UC DAVIS

SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

An Institute of Transportation Studies Program

Fuel Cells and Hydrogen in Long-Haul Trucks

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Outline of the Presentation

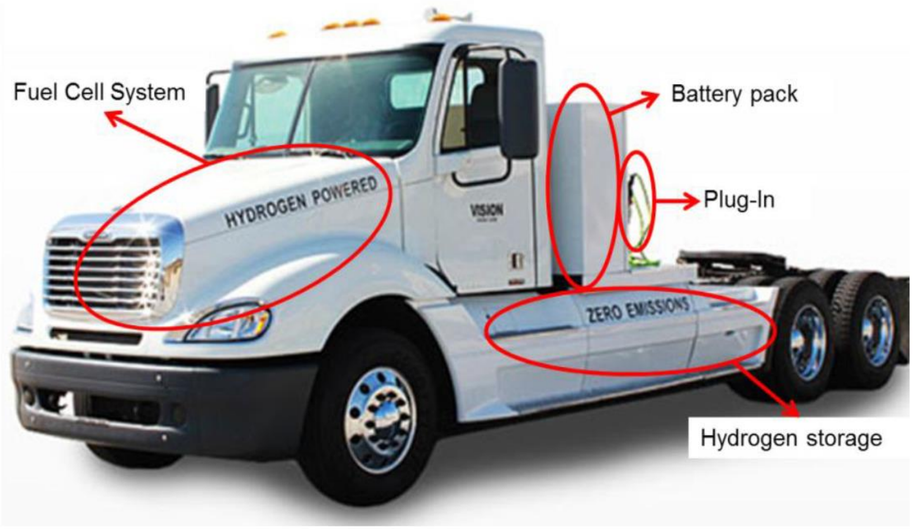
- **Status of fuel cell truck demonstrations**
- **The Fuel cell truck drivelines**
- **Hydrogen fuel consumption**
- **Compressed gas hydrogen storage on the trucks**
- **Cryo-compressed hydrogen storage on the trucks**
- **Hydrogen refueling stations along highways**
- **Technical and cost challenges**

Fuel cell truck demonstrations

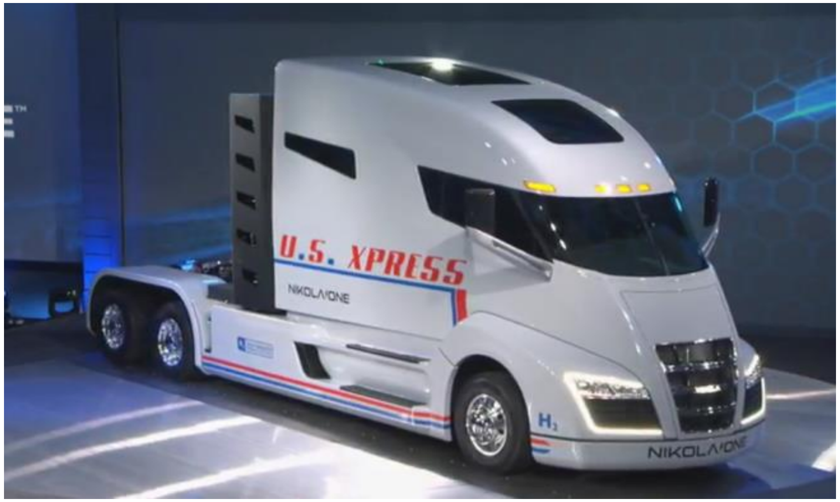
- Drayage trucks at ports (ex. TransPower)
- Refuse trucks
- Tyrano (Vison Motor Corp.)
- Nikola One (Nikola Motor Corp.)
- Project Portal (Toyota)

