

Project 52

Comparative assessment of electrification strategies for aviation

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Cost share partners: NuFuels, MIT

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.

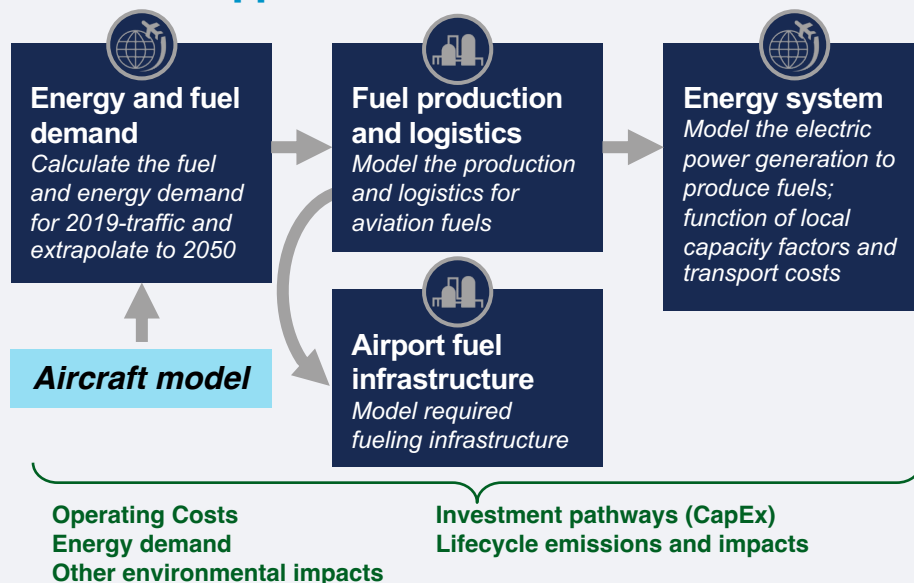
Today's focus:

Assessment of LH₂ as an aviation fuel

Project Benefits:

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

Research Approach:



Major Accomplishments (current period):

For LH₂ fuel, we analyzed

- 1 the environmental performance
- 2 production costs and global supply chain designs
- 3 implications of LH₂ use onboard aircraft

Future Work / Schedule:

- Further integration of aircraft model to assess feasibility and impacts at the system-level
- Infrastructure considerations for battery-electric aircraft

Environmental footprint of hydrogen use in aviation: *lifecycle GHG emissions and direct non-CO₂ impacts*

- LH₂ use is not linked to **direct CO₂ emissions**
- Depending on the production process of LH₂, **life-cycle GHG emissions** can be substantially lower than for fossil Jet-A.
- LH₂ may still be associated with **direct non-CO₂ impacts**

Lifecycle (“well-to-tank”) GHG emissions of LH₂ vary significantly by production pathway, gCO₂e/MJ



