Challenges and Strategies for Aviation Using Electrified Propulsion: Focusing on Hydrogen Fuel Cell Commuters

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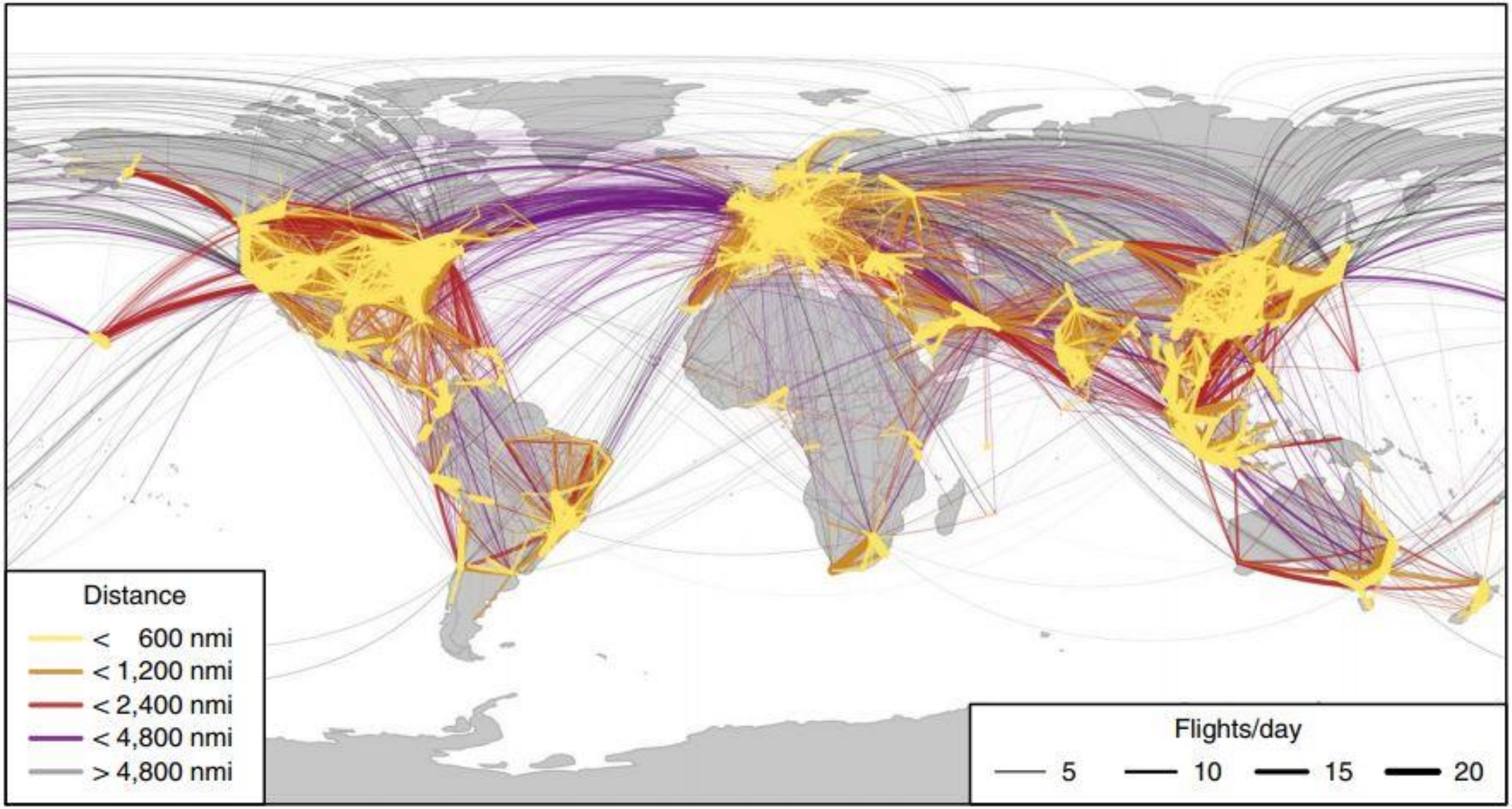
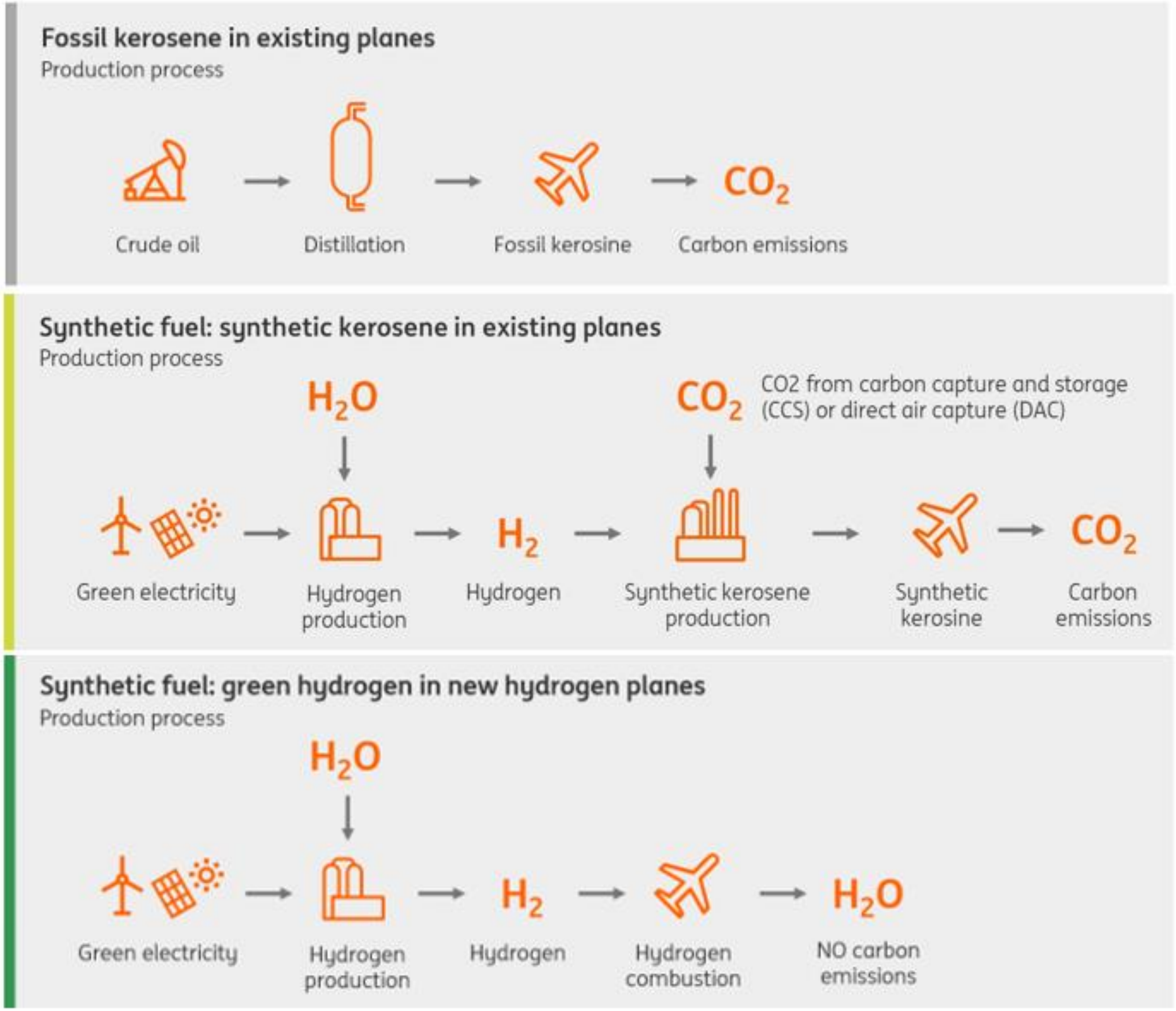
The Impact of Aviation on the Environment



Schäfer et al., Technological, economic and environmental prospects of all-electric aircraft, Nature Energy, 2019.

