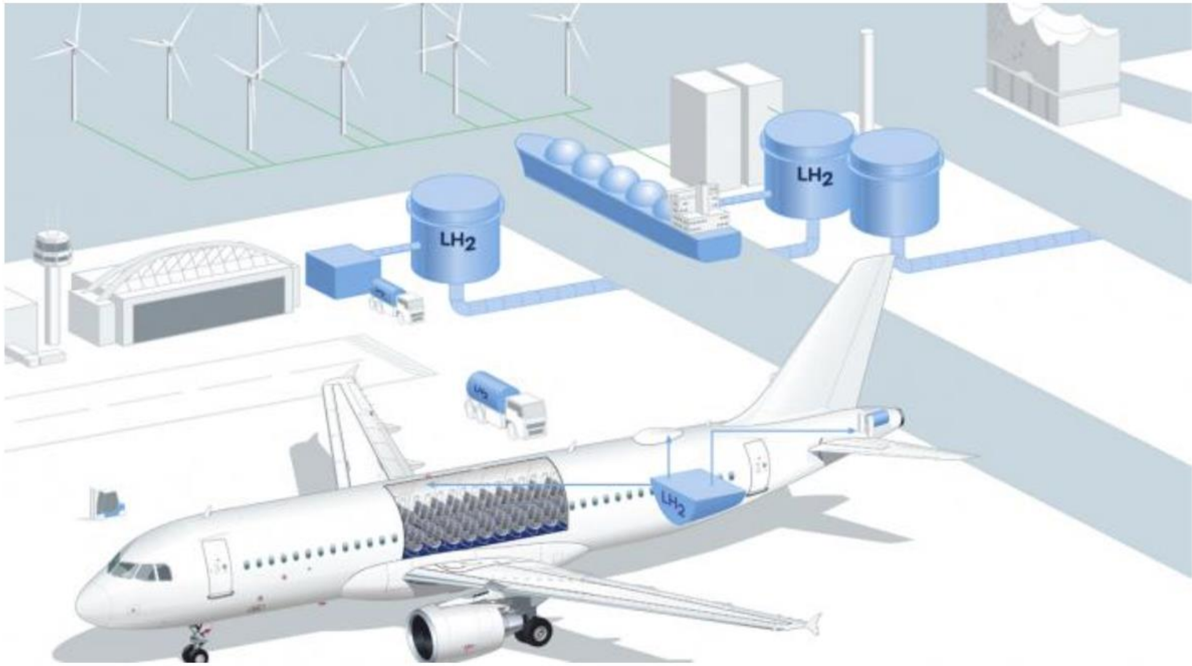
Hydrogen aviation (Vätgasflyg)

contributing to decarbonisation of the aviation segment



Hamburg Airport goes for hydrogen

Hydrogen production

Hydrogen logistics

Infrastructure

Hydrogen storage

Weight

Combustion process (Turbine)

Heat rejection (Fuel Cell)

Source:
https://airportinfo.com/hamburg-airport-goes-for-hydrogen/

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Hydrogen aviation (Vätgasflyg)

contributing to decarbonisation of the aviation segment

Fueling the Future: Key Catalysts for Expanding Hydrogen Fuel Cell Deployment **Fuel Cell**

Andreas Bodén, PowerCell Group

Advancing Hydrogen Electric Propulsion: Insights from the H2GEAR Project **Fuel Cell**

Simon Taylor, GKN Aerospace **LH_2**

Hydrogen aircraft of the future: Technology, potential and performance **H_2-turbine**

Thomas Grönstedt, Chalmers University of Technology

Fossil-free airplanes with liquid hydrogen - experiences from Umeå Airport **LH_2-infra**

Anders Lundblad, RISE, **John Nilsson**, Swedavia

Can hydrogen power all aviation in Sweden?

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Yes.

SWEDISH PERSPECTIVE

SUSTAINABLE AVIATION FOR SWEDEN -TECHNOLOGY & CAPABILITY ASSESSMENT TARGETING 2045 [1]

Christopher Jouannet, Ingo Staack, Tomas Grönstedt, Xin Zhao, Petter Krus, Anders Lundbladh, Björn Nagel

Out from the daily demand, 25 flight routes represent 70% of the total flight demand. Those 25 routes are based on 10 cities, Stockholm, Malmö, Gothenburg, Umeå, Luleå, Ronneby, Ängelholm, Växjö, Åre and Skellefteå, illustrated in Figure 2. It should be noted that the point-to-point demand below eight daily passengers represent ca. 12% (1,166 out of 9,545 passenger) of the total daily passenger demand.