Non-CO₂ impacts remain but are uncertain

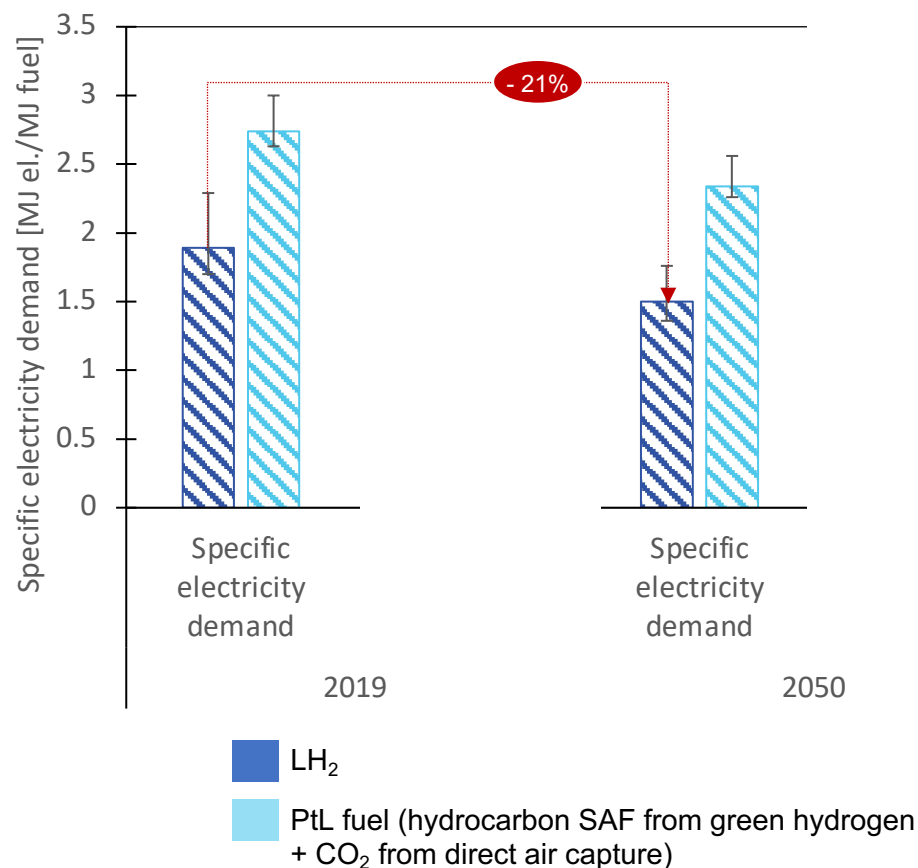
- **Contrails:**
Trade-off: less particle emissions vs. higher water emissions
- **NO_x:** Depends on hydrogen use (i.e., fuel cell vs. combustion); may not be zero
- **Higher water emissions**
- **Boil-off / leakage?**

Hydrogen from electrolysis: *electricity requirements for scale-up*

(for constant aircraft energy efficiency)

Specific energy demand and year-2019 & 2050 fuel replacement with PtL & LH₂

*Specific energy demand in MJ (elec)/MJ(fuel),
total electricity demand in TWh*



* Renewable electricity excluding nuclear.

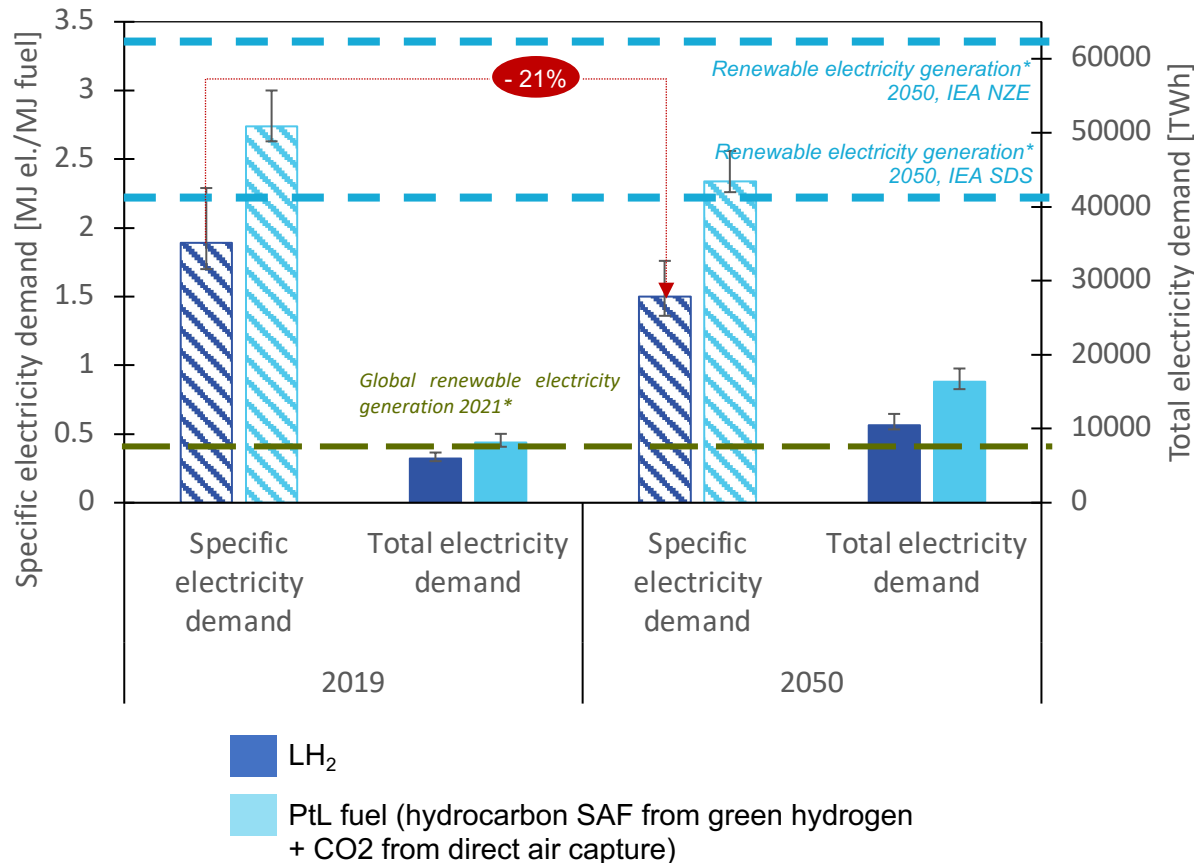
- Specific energy demand of LH₂ production is driven by electrolysis (2020: ~80%; 2050: ~90%) and liquefaction (2020: ~15%; 2050: ~10%)

