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 LH_2 as an aviation fuel

Project Benefits:

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

Research Approach:

Energy and fuel demand
Calculate the fuel and energy demand for 2019-traffic and extrapolate to 2050

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

Energy system
Model the electric power generation to produce fuels; function of local capacity factors and transport costs

Aircraft model

Airport fuel infrastructure
Model required fueling infrastructure

Operating Costs
Energy demand
Other environmental impacts

Investment pathways (CapEx)
Lifecycle emissions and impacts

Major Accomplishments (current period):

For LH_2 fuel, we analyzed

1. the environmental performance
2. production costs and global supply chain designs
3. implications of LH_2 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

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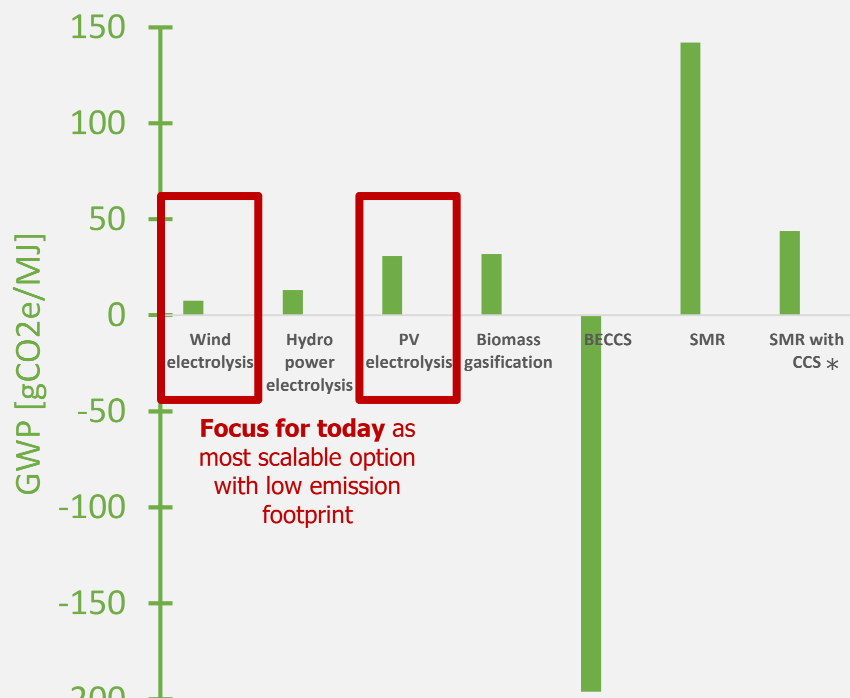
Environmental footprint of hydrogen use in aviation: *lifecycle GHG emissions and direct non-CO_2 impacts*

- LH_2 use is not linked to **direct CO_2 emissions**
- Depending on the production process of LH_2, **life-cycle GHG emissions** can be substantially lower than for fossil Jet-A.
- LH_2 may still be associated with **direct non-CO_2 impacts**

Lifecycle ("well-to-tank") GHG emissions of LH_2 vary significantly by production pathway, gCO_2e/MJ



