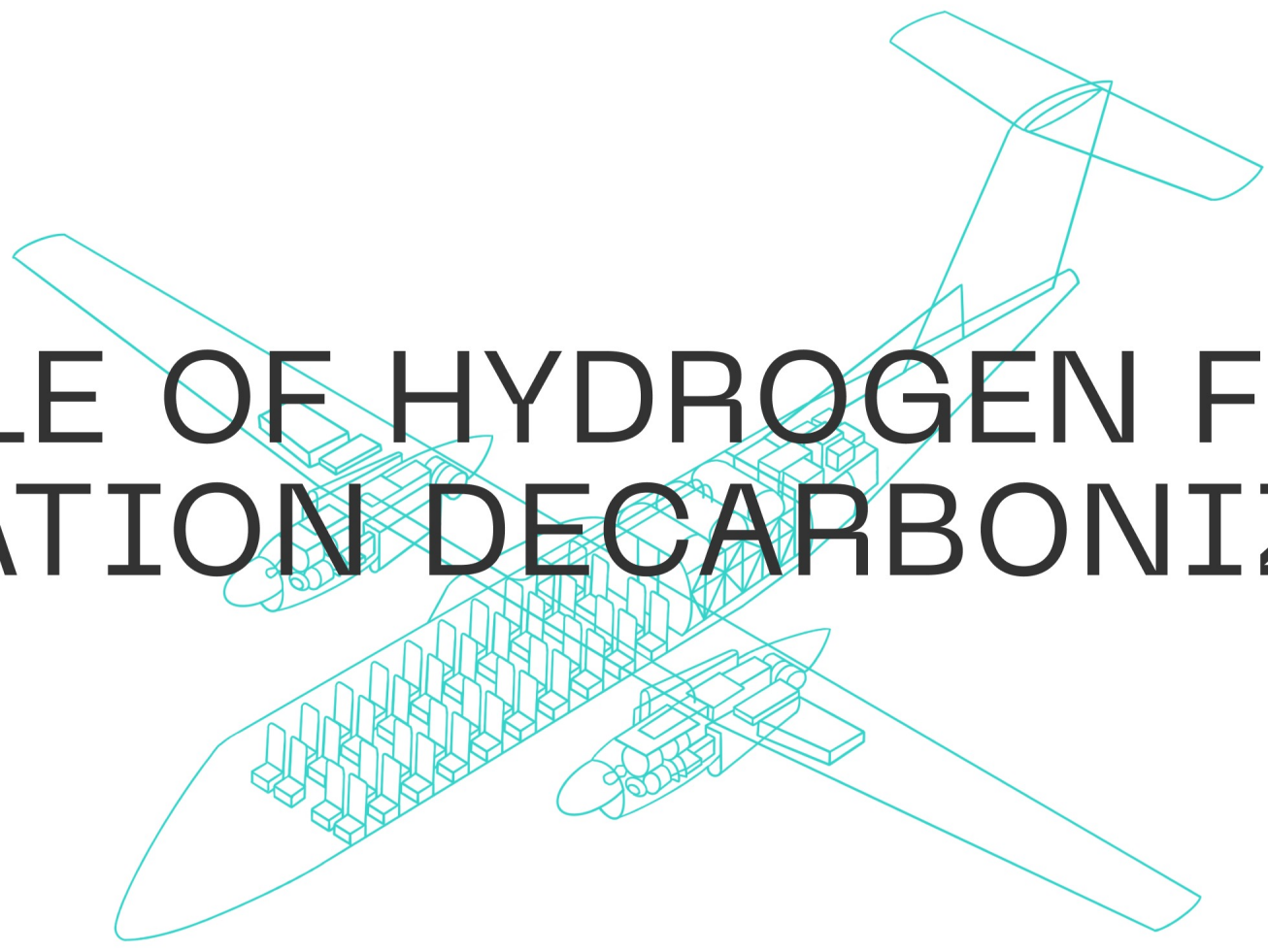




THE ROLE OF HYDROGEN FUELING IN AVIATION DECARBONIZATION



Students Jon Gordon
Jaih Hunter-Hill
Anna Cobb
Xiaohan Wu
Dorothy Li

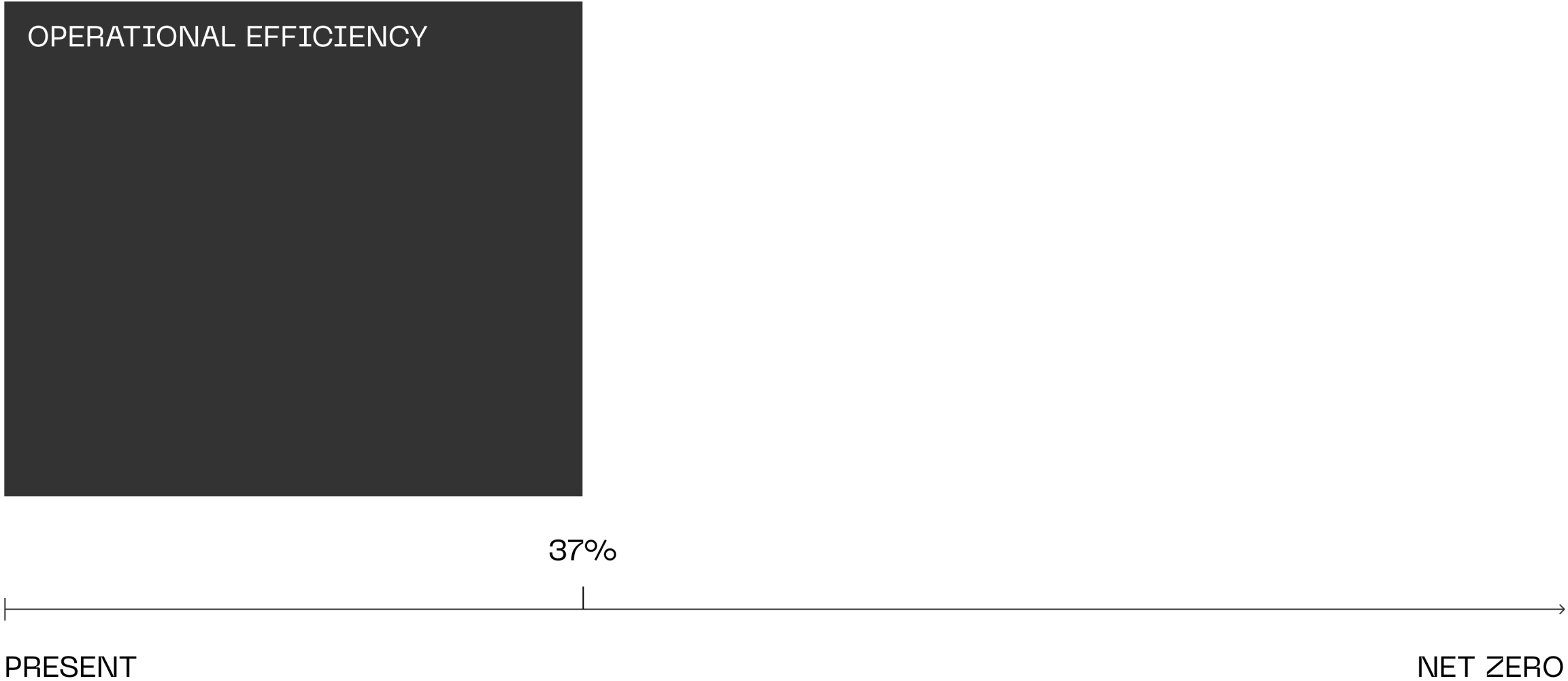
Advisors Dr. Peter Zhang
Dr. Jared Cohon



2050

NET ZERO AVIATION

Aviation Decarbonization Levers



Aviation Decarbonization Levers

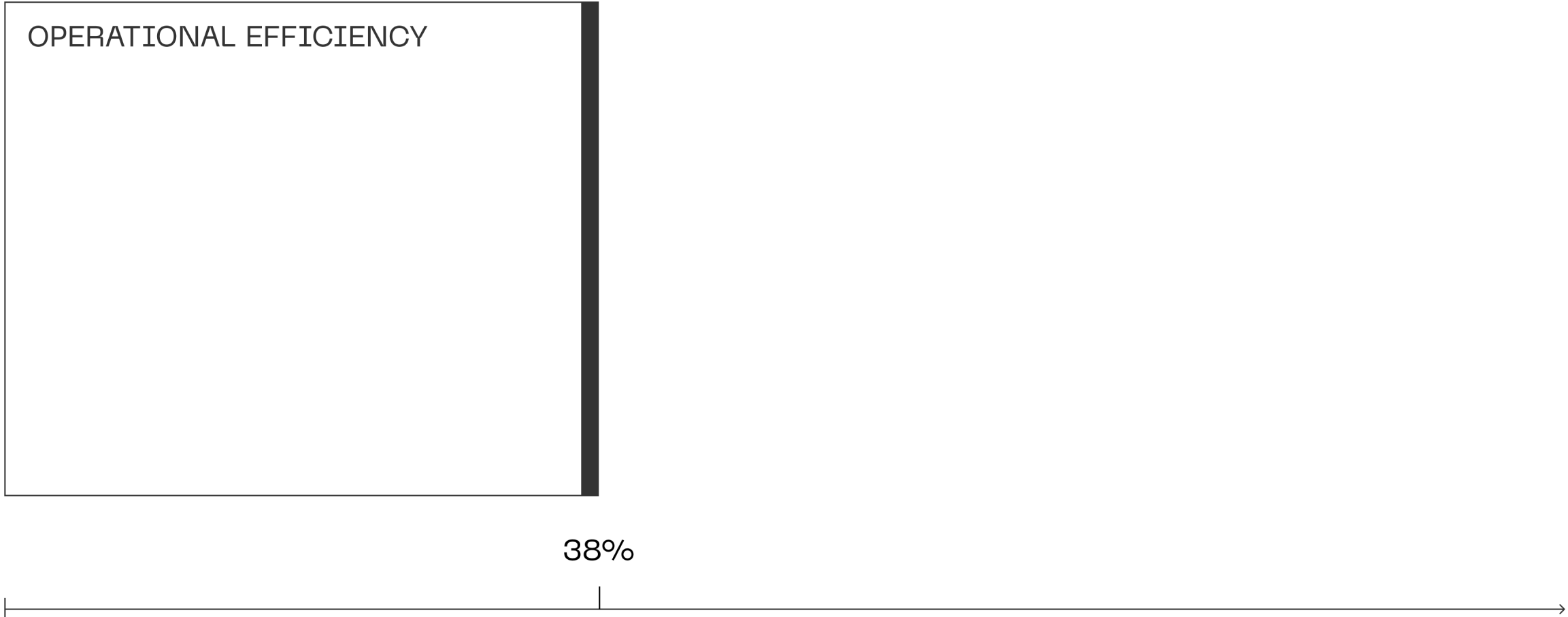
ALTERNATIVE
FUELS

OPERATIONAL EFFICIENCY

38%

PRESENT

NET ZERO



Aviation Decarbonization Levers

ALTERNATIVE
FUELS



53%

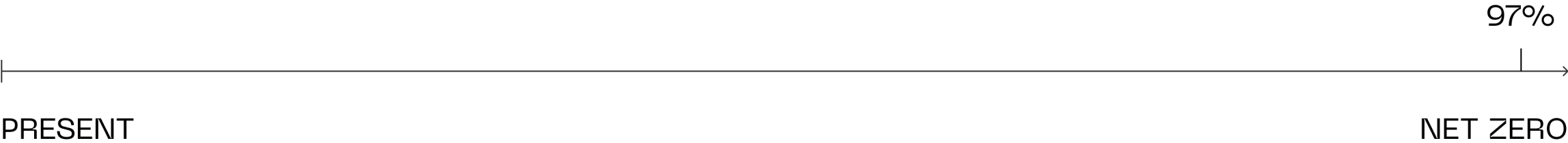
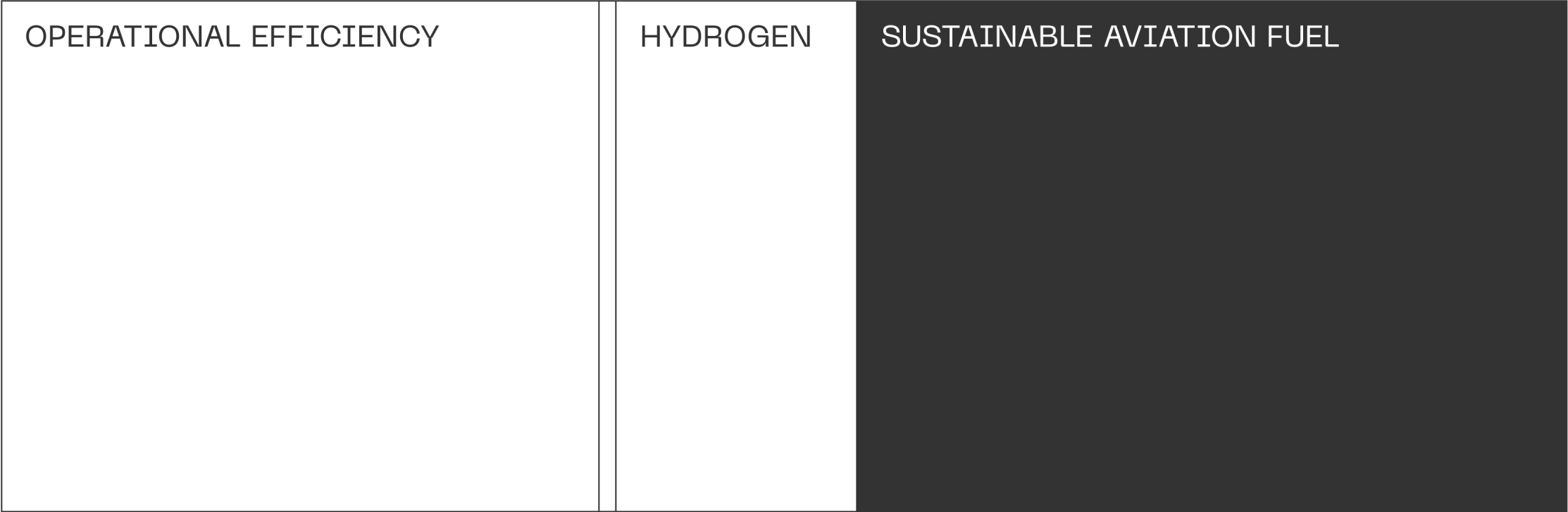