Vision's Tyrano

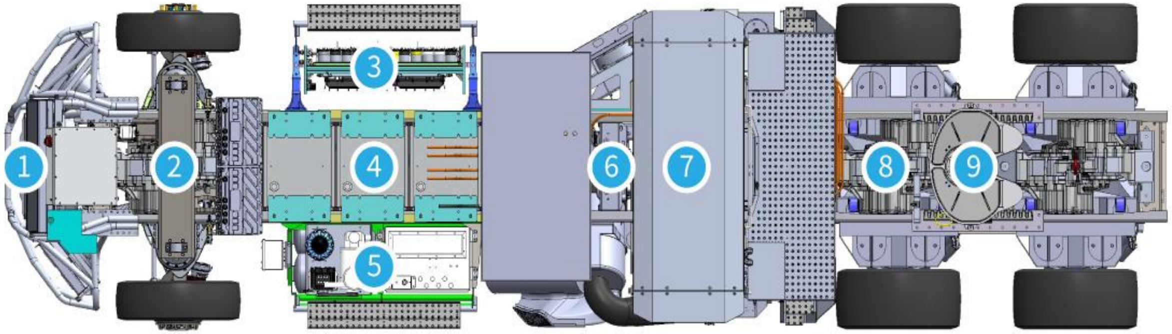
Vision's Tyrano



Source: Vision Motor Corp., 2012.



Nikola One



Nikola One Drivetrain Arrangement (Source: nikolamotor.com)

① front radiator assembly; ② front motor gearbox; ③ power electronics; ④ battery storage system; ⑤ chiller and air tanks; ⑥ fuel cell; ⑦ hydrogen fuel system; ⑧ rear motor gearbox; ⑨ 5th wheel

Hydrogen Fuel Cell Electric Trucks

Specification & performance comparison of Tyrano and Nikola One

Fuel Cell Trucks	Tyrano	Nikola One
Motor	320 kW	2 motors with power up to 1000 hp
Fuel Cell	65 kW	300 kW
Battery	130 kWh	320 kWh
Hydrogen Fuel	20 kg Compressed hydrogen at 350 bar	Not available (estimated 100 kg) in compressed or liquid hydrogen form
Refuel Time	10-15 min. at 430 bar	15 minutes (Nikola Stations)
Charging Port	Level 2	DC Fast
Range	200 miles	800 - 1,200 miles
Weight	Not available	2,000 lbs lighter than a diesel truck
Application	Class 8 short haul semi day cab	Class 8 long haul semi sleeper cab

Toyota fuel cell truck   Project Portal   Port of LA/LB

Two Mira fuel cells (230kW), 12 kWh battery, 300 kW motor (est.), 200 mile range fully loaded, 25 kg H2 (est.)

Inputs for the simulations

Class 8 Truck Inputs (33,000 – 80,000 lbs)

Component	Model Characteristics
Aero Drag Coefficient (Cd)	0.6
Frontal Area (A: m2)	10
Tire Rolling Resistance (eta)	0.0065
Curb Weight Including Empty Trailer (kg)	15,700
Gross Vehicle Weight Rating (kg)	25,400 kg *
Transmission 10 Speed efficiency	98%
Axle Efficiency	98%
Electrical Accessories	4 kW
Motor Efficiency	94%
Inverter Efficiency	99%
Average mileages	500 miles/day 90,000 miles/year

** 70% of the rated load of 36,280 kg*

Hydrogen consumption of long haul fuel cell trucks

Long haul (highway) trucks

2030

Long haul* **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 100 miles	kgH_2 for 300 miles	kgH_2 for 500 miles
GEM65	8.9	8.5	13.07	39	65
GEM55	9.4	9.0	12.35	37	62
HHDT-CR	9.9	9.45	11.76	35	59
65mph const	8.8	8.4	13.23	40	66

* C_D =.55, A_F =9.5, wt. =29500 kg, f_r =.0055, 1.5 kW access. load

2050

Long haul * **Driving cycles**	mi/gal gasoline equiv.	mi/kgH_2**	kgH_2 for 100 miles	kgH_2 for 300 miles	kgH_2 for 500 miles
GEM65	9.2	8.78	12.66	38	63
GEM55	10.1	9.64	10.37	31	52
HHDT-CR	10.9	10.41	10.67	32	53
65mph const	9.3	8.8	11.36	34	57

