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Comparative analysis of decarbonization strategies for transportation via direct air capture of CO₂

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Drop-in hydrocarbon fuels are an integral component of ambitious decarbonization goals for aviation

Ambitious climate goals for the aviation sector

Key stakeholders have recently committed to increasingly ambitious net-zero carbon goals

Examples:

- IATA's net-zero goal at their 2021 Annual General Meeting
- U.S. Aviation Climate Action Plan
- ICAO Long-Term Aspirational Goal
- ...



Net zero strategies for aviation require the use of “net-zero compatible” drop-in fuels

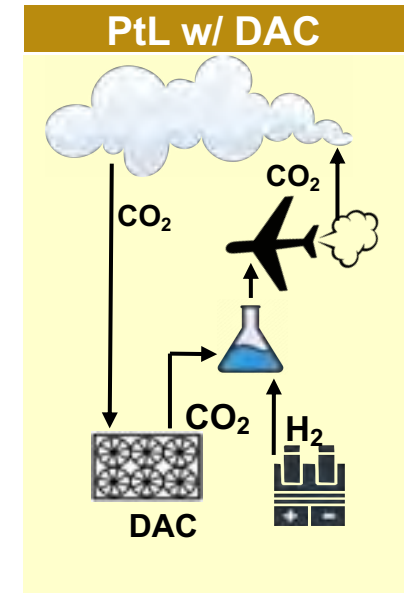
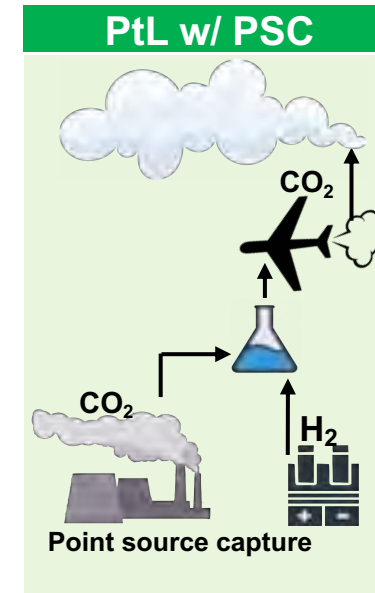
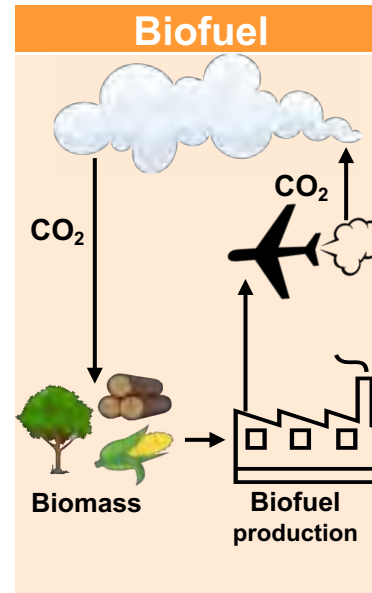
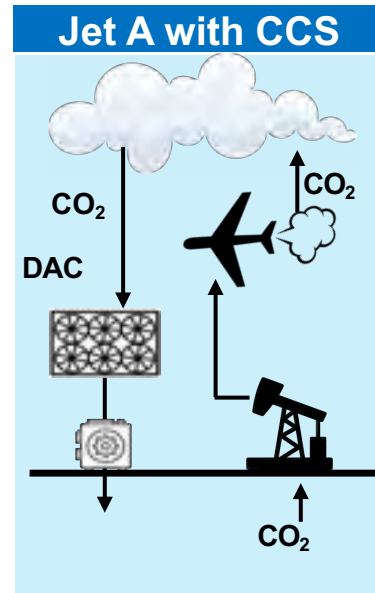
1. The introduction of non-drop-in fuels at scale will require **substantial investments** (possibly trillions of \$) in the supply chain; there is currently **no consensus on a non-drop-in fuel** to drive such investments.
2. **Development of aircraft compatible with a non-drop-in fuel** could take a decade or more; clean-sheet development of new aircraft with existing technologies recently took 7-10 years from announcement to EIS.
3. **Limitations in production capacity of aircraft** will slow down the introduction of new aircraft into the fleet.
4. **Economic life of aircraft** is 25+ years; aircraft built and delivered today will be in service by 2050 and will require drop-in fuels.



Hydrocarbon fuel use and the role of Direct Air Capture

Different options exist for carbon-neutral use of hydrocarbons to power transportation

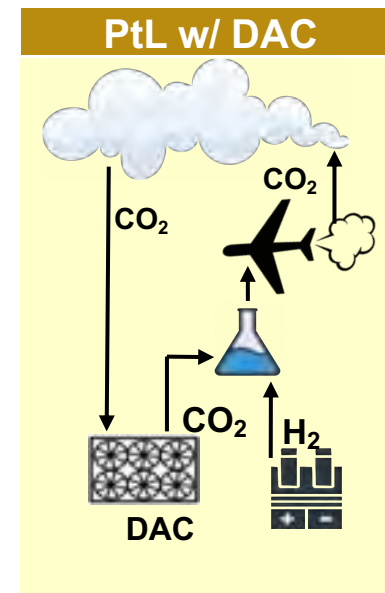
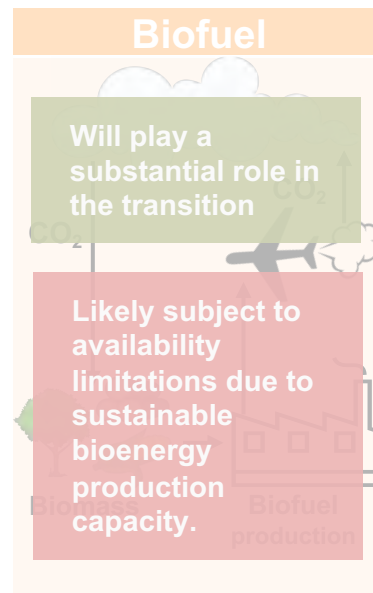
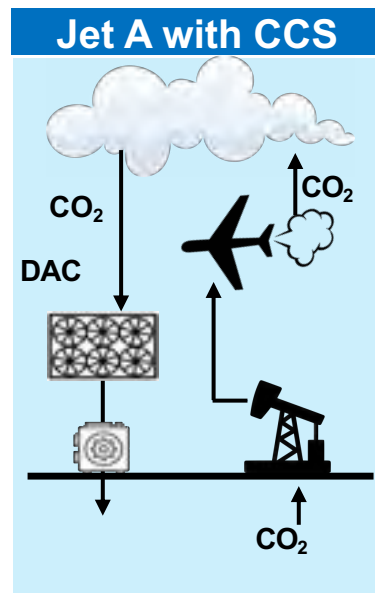
Example: Aviation



Hydrocarbon fuel use and the role of Direct Air Capture

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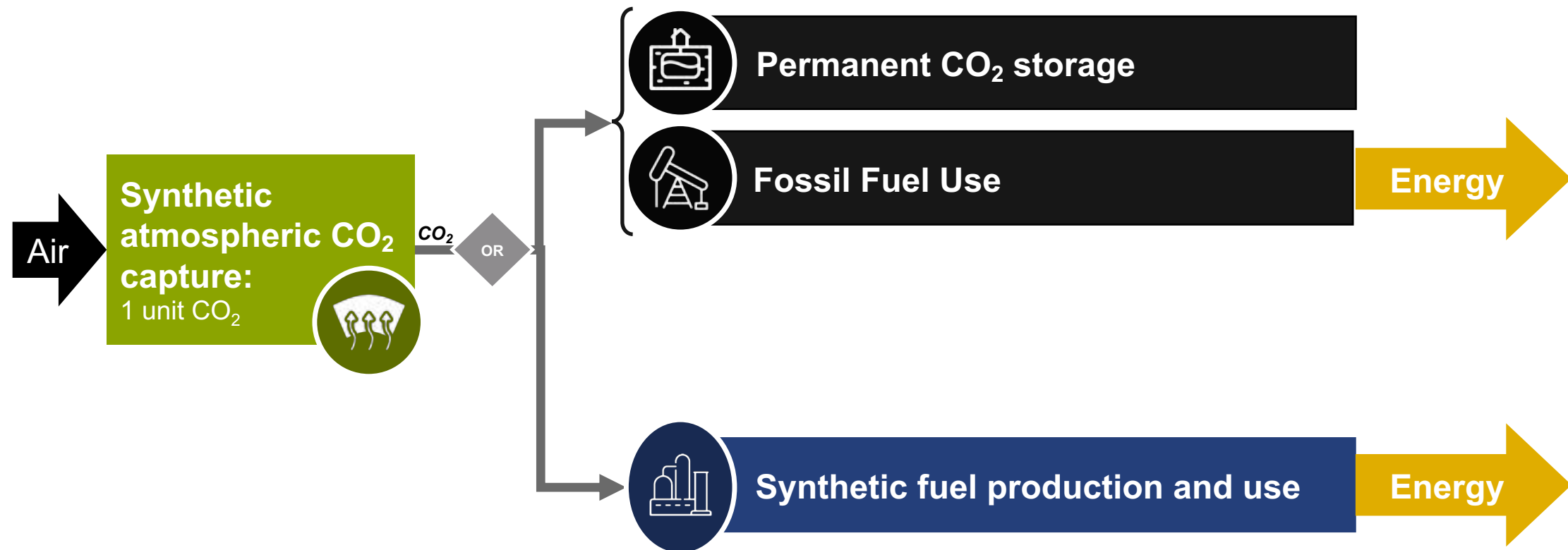
Example: Aviation



Guiding question:

What is the most effective use of atmospheric CO₂ removal to support T2DT decarbonization?

The technology stack for the two pathways of interest



Guiding research questions for today's presentation

Guiding question:

What is the most effective use of atmospheric CO₂ removal to support T2DT decarbonization?

1

What are the technological, economic, and environmental attributes of DAC technologies and assumptions for CCS and synfuel production?

2

How do the two DAC-based pathways compare in terms of emissions and costs under different technology scenarios?



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What is the most effective use of atmospheric CO₂ removal to support T2DT decarbonization?

