High-density hydrogen for heavy-duty transportation

David Jaramillo
CTO & Co-Founder
November 21, 2023

- CcH_2 and Verne intro
- Usable density comparisons
- Verne progress and conclusion

VERNE

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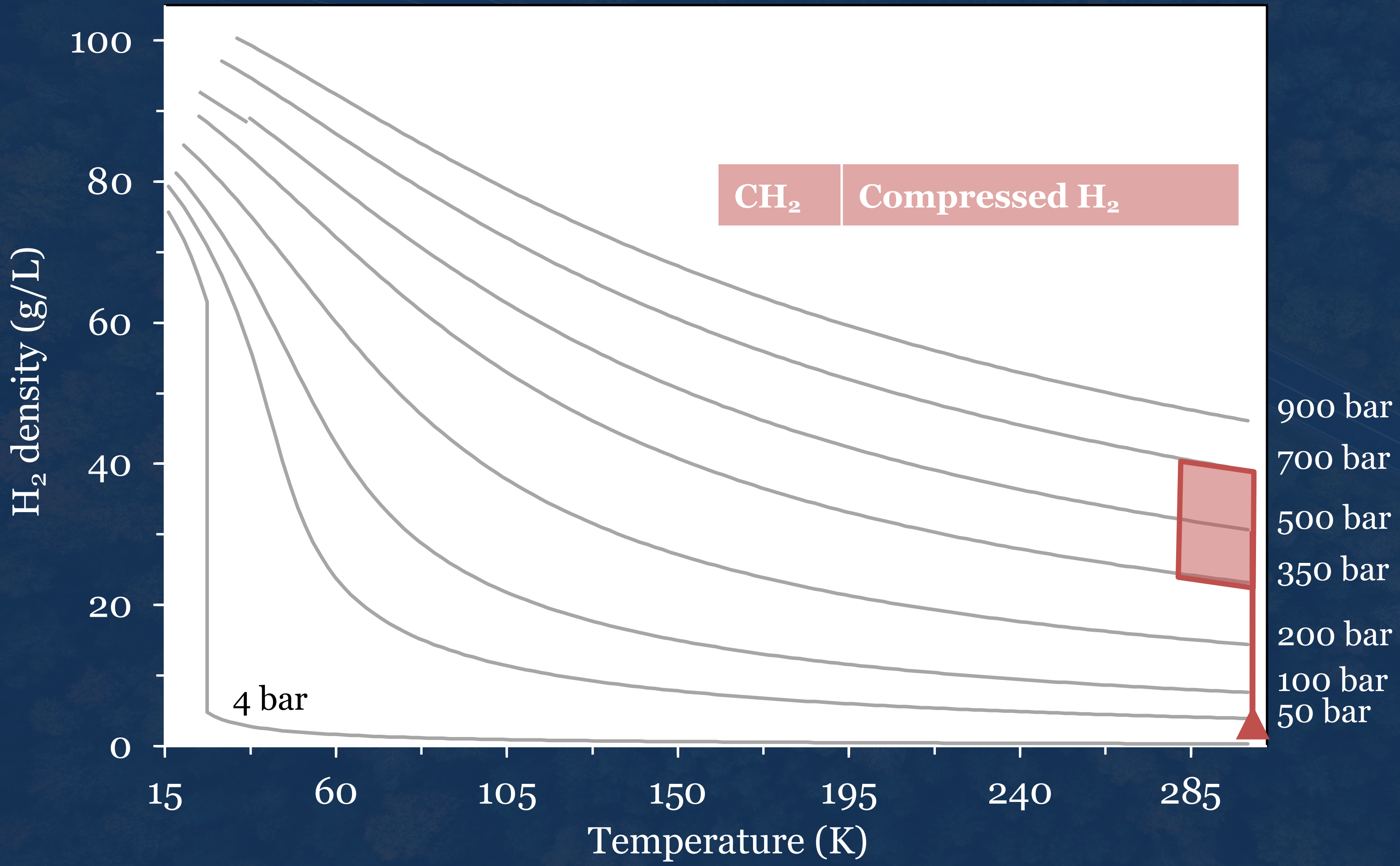
To enable broader adoption by long-haul trucking, a higher-density hydrogen system is required

Compressed hydrogen covers one narrow space of the hydrogen phase diagram



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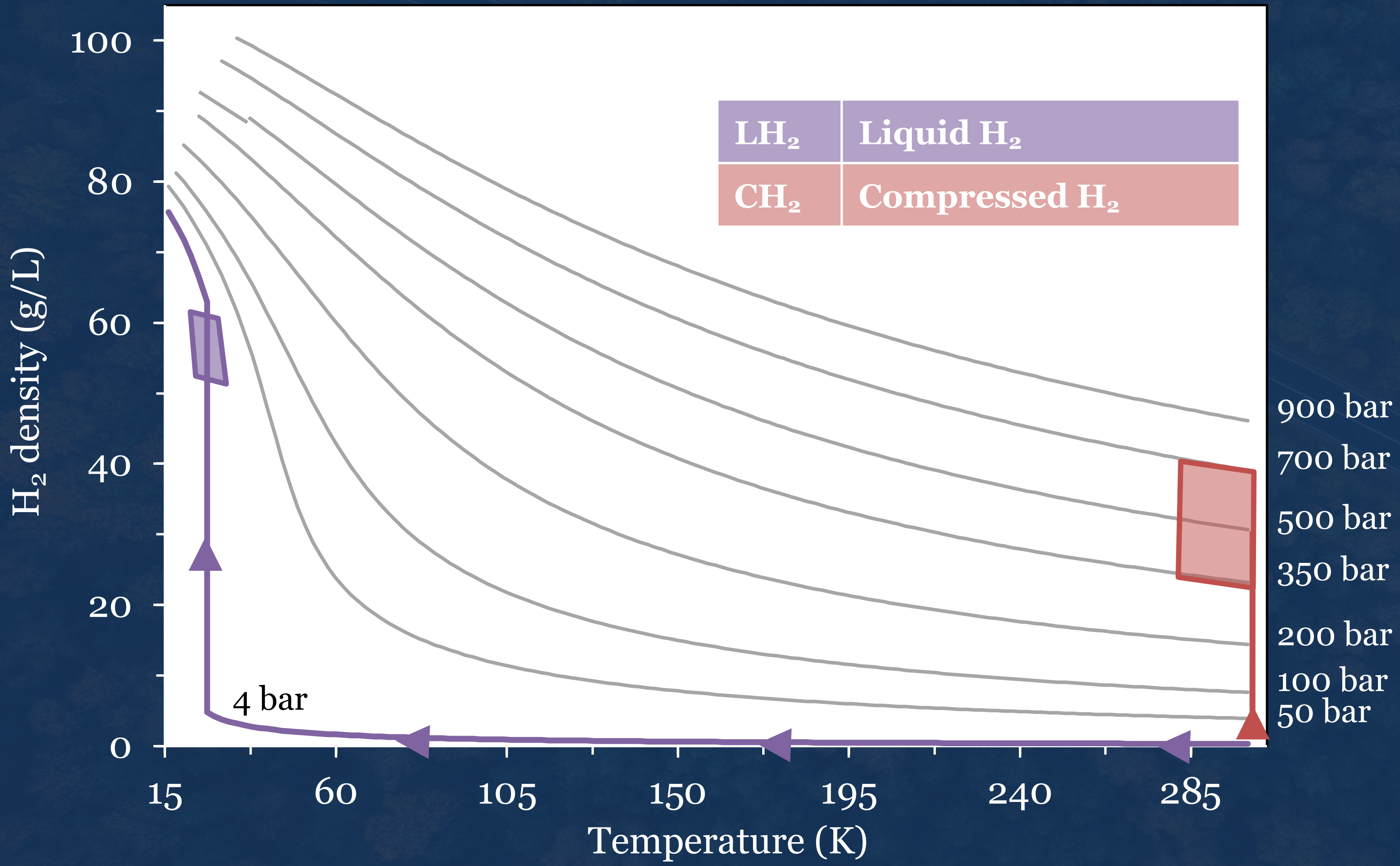
Liquid hydrogen enables higher densities than 700 bar