* 90% capture rate

Non-CO_2 impacts remain but are uncertain

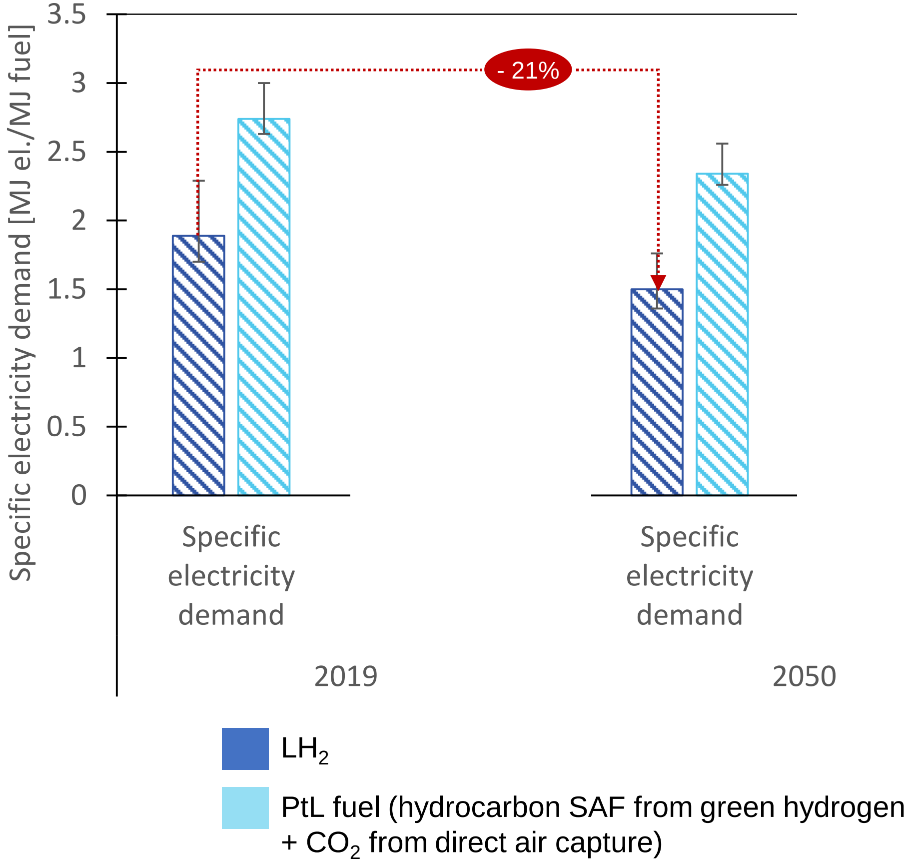
- ***Contrails:*** Trade-off: less particle emissions vs. higher water emissions
- ***NO_x:*** Depends on hydrogen use (i.e., fuel cell vs. combustion); may not be zero
- ***Higher water emissions***
- ***Boil-off / leakage?***

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

(for constant aircraft energy efficiency)

Specific energy demand and year-2019 & 2050 fuel replacement with PtL & LH_2

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



** Renewable electricity excluding nuclear.*

- Specific energy demand of LH_2 production is driven by electrolysis (2020: ~80%; 2050: ~90%) and liquefaction (2020: ~15%; 2050: ~10%)

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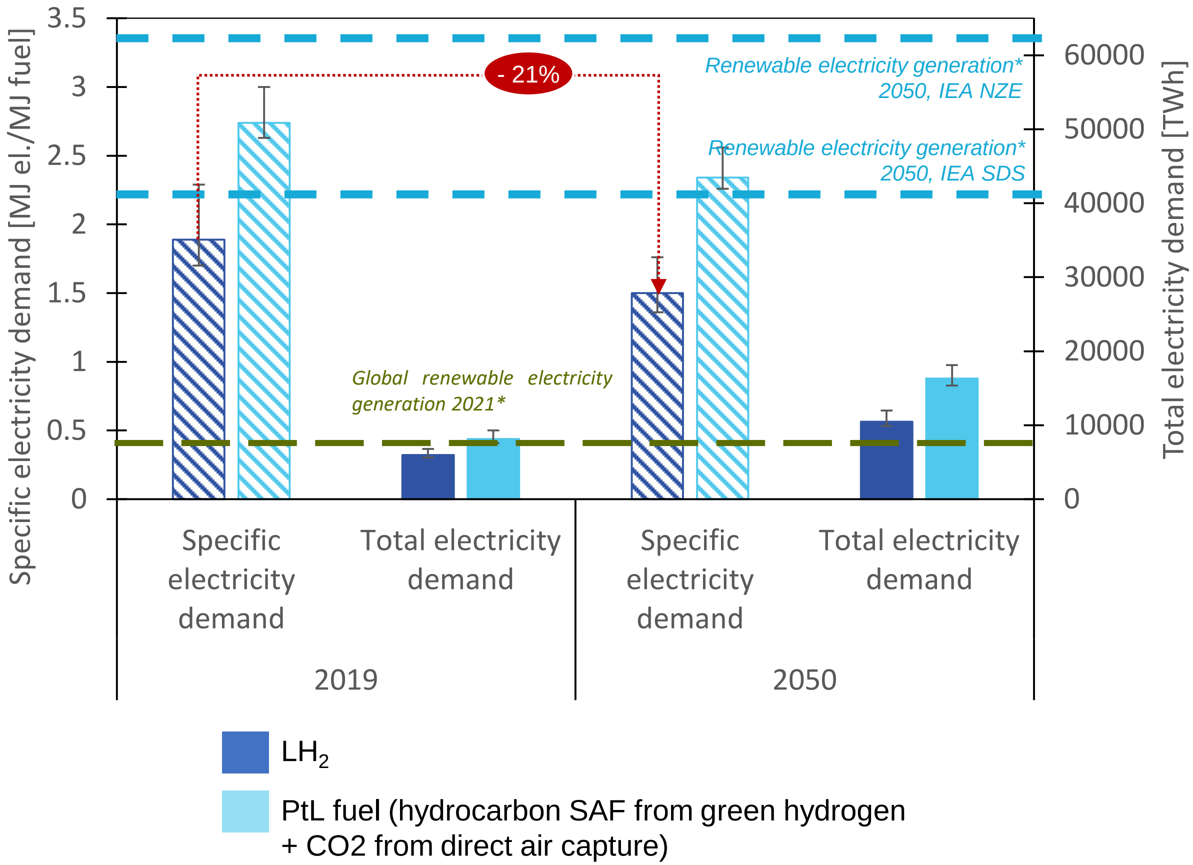