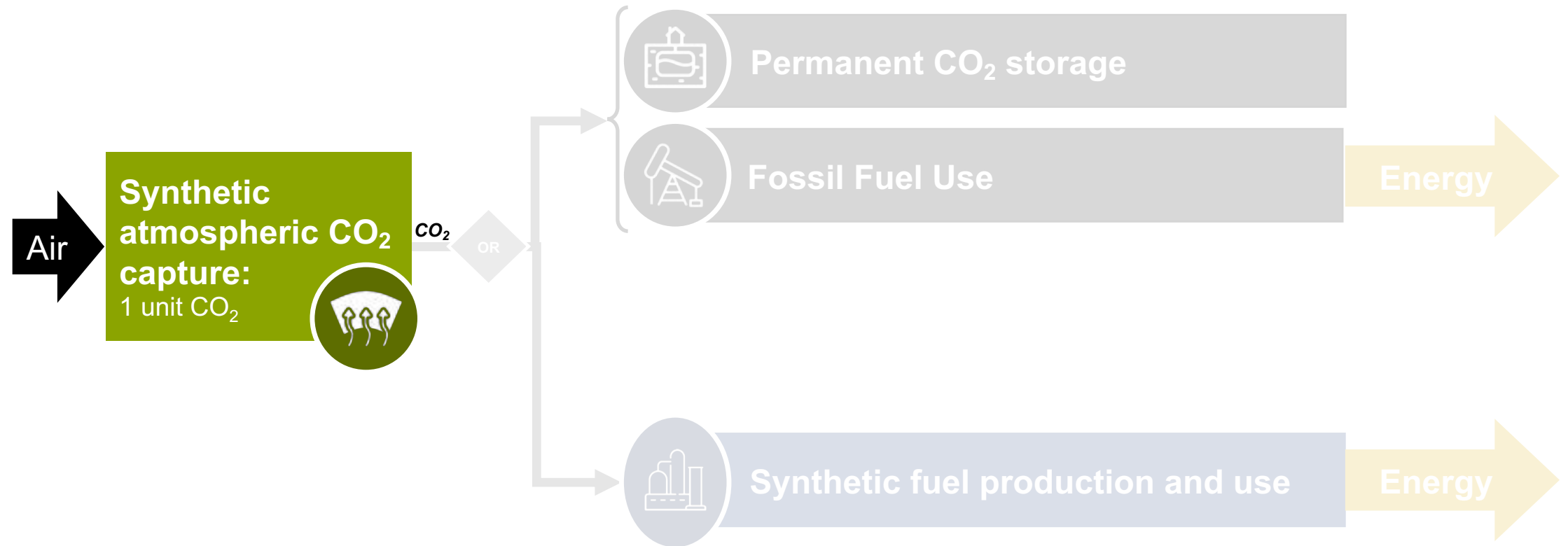
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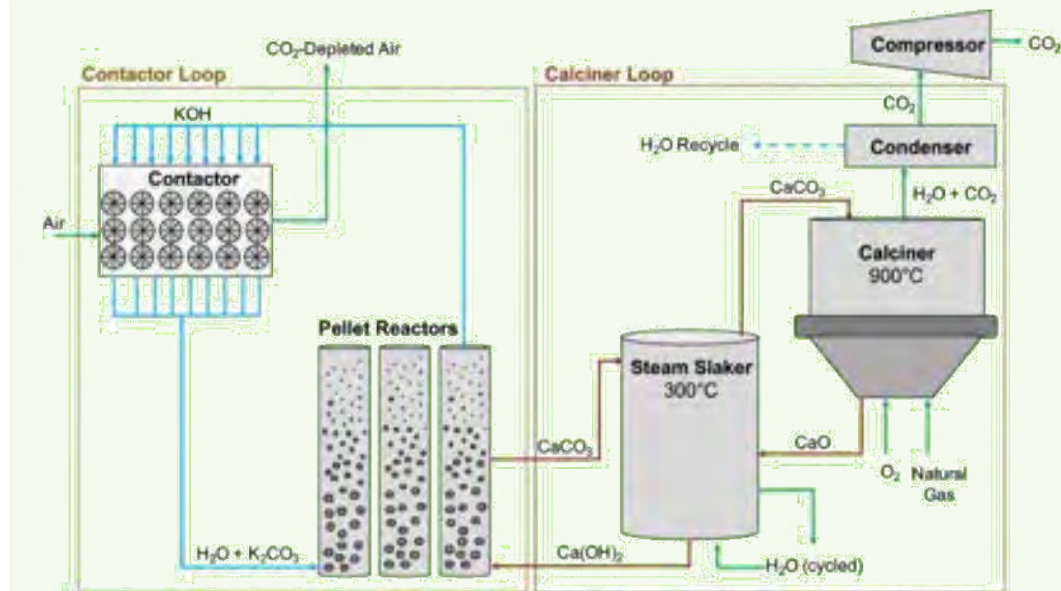
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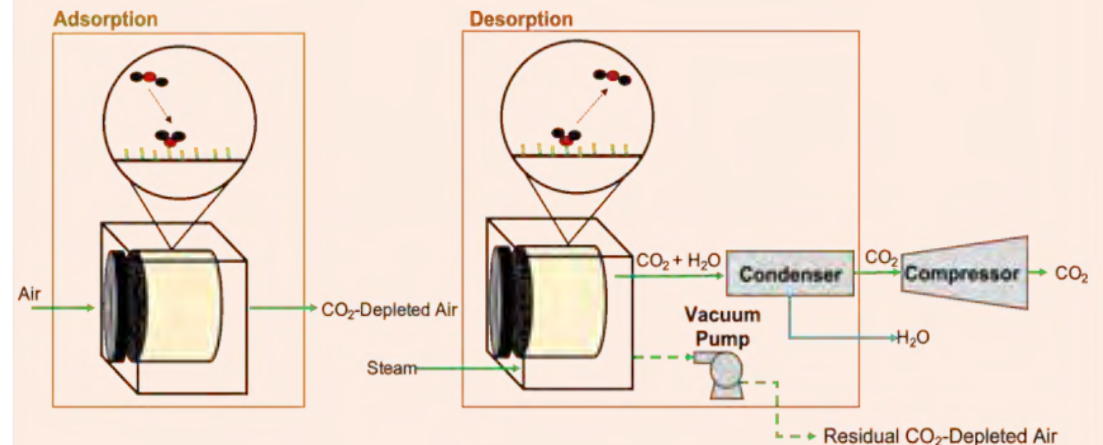


Direct Air Capture: focus on technologies currently considered for commercialization

Liquid Solvent (e.g. Carbon Engineering):



Solid Sorbent (e.g. Climeworks):

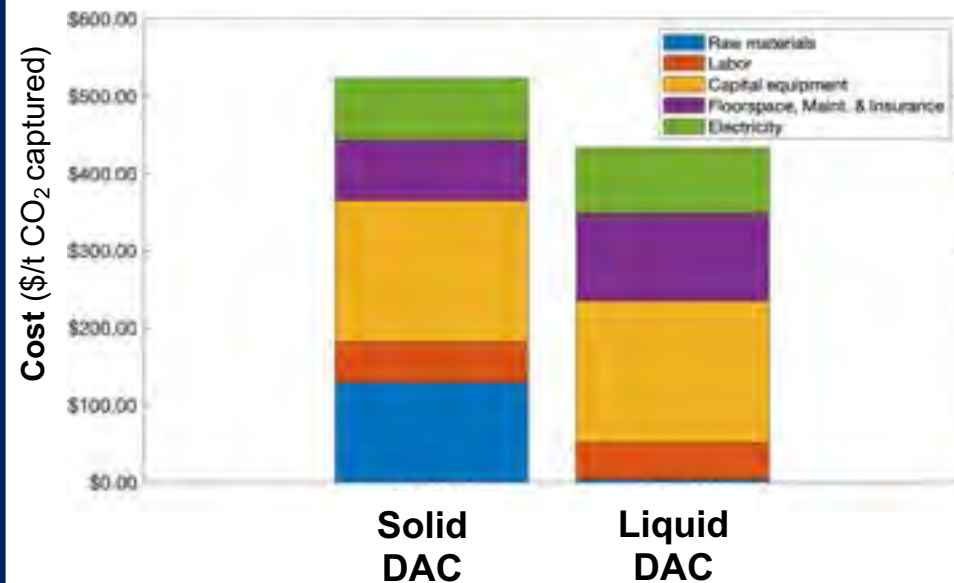


McQueen, Noah, et al. "A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future." *Progress in Energy* 3.3 (2021): 032001.

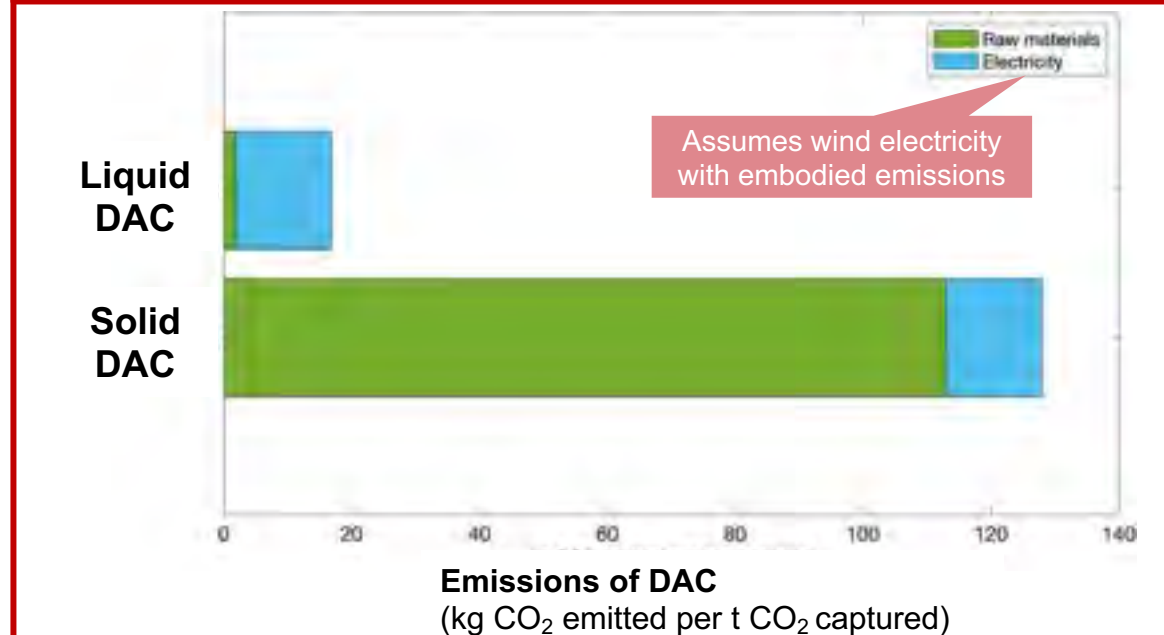
Other types of DAC are currently under development, but focus of this study is on liquid and solid DAC because they have highest TRL, therefore reasonable TEA's and LCA's can be performed

Direct Air Capture: techno-economic and lifecycle assessment show cost and emissions differences

Cost: CO₂ cost with “current” tech.



