Hydrogen-powered aviation

A fact-based study of hydrogen technology, economics, and climate impact by 2050

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With input from a broad industry and research coalition this study evaluated the potential of hydrogen for aviation

Project team

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Clean Sky 2

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Study focus

Evaluation of **potential**, **technical and economical feasibility** of hydrogen for aviation

Modeling of implications on **aircraft design**, **airport infrastructure** and **fuel supply chains**

Recommendation of a R&I roadmap

Hydrogen-powered aviation

A fact-based study of hydrogen technology, economics, and climate impact by 2050

Study results in a nutshell

Our perspective on hydrogen-powered aviation

Technology

Hydrogen could be feasible to power aircraft with entry-into-service as early as 2030-2035 for short-range segments; for the fuel supply and refueling infrastructure the switch to LH_2 can be handled by 2040; however, aircraft and infrastructure challenges seem manageable

Economics

Less than 20 USD per PAX additional costs on a H_2-powered short-range flight, 20% less compared to synfuel (from green hydrogen and direct air carbon capture) to achieve the same climate impact (medium range, 2040); synfuel will likely remain more competitive for long-range aircraft in 2050

Climate impact

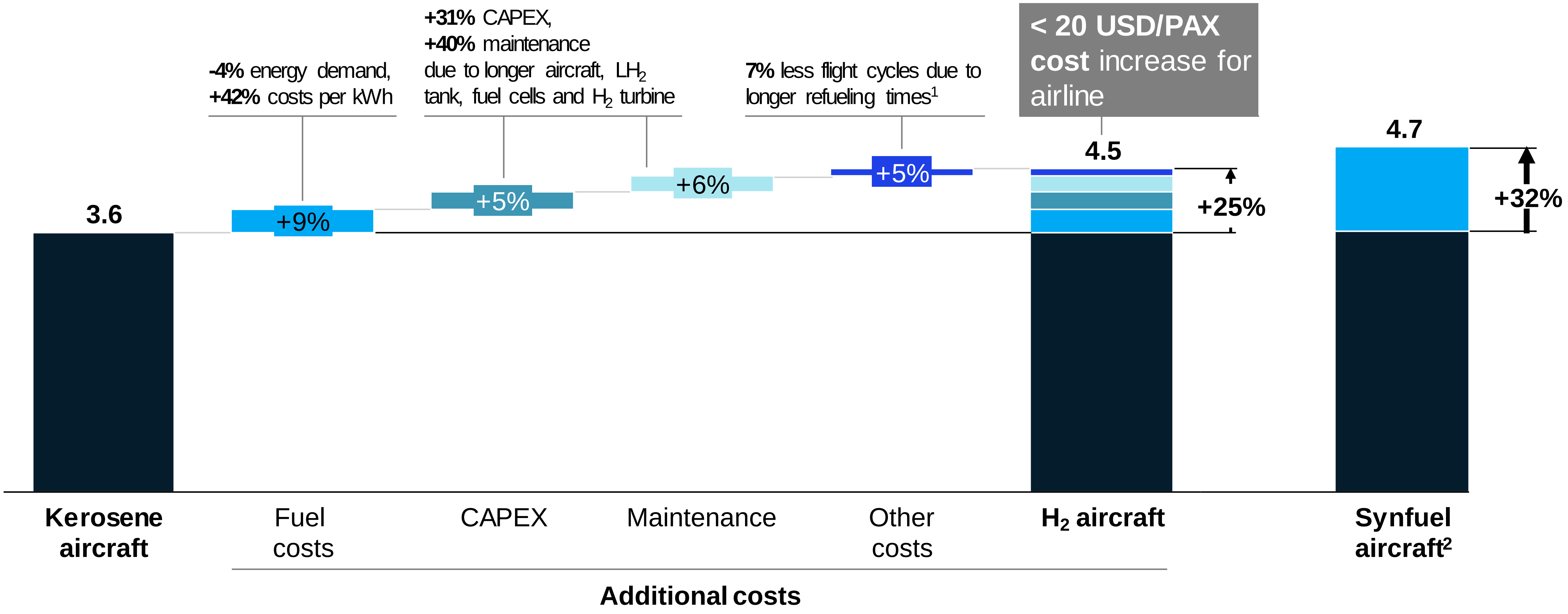
Zero CO_2 and 70% reduction in climate impact by converting 40% of the fleet to H_2 with 15% less global green energy requirements for the sector in 2050. Hydrogen reduces tailpipe CO2 emissions to zero and reduces non-CO_2 emissions such as NOx and contrails