** Renewable electricity excluding nuclear.*

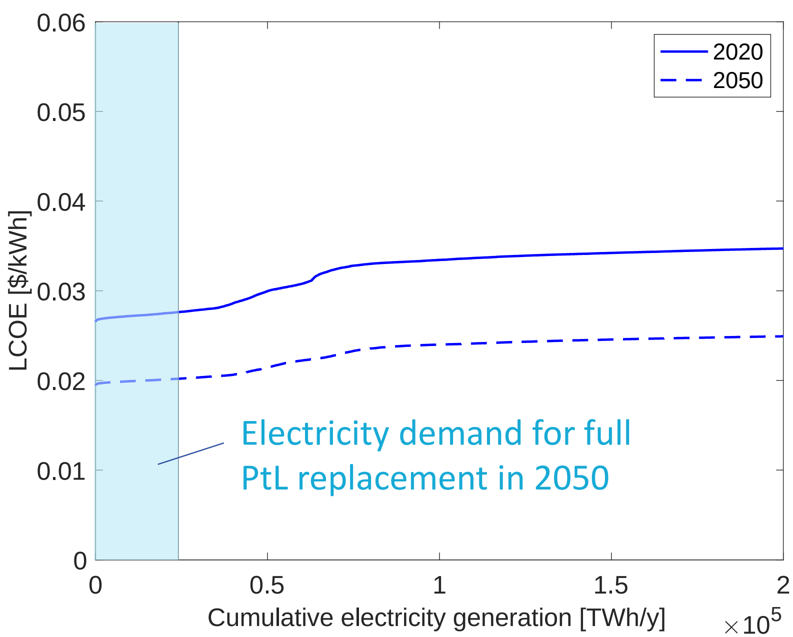
- Specific energy demand of LH_2 production is driven by electrolysis (2020: ~80%; 2050: ~90%) and liquefaction (2020: ~15%; 2050: ~10%)
- 2050 electricity demand for aviation LH_2 requires:
  - ~30% of solar+wind electricity generation in IEA SDS
  - ~20% of renewable electricity generation in IEA NZE 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