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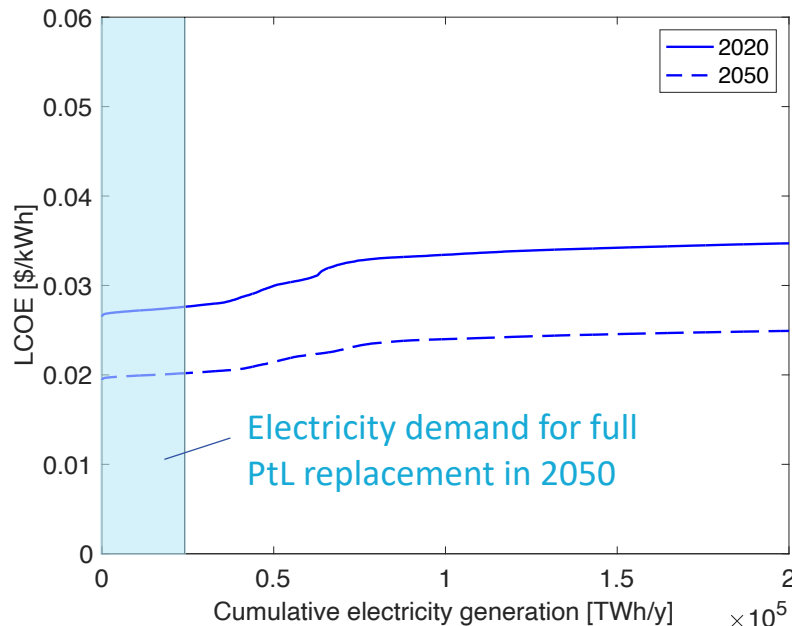
- Specific energy demand of LH₂ production is driven by electrolysis (2020: ~80%; 2050: ~90%) and liquefaction (2020: ~15%; 2050: ~10%)
- 2050 electricity demand for aviation LH₂ requires:
 - ~30% of solar+wind electricity generation in IEA SDS
 - ~20% of renewable electricity generation in IEA NZE in 2050
- Electricity generation in 2050 would require ~0.5 M wind turbines or ~32,000 km² of solar PV (1.3x MA)