* C_D =.45, A_F =9.5, wt. =29000 kg, f_r =.005, 1.5 kW access. load

Comparisons of energy use with FC and other drivelines

Highway driving at 65 mph

Long haul truck

powertrain	mi/galD	Ratio
Diesel	8.2	1.0
H2FC	9.9	1.21

Intercity bus

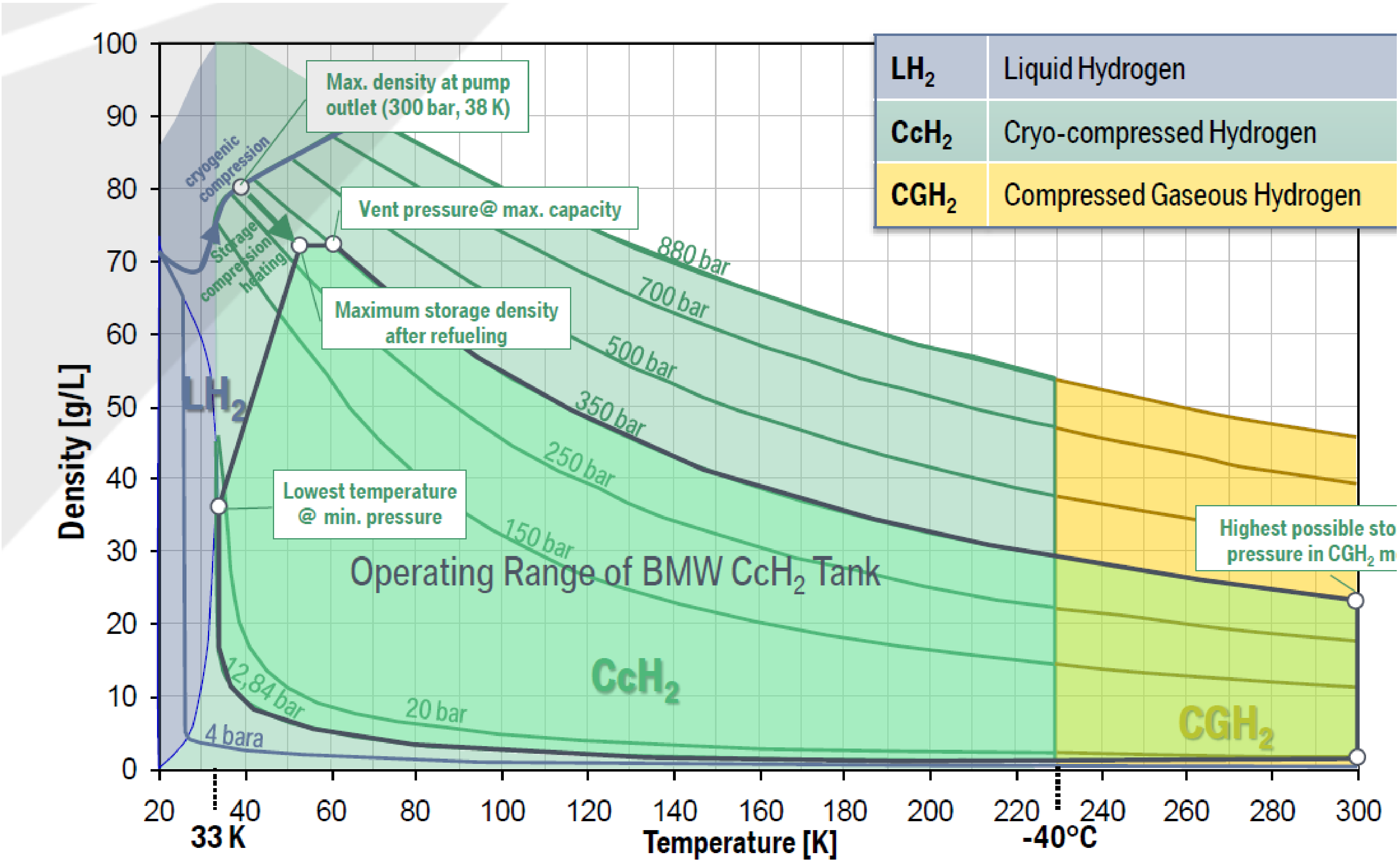
powertrain	mi/galD	Ratio
Diesel	10.1	1.0
H2FC	16.9	1.7
EV	26.1	2.6