PRESENT

NET ZERO

Aviation Decarbonization Levers

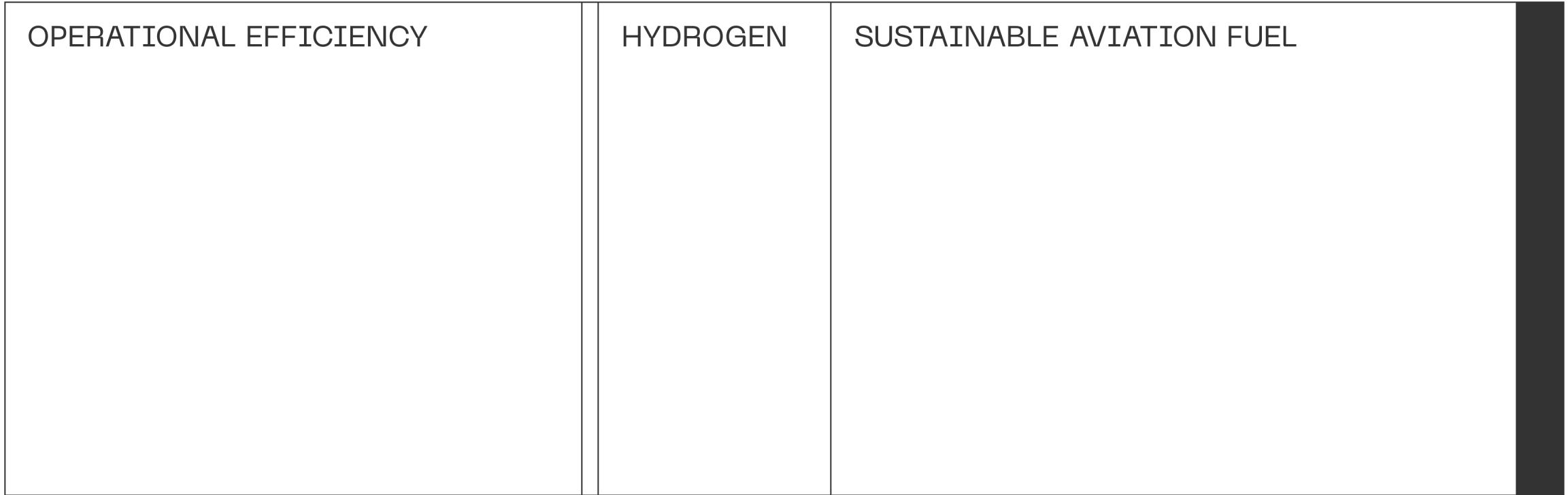
ALTERNATIVE FUELS



Aviation Decarbonization Levers

ALTERNATIVE
FUELS

CARBON
CREDITS



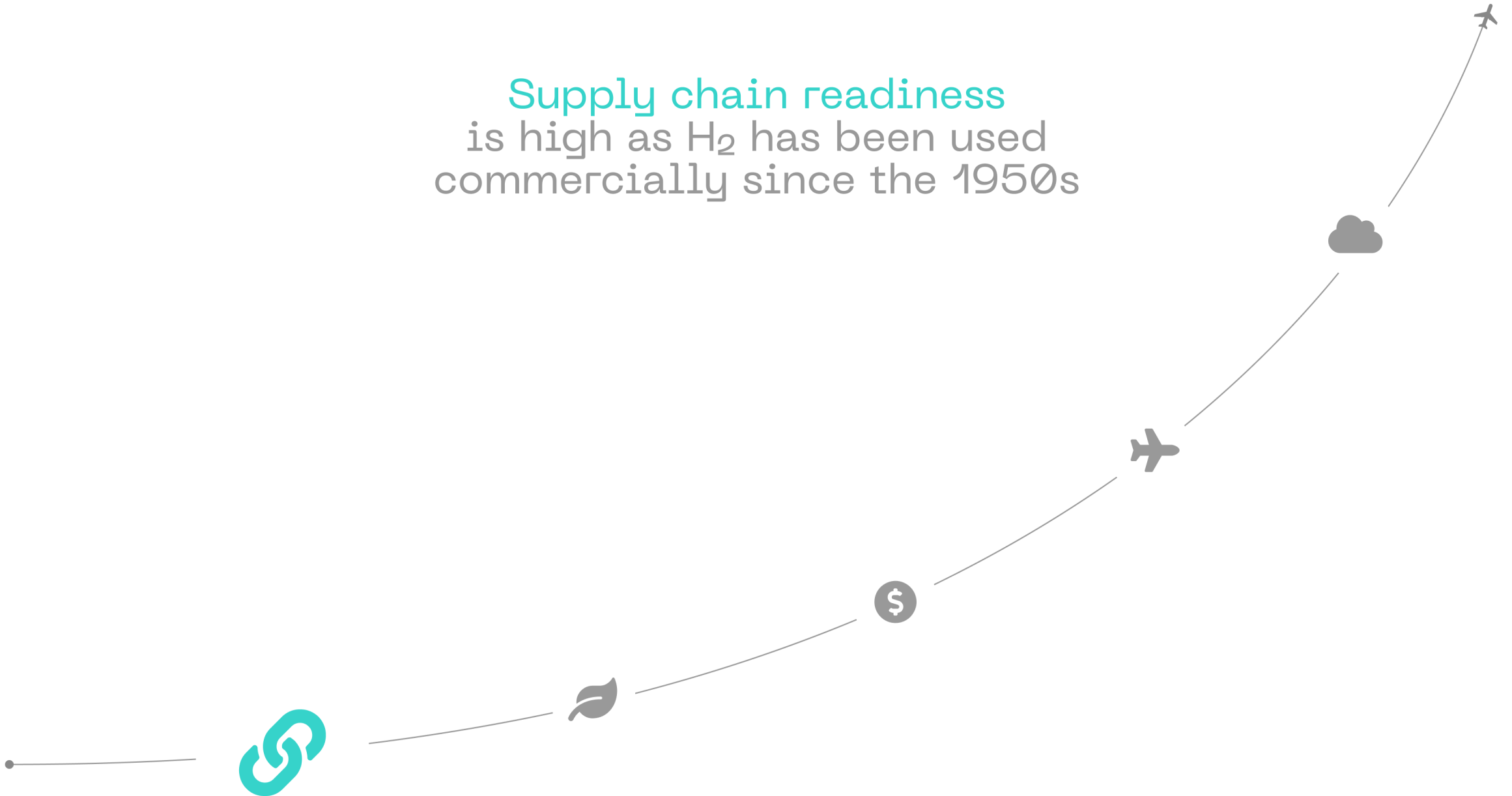
100%

PRESENT

NET ZERO

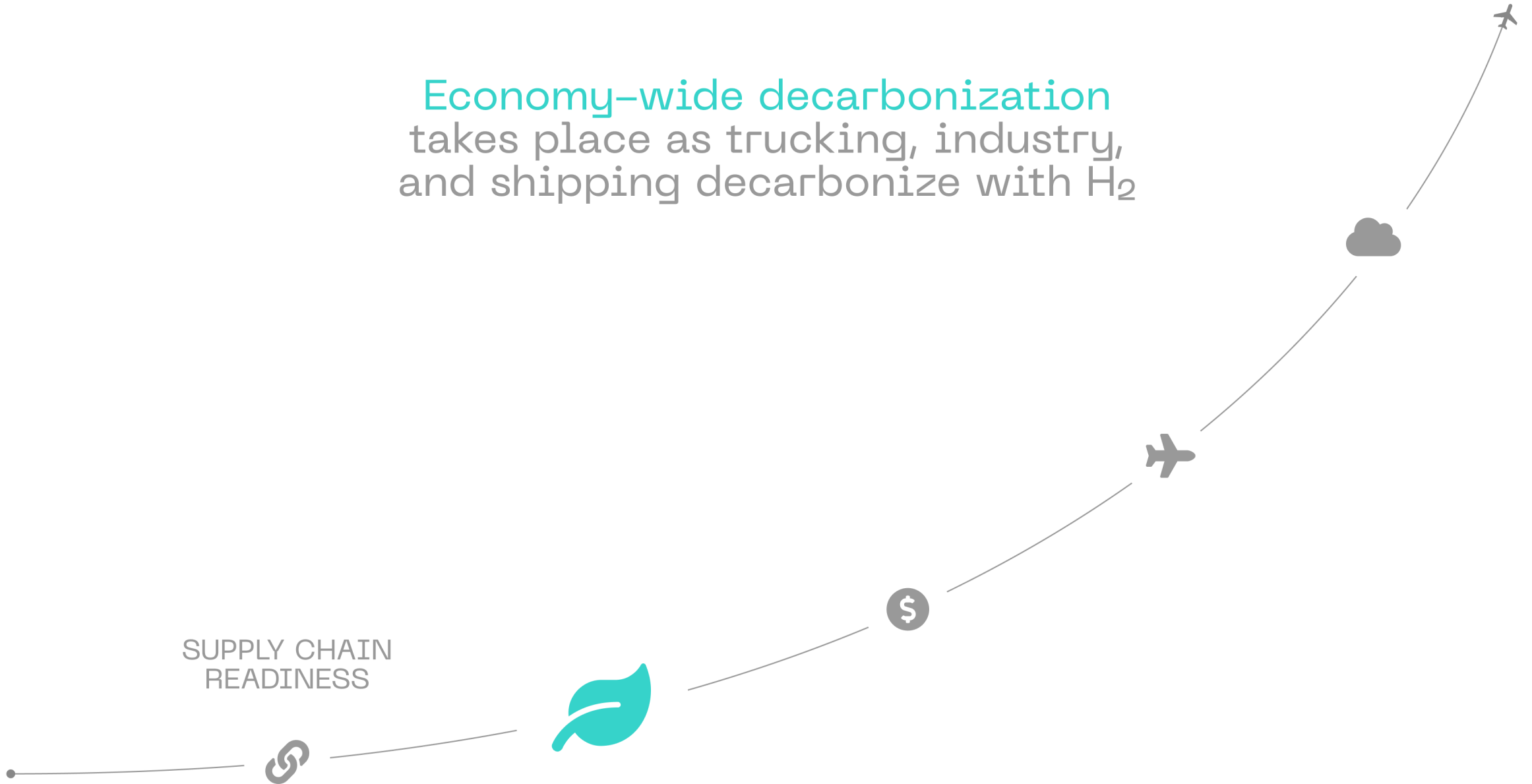
Why Hydrogen

Supply chain readiness
is high as H₂ has been used
commercially since the 1950s



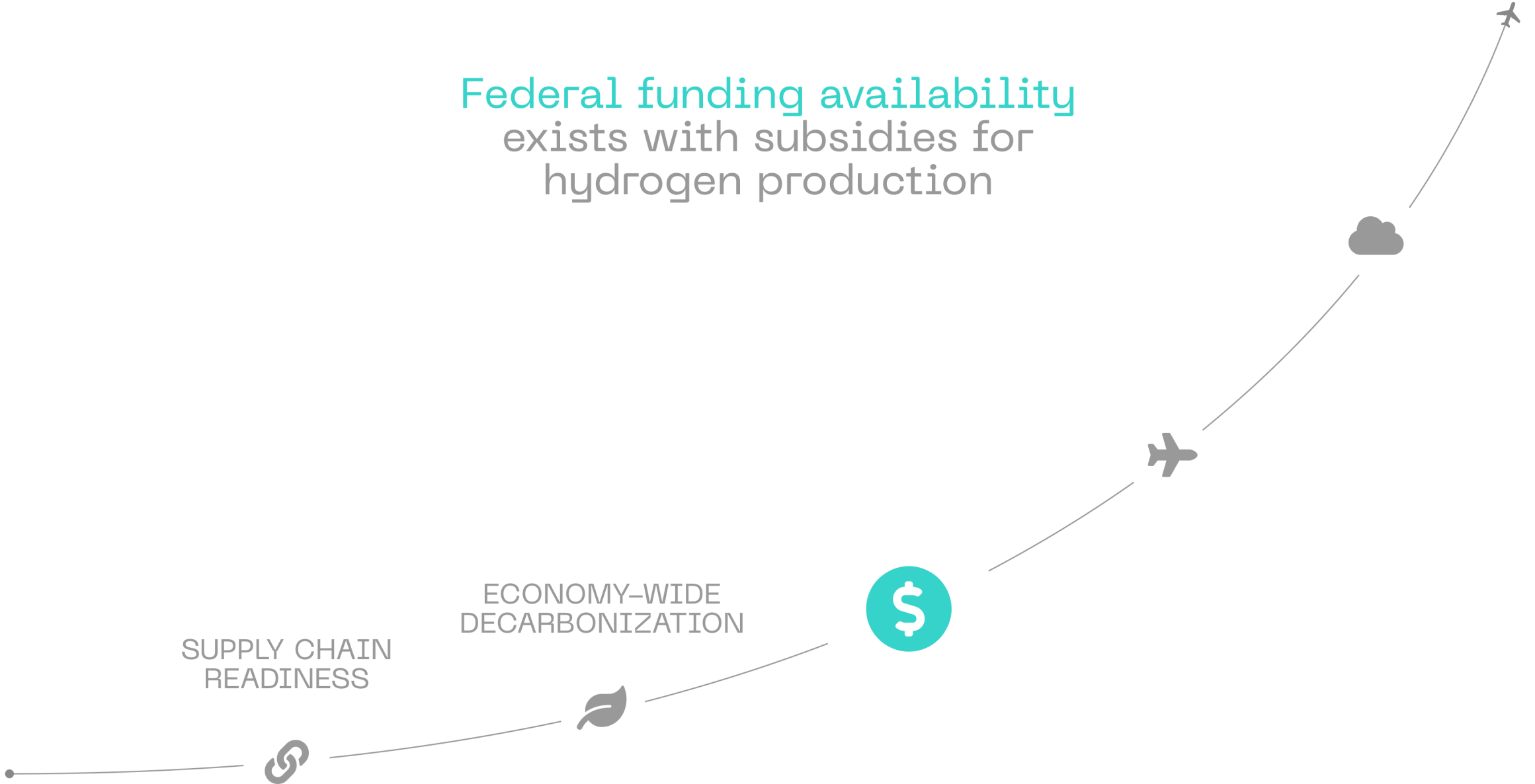
Why Hydrogen

Economy-wide decarbonization takes place as trucking, industry, and shipping decarbonize with H₂



