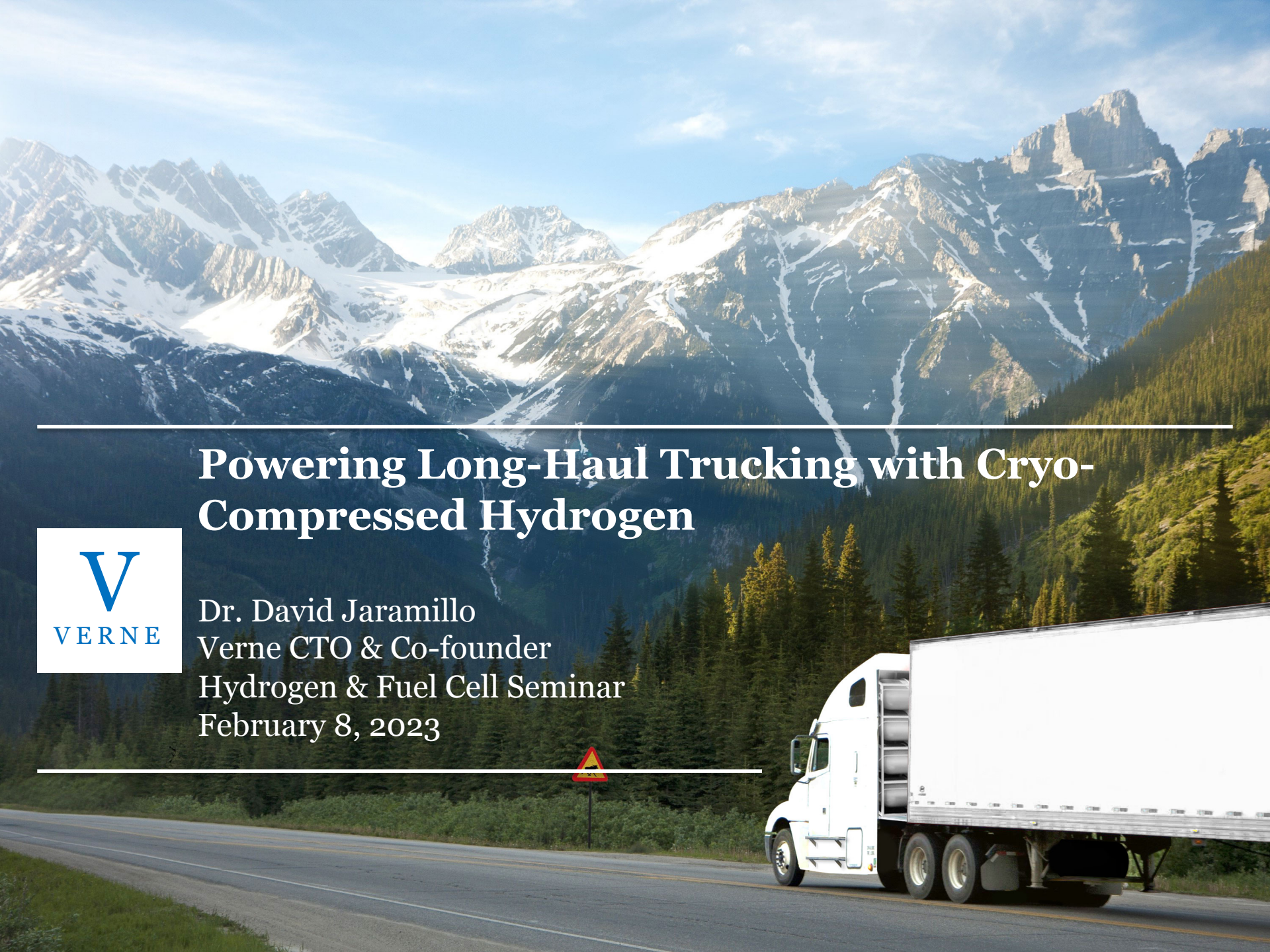


Powering Long-Haul Trucking with Cryo-Compressed Hydrogen

VERNE

Dr. David Jaramillo
Verne CTO & Co-founder
Hydrogen & Fuel Cell Seminar
February 8, 2023


40% of heavy duty trucks are
long-haul or weight limited

Hydrogen is a zero-emission solution

All major truck companies have hydrogen pilots

DAIMLER · VOLVO · TRATON · IVECO · PACCAR · Cummins · HYUNDAI · TOYOTA · HINO · HYZON · NIKOLA

Leading fleets support hydrogen

amazon · Walmart · Anheuser-Busch · pepsi · TTSI · U.S. XPRESS · PGT INC. The Proud Professionals TRUCKING · J.B. HUNT · ups

according to industry leaders

Compressed H_2 storage is available today and has allowed early deployments

Kenworth Toyota in LA

- **300-mile** range and 60 kg of H_2
- 700 bar storage and refueling
- 10 trucks

Hyundai in Switzerland

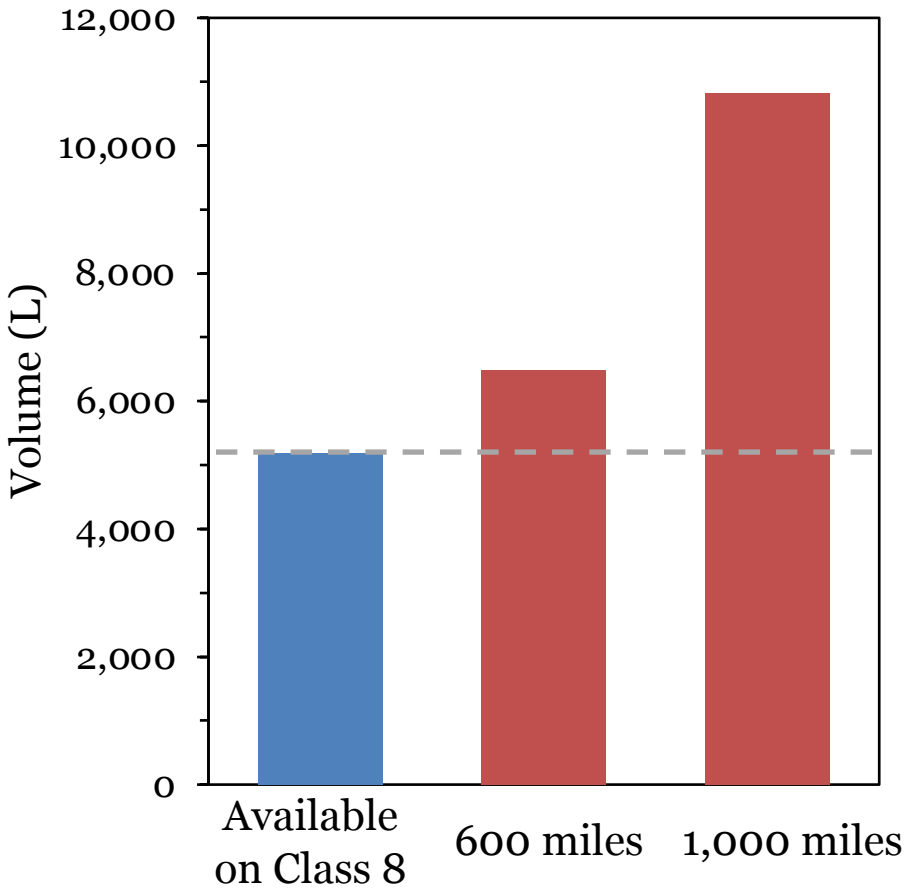
- **250-mile** range and 31 kg of H_2
- 350 bar storage and refueling
- 50 trucks