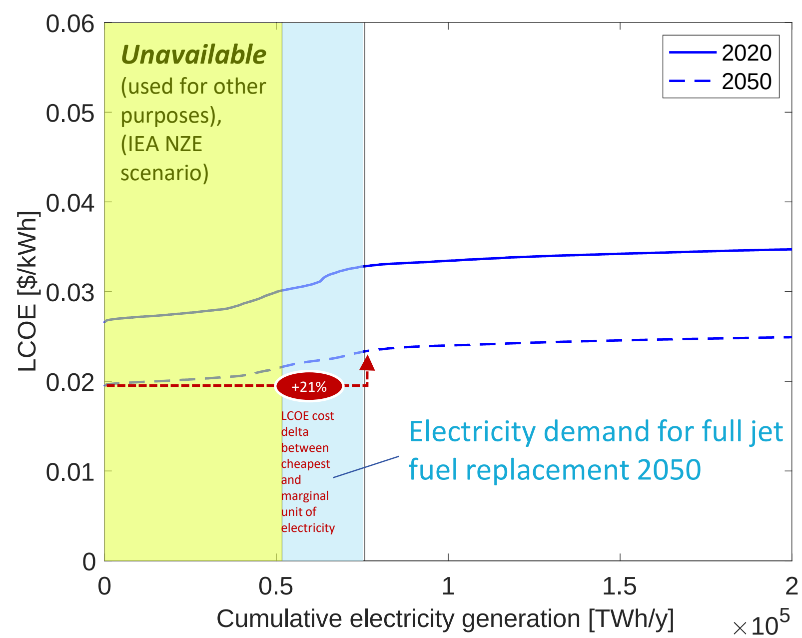
LCOE [$/kWh] for 2020 and 2050



Worst case: Aviation gets *marginal* ren. electricity

Global cost-supply curves for ren. electricity

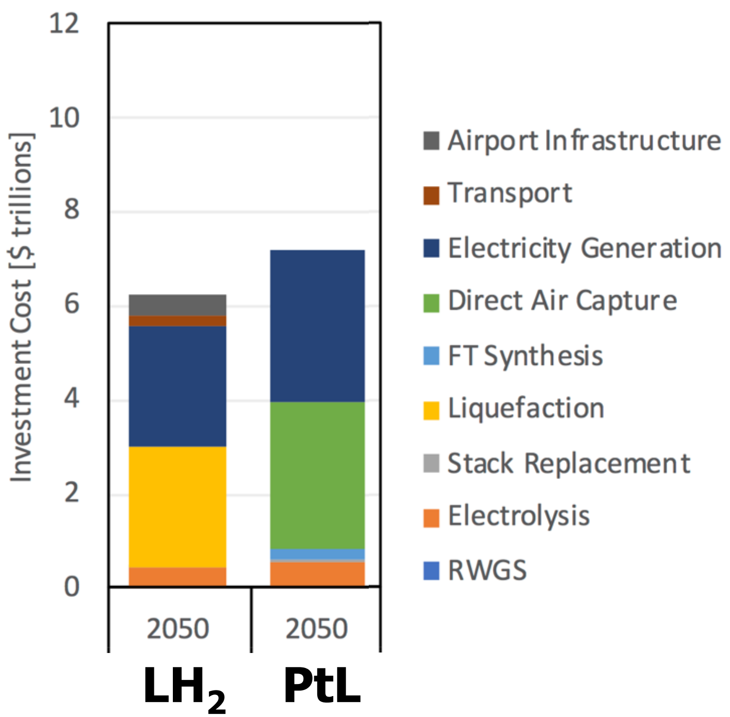
LCOE [$/kWh] for 2020 and 2050



Investment for full replacement with LH_2 is in line with CapEx requirements of the global energy transition (without considering aircraft replacement)

Cumulative required investment for full LH_2 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]

[1] Source: IEA World Energy Investment 2021
[2] Source: World Energy Transitions Outlook 2021
[3] S&P Global Market Intelligence, 2021 projections

General observations:

- LH_2 CapEx lower than PtL CapEx (w/o aircraft investments)
- Major investment costs
  - LH_2: Electricity, liquefaction
  - PtL: DAC, electricity

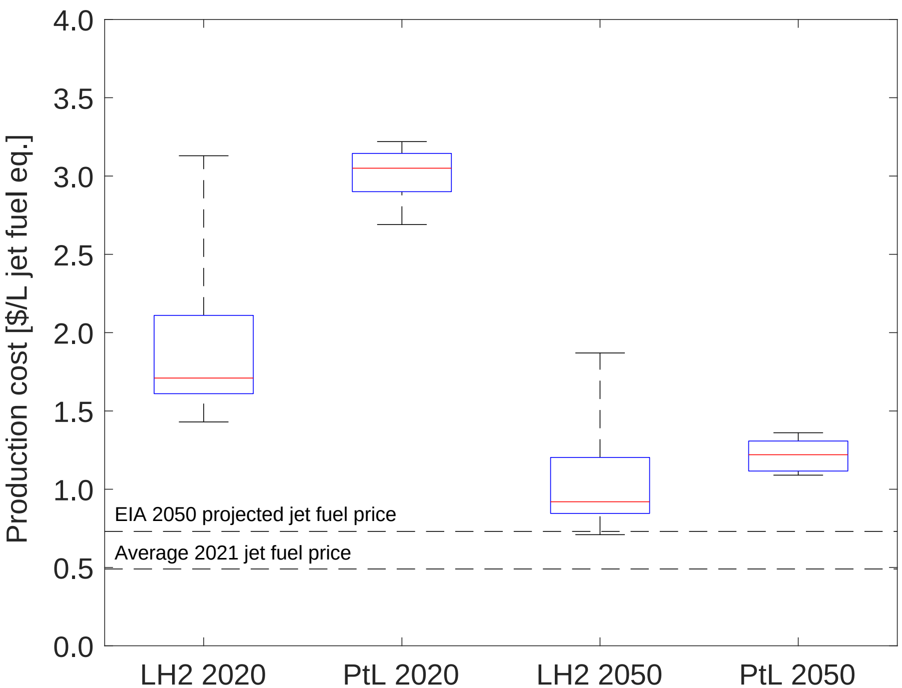
Required investments (2050):