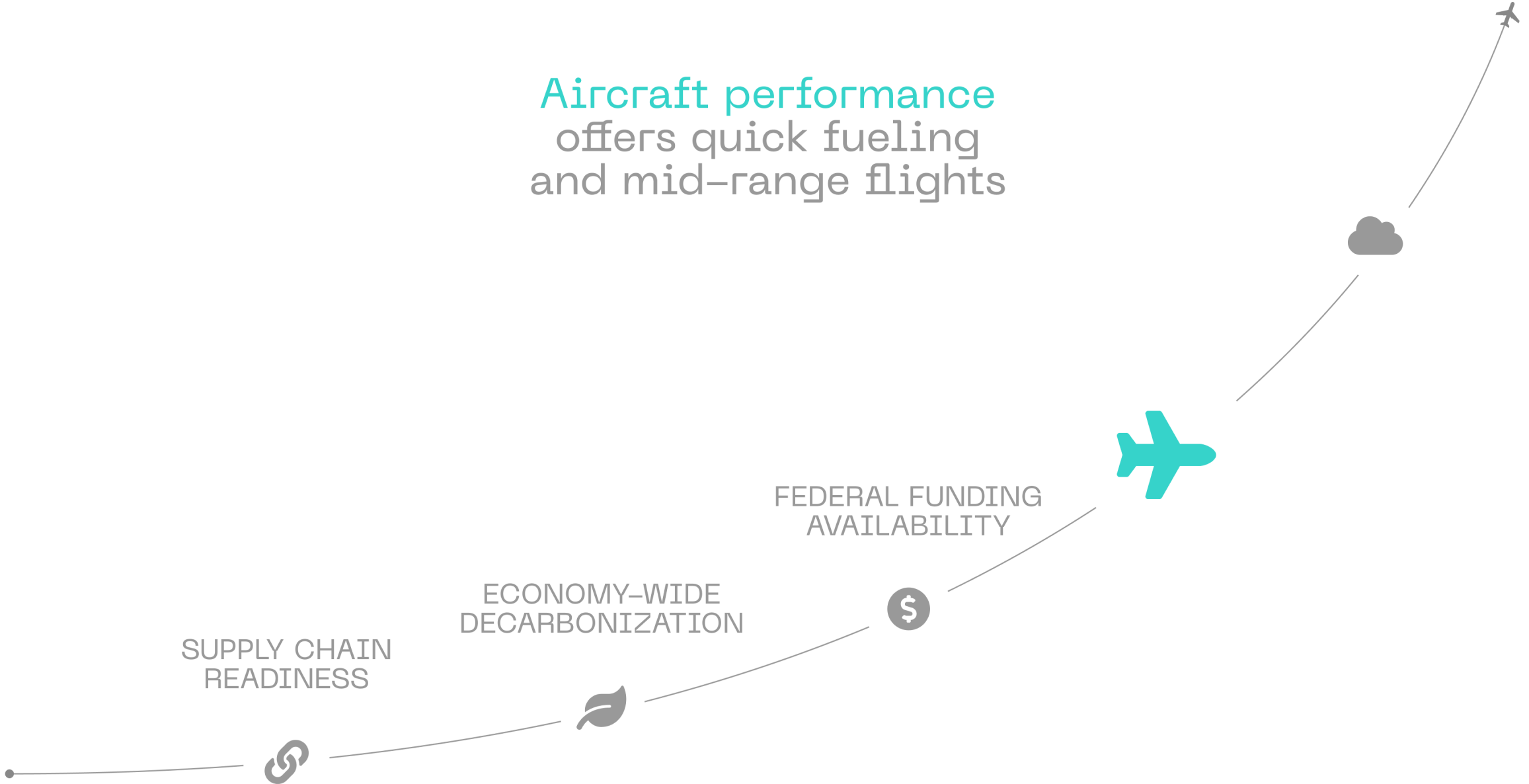
Why Hydrogen

Federal funding availability
exists with subsidies for
hydrogen production



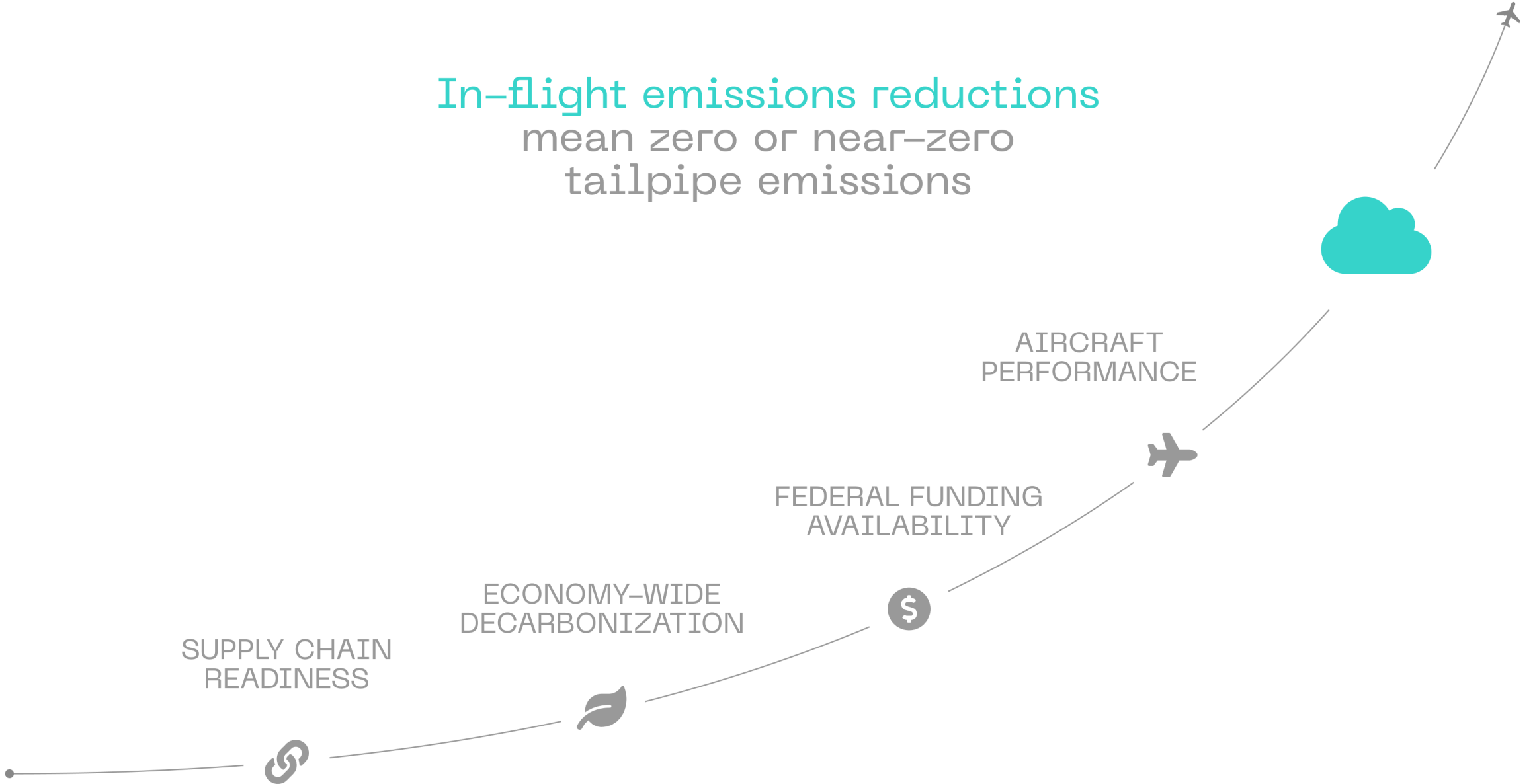
Why Hydrogen

Aircraft performance
offers quick fueling
and mid-range flights

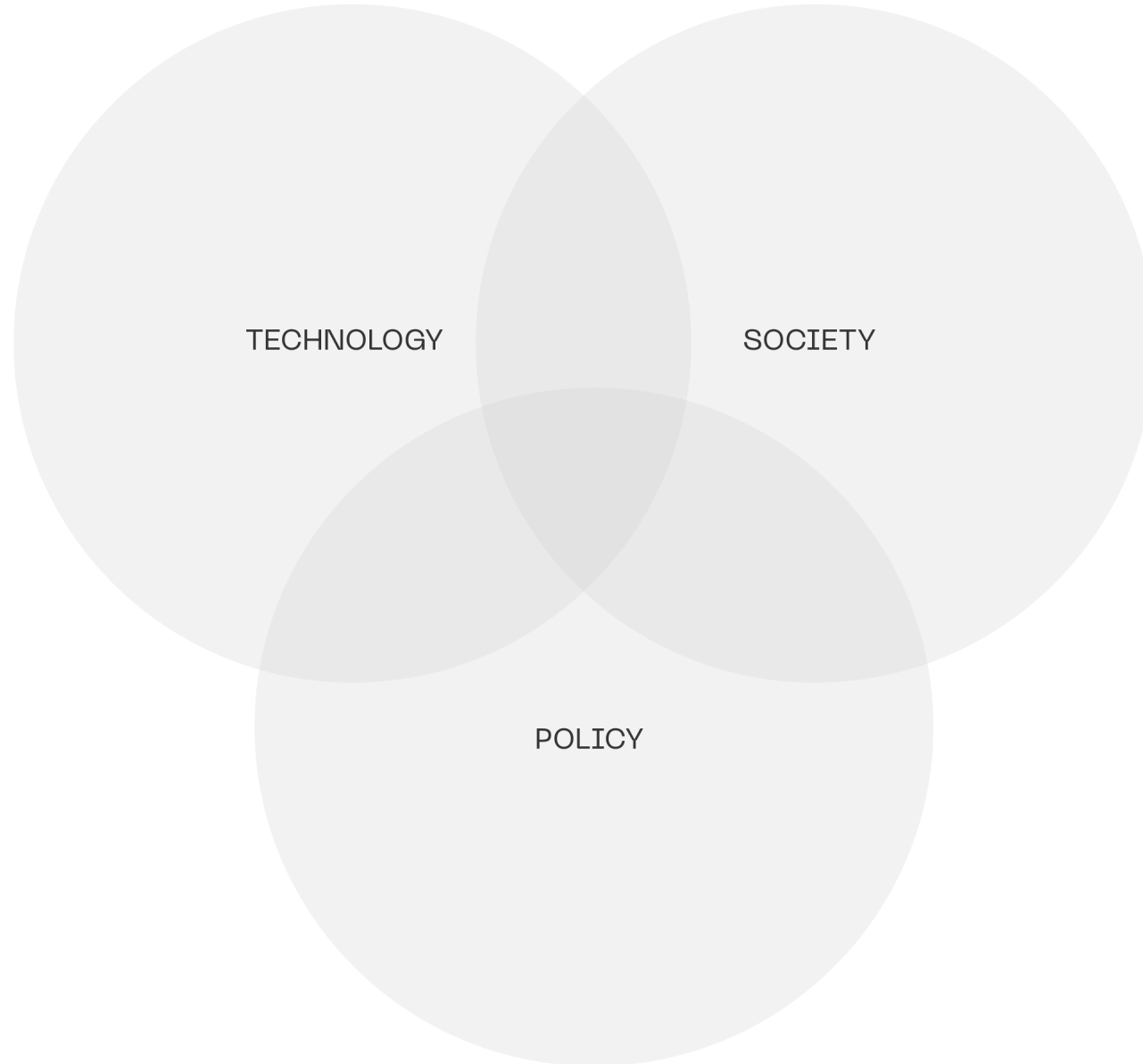


Why Hydrogen

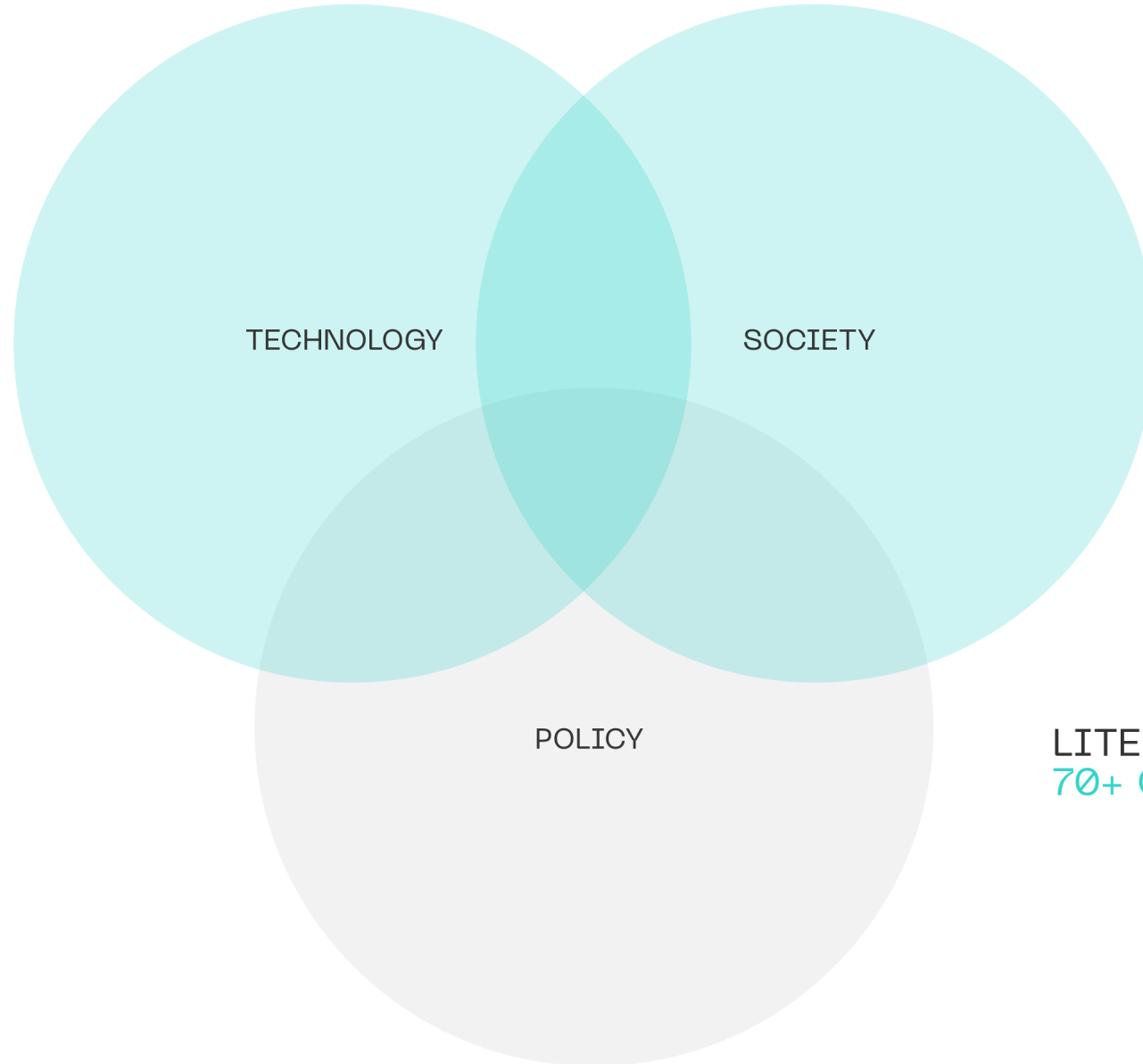
In-flight emissions reductions
mean zero or near-zero
tailpipe emissions



