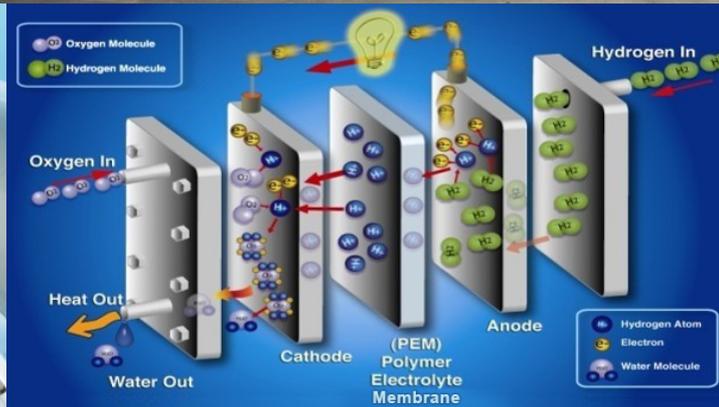


U.S. Department of Energy Fuel Cell Technologies Office

U.S. DEPARTMENT OF
ENERGY | Energy Efficiency &
Renewable Energy



An Overview of the FCTO Hydrogen Storage Program's Compressed Gas Storage R&D Challenges and Strategies

Brian Rice

Courtesy of Ned Stetson

Fuel Cell Technologies Office
U.S. Department of Energy

Hydrogen Fuel Cell Vehicles are Now Available!

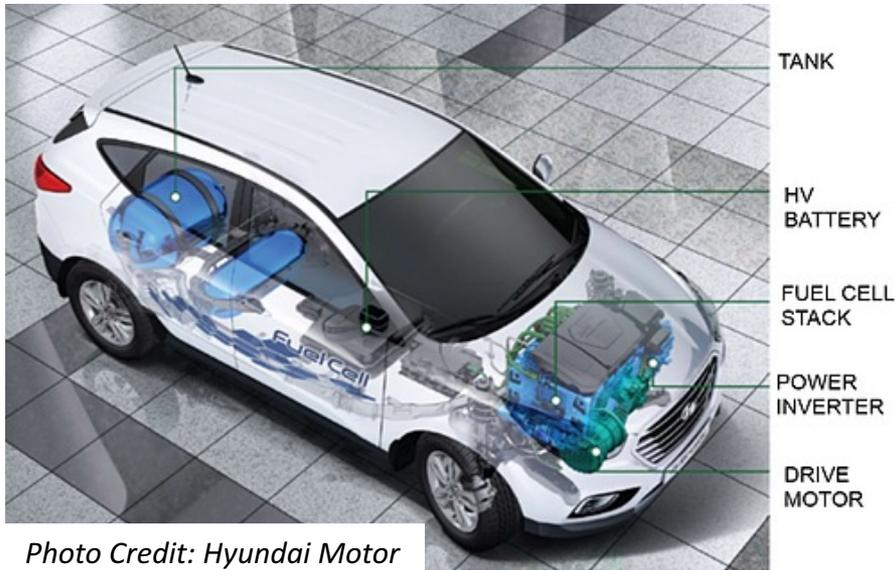
All current commercial FCEVs use two 700 bar composite overwrapped pressure vessels for onboard hydrogen storage