HD pickup truck

powertrain	mi/galD	Ratio
Diesel	23.5	1.0
Hybrid diesel	31	1.3
H2FC	38.7	1.7
EV	82.7	3.5

Hydrogen storage on-board the truck

- **Compressed gas 5-10 kpsi**
- **Liquid (23 deg K, 4 atm.)**
- **Cryo-compressed (38 deg K, 300 atm.)**



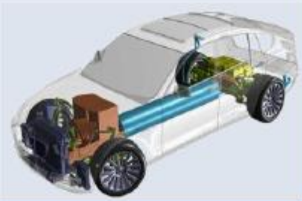
100
90
80
70
60
50
40
30
20
10
0
Density [g/L]
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
33 K
Temperature [K]
-40°C
LH2
Liquid Hydrogen
CcH2
Cryo-compressed Hydrogen
CGH2
Compressed Gaseous Hydrogen
Max. density at pump outlet (300 bar, 38 K)
Vent pressure@ max. capacity
Maximum storage density after refueling
Lowest temperature @ min. pressure
Highest possible sto pressure in CGH2 m
cryogenic compression
Storage compression heating
880 bar
700 bar
500 bar
350 bar
250 bar
150 bar
12,84 bar
20 bar
4 bara
LH2
Operating Range of BMW CcH2 Tank
CcH2
CGH2

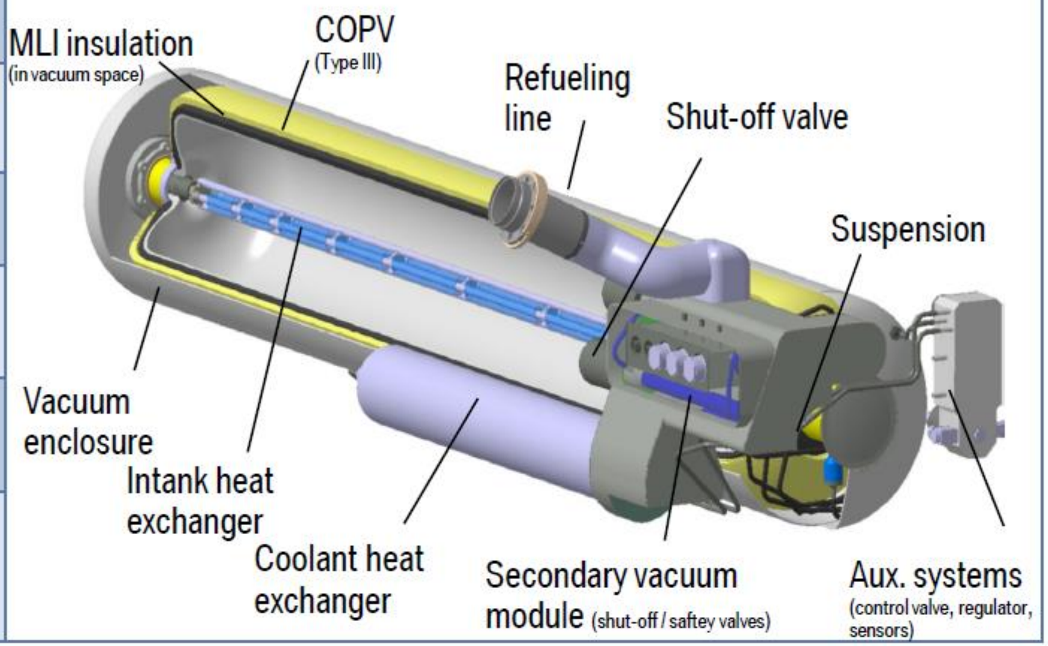
CRYO-COMPRESSED HYDROGEN STORAGE. SYSTEM LAYOUT – BMW PROTOTYPE 2011.