Required electricity can be produced from PV and wind at low costs; sector needs to secure resource access

Best case: Aviation gets *cheapest* ren. electricity

Global cost-supply curves for ren. electricity

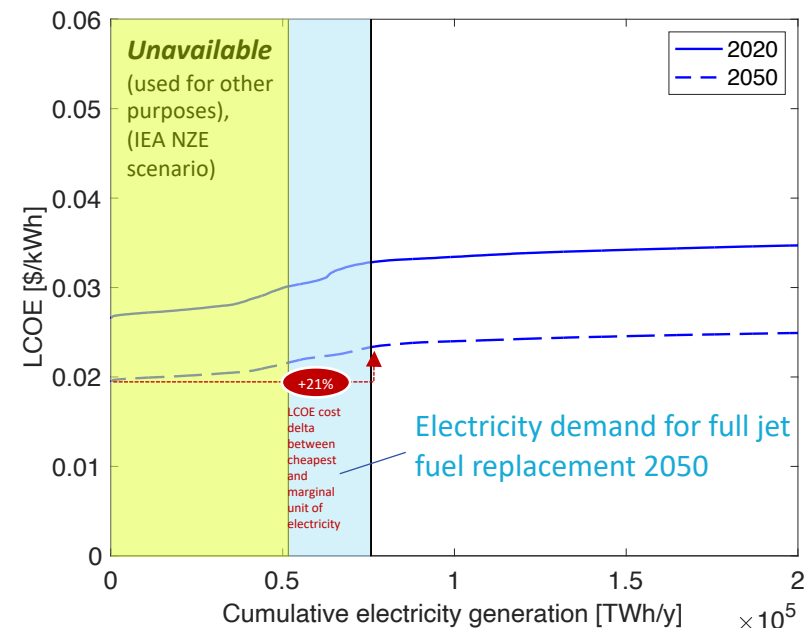
LCOE [\$/kWh] for 2020 and 2050



Worst case: Aviation gets *marginal* ren. electricity

Global cost-supply curves for ren. electricity

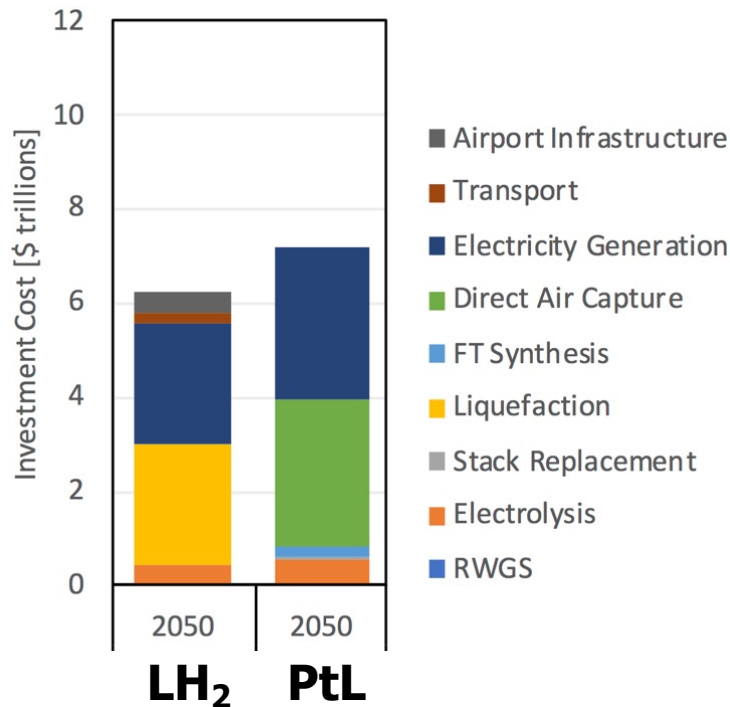
LCOE [\$/kWh] for 2020 and 2050



Investment for full replacement with LH₂ is in line with CapEx requirements of the global energy transition (without considering aircraft replacement)