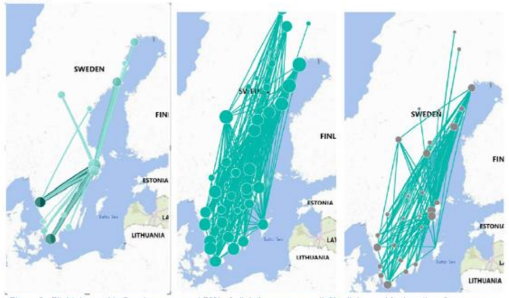


Figure 2: Flight demand in Sweden, represent 70% of all daily passengers (left), all demand for less than 9 passengers (middle), and routes with a demand superior to 9 passengers (right)

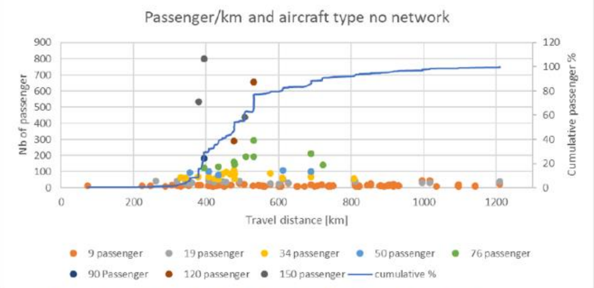


Figure 1: Passenger kilometre and hypothetical associated aircraft type based on point-to-point service

Sources:
[1] https://research.chalmers.se/en/publication/533677

Cummulative H2 DIrect — cummulative H2Fuel Cell — Cummulative SAF

A/C Capacity	EL	H2	H2FC	SAF	Total
9	4			44	48
19			18	6	24
34			30	8	38
50		8			8
76			78		78
90		2			2
120		2			2
150		0			0
Total	4	12	126	58	200

138

SAF Only	
A/C Capacity	Total
9	48
19	18
34	14
50	10
76	2
90	10
120	16
150	32

SWEDISH PERSPECT

SUSTAINABLE AVIATION FOR SWEDEN –T

Christopher Jouannet, Ingo Staack, Tomas Grönstedt, Xi

Swedish demand is particular many low passeng
9 and 19 pax aircraft would represent a large nun
flights

No single technology will realise the demand

Hydrogen has a good potential (direct combustio
Hydrogen creation and distribution are key challe
technical challenges

SAF as an interim solution and longer distances

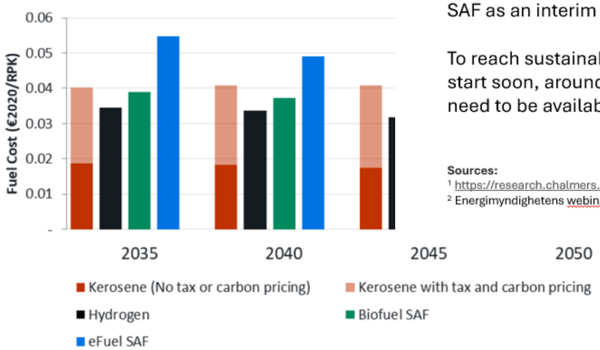
To reach sustainable aviation by 2045 a fleet replacement must start soon, around 2030. Means that many of the technologies need to be available now or really soon…

Sources:
[1] https://research.chalmers.se/en/publication/533677
[2] Energimyndighetens webinarium Fossilfrittflyg 2045, 2023-01-13, presentation