DAC Emissions: Carbon removal efficiency



Distinguish

1. Cost per tonne captured: CO₂ Input cost
2. Cost per tonne removed: Effective removal cost, considering process emissions

Direct Air Capture: What cost trajectories can we realistically expect into the future?



Cost improvements possible

Areas where cost improvements are possible:

- Capital equipment
- Labor
- Electricity
- Maintenance & Insurance

Learning factors

	Liquid DAC		Solid DAC	
	Low LR	High LR	Low LR	High LR
Capital learning	95%	90%	90%	80%
Labor learning	90%	80%	90%	80%
Electricity learning	90%	80%	90%	80%

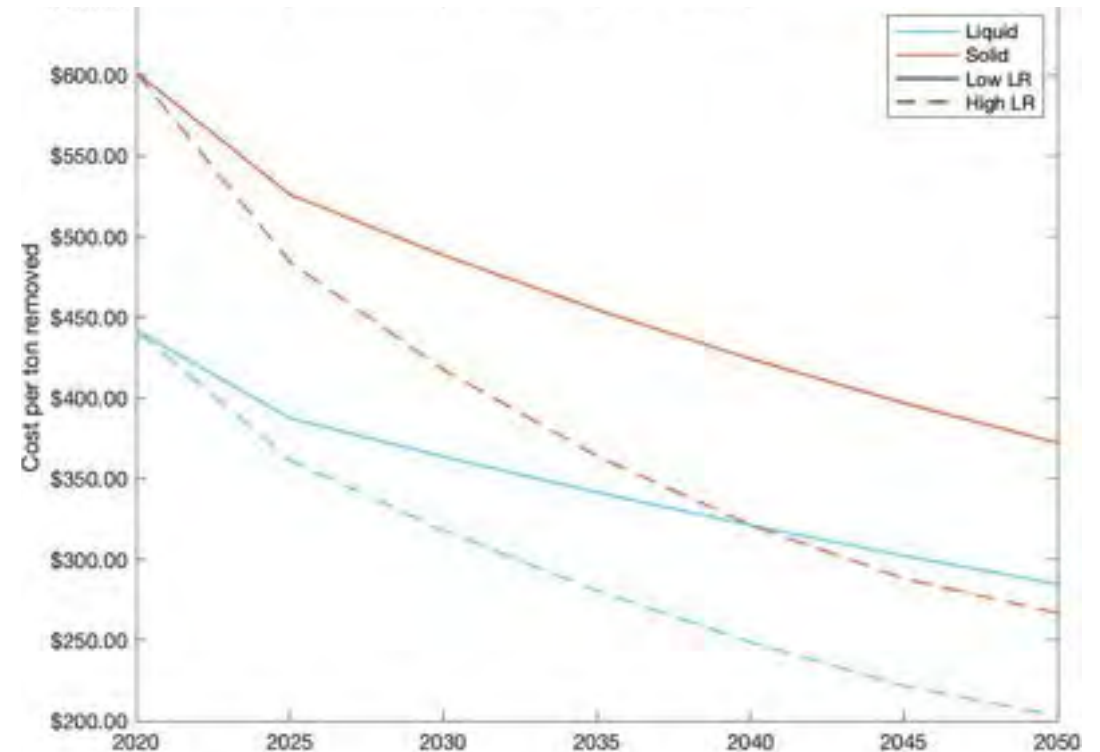
Floor limitation on energy improvement:

2nd law efficiency maximum of 15% (currently technology is 7-11%)

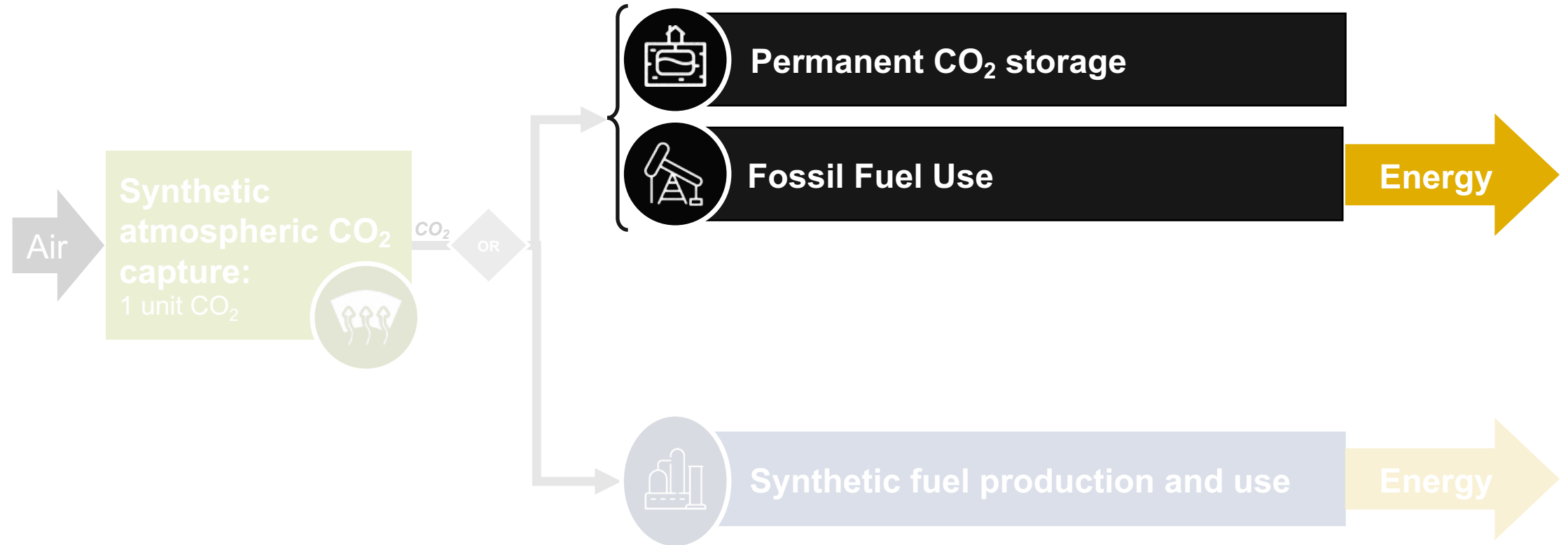
No learning

- Raw materials
- Floorspace

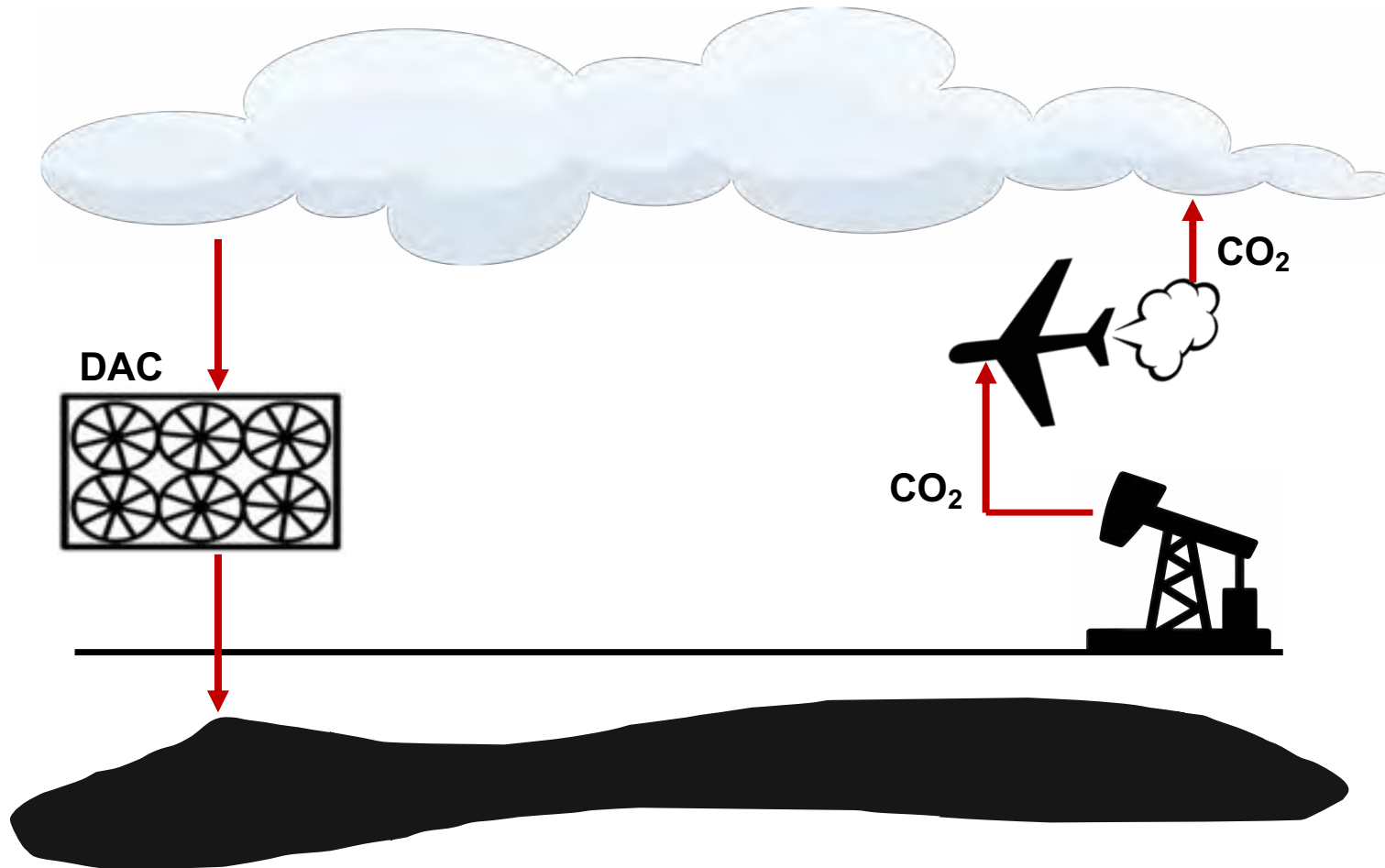
Potential cost trajectories based on learning curves for the sector, \$ per ton removed