Research & Innovation

First prototype by 2028 required for short-range – significant investments for R&I needed now to meet 2050 target. Advancement on components, aircraft systems, infrastructure and regulatory framework needed

Total cost of ownership increases by 25% or 20 USD/PAX for a short-range aircraft

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



-4% energy demand, **+42%** costs per kWh

+31% CAPEX, **+40%** maintenance due to longer aircraft, LH_2 tank, fuel cells and H_2 turbine

7% less flight cycles due to longer refueling times[1]

< 20 USD/PAX cost increase for airline

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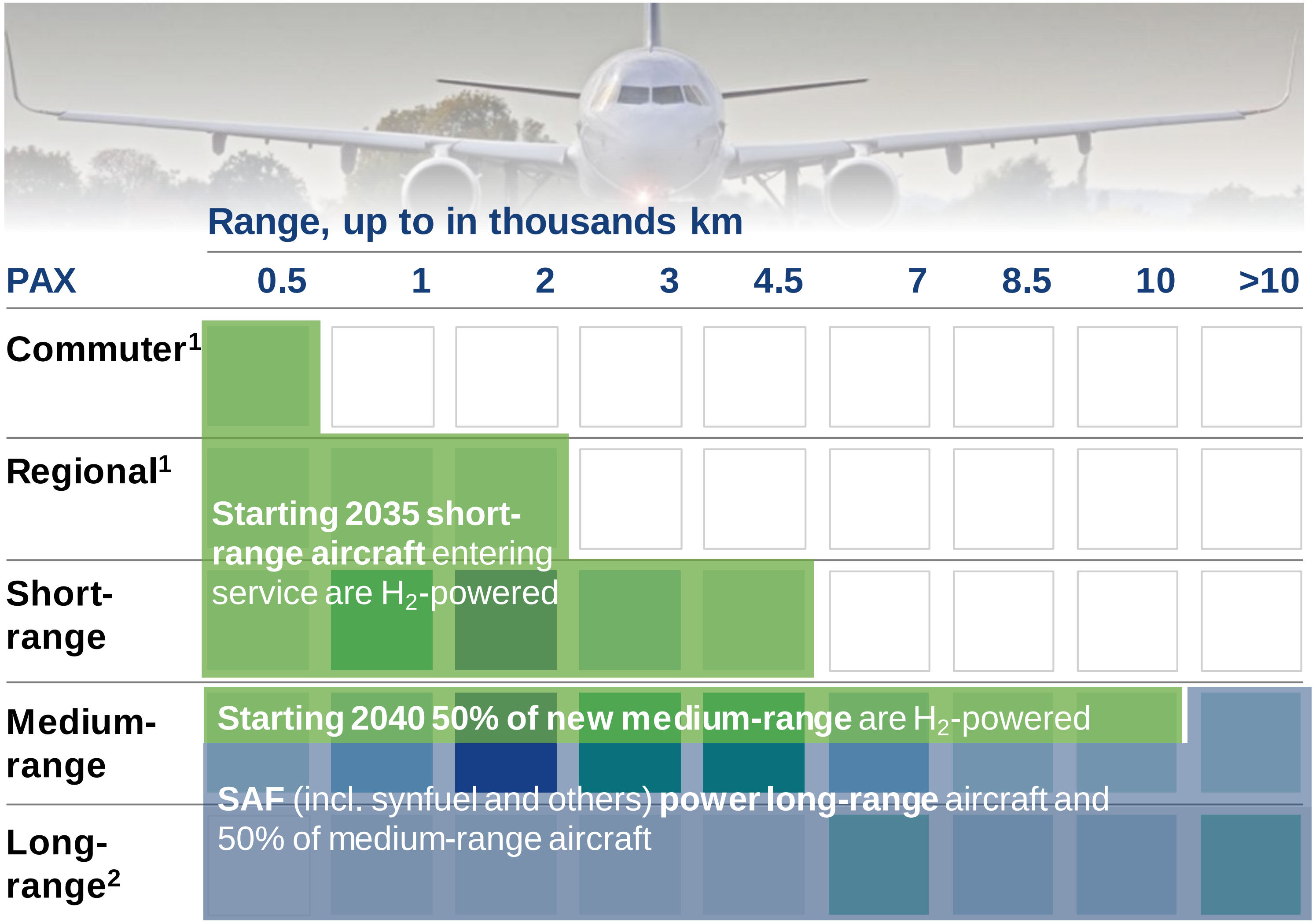
1. As the number of flight cycles decrease, CAPEX and crew costs will increase. Other costs also cover increased fees due to higher MTOW
2. Synfuel from green hydrogen with carbon from direct air capture