Early demonstrations have not met long-haul needs

VERNE Images from pressroom.toyota.com and fleetmaintence.com

700 bar doesn't meet volumetric energy densities for long-haul trucking

Volume available and volume needed



Back-of-cab 700 bar storage system

700 bar storage does not meet 500+ miles range for long-haul

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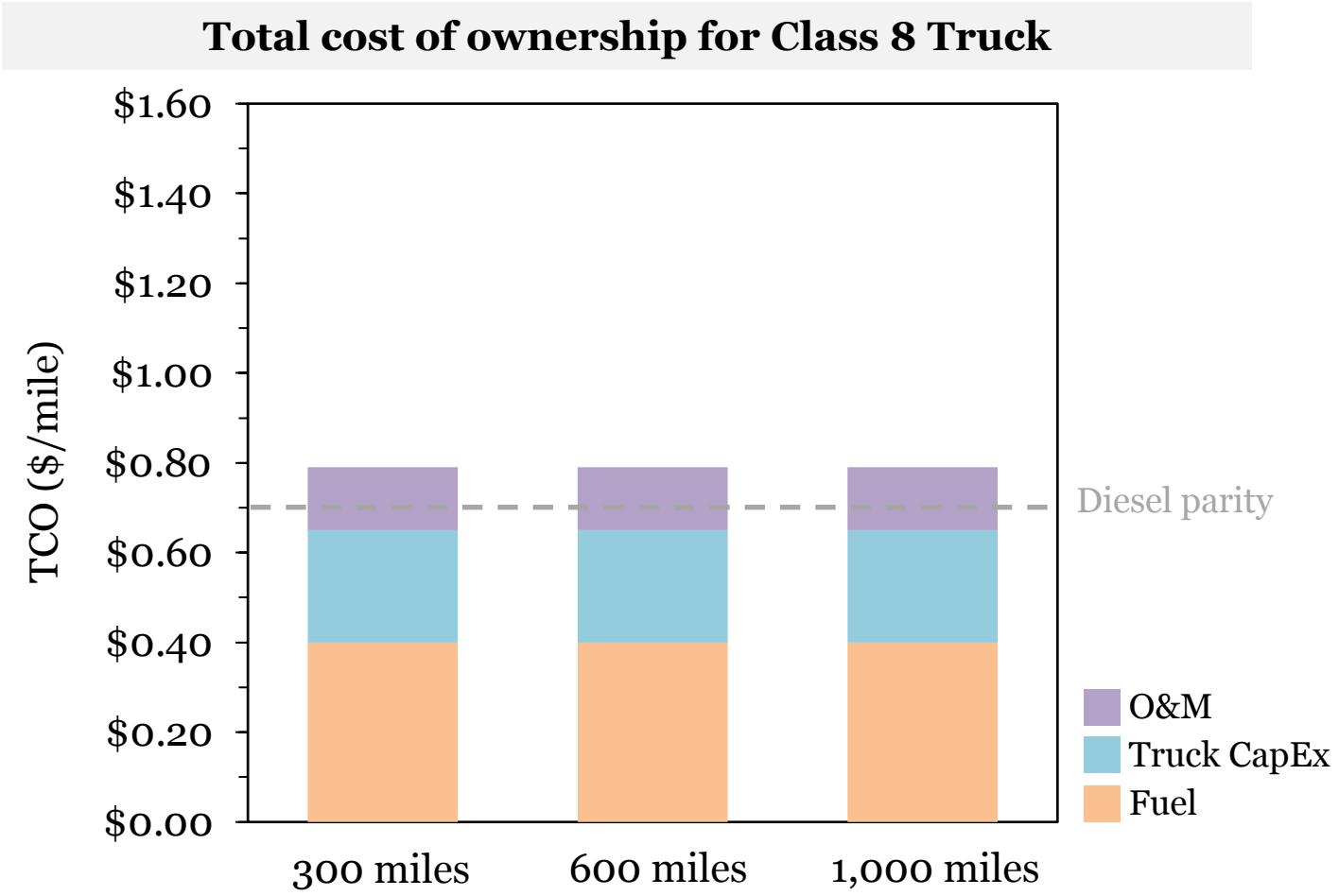
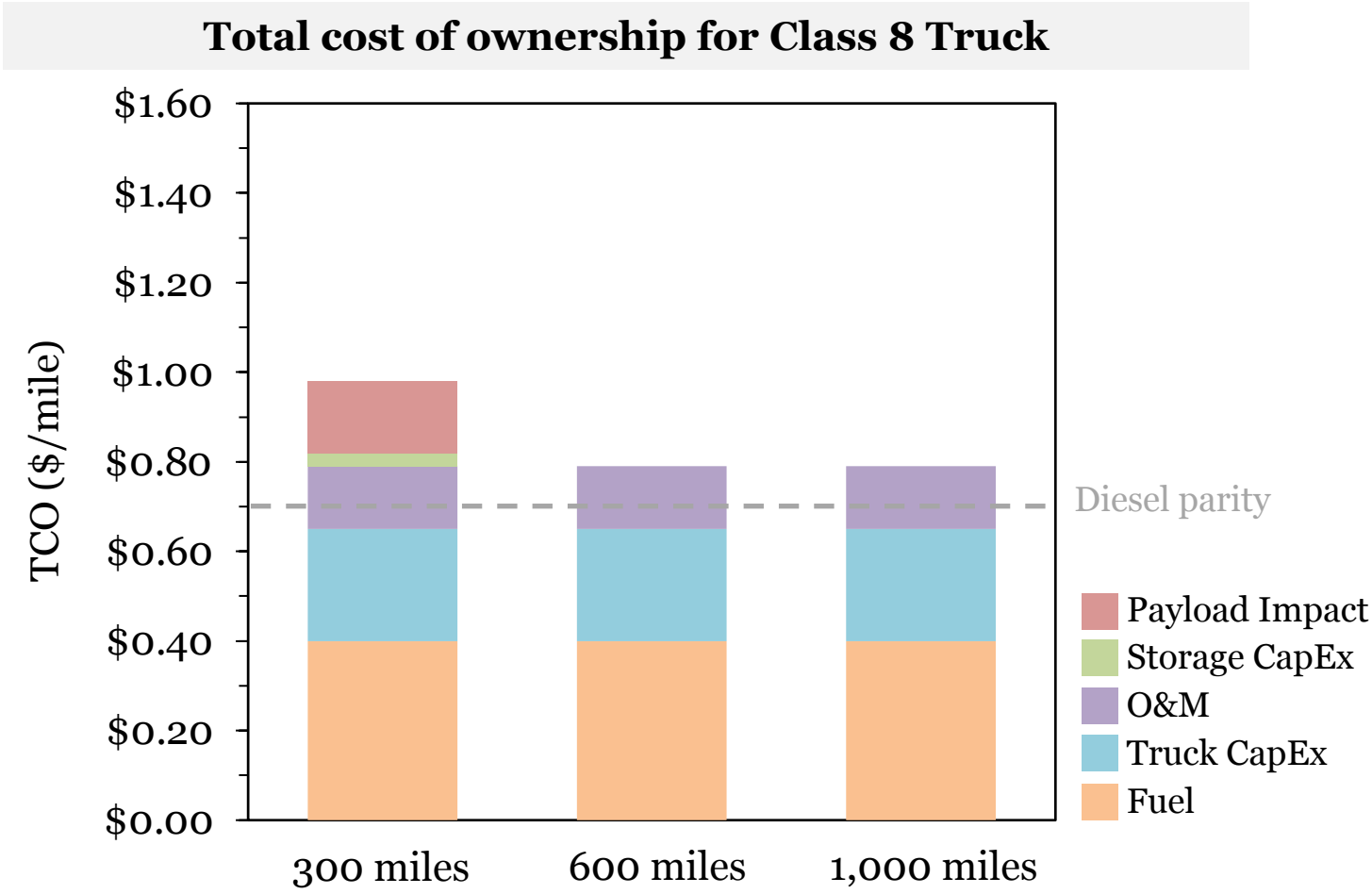
Image on the right: Kenworth.com

Low gravimetric energy density increases total cost of ownership



Key inputs: NREL TCO Analysis, September 2021; DOE HFTO Program Record 19008, 2019.
Notes: Excludes driver cost. Based on near term predicted costs. Based on 7 mpkg

Low gravimetric energy density increases total cost of ownership



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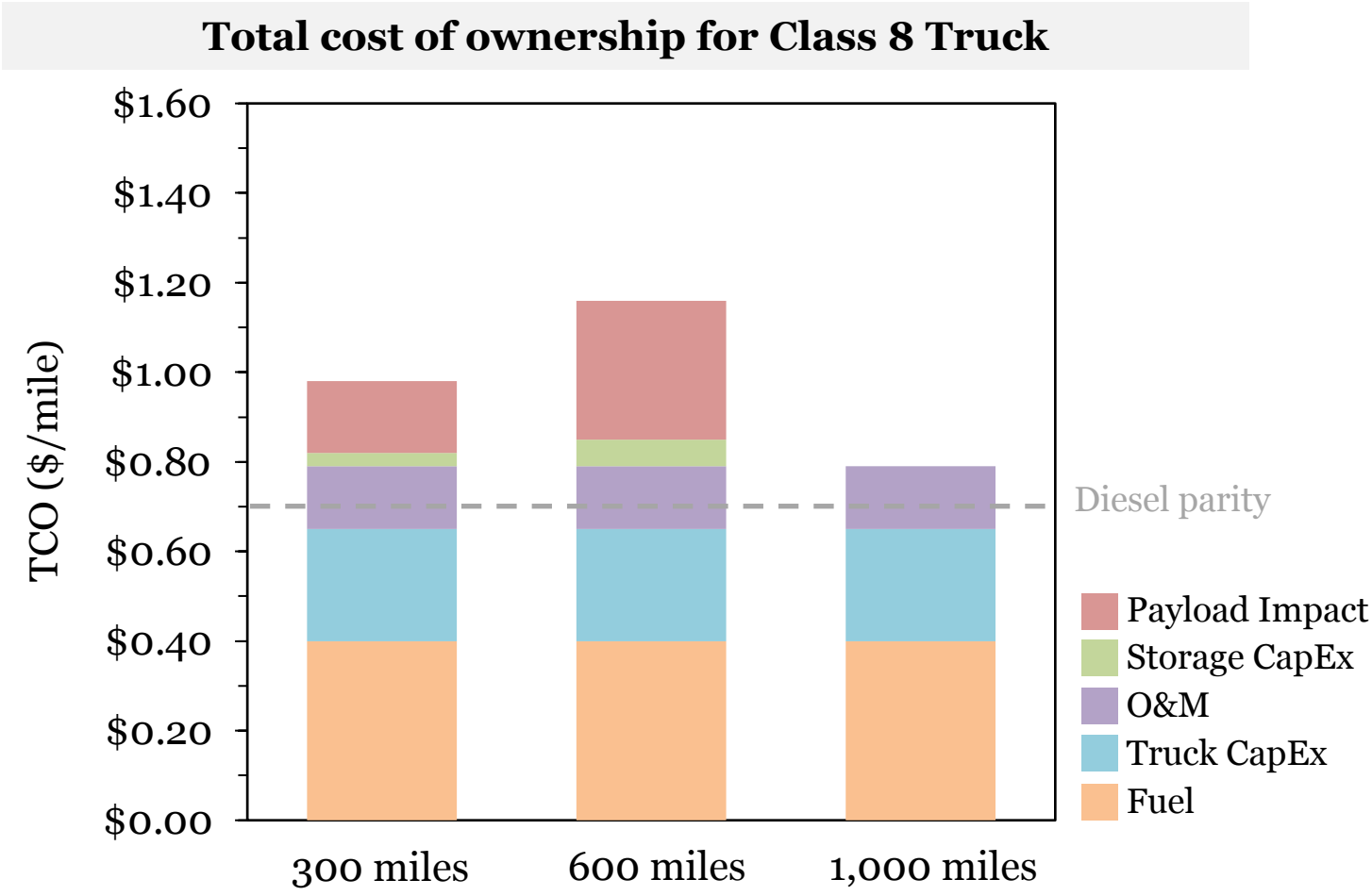

