

Considerations for Commercial Adoption of Cryogenic Hydrogen for Propulsion Applications



CEC/ICMC 2023

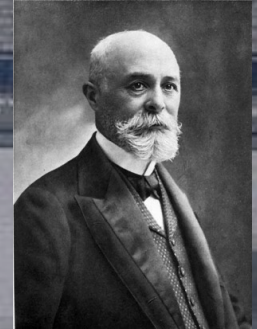
Ref: M2Or1D-03

Jim Fritz

11 July 2023

1883 - FIRST ROOFTOP SOLAR ARRAY

Demonstrated by Charles Fritts in New York City

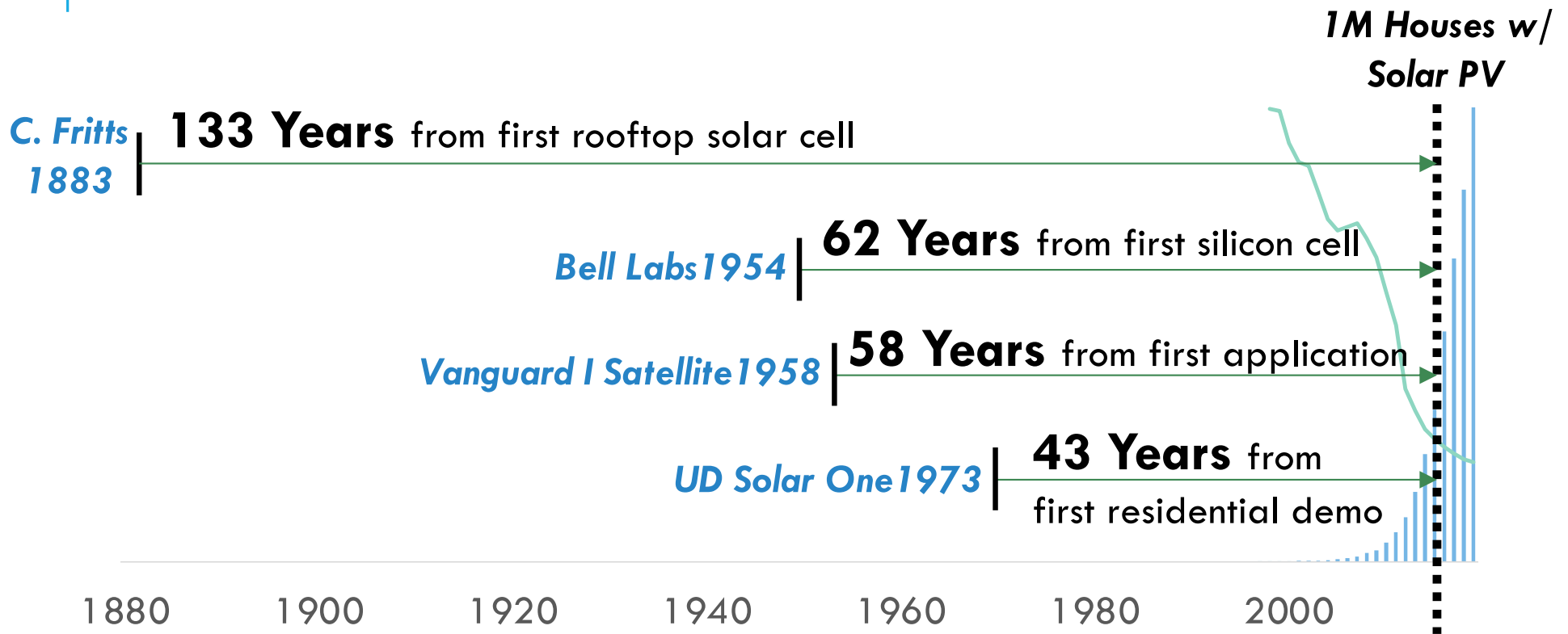


An aerial photograph of a suburban residential neighborhood. The houses are densely packed, and many of them have blue solar panels installed on their roofs. The houses are surrounded by green trees and lawns. In the background, there are more houses and some commercial buildings under a blue sky with scattered white clouds. The text is overlaid on the top half of the image.