Scenario for full decarbonization in 2050: Hydrogen and synfuels where most economic



Range, up to in thousands km

PAX 0.5 1 2 3 4.5 7 8.5 10 >10

Commuter[1]

Regional[1]

Short-range

Medium-range

Long-range[2]

Starting 2035 short-range aircraft entering service are H_2-powered

Starting 2040 50% of new medium-range are H_2-powered

SAF (incl. synfuel and others) **power long-range** aircraft and 50% of medium-range aircraft

Potential impact by 2050

- **~40% aircraft** of fleet powered by H_2
- **1.8 Gtons of CO_2 abated** achieving net zero target
- **0.8 Gtons** additional reduction of non-CO_2 emissions[3]

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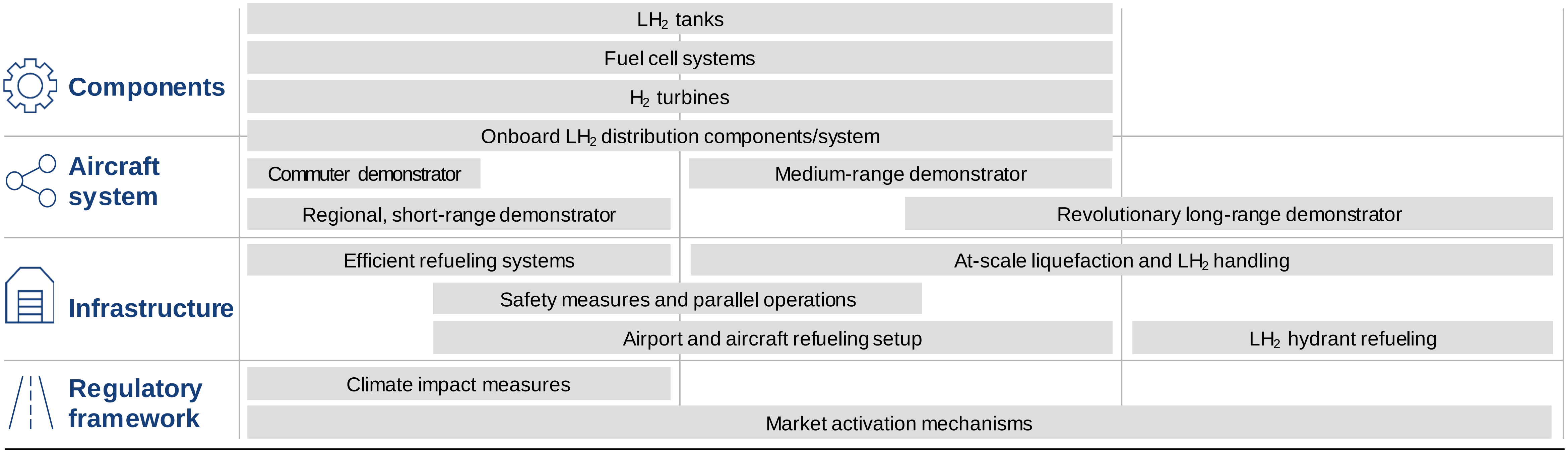
1. Potential EIS in 2030
2. Technical feasible with H_2 propulsion, but not as economic as synfuels
3. Measured in CO_2eq; As the deployment of H_2 aircraft will further grow after 2050 the reduction of climate impact will scale to 70%