DIFFERENT TECHNO

COMPARASION OF NEW TECHNOLOGIES

Figure 4.13: Hydrogen cost vs. kerosene and SAFs (EU Reference Scenari

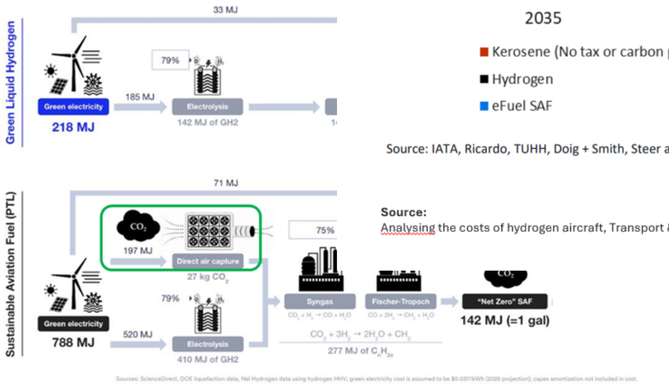


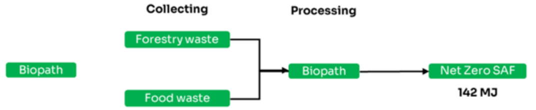
Source: IATA, Ricardo, TUHH, Doig + Smith, Steer analysis

Source:
Analysing the costs of hydrogen aircraft, Transport & Environment (April 2023)

DIFFERENT TECHN

COMPARASION OF HYDROGEN AND SA



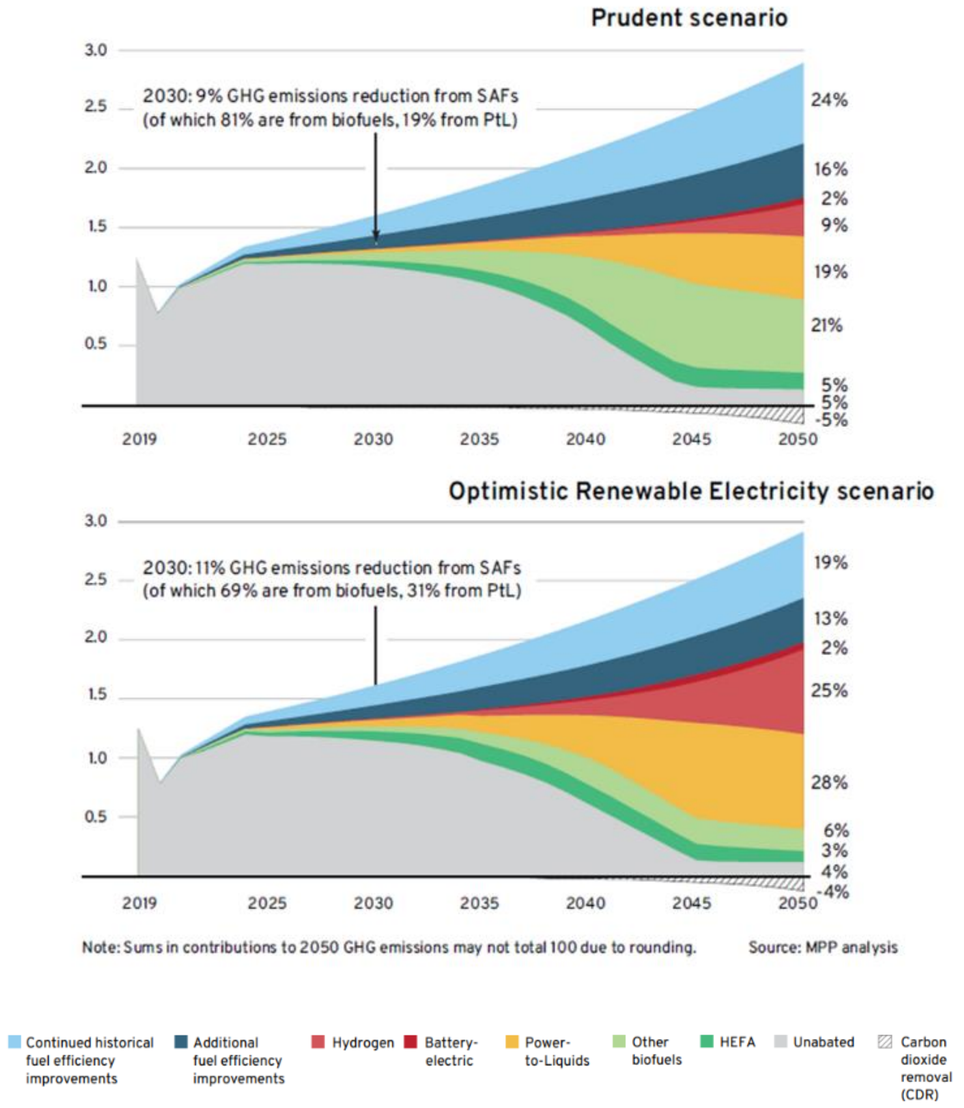


H_2OPE

Hydrogen forecasted to be fuel for
33 - 40% of global aircraft fleet in 2050 [1]