2016 - ONE MILLION SOLAR ROOFTOP ARRAYS

133 Years from >TRL1 to reach one million adopters

GETTING TO EARLY ADOPTER – THE PV TIMELINE

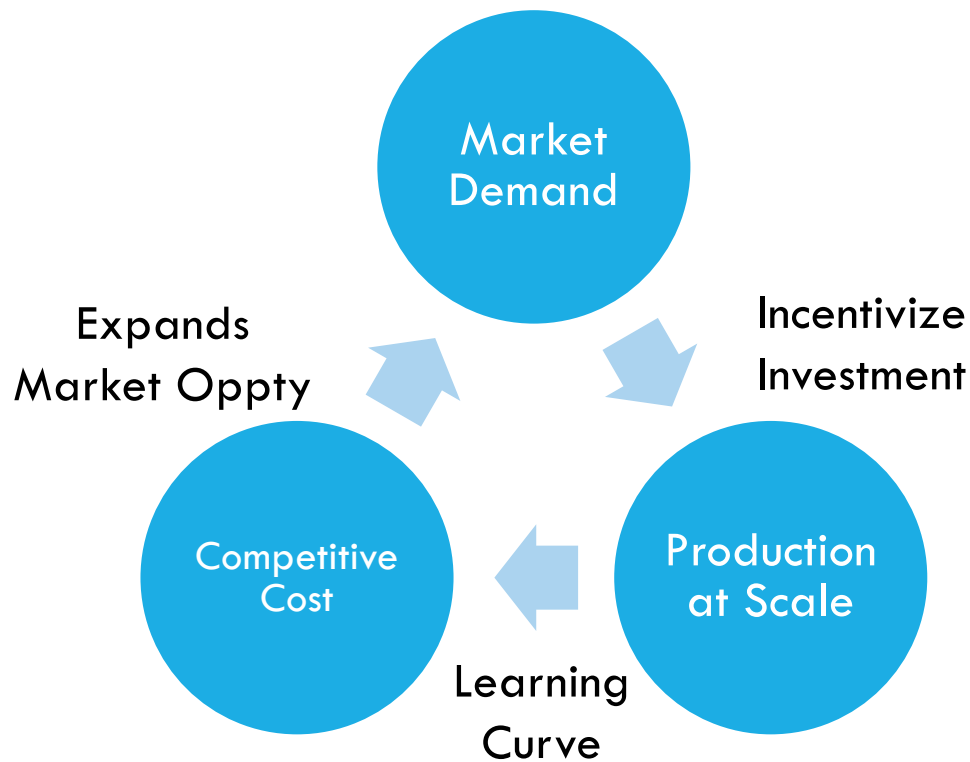


DO WE HAVE 133 YEARS TO DEPLOY?

...the technological advances that will be needed demand a step change in both the speed at which innovation occurs and the scale at which new technologies are deployed.*”

Roughly three-quarters of the cumulative reductions needed by 2050 come from technologies that have not yet reached maturity.

THE COMMERCIALIZATION DILEMMA.