Hydrogen requires significant Research & Innovation
4 main research areas for roadmap

	2020	2028	2035	2050
Main milestones		Proof of tech. feasibility and **certification of commuter** aircraft **Short-range** aircraft **demonstrator**	**Medium-range** aircraft **demonstrator** Safe and efficient **airport refueling** setup	Demonstrator of **revolutionary long-range aircraft** **Large scale refueling** infrastructure



Components

- LH_2 tanks
- Fuel cell systems
- H_2 turbines
- Onboard LH_2 distribution components/system

Aircraft system

- Commuter demonstrator
- Medium-range demonstrator
- Regional, short-range demonstrator
- Revolutionary long-range demonstrator

Infrastructure

- Efficient refueling systems
- At-scale liquefaction and LH_2 handling
- Safety measures and parallel operations
- Airport and aircraft refueling setup
- LH_2 hydrant refueling

Regulatory framework

- Climate impact measures
- Market activation mechanisms

Key takeaway: Hydrogen propulsion has significant potential as one major lever of decarbonization alongside other technologies

Technology

Hydrogen is a compelling option to power aircraft, key technologies to be developed and uncertainties addressed

Research & Innovation

Demonstrator by 2028 required for short-range and significant investments for R&I needed now to meet 2050 target

Economics

Less than 18 EUR per PAX additional costs on a H2-powered short-range flight

Climate impact

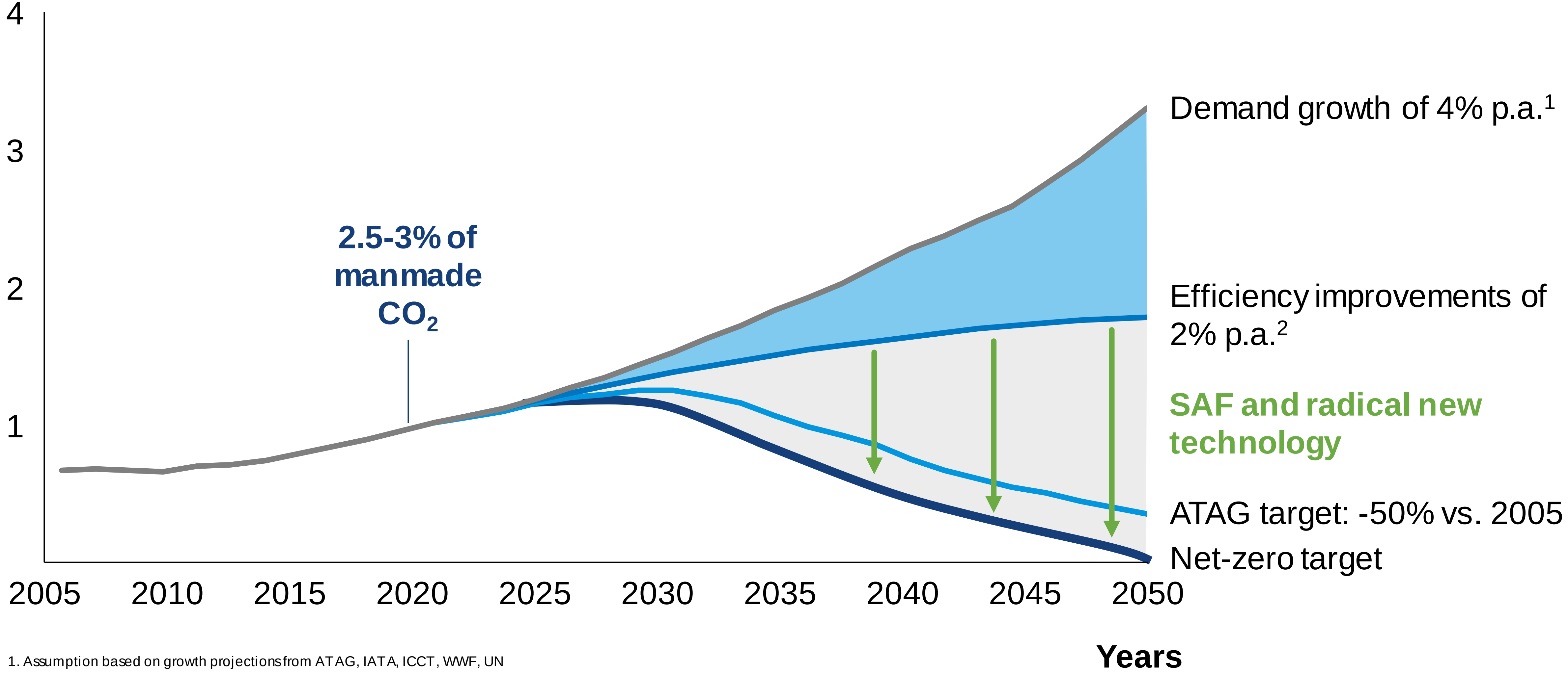
Zero CO_2 emissions and up to 70% reduction of total climate impact compared to a kerosene-powered aircraft in 2035