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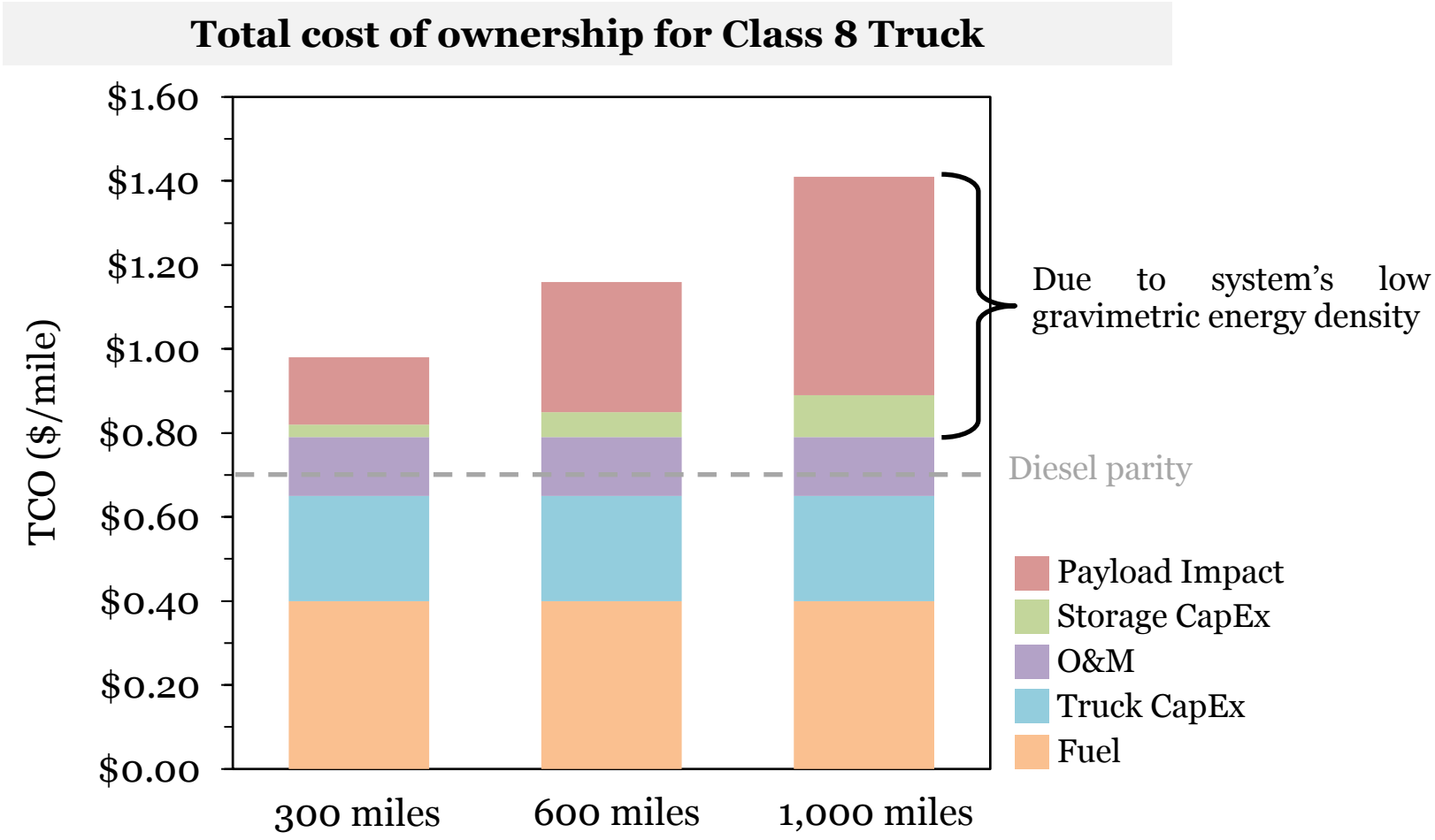

Green premium remains prohibitively high for long-haul (<100%)

Key inputs: NREL TCO Analysis, September 2021; DOE HFTO Program Record 19008, 2019.
Notes: Excludes driver cost. Based on near term predicted costs. Based on 7 mpkg

700 bar technology does not meet long-haul needs

Storage & refueling options	700 bar
Long Range	✗
High Payload	✗
Quick Refueling	✓
Low Fuel Cost	✓
Many Fuel Locations	✓

