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TO MAKE OUR PLANET GREEN, AGAIN

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CRYOGAS / CRYO-COMPRESSED HYDROGEN GAS FUELING

TECHNOLOGY OPPORTUNITIES, CHALLENGES, ROADMAP AND STANDARDIZATION NEEDS

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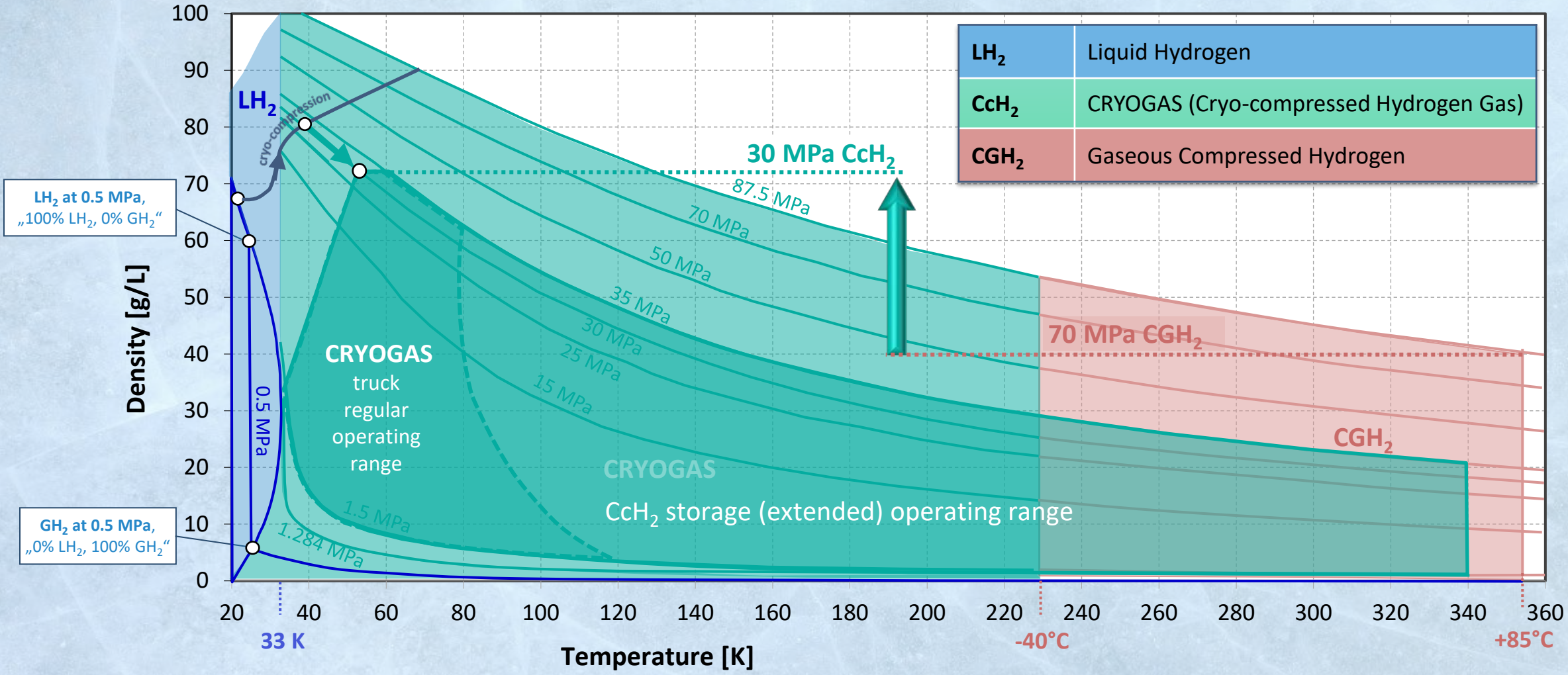
WHAT IS CcH_2-CRYOGAS?

Cryo-compressed Hydrogen Gas (CcH_2)

- Compressed gaseous hydrogen up to 35 MPa at cryogenic temperature (30 K – 200 K, extended range 30 K – 340 K)
- Generated by cryo-compression of liquid hydrogen (LH_2) or by cryo-cooling of gaseous hydrogen (GH_2)
- Denser than liquid hydrogen (LH_2) at the pump: up to 80 g/L and more
- A vehicle fuel for onboard storage with good heat receptivity and strong self-cooling capability
- A fuel for quick single-flow fueling with no need for communication between station and vehicle

CRYOGAS / CRYO-COMPRESSED HYDROGEN REFUELING

THERMODYNAMIC CLASSIFICATION AND OPERATING RANGE



CRYOGAS / CRYO-COMPRESSED HYDROGEN REFUELING

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CcH_2-CRYOGAS ONBOARD STORAGE OPPORTUNITIES