Backup

Aviation needs new propulsion technologies and/or fuels to decarbonize

Gt CO_2 emissions from aviation

DOES NOT INCLUDE COMPENSATION SCHEMES

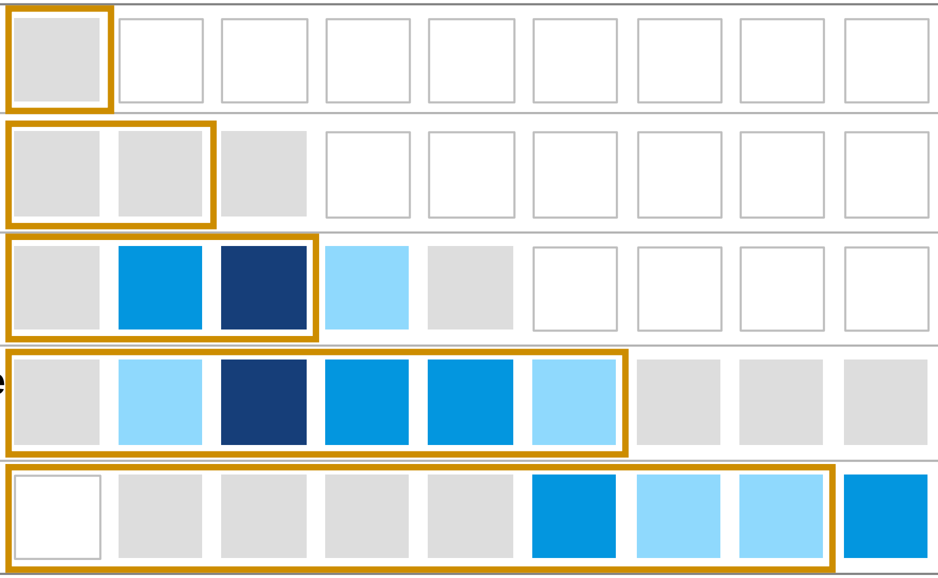


1. Assumption based on growth projections from ATAG, IATA, ICCT, WWF, UN
2. ICAO ambition incl. efficiency improvements in aircraft technology, operations and infrastructure – however highly ambitious compared to other sources (EASA)

Methodology: We evaluated the potential of hydrogen propulsion in five segments

Share of total CO_2 emissions

□ < 0.1% ░ 0.1-2% ▒ 2-5% ▓ 5-10% █ 10-15%



PAX	Range up to in thousand km									Share of total	
	0.5	1	2	3	4.5	7	8.5	10	>10	CO_2 emissions	Global fleet
Commuter <19	░	□	□	□	□	□	□	□	□	<1%	4%
Regional 20-80	░	░	░	□	□	□	□	□	□	3%	13%
Short-range 81-165	░	▓	█	▒	░	□	□	□	□	24%	53%
Medium-range 166-250	░	▒	█	▓	▓	▒	░	░	░	43%	18%
Long-range >250	□	░	░	░	░	▓	▒	▒	▓	30%	12%