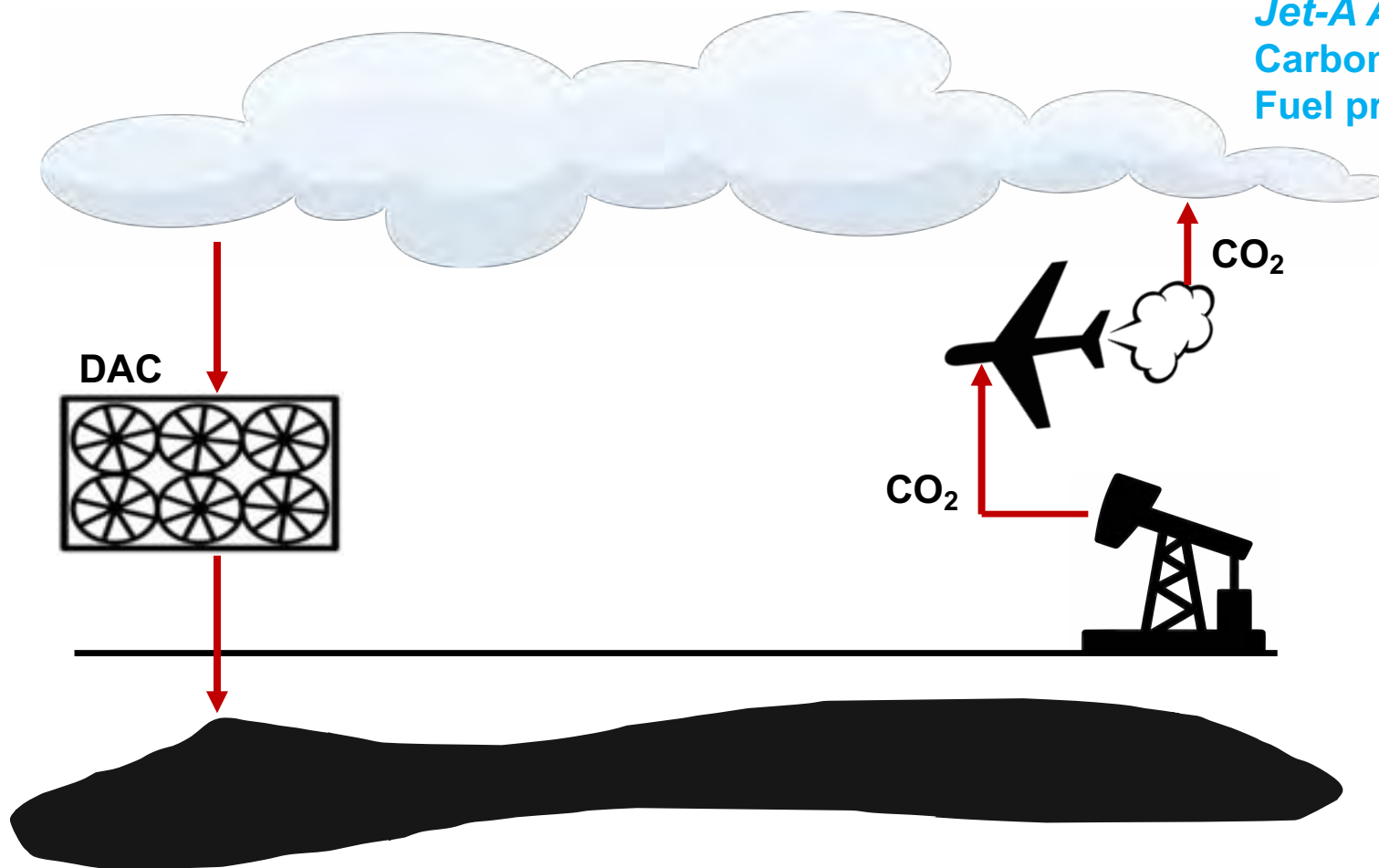
The technology stack for the two pathways of interest



Jet-A with DACCS



Jet-A with DACCS: Baseline Assumptions



Jet-A Assumptions:

Carbon intensity = 89 gCO₂/MJ

Fuel price = \$0.50/L (\$0.11 - \$1.30/L)

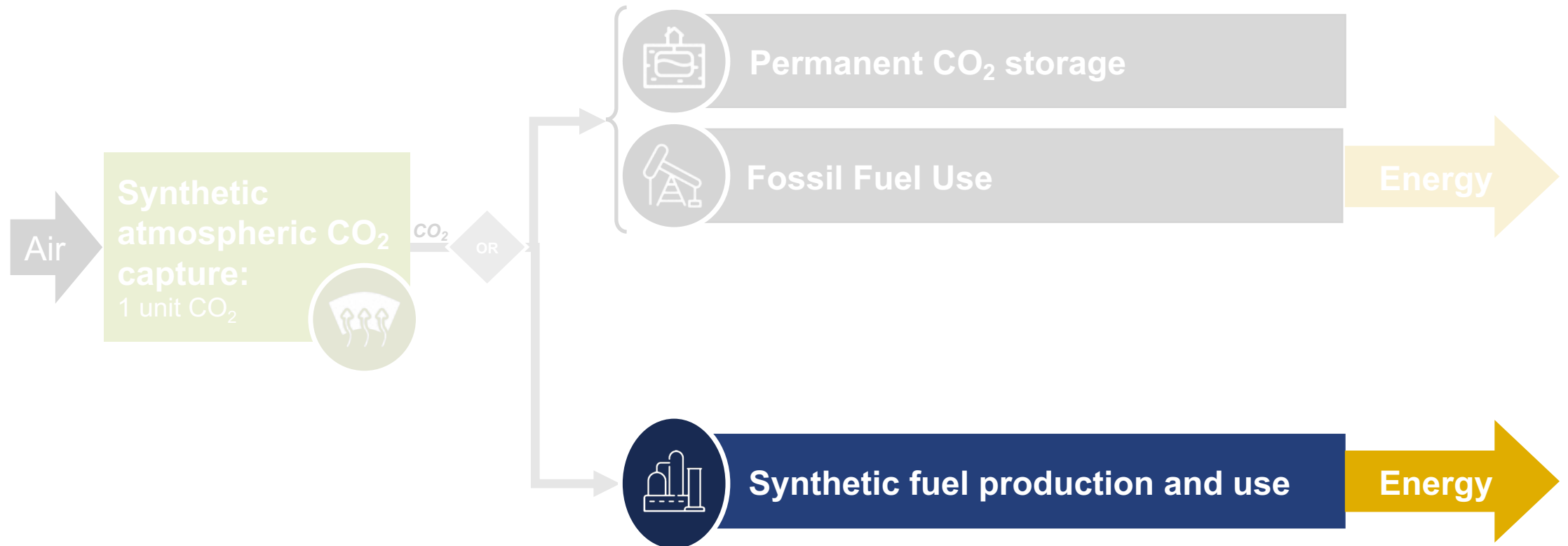
Storage Assumptions:

Assume no leakage

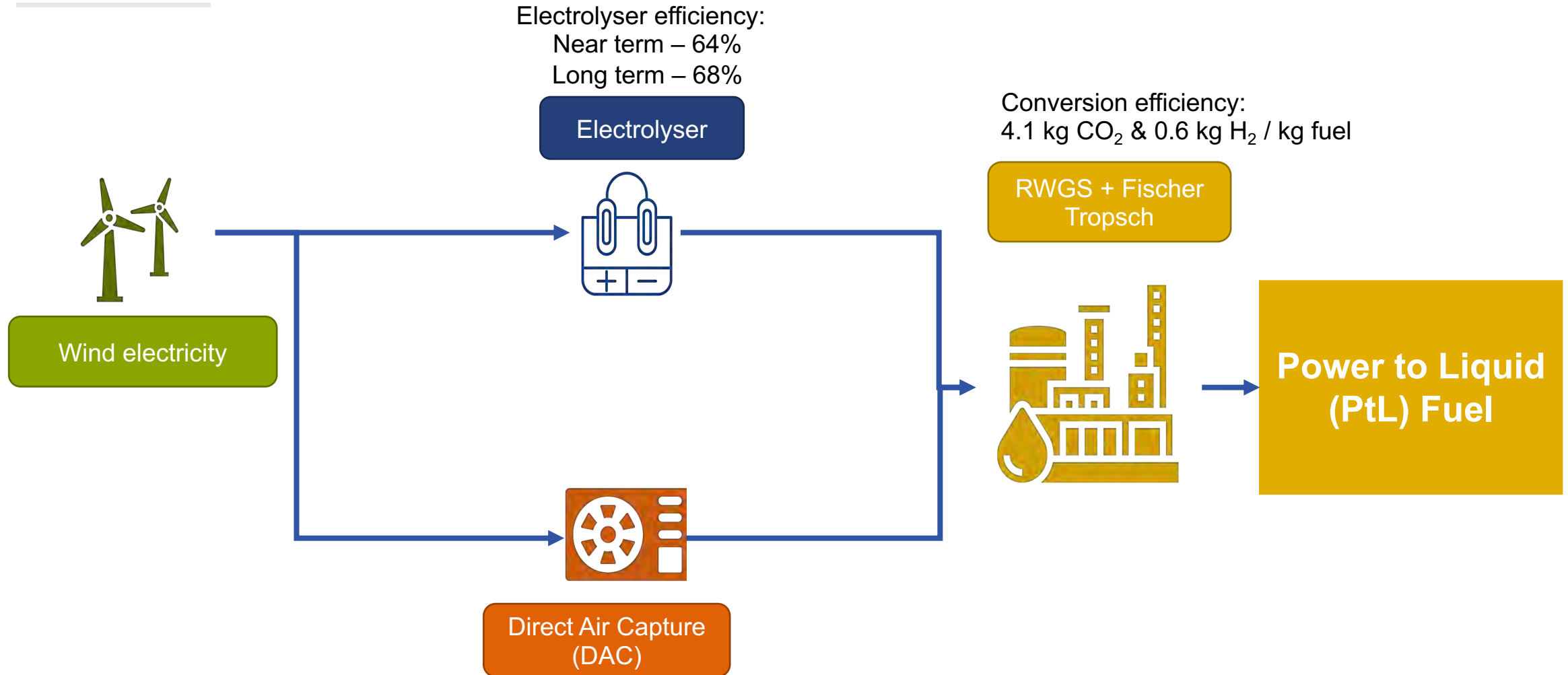
Storage cost = \$14/tCO₂ (\$7 - \$23/tCO₂)

