Project 52

Comparative assessment of electrification strategies for aviation

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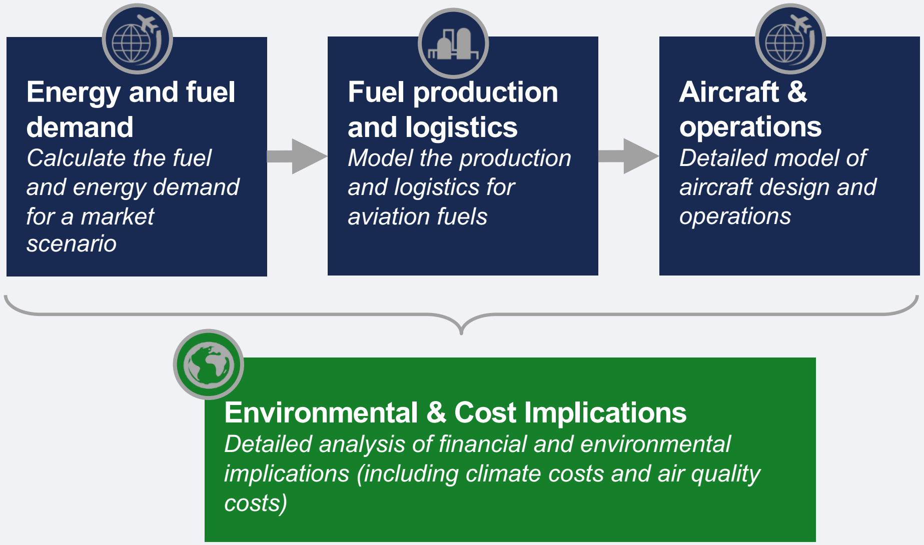
Cost share partners: NuFuels, MIT



Energy and fuel demand
Calculate the fuel and energy demand for a market scenario

Fuel production and logistics
Model the production and logistics for aviation fuels

Aircraft & operations
Detailed model of aircraft design and operations

Environmental & Cost Implications
Detailed analysis of financial and environmental implications (including climate costs and air quality costs)

Objective:

To evaluate:

(1) the operational and economic feasibility of electrification strategies, and

(2) the life-cycle GHG emissions and their associated impacts, relative to conventional petroleum-powered aircraft.

Today's focus:

Assessment of electricity-powered aviation with near-zero impact on climate and air quality

Project Benefits:

Provide data and guidance on the most promising electrification approaches for aviation

Major Accomplishments (to date):

- Compared aviation systems using LH_2 and PtL from environmental and cost perspective in an integrated systems model.
- Provided analysis of the parameters that drive the comparison between SAF and LH_2 systems.
- Global assessment of supply chains for scaled-up LH_2 and PtL production using renewable electricity.

Future Work / Schedule:

- Infrastructure considerations for battery-electric aircraft
- "Optimal aviation fuel" made from electricity?

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Design an aviation system with near-zero environmental impact, considering:

- Aviation CO_2 climate impacts
- Aviation non-CO_2 climate impacts

Objective:
(Net) zero climate impact

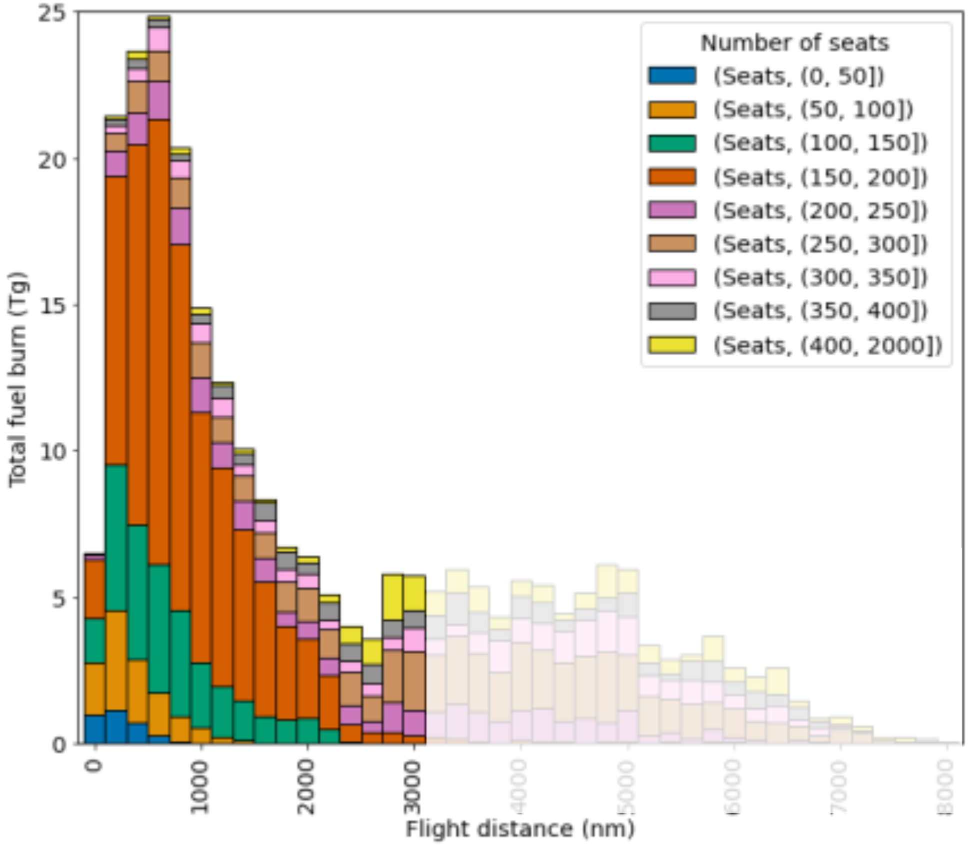
- Air pollution

Objective:
95% reduction

Initial market study: *short- and medium-range market selected based on global fuel burn distribution*