5 segments defined for evaluation, covering ~90% of total emissions

Dimensions of evaluation

Climate impact

Technical feasibility:

Aircraft design

Infrastructure

Economics

Climate impact: H_2 propulsion has no CO_2 emissions and biggest potential to reduce climate impact

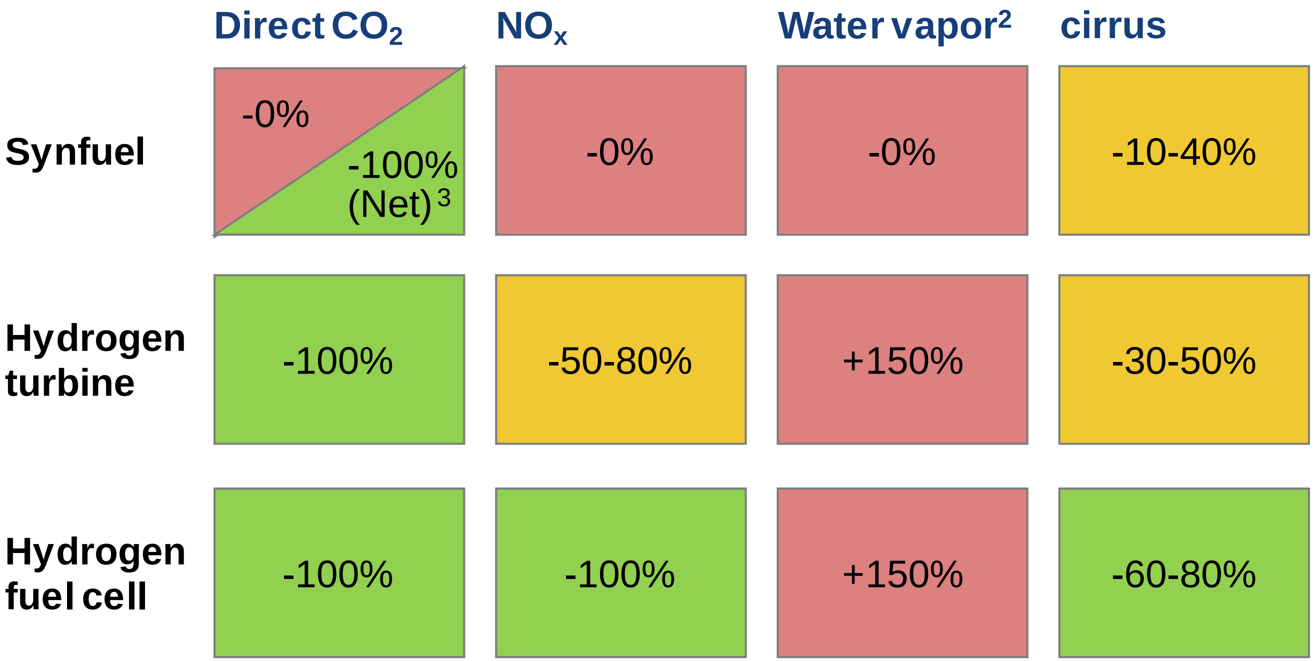
Compared to kerosene-powered aircraft, timeframe until 2100

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]



	Direct CO_2	NO_x	Water vapor[2]	Contrails, cirrus	Climate impact reduction potential[4]
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%**