- ~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

Production costs of LH_2: LH_2 likely less costly than PtL due to lower energy demand and process complexity

Production costs of LH_2 and PtL using global optimized locations

2019 demand with 2019 technology, 2050 demand with 2050 technology

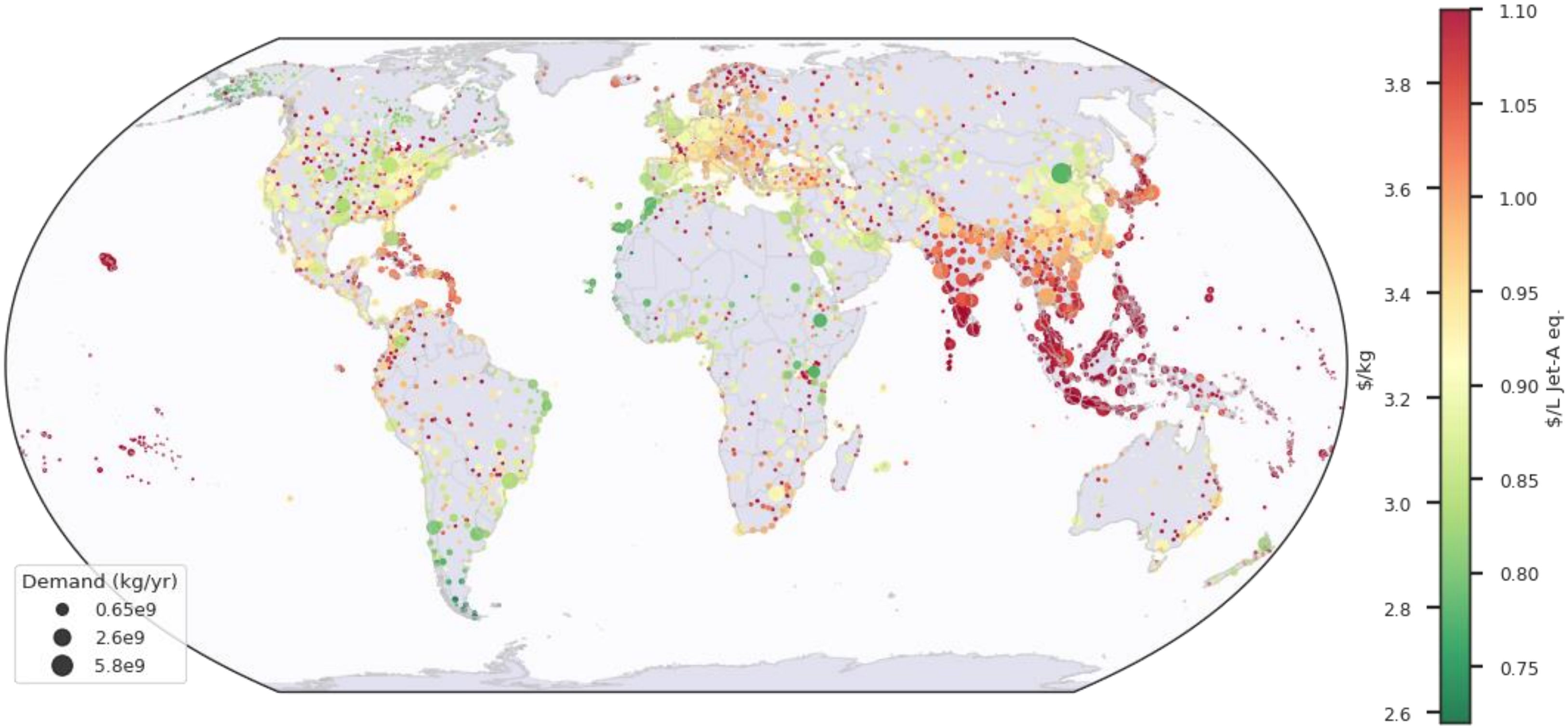


- Model identifies **optimal production locations** for LH_2 and PtL to minimize cost-at-airport (incl. logistics and distribution as well as considering local production conditions)
- **Cost variation** is largely due to different capacity factors for power generation at the production locations