Hydrogen could by 2050 depending on scenario enable
9-25 % of total GHG emissions reduction in aviation [2]

Share of fleet estimated to be replaced by fuel cells by
8 % @ 2035 & 16 % 2040 [3]



Sources:
1: Decarbonizing the aviation sector: Making net zero aviation possible (McKinsey & Co, 2022)
2: Making net-zero aviation possible. An industry-backed, 1.5°C-aligned transition strategy (2022)
3: Hydrogen Powered Aviation, 2020 - a fact-based study prepared by McKinsey & Company for the Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU

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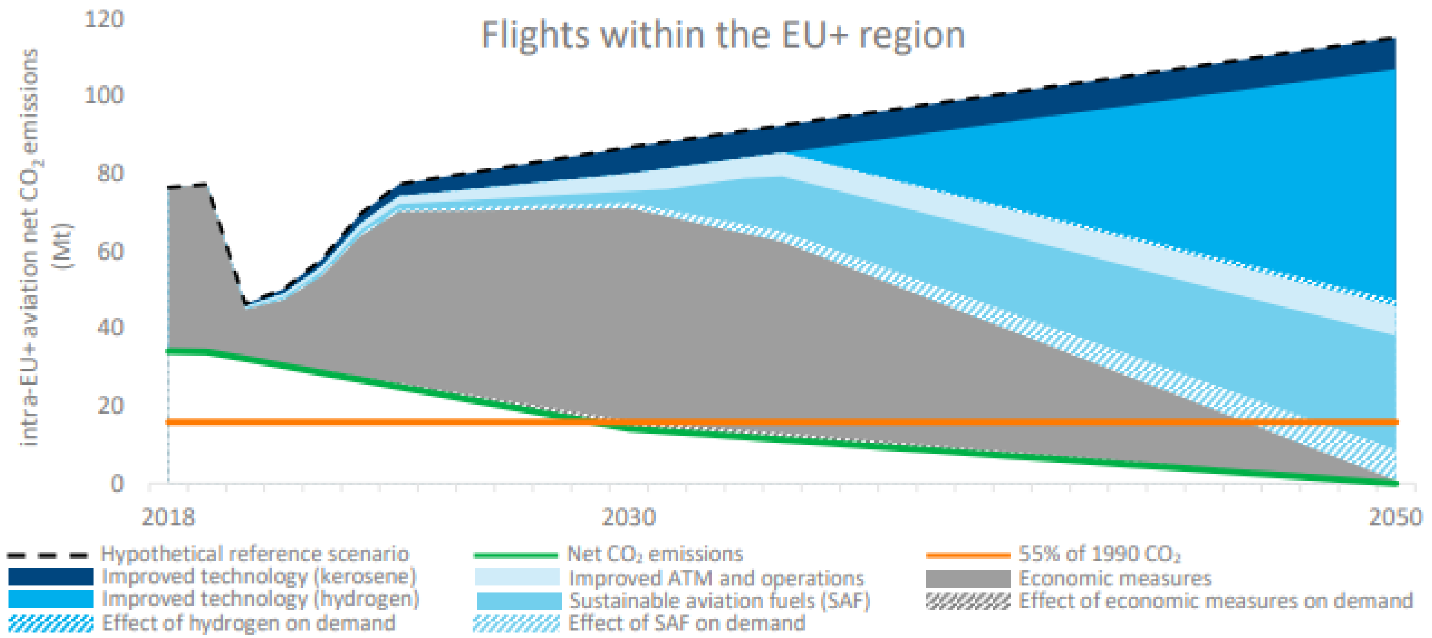
H_2OPE



Intra-EU[2] only. Modelled for 2030 and 2050, the impacts are linearly interpolated. The base year for this study is 2018.

Non-drop-in fuels such as **Hydrogen**. Burning drop-in fuels results in low or net-zero CO_2 emissions whilst burning zero-carbon hydrogen results in CO_2-free emissions.

Sustainable Aviation Fuels (SAF) are categorised into net carbon-neutral drop-in fuels such as synthetic or bio-fuels

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H_2OPE

Hydrogen used in **turbine** or electric flight using **fuel cells**,

have **lower climate impact** and **lower cost** compared to synthetic aviation fuels.