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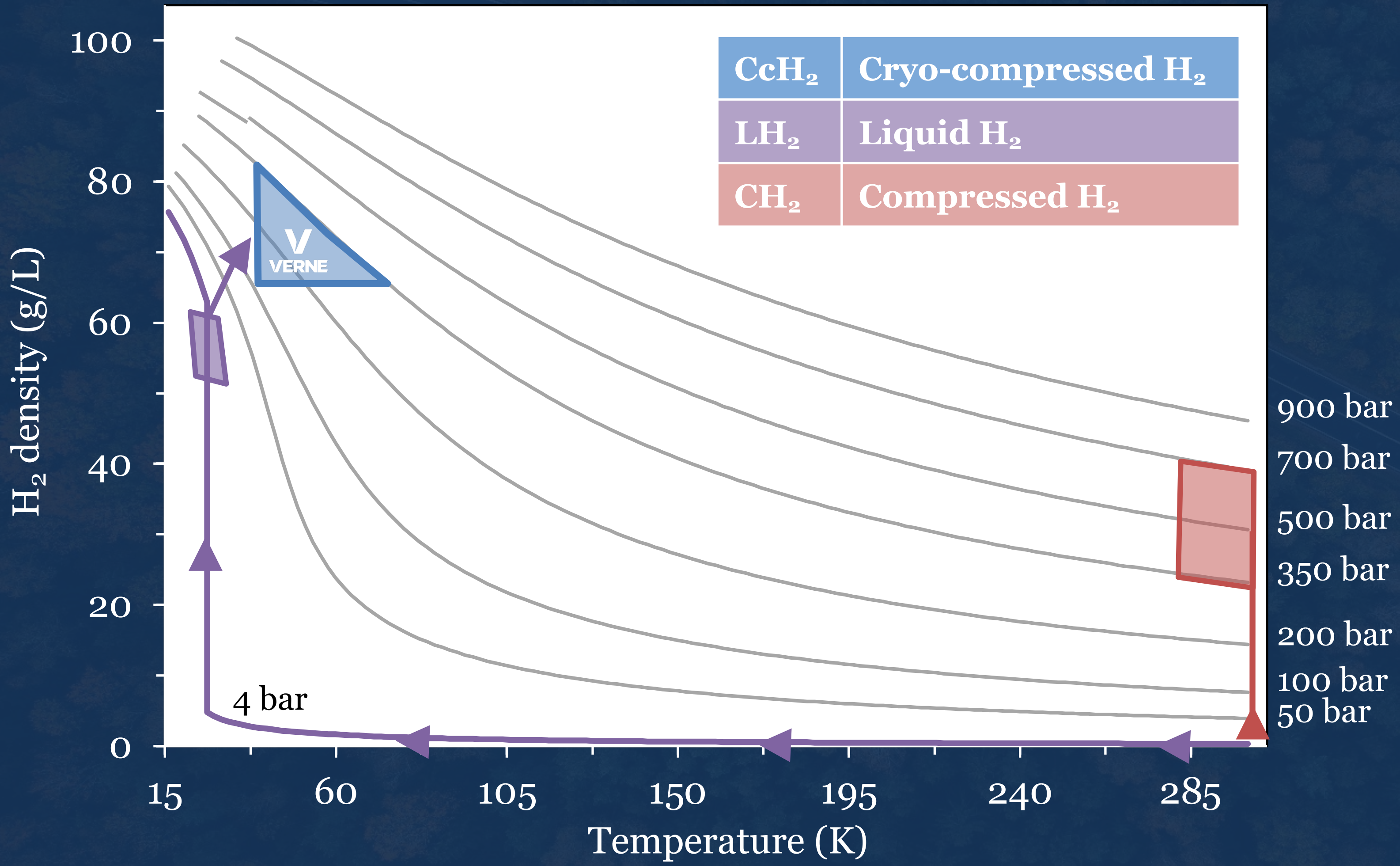
Cryo-compressed hydrogen enables the highest density solution with monophasic operations



CcH_2	Cryo-compressed H_2
LH_2	Liquid H_2
CH_2	Compressed H_2

1. **Higher than LH_2 density**
2. **Simplified operations**

- CcH_2 is a cold gas, enabling monophasic refueling and on-board operations
- Minimized “boil off” or venting

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Verne develops cryo-compressed hydrogen storage and refueling solutions

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Impact: maximize heavy-duty truck performance

Current hydrogen
700 bar compressed

6 tanks

450 mi

Verne Configuration 1
Long-range

4 tanks

850+ mi

Similar volume

Double Operating Range

Verne Configuration 2
Ultra-light

2 tanks

450 mi

2,000 lbs lighter

Double Profit Margins

VERNE **Notes**: Assumes 700 bar BOC weight of 3,300 lb; Verne BOC stores 121 kg of usable H_2; Verne frame-mounted system is 1,300 lb

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Comparative truck model for CcH_2, LH_2, and sLH_2

Goal	Establish an approach with clear inputs, that enables direct comparisons for the metrics that matter, system usable densities
Outcome	Help truck fleets and stakeholders make informed decisions

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Comparative truck model for CcH_2, LH_2, and sLH_2

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Example of key assumptions made for comparative model

Storage system properties	Driving profile	Heat flux	Hydrogen extraction
• 560 L storage volume per tank	• Refueling in the AM and drive until empty (6 bar) • 45-minute break every 4.5 hours • Monday – Friday with refueling Monday AM	• Assumes 2 W/m^2	• 7 miles per kg of H_2 and 55 mph • 7.86 kg/hr

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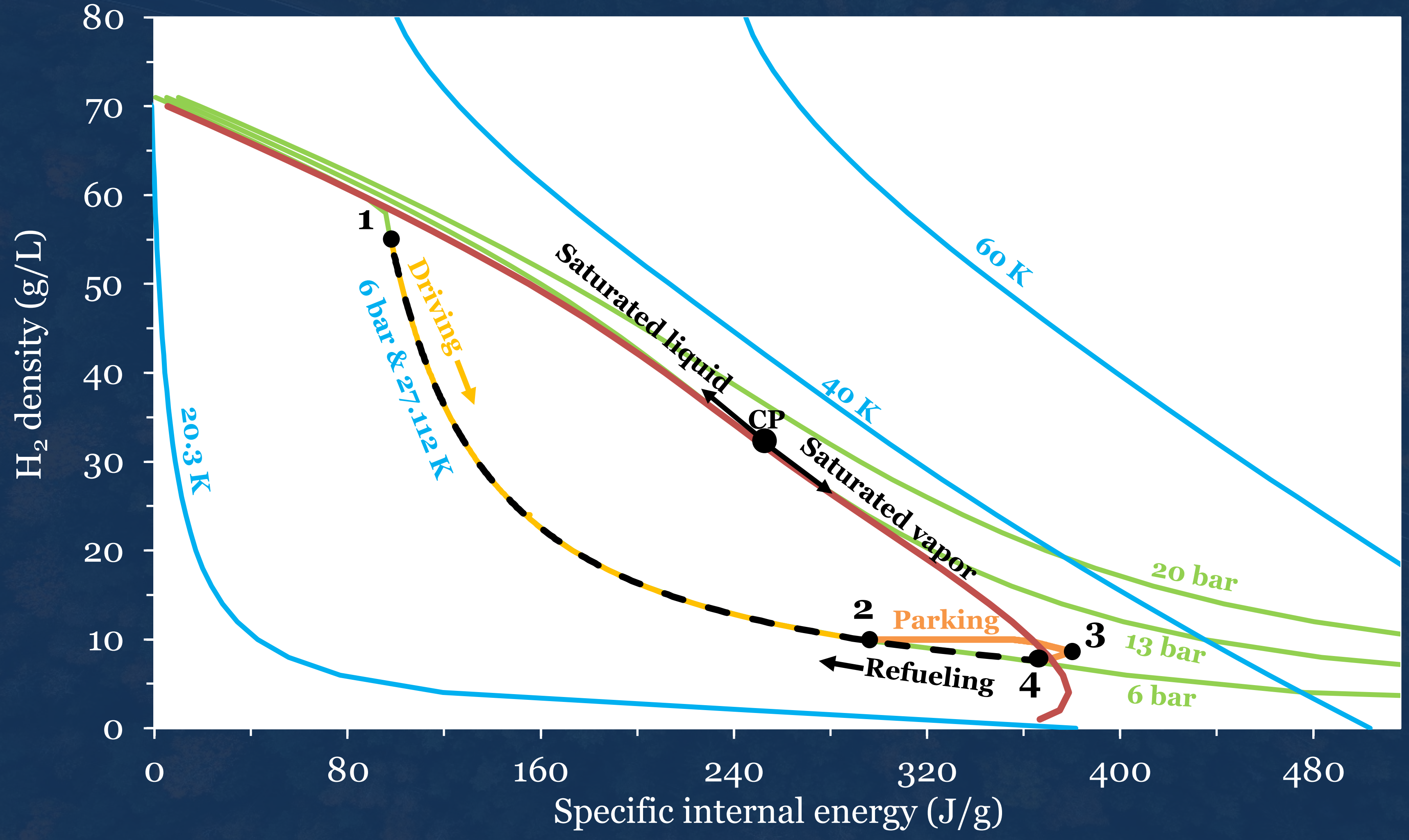
LH_2 at 6 bar shows usable density of 82% or 45 g/L