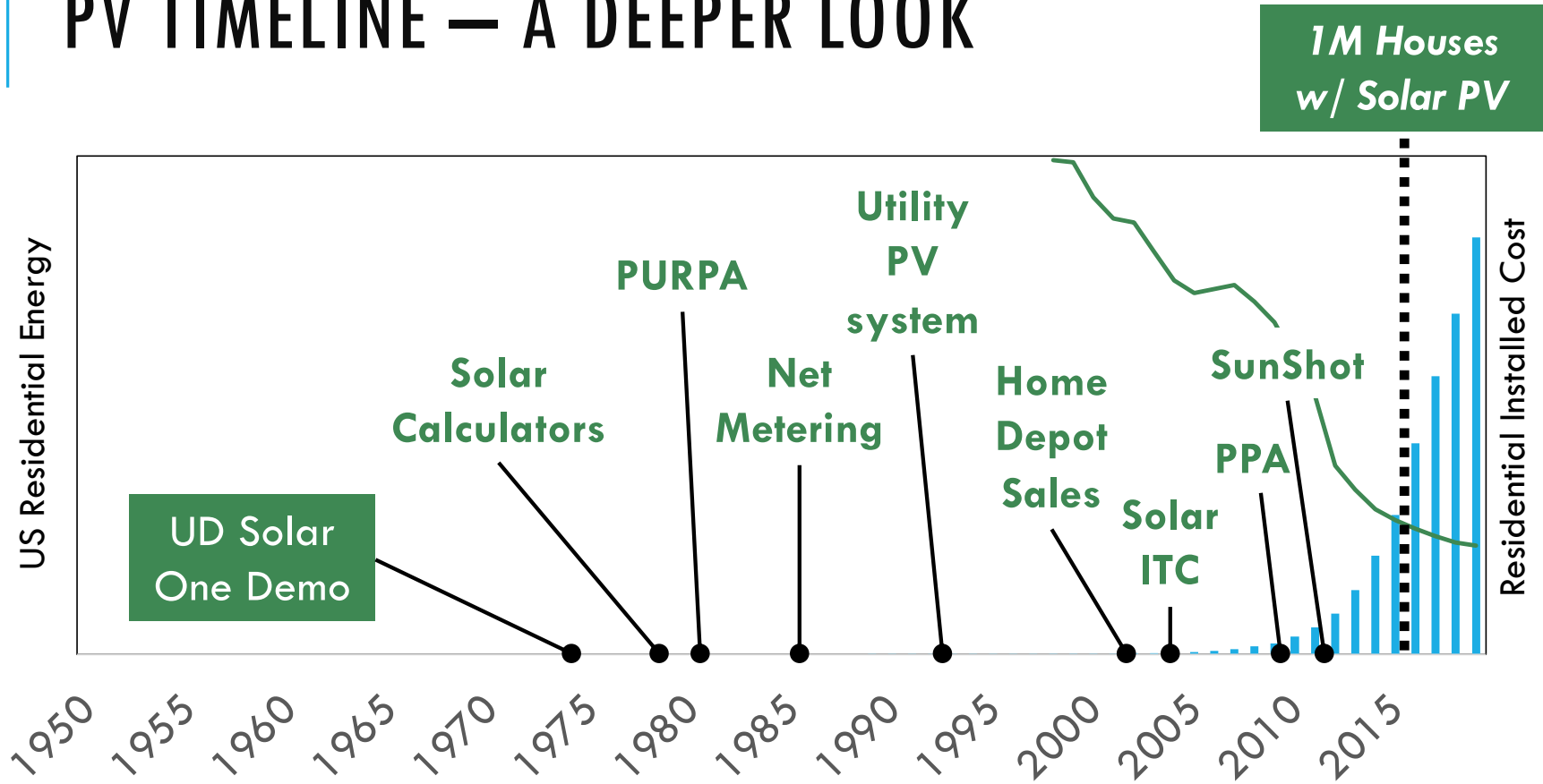


Widescale Adoption Requires
Cost Competitiveness.

Cost Competitiveness
Requires Production at Scale.

Production at Scale Requires
Demand in the Market.

PV TIMELINE – A DEEPER LOOK



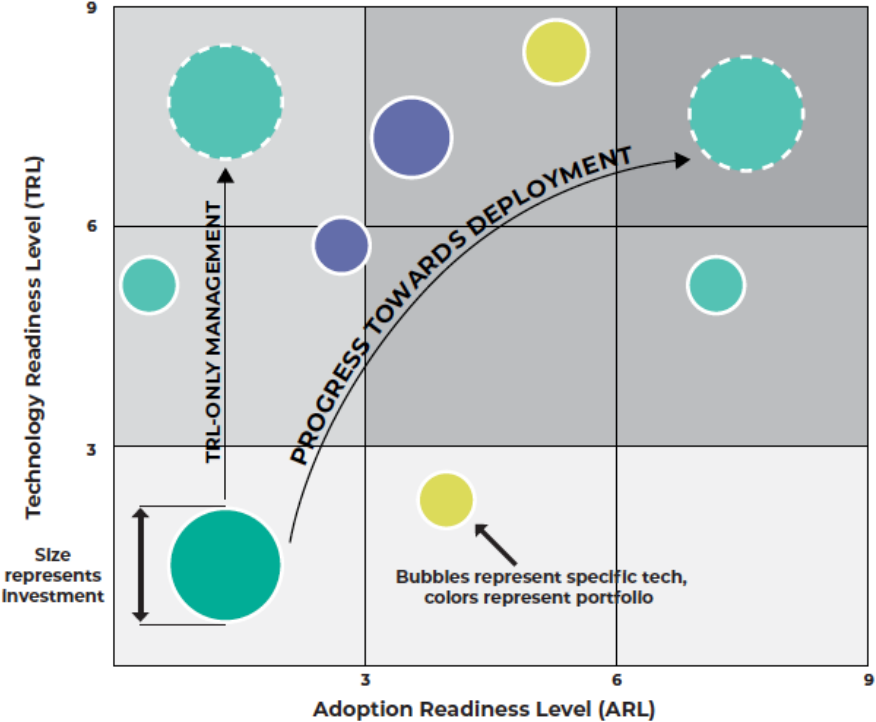
Data shown for total US residential solar PV energy generated (blue bar) and cost per KW (green line)

ASSESSING MARKET READINESS: COMMERCIAL ADOPTION READINESS ASSESSMENT TOOL (CARAT)

CARAT can be used to:

- Discover barriers
- Structure discussions
- Compare challenges

https://www.energy.gov/sites/default/files/2023-03/CARAT-R9_3-22-23.pdf



CARAT RUBRIC HIGHLIGHTS 17 DIMENSIONS



SCOPE OF LH2 PROPULSION (PRELIM) ASSESSMENT



Rail



Trucking

The application of cryogenic (liquid) H₂ for propulsion in traditional hard-to-abate aviation, shipping, rail, and long haul trucking sectors.