Low volumetric energy density prevents long-haul applications

Low gravimetric energy density increases TCO and slows adoption

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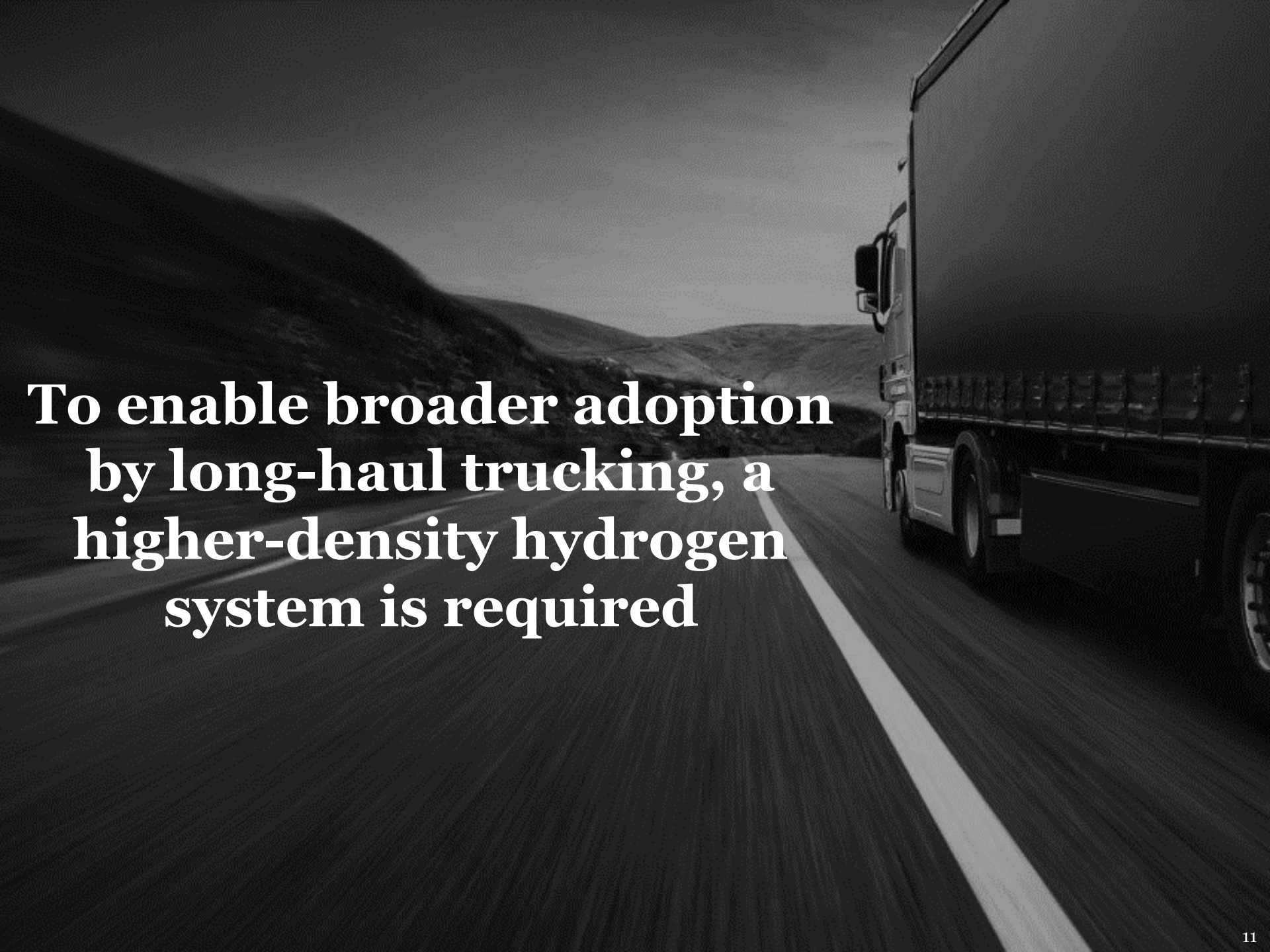
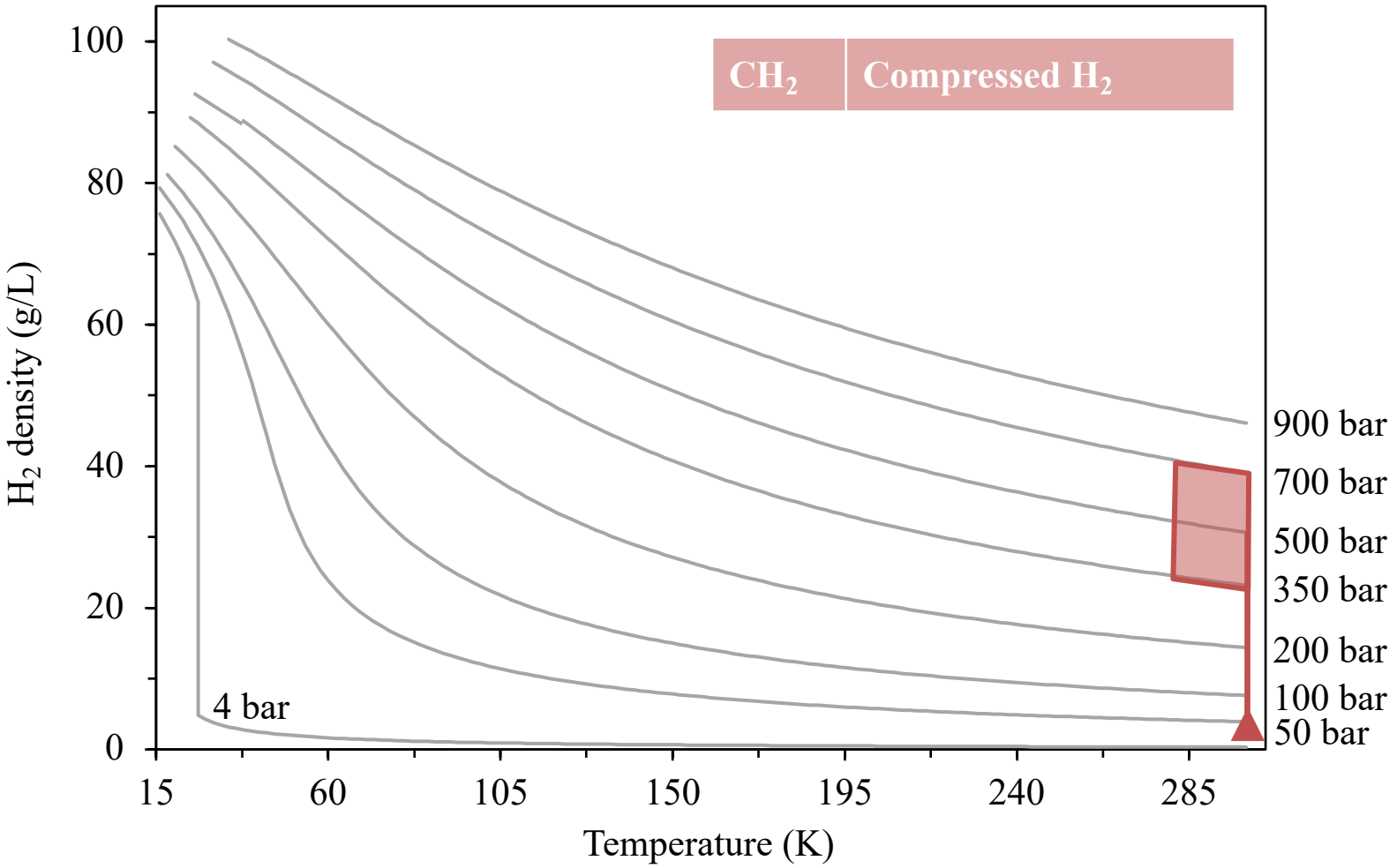
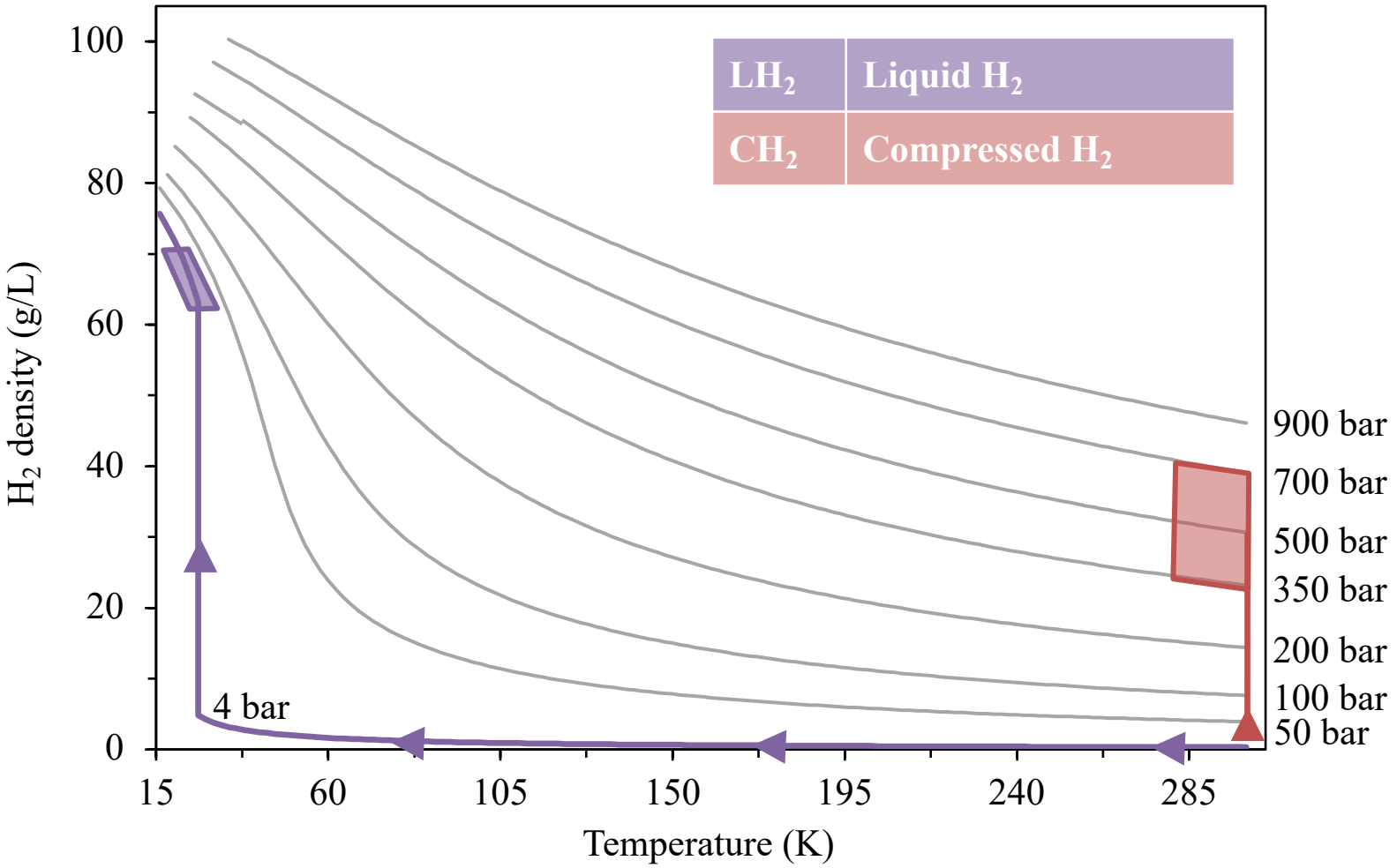

To enable broader adoption by long-haul trucking, a higher-density hydrogen system is required