Road to Near Zero-emission Aviation: Options



ING, Synthetic fuel could be the answer to aviation's net-zero goal, Feb. 2023.

Road to Near Zero-emission Aviation: Time Frame

	2025	2030	2035	2040	2045	2050
Regional & short haul **< 1,500 km** c.20% of industry CO_2	SAF	SAF	Electric or Hydrogen combustion and/or SAF	Electric or Hydrogen combustion and/or SAF	Electric or Hydrogen combustion and/or SAF	Electric or Hydrogen combustion and/or SAF
Medium haul **1,500-4,000 km** c.30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF potentially some hydrogen
Long haul **> 4,000 km** c.50% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF

ING, Synthetic fuel could be the answer to aviation's net-zero goal, Feb. 2023.

Europe's Roadmap for Future Aviation

Key features of zero-carbon and zero-emissions aircraft by 2040

Hydrogen fuel cell electric aircraft

Up to 1000 km
Distance range

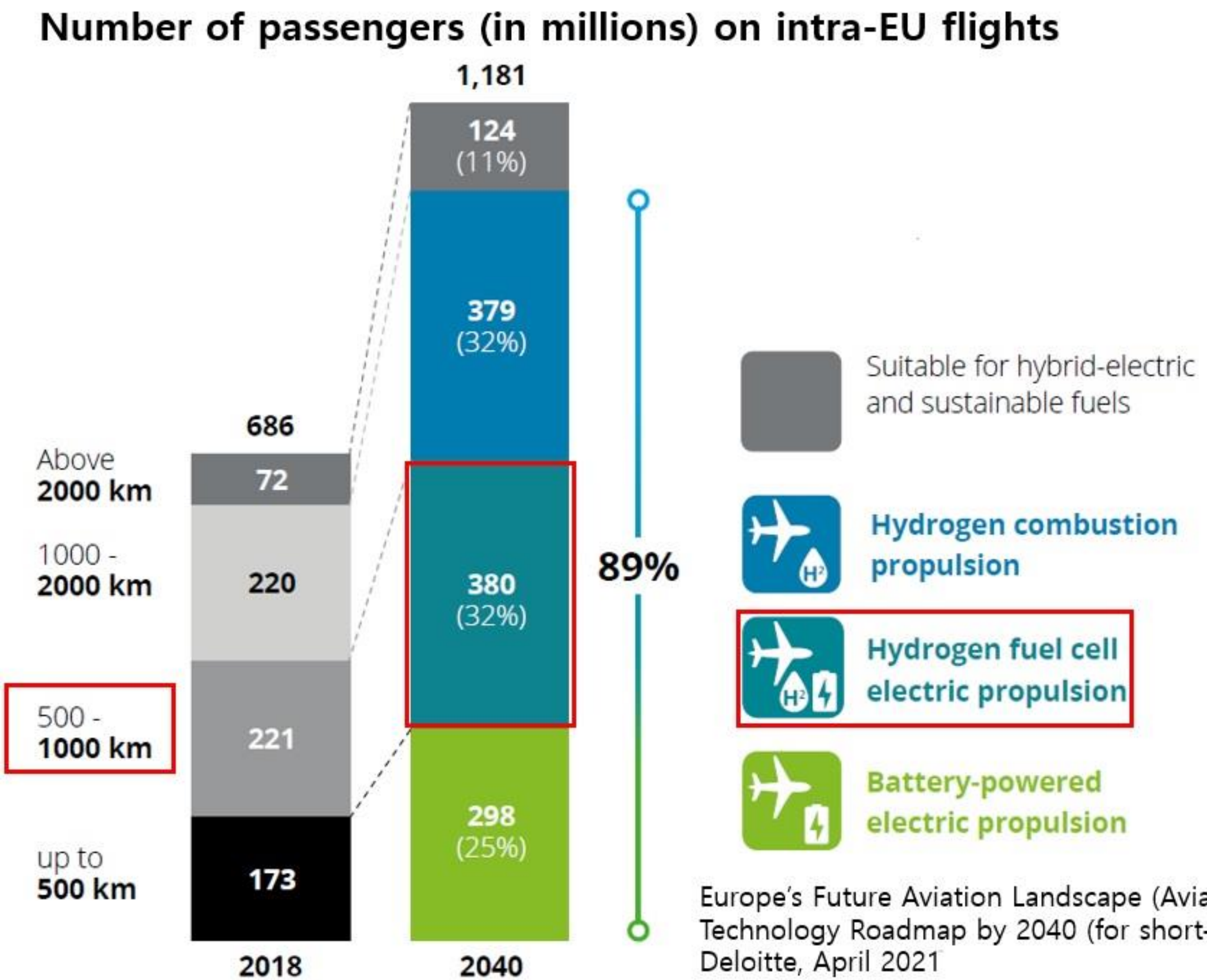
Hydrogen is reacted in a fuel cell to provide electricity to electric motors and then spin propellers or ducted fans to generate thrust

– 75-90% Climate impact reduction potential	**+ 20-30%** Flight time	**+ 0-15%** Ticket price

- ✓ **Near-Zero emissions (water is still produced)**
- ✓ **Quieter engines**
- ✓ **Economy of scale benefits from synergies with other hydrogen dependent industries**

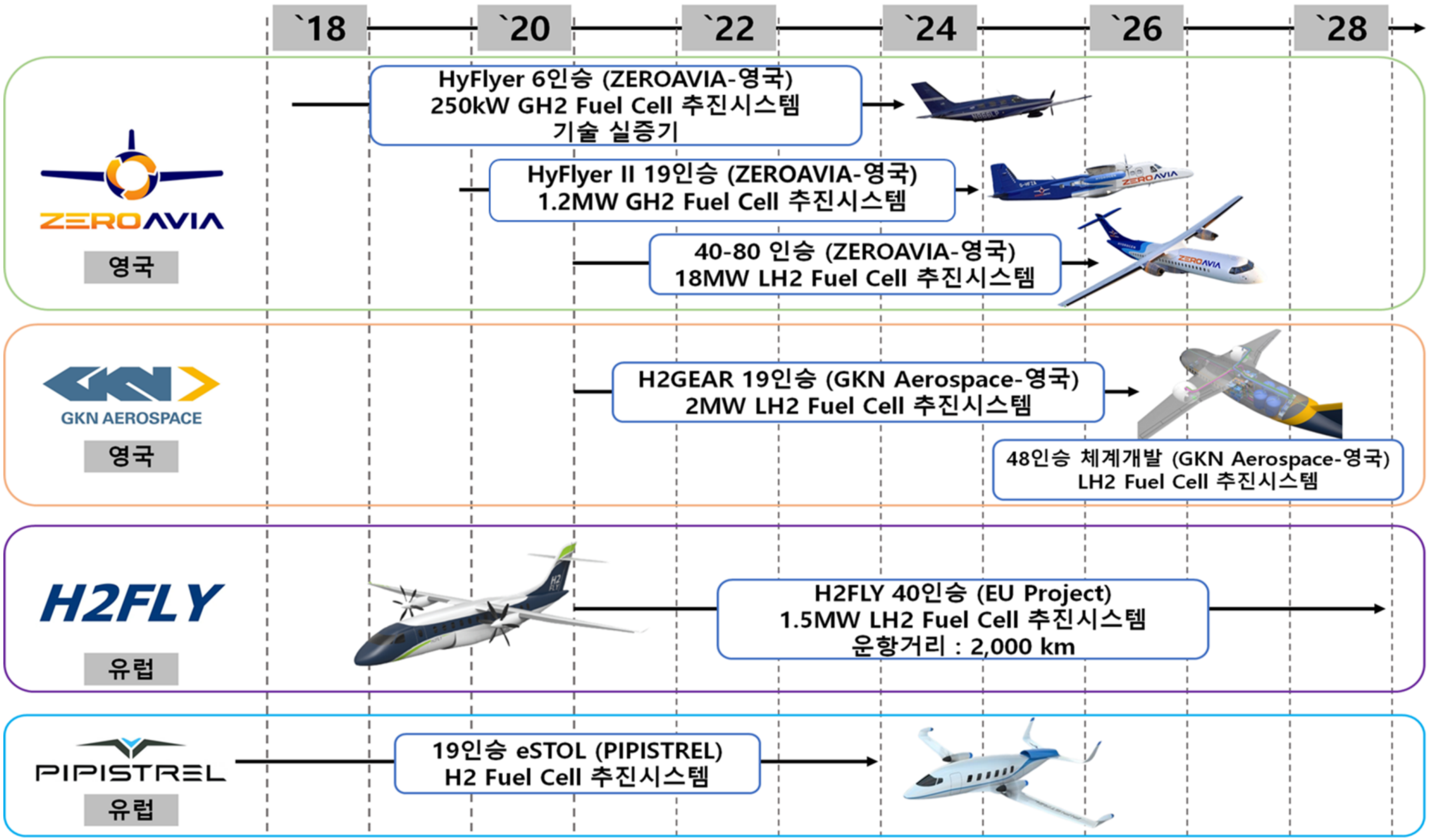
Europe's Future Aviation Landscape (Aviation Technology Roadmap by 2040 (for short-haul flights)), Deloitte, April 2021