Distribution of global fuel burn by mission length and aircraft capacity

Scheduled pax aviation only, year 2019



Mission focus for analysis

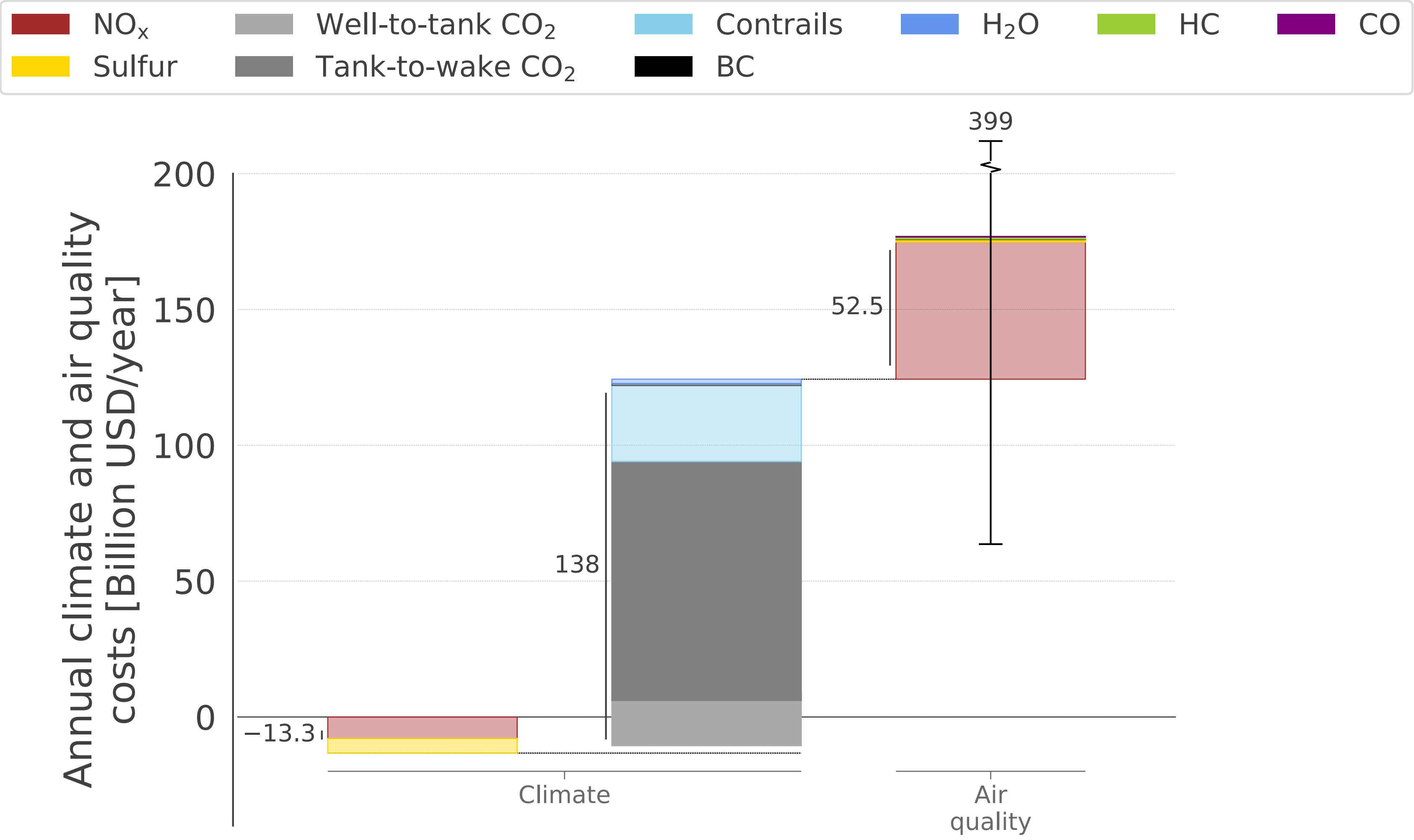
System with similar capabilities as the Boeing 737-9 Max

- *Design range of 3,000 nmi*
- *Capacity of 220 passengers*

→ System could cover missions which (pre-COVID) caused ~44% of fuel burn

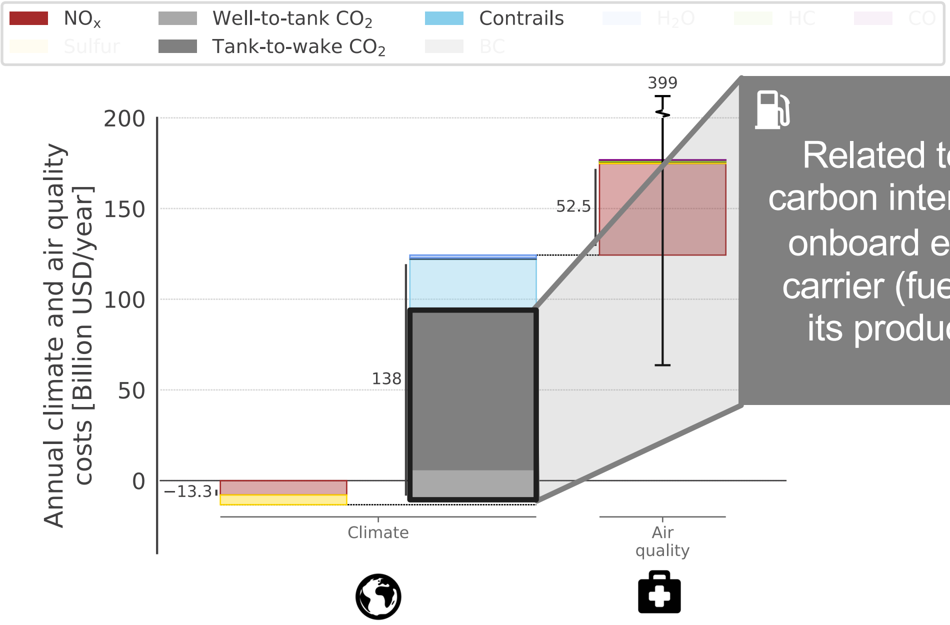
Preliminary

Monetized climate and air quality impact of narrowbody aviation system with current aircraft technology