Cryogenic hydrogen is required for higher densities



Cryogenic hydrogen is required for higher densities



Liquid hydrogen can enable higher densities than 700 bar

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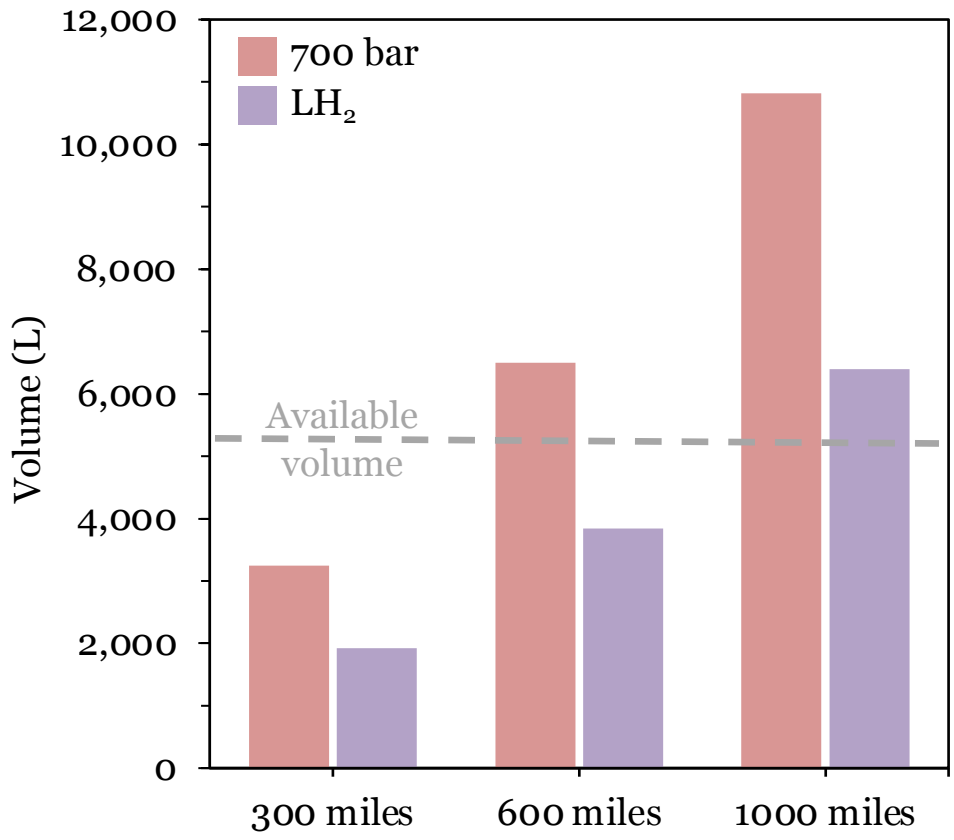
LH_2 storage offers higher volumetric density, enabling long haul applications

Volume available and volume needed

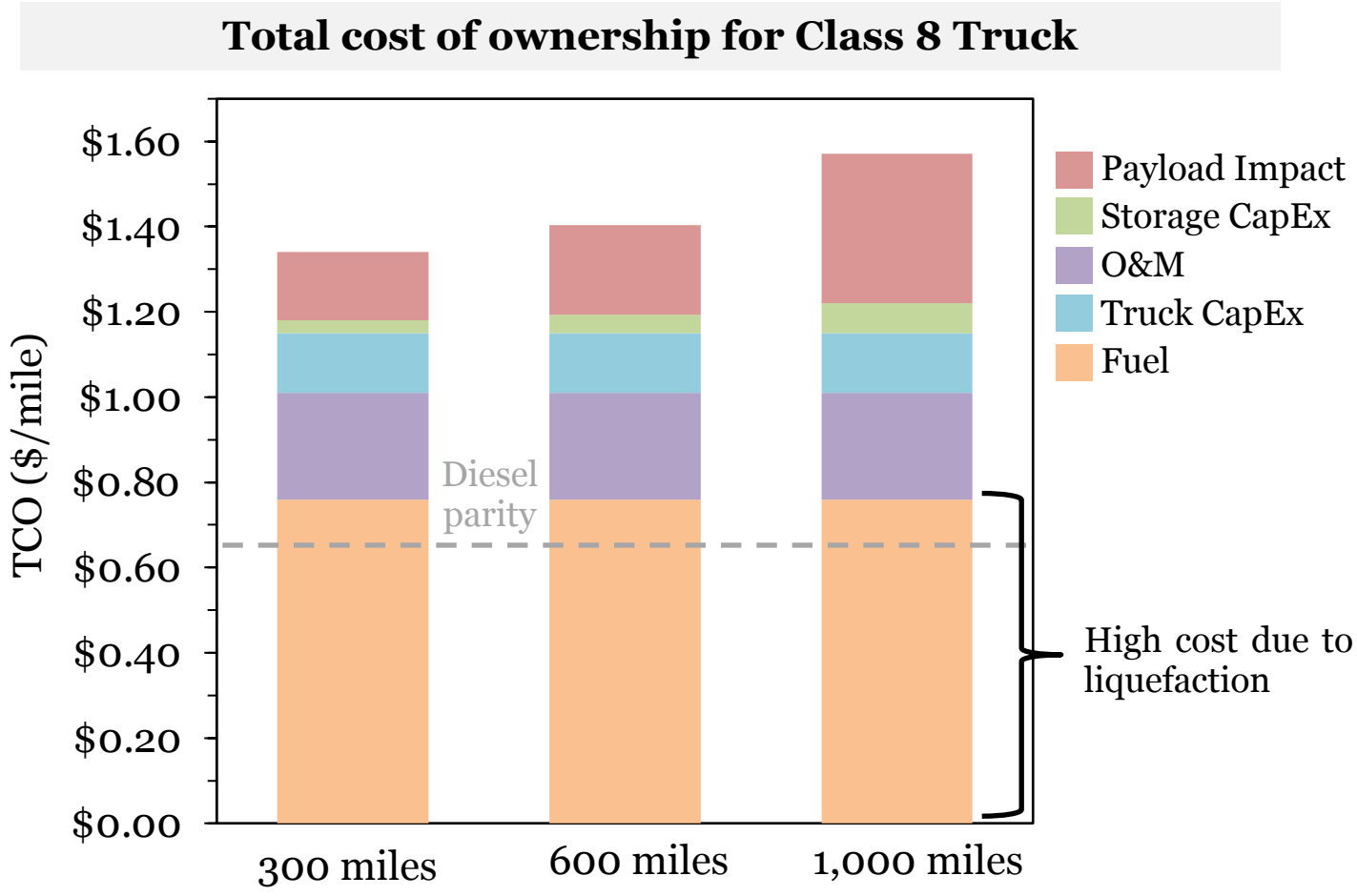


Back-of-cab system

- LH_2 storage tanks offer system densities of 40 g/L
- These densities can enable long haul truck applications (500+ miles)

Volumetric density based on multiple sources including: Ahluwalia, R. K., et al. "Liquid hydrogen storage system for heavy duty trucks: Configuration, performance, cost, and safety." *Int. J. Hydrog. Energy*, 2023.

While long haul is possible, green premium is very high due to fuel cost



- Liquefaction adds **$0.16/mile** relative to 700 bar fuel cost
- Massive impact considering profit margin is **$0.05/mile**

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Key inputs: NREL TCO Analysis, September 2021;
Notes: Excludes driver cost. Based on near term predicted costs. Based on 7 mpkg; 30 tpd LH_2 site assumed

LH_2 faces boil-off issues and overall thermal complexity

- LH_2 refilling can require pre-cooling and venting
- Diphasic conditions increase complexity and cost

Image from Daimler Truck website

LH_2 enables long range but limited by cost and supply

Storage & refueling options	700 bar	LH_2
Long Range	✗	✓
High Payload	✗	✓
Quick Refueling	✓	✓
Low Fuel Cost	✓	✗
Many Fuel Locations	✓	✗