Our Methodology



Our Methodology



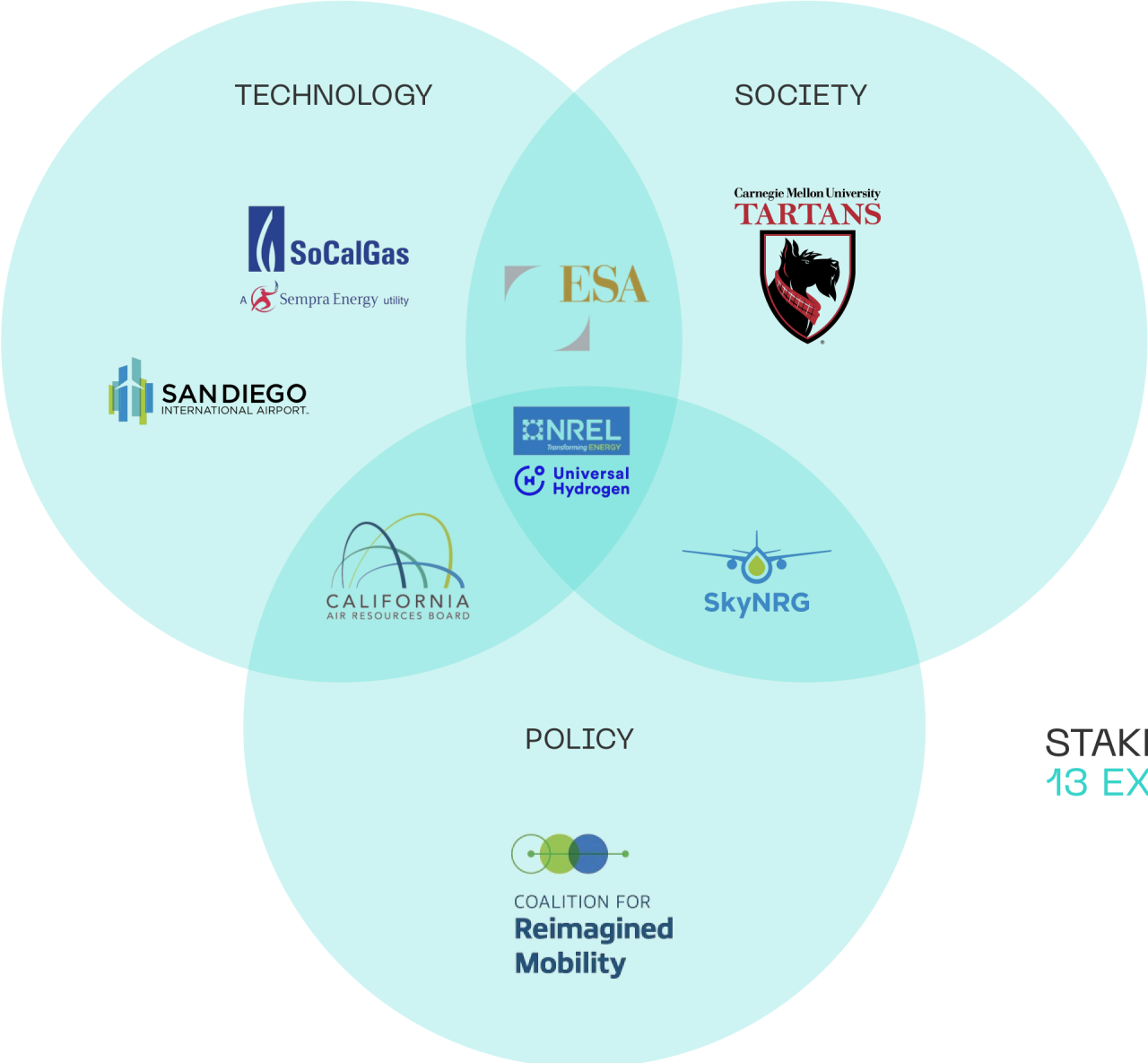
TECHNOLOGY

SOCIETY

POLICY

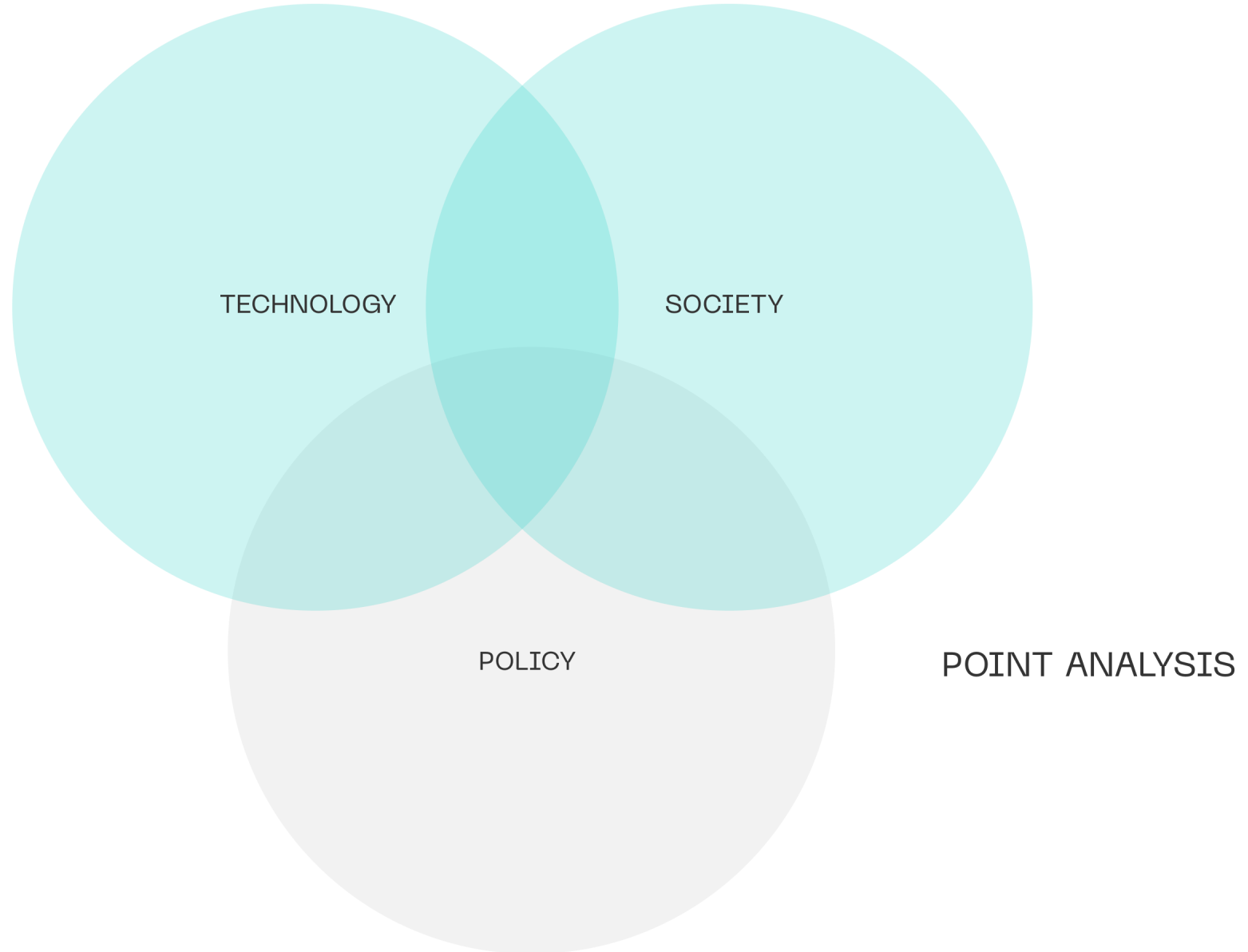
LITERATURE REVIEW
70+ CITATIONS

Our Methodology



STAKEHOLDER INTERVIEWS
13 EXPERTS

Our Methodology



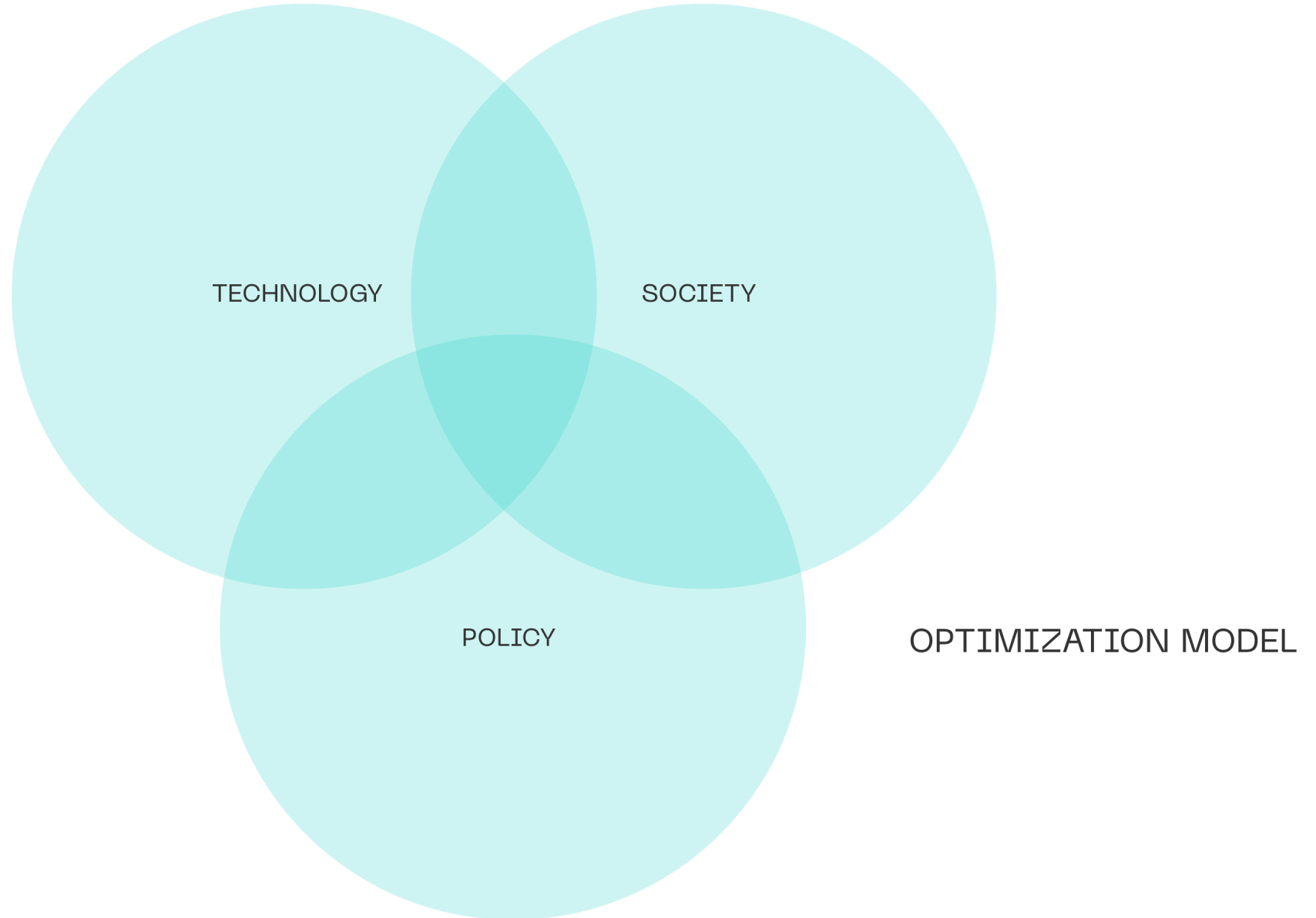
TECHNOLOGY

SOCIETY

POLICY

POINT ANALYSIS

Our Methodology



Hydrogen Supply Chain

 MAKE

 MOVE

 STORE

 LAST MILE



Nuclear



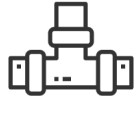
SMR with CCS



Electrolysis



New Pipeline



Retrofit Pipeline



Diesel Truck



Zero-Emission Truck



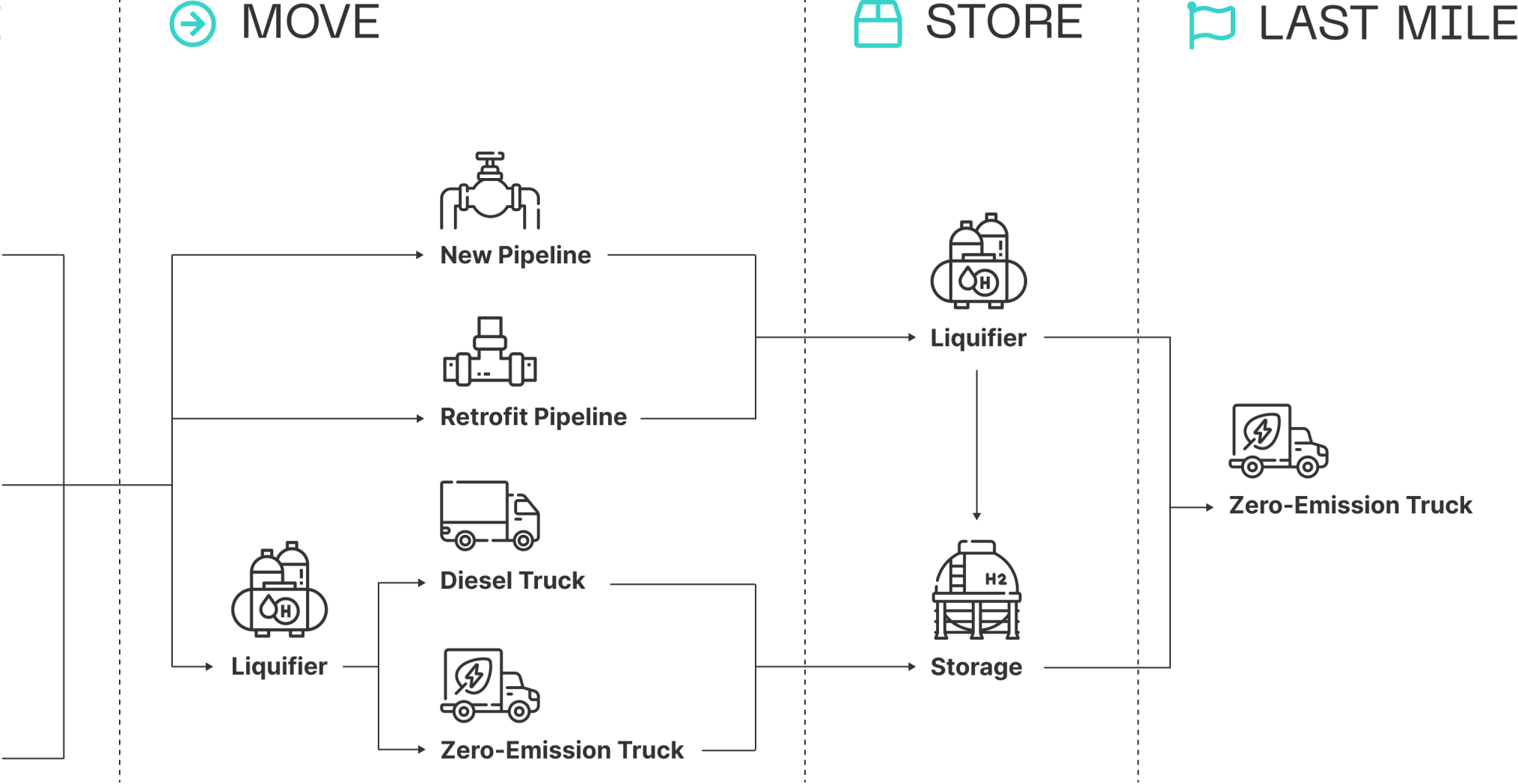
Liquifier



Storage

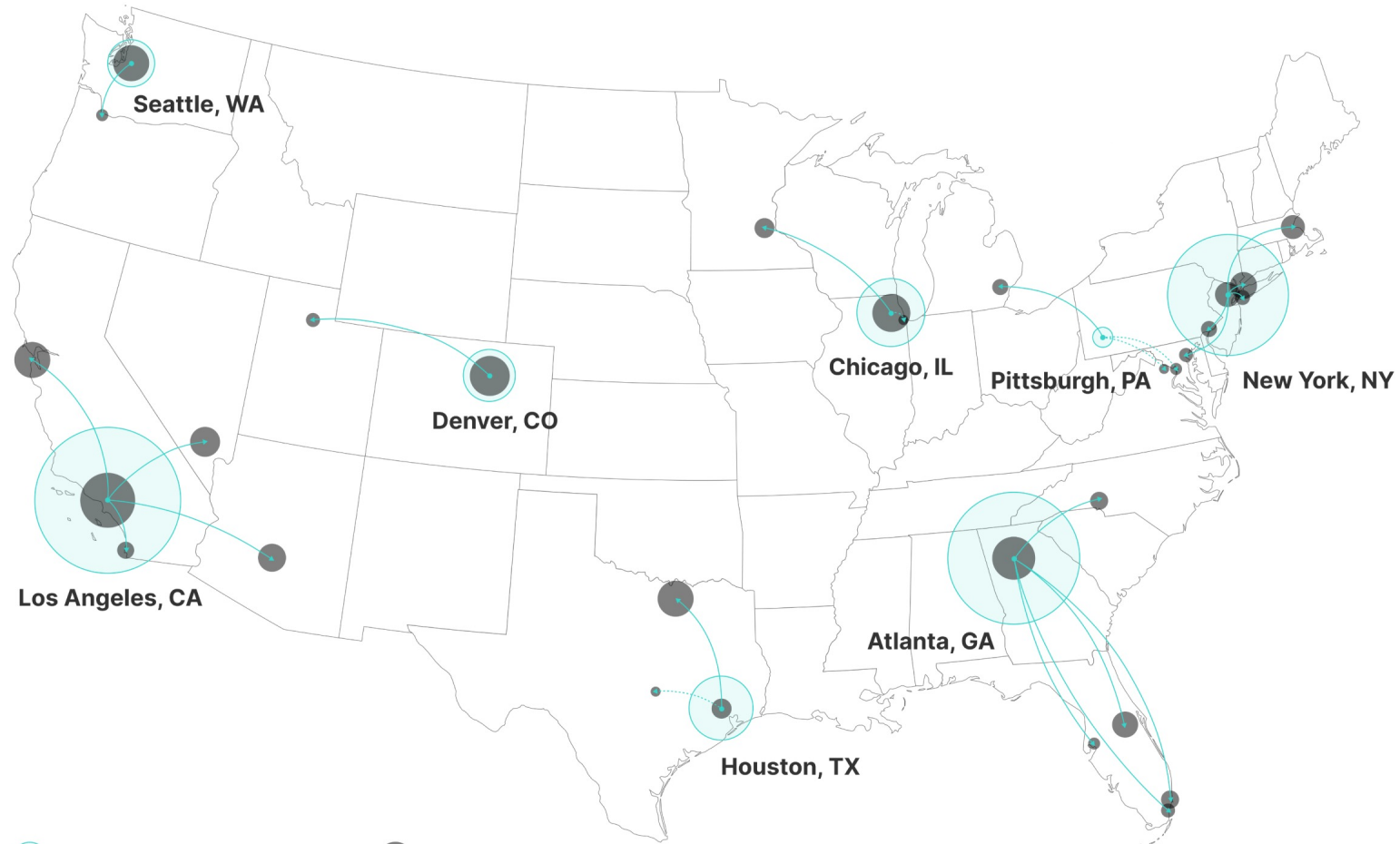




Zero-Emission Truck









Hydrogen Supply Chain



 Hydrogen Hub
 500 million kg
The size of the circle is based on the annual quantity of H₂ produced.