Preliminary

CO_2 contribution to climate impacts can be addressed via deployment of low-carbon energy carriers



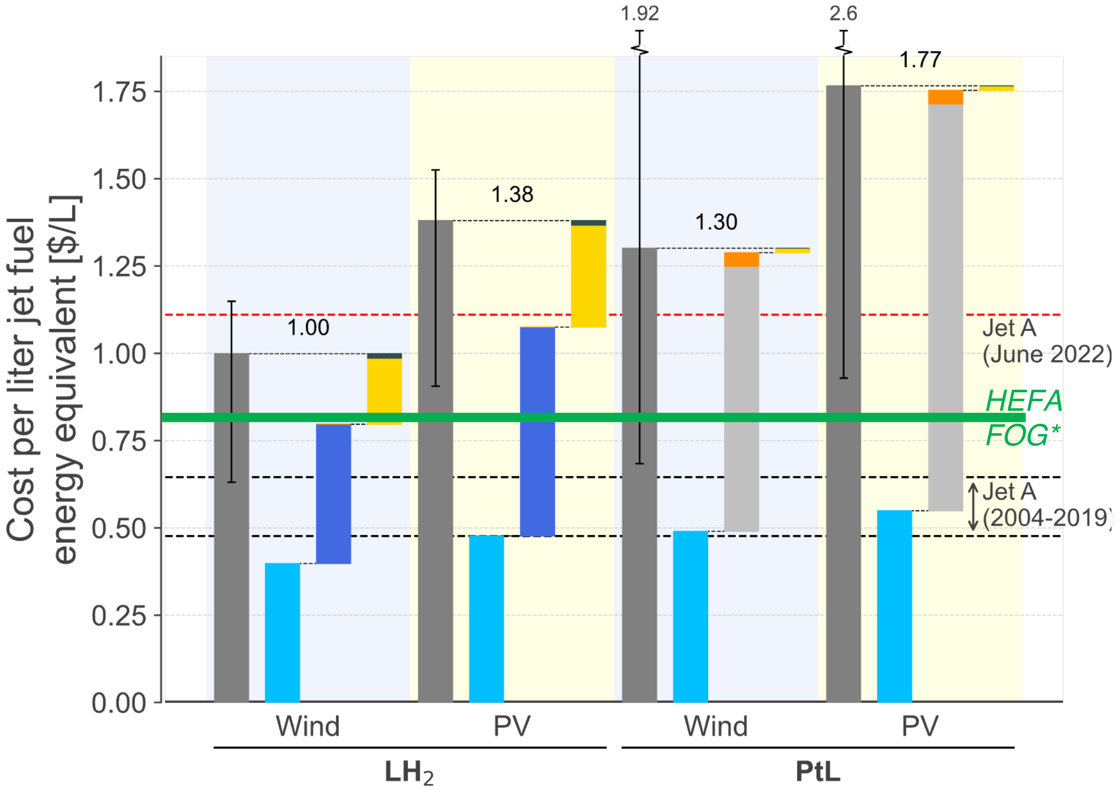
Related to the carbon intensity of onboard energy carrier (fuel) and its production

The **production, transportation** (of feedstock and final fuel) and **combustion** on board aircraft need to be **low-carbon**

Energy costs likely to increase with electrofuels, but …

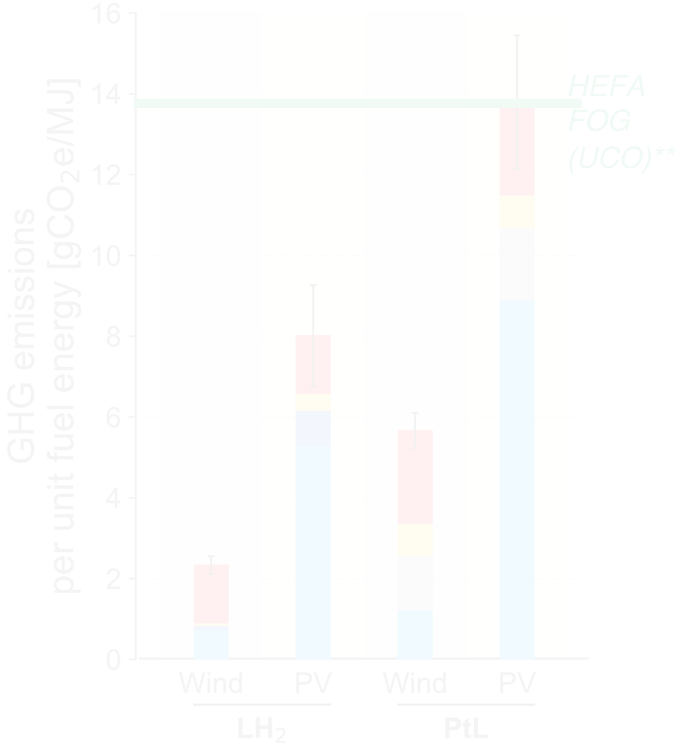
Comparison of energy cost under future technologies

LH_2 and PtL for different electricity sources



LCA for energy carriers

LH_2 and PtL for different electr. Sources, future conditions



Total	Liquefaction	Conversion	Fueling
H_2 production	CO_2 capture	Transport	Embodied Emissions