Transportation cost = \$3.40/tCO₂ (\$1.40 - \$7/tCO₂)

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PtL Baseline Assumptions



PtL Scenario Assumptions

	Pessimistic	Baseline	Optimistic
Near term (i.e. 2030)	- Pioneer technology assumptions for near term - Low-cost fossil energy - High-cost renewable energy for near term	- Mid-point technology assumptions for near term - Average cost fossil energy - Average cost renewable energy for near term	- Advanced technology assumptions for near term - High-cost fossil energy - Low-cost renewable energy for near term
Long term (i.e. 2050+)	- Pioneer technology assumptions for long term - Low-cost fossil energy - High-cost renewable energy for long term	- Mid-point technology assumptions for long term - Average cost fossil energy - Average cost renewable energy for long term	- Advanced technology assumptions for long term - High-cost fossil energy - Low-cost renewable energy for long term

PtL Scenario Assumptions

	Pessimistic	Baseline	Optimistic
Near term (i.e. 2030)	- Pioneer technology Electrolyzer efficiency: 53% Jet-A: \$0.11/L Wind electricity: \$0.14/kWh	- Mid-point technology assumptions for near term - Average cost fossil energy - Average cost renewable energy for near term	- Advanced technology assumptions for near term - High-cost fossil energy - Low-cost renewable energy for near term
Long term (i.e. 2050+)	- Pioneer technology assumptions for long term - Low-cost fossil energy - High-cost renewable energy for long term	- Mid-point technology assumptions for long term - Average cost fossil energy - Average cost renewable energy for long term	- Advanced technology assumptions for long term Electrolyzer efficiency: 80% Jet-A: \$1.34/L Wind electricity: \$0.03/kWh

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How do the two DAC-based pathways compare in terms of emissions and costs under different technology scenarios?

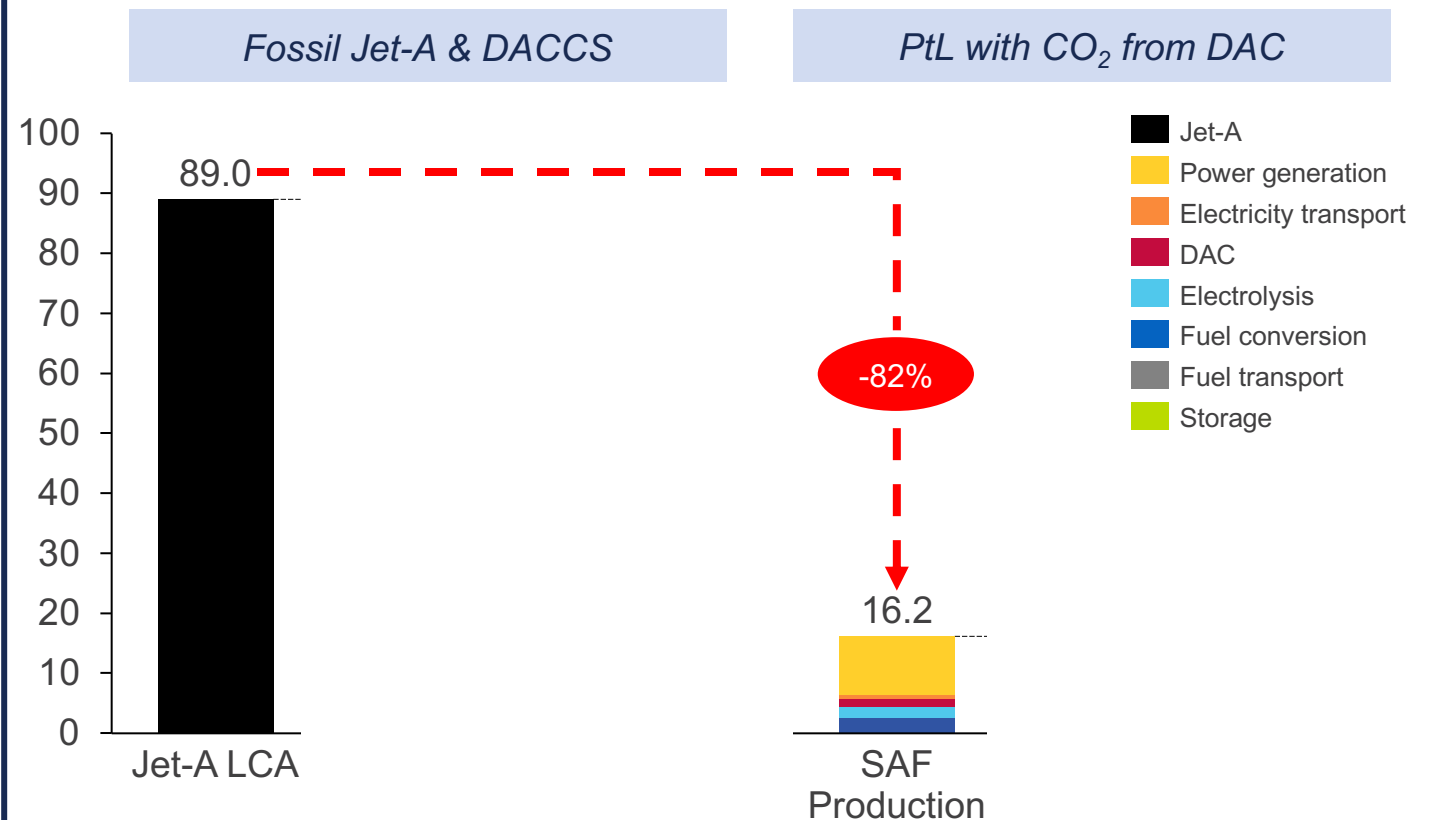
Comparisons between the two DAC-based pathways require consistent assumptions in emissions assessments

Scope of LCA

- Generally, transportation fuel LCAs use **well-to-wheel** / **well-to-wake approach**
- Renewable electricity associated with **embodied emissions** of power generation (not typically included for biofuels as impacts are secondary)
- **Emissions of carbon capture and storage** fall within this system boundary