Thermodynamic evolution for LH_2 with P_{min} at 6 bar during weekly operations



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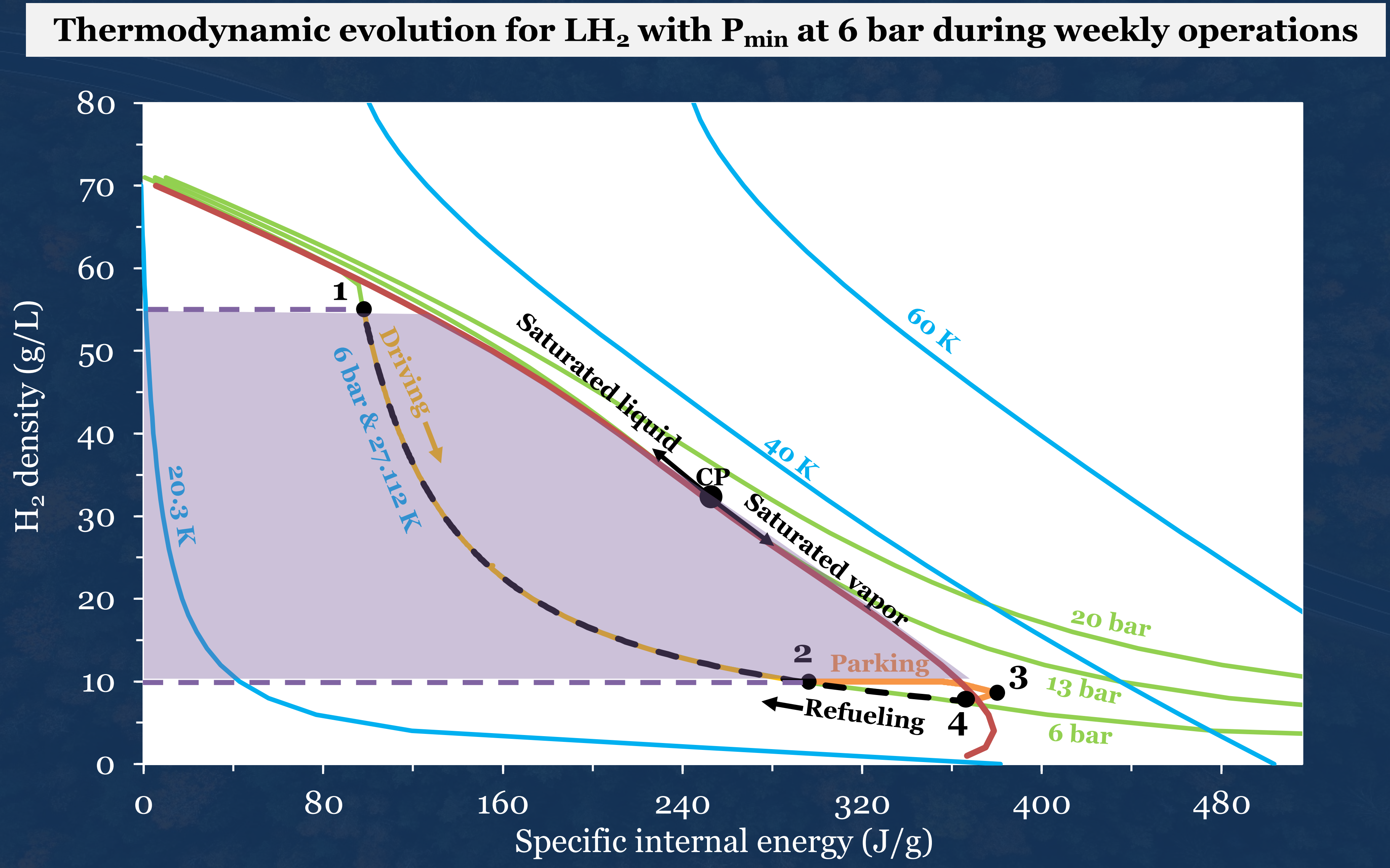
LH_2 at 6 bar shows usable density of 82% or 45 g/L



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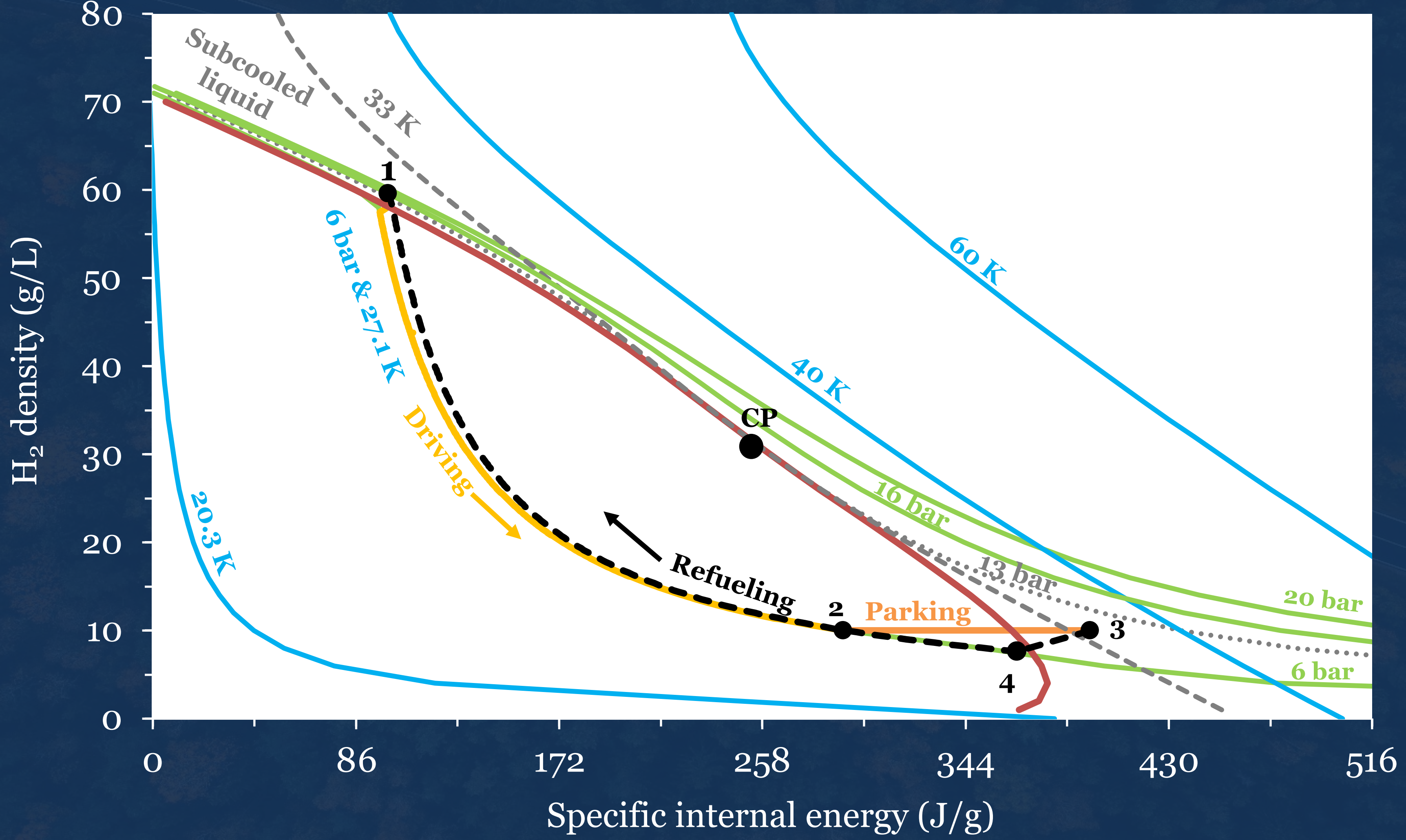
sLH_2 at 6 bar shows usable density of 83% or 49 g/L