 Major Airport
 500 million kg
The size of the circle is based on the demand of H₂ for each airport.

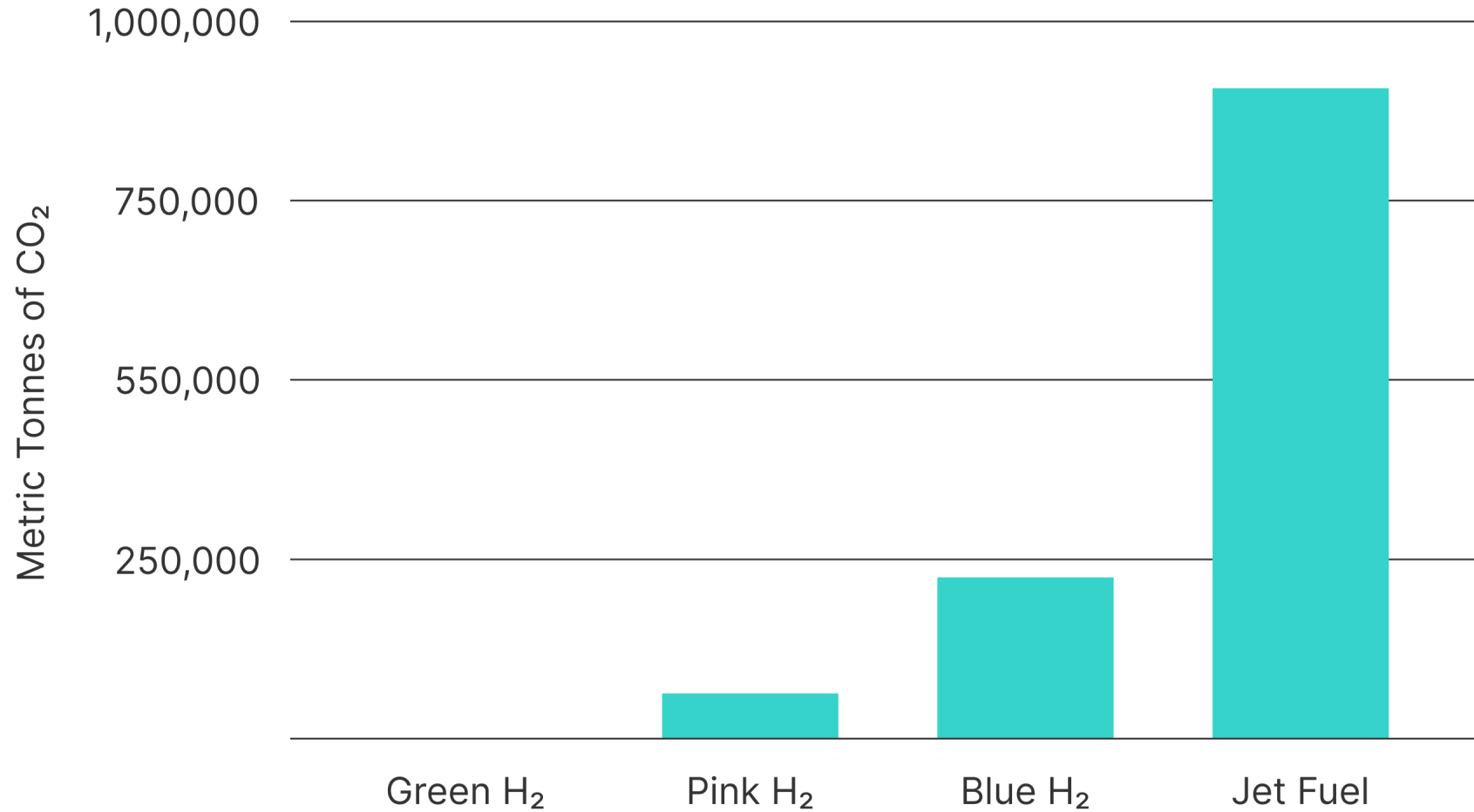
 Pipeline Transport
 Truck Transport

We aim to connect hydrogen produced at DOE Hydrogen Hubs with the nation's thirty largest airports through new and retrofit pipelines, diesel and zero-emissions trucks.



Hydrogen Supply Chain

Emissions of Energy-Equivalent Quantities of Fuel



Hydrogen Supply Chain

 MAKE

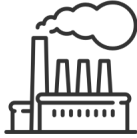
 MOVE

 STORE

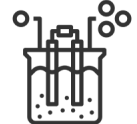
 LAST MILE



Nuclear



SMR with CCS



Electrolysis



New Pipeline



Retrofit Pipeline



Diesel Truck



Zero-Emission Truck



Liquifier



Storage

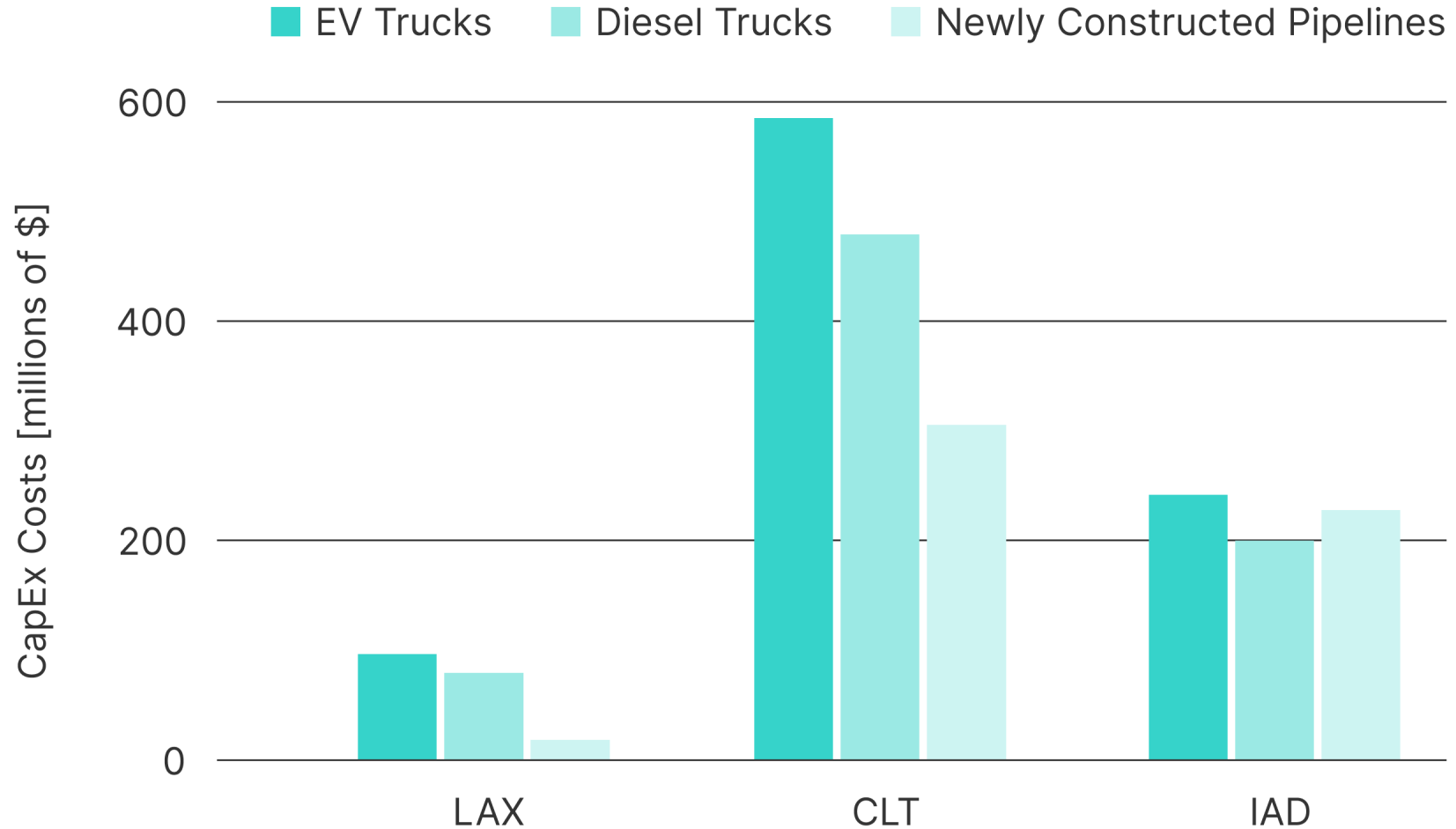


Zero-Emission Truck



Hydrogen Supply Chain

H₂ Transport Costs for Different Sized Airports



Hydrogen Supply Chain

 MAKE

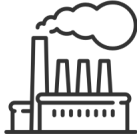
 MOVE

 STORE

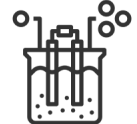
 LAST MILE



Nuclear



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Zero-Emission Truck



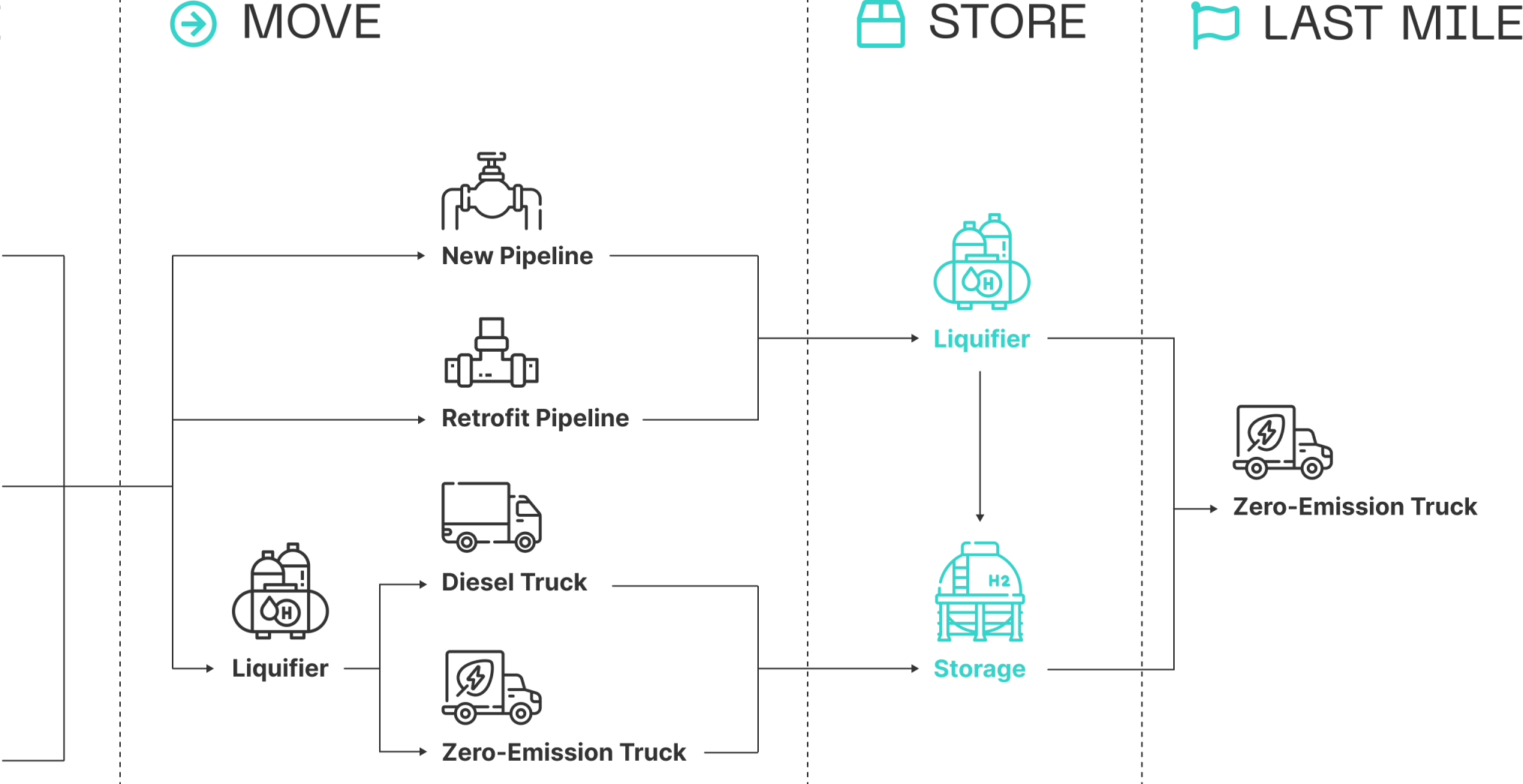
Liquifier

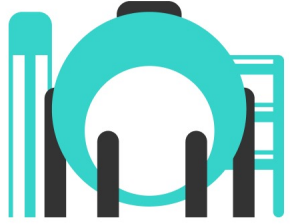


Storage



Zero-Emission Truck





Hydrogen Supply Chain



Liquid hydrogen storage. FSEC®. (2018, July 6). [Image] Retrieved from <https://energyresearch.ucf.edu/research/hydrogen/liquid-hydrogen-storage/>

Hydrogen Supply Chain

 MAKE

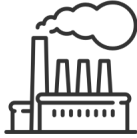
 MOVE

 STORE

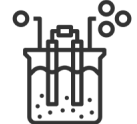
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Nuclear



