CryoH$_2$

Enabling practical & affordable hydrogen at scale(s)

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How will H_2 scale up ?

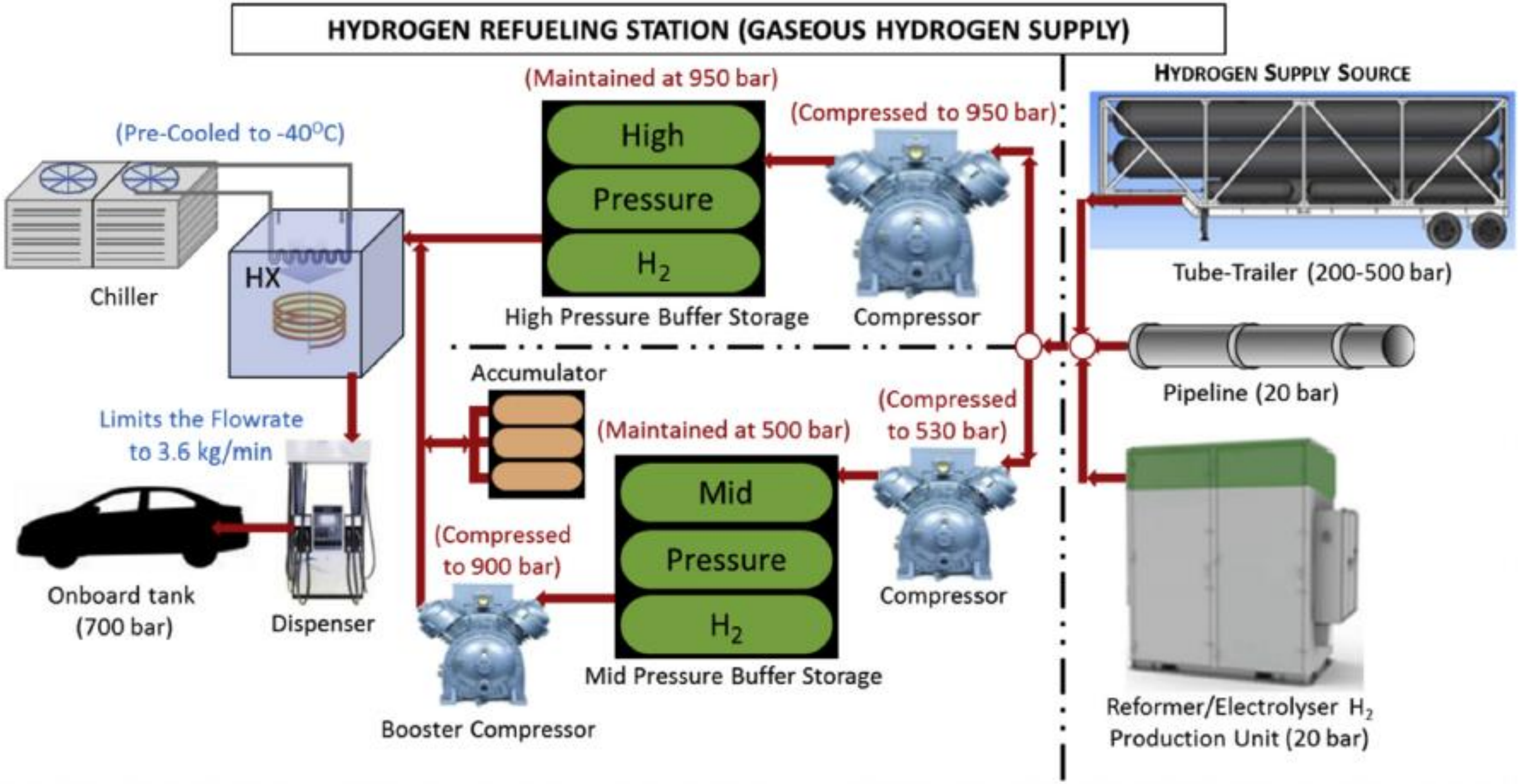
1 hose, 200 kgH_2 /day

Today

8 hoses, 4000 to 6000 kgH_2/day

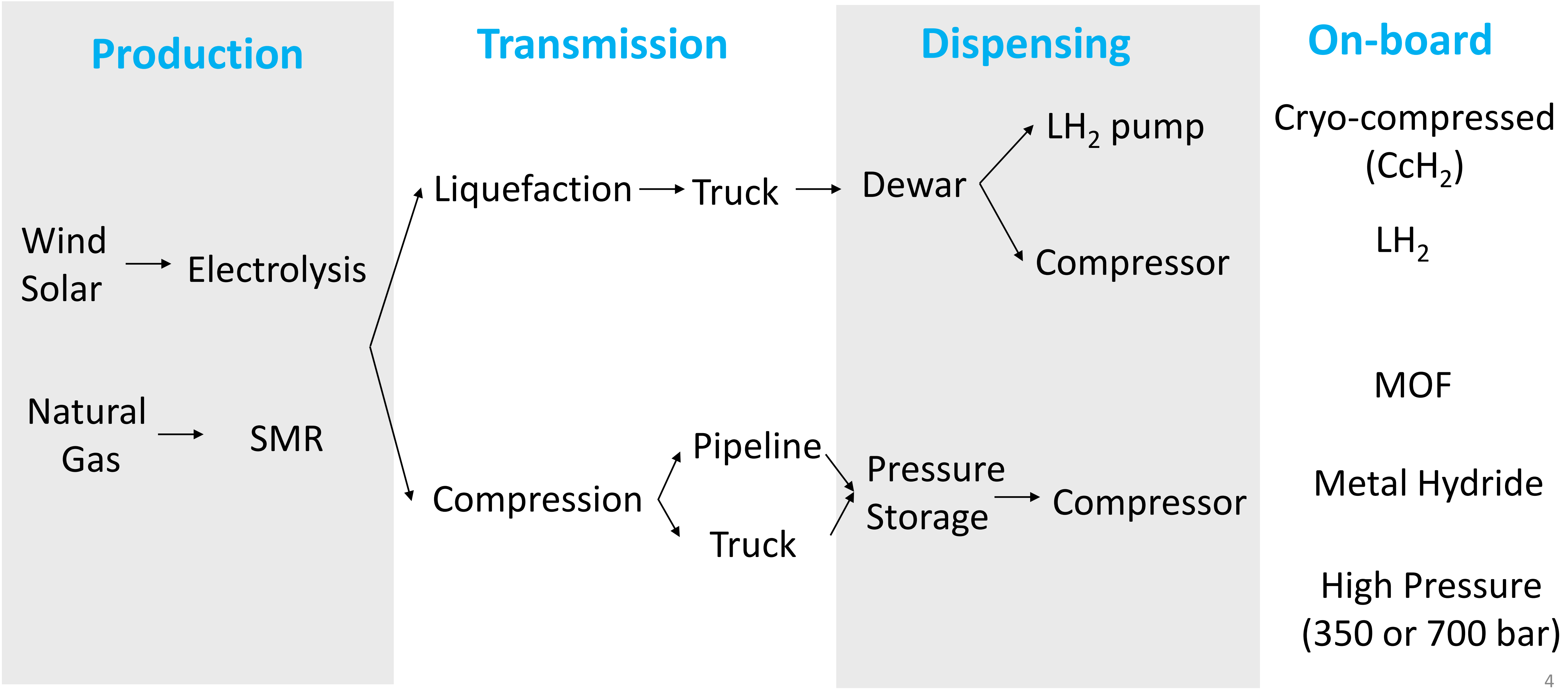
Tomorrow

Today's standard: 700 bar refueling with pre-cooling

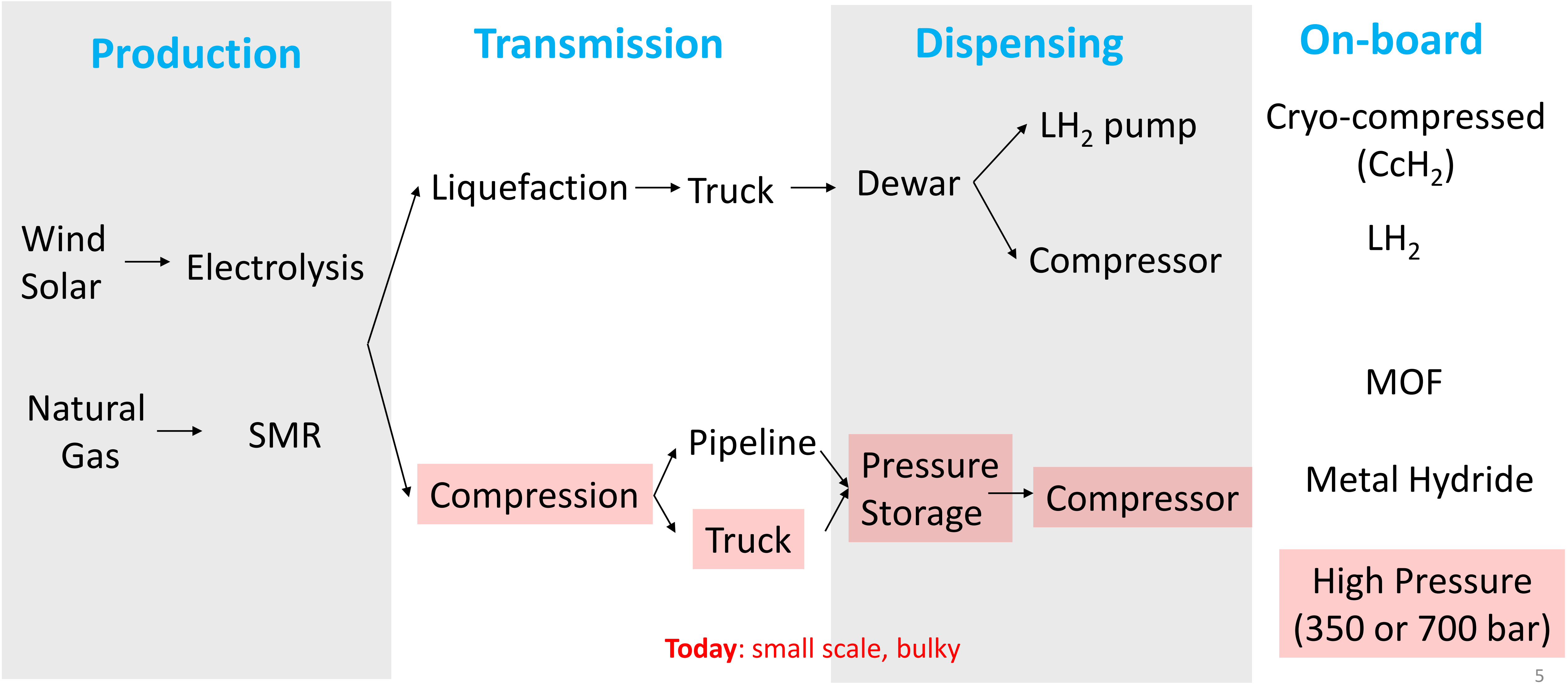


Does "multiplying" this design for large stations make sense ?

