape the optima.

Mission energy

Full-electric: 27.7% / 22.1% less energy than K at 80 / 100 passengers.
Hybridization cuts kerosene use by more than 90%.

Economic performance

Full-electric leads at baseline and favourable H_2 prices.
Conventional propulsion leads with unfavourable H_2 prices.

Backup slide : 80-passenger numerical results

Parameter	K80	H80	KH80
Wing area (m^2)	65.0	83.9	86.5
Wing aspect ratio	14	14	14
Installed GT power (MW)	5.5	None	1.0
Installed gross FC power (MW)	None	6.7	6.3
Hybridization factor (%)	Not applicable	Not applicable	86.3
Take-off field length (m)	1244	1350	1300
Landing field length (m)	1292	1330	1327
Maximum take-off mass (kg)	27,651	35,412	36,618
Operating empty mass (kg)	16,606	26,030	27,108
Block kerosene (kg)	1799.3	None	104.7
Block hydrogen (kg)	None	466.0	462.9
Block energy (MJ)	77,370	55,920	60,050
DOC baseline	23.54	21.72	24.52
DOC H_2 -unfavourable	21.06	22.74	25.25
DOC H_2 -favourable	27.55	21.05	24.09

Backup slide: 100-passenger numerical results

Parameter	K100	H100	KH100
Wing area (m²)	87.5	102.2	102.2
Wing aspect ratio	14	12.7	12.7
Installed GT power (MW)	6.0	None	1.5
Installed gross FC power (MW)	None	8.1	6.8
Hybridization factor (%)	Not applicable	Not applicable	81.9
Take-off field length (m)	1140	1350	1350
Landing field length (m)	1207	1331	1328
Maximum take-off mass (kg)	33,013	43,141	43,323
Operating empty mass (kg)	19,492	31,436	31,418
Block kerosene (kg)	2019.9	None	176.5
Block hydrogen (kg)	None	563.9	547.8
Block energy (MJ)	86,856	67,668	73,326
DOC baseline	21.04	20.09	22.26
DOC H_2 -unfavourable	18.81	21.07	22.83
DOC H_2 -favourable	24.64	19.21	22.04