Cumulative required investment for full LH₂ and PtL replacement

2050 demand with 2050 technology



For reference



Global year-2020 power generation investment:
0.51 trl USD/y ¹



Global year-2020 fuel production investment:
0.43 trl USD/y ¹



Global energy system invest. to reach 1.5C goal:
131 trl USD (2020-2050) ²
[5.7trl USD / y 2021-2030, 3.7 trl USD / y 2031-2050]



CapEx of 2,000 largest nonfinancial companies:
3.7 trl USD ³

General observations:

- LH₂ CapEx lower than PtL CapEx (w/o aircraft investments)
- Major investment costs
 - LH₂: Electricity, liquefaction
 - PtL: DAC, electricity

Required investments (2050):

- ~5% of required energy investment for 1.5C pathway (IRENA)
- Annualized:
 - Factor 2 of current commercial aircraft market
 - ~50% of current yearly CapEx for fuel production

¹ Source: IEA World Energy Investment 2021

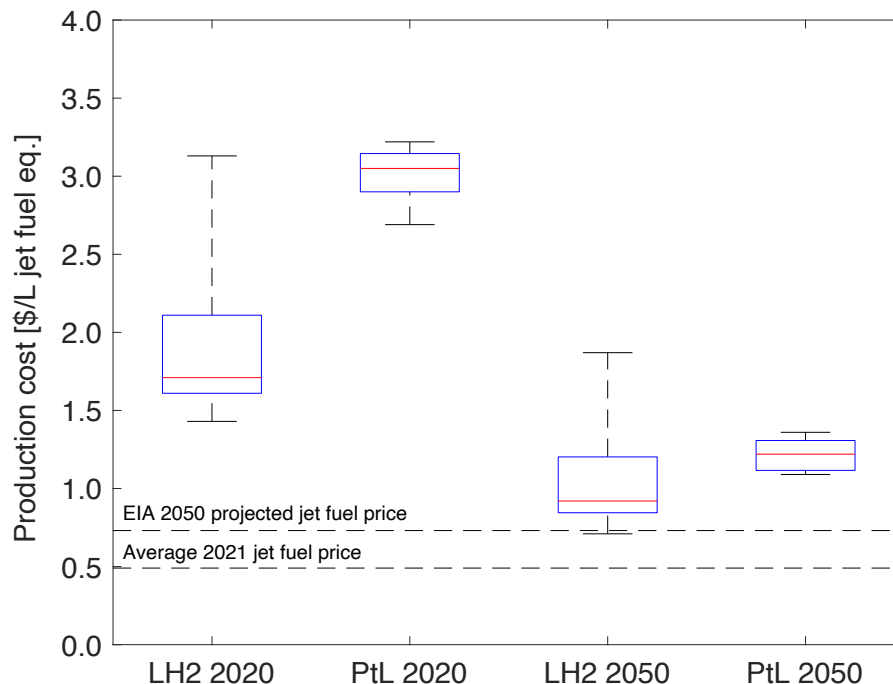
² Source: World Energy Transitions Outlook 2021

³ S&P Global Market Intelligence, 2021 projections

Production costs of LH₂: LH₂ likely less costly than PtL due to lower energy demand and process complexity