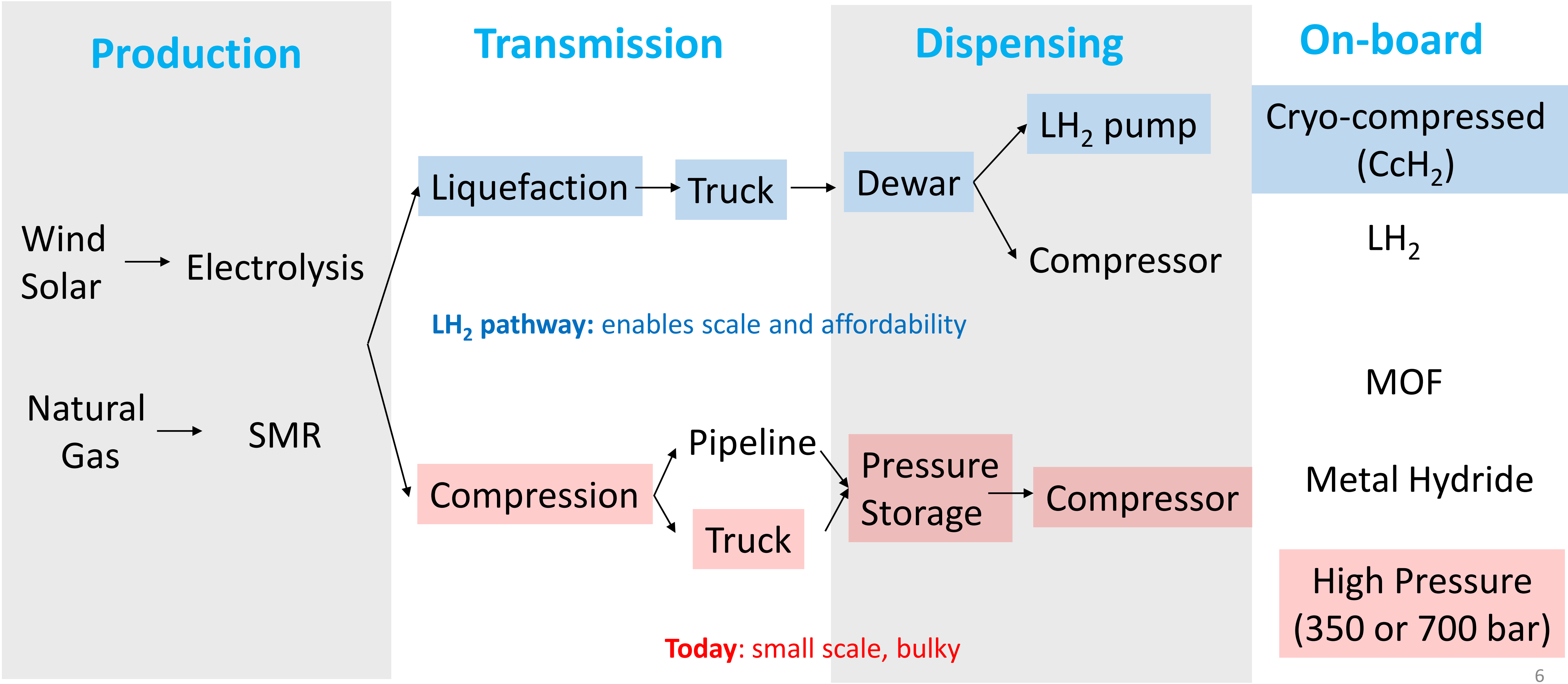
Different options exist for H_2 infrastructure



Different options exist for H_2 infrastructure

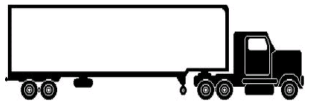


Different options exist for H_2 infrastructure



Liquid hydrogen (LH_2) has many benefits, especially at large scale(s)

- High density LH_2 allows minimum volume & mass, thus **minimum storage & transmission cost**
- High capacity per truck & short transfer times **facilitates delivery logistics/scheduling**
- **Low potential burst energy**: 20 K and <6 bar vs. 300 K and >200 bar
- LH_2 pumps provide **high throughputs at low dispensing costs**
- High density of LH_2 can be transferred to **compact onboard solutions** (cryo/cold)