Lifecycle GHG emissions (WTW) for jet fuel, gCO₂e/MJ

Near-term technology



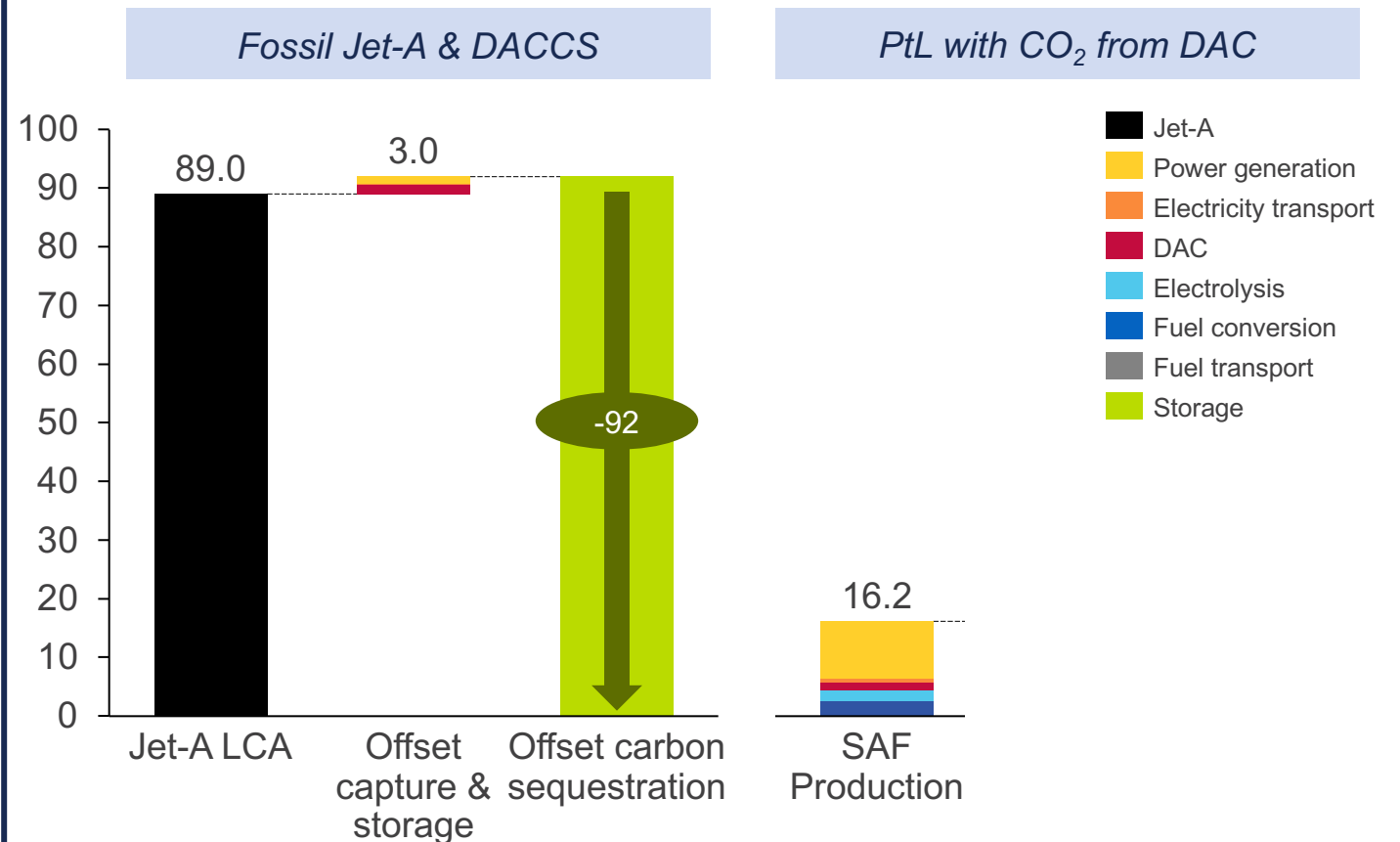
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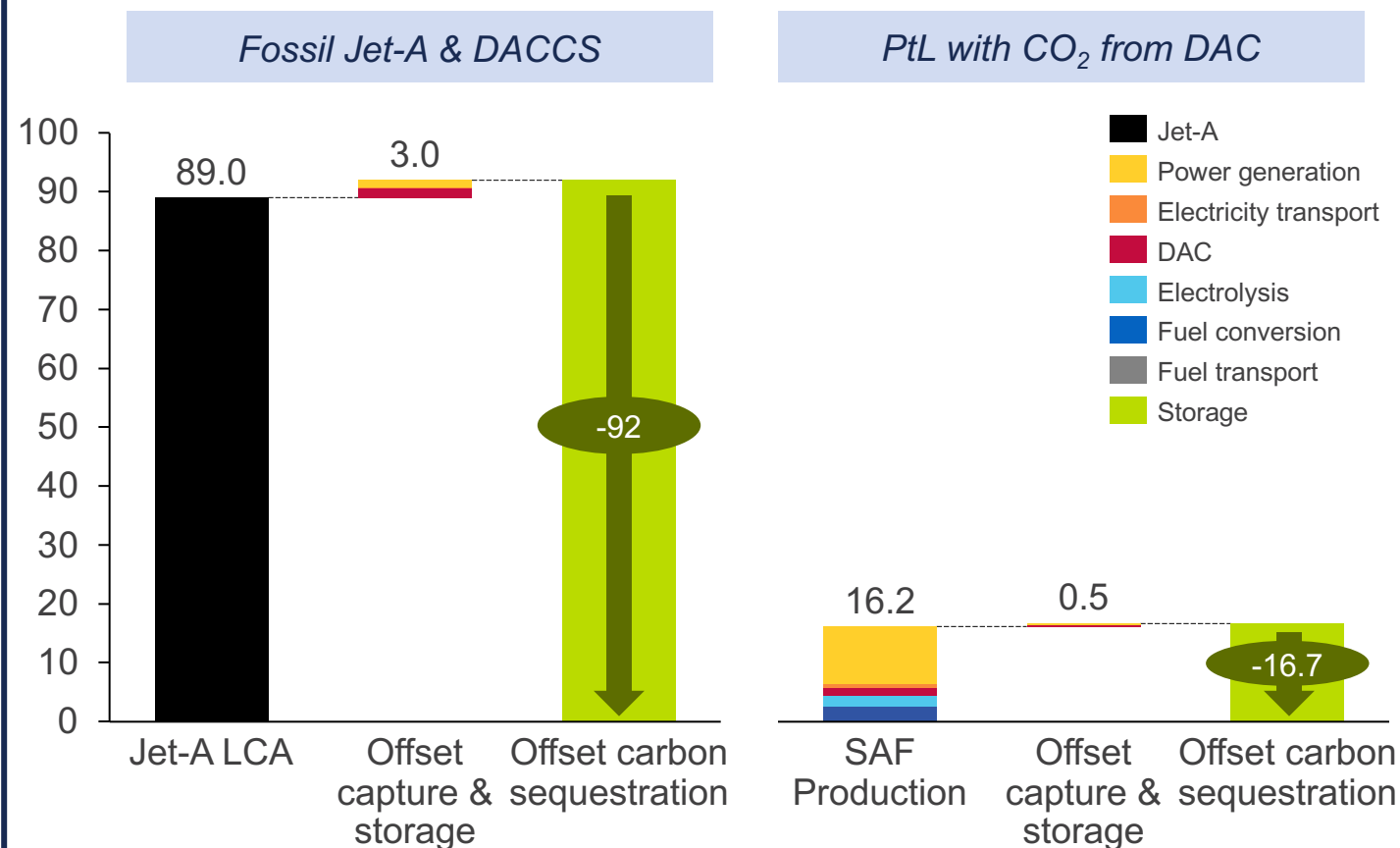
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Net-zero goal to be used as constraint

Comparison of pathways requires comparable environmental attributes

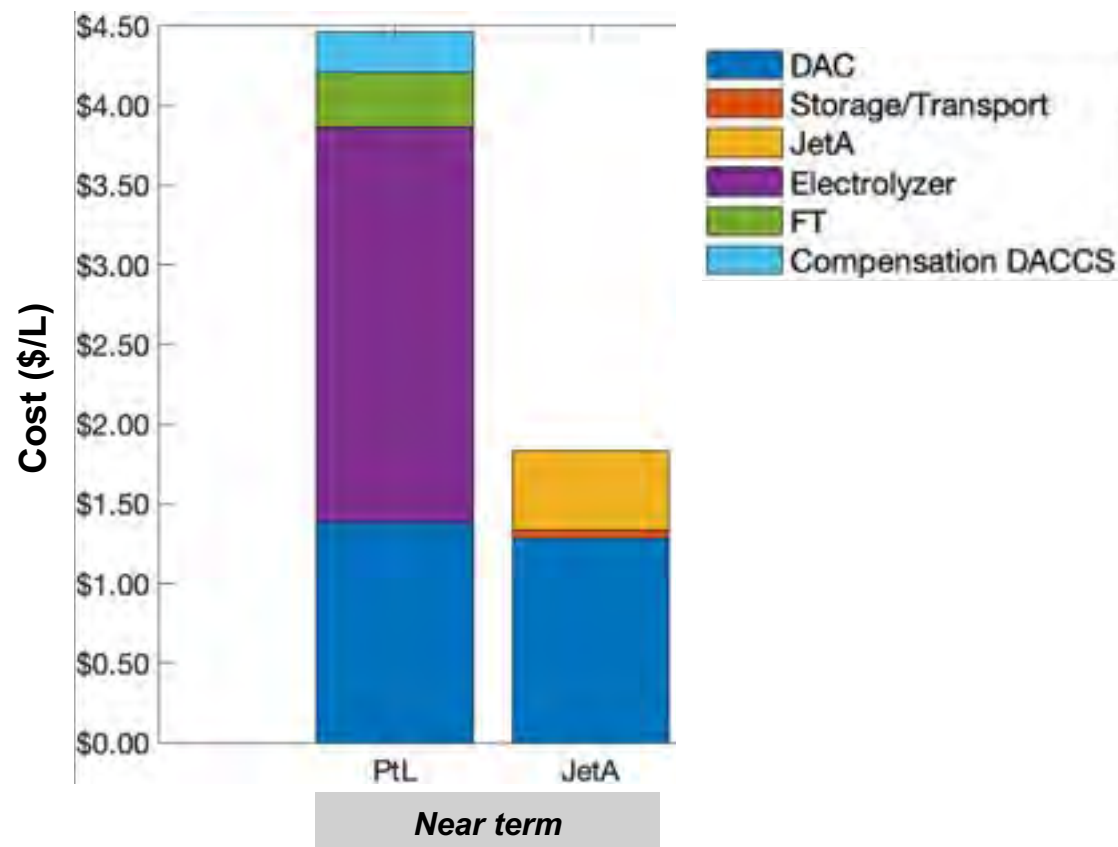
Any lifecycle GHG emissions should be compensated via DACCS mechanisms

Lifecycle GHG emissions (WTW) for jet fuel, gCO₂e/MJ



Baseline cost comparison: high cost of DAC dominates baseline costs; maturing of PtL technology needed

Cost comparisons of pathways under different technology assumptions, \$/ liter



Cost drivers

PtL

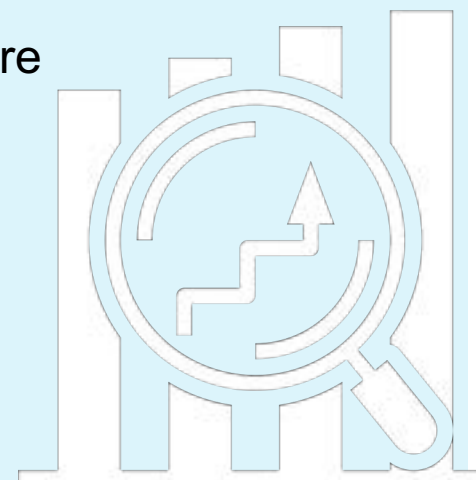
Largely driven by:

- High cost of electrolysis (incl. renewable electricity)
- DAC
- Conversion costs are secondary

Jet-A + DACCS

DAC cost alone is nearly factor 3 of jet fuel cost

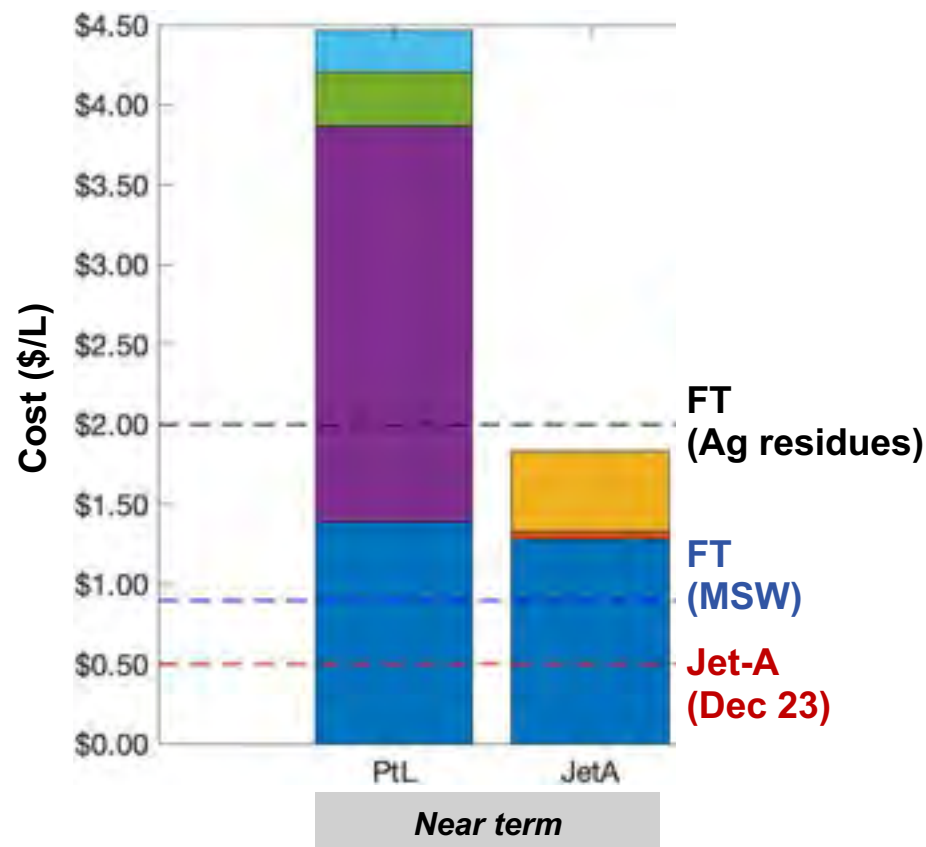
Near-term technology



*Assuming liquid DAC

Baseline cost comparison: high cost of DAC makes both pathways more expensive than bio-based fuels