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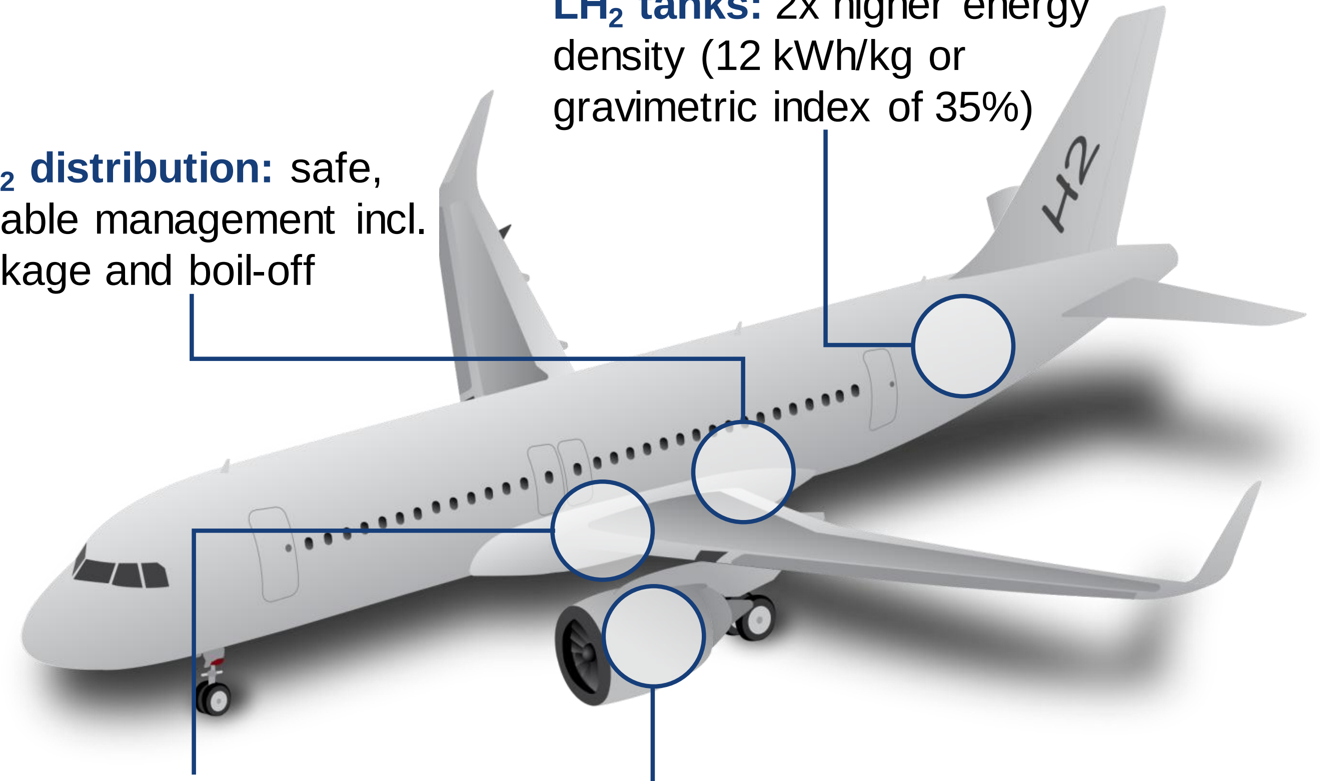
1. No full LCA considered, but assuming decarbonized production and transportation of fuels in 2050
2. 10 times lower climate impact than from CO_2 emissions
3. Net CO_2 neutral if produced with CO_2 captured from the air
4. Measured in CO_2 equivalent compared to full climate impact of kerosene-powered aviation

Aircraft design: four technology improvements…

TIMEFRAME 2035

EXEMPLARY PICTURE



LH_2 tanks: 2x higher energy density (12 kWh/kg or gravimetric index of 35%)

LH_2 distribution: safe, reliable management incl. leakage and boil-off

Fuel cell system: 2-3x higher power density (2 kW/kg), high life-time

H_2 turbines: high efficiency and low NOx emissions

…could enable H_2 aircraft

Example result of simulation of H_2-powered short-range aircraft

Mission: 2,000 km, 165 PAX, Mach 0.72

Propulsion: parallel hybrid of H_2 turbines and fuel cell system

Evolutionary design: adjusted for LH_2 systems, **+10% longer fuselage**

100% decarbonization

75% climate impact reduction

-5% energy demand

15 years to entry-into-service

Clean Sky 2

Three major infrastructure challenges to roll out LH_2 aviation; refueling challenge most significant

⬜ Can be accommodated in prevailing infrastructure

🟦 Updates of infrastructure / operations required

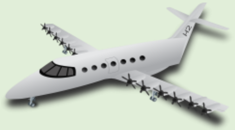
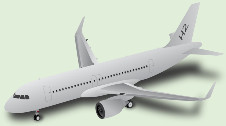
■ Full overhaul of infrastructure / operations required