Thermodynamic evolution for sLH_2 with P_{min} at 6 bar during weekly operations



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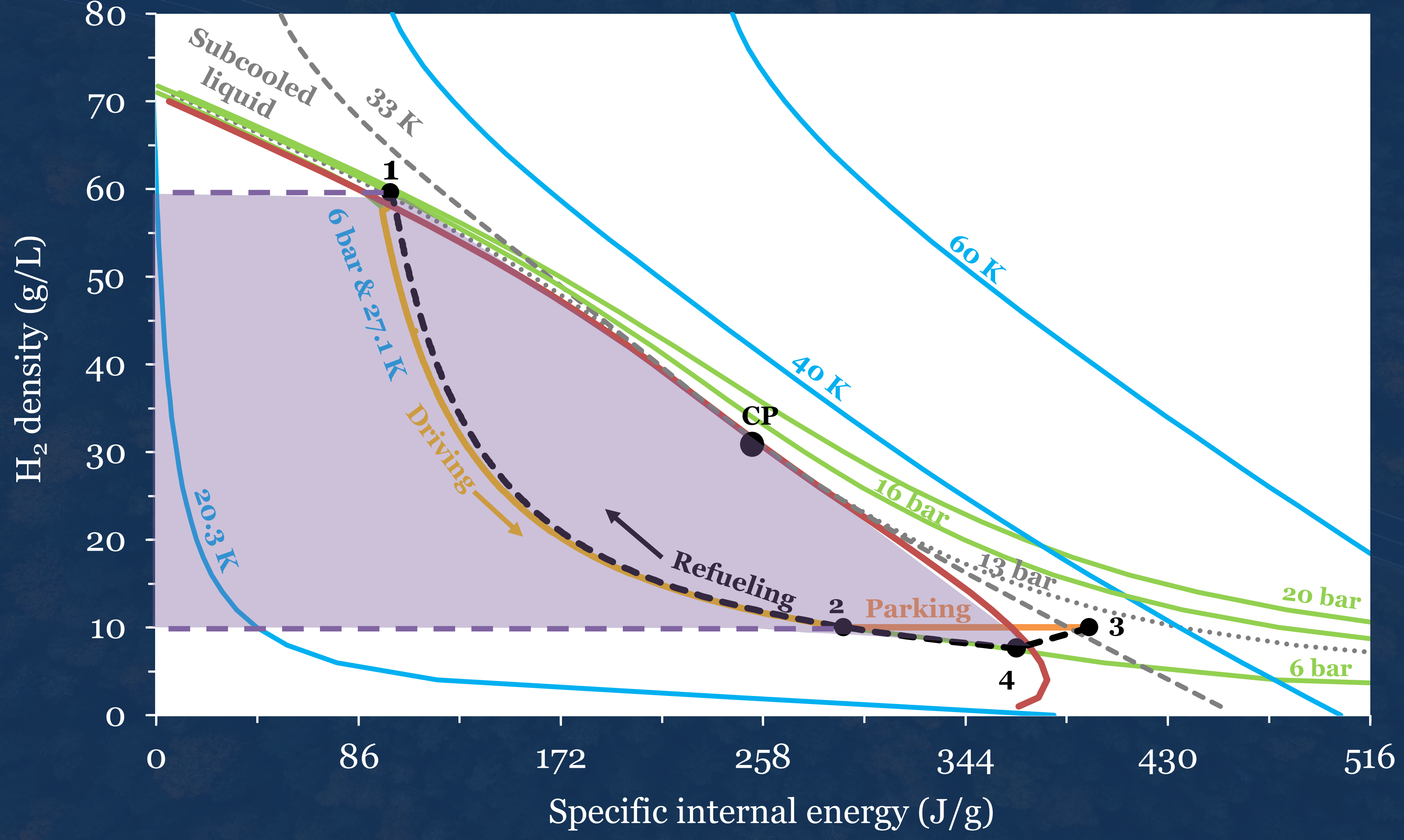
sLH$_2$ at 6 bar shows usable density of 83% or 49 g/L

Thermodynamic evolution for sLH$_2$ with P_{min} at 6 bar during weekly operations



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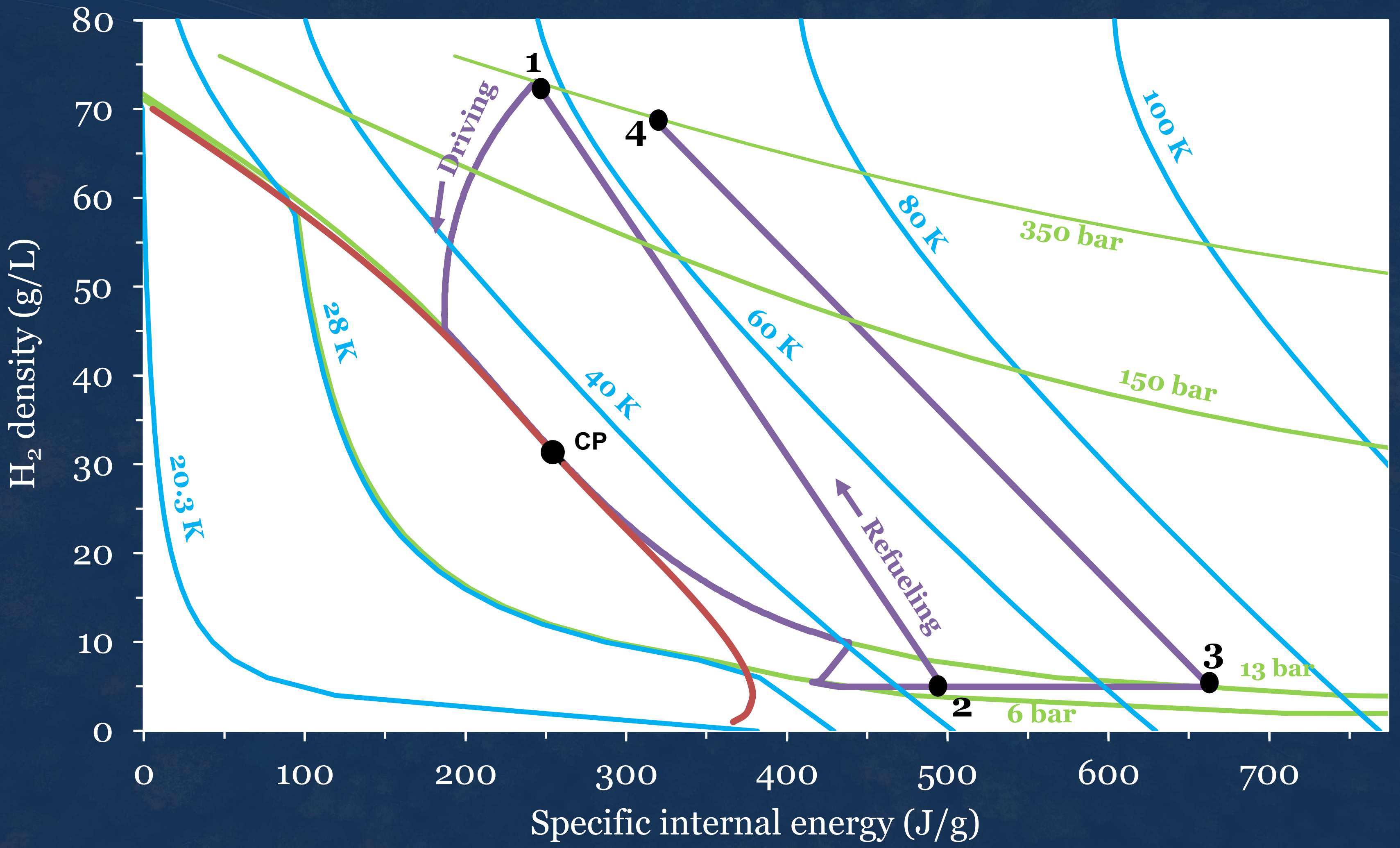
CcH_2 shows usable density of 93% or 68 g/L