Liquefaction adds **$0.16/mile** relative to 700 bar

Global LH_2 production could hypothetically power **6,000 trucks/day**

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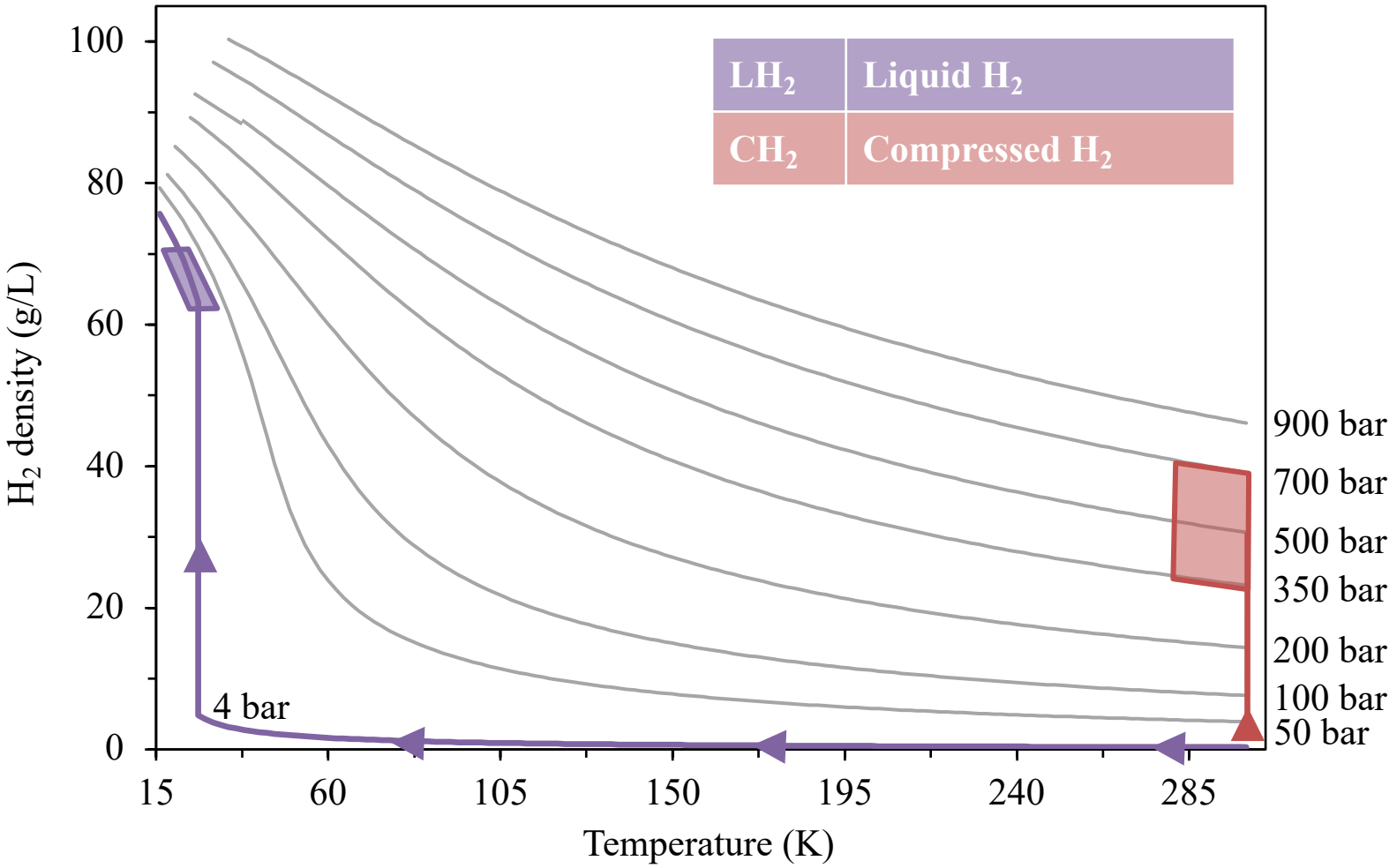
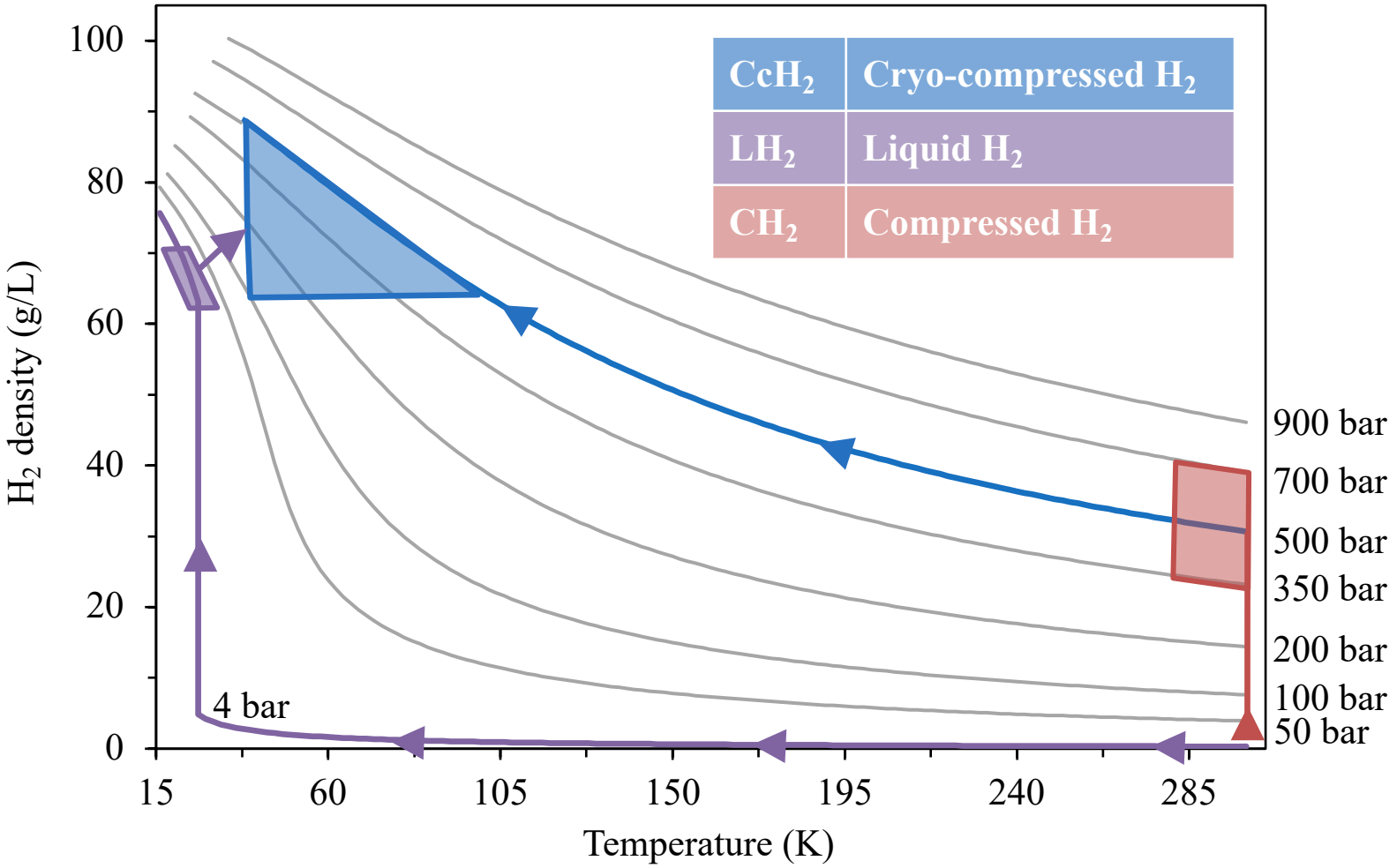
Cryogenic hydrogen is required for higher densities



Cryo-compressed hydrogen offers high density with minimal complexity and supply flexibility



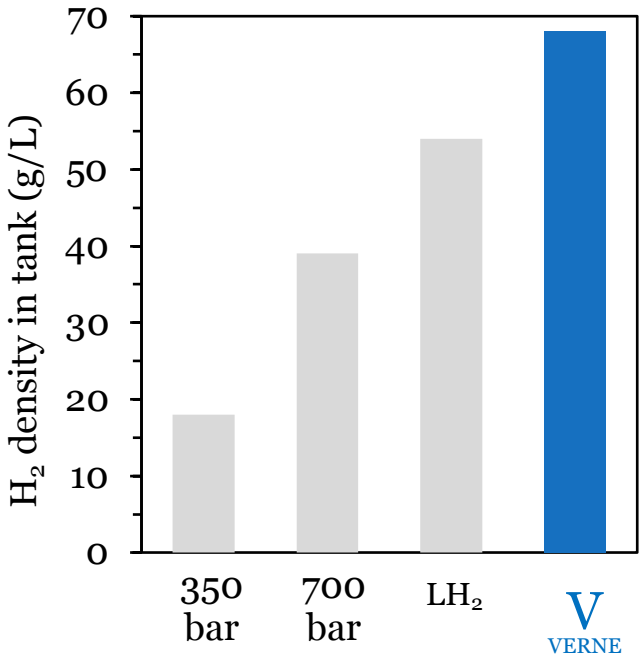
Higher than LH_2 densities from LH_2 or GH_2 source and monophasic operations