Production costs of LH₂ and PtL using global optimized locations

2019 demand with 2019 technology, 2050 demand with 2050 technology

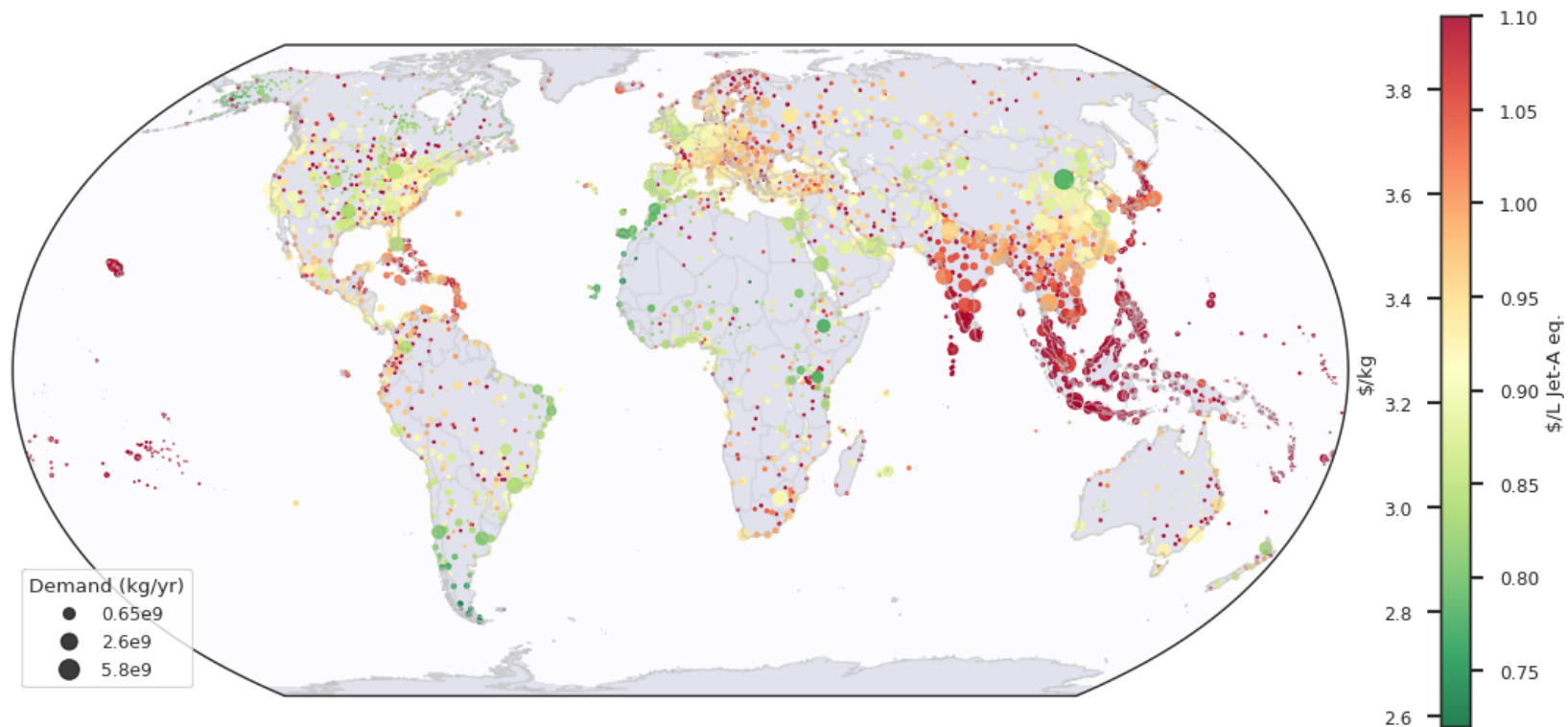


- Model identifies **optimal production locations** for LH₂ and PtL to minimize cost-at-airport (incl. logistics and distribution as well as considering local production conditions)
- **Cost variation** is largely due to different capacity factors for power generation at the production locations
 - LH₂ has a wider distribution because of higher transport costs
 - PtL has low transport costs which allows using the globally cheapest locations
- **Costs are projected to decline** due to efficiency improvements and reductions of component costs (especially electrolyzers and DAC)

Global distribution of cost-minimal production and costs of LH₂ (2050 demand, future technology)