Thermodynamic evolution for CcH_2 with P_{min} at 6 bar during weekly operations



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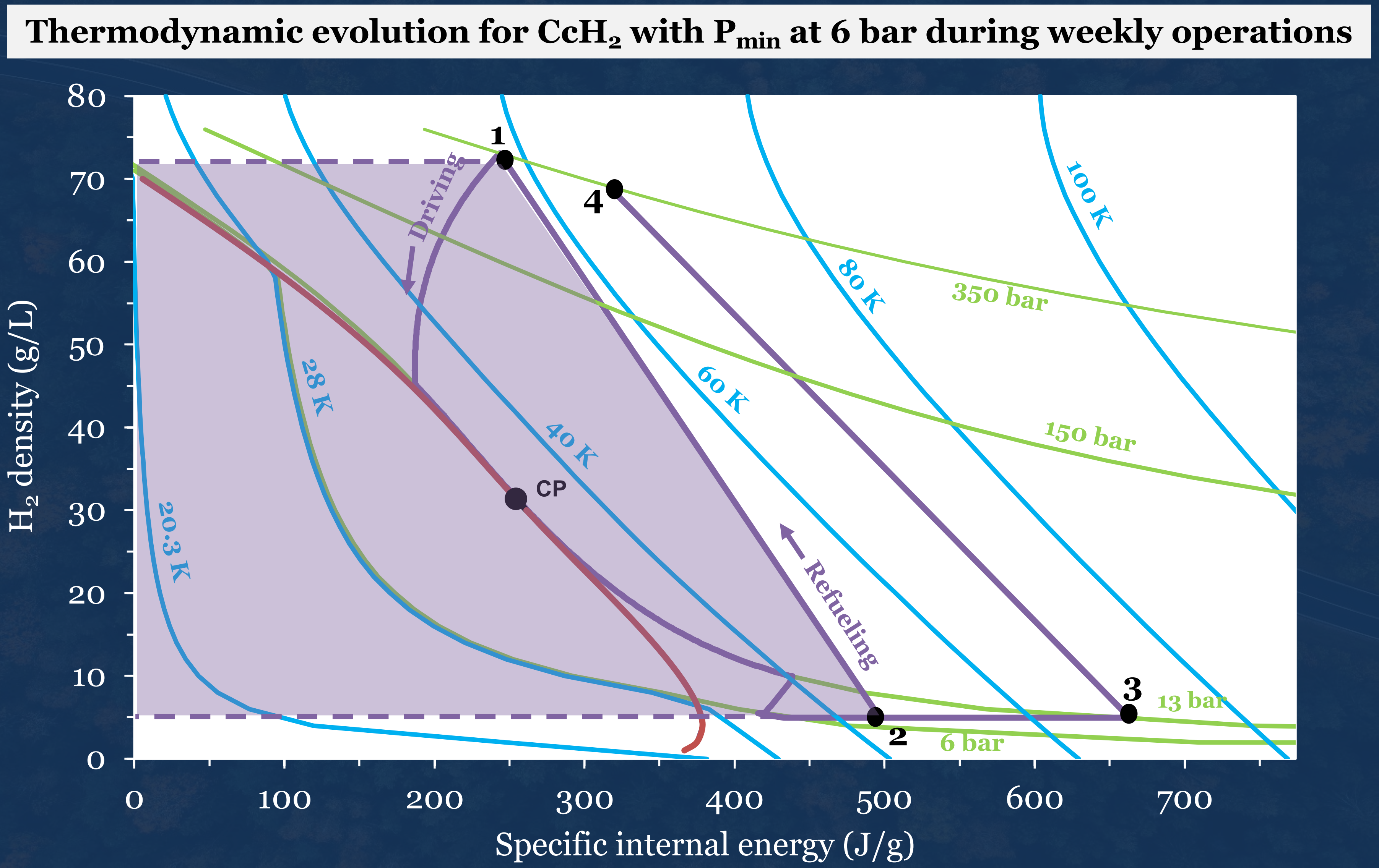
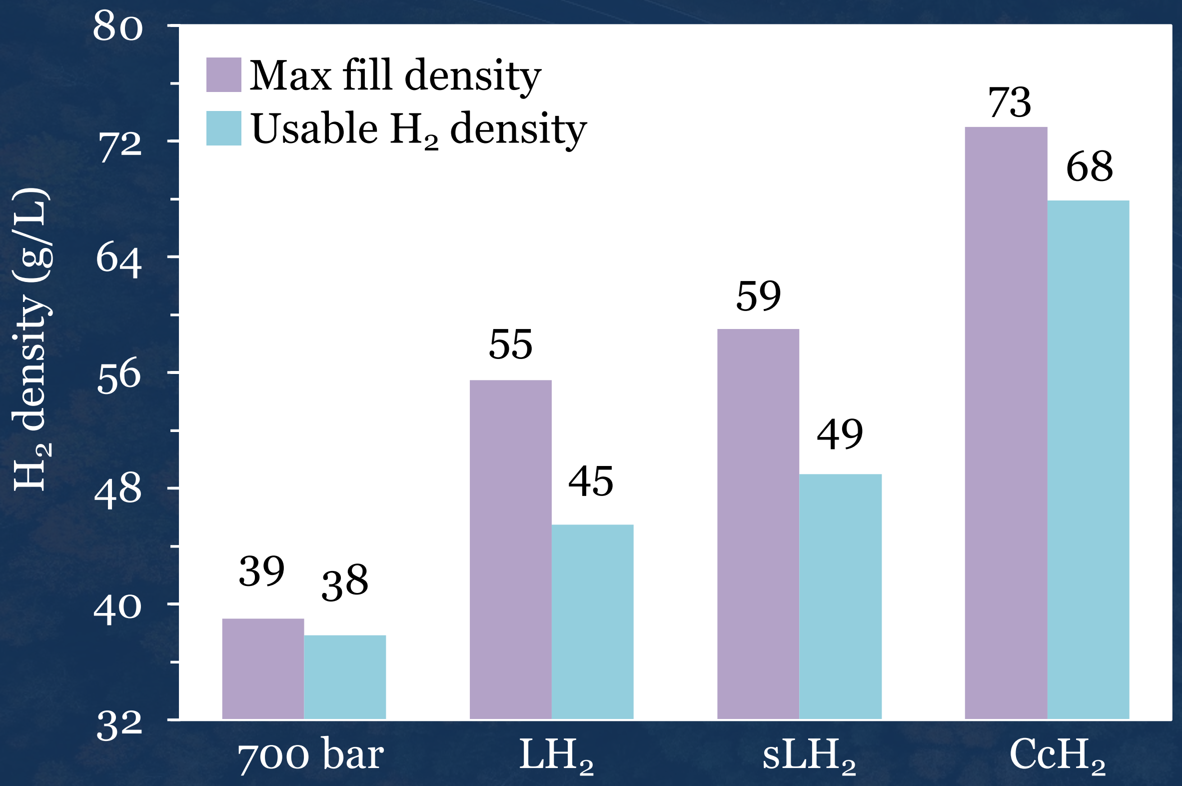
CcH_2 shows usable density of 93% or 68 g/L



CcH_2 exhibits the highest H_2 usable densities

Max density and usable density comparison



- sLH_2 systems exhibit 30% greater usable density relative to 700 bar
- CcH_2 exhibits 80% higher usable density relative to 700 bar
- CcH_2 exhibits 40% higher usable densities relative to sLH_2

Notes: For refueling, assumes 6 kJ/kgK for CcH_2 and 60% isentropic efficiency for LH_2 systems. In-tank heating is assumed for cryogenic solutions. Usable capacity % based on analysis as shown before. Max fill density assumes 6 bar and 28 K (59 g/L) with 6% ullage.