Verne's approach with CcH_2: high-density & supply flexibility

Long-range storage

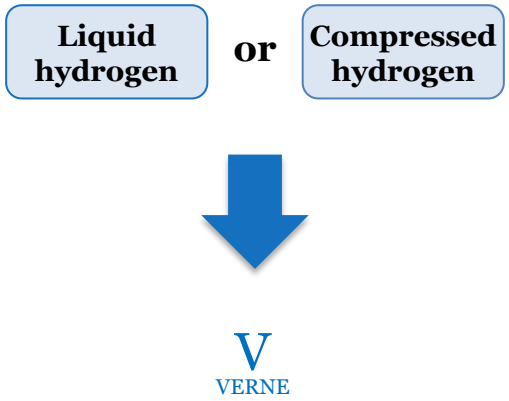
100+ kg system

Highest density



20% higher density than LH_2

Supply flexibility



Refuel with the lowest cost source of hydrogen

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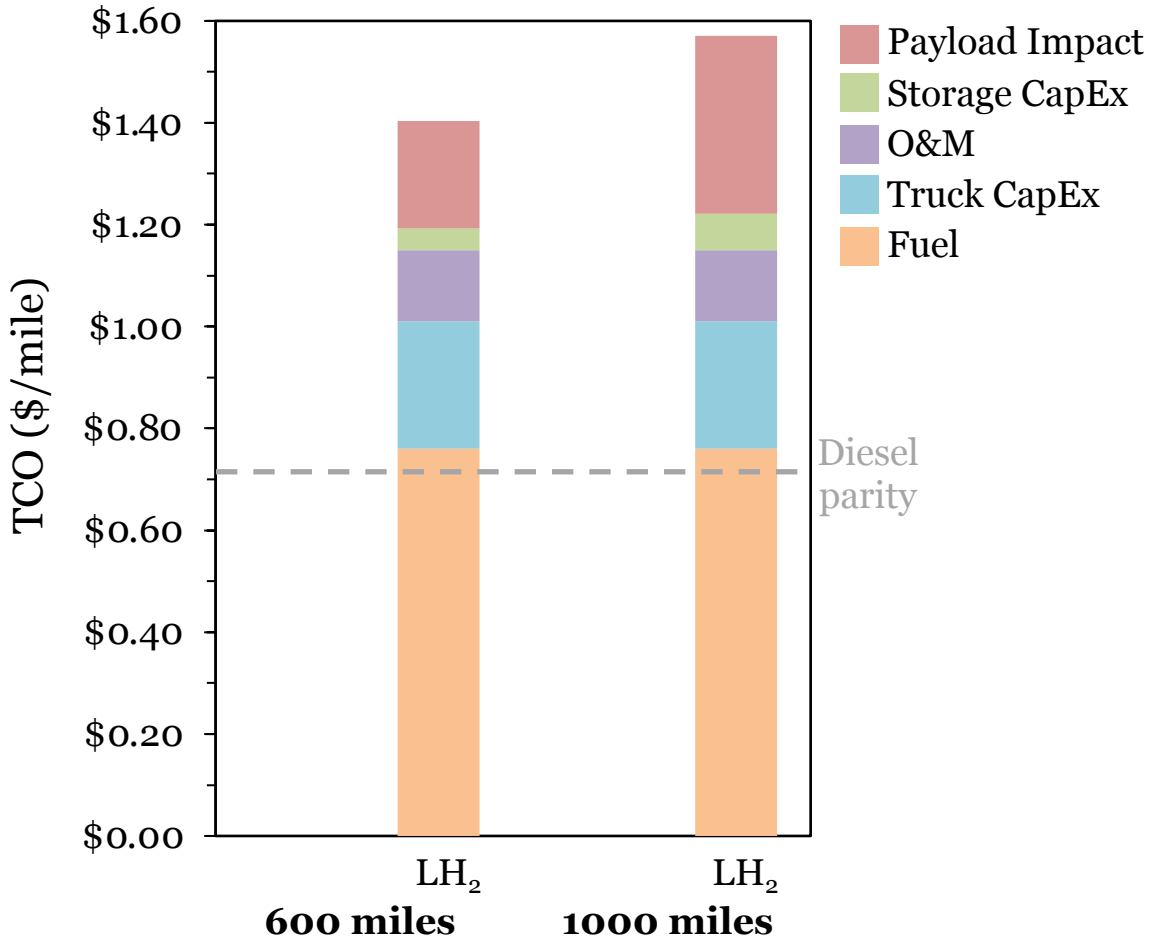
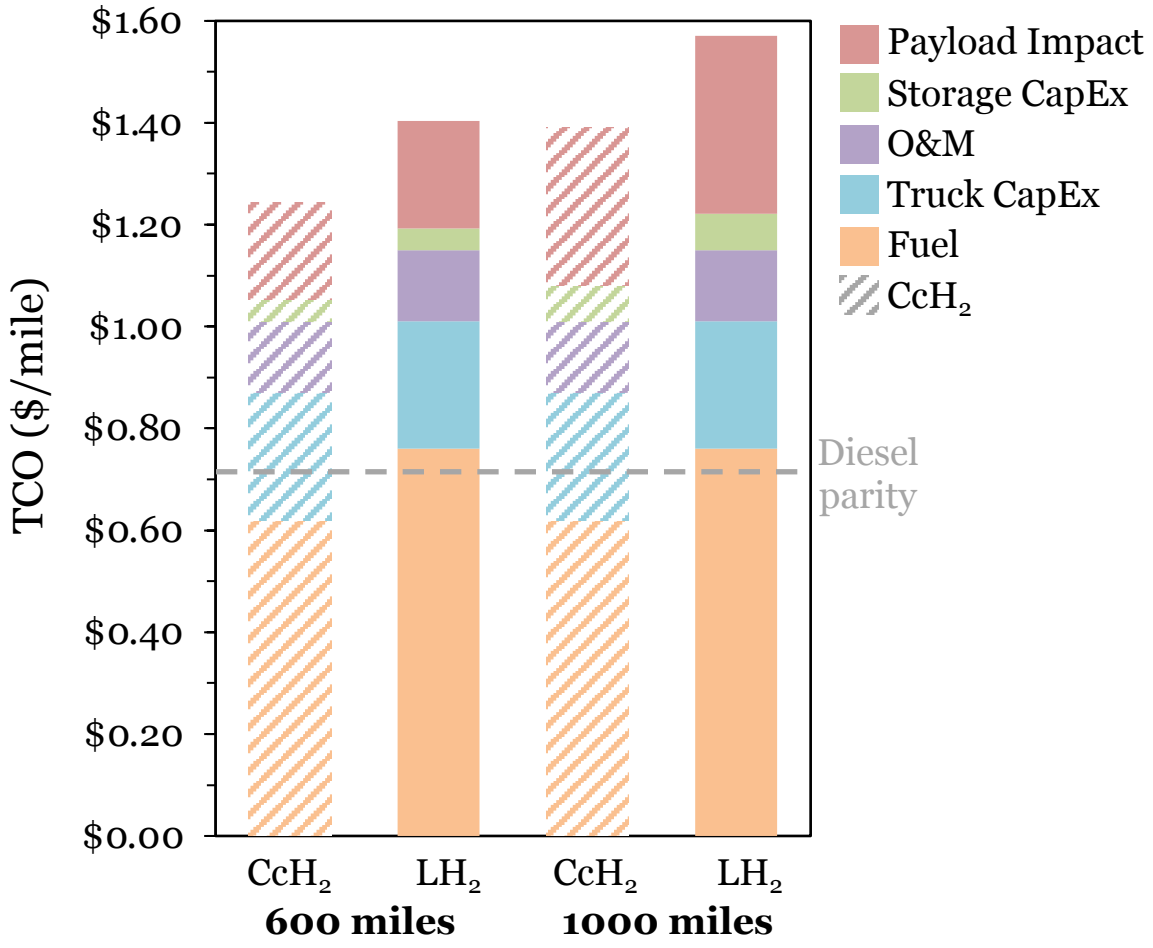
CcH_2 offers long range at lower cost than LH_2



Key inputs: NREL TCO Analysis, September 2021;
Notes: Excludes driver cost. Based on near term predicted costs. Based on 7 mpkg; 30 tpd LH_2

CcH_2 offers long range at lower cost than LH_2



- CcH_2 enables ~$0.20/mile savings
- Massive saving considering profit margin is $0.05/mile

Key inputs: NREL TCO Analysis, September 2021;
Notes: Excludes driver cost. Based on near term predicted costs. Based on 7 mpkg; 30 tpd LH_2

CcH_2 offer high density with supply flexibility

Storage & refueling options			
	700 bar	LH_2	CcH_2
Long Range	✗	✓	✓
High Payload	✗	✓	✓
Quick Refueling	✓	✓	✓
Low Fuel Cost	✓	✗	✓
Many Fuel Locations	✓	✗	✓