    - LH_2 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 LH_2 (2050 demand, future technology)

LH_2 production locations to meet year-2050 demand with future technology

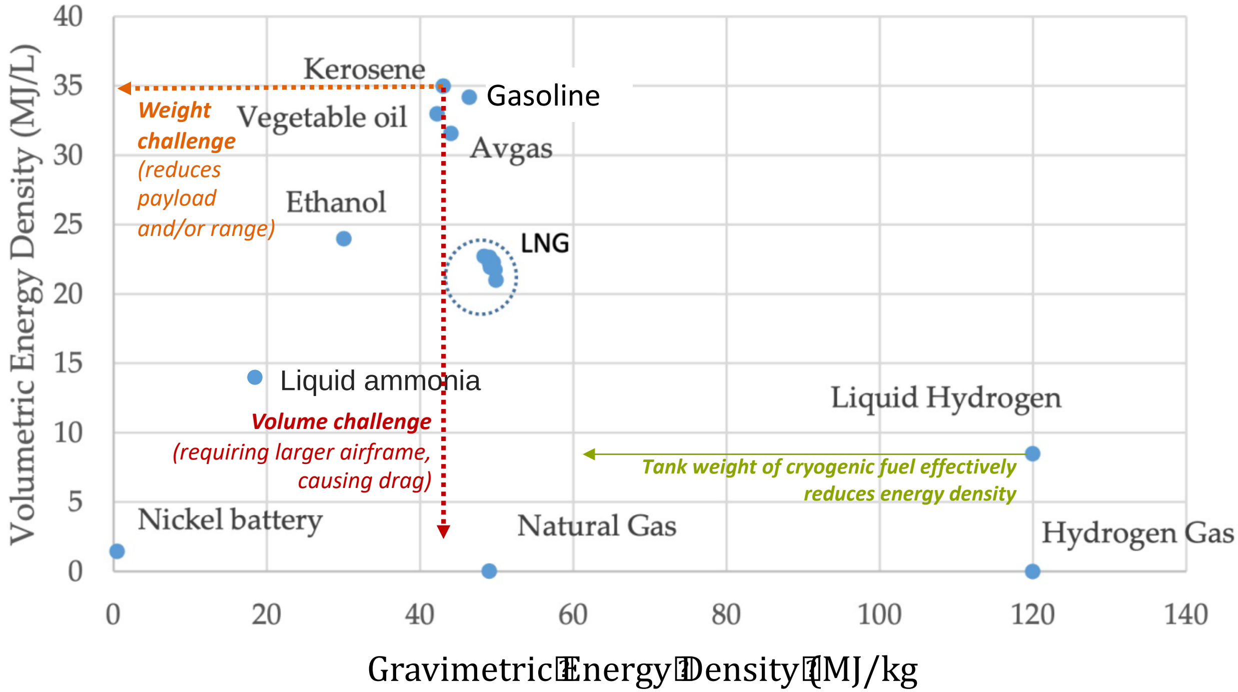
Circles represent airport locations, color production cost



- **Production costs** at airports depend on availability of cheap renewable electricity
- **Electricity generation** from wind and PV energy
- Relative global **cost spread** for LH_2 is relatively high (as compared to PtL) due to:
  - Relatively high transportation costs
  - Limitation of available areas for power generation

Using (L)H_2 as an aviation fuel: *Non-drop-in nature of (L)H_2 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 (NH_3)