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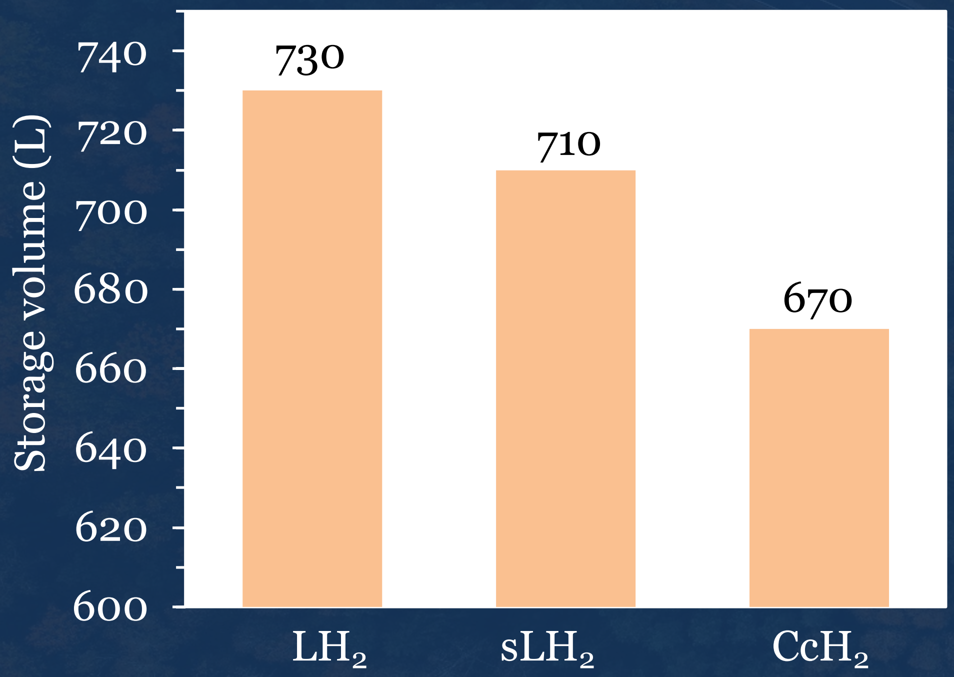
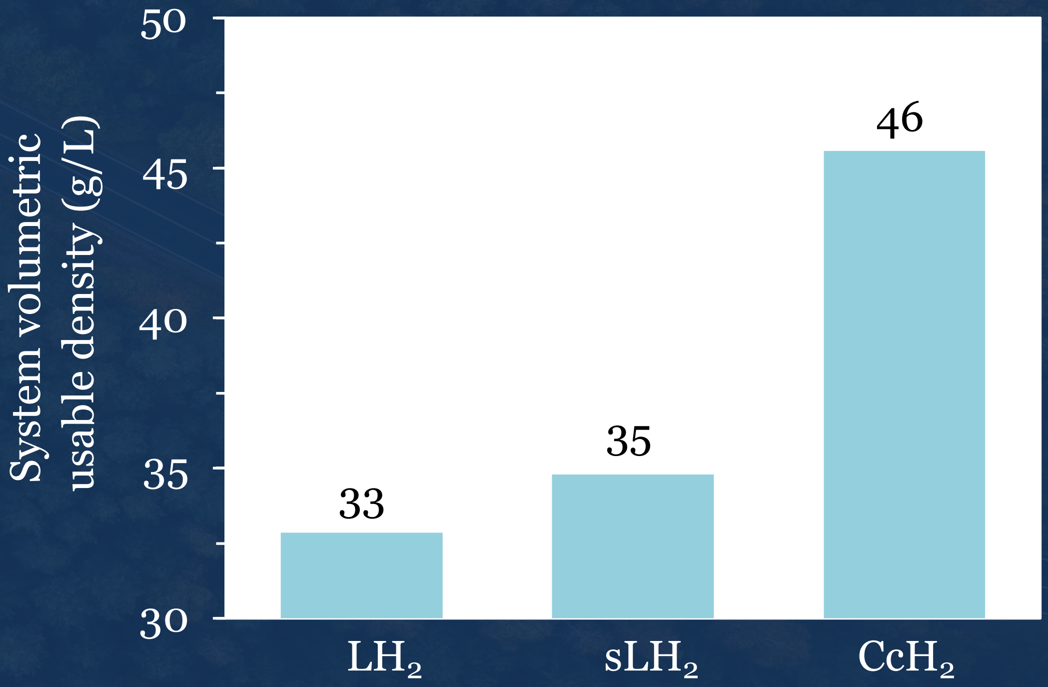
These high H_2 densities enable highest system volumetric usable densities

Given an external volume of 1,000L:
Remaining volume available for H_2 storage



Given an external volume of 1,000L:
System volumetric usable density



- CcH_2 has lower storage volume available but, due to much higher usable densities, the overall system volumetric density is highest for CcH_2

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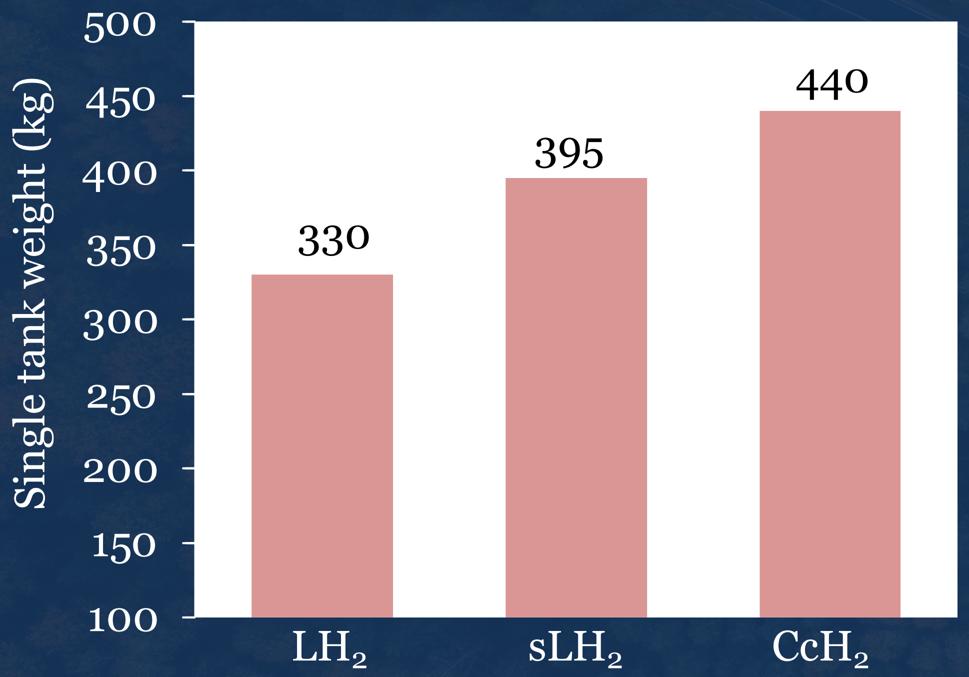
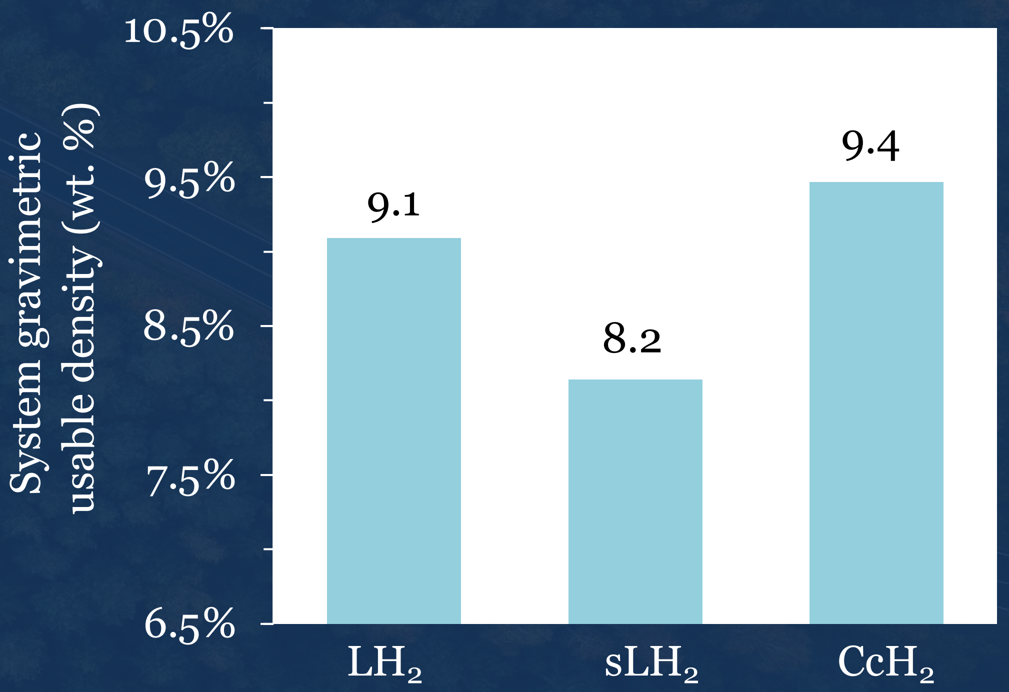
Notes: Some BOP considered. A helpful metric is volumetric efficiency (storage volume/outer volume). LH_2 and sLH_2 volume based on various inputs, including SAG White Paper, 2022.