Europe's Future Aviation Landscape



Europe's Future Aviation Landscape (Aviation Technology Roadmap by 2040 (for short-haul flights)), Deloitte, April 2021

Hydrogen Aircraft Programs Worldwide



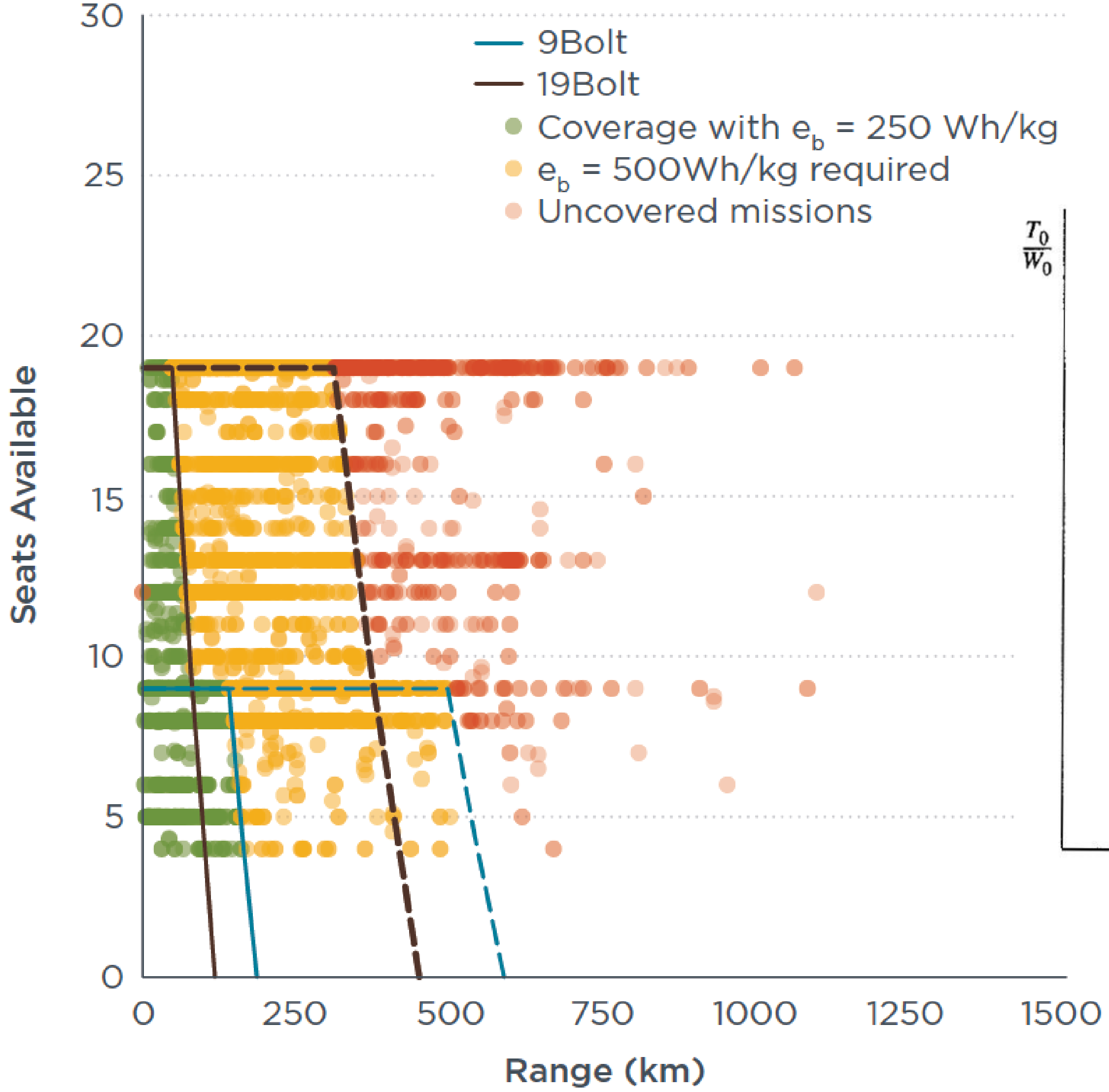
19-passenger (Part 23) Conventional Aircraft

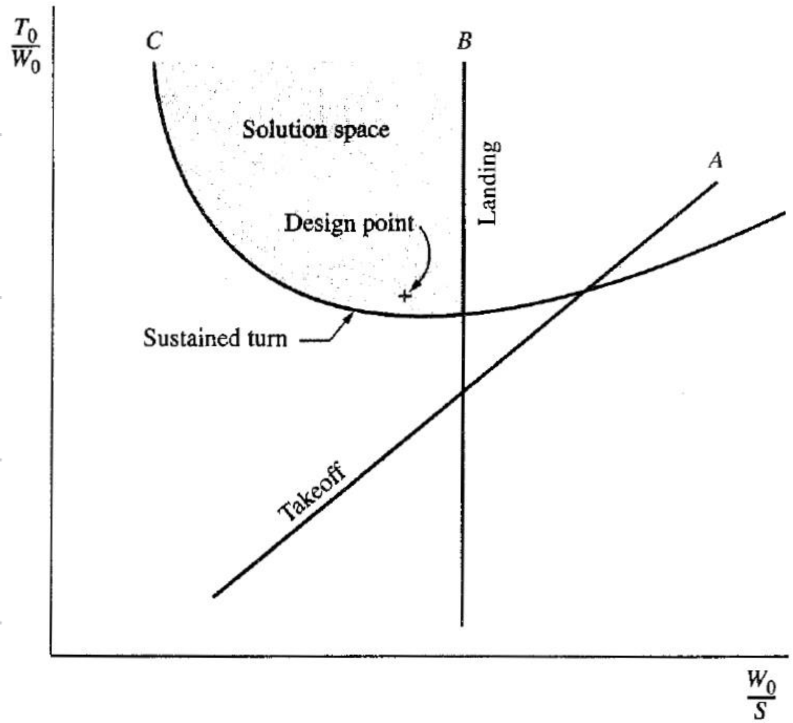
Aircraft	Beechcraft 1900	Embraer 110	Jetstream 31
Image			
MTOW (lb)	16,600	13,000	16,200
Empty Weight (lb)	10,140	8,490	10,400
Range (km)	2,370	1,960	1,260
Take-off/Landing Distance (m)	1,750 or 1,160	1,230	1,380
CO_2 Emissions (kg) (TO/L)	392.8	242.2	295.3
CO_2 Emissions (kg/min) (Cruise)	12.3	7.1	14.3