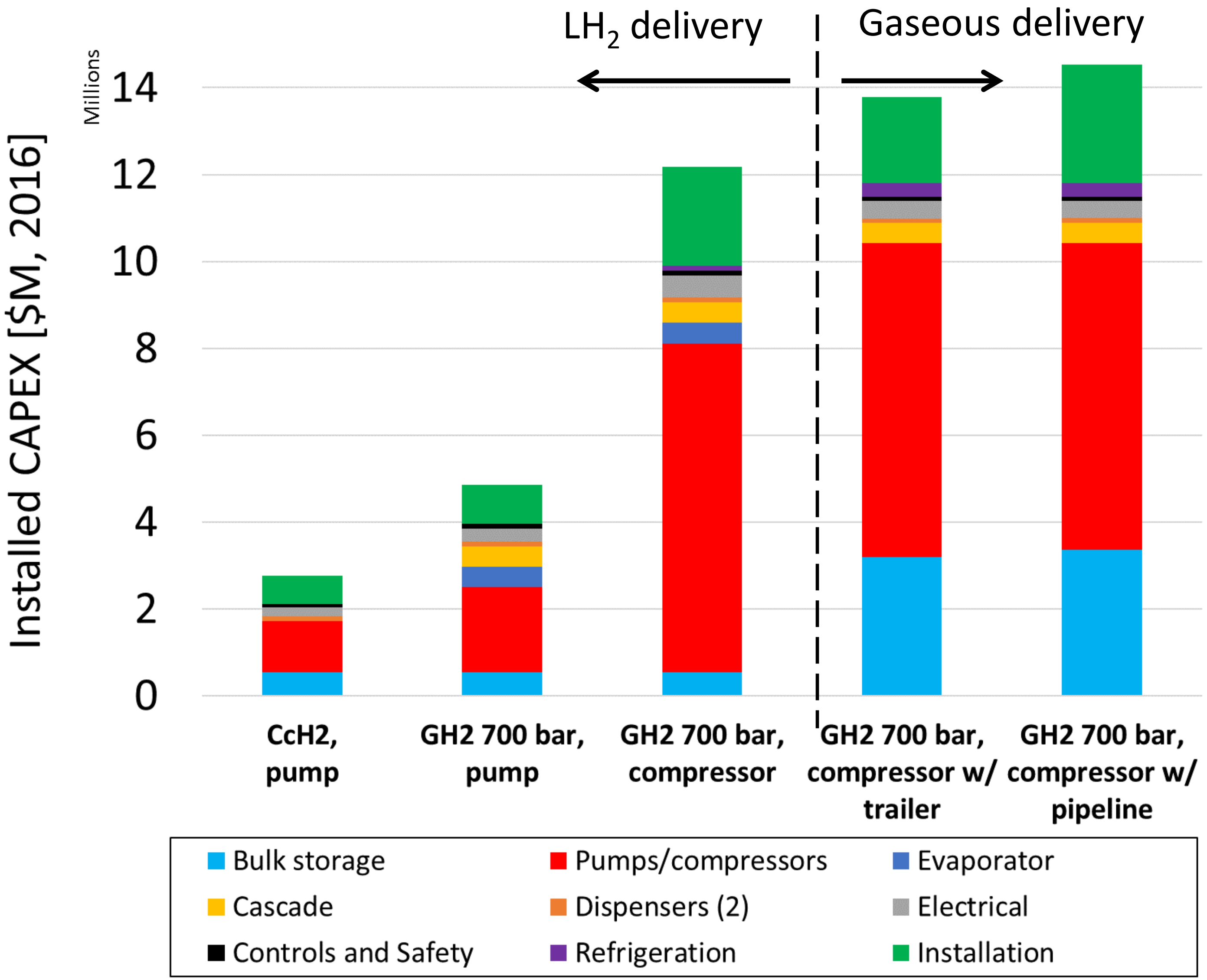
4,300 kg H_2 capacity
$167/kg
LH_2

800 kg H_2 capacity
$783/kg
350 bar, composite

250 kg H_2 capacity
$1000/kg
190 bar, steel

From Reddi *et al*, 2016

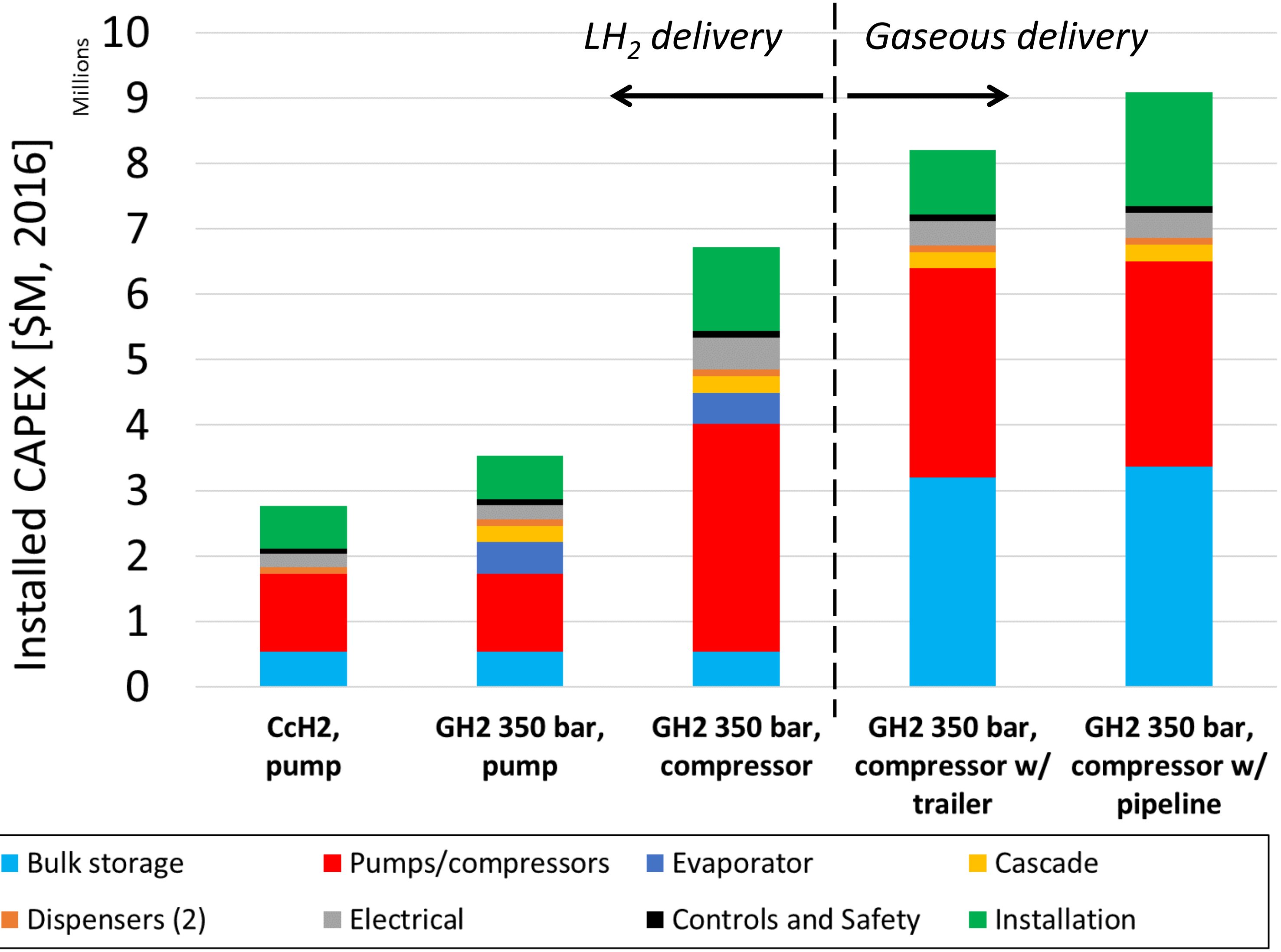
Comparison LH_2 vs. gaseous pathway: refueling station **CAPEX**



Comparison with 700 bar

- Station designed for 80 trucks or buses per day, 50 kg capacity each (**4,000 kg/day**)