And unlocks highest system gravimetric usable density

Given an external volume of 1,000L:
Weight of tank without H_2



Given an external volume of 1,000L:
System gravimetric usable density



- CcH_2 tank system without H_2 is heavier but, due to much higher usable densities, the overall system gravimetric density is highest for CcH_2

VERNE **Notes:** BOP considered, such as in-tank heater, external heater, H_2 tubing. LH_2 and sLH_2 volume based on various inputs, including SAG White Paper, 2022.

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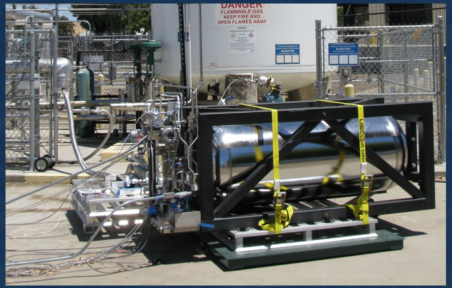
Rapid development progress since 2022

Closed Investment Round

Full-scale storage systems built

On-road vehicle demo with driving >100 mph

Lawrence Livermore National Laboratory

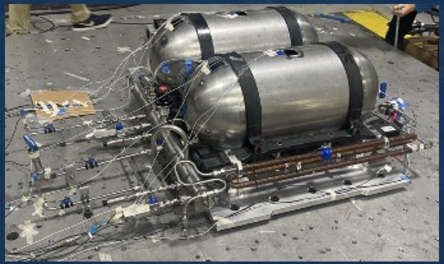


30 kg system demonstrated

2022 | **2023**

DOE ARPA-E Project started

Multi-tank system tested for durability



Fleet LOI 's for >150 trucks with Verne storage systems

Multiple Class 8 Truck Fleets

Four programs with OEMs on Verne storage systems

Four different HD OEMs

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Key upcoming milestones for Verne CcH_2 trucking

Class 8 truck demos
with 2 OEMs

Two top 10 fleets
planning subsequent
pilots

2024 – 2026

First truck pilot:
Multiple trucks, 2 fleets, >1 year

Full truck and refueling
commercial operations
in late 2026

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Final takeaways

1. **The metrics that matter include steady-state usable system densities:**
   - CcH_2 enables 30% greater usable volumetric system density

2. **Multiple CcH_2 tests have all been successfully completed**
   - Verne has completed CcH_2 vehicle pilot and multiple tank system demo's

3. **Verne is now working on integrations with Class 8 trucks**
   - Multiple fleets and OEMs for first pilots
   - Results from early demos can help inform key stakeholders on H_2 rollout

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A team of global experts

Leadership

Ted McKlveen
CEO
Bain & Company

David Jaramillo
CTO
Berkeley University of California

Bav Roy
COO
BCG, UNSW Australia

Kaushik Mallick
Head of H_2 Storage
Steelhead Composites, Quantum Fuel Systems

Vincent Heloin
Head of H_2 Engineering
Air Liquide, SLAC

Advisory Board

Tom Linebarger
Ex-CEO Cummins
Cummins

Salvador Aceves
Cryo-compression
Lawrence Livermore National Laboratory

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Ryan Kemmet
Truck Fuels
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John Formisano
HD Truck Fleet
FedEx

Dolly Singh
Talent
SpaceX

Technical Consultants

Rob Pahl
Metals R&D
Alcoa

Markus Kampitsch
Hydrogen Vehicles
BMW

Funding

Grants
Breakthrough Energy, arpa-e U.S. Department of Energy

Private
amazon, Caterpillar

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A diesel-free future. Powered by Verne.