Modular Super-insulated Pressure Vessel (Type III)

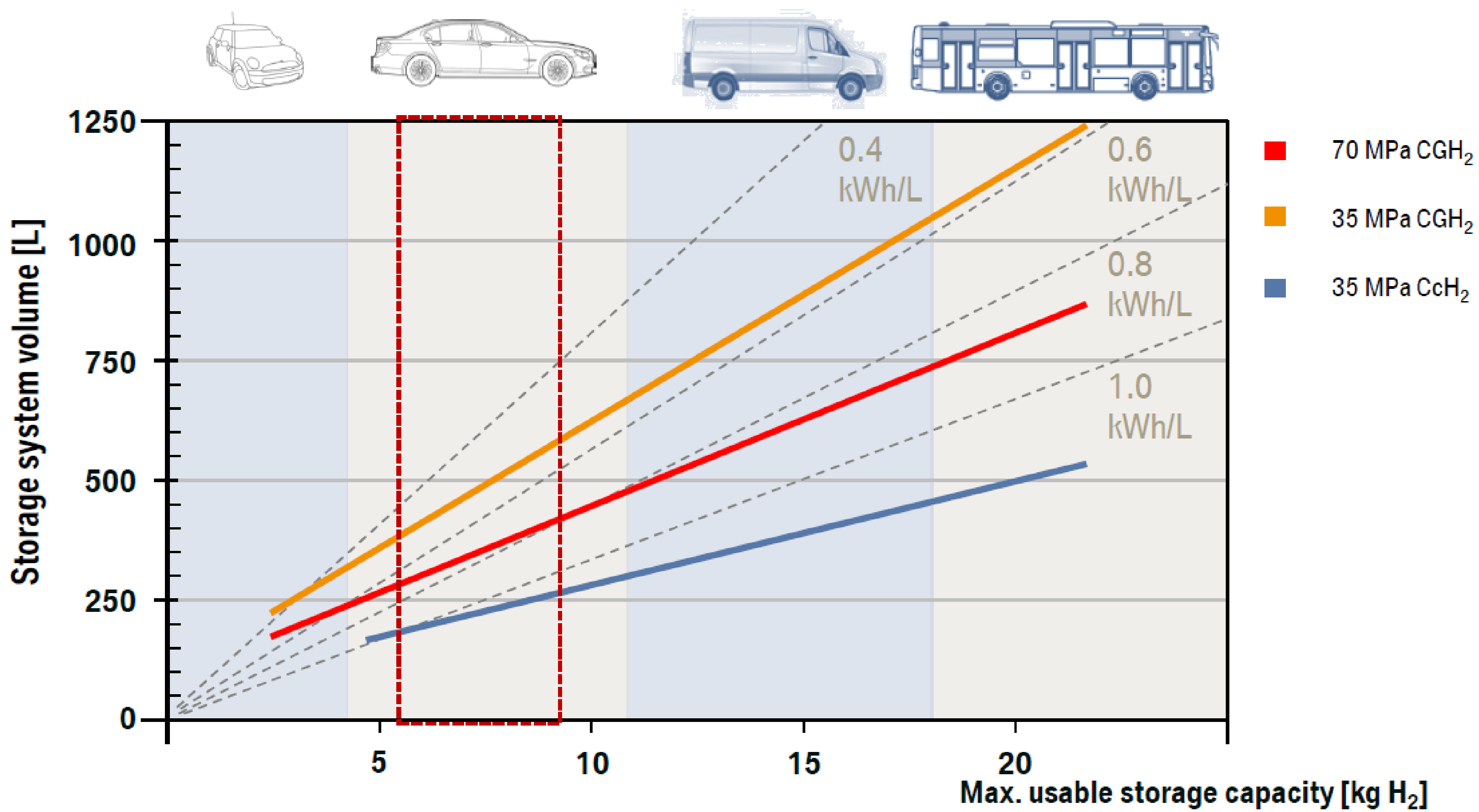
Max. usable capacity	CcH_2: 7.8 kg (260 kWh) CGH_2: 2.5 kg (83 kWh)
Operating pressure	≤ 350 bar
Vent pressure	≥ 350 bar
Refueling pressure	CcH_2: 300 bar CGH_2: 320 bar
Refueling time	< 5 min
System volume	~ 235 L
System weight (incl. H_2)	~ 145 kg
H_2-Loss (Leakage I max. loss rate I infr. driver)	<< 3 g/day I 3 – 7 g/h (CcH_2) I < 1% / year