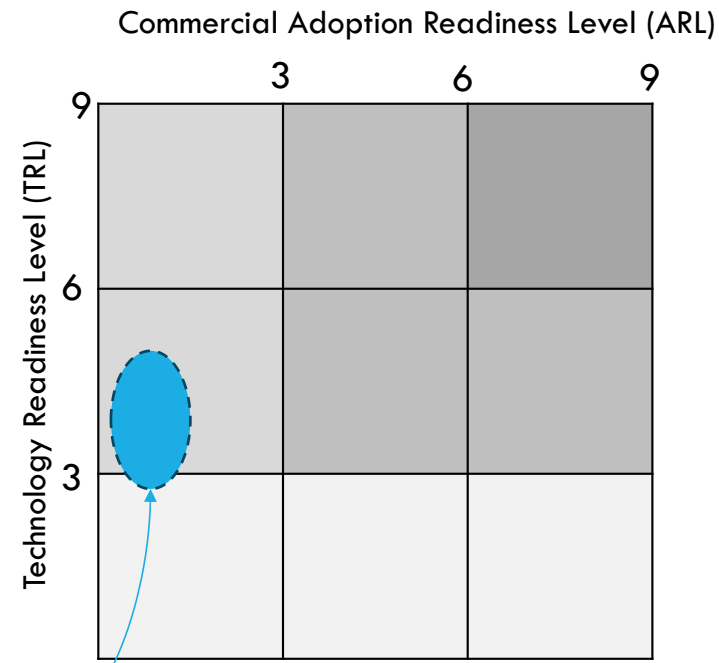
Shipping



Aviation

LH2 FOR PROPULSION: PRELIMINARY ADOPTION READINESS ASSESSMENT

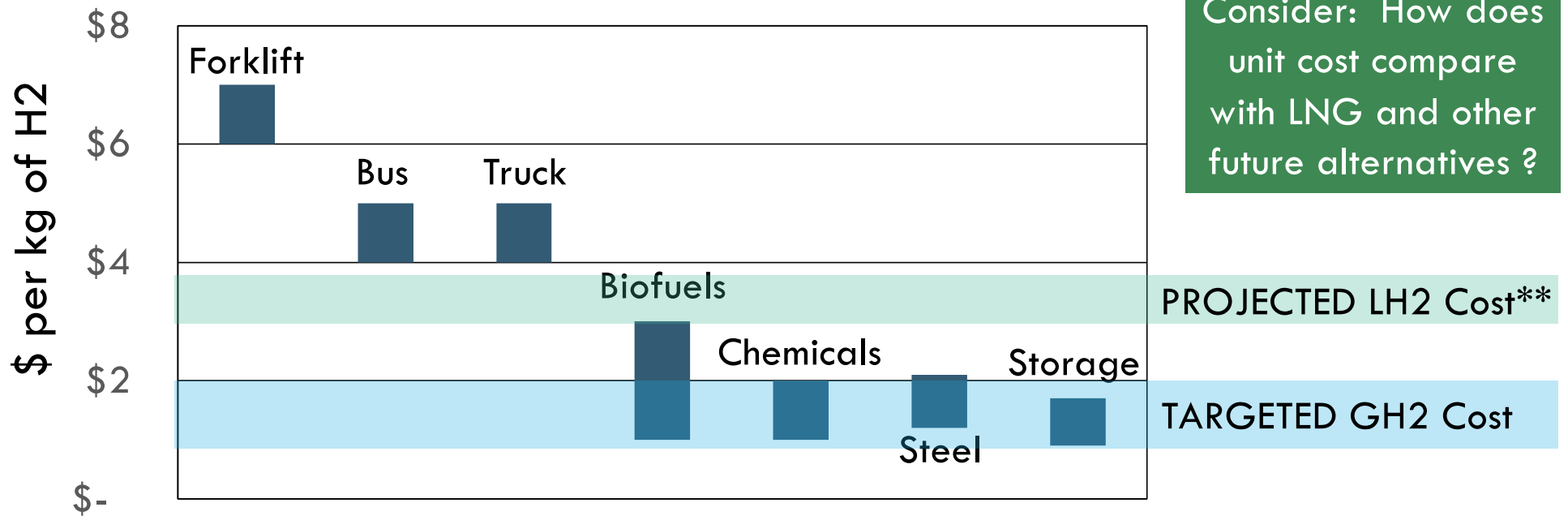
| | | No. of High Risk Dimensions | | | | | | | | |
|-------------------------------|----|-----------------------------|---|---|---|---|---|---|---|----|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8+ |
| No. of Medium Risk Dimensions | 0 | 9 | 8 | 7 | 5 | 3 | 1 | 1 | 1 | 1 |
| | 1 | 8 | 7 | 6 | 4 | 2 | 1 | 1 | 1 | 1 |
| | 2 | 8 | 7 | 6 | 4 | 2 | 1 | 1 | 1 | 1 |
| | 3 | 7 | 6 | 5 | 3 | 1 | 1 | 1 | 1 | 1 |
| | 4 | 7 | 6 | 5 | 3 | 1 | 1 | 1 | 1 | 1 |
| | 5 | 6 | 5 | 4 | 2 | 1 | 1 | 1 | 1 | 1 |
| | 6 | 5 | 4 | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 7 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 8+ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |



Low
Acceptance
Readiness,
Value is in
*Discovering
Barriers &
Opportunities*

VALUE PROPOSITION – CAN LH2 WIN ON COST?

Willingness to Pay*, \$/kg H₂



Consider: How does unit cost compare with LNG and other future alternatives?

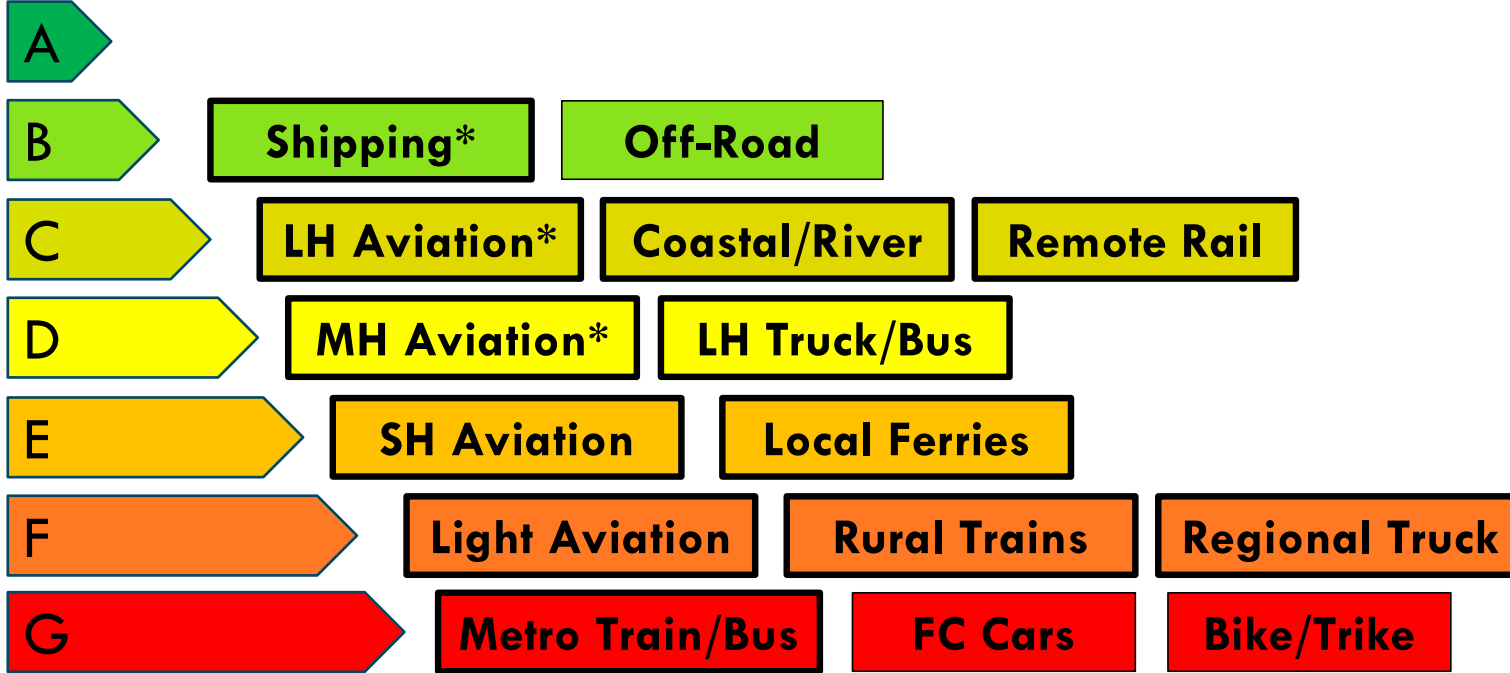
*U.S Department of Energy, "U.S. National Clean Hydrogen Strategy and Roadmap," June, 2023 (Figure 10, page 19)

**Hydrogen Council, "Hydrogen Insights," Feb 2021; page 23 of <https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf>

VALUE PROPOSITION: CAN LH2 WIN ON PERFORMANCE?