Cost comparisons of pathways under different technology assumptions, \$/ liter



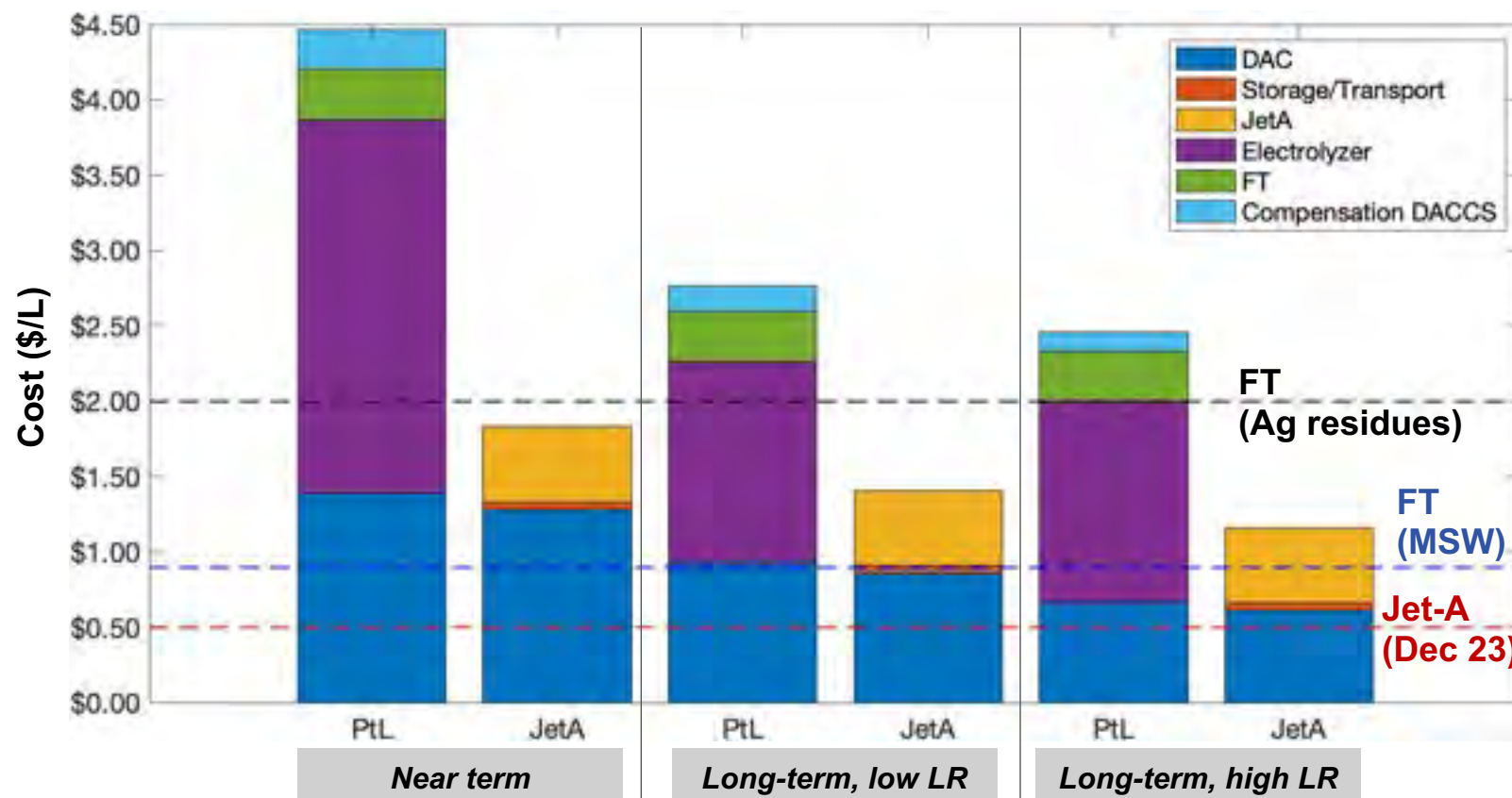
Near-term technology:

- DAC cost alone is higher than Jet-A cost; Jet-A + DACCS cost higher than expected cost for biofuels
- PtL technology leads to cost mark-ups (factor 2.5)

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Baseline cost comparison: learning rates for DAC can reduce cost premiums over biofuels

Cost comparisons of pathways under different technology assumptions, \$/ liter



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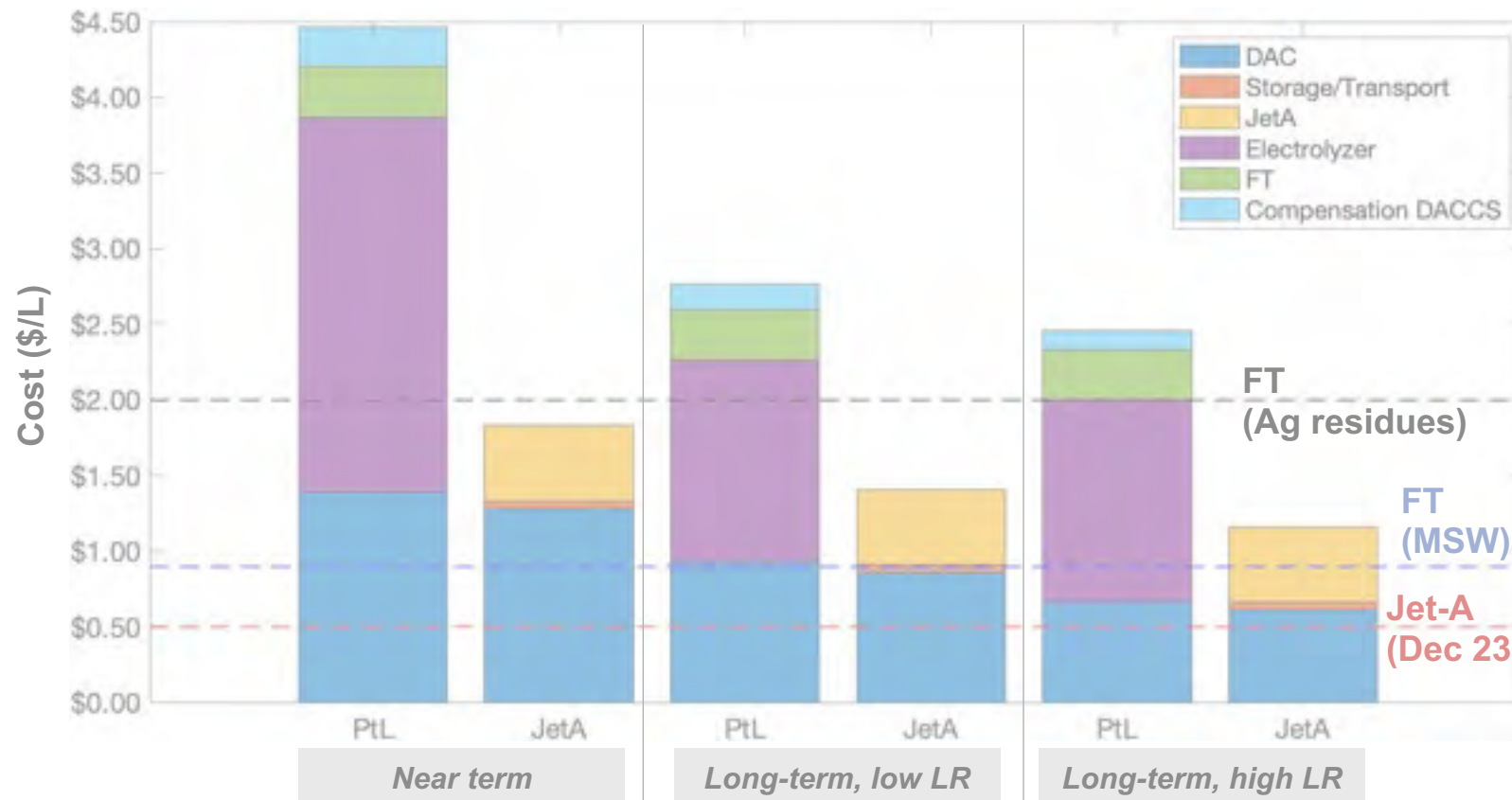
Long-term technology:

- Learning could reduce cost for Jet-A+DACCS to be within range of biofuels
- Under mid-point PtL assumptions, mark-ups for PtL remain, both over Jet-A + DACCS and biofuels

*Assuming liquid DAC

Baseline cost comparison: learning rates for DAC can reduce cost premiums over biofuels