- Cost projections from ANL (HDSAM)
- Centralized production of H_2
- Assumes high volume production
- Pipeline has high transmission costs ($500k-$1m per mile)
- Direct fill: **16** compressors have same throughput as **5** pumps ….

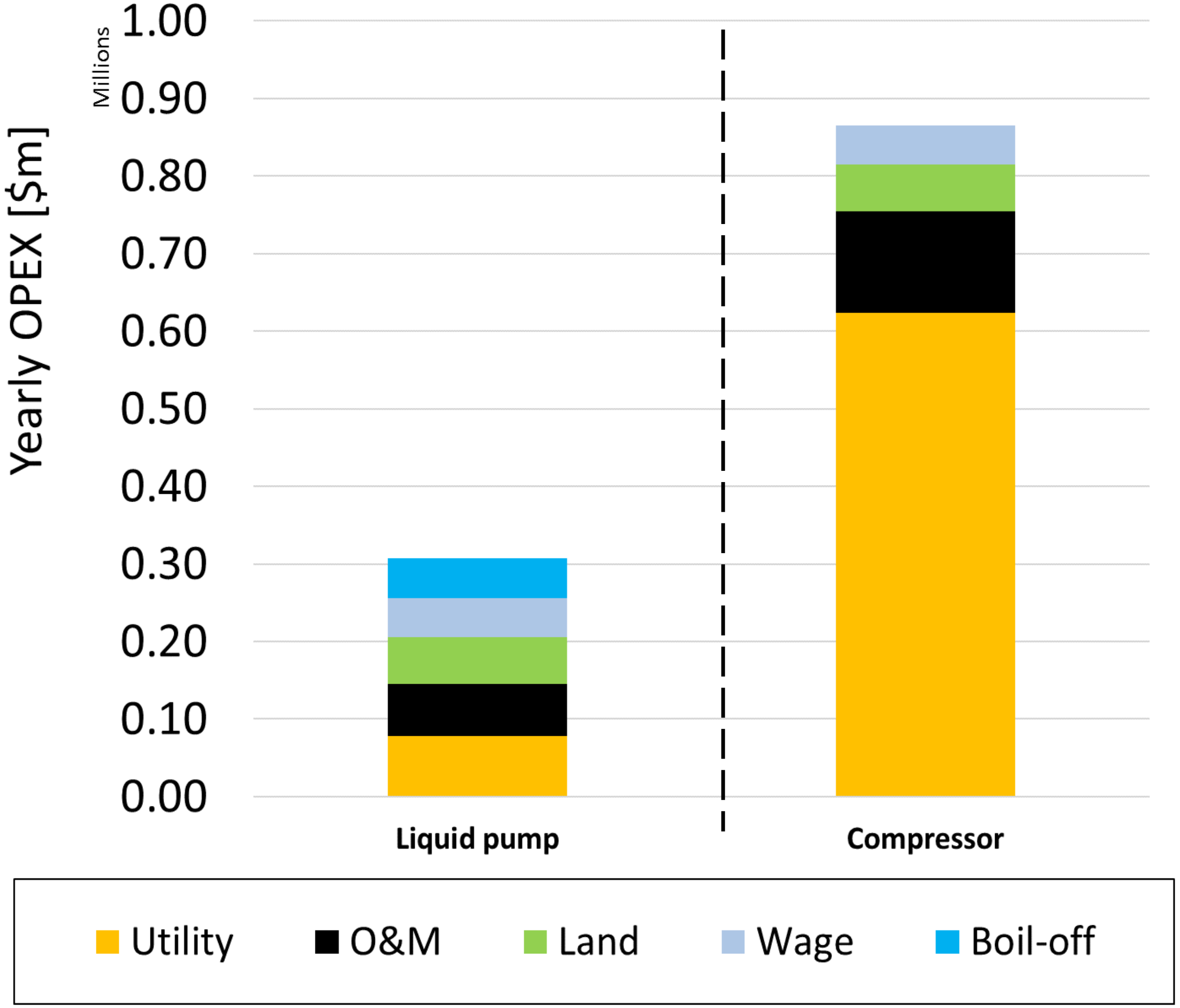
Comparison LH_2 vs. gaseous pathway: refueling station **CAPEX**