19-passenger (Part 23) Hydrogen Aircraft

Program	HyFlyerⅡ	H2GEAR	Miniliner
Image			
Company	ZEROAVIA (UK)	GKN Aerospace (UK)	Pipistrel Aircraft (Slovenia) & Textron eAviation (US)
Fuel Type	Compressed Gaseous H2 Fuel Cell	Liquid H2 Fuel Cell	Liquid H2 Hybrid
Powertrain	1.2 MW	1 MW	2 MW (1 MW Each for FC and Battery)
Investment	36 Million USD	57 Million USD	-

Challenges of Developing Hydrogen Commuter



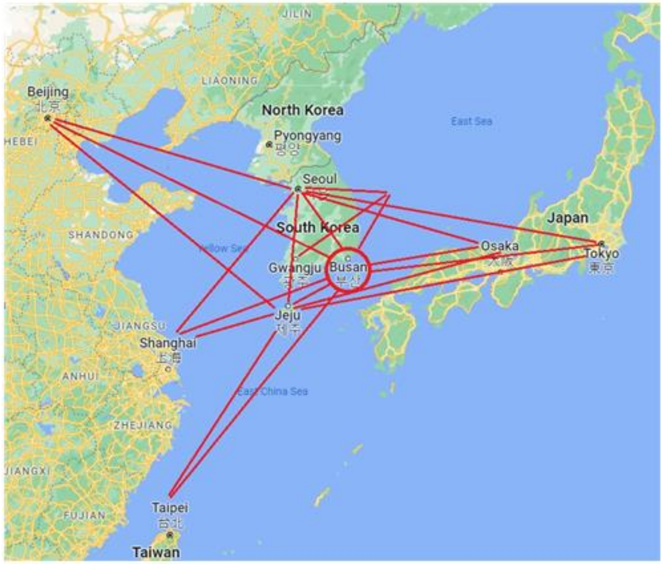


White Paper (July 2022)
The Int. Council on Clean Transportation

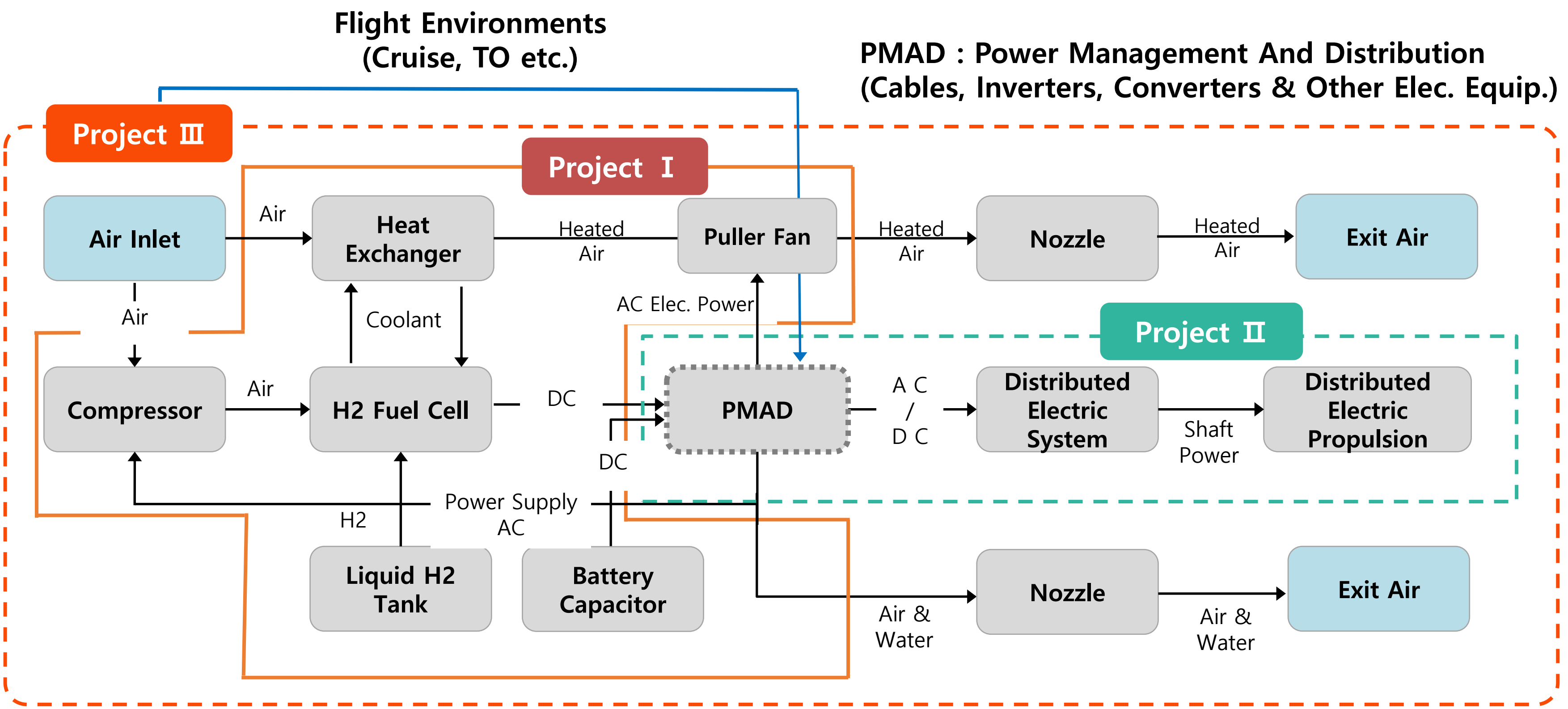
Korean Hydrogen Commuter Mega Project

Project Title	Technology for commuter-class aircraft using hydrogen-fuel-cell-powered hybrid distributed electric propulsion
Participating Organizations	10 including GNU (Leading), UNIST, KERI, KAI, Hanwha Aerospace Co. 2 Local Government: Gyeongnam & Ulsan
Budget	6.42 Million USD (1 Phase; 2023-25) 61.1 Million USD (2-3 Phase; 2026-2032)

Regional Innovation Mega Project (**RIMP**)



Core Technology for Hydrogen Commuter Project



Requirements

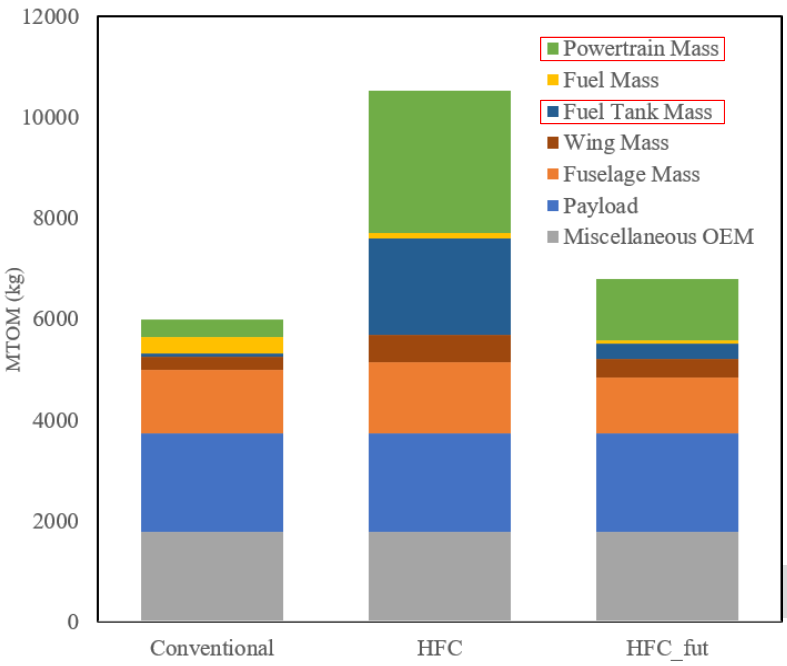
19 Passenger (Part 23), Range (500~1,000 km), Payload (30%), TO/Landing Distance (500~800 m), Carbon Reduction (75~90%), Low Noise (Below 75 dB)