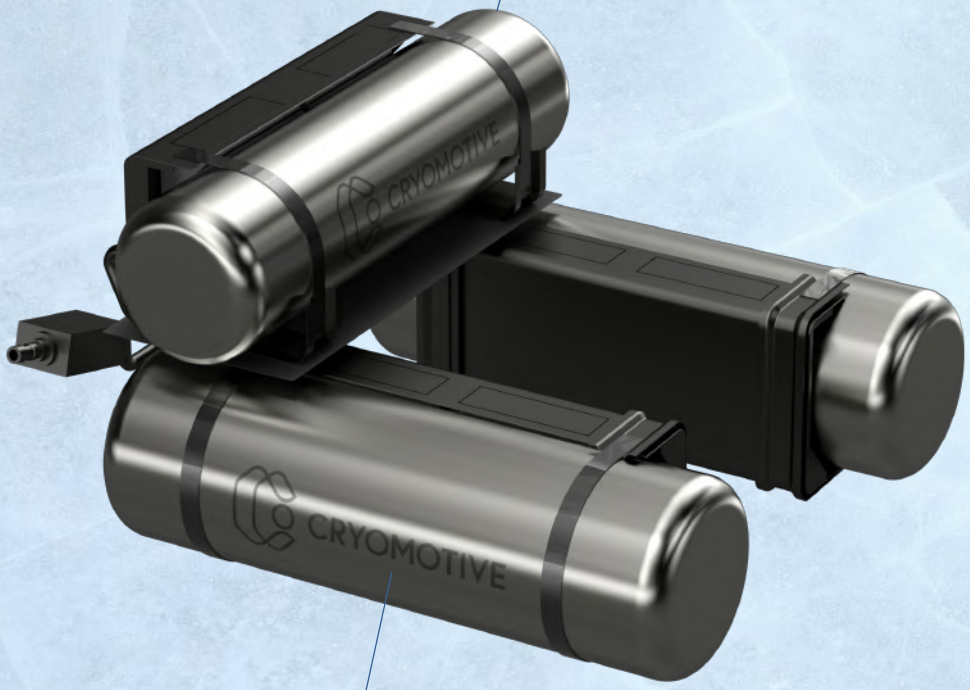
Cryo-compressed Hydrogen Storage
=
CRYOGAS storage in
an insulated cryogenic pressure vessel

- High physical and system storage density
  - 40% higher volumetric system density than CGH_2 70 MPa in a typical truck package
  - 10 times lighter than a battery in a battery electric truck with the same range
- Lighter than high-pressure gaseous hydrogen storage at 35 MPa and 70 MPa
- Flexible package integration in multi-vessel configurations
- Adaptive pressure supply to power any fuel cell and hydrogen internal combustion engine
- Robust thermal behavior allows a simplified mass producible insulation
- Cost-effective design: moderate material and manufacturing cost

CRYOGAS ONBOARD STORAGE OPPORTUNITIES

STORAGE CAPACITY, WEIGHT AND INSULATION OPPORTUNITIES

Behind the cabin:
25 - 30 kg CcH_2 per vessel



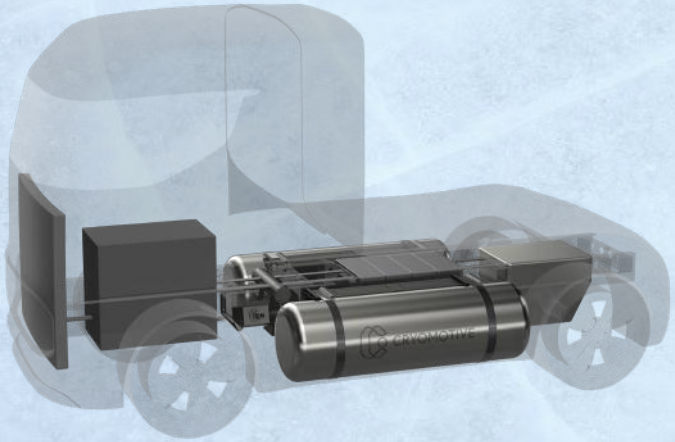
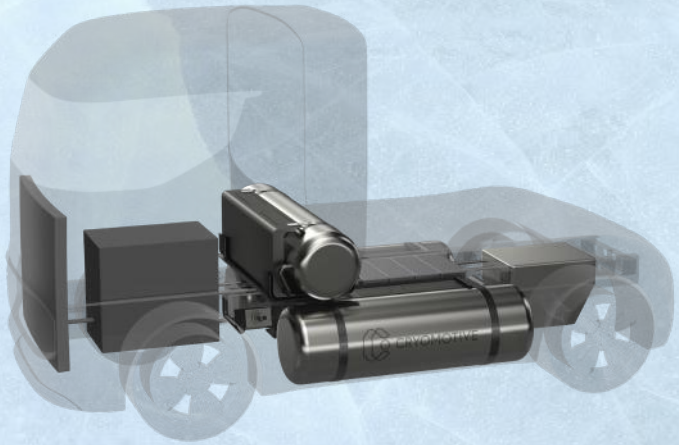
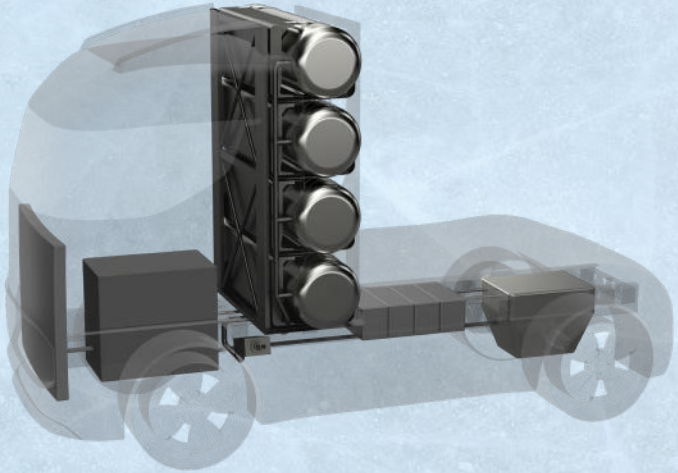
Frame-integrated:
35 - 40 kg CcH_2 per vessel