+ Active tank pressure control
+ Load carrying vehicle body integration
+ Engine/fuel cell waste heat recovery

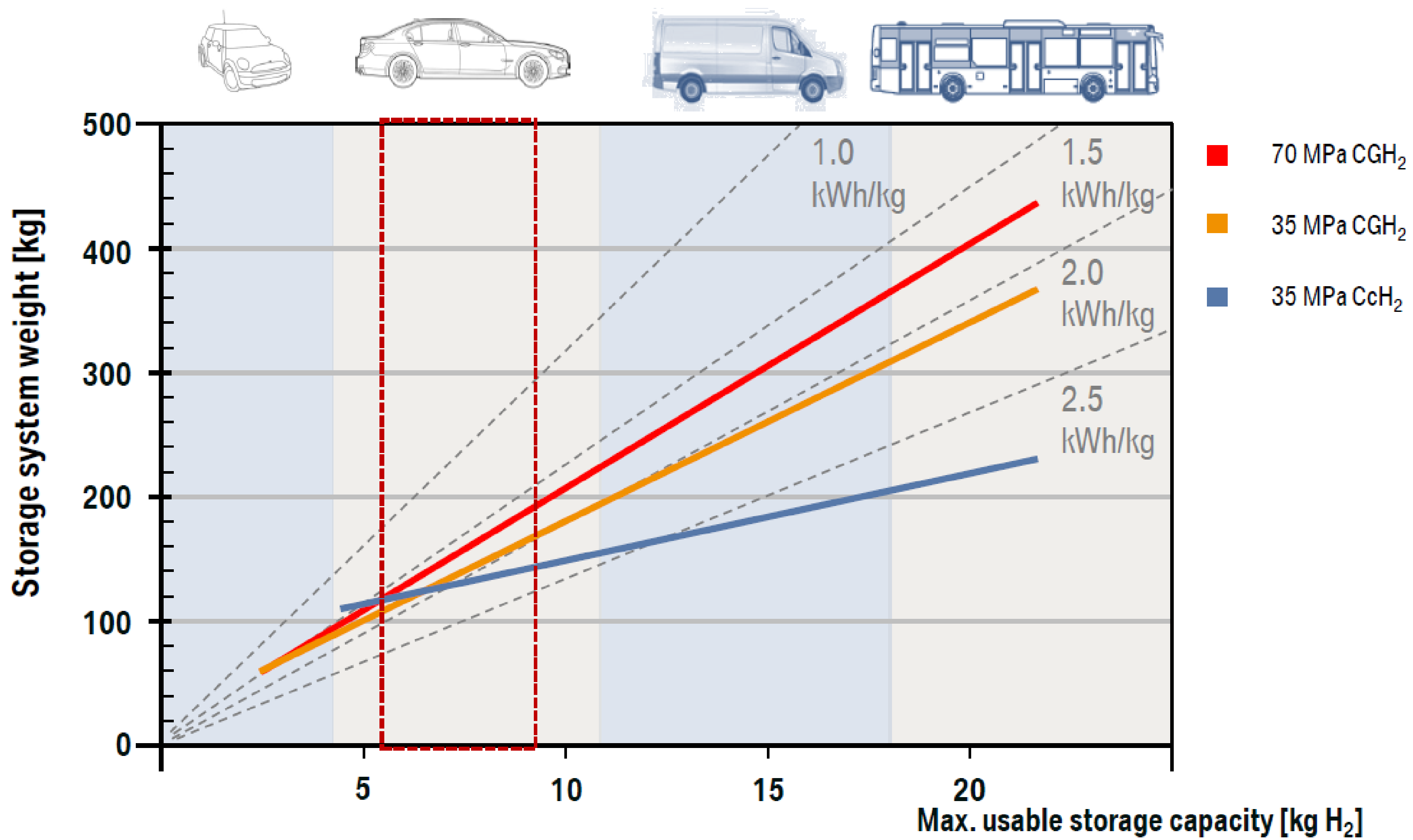




BMW CRYO-COMPRESSED HYDROGEN STORAGE. STORAGE SYSTEM VOLUME COMPARISON.



BMW CRYO-COMPRESSED HYDROGEN STORAGE.
STORAGE SYSTEM WEIGHT COMPARISON.



Hydrogen storage technology comparisons (DOE)

Current status of hydrogen storage technologies [Stetson, 2016]

Storage Targets	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs $/kWh ($/kg H_2)
2020	1.8 (0.055)	1.3 (0.040)	$10 ($333)
Ultimate	2.5 (0.075)	2.3 (0.070)	$8 ($266)

Projected H_2 Storage System Performance (5.6 kg H_2 usable)	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs* $/kWh ($/kg H_2)