Cost comparisons of pathways under different technology assumptions, \$/ liter



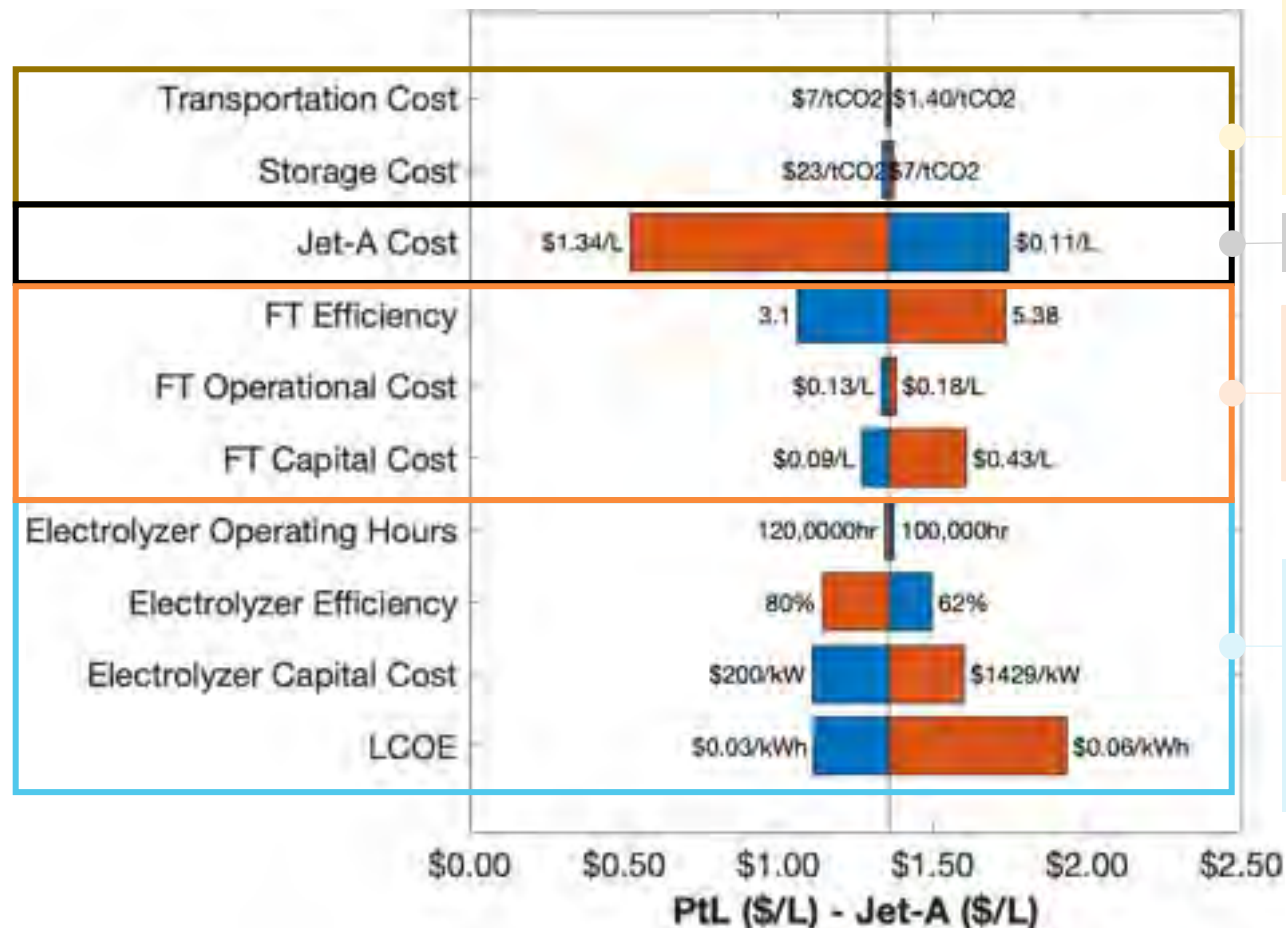
Are there realistic pathways for PtL technologies to become a competitive user of carbon from DAC while also supplying energy to the transportation sector?

→ Analyze with future technology assumptions and high LR.

*Assuming liquid DAC

Cost sensitivity analysis of PtL mark-ups over Jet-A + DACCS: no single factor which could fully close the gap

Sensitivity of cost differential between PtL and Jet-A + DACCS, \$/ liter



Realistic ranges of costs for **CO₂ storage and transportation** have a very small impact on competitiveness of PtL

Jet fuel price trajectory is key!

FT conversion technology likely secondary, unless there are substantial breakthroughs in efficiency.

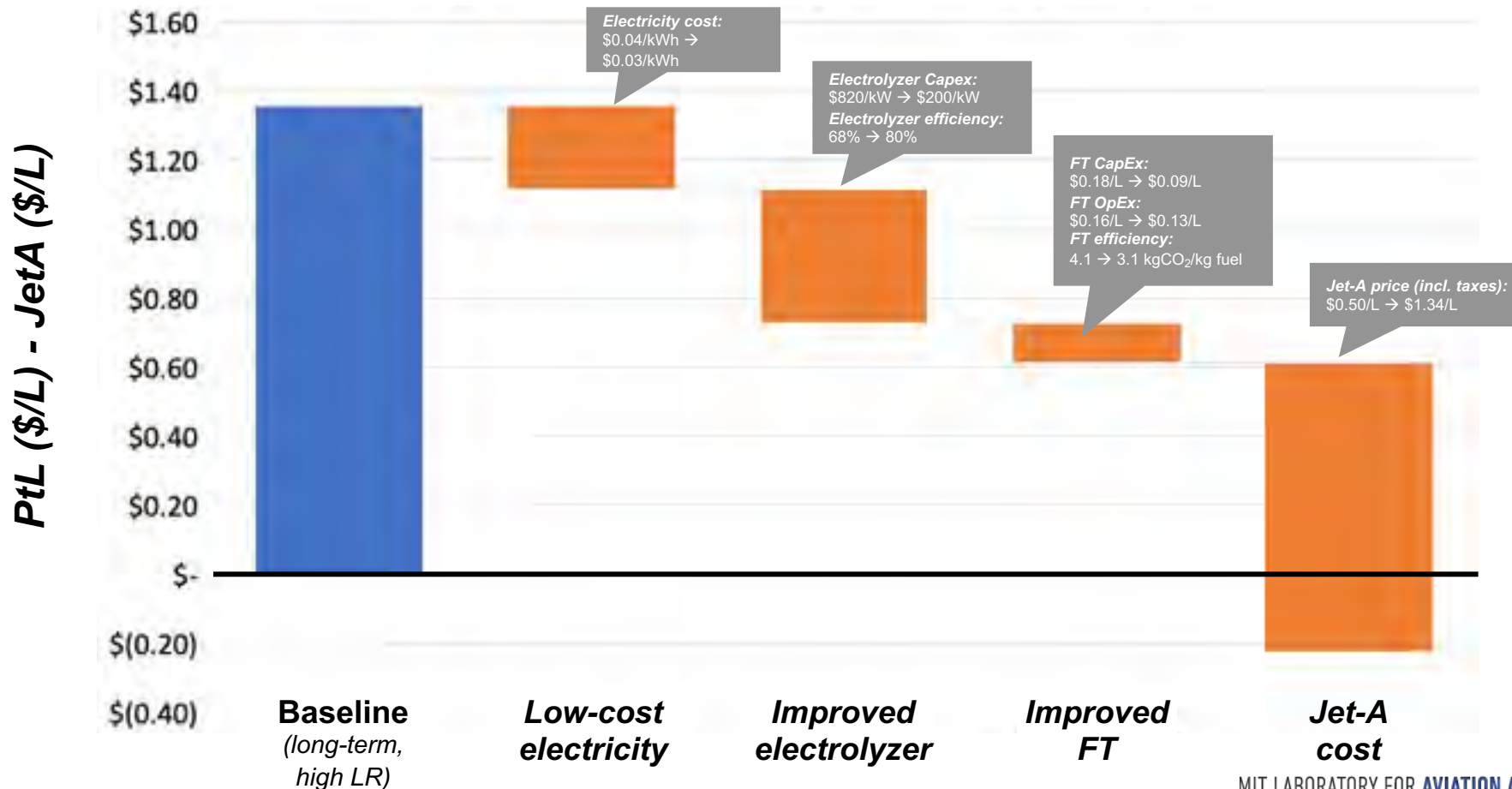
Renewable electricity costs and improvements in electrolyzer technology are among the most significant drivers of making PtL more competitive.

No single factor can close the cost gap

Are there realistic combinations of factors to close the gap?

Cost sensitivity analysis of PtL mark-ups over Jet-A + DACCS: combinations of factors can close the gap

Combinations of factors to close the cost gap between PtL and Jet-A + DACCS, \$/ liter



Requirements for closing the cost gap:

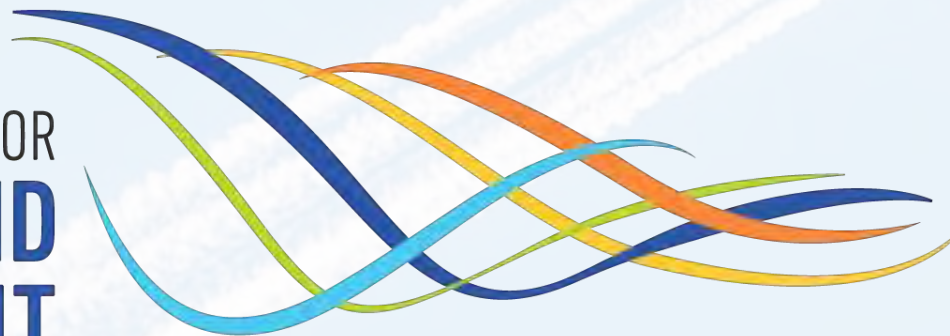
- Both substantial technological and economic/regulatory changes.
- Many drivers have to meet most optimistic assumptions.
- *Jet-A and DACCS may have additional burdens which have not been fully considered:*
 - *Leakage risk from storage*
 - *Potential de-fossilization goals*

Conclusions

1. **DAC-based strategies** require careful consideration of their **associated emissions** when comparing them to other solutions. Embodied carbon and process emissions within a reasonable system boundary must be considered.
2. **Without substantial technology improvements**, DAC-based decarbonization strategies may not be cost competitive relative to bio-based technologies. Even with realistic learning rates, **cost gaps will be hard to close**. DAC may still be needed as other sustainable carbon sources run out.
3. Significant **improvements in PtL technologies are needed to meet cost goals**, both relative to bio-based solutions and alternative use of DAC with fossil energy carriers. Without additional action (e. g., justified by defossilization goals or reductions in fossil feedstock availability) this gap may persist.



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