• Storage capacity per vessel:	10 – 100 kg CcH_2
• Storage system gravimetric density in typical truck configurations:	8 – 10 wt.-%
• Storage system volumetric density in typical truck configurations:	1.2 – 1.5* kWh/L_{system} * for large vessels
• Insulation demand for loss-free operation in typical truck configurations:	20 – 50 W heat leak
• Minimum holding time before vent (@ 100% capacity):	1 – 2 days according to insulation design
• Average holding time before vent (@ 50% capacity):	10 – 30 days according to insulation design

CRYOGAS ONBOARD STORAGE OPPORTUNITIES

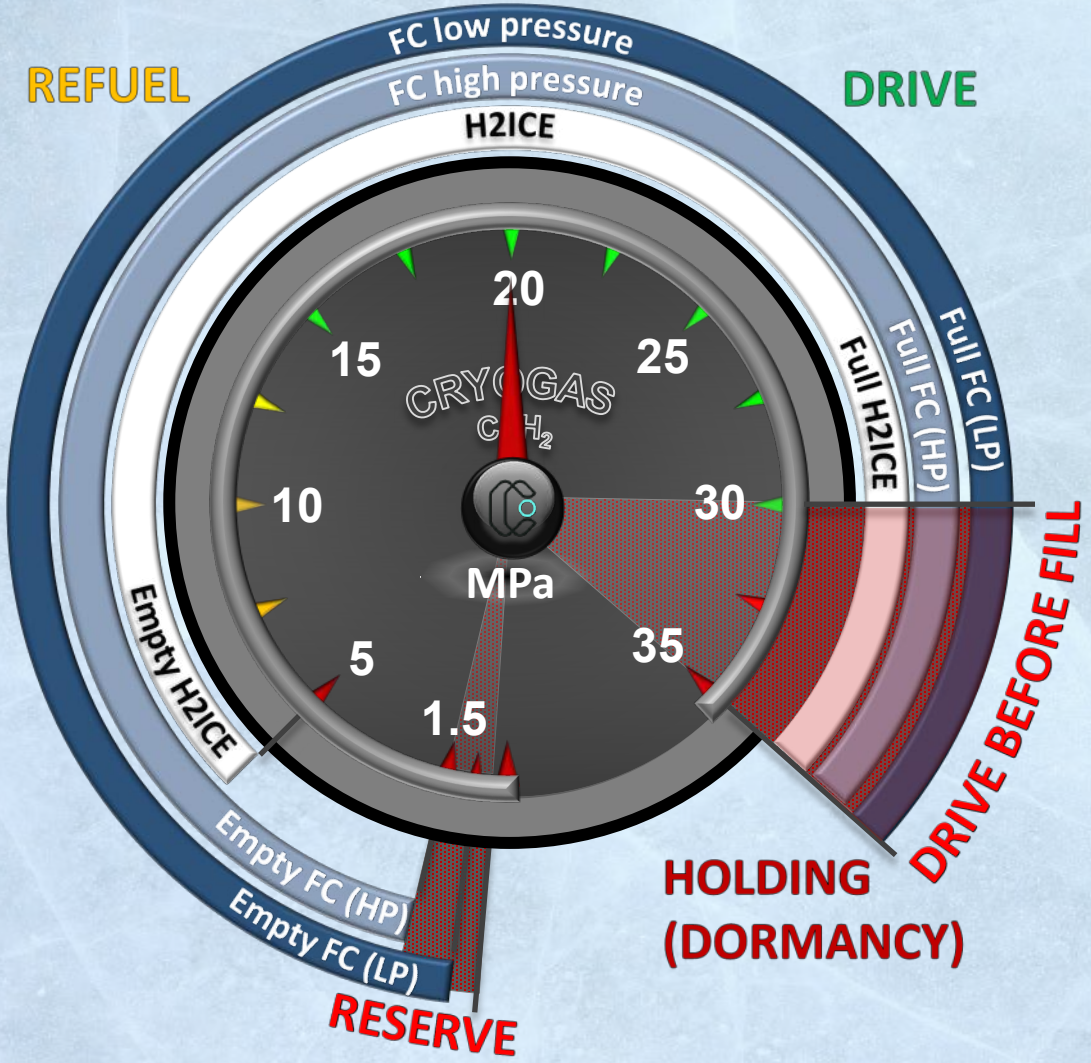
FLEXIBLE VEHICLE INTEGRATION IN MULTI-VESSEL CONFIGURATIONS IN TRUCKS

CcH_2 CRYOGAS storage offers flexible multi-vessel integration options with total capacities up to 115 kg CcH_2:

2-tank CcH_2 storage system along the frame	3-tank CcH_2 storage system along the frame and behind the cabin	4-tank CcH_2 storage system behind the cabin
		
up to 78 kg CcH_2	**up to 105 kg CcH_2**	**up to 115 kg CcH_2**

CRYOGAS ONBOARD STORAGE OPPORTUNITIES

PRESSURE SUPPLY TO POWER ANY FUEL CELL AND HYDROGEN INTERNAL COMBUSTION ENGINE

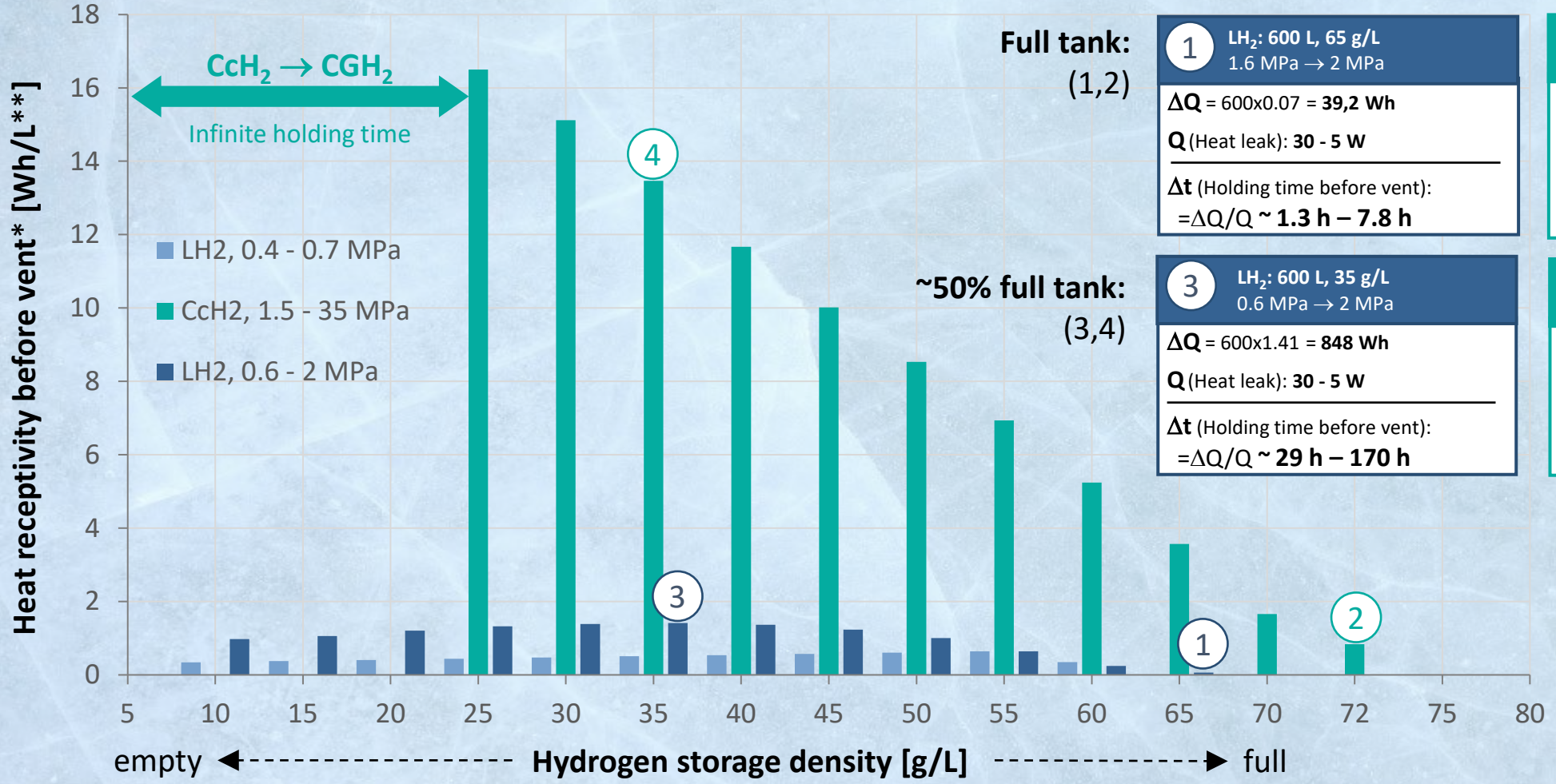


- Usable range depends on the minimum supply pressure between 0.6 MPa and 5 MPa to 30 MPa
- Drive before fill is required in a storage pressure range between 30 and 35 MPa**
- Minimum supply pressure to the fuel cell / hydrogen engine can be adapted in a range of 0.5 MPa and 5 MPa
- Usable storage densities at full power vary according to supply pressure demand:
  - Fuel Cell (1.5 MPa*): 66 g/L
  - Fuel Cell (0.6 MPa*): 69 g/L
  - H2ICE / Engine (5 Mpa*): 58 g/L
- Reserve mode strategies will enable total usable densities up to 70 g/L

*) pressure demand at the fuel cell /engine regulator
**) Pressure of 30 to 35 MPa can only occur after longer dormancy; the remaining range stays above 40% of the maximum capacity

CRYOGAS ONBOARD STORAGE OPPORTUNITIES

HIGH HEAT RECEPTIVITY ALLOWS A SIMPLIFIED INSULATION WITH STILL LONG HOLDING TIME (DORMANCY)



Full tank:
(1,2)

~50% full tank:
(3,4)