Comparison with 350 bar

- Station designed for 80 trucks or buses per day, 50 kg capacity each (**4,000 kg/day**)
- Cost projections from ANL (HDSAM)
- Centralized production of H_2
- Assumes high volume production
- Pipeline has high transmission costs ($500k-$1m per mile)
- Direct fill: **16** compressors have same throughput as **5** pumps ….

Comparison LH_2 vs. gaseous pathway: refueling station **OPEX**

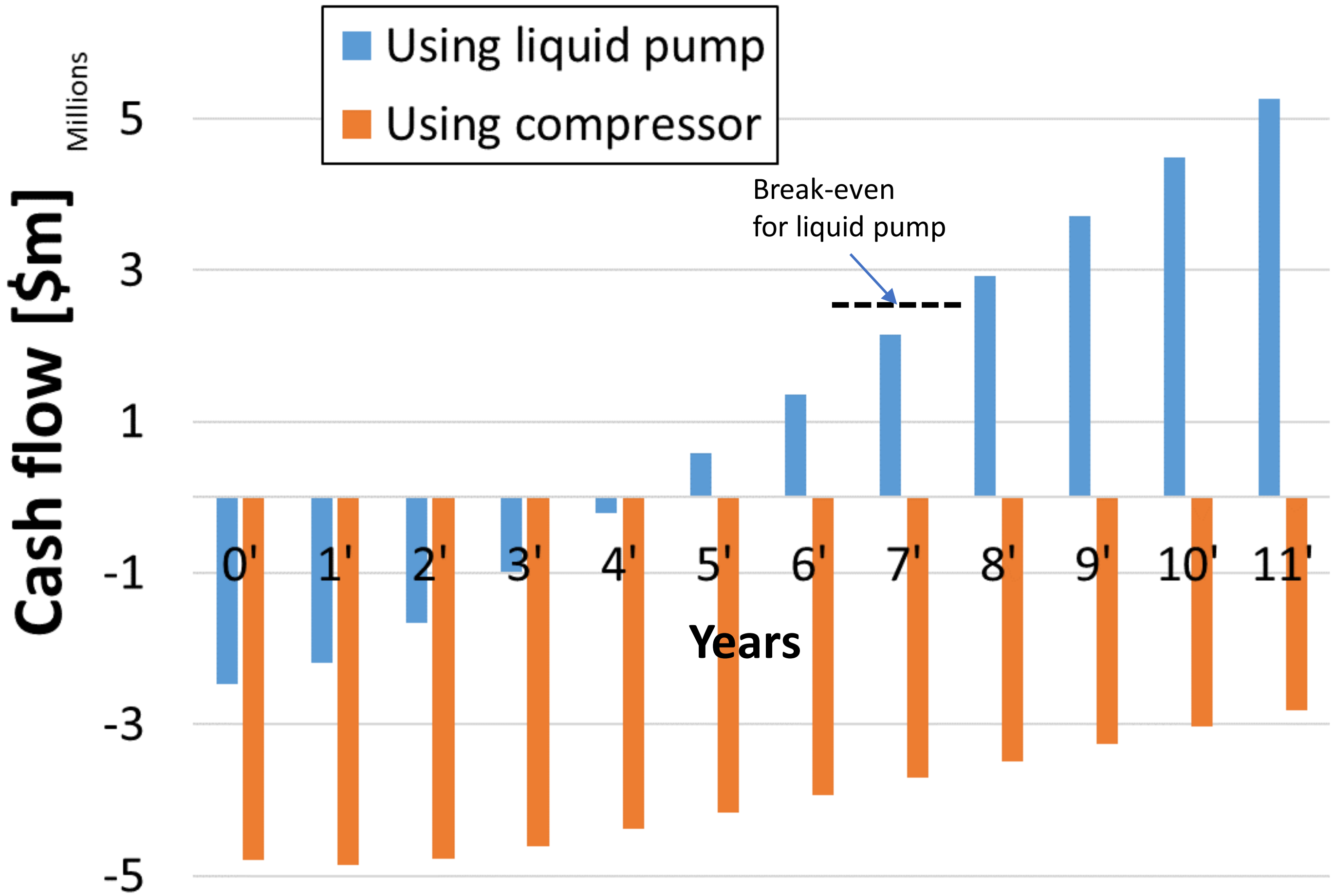


- Station designed for 80 trucks or buses per day, 50 kg capacity each (**4,000 kg/day**)

- Land: $5k/month
- Electricity: $0.15/kWh
- O&M: 3% of CAPEX/year
- Wage: $60k/year
- Boil-off: 1%/kgH_2, $5/$kgH_2$