SMR with CCS



Electrolysis



New Pipeline



Retrofit Pipeline



Diesel Truck



Zero-Emission Truck



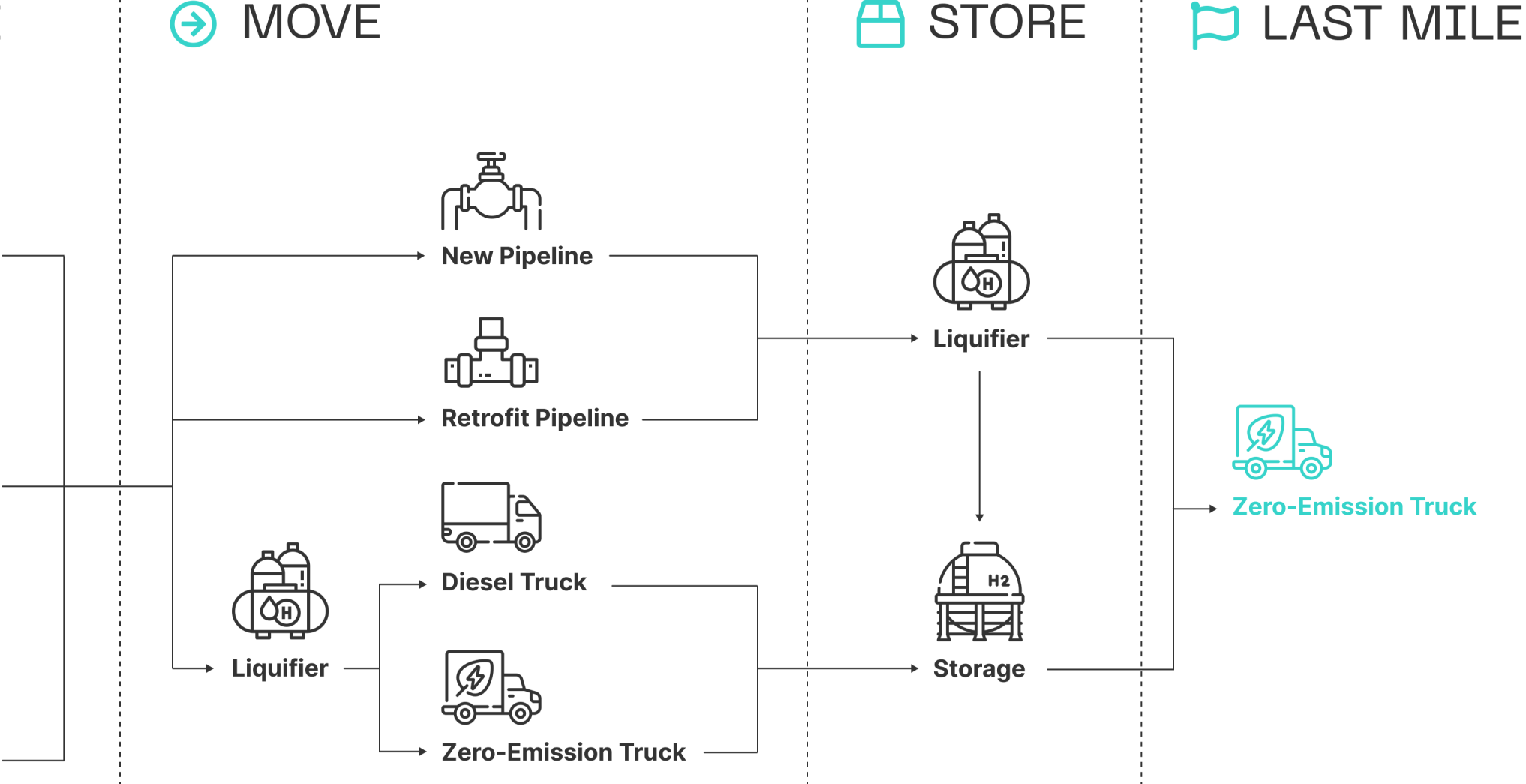
Liquifier



Storage



Zero-Emission Truck



[3] LAST MILE

Hydrogen Supply Chain



Duncan Aviation. (2019). Six Questions to Ask Any FBO about Their Fuel Handling Procedures [Image]. Retrieved from <https://www.duncanaviation.aero/intelligence/2019/December/six-questions-to-ask-any-fbo-about-their-fuel-handling-procedures>

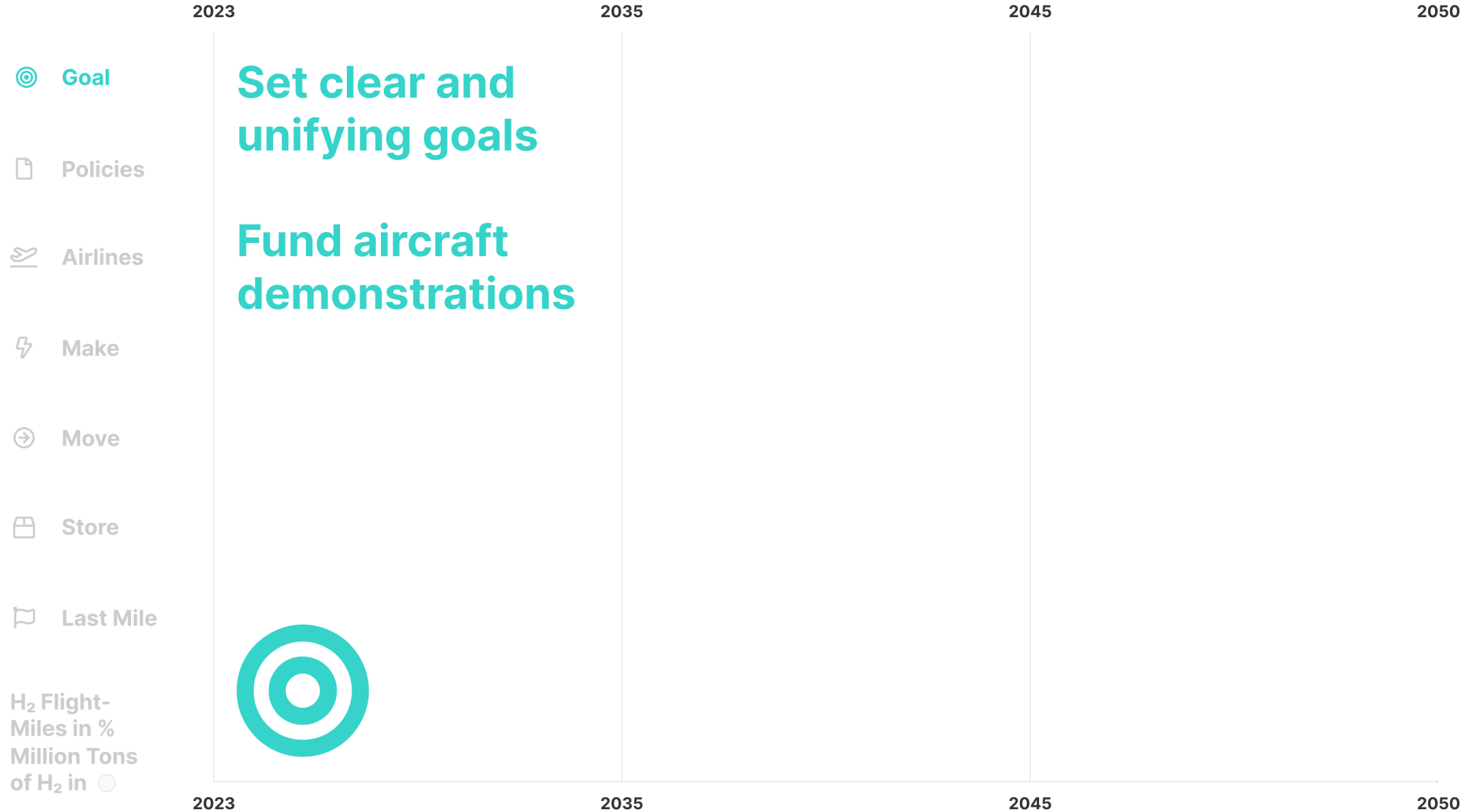


Wikimedia Foundation. (2023, May 6). Aviation fuel [Image]. Retrieved from https://en.wikipedia.org/wiki/Aviation_fuel

Timeline to Success



Timeline to Success



Timeline to Success

2023

2025

2030

2035




🎯 **Goal**

Set clear, unifying goals, fund demonstrations




Timeline to Success

	2023	2025	2030	2035
🎯 Goal	Set clear, unifying goals, fund demonstrations			
📄 Policies	Set clear, unifying goals	Fund demonstrations, permitting reform		






Timeline to Success

	2023	2025	2030	2035
 Goal	Set clear, unifying goals, fund demonstrations			
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 Airlines	Pre-commercial testing, FAA Airworthiness, demonstration stakeholder selected			







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 Make	DOE H2 hubs selected	Constructed, \$1/kg	Fully operational	








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 Store	Improvements in LH2 storage and liquefaction		H2 storage construction	

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 Last Mile			Trucks for delivery	

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 Last Mile			Trucks for delivery	
H₂ Flight-Miles in % Million Tons of H₂ in ○	2023	2025	2030	2035

Timeline to Success



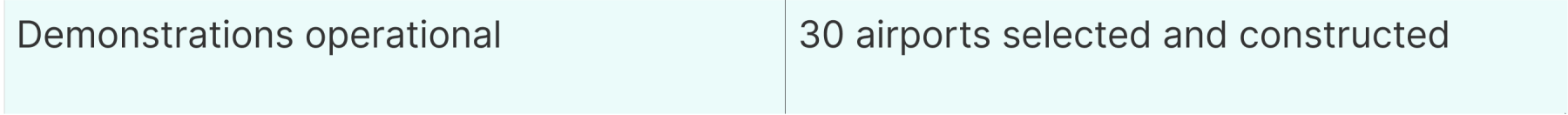
Timeline to Success

2035



2040

2045




🎯 Goal



Timeline to Success

	2035	2040	2045
 Goal	Demonstrations operational		30 airports selected and constructed
 Policies	Subsidies		Regulations






Timeline to Success

	2035	2040	2045
 Goal	Demonstrations operational	30 airports selected and constructed	
 Policies	Subsidies	Regulations	
 Airlines	More airlines use H2	Short and mid-range flights	







Timeline to Success

	2035	2040	2045
 Goal	Demonstrations operational	30 airports selected and constructed	
 Policies	Subsidies	Regulations	
 Airlines	More airlines use H2	Short and mid-range flights	
 Make	H2 hubs at full capacity	CCS fully commercialized	








Timeline to Success

	2035	2040	2045
 Goal	Demonstrations operational	30 airports selected and constructed	
 Policies	Subsidies	Regulations	
 Airlines	More airlines use H2	Short and mid-range flights	
 Make	H2 hubs at full capacity	CCS fully commercialized	
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Timeline to Success

	2035	2040	2045
 Goal	Demonstrations operational		30 airports selected and constructed
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 Airlines	More airlines use H2		Short and mid-range flights
 Make	H2 hubs at full capacity		CCS fully commercialized
 Move	More H2 pipelines and zero-emission trucking		
 Store	Airport H2 storage dispensing H2 to aircraft, GSE, and airport backup power		

Timeline to Success

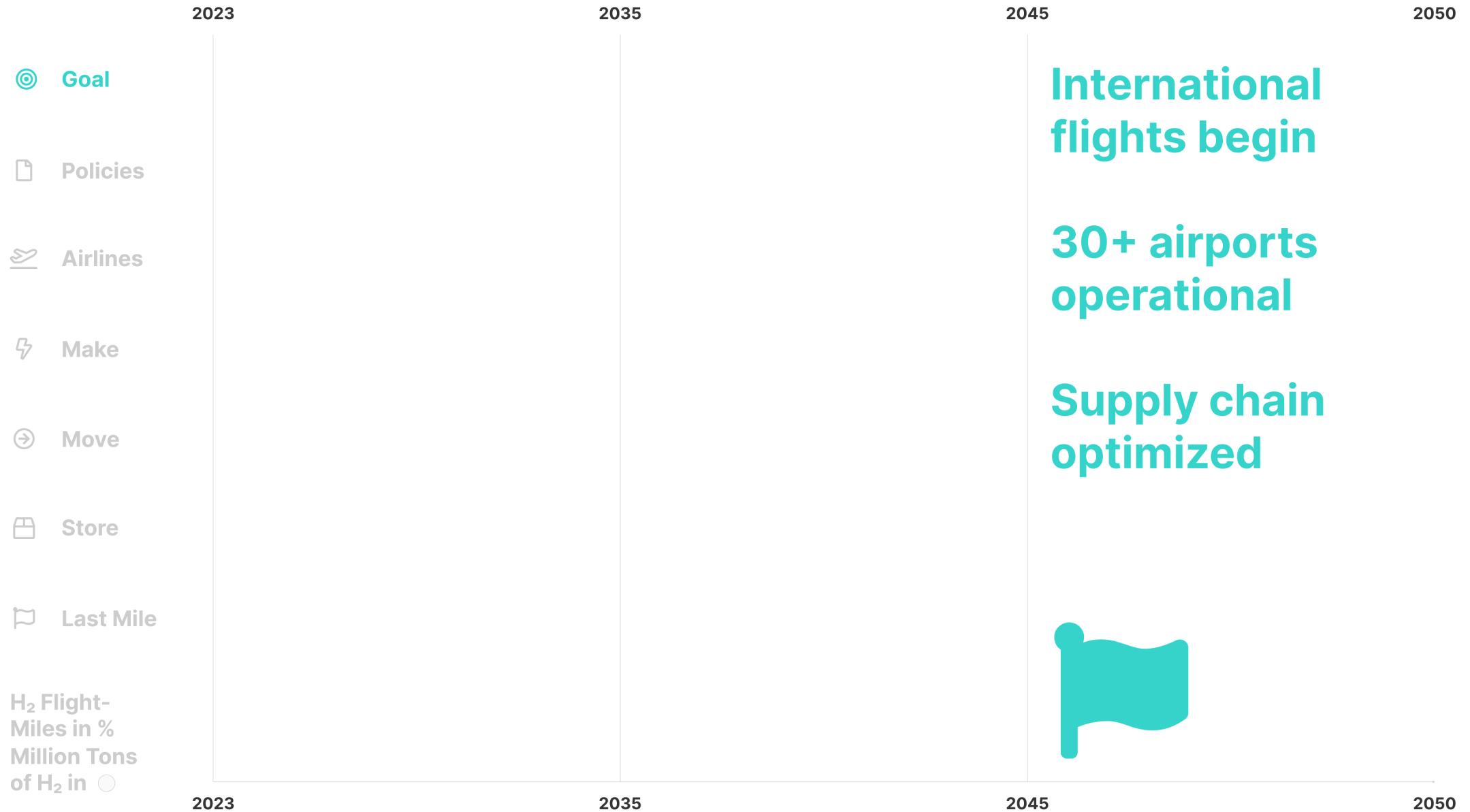
	2035	2040	2045
 Goal	Demonstrations operational		30 airports selected and constructed
 Policies	Subsidies		Regulations
 Airlines	More airlines use H2		Short and mid-range flights
 Make	H2 hubs at full capacity		CCS fully commercialized
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 Last Mile	Zero-emission trucks fueling airplanes		

Timeline to Success

	2035	2040	2045
Goal	Demonstrations operational		30 airports selected and constructed
Policies	Subsidies		Regulations
Airlines	More airlines use H2		Short and mid-range flights
Make	H2 hubs at full capacity		CCS fully commercialized
Move	More H2 pipelines and zero-emission trucking		
Store	Airport H2 storage dispensing H2 to aircraft, GSE, and airport backup power		
Last Mile	Zero-emission trucks fueling airplanes		



Timeline to Success



Timeline to Success

2045

2048

2050

🎯 Goal




International flights

30+ airports operational





Timeline to Success

	2045	2048	2050
🎯 Goal	International flights		30+ airports operational
📄 Policies	Achieve net zero aviation in the US		






Timeline to Success

	2045	2048	2050
 Goal	International flights		30+ airports operational
 Policies	Achieve net zero aviation in the US		
 Airlines	Hydrogen is able to serve a substantial portion of short and mid-range flights		







Timeline to Success

	2045	2048	2050
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 Policies	Achieve net zero aviation in the US		
 Airlines	Hydrogen is able to serve a substantial portion of short and mid-range flights		
 Make	H2 produced in sectors like aviation, industry, trucking, and shipping		