LIEBREICH'S CLEAN HYDROGEN LADDER

UNAVOIDABLE



UNCOMPETITIVE

* Via Ammonia or e-fuel, not GH2 or LH2

Ammonia or e-fuel wins



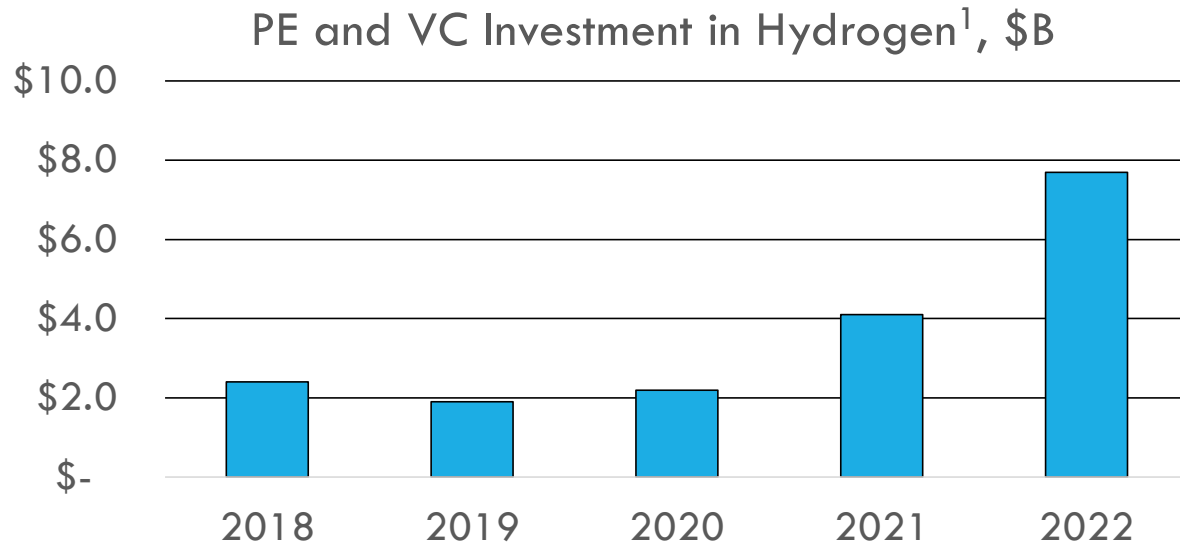
Opportunity?



Electrification wins

**Published Leibreich graphic modified to merge both Aviation & Shipping ladder with Road Transportation ladder
 SOURCE: Liebreich Associates (Concept credit: Adrian Hiel/Energy Cities)

RESOURCE MATURITY: IS INVESTMENT FLOWING?