1 **LH_2: 600 L, 65 g/L**
1.6 MPa → 2 MPa

ΔQ = 600x0.07 = **39,2 Wh**

Q (Heat leak): **30 - 5 W**

Δt (Holding time before vent):
=ΔQ/Q **~ 1.3 h – 7.8 h**

2 **CcH_2 CRYOGAS: 600 L, 72 g/L**
30 MPa → 35 MPa

ΔQ = 600x0.85 = **503 Wh**

Q (Heat leak): **30 - 5 W**

Δt (Holding time before vent):
=ΔQ/Q **~ 16,8 h - 101 h**

3 **LH_2: 600 L, 35 g/L**
0.6 MPa → 2 MPa

ΔQ = 600x1.41 = **848 Wh**

Q (Heat leak): **30 - 5 W**

Δt (Holding time before vent):
=ΔQ/Q **~ 29 h – 170 h**

4 **CcH_2 CRYOGAS: 600 L, 35 g/L**
1.5 MPa → 35 MPa

ΔQ = 600x13.47 = **8080 Wh**

Q (Heat leak): **30 - 5 W**

Δt (Holding time before vent):
=ΔQ/Q **~ 11 days – 67 days**

*) net hydrogen volume
**) per liter net hydrogen volume

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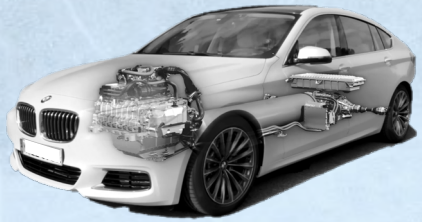
CcH_2-CRYOGAS ONBOARD STORAGE CHALLENGES

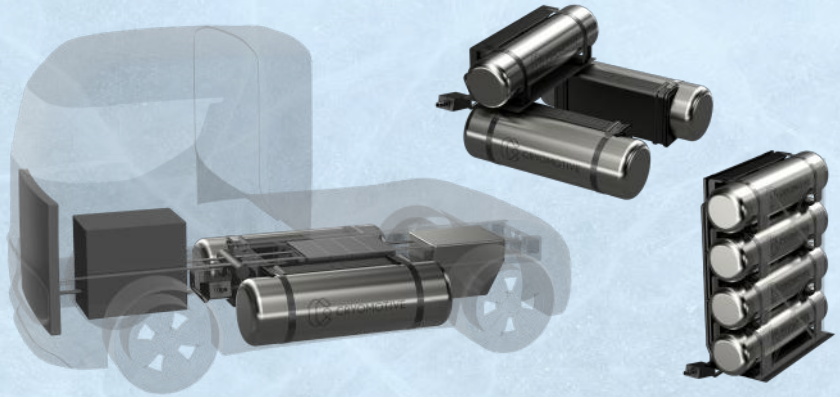
Technology Transfer Challenges

- Transfer storage design from passenger car to commercial vehicle applications
  - Use opportunities by continuous operation and large vessel dimensions
  - Optimize thermal design to simplify insulation and improve fuel cell cooling
  - Design for longer durability
- Standardize design to deploy to multiple applications
- Design-to-Manufacturing and Design-to-Cost

CRYOGAS ONBOARD STORAGE CHALLENGES

NEW REQUIREMENTS IN A TRUCK ENVIRONMENT





340 mm / 2000 mm	**Dimensions**	**600 - 700 mm** / 2350 - 2650 mm
7 kg	**Capacity**	**75 - 115 kg**
Single vessel	**System**	**Multiple vessels** (2 – 4)
-230°C to +85°C	**Operating range**	-230°C to -**150°C**
5.500 h / 500 refueling cycles	**Durability**	**30.000 h / 2000** refueling cycles
2 kg/min	**Refueling**	**8 - 10 kg/min**
Low	**Cooling need for the drive** (fuel cell)	**High** (e.g. uphill climbing)

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CcH_2-CRYOGAS REFUELING

Refueling Strategies and Concepts

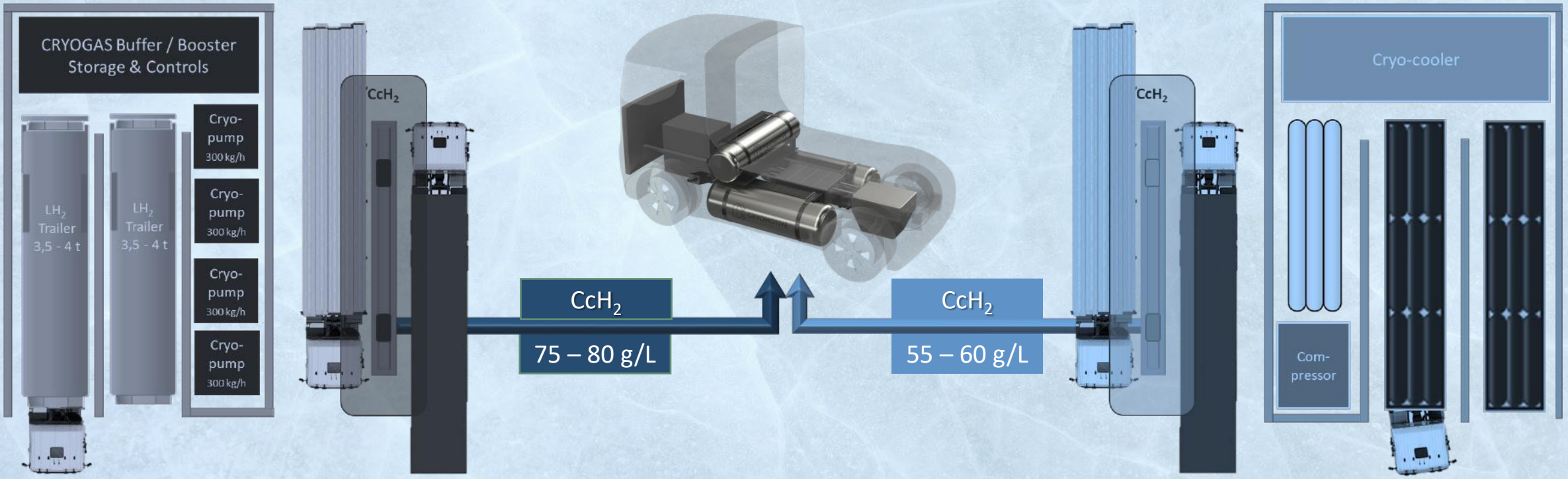
- Flexible CcH_2 refueling station concept
  - CcH_2-CRYOGAS from cryo-compression of liquid hydrogen (LH_2)
  - CcH_2-CRYOGAS from cryo-cooling of gaseous hydrogen (35 MPa CGH_2)
- Leverage synergies with 35 MPa infrastructure
  - Combine CcH_2-CRYOGAS and H35 stations with LH_2 supply and cryo-compression
  - Combine CcH_2-CRYOGAS and H35 stations with GH_2 supply and cryo-cooling