	Until 2040 (hydrogen 15% of fleet)	From 2040 to 2050 (hydrogen 40% of fleet)
1 **H_2 production and distribution for aviation**	⬜ **5% of global hydrogen** demand Can be **served with LH_2 trucks** from central production sites or on-site	🟦 **10% of global hydrogen** demand At-scale distribution **requires pipelines** to airport
2 **Required LH_2 airport infrastructure**	⬜ **Centralized liquefaction** (unless on-site production) **Truck-based** refueling **No** major infrastructure updates	🟦 **Onsite liquefaction** **At-scale** refueling systems **Larger** gate sizes and on-ground traffic changes
3 **Refueling times**	🟦 **Within usual turnaround times** for shorter range flights **New safety regulations required** for parallel operations	■ **Extends beyond usual turnaround times** for longer range flights[1]
	No insurmountable roadblocks in early ramp-up years	**Significant but manageable challenges in scale-up years**

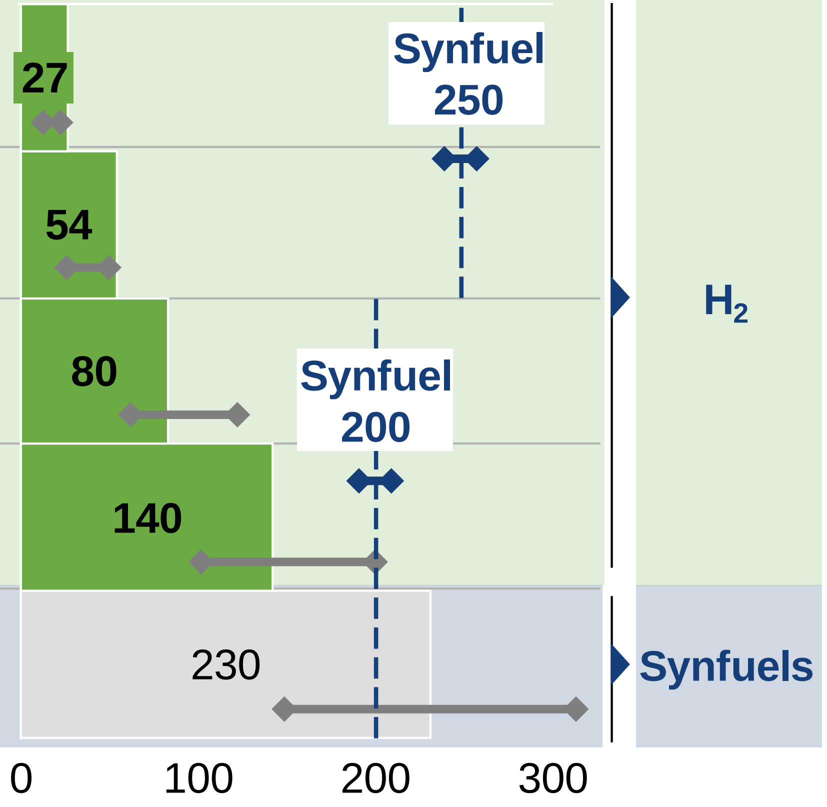
1. Considering similar flow rates like kerosene and double the amount of refuelling points

H_2 propulsion could be lower cost up to medium-range compared to synfuels which would be more competitive for long-range

TIMEFRAME 2040

		Projected years until earliest EIS[1]	Costs compared to	
			Kerosene	Synfuel
	**Commuter** 19 PAX, 500 km	10	+5%	-10%
	**Regional** 80 PAX, 1,000 km	10-15	+10%	-10%
	**Short-range** 165 PAX, 2,000 km	15	+25%	-5%
	**Medium-range** 250 PAX, 7,000 km	20	+35%	+/- 0%
	**Long-range** 325 PAX, 10,000 km	20-25	+50%	+10%

Abatement costs
EUR per ton CO_2eq



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1. Entry-Into-Service
2. Cost per available seat kilometer