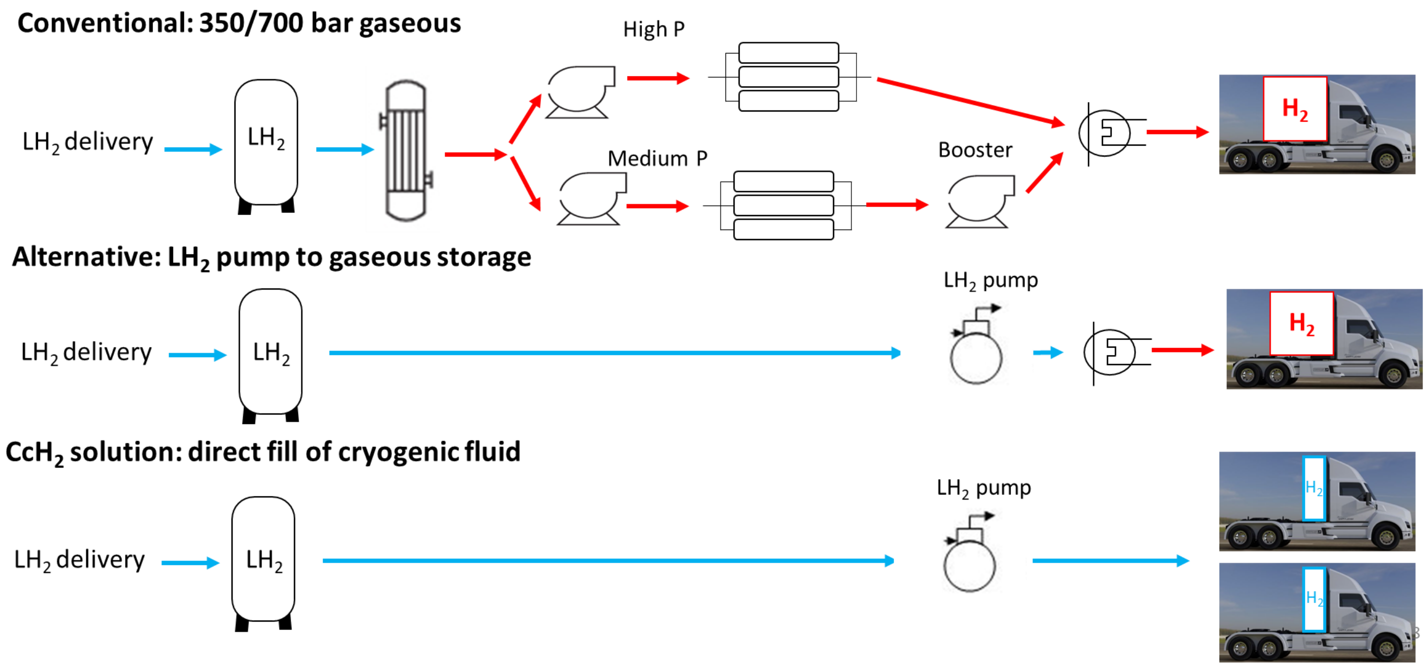
- Different efficiencies: **4** kWh_e/kgH_2 for compressors vs. **0.25** to **0.5** kWh_e/kgH_2 for LH_2 pumps…

Comparison LH_2 vs. gaseous pathway: refueling station **cash flow**



- Station designed for 80 trucks or buses per day, 50 kg capacity each (**4,000 kg/day**)
- Revenue: \$1/kgH_2, 5 days/week: ~ \$1m/year
- Both options are LH_2 delivered (lowest CAPEX)
- Liquid pump solution breaks even after 7-8 yrs
- Under those assumptions, compressor solution does not break even (revenue~OPEX…)

Beyond LH_2 at the station….



	Gaseous storage	CcH_2
Station Availability ("back-to-back")	Limited	✓ Unlimited
Station Footprint	Large	✓ Compact
Onboard-Storage Footprint	Large	✓ Compact

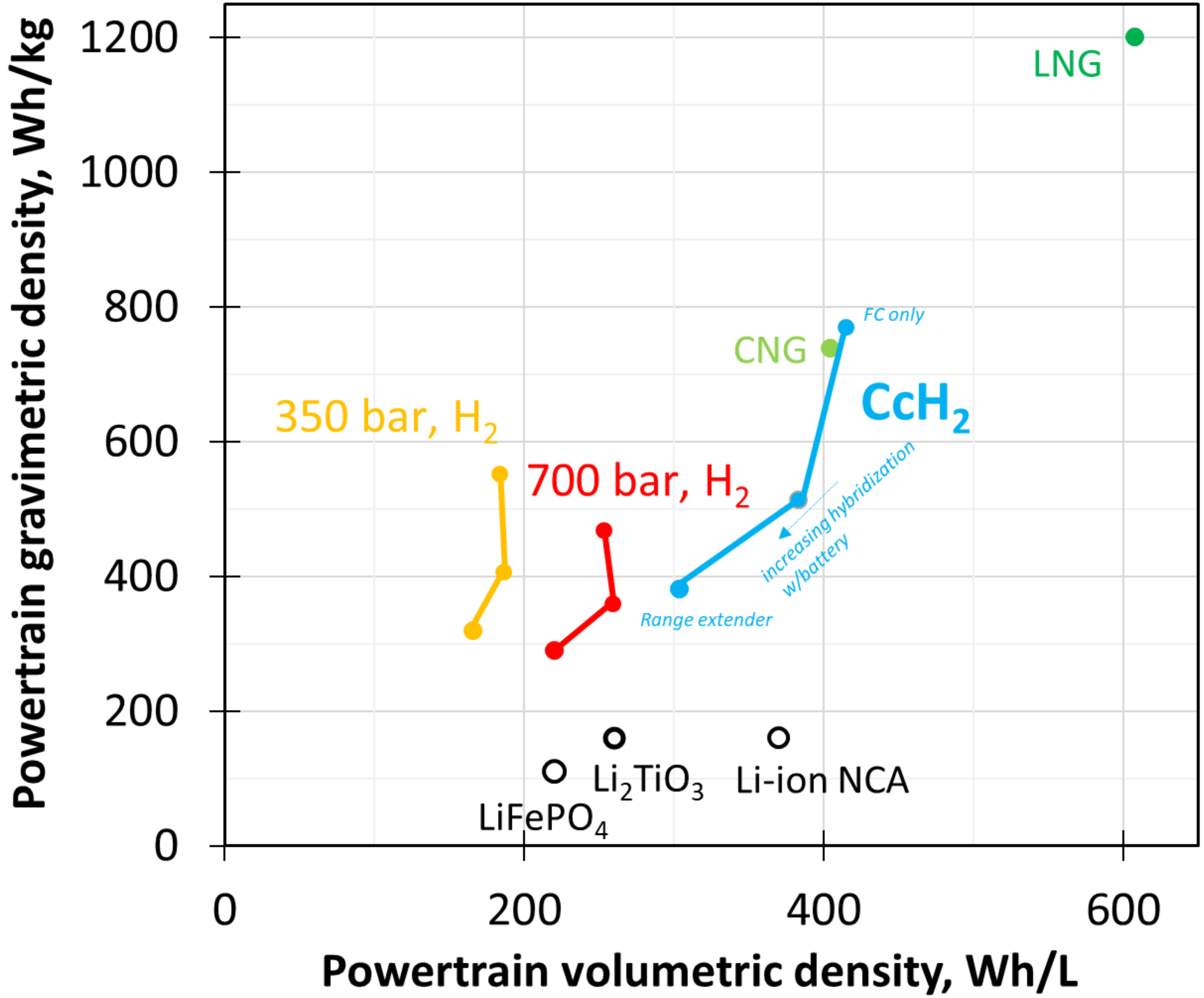
- Using a LH_2 pump offers drastic CAPEX and OPEX advantages at the station: ***at least*** 50% reduction over gaseous
- R&D on LH_2 supply chain up to the station is on-going and mature (Linde AG, ACD, Praxair….)
- Cryo-compressed (CcH_2) on-board storage offers additional benefits at the station (no need for cascade nor evaporator, "unlimited" station availability) and **has an even stronger value for the end-user**