700 bar compressed (Type IV, Single Tank)	1.4 (0.044)	0.8 (0.024)	$15 ($500)
Metal Hydride ($NaAlH_4$/Ti)	0.4 (0.012)	0.4 (0.012)	$43 ($1,432)
Sorbent (MOF-5, 100 bar, MATI, LN2 cooling)	1.3 (0.04)	0.7 (0.020)	$16 ($533)
Chemical Hydrogen Storage (AB-50 wt.%)	1.4 (0.043)	1.3 (0.040)	$17 ($566)

* projected at 500,000 units per year (light-duty vehicles)

Comparisons of the various hydrogen storage technologies with the DOE goals

Storage of 25kgH2 useable	Compressed gas (350 atm.)	Cryo-compressed BMW)	DOE goals
Weight (kg)	500	250**	
Volume (L)	988	607**	
			2020 ultimate
kgH2/kg syst.	.050 (.044)*	.100	.055 .075
KgH2/L syst.	.025 (.024)*	.041	.04 .07

*present status from DOE

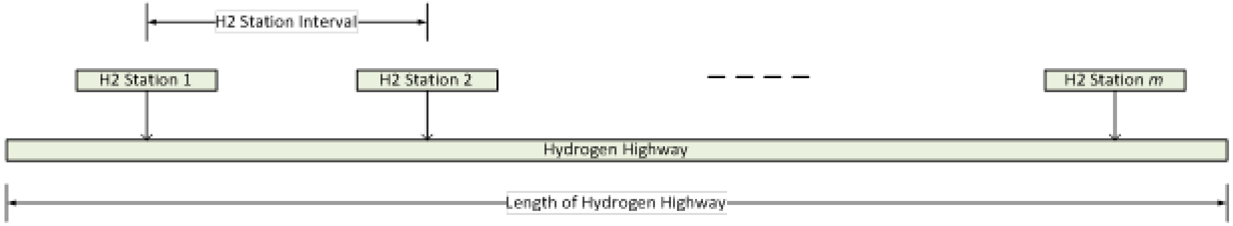
** 3400 Wh/kg, 1400 WH/l

Vehicle Component Cost (2025)