* n-th plant cost following ICAO Rules of Thumb

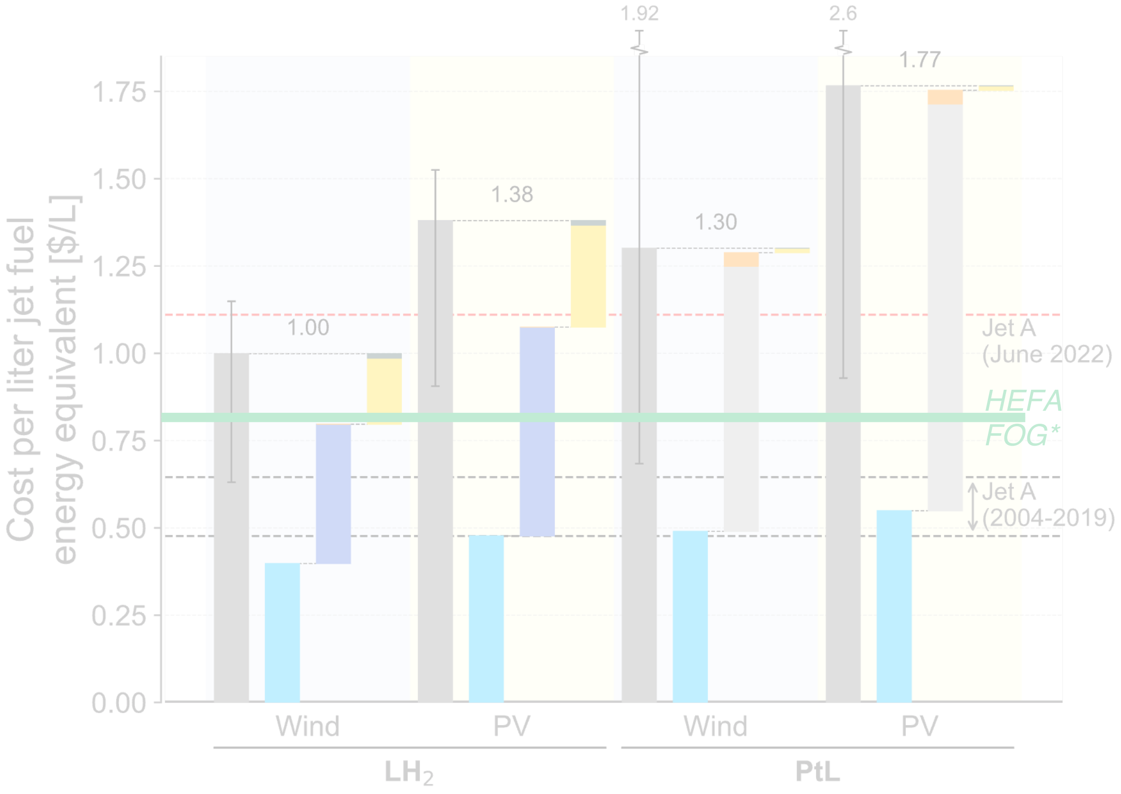
** CORSIA default LCA value

Preliminary

Energy costs likely to increase with electrofuels, but lifecycle emissions reduced by 85% or more compared to Jet-A

Comparison of energy cost under future technologies

LH_2 and PtL for different electricity sources



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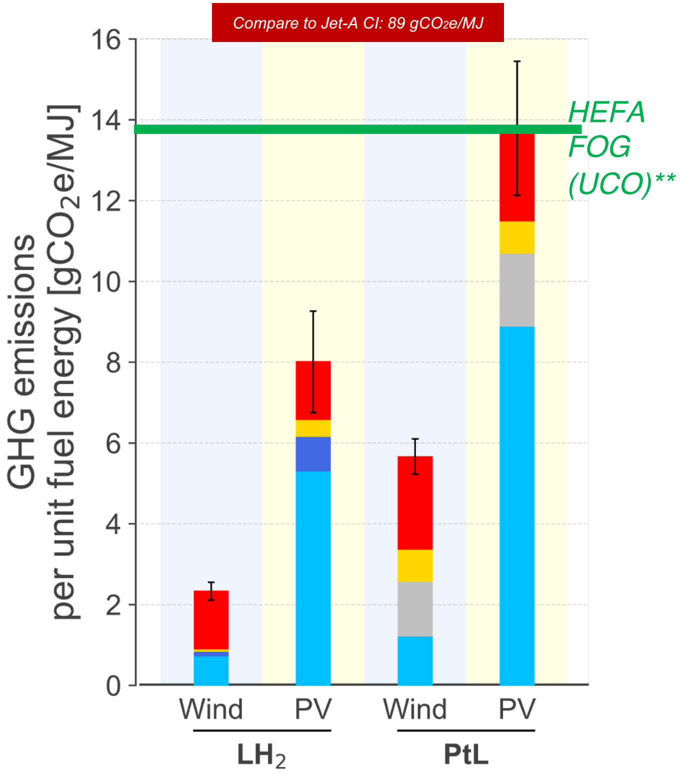

■ Total	■ Liquefaction	■ Conversion	■ Fueling
■ H_2 production	■ CO_2 capture	■ Transport	■ Embodied Emissions

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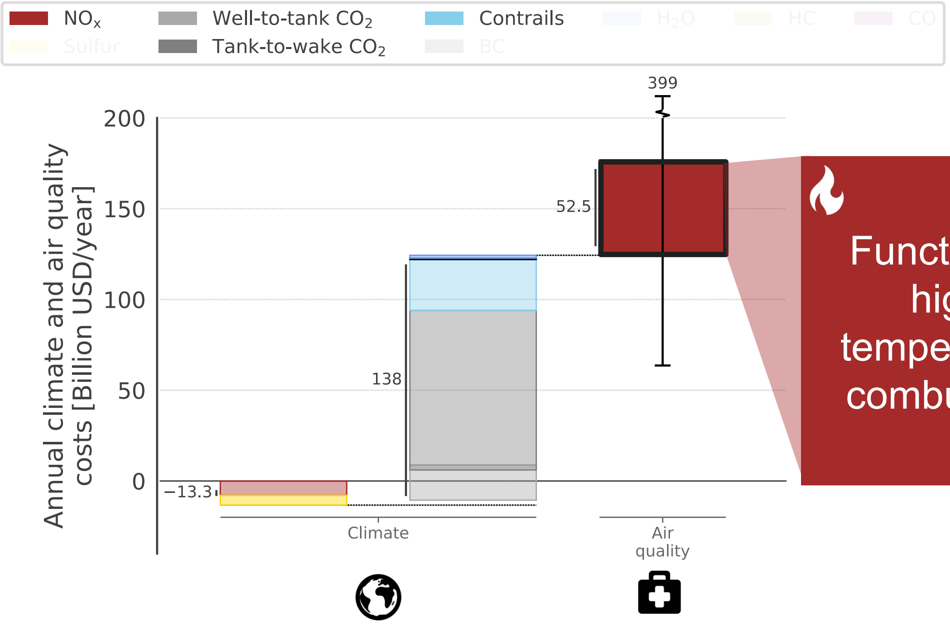
Preliminary