Exhibit 4

Comparison of climate impact from H_2 propulsion and synfuel

Compared to kerosene-powered aircraft, timeframe until 2100

Ongoing scientific debate about full climate impact, in particular:
- Contrail/cirrus formation
- Aggregate measure

Total climate impact could be 2 to 4 times compared to CO_2 emissions alone

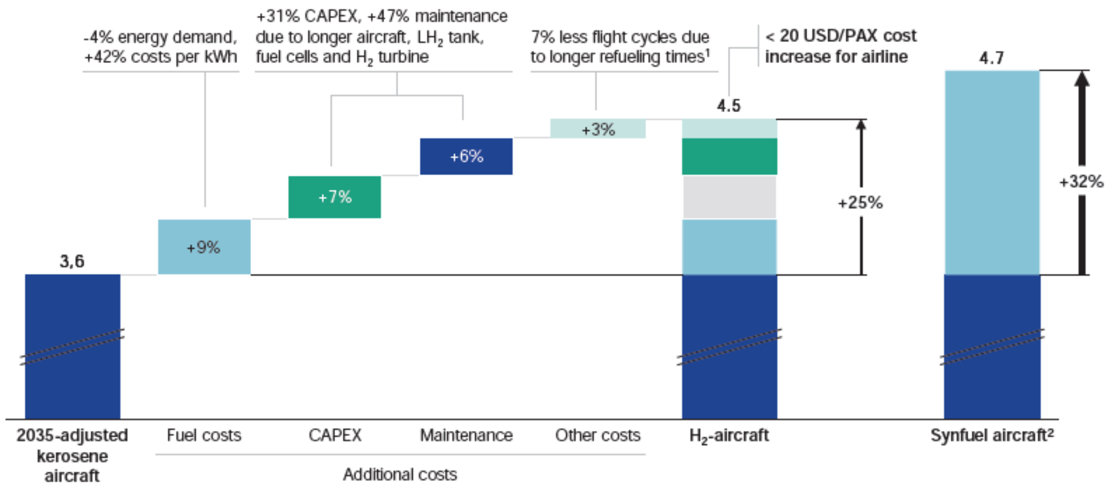
	Change of in-flight emissions and emission related effects[1]				Climate impact reduction potential[4]
	Direct CO_2	NO_x	Water vapor[2]	Contrails, cirrus	
Synfuel	-0% / -100% (Net)[3]	-0%	-0%	-10-40%	-30-60%[3]
Hydrogen turbine	-100%	-50-80%	+150%	-30-50%	-50-75%
Hydrogen fuel cell	-100%	-100%	+150%	-60-80%	-75-90%

1. Assuming decarbonized production and transportation of fuels in 2050
2. 10 times lower climate impact than from CO_2 emissions
3. Net CO_2 neutral if produced with CO_2 captured from the air
4. Measured in CO_2 equivalent compared to full climate impact of kerosene-powered aviation

Exhibit 5

Cost comparison of H_2 short-range aircraft versus kerosene and synfuel aircraft

USD cents per available seat kilometer (CASK), 2,000 km flight with 165 PAX in 2040



1. As the number of flight cycles decrease, CAPEX and crew costs will increase. Other costs also cover increased fees due to higher MTOW
2. Synfuel from green hydrogen with carbon from direct air capture

Source: Hydrogen Powered Aviation, 2020 - a fact-based study prepared by McKinsey & Company for the Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU

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H_2URDLES

Hydrogen electric aviation with Fuel Cell is a good fit for commuter and regional aircraft

Hydrogen used in turbine is good for regional and short range aircrafts

Hydrogen storage, Weight, Combustion process (turbine), Heat rejection (Fuel Cell)

Target is Enter Into Service **(EIS) by 2035**

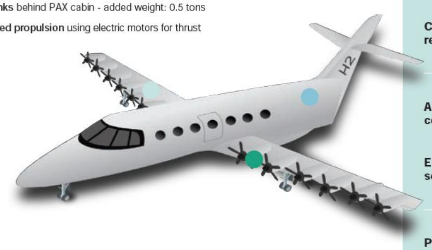
Exhibit 6

Commuter aircraft powered by fuel cells

Revolutionary aircraft

Design mission: 19 PAX, 500 km range, cruise speed 500 km/h

- **Highly efficient** wing
- **2 LH_2 tanks** behind PAX cabin - added weight: 0.5 tons
- **Distributed propulsion** using electric motors for thrust