Honda Clarity

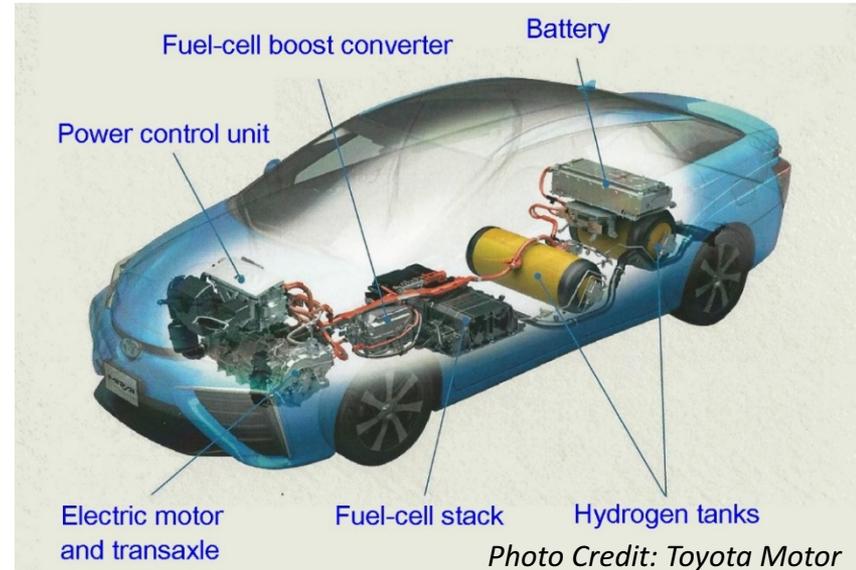
Photo Credit: Honda Motor



Hyundai Tucson Fuel Cell

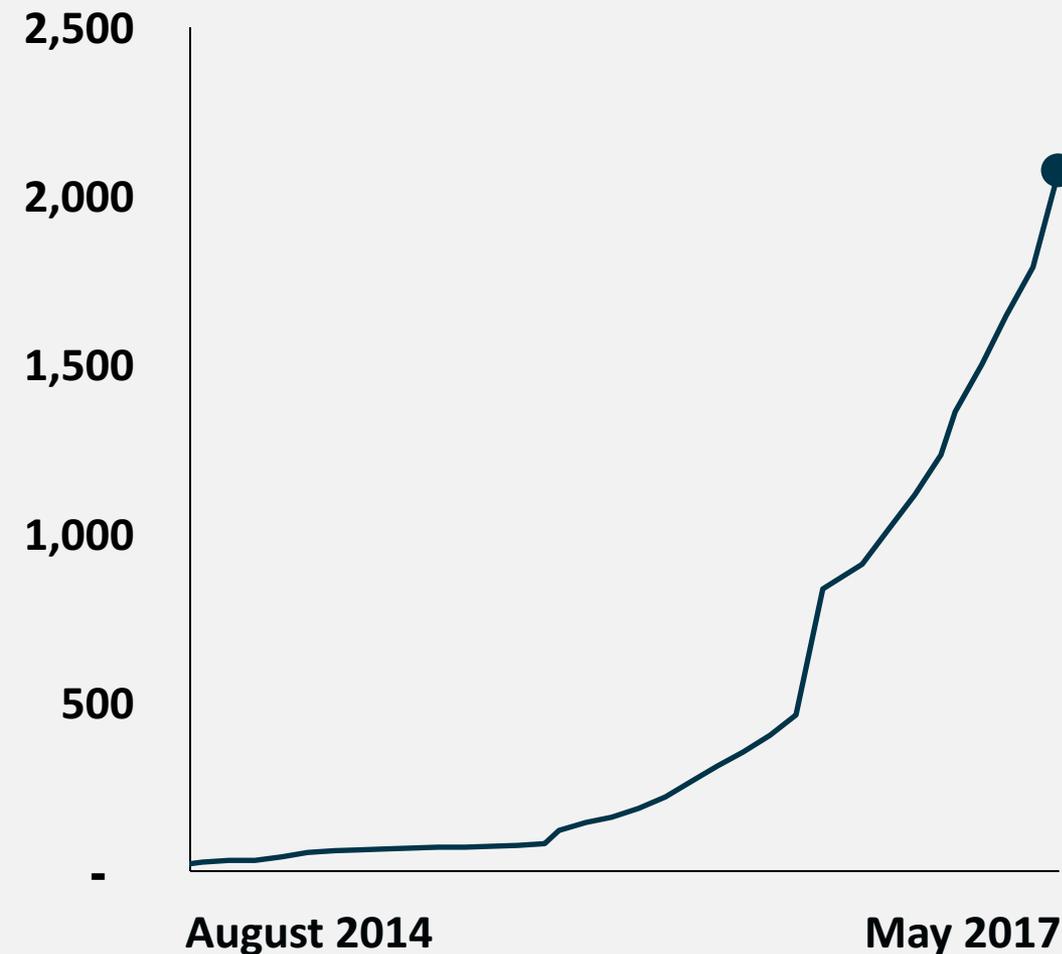


Toyota Mirai



Initial vehicle rollout occurring with compressed 700 bar pressure hydrogen storage

Fuel Cell Car Sales Growing



Note: Cumulative number of vehicles sold/leased. Source: hybridcars.com



2,000
fuel cell cars

sold or leased in the U.S.