NO$_x$ emissions can be addressed through the design of the aircraft-propulsion system



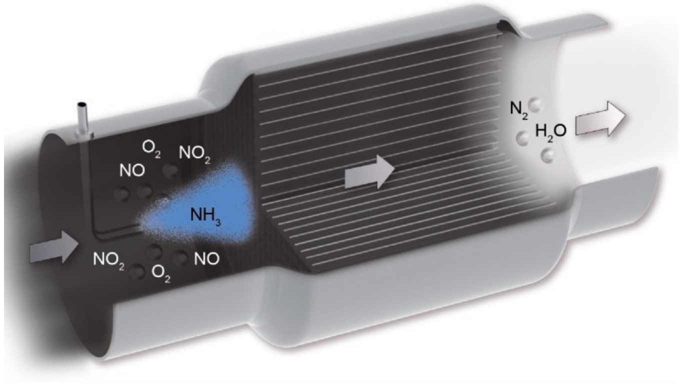
Function of high temperature combustion

The **aircraft-propulsion system** design needs to **minimize / eliminate emissions of NO$_x$**

Preliminary

Post-combustion emission control (PCEC) effective for NO_x reduction; possible implementation with small core engines

Solution in other sectors:
Selective Catalytic Reduction (SCR) devices to reduce NO_x emissions



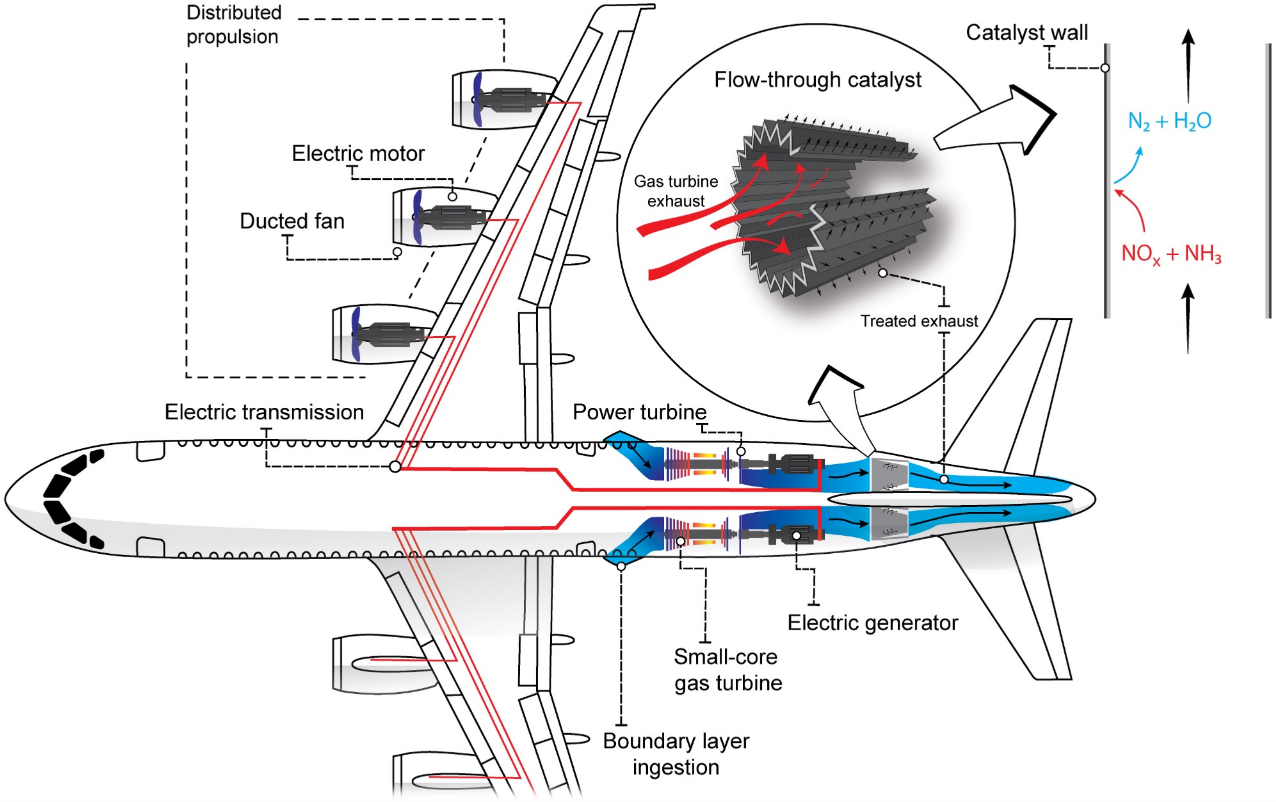
$NO_x + O_2$ → Reducing agent → Catalyst → $N_2 + H_2O$

Small core, high power density engines open opportunities for emissions control

- There is a move towards smaller, power-dense engine cores with lower mass flow rates
- Fraction of thrust produced by core compared to total thrust has decreased
- Implementation of PCEC “under wing” remains difficult due to the size of the device and associated drag; can be combined with turbo-electric architecture