Hydrogen Fuel Cell Commuter: A Case Study

	Conventional	HFC	HFC_{future}
Propeller efficiency	0.8	0.8	0.8
SFC [kg/(kN·s))]	$1.141\cdot10^{-6}$	$2.492\cdot10^{-7}$	$2.361\cdot10^{-7}$
C_L/C_D	10.98	14.5	14.5
W_{empty} [kg]	3725	8461	4654
Cruise - W_{fuel} [kg]	269.1	76.1	45.75
Climb, Descent - W_{fuel} [kg]	40.4	19.12	12.44
$W_{fuel\ total}$	309.5	95.22	58.19
$W_{payload}$ [kg]	1960	1960	1960
MTOM [kg]	**5995**	**10517**	**6672**
$Range_{cruise}$ [km]	338.1	338.1	338.1
$Range_{climb,descent}$ [km]	57.9	57.9	57.9

$$Range_{cruise} = \frac{\eta_{prop}}{SFC}\frac{C_L}{C_D}\ln\left(\frac{W_{empty}+W_{payload}+W_{fuel}}{W_{empty}+W_{payload}}\right)$$

Hydrogen Fuel Cell Commuter: A Case Study

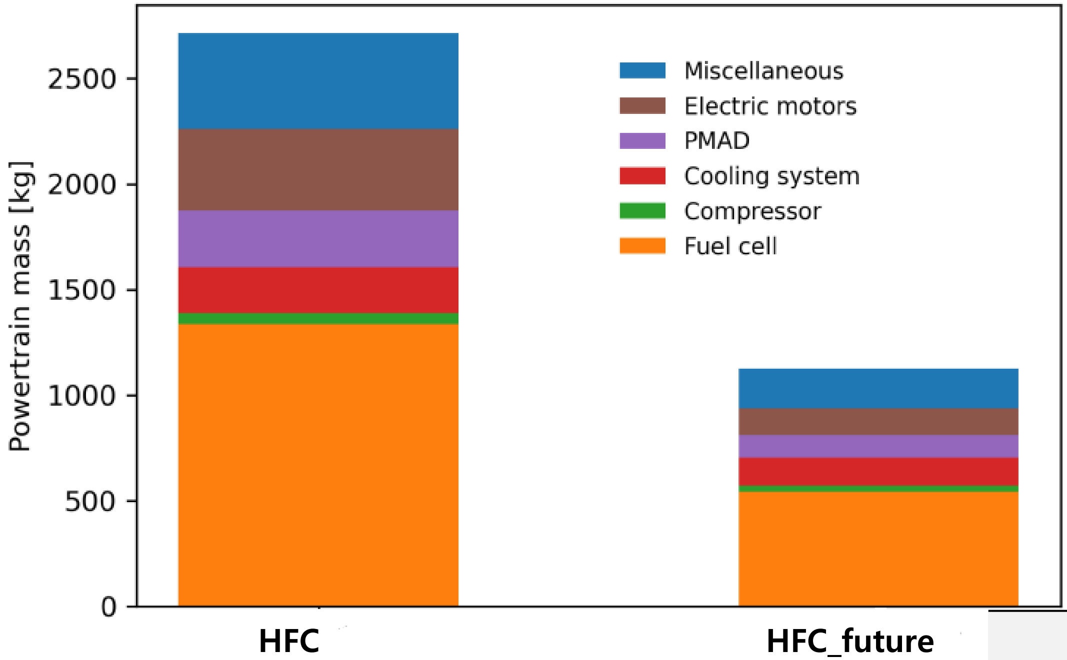


Required power increasing in HFC using electric motors and PMAD, compressor etc.

Specific energy: 3kW/kg (Kerosene) vs 2kW/kg (HFC)
Storage efficiency of fuel tank: 0.95 vs 0.2

	Conventional	HFC	HFC_future
Fuel Mass	309.6	95.22	59.16
Payload	1960	1960	1960
Powertrain Mass	**358.8**	**2823**	**1214**
Fuel Tank Mass	**81.47**	**1904**	**295.8**
Wing Mass	257.4	545.7	385.9
Fuselage Mass	1260	1422	1100
Miscellaneous OEM	1767	1767	1767
MTOM	5995	1052	6782
OEM	3725	8463	4763

Hydrogen Fuel Cell Commuter: A Case Study

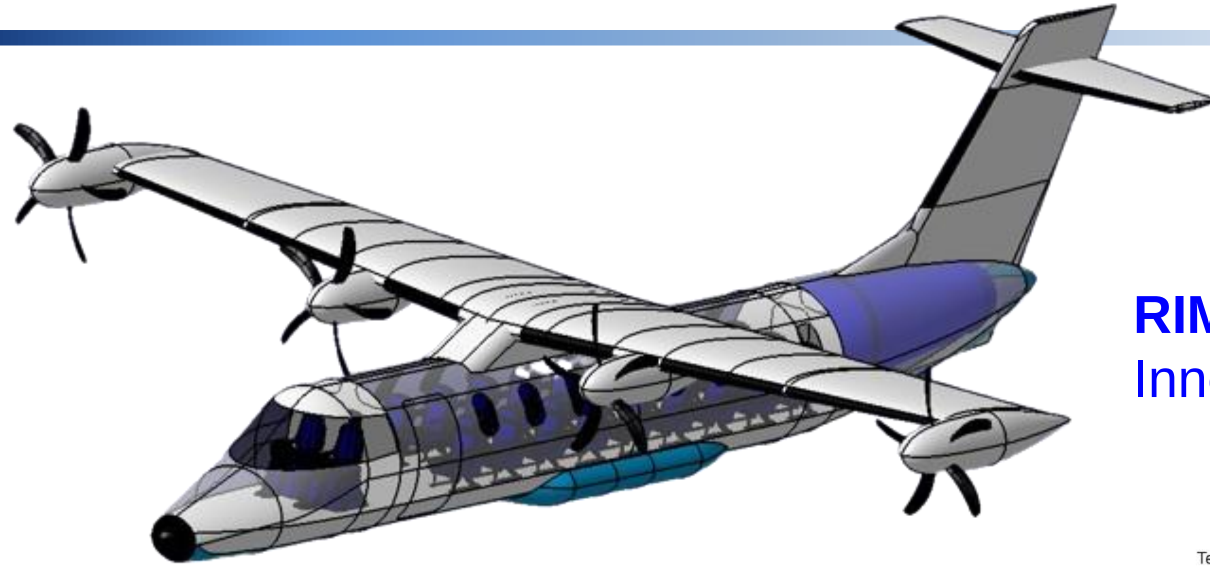


Electric motor specific energy:
5kW/kg vs 10kw/kg (Future)

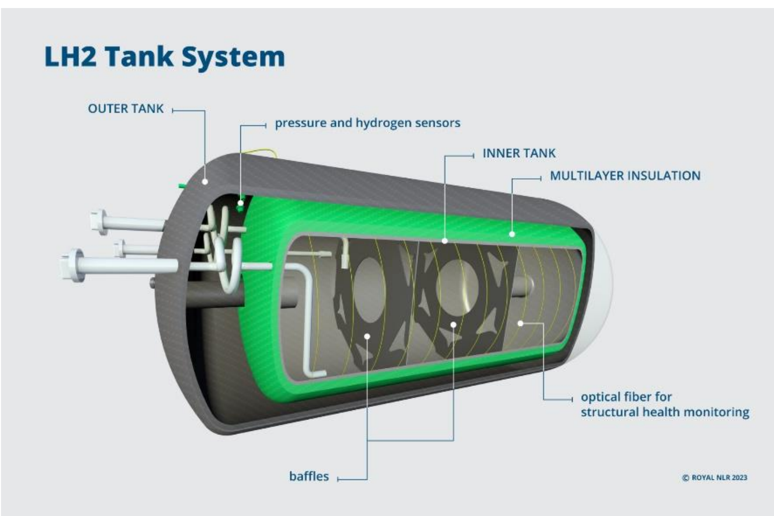
Fuel cell specific energy:
2kW/kg vs 3kW/kg (Future)