78%
of executives



Absolutely or partly
agree that

**Fuel cell cars will be
the real breakthrough
for electric mobility**

Fuel Cells: Big leaps in Heavy Duty Truck Space

Fuel cell electric delivery and parcel trucks
– First of its kind demonstration - FedEx and UPS starting deliveries this summer!



Industry demonstrates first heavy duty truck



Fuel cell buses in CA surpass 17M passengers

ZH2: U.S. Army and GM collaboration
First of its kind



Fuel Cell Forklift Orders on the Rise

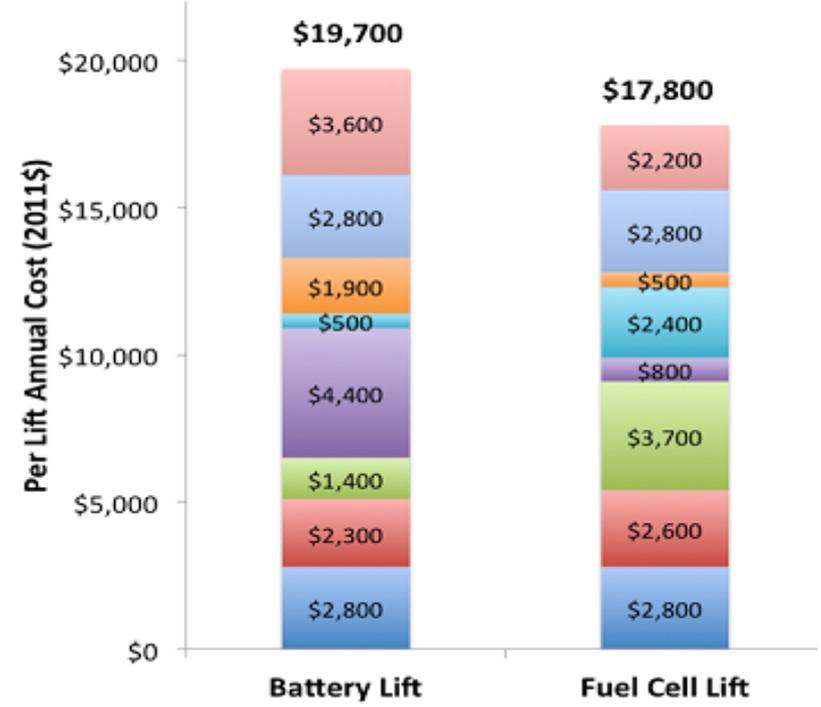


BMW plant in Greer, South Carolina

Over 15,000 fuel cell forklifts
 deployed or on order by industry

Approx. 6 million hydrogen
 refuelings to date

Annualized Cost Example

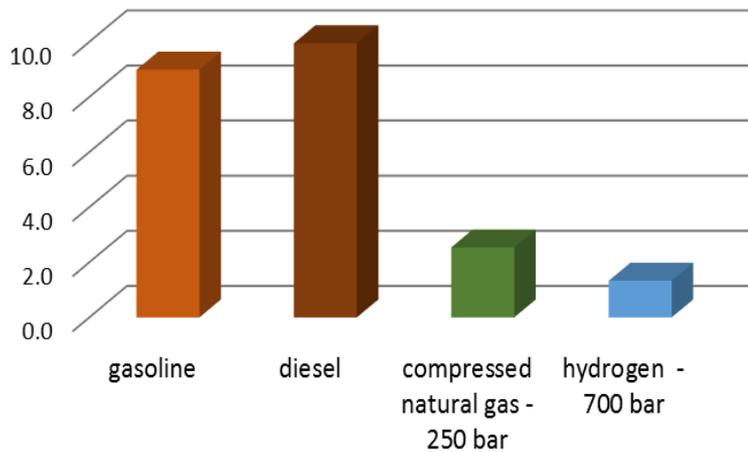


- Battery / Fuel Cell Maintenance
- Lift Truck Maintenance
- Cost of Infrastructure Warehouse Space
- Cost of Electricity / Hydrogen
- Labor Cost for Battery Charging & H2 Fueling
- Per Lift Cost of Charge / Fuel Infrastructure
- Amortized Cost of Battery / Fuel Cell Packs
- Amortized Cost of Lift