Energy demand[1]	-10%
CO_2 reduction	100%
Climate impact reduction	80-90%
Additional cost	0-5% CASK[2]
Entry into service	<10 years
Propulsion power	Fuel cell system
MTOW[3]	+15%

1. Major assumptions: 25% gravimetric index of LH_2 tank, 90% useable LH_2 fuel, FCS mass 1.5 kW/kg (incl. cooling) and 58% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg
2. Cost per available seat kilometer
3. Maximum take off weight

Exhibit 7

Regional aircraft powered by fuel cells

Revolutionary aircraft

Design mission: 80 PAX, 1,000 km range, cruise speed Mach 0.44

- **Highly efficient** wing
- **2 LH_2 tanks** behind PAX cabin - added weight: 2 tons
- **Distributed propulsion** using electric motors for thrust

Energy demand[1]	-8%
CO_2 reduction	100%
Climate impact reduction	80-90%
Additional cost	5-15% CASK[2]
Entry into service	10-15 years
Propulsion power	Fuel cell system
MTOW[3]	+10%

1. Major assumptions: 30% gravimetric index of LH_2 tank, 90% useable LH_2 fuel, FCS mass 1.75 kW/kg (incl. cooling) and 59% peak efficiency (LHV), e-motors and PMAD with 97%
2. Cost per available seat kilometer
3. Maximum take off weight

Exhibit 8

Short-range aircraft powered by hybrid H_2 propulsion

Revolutionary aircraft

Design mission: 165 PAX, 2,000 km range, cruise speed Mach 0.72

- **2 LH_2 tanks** behind PAX cabin -added weight: 4 tons
- **Fuel cell system (11 MW)** powering electric motors
- **Electric motor** driving main turbine fan shaft during cruise, while H_2 turbine is turned off

Energy demand[1]	-4%
CO_2 reduction	100%
Climate impact reduction	70-80%
Additional cost	20-30% CASK[2]
Entry into service	15 years
Propulsion power	Hybrid
MTOW[3]	+14%

1. Major assumptions: 35% gravimetric index of LH_2 tank, 91% useable LH_2 fuel, FCS mass 2 kW/kg (incl. cooling) and 60% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg, H_2-turbine with 45% cruise efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

Source: Hydrogen Powered Aviation, 2020 - a fact-based study prepared by McKinsey & Company for the Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU

H_2OPE

Clean Aviation Joint Undertaking phase 1

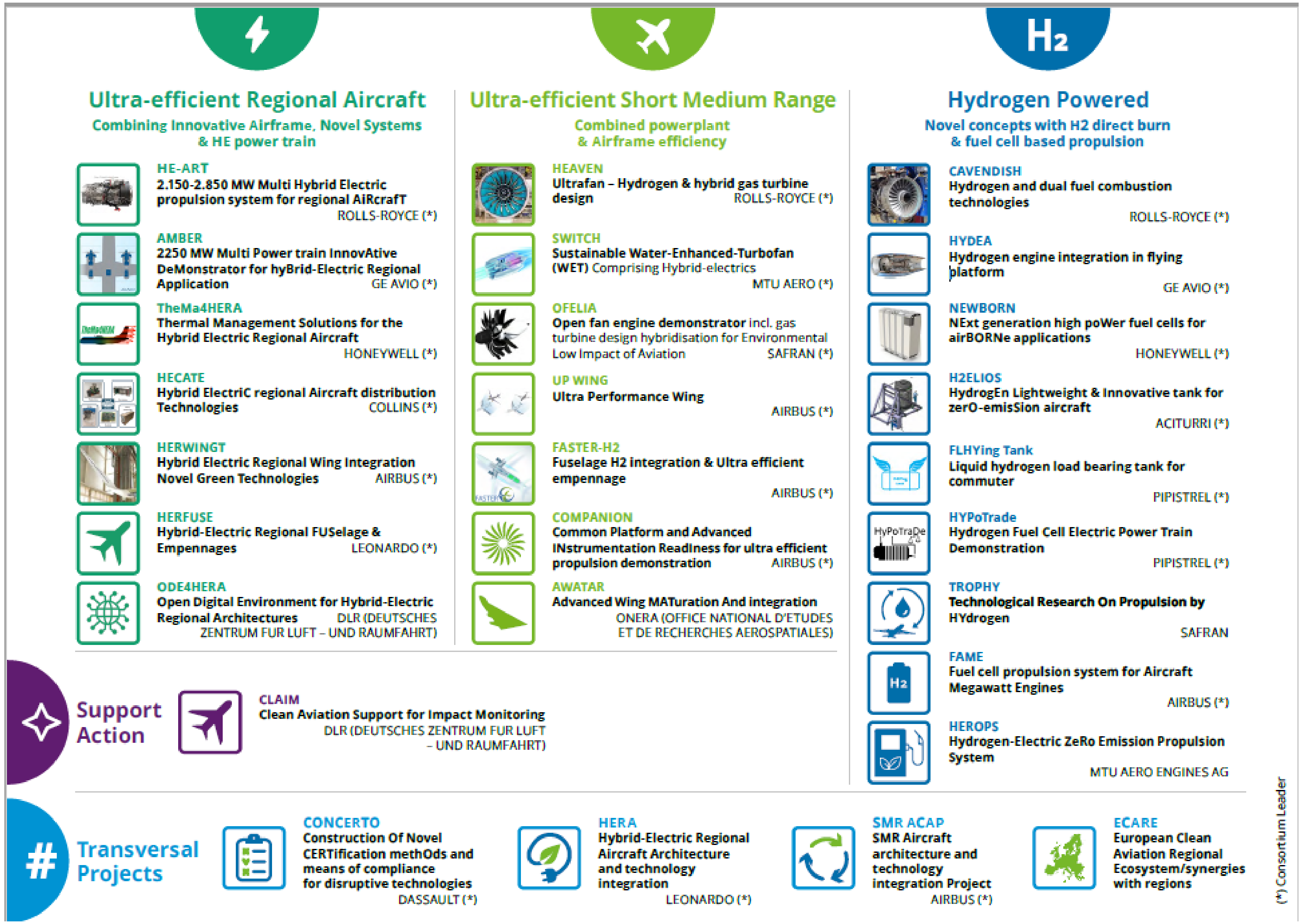
11/23 projects related to:

Hydrogen storage

Hydrogen turbine

Fuel Cell

US, Japan, UK, etc.



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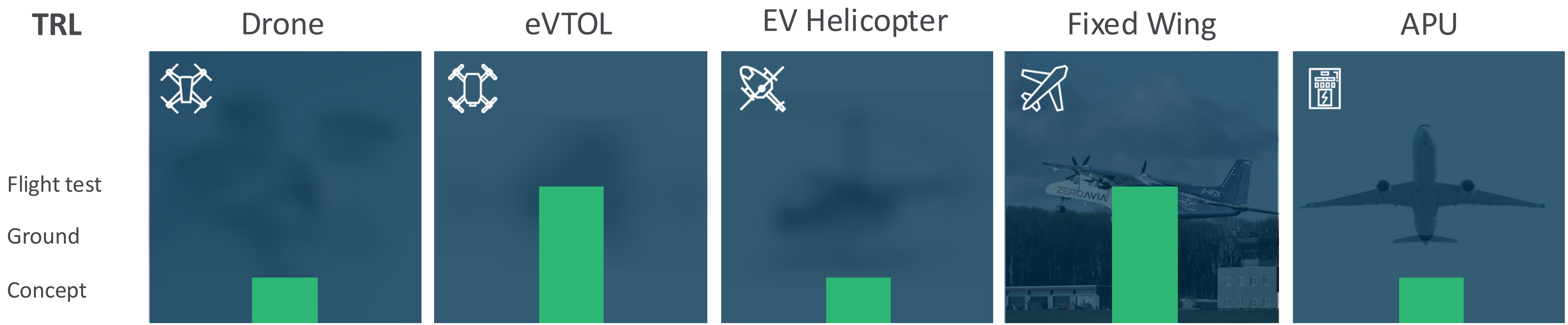
NEWBORN

Fuel cell stack development and delivery

- Lower weight per kW (2-4 units of 300kW stack block)
- Reduced cooling need (higher operating temperature)

Efficiency	~49-60%
Operating temperature	105 °C
Fuel cell technology	PEM
Power / Stack	Modular (range: 300 kW – 1 MW)
Power density	>5 kW/kg

Aviation Applications



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