Notional implementation of PCEC on a turbo-electric aircraft

Notional implementation for a narrowbody aircraft

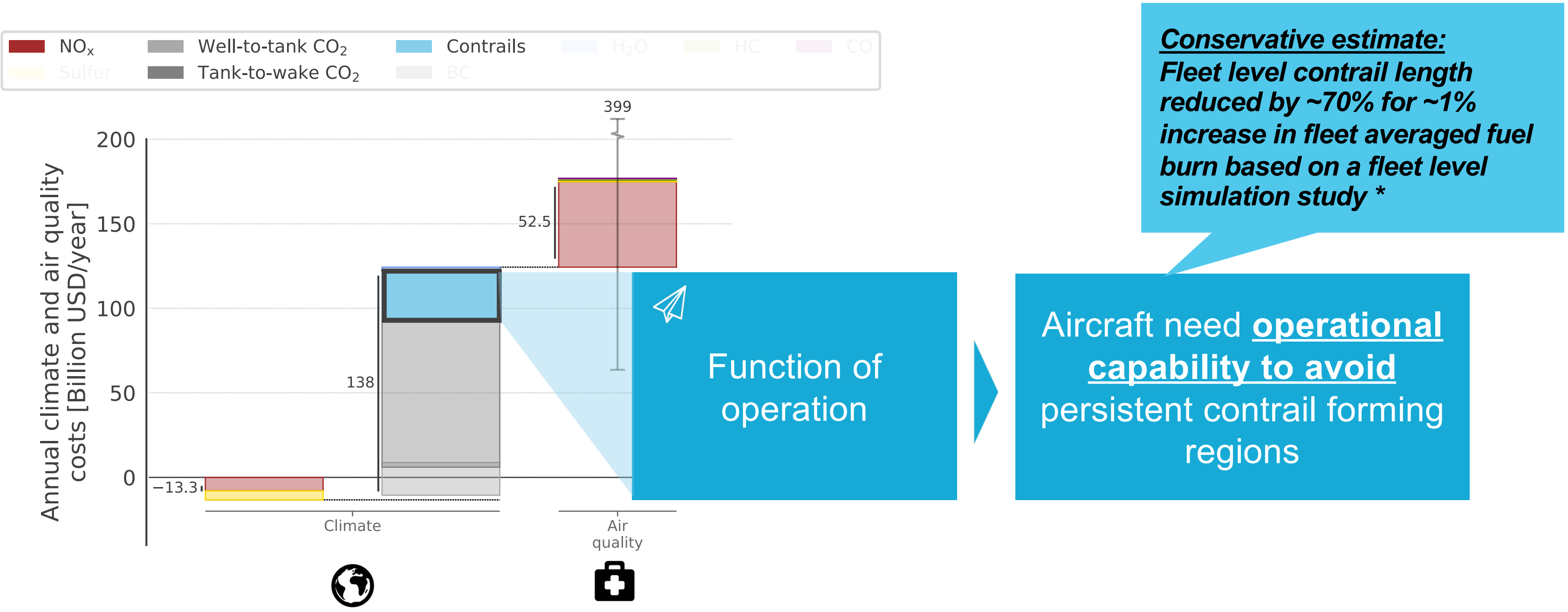


Performance metrics	
NO_x reduction (deNO_x)	95%
Increase in mission fuel burn*	0.5%
Catalyst mass (per engine)	91 kg
Reductant mass (1500 km mission)	21 kg
Additional system mass (pumps, storage tanks, etc.)	128 kg

* due to catalyst, reductant and related systems.

Prashanth, P., Speth, R. L., Eastham, S. D., Sabnis, J. S., and Barrett, S. R. H. H. "Post-Combustion Emissions Control in Aero-Gas Turbine Engines." Energy & Environmental Science, Vol. 14, No. 2, 2021, pp. 916–930. https://doi.org/10.1039/d0ee02362k.

Contribution of contrails to climate impacts can be reduced via operational contrail avoidance



Conservative estimate:
Fleet level contrail length reduced by ~70% for ~1% increase in fleet averaged fuel burn based on a fleet level simulation study *

Function of operation

Aircraft need **operational capability to avoid** persistent contrail forming regions

* *See ASCENT 78 for more detailed analyses*

Preliminary

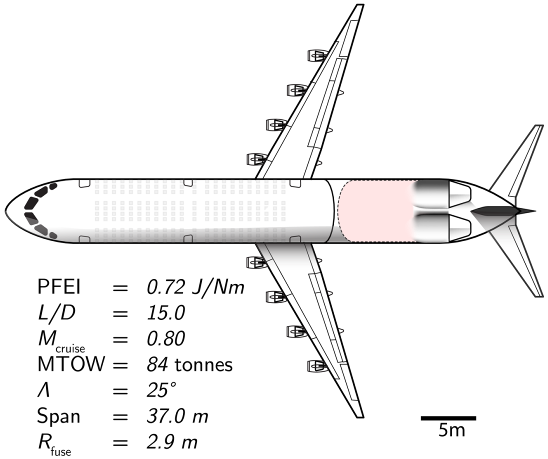
Aircraft assessed using MIT's TASOPT code; short haul (net)-zero impact LH_2 aircraft with ~20% higher energy consumption compared to SAF

Conceptualization of the aircraft system based on TASOPT

- *Physics-based design tool that combines structural, aerodynamic, and thermodynamic sub-models to produce aircraft performance metrics.*
- *Relies on first-principles approach when possible, rather than extrapolated fits from empirical data.*
- *Includes joint optimization of airframe, propulsion, and operations.*