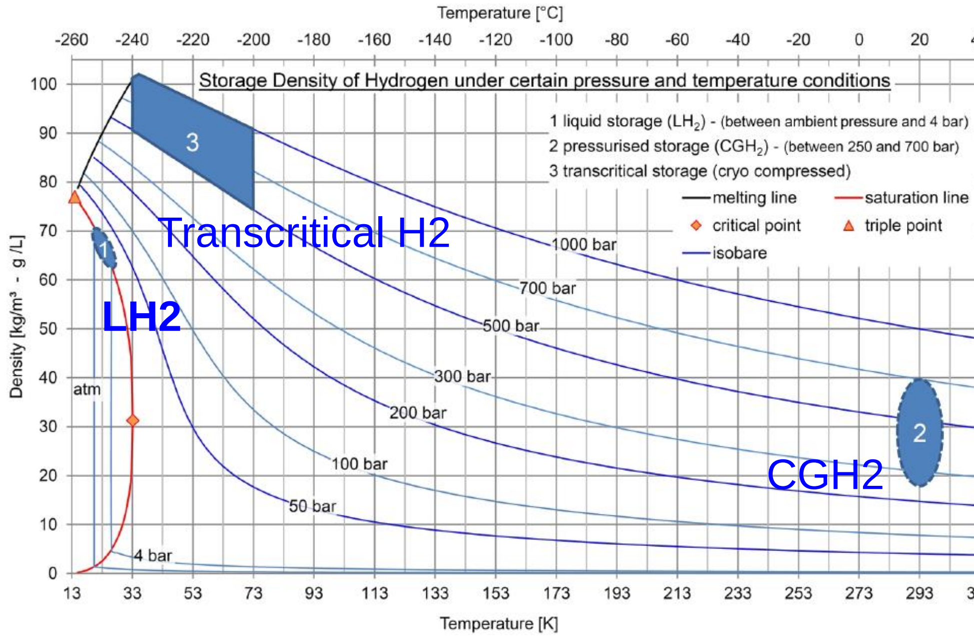
	HFC	HFC_future
Miscellaneous	430.1	202.3
Electric motors	**371.4**	**135.3**
PMAD	254.7	117.2
Cooling system	202.8	140.1
Compressor	48.14	33.22
Fuel Cell	**1274**	**585.9**

Hydrogen Fuel Cell Commuter: RIMP Version 1

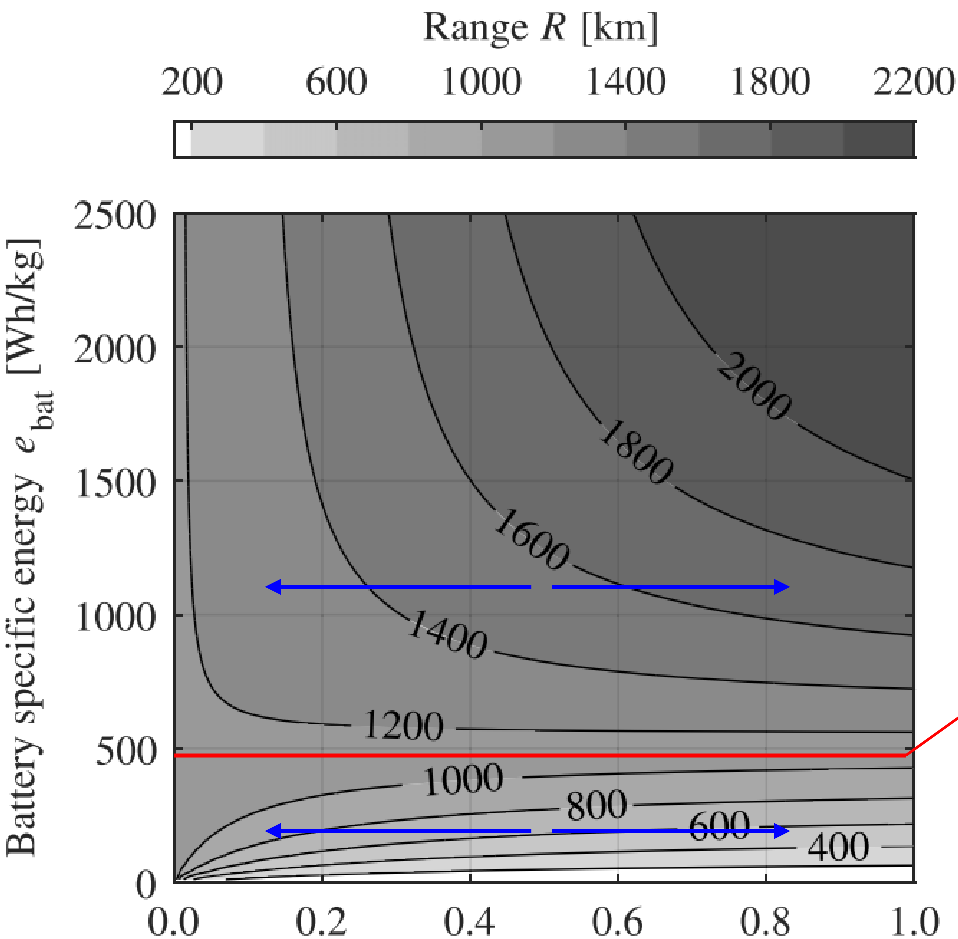


RIMP (Regional Innovation Mega Project)





Hybrid: Combination of Fuel Cell and Battery



Fuel-based

Battery-based

Fuel cell only

$$\eta_{prop} e_{fuel} \frac{C_L}{C_D} \eta_{fuel-cell} \mathbf{Log_{exp}} \left(\frac{W_{empty} + W_{payload} + W_{fuel}}{W_{empty} + W_{payload}} \right)$$

Hybrid

$$\eta_{prop} e_{battery} \frac{C_L}{C_D} \eta_{elec.-motor} \left(\frac{W_{empty} + W_{payload} + W_{fuel}}{W_{empty} + W_{payload}} \right)$$

Battery only

High transmission efficiency of the electrical powertrain branch leading to an energy saving that offsets the weight penalty of the batteries

Dividing line depending on the weight breakdown and the transmission efficiency of the powertrain

High energy density of fuel compensating the lower conversion efficiency

Challenges: Land Operation vs Aviation

	Fuel Cell for Land Operation	Fuel Cell for Aviation
Characteristics	Frequent stop & easy refueling (fast charging critical) Compressed hydrogen gas tank	Non-stop & no refueling (high-capacity charging) Liquid hydrogen tank
Weight & Thermal Management	Moderate	Critical in performance
Required Power	Low required power (100kw for NEXO)	High power required (1.2 MW for 19-passenger commuter) leading to HFC efficiency degradation
Operational Environment	Moderate change (15℃ / 1 atm)	Severe change (-30℃ / 0.41 atm at altitude of 7 km)
Missions	Moderate variations	High power : TO, landing, re-climbing Low power : cruise, descent, turn
Certification	Standards established	Challenging
Reliability	High level	High reliability required