LH₂ production locations to meet year-2050 demand with future technology

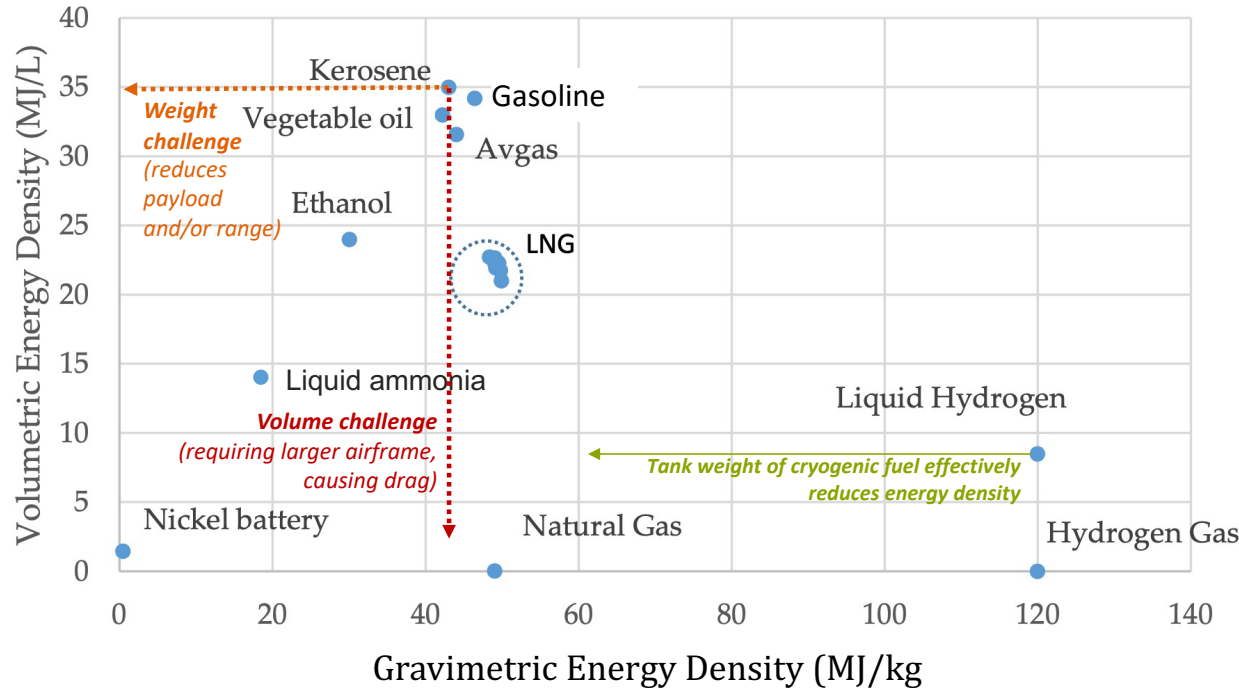
Circles represent airport locations, color production cost



- **Production costs** at airports depend on availability of cheap renewable electricity
- **Electricity generation** from wind and PV energy
- Relative global **cost spread** for LH₂ is relatively high (as compared to PtL) due to:
 - Relatively high transportation costs
 - Limitation of available areas for power generation

Using (L)H₂ as an aviation fuel: *Non-drop-in nature of (L)H₂ requires adjustment of the airframe to accommodate the fuel*

Volumetric vs. gravimetric energy density of fuels



Source: *Energies* **2020**, 13, 5925 and own data addition (NH₃)

LH₂ aircraft are subject to a trade-off:

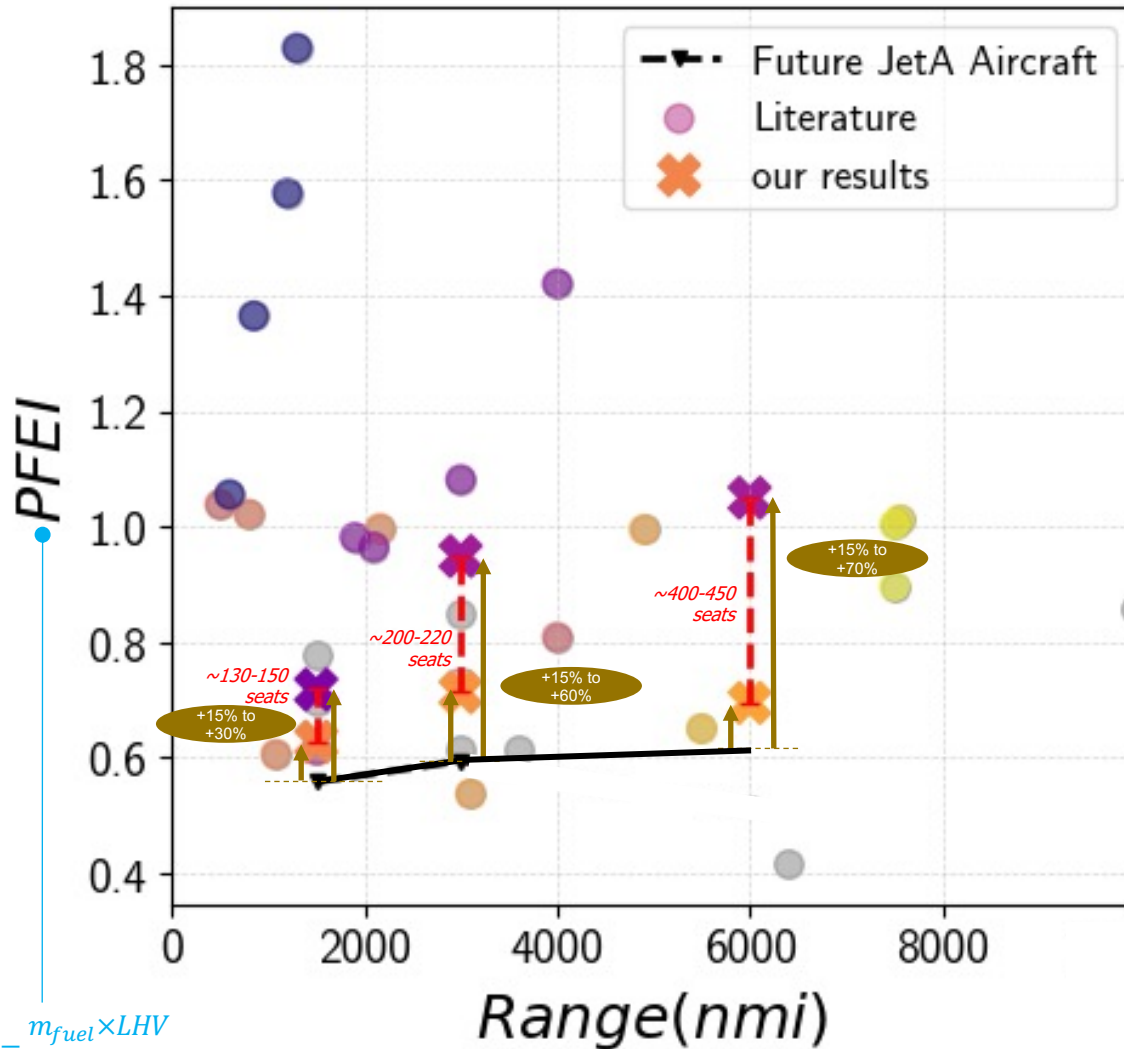
Lower fuel weight
(but heavier tank)

vs.

higher fuel
volume

Impacts of introducing LH₂ aircraft: Additional energy consumption at the aircraft-level

(Normalized) aircraft energy consumption vs. range for hydrogen aircraft, *Review of literature*



Additional insights

- **Tank characteristics**, especially gravimetric index, are a significant driver of energy efficiency (lighter tank = less energy consumption)
- For given tank technologies, **trade-offs between boil-off and tank weight** exist
- **Aircraft energy penalties** could offset lower energy demand in fuel production compared to PtL, under certain circumstances