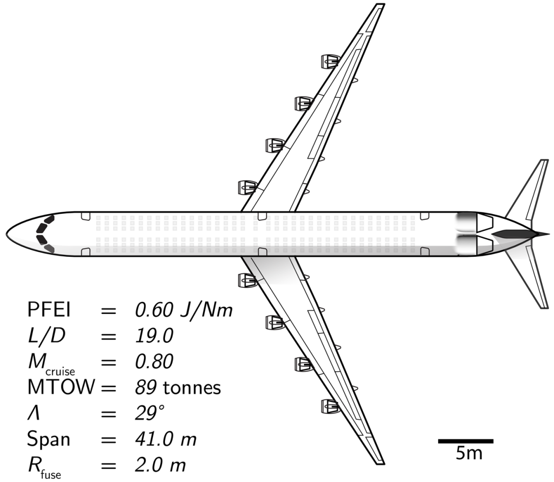
Outputs for 220pax, 3000nmi range class aircraft

Zero Impact Aircraft powered by LH2



PFEI = *0.72 J/Nm*
L/D = *15.0*
M_{cruise} = *0.80*
MTOW = *84* tonnes
Λ = *25°*
Span = *37.0 m*
R_{fuse} = *2.9 m*

Zero Impact Aircraft powered by SAF



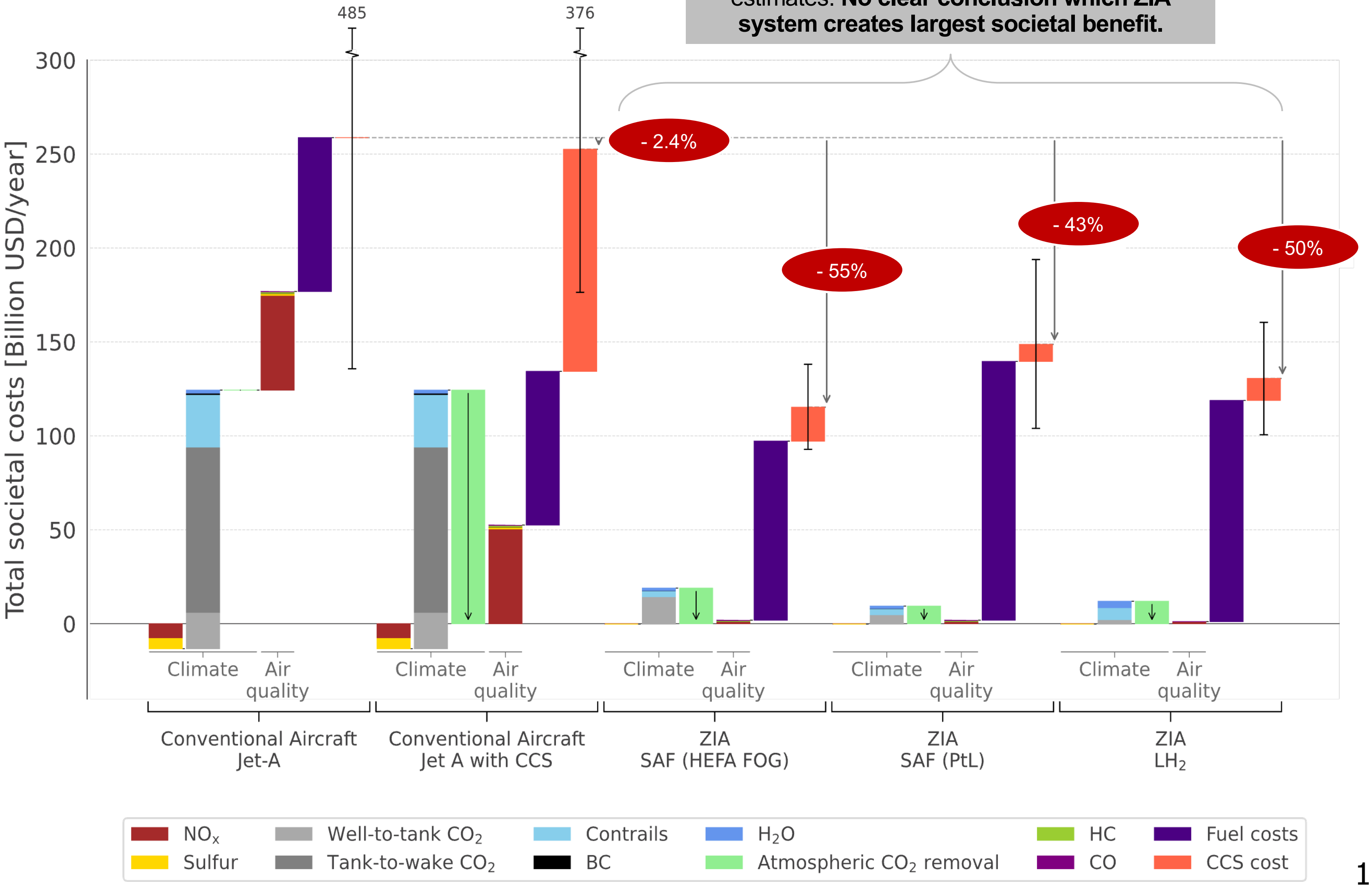
PFEI = *0.60 J/Nm*
L/D = *19.0*
M_{cruise} = *0.80*
MTOW = *89* tonnes
Λ = *29°*
Span = *41.0 m*
R_{fuse} = *2.0 m*

- LH_2 powered aircraft requires **~20% more energy** than a SAF aircraft for the same mission – heavy tanks, increased fuselage drag, reduced wing relief, *no consideration of potential cycle benefits*.
- Fleet average **reduction in NO_x of ~96%**

Preliminary

Results: ZIA concept reduces net societal cost (fuel (incl. CCS) + environment) of aviation by ~43-55%, while accounting for higher fuel costs

Uncertainty analysis reveals overlapping cost estimates. **No clear conclusion which ZIA system creates largest societal benefit.**