Timeline to Success

	2045	2048	2050
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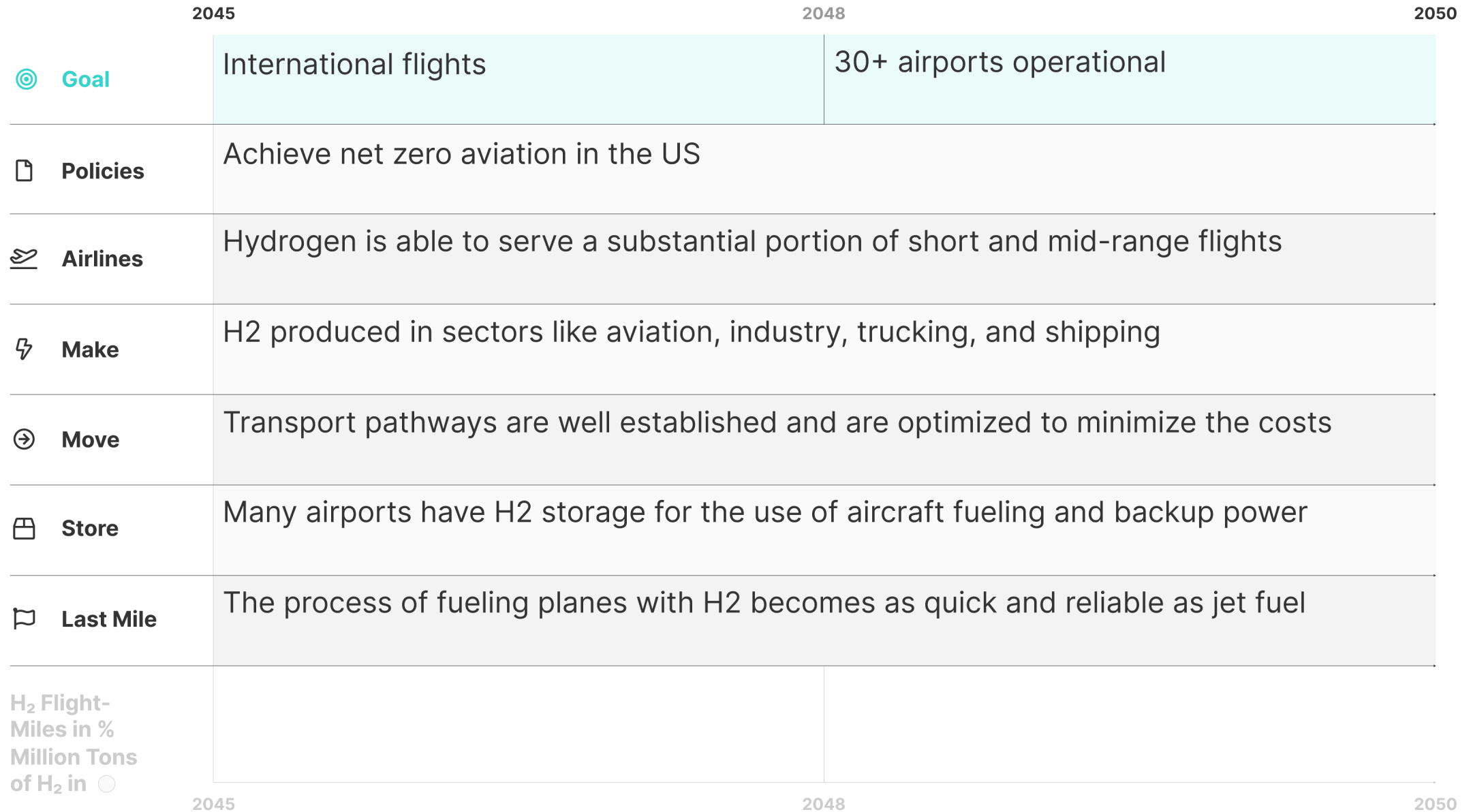
Timeline to Success

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 Make	H2 produced in sectors like aviation, industry, trucking, and shipping		
 Move	Transport pathways are well established and are optimized to minimize the costs		
 Store	Many airports have H2 storage for the use of aircraft fueling and backup power		

Timeline to Success

	2045	2048	2050
 Goal	International flights		30+ airports operational
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 Make	H2 produced in sectors like aviation, industry, trucking, and shipping		
 Move	Transport pathways are well established and are optimized to minimize the costs		
 Store	Many airports have H2 storage for the use of aircraft fueling and backup power		
 Last Mile	The process of fueling planes with H2 becomes as quick and reliable as jet fuel		

Timeline to Success



Optimization Model

Objective Function

$$\min(\alpha * E[C_r] + (1-\alpha) * E[E_r])$$

Optimization Model

Objective Function

$$\min(\alpha * E[C_r] + (1-\alpha) * E[E_r])$$

α is the preference weights

Optimization Model

Objective Function

$$\min(\alpha * E[C_r] + (1-\alpha) * E[E_r])$$

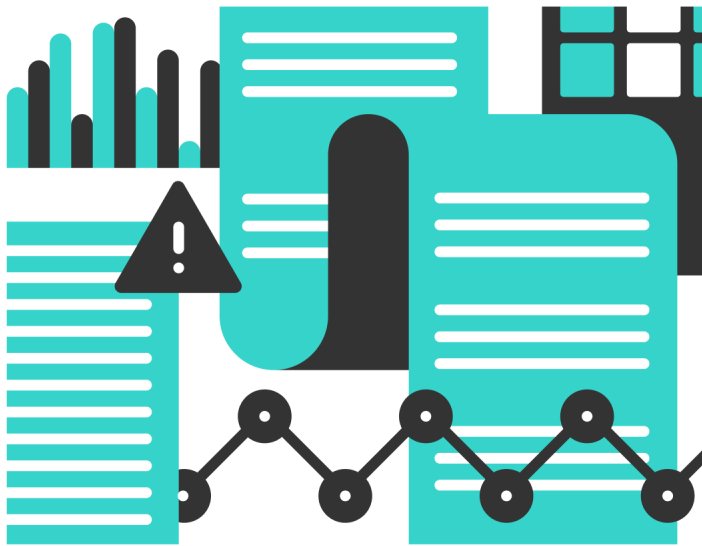
C is total cost across supply chain

E is total emissions across supply chain

r is the market capitalization scenario

Model Implications

POLICY INTERVENTION



TRUCKS/PIPELINES ARE NECESSARY



GREEN PRODUCTION



Model Implications

POLICY INTERVENTION



TRUCKS/PIPELINES ARE NECESSARY



GREEN PRODUCTION



Model Implications

POLICY INTERVENTION



TRUCKS/PIPELINES ARE NECESSARY



GREEN PRODUCTION

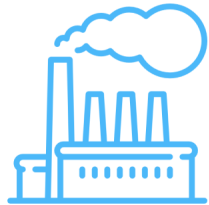


Key Barriers

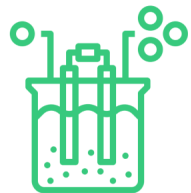
WATER



Nuclear
76-85 gallons/kg H₂



SMR with CCS
8-12 gallons/kg H₂



Electrolysis
19-28 gallons/kg H₂

PUBLIC PERCEPTION

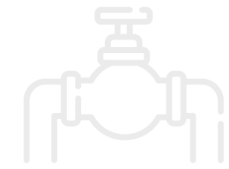


Library of Congress. (1937). Hindenburg disaster [Image]. Retrieved from https://commons.wikimedia.org/wiki/File:Hindenburg_disaster.jpg



Harrington, M. (2017). Block Island, R.I.: View of wind turbines, located three miles off the bluffs of Block Island, Rhode Island on September 9, 2017 [Image]. Retrieved from Getty Images website: <https://www.gettyimages.com/detail/news-photo/block-island-r-i-view-of-wind-turbines-located-three-miles-news-photo/845051694>

INFRASTRUCTURE



Pipeline
Strong resistance
Long construction timeline



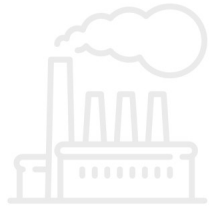
Truck
Increased congestion
Boil-off

Key Barriers

WATER



Nuclear
76-85 gallons/kg H₂



SMR with CCS
8-12 gallons/kg H₂



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PUBLIC PERCEPTION

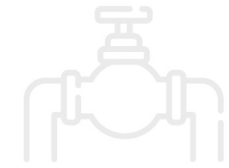


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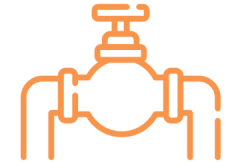


Library of Congress. (1937). Hindenburg disaster [Image]. Retrieved from https://commons.wikimedia.org/wiki/File:Hindenburg_disaster.jpg



Harrington, M. (2017). Block Island, R.I.: View of wind turbines, located three miles off the bluffs of Block Island, Rhode Island on September 9, 2017 [Image]. Retrieved from Getty Images website: <https://www.gettyimages.com/detail/news-photo/block-island-r-i-view-of-wind-turbines-located-three-miles-news-photo/845051694>

INFRASTRUCTURE



Pipeline
Strong resistance
Long construction timeline



Truck
Increased congestion
Boil-off

Safety

HYDROGEN

- ✓ Non-toxic and not carcinogenic
- ✓ Disperses into atmosphere upon spill
- ✓ High temperatures and oxygen levels to ignite
- ✓ Flames burn up

JET FUEL

- ✗ Can be carcinogenic through direct contact
- ✗ Can contaminate groundwater upon spill
- ✗ Ignites at lower temperatures and oxygen levels
- ✗ Flames burn circumferentially

Safety

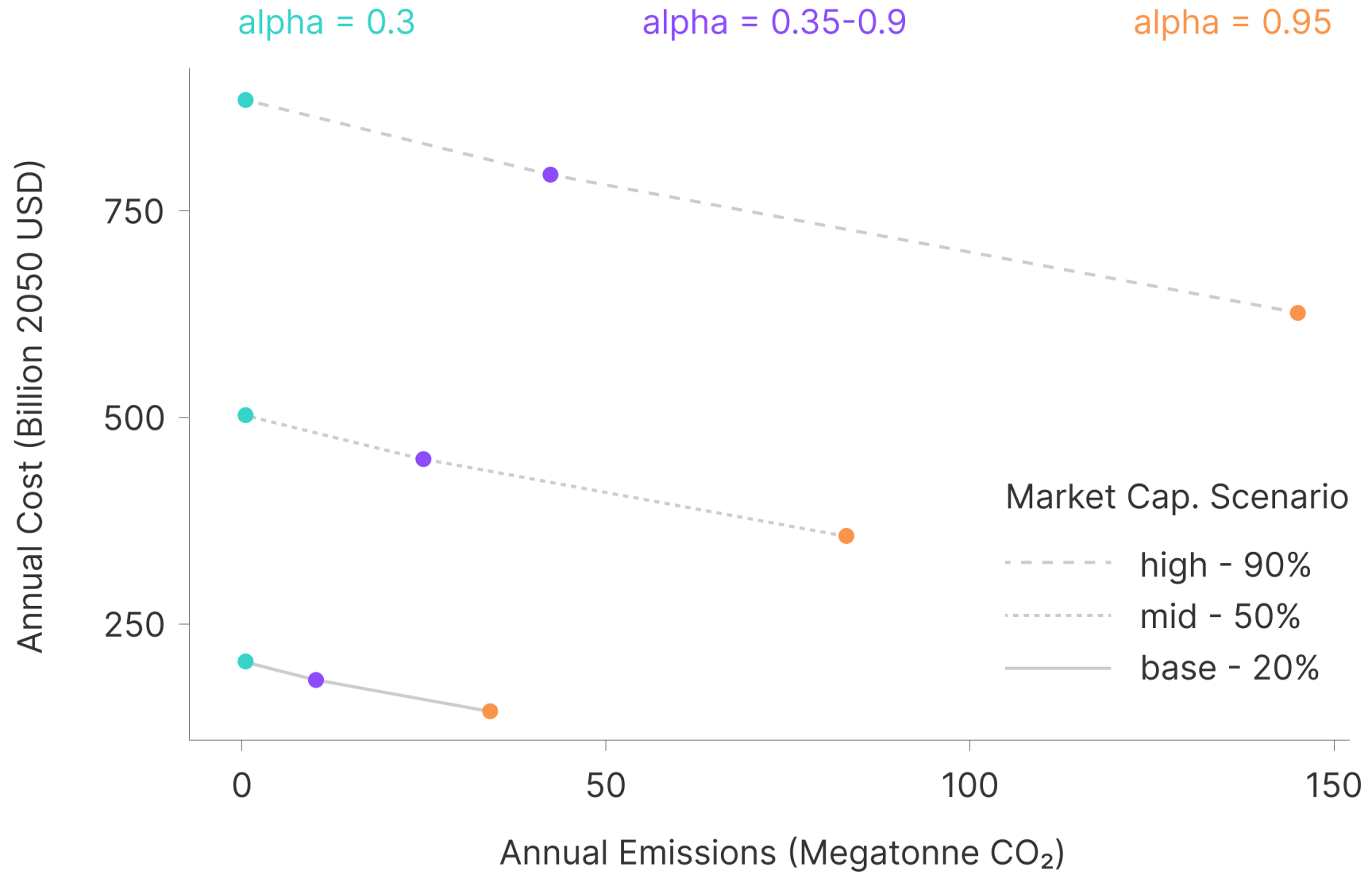
HYDROGEN

- ✓ Non-toxic and not carcinogenic
- ✓ Disperses into atmosphere upon spill
- ✓ High temperatures and oxygen levels to ignite
- ✓ Flames burn up
- ✗ Leaks easily
- ✗ Flames nearly invisible in daylight

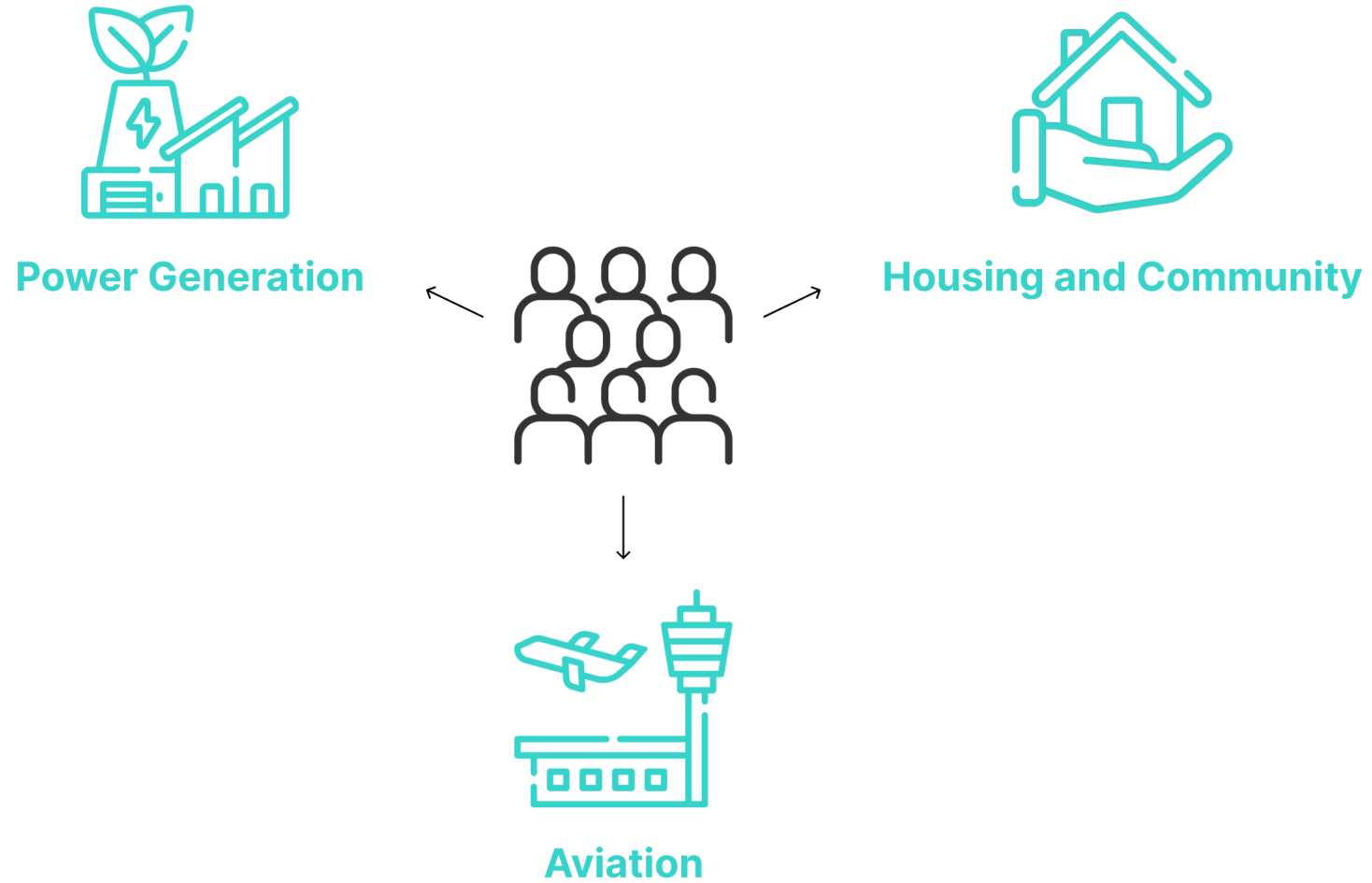
JET FUEL

- ✗ Can be carcinogenic through direct contact
- ✗ Can contaminate groundwater upon spill
- ✗ Ignites at lower temperatures and oxygen levels
- ✗ Flames burn circumferentially