LH$_2$ aircraft are subject to a trade-off:

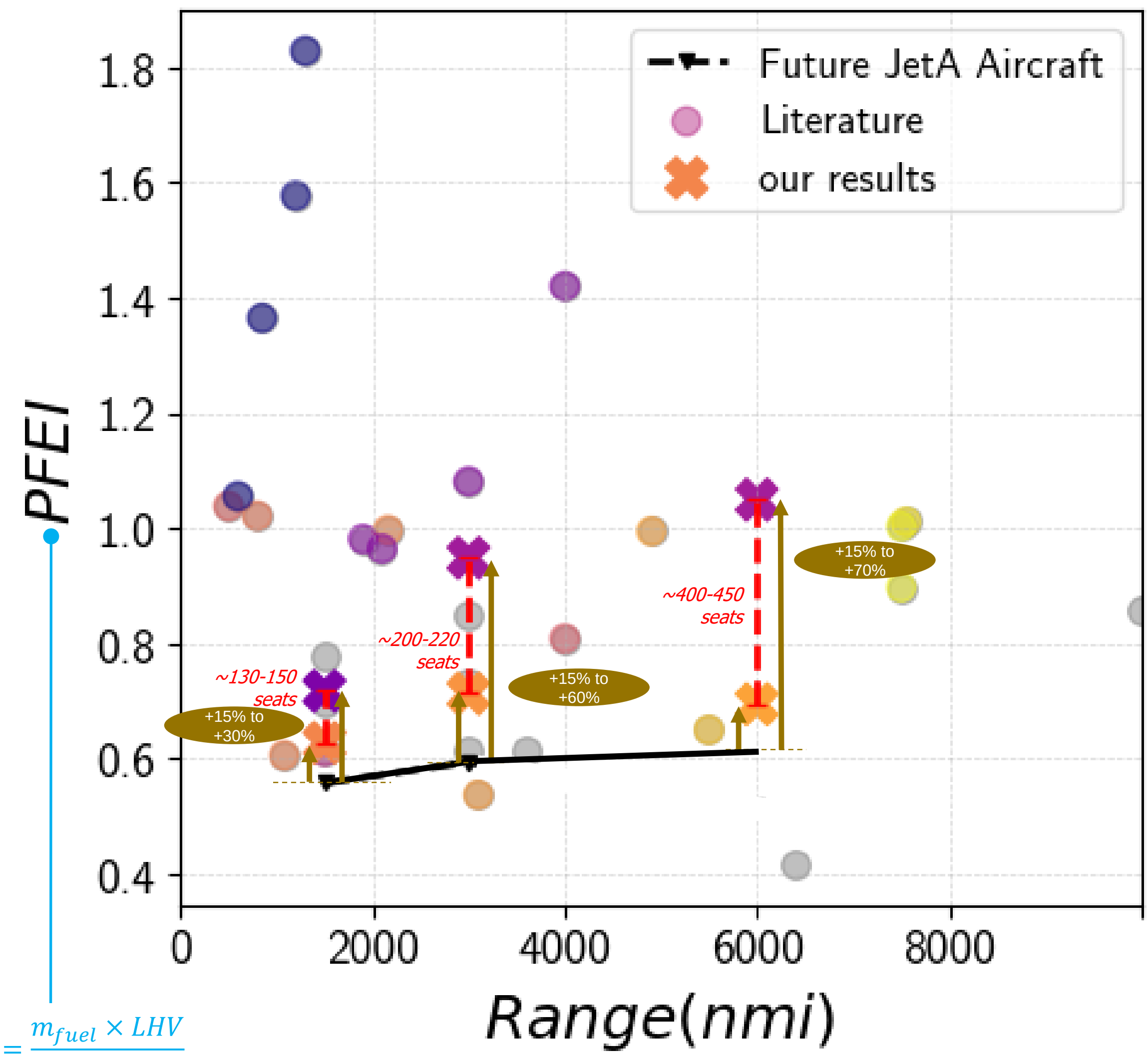
Lower fuel weight (but heavier tank)

vs.

higher fuel volume

Impacts of introducing LH_2 aircraft: Additional energy consumption at the aircraft-level

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



$$PFEI = \frac{m_{fuel} \times LHV}{W_{pay}\, R}$$

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