Is on-board gaseous storage (350 or 700 bar) **good enough** ?

Cryo-compressed H_2 (CcH_2) uses high-pressure to virtually eliminate boil-off, enabling high-density of LH_2

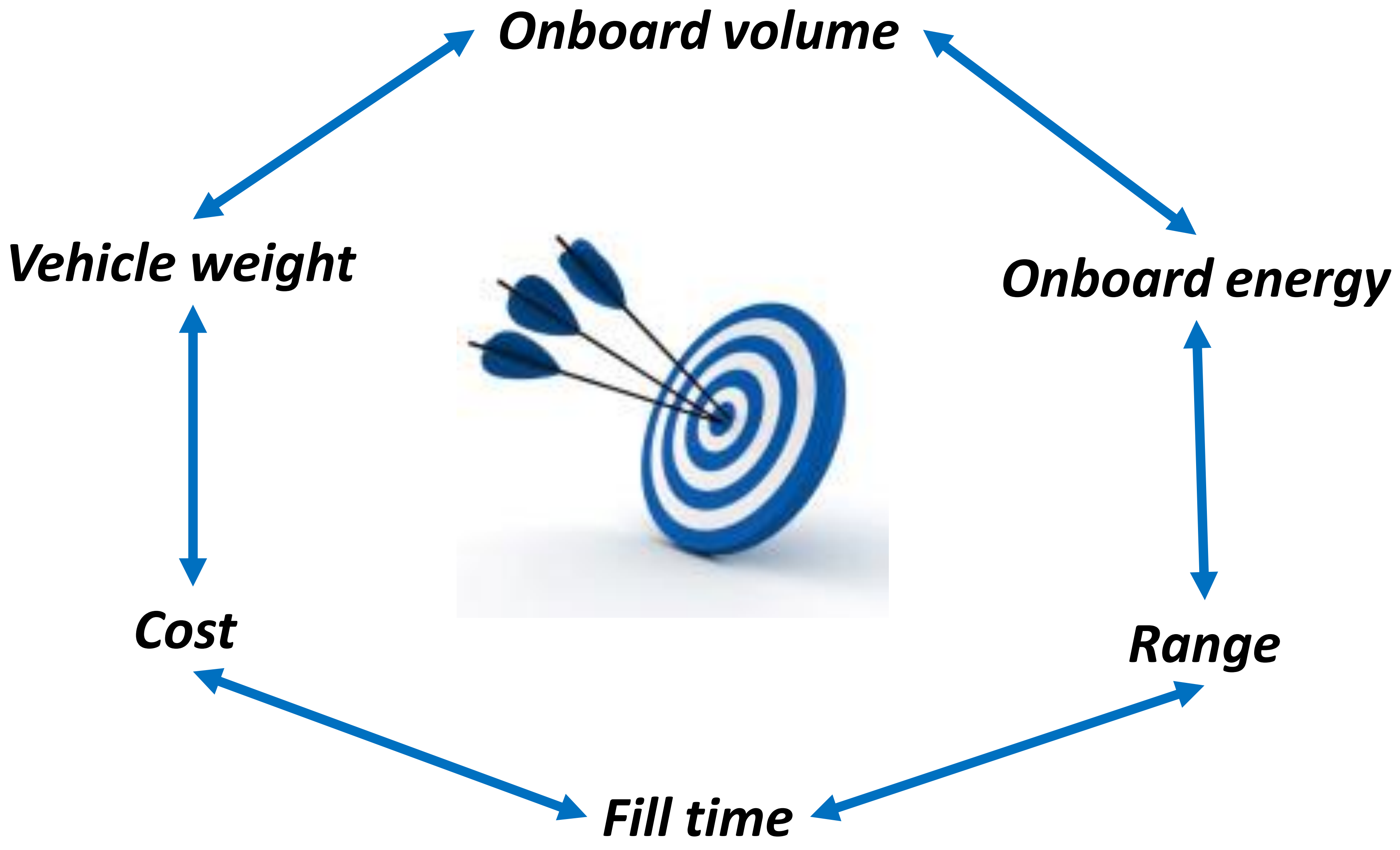
LH_2, 350 to 700 bar

CcH_2's competitive advantage resides in **high** energy density



- Powertrain=storage + FC/engine
- Takes into account efficiency losses through FC and engine
- Range for all solutions: ~ 300 miles
- Baseline configuration: 85 kW FC, 100 kWh battery, 37.5 kg H_2 capacity
- Black circles are battery technologies

High energy density provides flexibility for design optimization



CcH_2 provides optimal solution for zero-emission transit

Same <u>onboard energy</u> **Same fueling speed: 180 miles/hr** **Same body: carbon fiber**	*Curb weight* *Assuming carbon fiber body*	*Powertrain volume*	*Range*	*Power draw on grid at station (kW)*
CcH_2	22,300 lbs 20 % lighter than battery	1.4 m^3	540 miles 25% more range than battery 40 kg H_2	3.25
 *350 bar, H_2*	23,000 lbs	3.3 m^3	526 miles 40 kg H_2	53
 *Battery*	29,900 lbs	2.5 m^3	426 miles	275