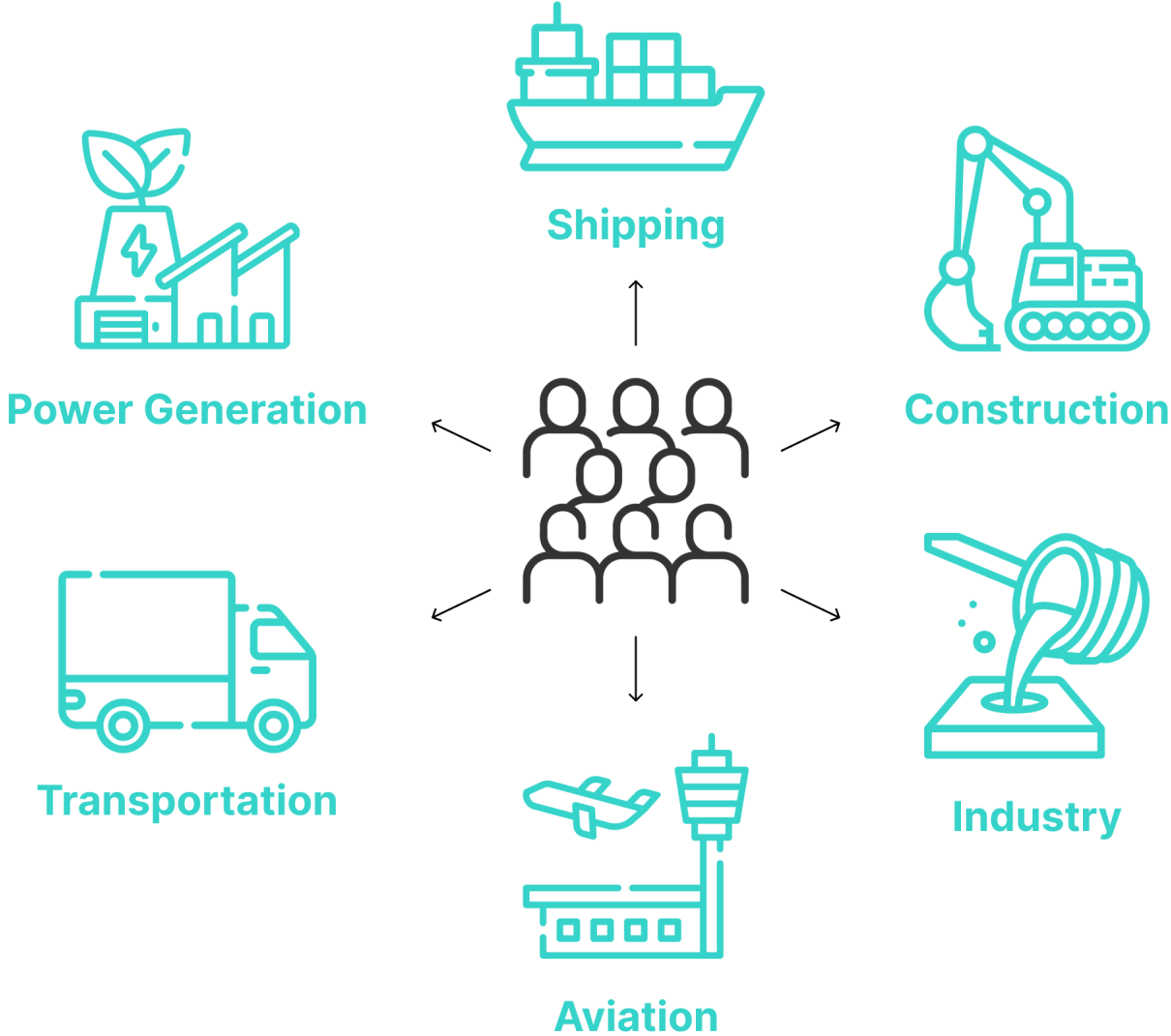
Special attention needed to ensure H₂ offers environmental justice



Emissions Reductions and Environmental Justice



Green Jobs





H₂

N330EN

Univers
Hydrogen



THANK YOU



Jon Gordon



Jaih Hunter-Hill



Anna Cobb



Xiaohan Wu



Dorothy Li

Appendix: Energy-Equivalent Fuel Production Emissions Values

Average H₂ Demand per airport: 232,182,767.9 kg

Fuel Type	Green H ₂	Pink H ₂	Blue H ₂	Jet A Fuel	
CO ₂ Emissions of Production [kg CO ₂ /kg fuel]	0	0.288 ²	0.988 ³	1.404 ⁴	
Cost with IRA [\$ /kg]	2.76 ¹	2.14 ²	1.008 ³	1.45 ^{5,*}	3.17 ^{5,*}

*in units of \$/gal. Also, representative of a low and high cost scenario

Citations:

[1] Lazard. (2021, October). Lazard's levelized cost of hydrogen analysis, version 2.0 [PDF file]. Retrieved from <https://www.lazard.com/media/erzb5rkv/lazards-levelized-cost-of-hydrogen-analysis-version-20-vf.pdf>

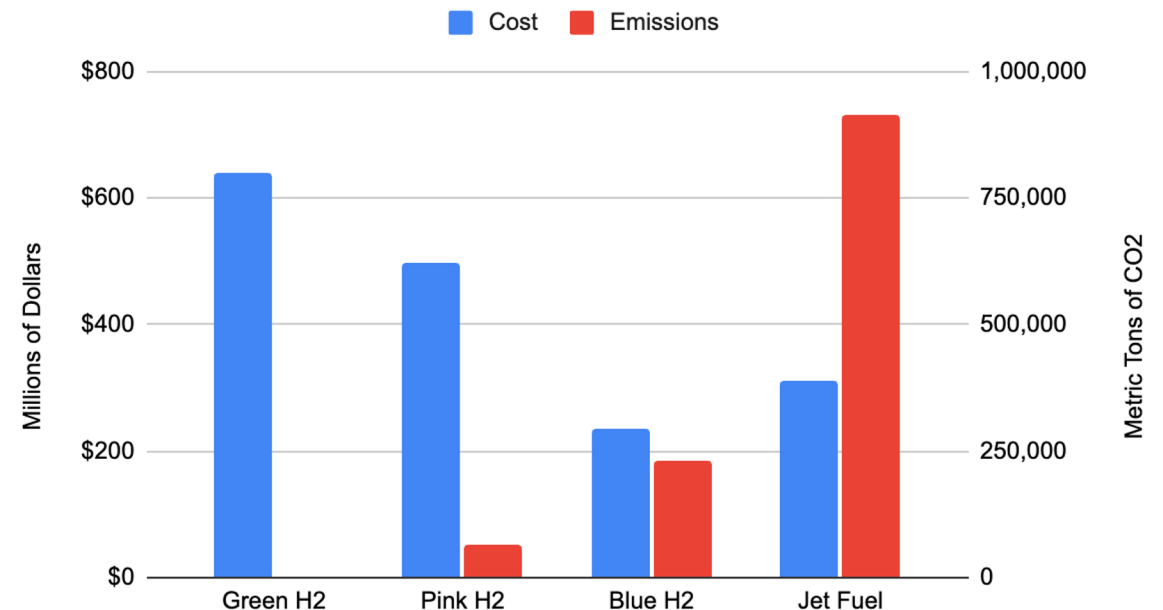
[2] Idaho National Laboratory. (2016). Characterization of alternative fuel blends [PDF file]. Retrieved from <https://inldigitallibrary.inl.gov/sites/sti/sti/4886652.pdf>

[3] Collodi, G., Azzaro, G., Ferrari, N., & Santos, S. (2017). Techno-economic Evaluation of Deploying CCS in SMR Based Merchant H₂ Production with NG as Feedstock and Fuel. Energy Procedia, 114, 2690-2712. <https://doi.org/10.1016/j.egypro.2017.03.1533>

[4] Jing, L., El-Houjeiri, H.M., Monfort, JC. et al. Understanding variability in petroleum jet fuel life cycle greenhouse gas emissions to inform aviation decarbonization. Nat Commun 13, 7853 (2022). <https://doi.org/10.1038/s41467-022-35392-1>

[5]

Cost and Emissions of Energy-Equivalent Quantities of Fuel



Appendix: Transportation Emissions

Transport Type	Variable	Units	Value
Newly Constructed Pipeline (36" Diameter)	Pipeline capacity (flow rate)	kg/s	69.54 ¹
	Pipeline operating power	kWh/mile	162.00 ¹
Class 8 Electric Truck	"Fuel" Economy	kWh/mile	2.00 ²
Class 8 Diesel Truck	Fuel Economy	km/liter	2.6 ³
	Diesel Combustion Emissions	g CO ₂ /MJ	74.00 ³

Grid Region (corresponds to H ₂ Hubs)	Projected 2050 Emissions [kg CO ₂ /kWh] ⁴
California	0.009
Washington	0.007
Colorado	0.01
Georgia	0.009
Illinois	0.008
Texas	0.009
Pennsylvania	0.009
New York	0.008

Citations:

- [1] DeSantis, D., James, B. D., Houchins, C., Saur, G., & Lyubovsky, M. (2021). Cost of long-distance energy transmission by different carriers. *iScience*, 24(12), 103495. <https://doi.org/10.1016/j.isci.2021.103495>
- [2] Gordon, J., LeCroy, C., Latif, B., Ichien, D., Arora, M., Johnson, K., Kailas, A., Fenton, D., & Brandis, K. (2022). The Zero-Emission Freight Revolution: California Case Studies. In 35th International Electric Vehicle Symposium and Exhibition (EVS35), Oslo, Norway, June 11-15, 2022.
- [3] Argonne National Laboratory. (n.d.). HDSAM: Hydrogen Demand and Supply Analysis Model. Retrieved from <https://hdsam.es.anl.gov/index.php?content=hdsam>
- [4] U.S. Energy Information Administration. (n.d.). State energy-related carbon dioxide emissions. Retrieved from <https://www.eia.gov/environment/emissions/state/>

Appendix: Transportation Costs

Transport Type	Variable Description	Units	Value
Newly Constructed Pipeline	CAPEX	\$/mile	1,380,000 ¹
	OPEX	\$/mile/year	138,000 ¹
Diesel Truck	CAPEX	\$/truck	1,065,000 ²
	OPEX	\$/truck/year	89,106.42 ²
Battery Electric Truck	CAPEX	\$/truck	1,300,000 ^{2,3}
	OPEX	\$/truck/year	67,143.57 ^{2,3}
	time cost of charging	minutes/mile	1.44 ³

Citations:

- [1] DeSantis, D., James, B. D., Houchins, C., Saur, G., & Lyubovsky, M. (2021). Cost of long-distance energy transmission by different carriers. *iScience*, 24(12), 103495. <https://doi.org/10.1016/j.isci.2021.103495>
- [2] Argonne National Laboratory. (n.d.). HDSAM: Hydrogen Demand and Supply Analysis Model. Retrieved from <https://hdsam.es.anl.gov/index.php?content=hdsam>
- [3] Gordon, J., LeCroy, C., Latif, B., Ichien, D., Arora, M., Johnson, K., Kailas, A., Fenton, D., & Brandis, K. (2022). The Zero-Emission Freight Revolution: California Case Studies. In 35th International Electric Vehicle Symposium and Exhibition (EVS35), Oslo, Norway, June 11-15, 2022.

$$\text{number of trucks} = \frac{\text{number of trips} * \text{round trip distance [miles]}}{\text{max yearly mileage [miles]}}$$

where:

$$\text{number of trips} = \frac{H_2 \text{ Demanded [kg]}}{\text{truck capacity [kg]}}$$

Appendix: Storage Emissions

Energy consumption per storage tank (comes from cryogenic pump): 1,375 kWh (annual)¹ Citations:

Grid Region (corresponds to H ₂ Hubs)	Projected 2050 Emissions [kg CO ₂ /kWh] ²
California	0.009
Washington	0.007
Colorado	0.01
Georgia	0.009
Illinois	0.008
Texas	0.009
Pennsylvania	0.009
New York	0.008

[1] Argonne National Laboratory. (n.d.). HDSAM: Hydrogen Demand and Supply Analysis Model. Retrieved from <https://hdsam.es.anl.gov/index.php?content=hdsam>

[2] U.S. Energy Information Administration. (n.d.). State energy-related carbon dioxide emissions. Retrieved from <https://www.eia.gov/environment/emissions/state/>

Appendix: H₂ Aircraft Design & Ranges

Company	Aircraft Design	Propulsion Type	Range	Notes
Universal H2 [1]	ATR72 & De Havilland Canada Dash-8	fuel cell electric	>600 nm	conversion kit
ZeroAvia [2]	9-19 seat	fuel cell electric	300 nm	by 2025
	40-80 seat		1,000 nm	by 2027
Airbus ZEROe [3]	Turboprop (<100 seats)	hybrid (combustion + fuel cells)	1,000+ nm	
	Blended-Wing Body		2,000+ nm	
	Turbofan			
H2FLY [4]	“Regional Aircraft” (40 seats)	fuel cell electric	1,080+ nm	

Citations:

- [1] Universal Hydrogen. (2023). Product. Universal Hydrogen Co. Retrieved May 26, 2023, from <https://hydrogen.aero/product/>
- [2] ZeroAvia. (2023). Home. ZeroAvia. Retrieved May 26, 2023, from <https://www.zeroavia.com/>
- [3] Airbus. (2023). Zero-Emission Aircraft: ZEROe. Airbus. Retrieved May 26, 2023, from <https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe>
- [4] H2Fly. (2023). Company. H2Fly. Retrieved May 26, 2023, from <https://www.h2fly.de/company>

Appendix: Dominant Method of Hydrogen Production as a Function of Preference Weights



Appendix: Modes of Transportation as a Function of Preference Weights