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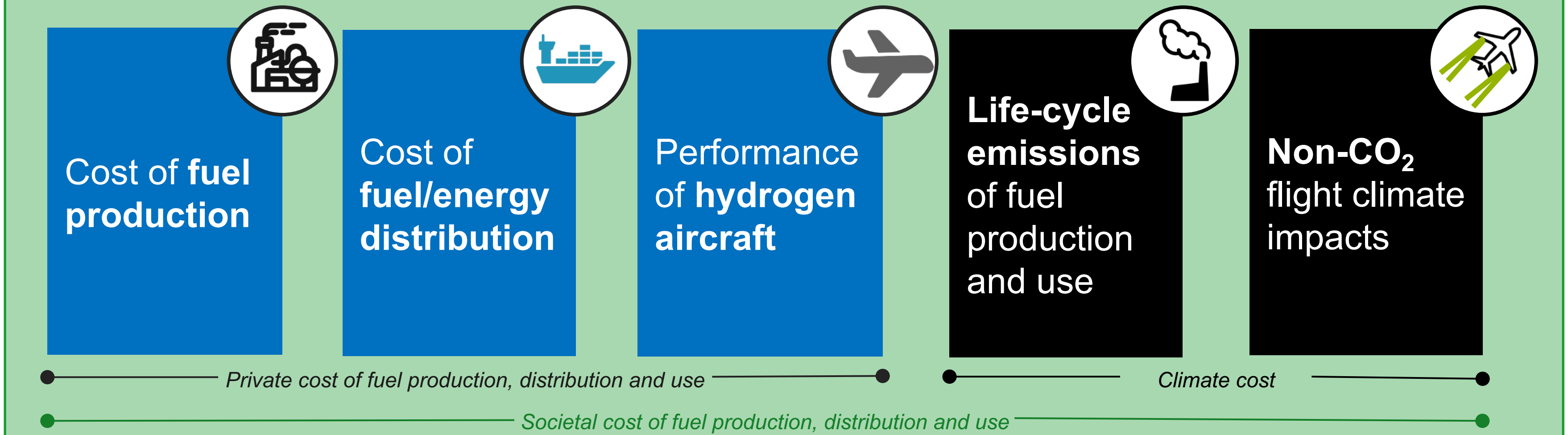
*Comparing the **cost** and **impact** of LH_2- and PtL-powered flight is challenging due to **uncertainties in key technical, cost, and environmental impact parameters***

Can we determine under which conditions PtL or LH_2 is the more beneficial fuel from a societal perspective if electricity is the main input to energy carrier production?



Cost of **fuel production**

Cost of **fuel/energy distribution**

Performance of **hydrogen aircraft**

Life-cycle emissions of fuel production and use

Non-CO_2 flight climate impacts

Private cost of fuel production, distribution and use

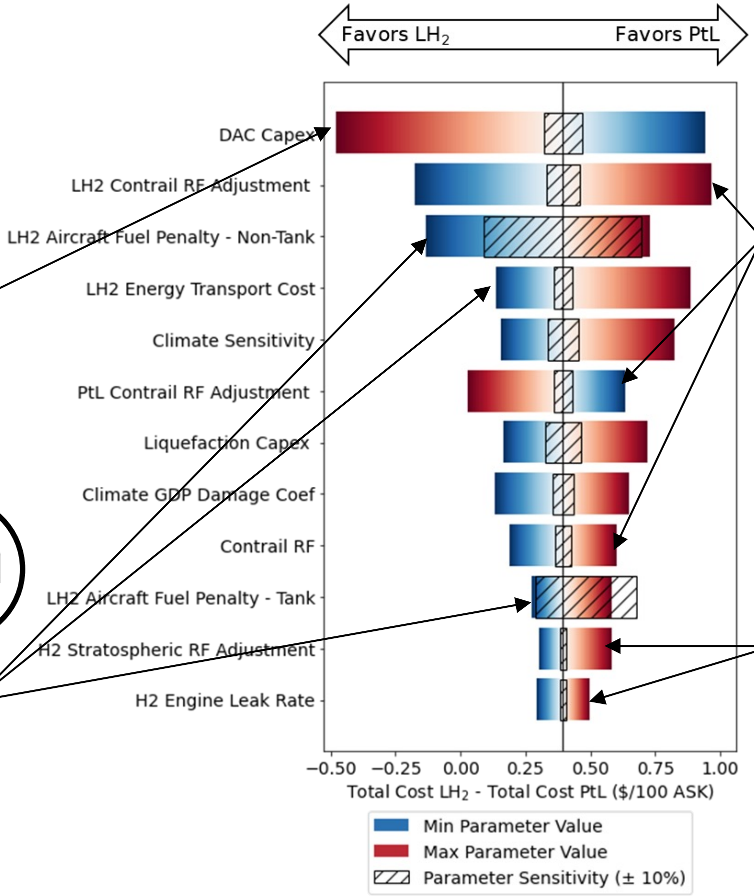
Climate cost

Societal cost of fuel production, distribution and use

Model Results: Comparison

The economic viability of PtL depends on the **development of industrial-scale DAC technology**

The feasibility of LH_2 aviation depends on **how much it affects aircraft fuel efficiency** and **how much it costs to distribute**



The most important climatic uncertainty for LH_2 and PtL is **contrail production**

The warming of **stratospheric H_2 leakage** is a secondary climate uncertainty for LH_2 flight

Takeaways

- Consider (at least) **climate and air quality** when discussing a zero-environmental-impact aviation system
- There is **no single optimal strategy** for electrofuel deployment (LH_2 vs. PtL) – attractiveness of each depends on **assumptions.**
- The **economic viability** of large-scale PtL production is contingent on the availability of **cheap direct air capture.** DAC CapEx >2000 USD/ton CO_2 is difficult to afford.
- The **feasibility of LH_2 aviation** will depend on the **efficiency of LH_2 aircraft** and the **cost penalty of LH_2 distribution.** Energy efficiency penalties of LH_2 aircraft >20% are problematic.
- Further research on the climate impact of **contrails** and **H_2 leakage** from hydrogen-derived fuels is needed to determine whether direct H_2 use can offer a **net environmental benefit.**

Preliminary