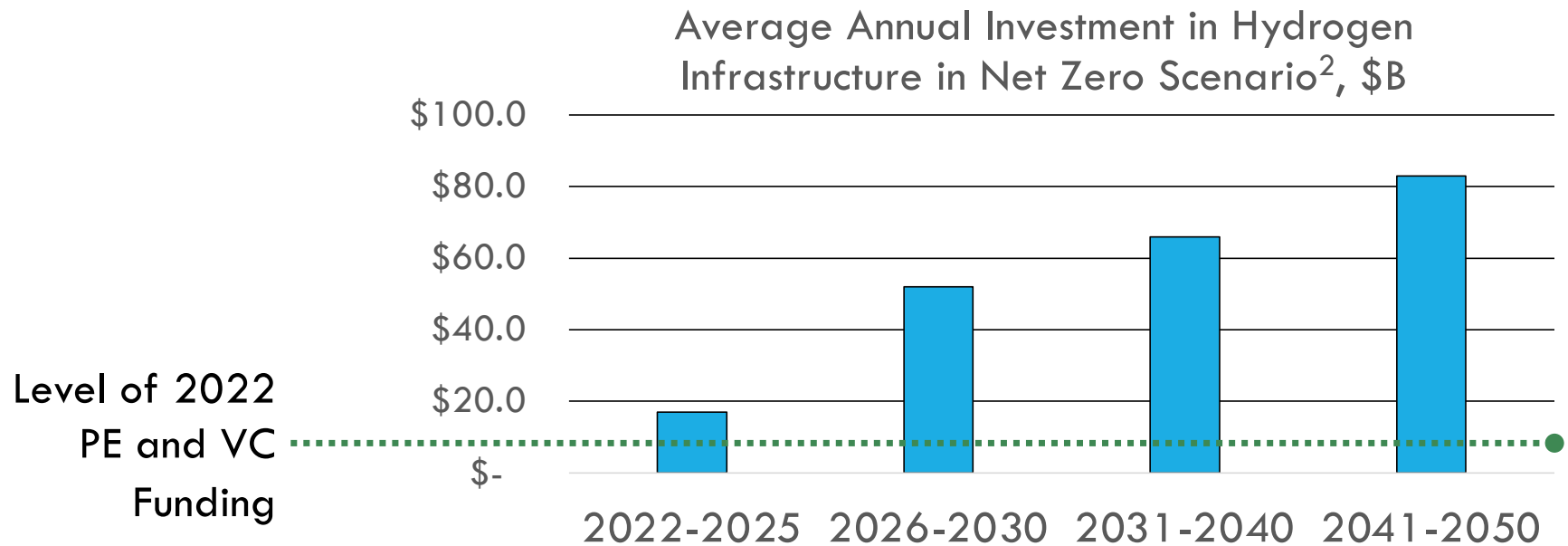
Nearly 4X Growth in
Venture Capital and
Private Equity Funding
to Hydrogen From
2020 - 2022

Consider: What are the full investments required and where will they come from?

¹The Economist, "Can a viable industry emerge from the hydrogen shakeout" 3 July 2023

²IEA 2023; ETP 2023, <https://www.iea.org/data-and-statistics/charts/average-annual-global-investment-in-hydrogen-and-natural-gas-infrastructure-in-the-net-zero-scenario-2016-2050>, License: CC BY 4.0

RESOURCE MATURITY: WILL INVESTMENT SCALE?

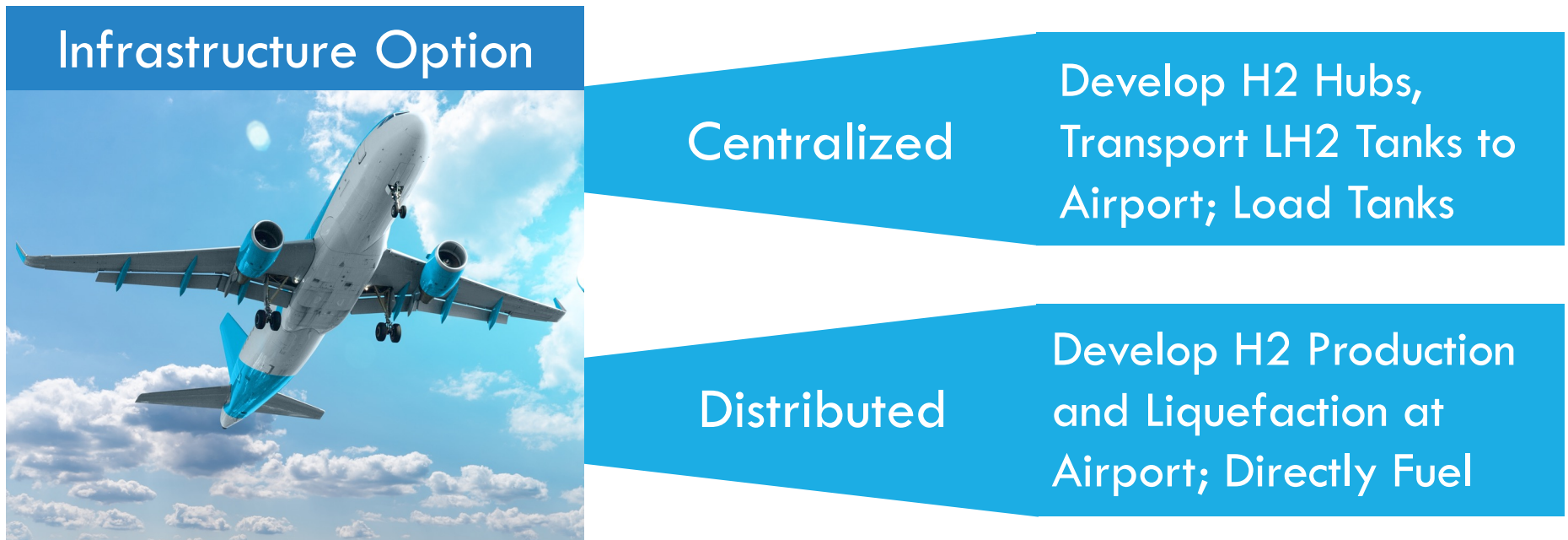


Consider: How Much Infrastructure Investment Required?