CRYOGAS REFUELING

FUEL FLEXIBILITY BY FILLING CRYOGAS FROM LH_2 AND CRYO-COOLED CGH_2

CcH_2 CRYOGAS FROM CRYO-COMPRESSION OF LH_2

CcH_2 CRYOGAS FROM CRYO-COOLING OF GH_2

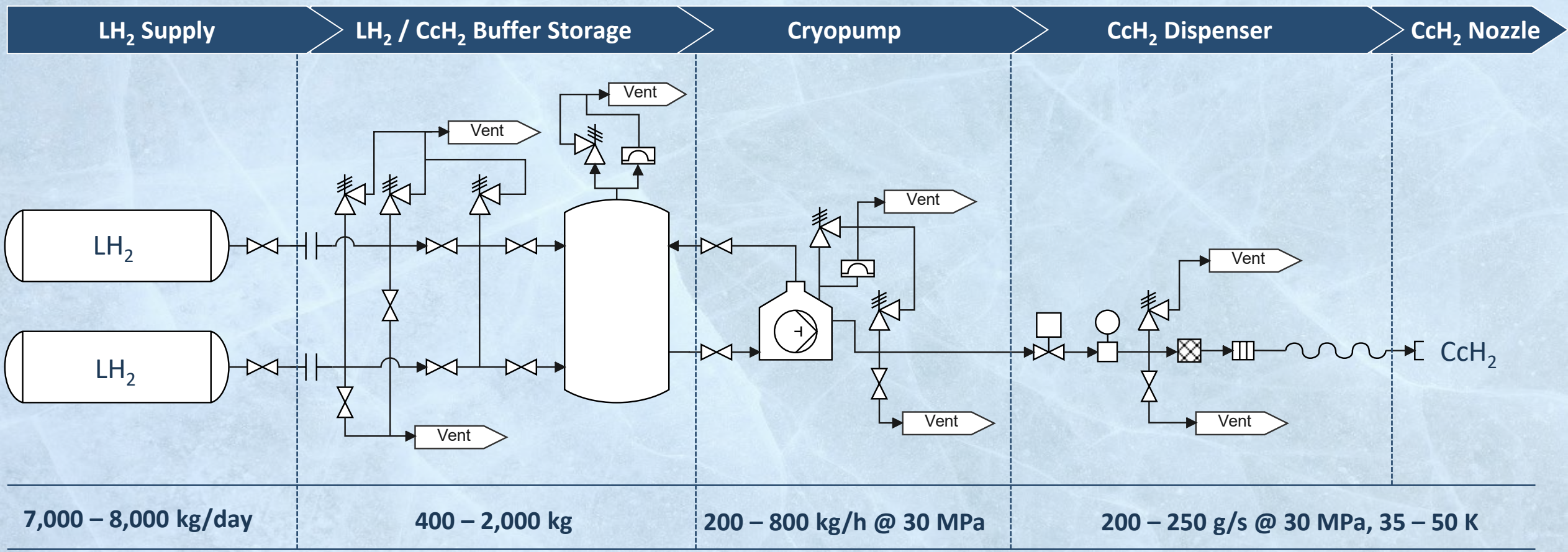


CRYO-COMPRESSION TO 30 MPa

CRYO-COOLING TO 77 – 80 K

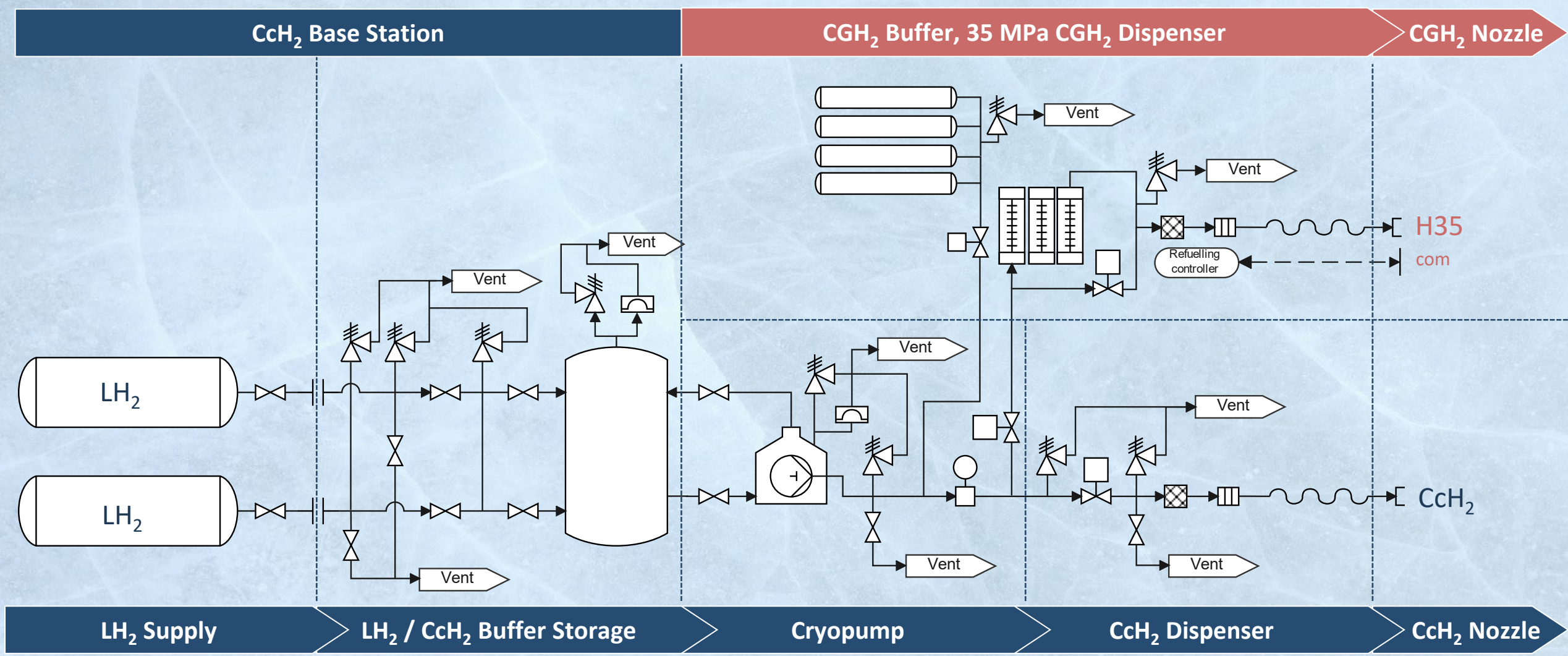
CRYOGAS REFUELING

REFUELING STATION CONCEPT: STAND-ALONE CRYOGAS REFUELING STATION



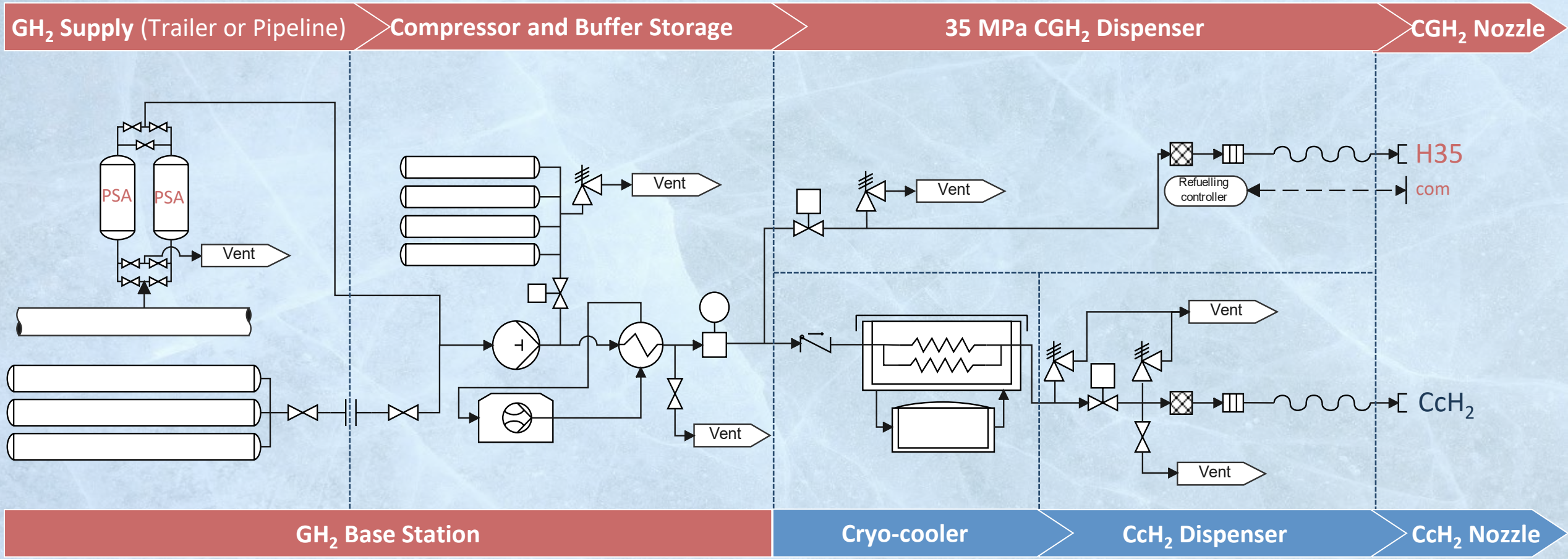
CRYOGAS REFUELING

REFUELING STATION CONCEPT: COMBINED CRYOGAS – 35 MPa CGH_2 STATION WITH LH_2 SUPPLY



CRYOGAS REFUELING

REFUELING STATION CONCEPT: COMBINED CRYOGAS – 35 MPa CGH_2 STATION WITH GH_2 SUPPLY



CRYOGAS REFUELING
SINGLE-FLOW NON-COM DISPENSING OPPORTUNITIES

• **Low energy needed for cryogenic LH_2 compression (< 0.5 kWh/kg) – high efficiency and least cost of energy**	✓
• Direct cold gas refueling to 30 MPa via cryopump with / without booster (**no pre-cooling, no heat exchange for warm-up**)	✓
• up to 800 kg/h fill rate doable (⇒ **13 kg/min**); no thermal limitation of flow rate	✓
• **No need for communication** between vehicle and dispenser	✓
• **Compact nozzle design** with **integrated air purging, leak monitoring, and freeze protection**	✓
• **Robust: loss-free refueling** at low and high utilization of the station; no need for service refueling capability	✓