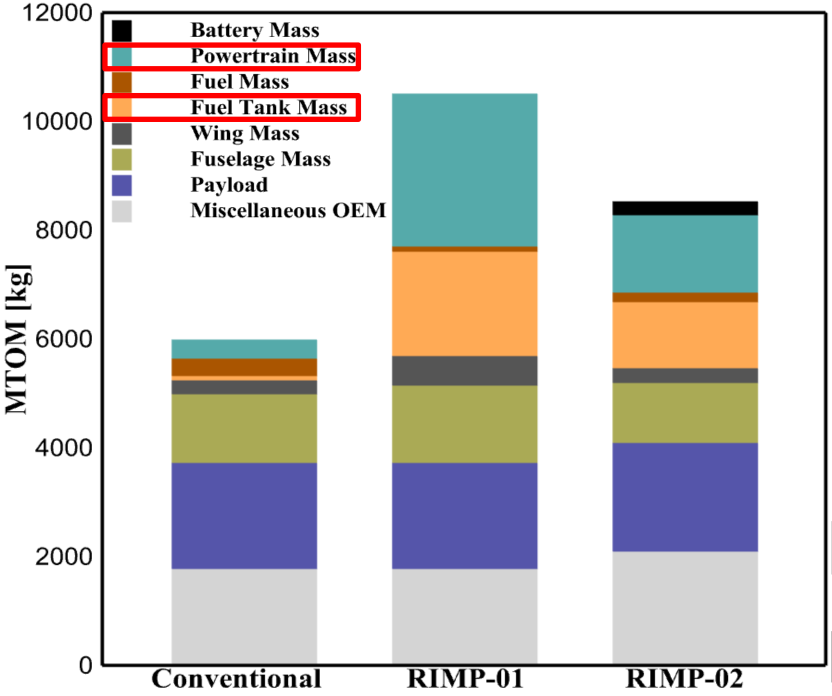
Strategies for the Mega Project

Scale-up & scale-down strategies	Apply first core technologies to commuters, and then extend to scale-up (over 19 passengers) and scale-down (less than 19 passengers)
Early identification of core technologies at the conceptual design stage	Identify the factors with the greatest impact and greatest improvement on aircraft performance
Frequent analysis of economic performance and markets	Regularly assess technical-economic feasibility and reflect core technologies in aircraft concept design Develop core components such as hydrogen fuel cell-based hybrid propulsion systems as major separate business items

Critical Future Technologies

Hybrid power system	Optimization of insulation thickness of storage tank Optimal control of fuel cell and battery energy considering flight phases Fuel cell power system considering low-density flight environments Hybrid system involving battery and super-capacitor
Distributed electric propulsion system	High-fidelity methods for computing air flows over wing-fuselage-propeller
High performance commuter	Reducing mass of powertrain and fuel tank (while increasing various efficiency) Sophisticated weight estimation modeling technique for powertrain and fuel tank High-lift, low-noise aerodynamic shape design

RIMP Version 2 (Hybrid): Total Weight



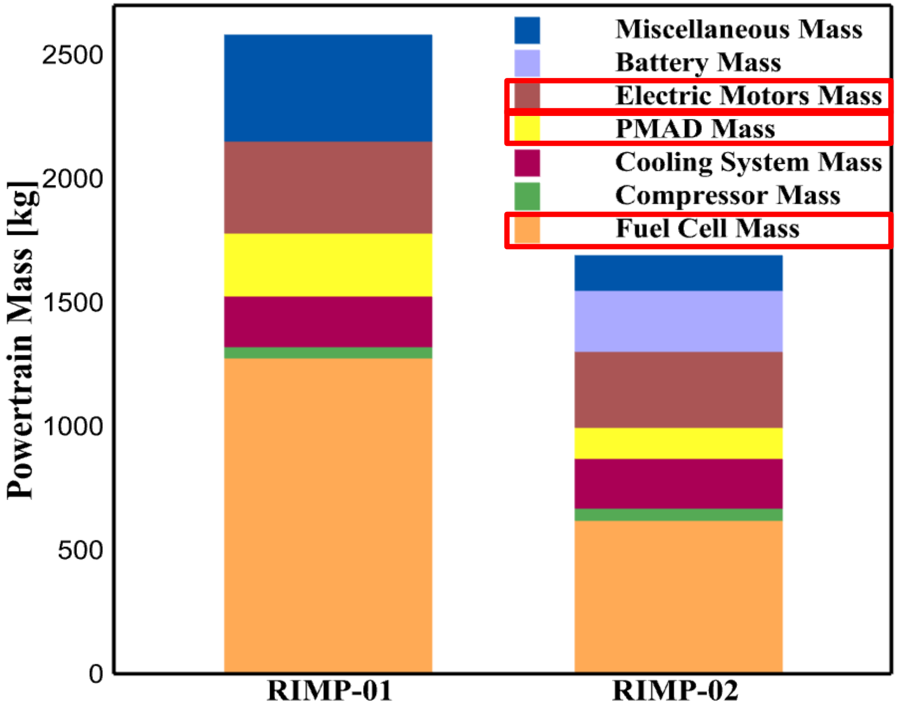
Reducing weight by adopting future technologies

Specific energy: 3kW/kg (Kerosene) vs 2kW/kg (Hydrogen) vs 3kW/kg (Future Hybrid Hydrogen)

Storage efficiency of fuel tank: 0.95 vs 0.2 vs 0.4

	Conventional	RIMP-01	RIMP-02
MTOM [kg]	**5994.92**	**10517.74**	**8524.9**
OEM [kg]	3725.33	8462.52	6362.51
Miscellaneous OEM [kg]	1767.34	1767.34	2086.39
Payload [kg]	1960	1960	2000
Fuselage Mass [kg]	1260.39	1422.16	1107.8
Wing Mass [kg]	257.38	545.65	272.88
Fuel Tank Mass [kg]	**81.47**	**1904.31**	**1217.9**
Fuel Mass [kg]	309.59	95.22	162.39
Powertrain Mass [kg]	**358.75**	**2823.06**	**1431.38**
Battery Mass [kg]	-	-	246.15

RIMP Version 2 (Hybrid): Powertrain & Battery



PMAD specific energy: 15kW/kg vs 20kw/kg

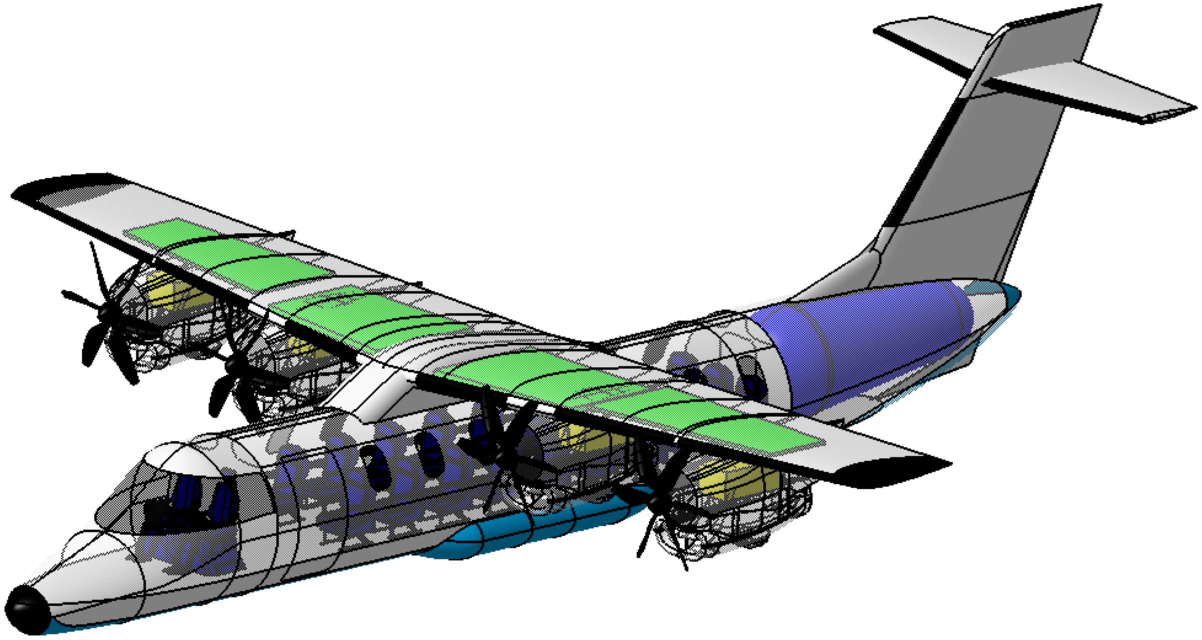
PMAD efficiency: 0.95 vs 0.98

Electric motor efficiency: 0.9 vs 0.922

Fuel cell specific energy: 2kW/kg vs 3kW/kg

	RIMP-01	**RIMP-02**
Miscellaneous [kg]	430.105	143.14
Electric motors [kg]	**371.44**	**307.07**
PMAD [kg]	**254.7**	**124.01**
Cooling system [kg]	202.75	200.51
Compressor [kg]	48.14	50.41
Fuel Cell [kg]	**1273.5**	**619.25**
Battery [kg]	-	246.15