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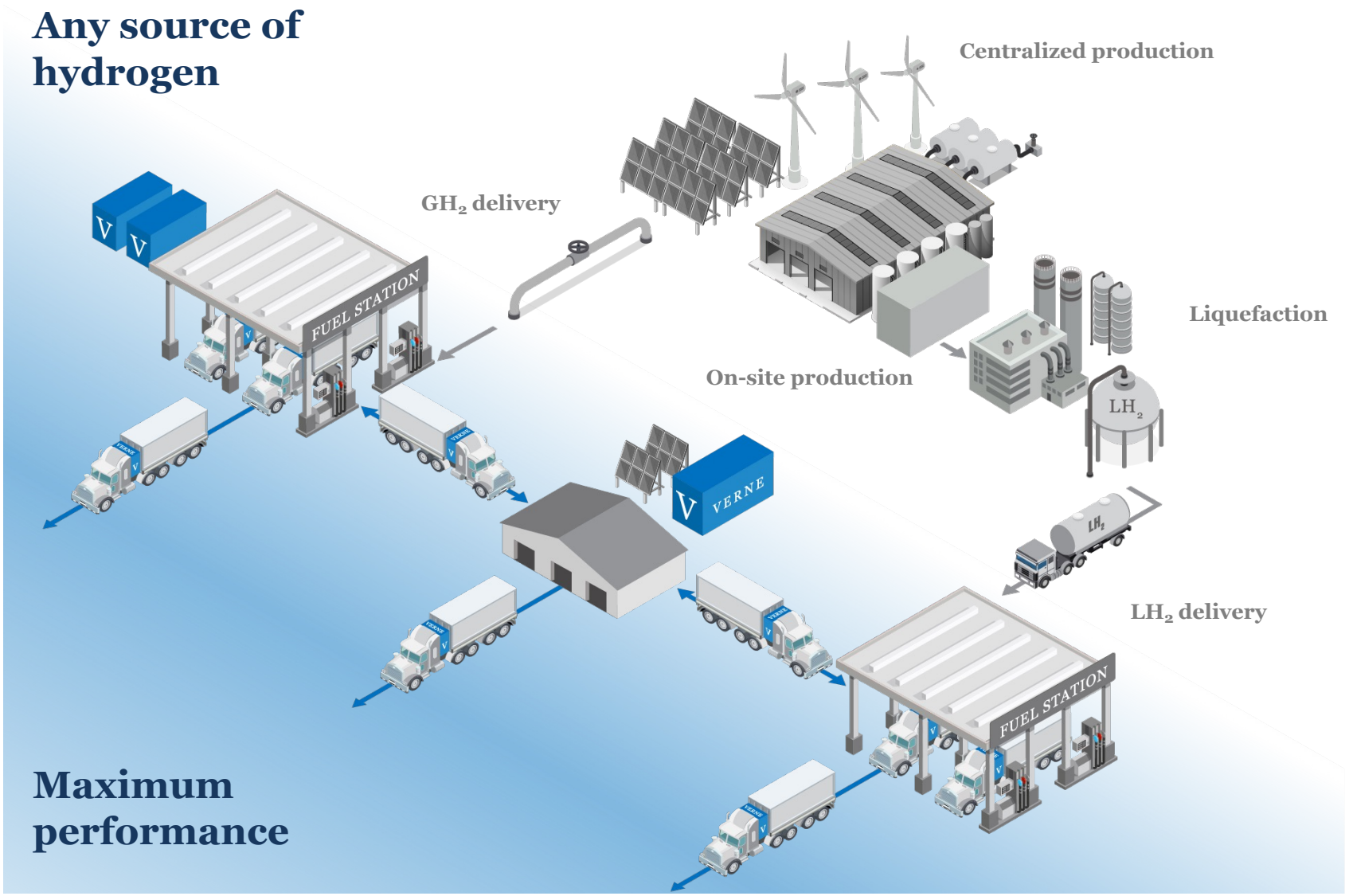
CcH_2 can accelerate the entire hydrogen ecosystem



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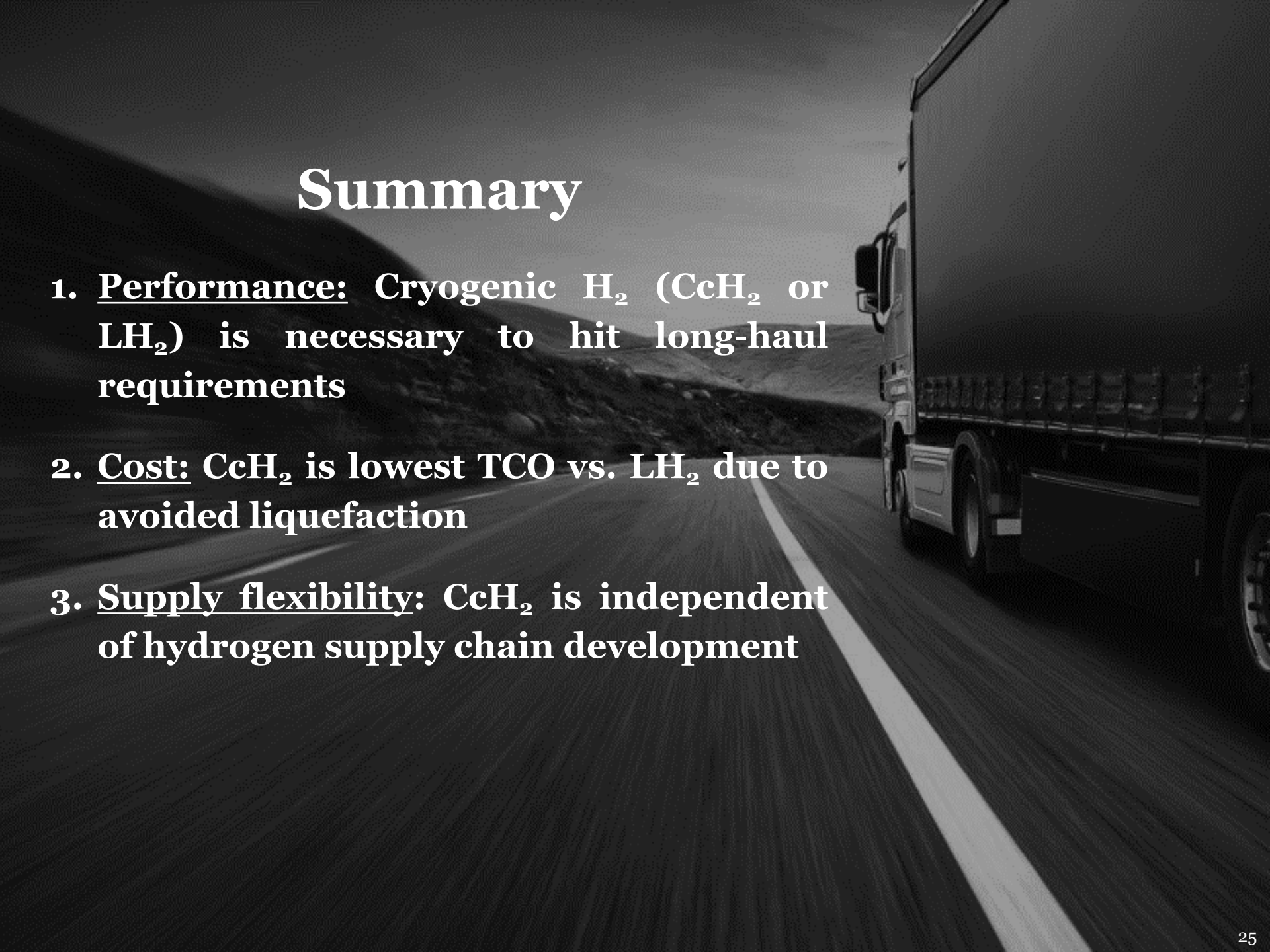


Summary

1. **Performance:** Cryogenic H_2 (CcH_2 or LH_2) is necessary to hit long-haul requirements
2. **Cost:** CcH_2 is lowest TCO vs. LH_2 due to avoided liquefaction
3. **Supply flexibility**: CcH_2 is independent of hydrogen supply chain development

Challenge for the CcH_2 trucking industry: refueling component development and standardization

ISO 197 and CcH_2standards

WG 5: Gaseous hydrogen land vehicle refueling connection devices

US DOE: world class CcH_2 test site

Lawrence Livermore National Laboratory

- Participation needed to shape Standards that can enable an open market
- LLNL and US have capabilities to help lead these efforts
- Verne is open to collaborate to accelerate market adoption

Verne's trajectory for commercializing CcH_2

10 kg system demonstrated

2022

Closed Seed Round

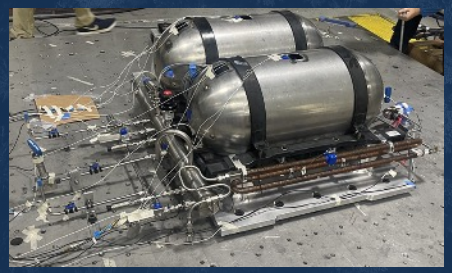
amazon

CATERPILLAR

Full-scale storage system built (10x scale up)

2023

Multi-tank system tested for durability



Truck demonstration

2024

Refueling demonstration

V VERNE

The Verne team

Ted McKlveen
CEO

David Jaramillo
CTO

Bav Roy
COO

+12 Full-time engineers

+8 Technical consultants & contractors

Key technical leaders, advisors & contractors

Salvador Aceves
Lawrence Livermore National Laboratory

Kaushik Mallick
STEELHEAD COMPOSITES

Vincent Heloin
Air Liquide
SLAC NATIONAL ACCELERATOR LABORATORY

Markus Kampitsch
BMW

Rob Pahl
Alcoa

Bob Boyd
Linde

Funding

Grants

Breakthrough Energy

arpa·e U.S. DEPARTMENT OF ENERGY

Private

amazon

CATERPILLAR

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Thank you!
Questions?
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