CcH_2 provides optimal solution for zero-emission transit

Same volume **Same fueling speed: 180 miles/hr** **Same body: carbon fiber**	*Curb weight* *Assuming carbon fiber body*	*Powertrain volume*	*Range*	*Power draw on grid at station (kW)*
CcH_2	23,000 lbs 18% lighter than battery	2.5 m^3	950 miles 75 kg H_2	3.4
 *350 bar, H_2*	22,500 lbs	2.5 m^3	350 miles 30 kg H_2	53
 *Battery*	29,900 lbs	2.5 m^3	426 miles	275

CcH_2 provides optimal solution for zero-emission trucking

Same <u>onboard energy & range</u>
Same fill time: 300 miles in 15 min

		Useful cargo (max: 18 tons)	*Powertrain volume*	*Range*	*Power draw on grid @ station (MW)*
CcH_2		17.5 tons	1.7 m^3	300 miles	0.05
	*350 bar, H_2* **Nikola**	17 tons	4 m^3	300 miles	0.8
	*700 bar, H_2* **Toyota**	17 tons	2.6 m^3	300 miles	1.4
	*Battery* **Tesla**	13 tons	2.2 m^3	300 miles	3

CcH_2 provides optimal solution for zero-emission trucking

Same <u>volume</u> **Same fill time: 300 miles in 15 min**	*Useful cargo (max: 18 tons)*	*Powertrain volume*	*Range*	*Power draw on grid at station (MW)*
CcH_2	17.5 tons	2.2 m^3	420 miles	0.05
 *350 bar, H_2* **Nikola**	17 tons	2.2 m^3	150 miles	0.8
 *700 bar, H_2* **Toyota**	17 tons	2.2 m^3	270 miles	1.4
 *Battery* **Tesla**	13 tons	2.2 m^3	300 miles	3

CcH_2 provides value to the **entire** zero-emission supply chain

H2

More throughput
(= more $$$)

Refueling station

More throughput
(= more $$$)
Faster payback
(lower CAPEX & OPEX)

On-board tank

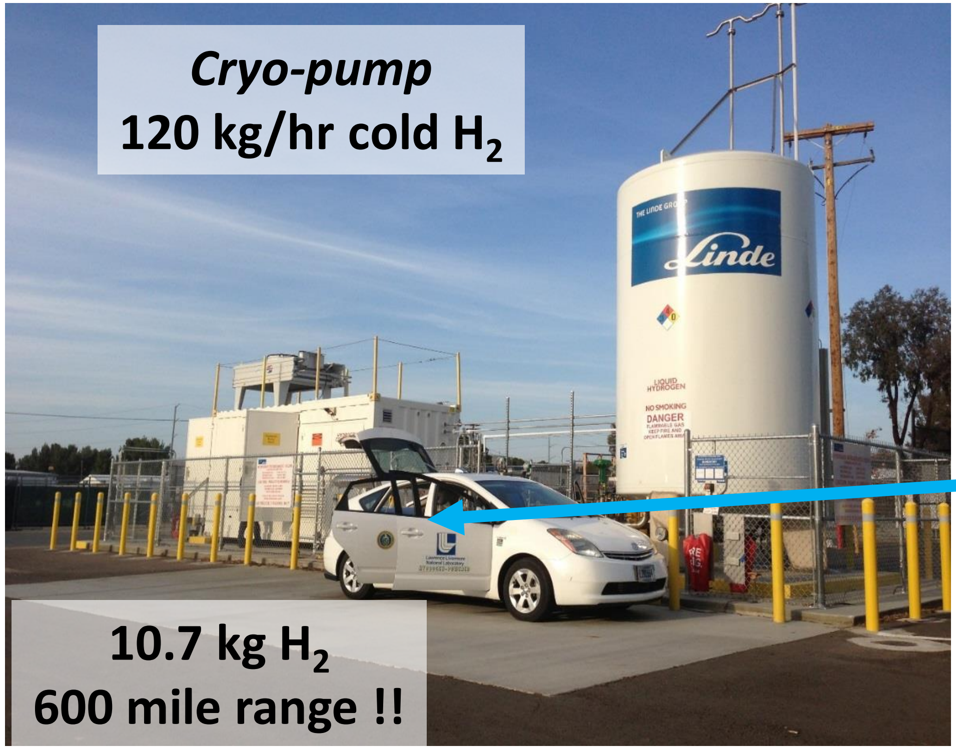
Truck/Bus

Smaller footprint
Integration with FC cooling
Lower CAPEX

Truck driver
Transit Agency

More cargo
Lower CAPEX & OPEX
Compact footprint

LLNL has pioneered CcH_2 using a comprehensive approach to improve system density, dormancy, cost, & safety with rapid fueling



Prototype R&D and testing at Lawrence Livermore National Laboratory

15 year R&D at LLNL

Now, TRL 6-7

4 patents,
2 patent applications,
1 provisional

Next step: demonstration of CcH_2 onboard a truck, with storage system that meets end-application requirements (C&S, duty cycles..)

Challenges towards commercialization of CcH_2

- **Background IP**: 3 granted patents, 3 provisional, 1 application. Overlap with BMW?
- **Codes and Standards**: CcH2 not recognized as a standard, although mentioned in GTR13. Standards recognition (SAE, ISO…) is generally lengthy…
- **Availability**: adequate pump has yet to be developed (flow rate, cost, boil-off, outlet temp) to best enable CcH2. No CcH2 manufacturer exists today.
- **Technical**: fatigue life at cryo temperatures could be optimized by developing new tank material. Outgassing of epoxy in VJ may be an issue for light-duty vehicles (no as much for fleets). Solutions exist and could be implemented
- **Manufacturability**: vacuum pumping not ideal for assembly line. IP addressing this issue is being secured. Vacuum pumping of LNG tanks an issue?

CcH_2 enables a cost-effective integrated solution

- Cheapest and most compact way to ship H_2
- Cheapest and most compact way to store H_2 in bulk
- Cheapest, fastest and most efficient way to dispense H_2
- Cheapest and most compact way to store H_2 on-board vehicles

+ Added BONUS: cryogenic H_2 has many safety features

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Suitable for External Audience (Unlimited)