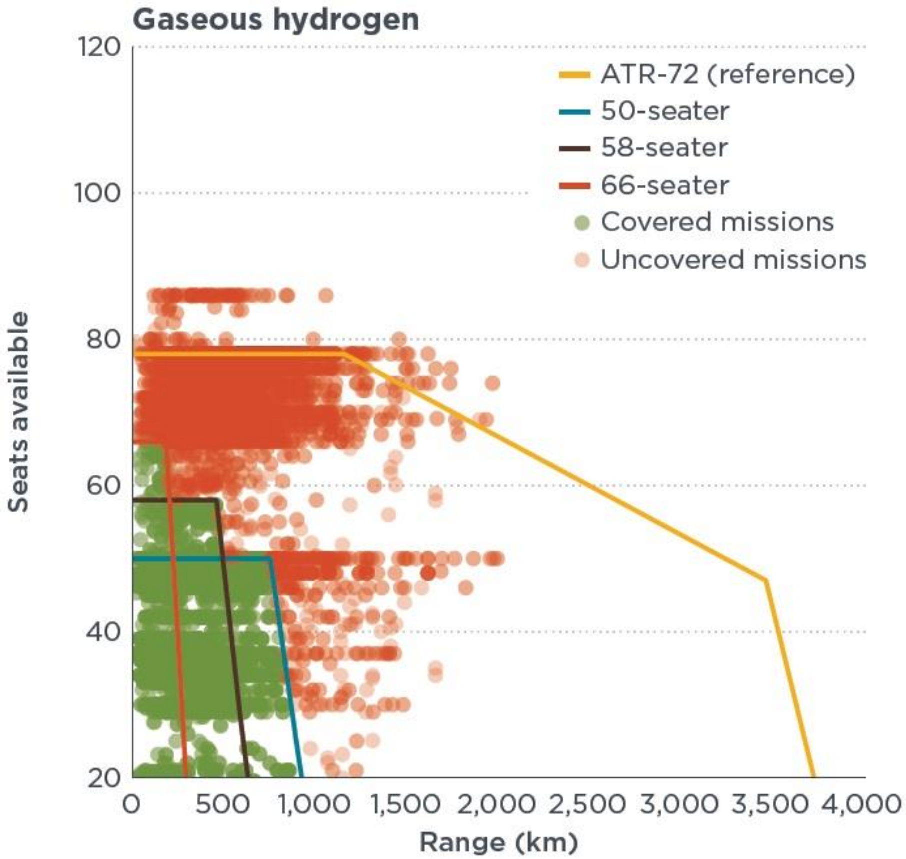
RIMP Version 2 (H2-Battery Hybrid)

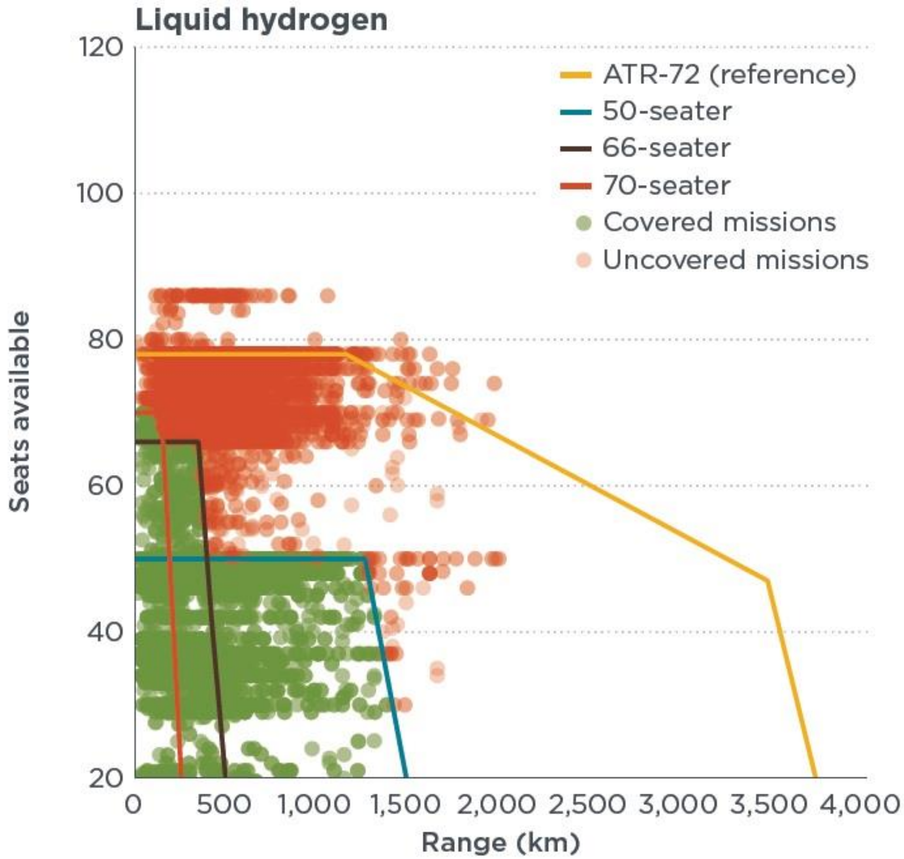


Standardization and Certification

Standardization	**Gaseous and liquid hydrogen storage tanks** - US CGA H-3-2019: Minimum design and performance applied to cryogenic hydrogen storage tanks - ISO 21011:2008: Design, manufacturing and testing requirements for valves for temperatures below -40 degrees Celsius **Hydrogen fuel cell power system** (IEC, EUROCAE, SEC, ANSI) **Distributed electric propulsion system** (ASTM, EASA, SAE)
Certification	**Certification standards for hydrogen fuel cell hybrid power systems for aviation** (AIR 6464, AS 6858, 6679, 7373) **No guideline for PMAD** **Certification standards for distributed electric propulsion system** (DO-311A, F3338-21, AIR 7765) **FAR Part 23**: In 2016, it was significantly reduced and integrated, but major safety standards such as SLD (supercooled large droplet) icing condition and crashworthiness were strengthened. Issues in certification of **retrofitted aircraft** with new carbon-free propulsion systems?

Retrofit





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Retrofit vs From Scratch: Pros & Cons

First deliveries of hydrogen/battery-powered passenger aircraft expected **between 2035 and 2040**. The complete renewal might take decades. (The lifetime of an aircraft 25 years)
The renewal can be accelerated by **mostly economics** (fuel-efficient aircraft, variation in air traffic demand, lower maintenance costs) and by stricter **governmental environmental regulations and financial incentives**.

Retrofit	From Scratch
Based on proven technology (but sometimes things can get out of control like the B737-Max)	Taking advantage of new technology developed in last 30-50 years (but sometimes things can get out of control like the MRJ)
Low development cost and certification risk	High development cost and certification risk
Short lifetime (10 years + new 15 years) Performance penalties & inevitable consequences like uselessness of fuel tank inside wings	Full lifetime and popular with customers Good performance and no penalty associated with retrofit
Not an option for everyone (because an aircraft to retrofit must be available) (Mainly for the purpose of demonstrating the feasibility)	Attractive option for latecomers (but investment resources and related infrastructure will be key)