Fuel_Cell_Cost	**80**	**$/kW**
H2_Storage_Cost	**500**	**$/kgH2**
Battery_Cost	**300**	**$/kWh**
Motor_Cost	**15**	**$/kW**
Motor_Ctrl_Cost	**10**	**$/kW**
WPT_Receiver_Cost	**25**	**$/kW**

Projected Truck Cost for 2025

Long-Haul Trucking Technology	Conv. Diesel	H2 Fuel Cell	Catenary Electric	Dynamic Charging
Glider	$95,539	$95,539	$95,539	$95,539
Engine	$21,881	-----	-----	-----
Aftertreatment	$15,750	-----	-----	-----
Transmission	$8,549	$2,000	$2,000	$2,000
Fuel cell	-----	$24,000	-----	-----
Hydrogen storage	-----	$36,000	-----	-----
Battery	-----	$15,000	$30,000	$30,000
Active pantograph & converter	-----	-----	$6,500	
wireless charge receiver	-----	-----	-----	$8,000
Motor and controller	-----	$8,750	$8,750	$8,750
Truck Cost	**$141,719**	**$181,289**	**$142,789**	**$144,289**



Infrastructure Cost for a 500-Mile Zero-Emission Highway Section

Long-Haul Highway Trucking Technology Scenarios	Conv. Diesel Truck	Hydrogen Highway	Catenary Electric Highway	Dynamic Inductive Charge Highway
Diesel station capital cost ($)	0	-----	-----	-----
Traction power distribution system				
Catenary system ($/route mile)	-----	-----	4,600,000	-----
Dynamic wireless charger ($/route mile)	-----	-----	-----	6,400,000
Hydrogen refueling stations (based on $21.8M /sta. for a 3000kg$H_2$/da. station)		672,530,000 *		
Daily fuel/electricity demand (DGE)	98,924	75,908	157,083	181,107
Daily h2 demand (kg) $4/kg H2		370, 200		
Daily electricity demand (kWh)			6,377,551	7,352,941
Total Electric power demand (kW)			261,643	301,659
Substation power rating (kW)			20,931	24,133
No. of Fuel Stations/Electrified Zones	10	10	13	13
Daily Station Diesel Supply (gallon/station)	9,892			
Daily Station H2 Supply (kg/station)		9,255		
Electric Power Demand (kW/electrified zone)			20,931	24,133
Infrastructure Cost (500 route miles)	**$0**	$673,661,680	$1,150,000,000	$1,600,000,000

*assumed base cost $20M for a 3000 kgH2/day station

Technical and cost challenges

Fuel cell

- Reduce cost ($/kW)
- Increase durability at high loads to at least 20,000 hr.

Hydrogen storage on board truck

- Increase kgH2/L to at least .05
- Increase cycle life to at least 3000 (full to empty)
- Reduce cost to at least $300/kgH2

Long haul truck

- Integration of electric drive, hydrogen storage, and power battery into the tractor/cab
- Reduce the cost of the fuel cell truck to be comparable to the diesel truck of the same range

Technical and cost challenges

Hydrogen refueling stations

- Increase dispensing capability to 9000 kgH2/day and rate of dispensing to 20-25 kgH2/min
- Store 40,000-50,000 kgH2 at the station or provide for on-site generation to meet H2 demand
- Store/dispense H2 as liquid and/or cryo-compressed gas
- Reduce cost of on-site storage and on-site generation

Conclusions – Fuel cells in trucks

- **Near term**

Urban, regional applications-drayage at ports, delivery, etc., range less than 200 miles

- **Longer term**

General long haul freight applications, range up to at least 500 miles, to replace diesel trucks