Picture Sources: BMW, GRC Fuel Cells, 2014

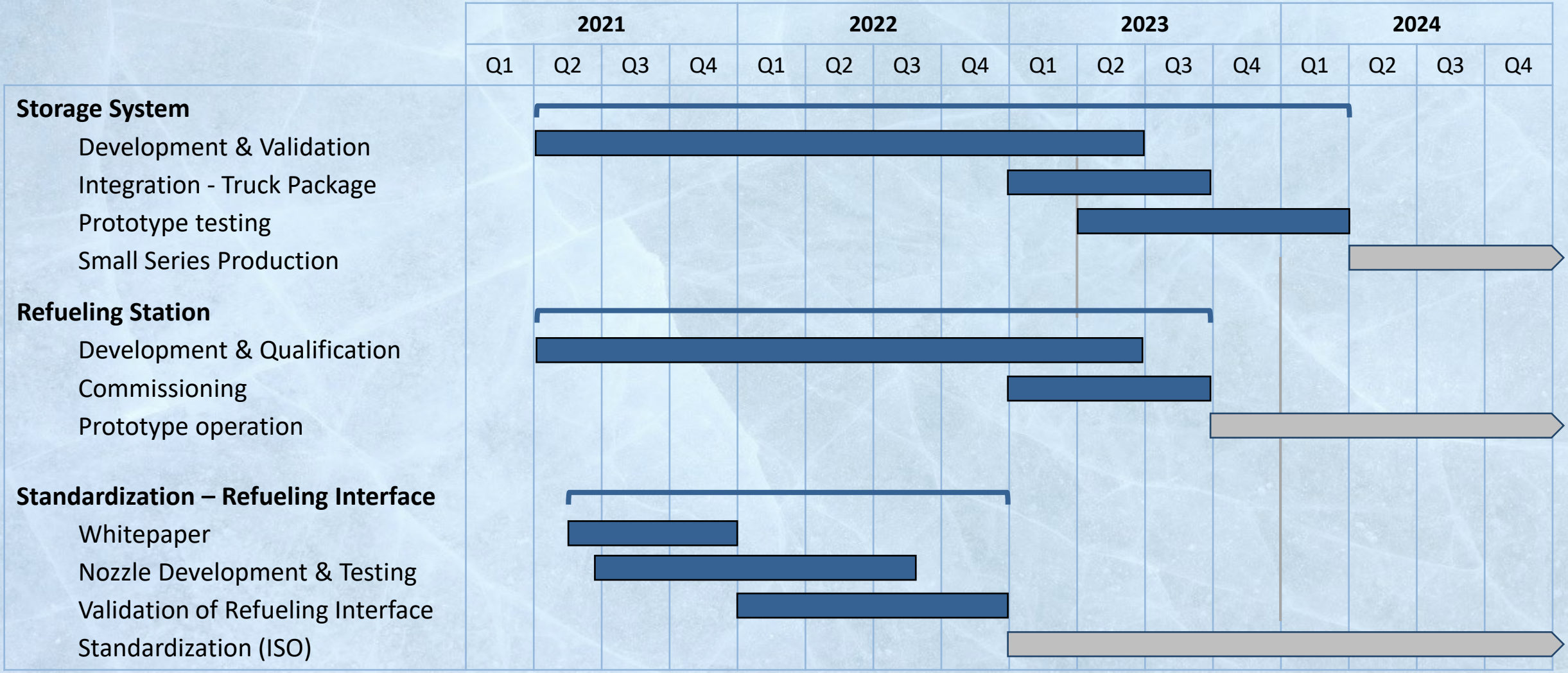
CRYOGAS ROADMAP

Development and Deployment Roadmap for CcH_2 CRYOGAS Storage and Refueling

- **Phase 1: 2021 - 2023**
  - Develop and validate a first truck CcH_2 storage system
  - Develop and validate a high-flow nozzle (200 – 250 g/s)
  - Develop and validate two CcH_2 prototype stations: 1x with LH_2 supply and 1x with GH_2 supply
  - START CcH_2 REFUELING INTERFACE STANDARDIZATION
- **Phase 2: 2024 - 2025**
  - Deploy a first small series of truck storage systems
  - Deploy the first CcH_2 stations on depots and public ground
  - Set-up manufacturing JVs in key markets
  - Transfer technology to further applications
  - COMPLETE REFUELING INTERFACE STANDARDIZATION
- **Phase 3: 2025+**
  - Scale-up of storage and station deployment

CRYOGAS ONBOARD STORAGE STATUS QUO

DEVELOPMENT PLAN: PHASE 1 2021 - 2023



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THANK YOU FOR YOUR ATTENTION

OPEN FOR QUESTIONS

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