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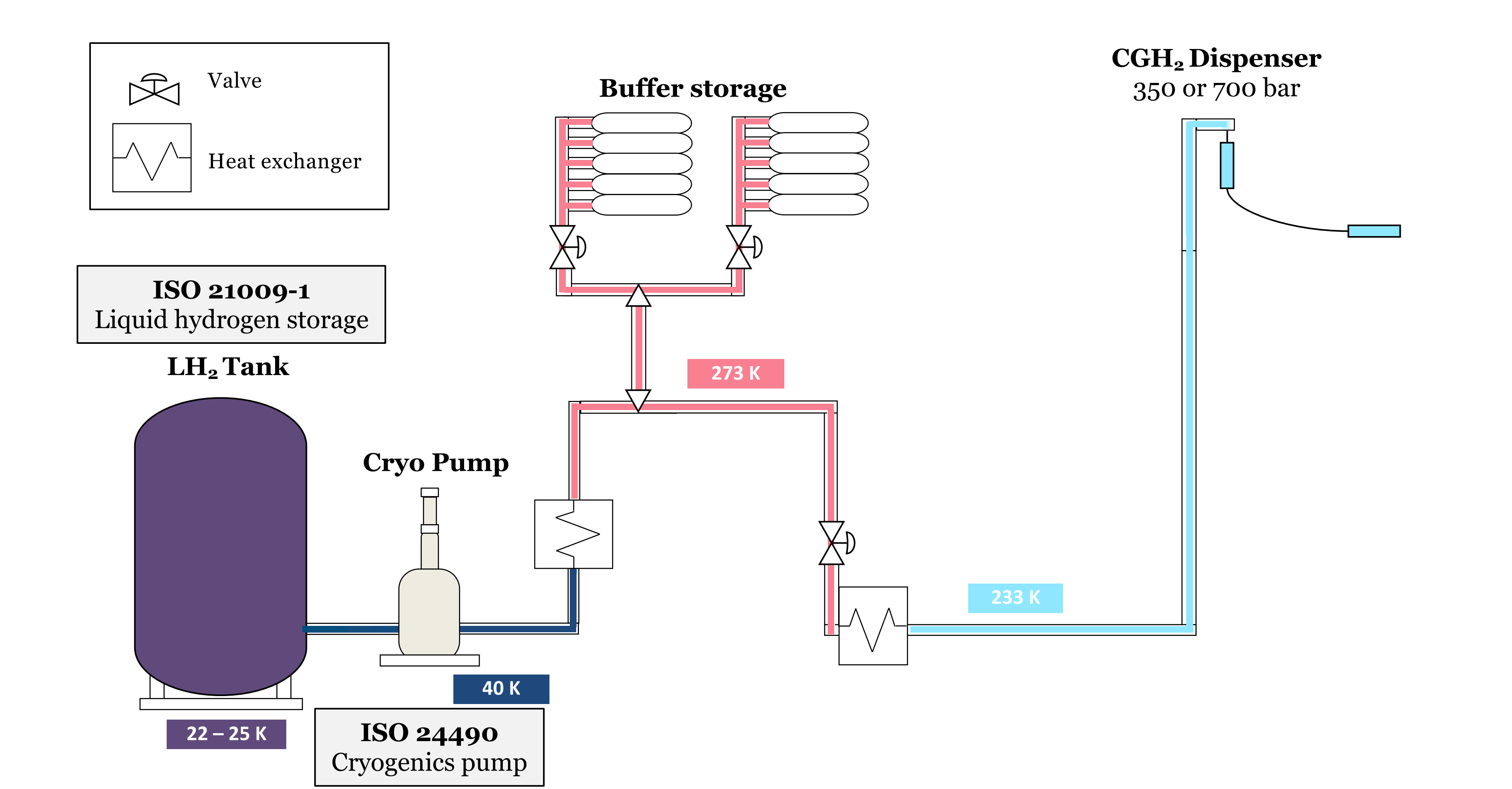
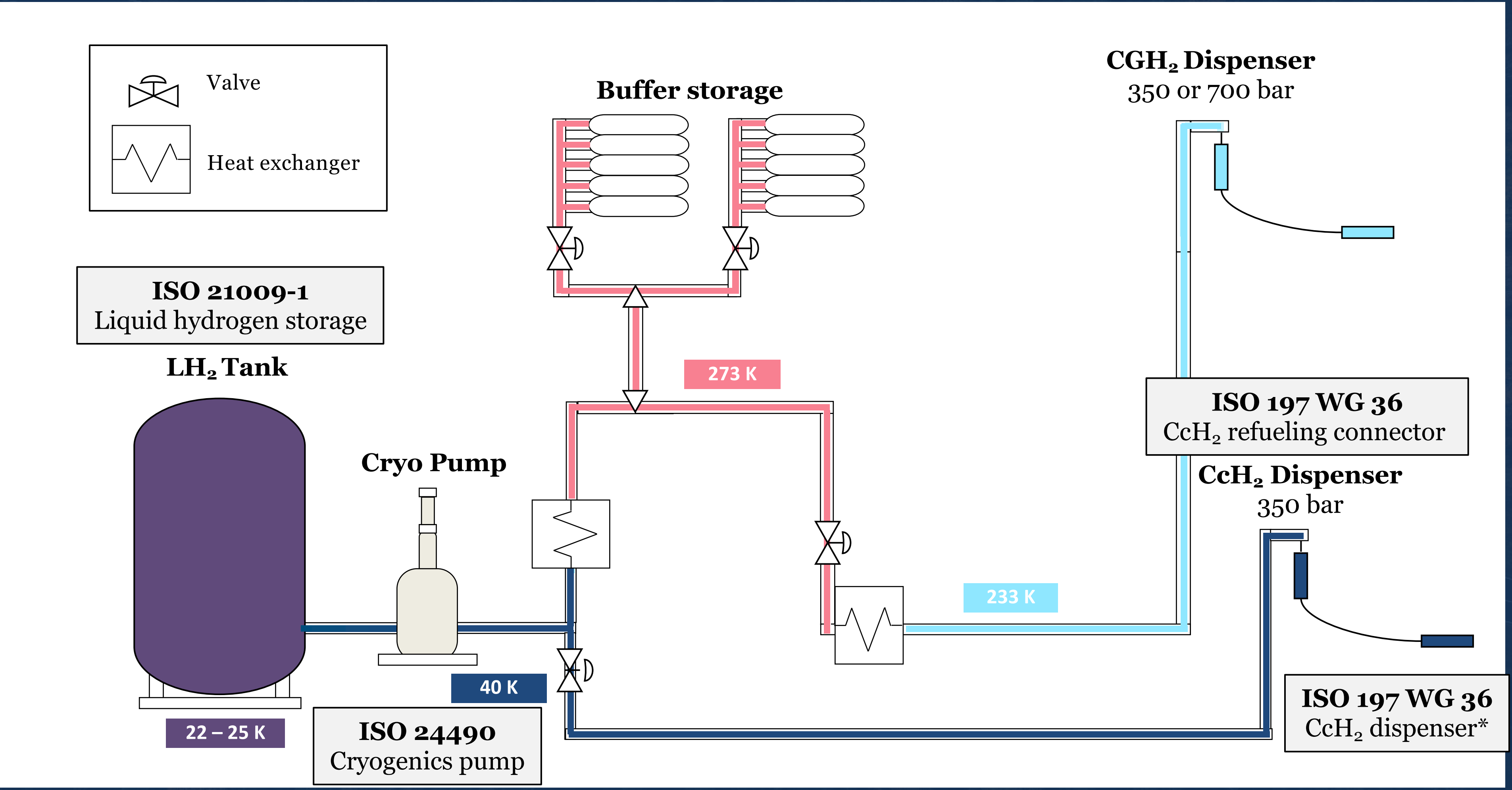
CcH_2 refueling from LH_2 requires minimal modification



CcH_2 refueling from LH_2 requires minimal modification



*ISO 197 WG 36 is currently focused on refueling connectors. The CcH_2 dispenser Work Item has not yet started

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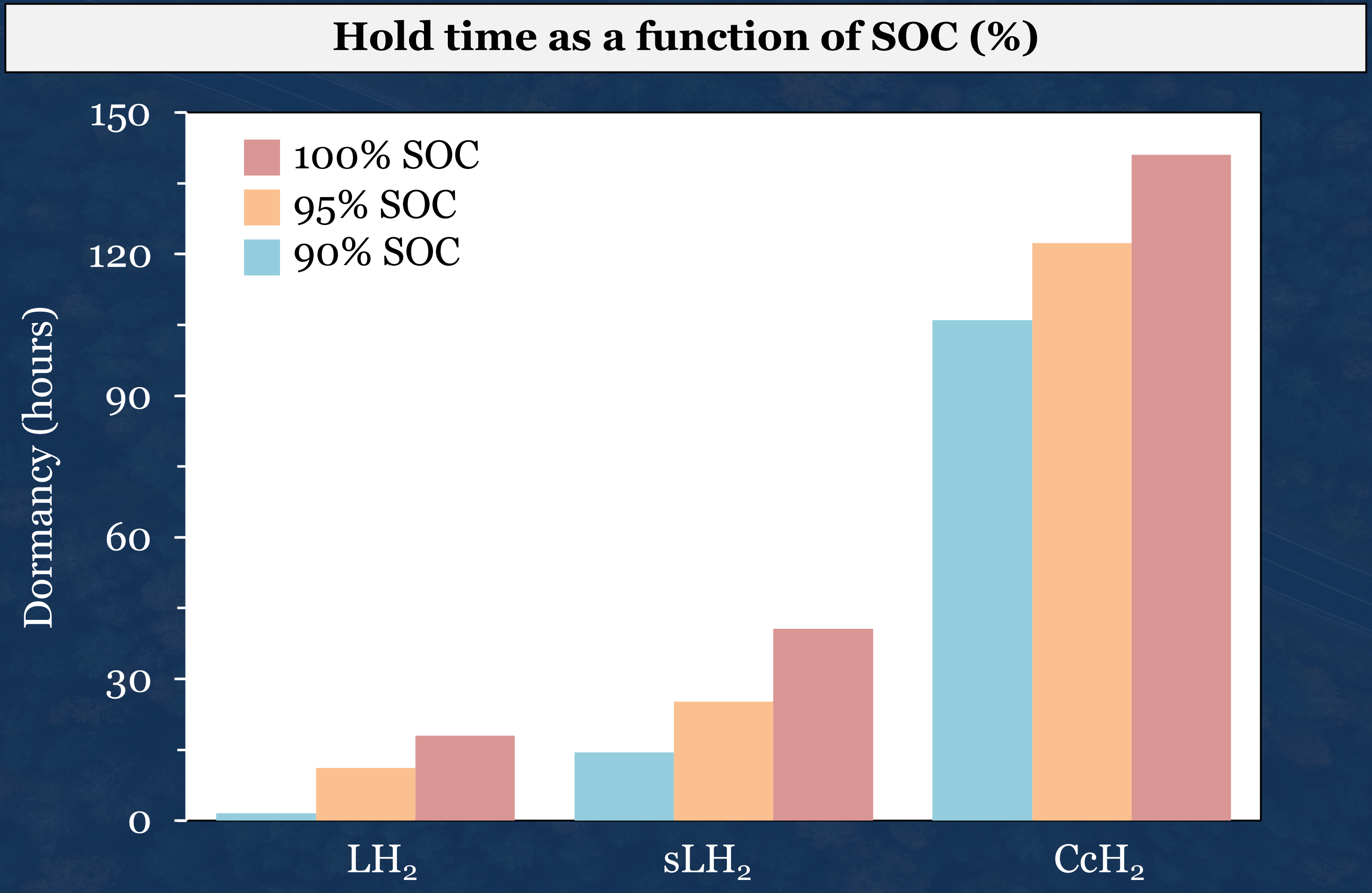
Magnitude improvement in dormancy unlocks use cases and low-cost system designs



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