¹The Economist, "Can a viable industry emerge from the hydrogen shakeout" 3 July 2023

²IEA 2023; ETP 2023, <https://www.iea.org/data-and-statistics/charts/average-annual-global-investment-in-hydrogen-and-natural-gas-infrastructure-in-the-net-zero-scenario-2016-2050>, License: CC BY 4.0

RESOURCE MATURITY: INFRASTRUCTURE OPTIONS?

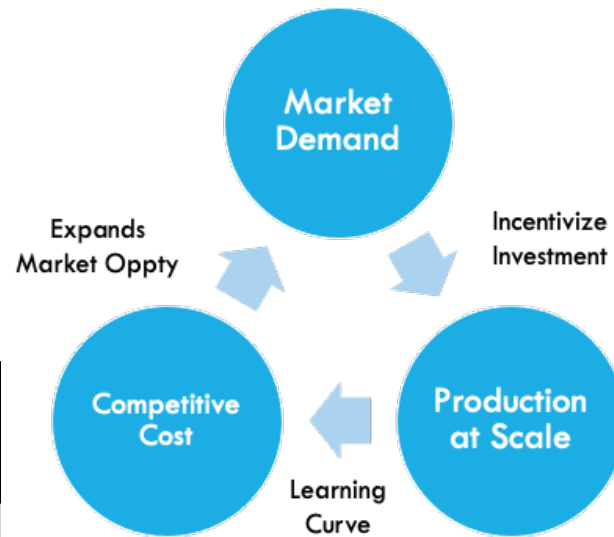


Consider: How Will Infrastructure Decisions Advance?

LICENSE TO OPERATE: IS POLICY SUPPORTIVE?

Consider: Will policy interventions enable market traction?

Up to \$3.00/kg PTC through IRA



H2 Demand, \$1B announced

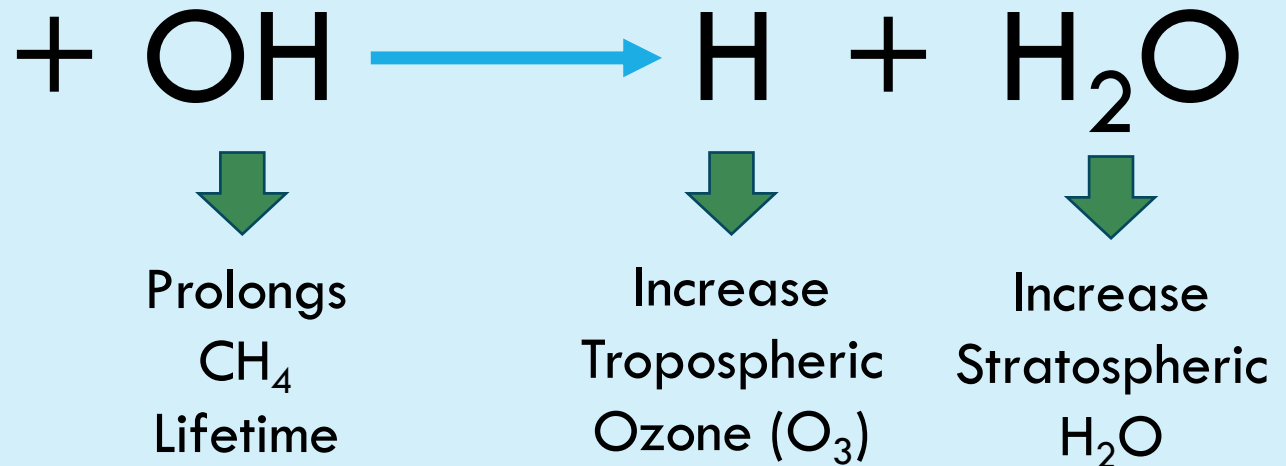


\$8B Hubs - BIL; LPO \$400B Auth



LICENSE TO OPERATE: IS THERE ENVIRONMENTAL RISK?

LEAKAGE



Consider: How Will Regulators Address Safety and Environmental Risks?

WRAP-UP:
WILL THE MARKET BE READY WHEN THE TECHNOLOGY IS?

Commercialization as a Continuum

Time is Tight – Look Ahead

Complex LH₂ Landscape - Much to Consider

DISCUSSION



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