MHE: Material Handling Equipment (MHE), Type I and II
 *Source: NREL.. An Evaluation of the Total Cost of Ownership of Fuel Cell –Powered MHE (2013)

Very Low Energy Density

Energy Density Comparison (kWh/L)



Even when compressed to high pressures, H₂ has low energy by volume compared than most other fuels!

H₂ fuel tanks onboard vehicles are larger than typical gasoline tanks
... even with efficiency of the fuel cell is considered

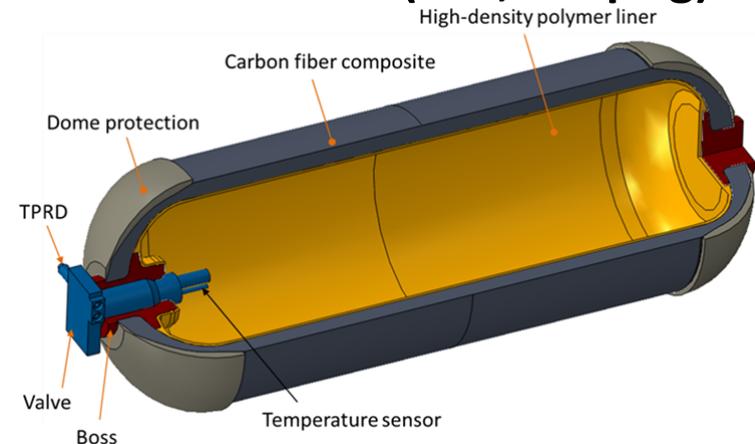
● Gasoline

Hydrogen @ 700 bar



~3.5x gasoline

Hydrogen is currently stored in Composite Overwrapped Pressure Vessels at 700 bar (~10,000 psig)



Hydrogen is a low-density gas under all practical conditions on earth

Current Status vs. Revised Targets

Storage Targets	Gravimetric kWh/kg (kg H ₂ /kg system)	Volumetric kWh/L (kg H ₂ /L system)	Costs ¹ \$/kWh (\$/kg H ₂)
2020	1.5 (0.045)	1.0 (0.030)	\$10 (\$333)
2025	1.8 (0.055)	1.3 (0.040)	\$9 (\$300)
Ultimate	2.2 (0.065)	1.7 (0.050)	\$8 (\$266)
Current Status ²			
700 bar compressed (5.6 kg H ₂ , Type IV, Single Tank)	1.4 (0.042)	0.8 (0.024)	\$15 (\$500)

The full set of H₂ storage targets can be found on the Program's website:

<https://energy.gov/eere/fuelcells/downloads/doe-targets-onboard-hydrogen-storage-systems-light-duty-vehicles>

¹ Projected at 500,000 units/year

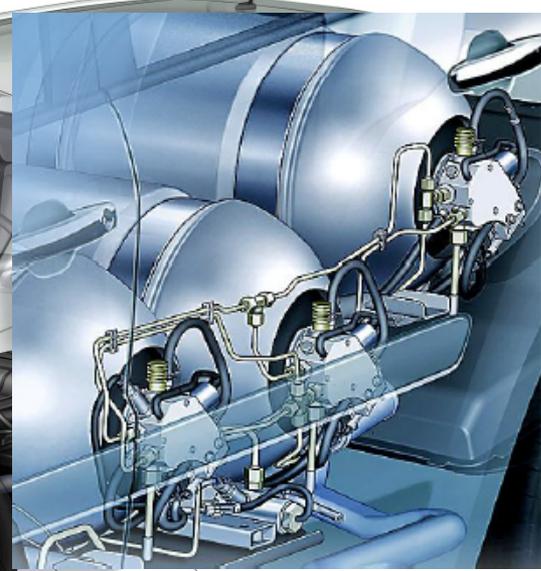
² FCTO Data Record #15013, 11/25/2015: https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

More Challenges for H₂ as an Energy Carrier

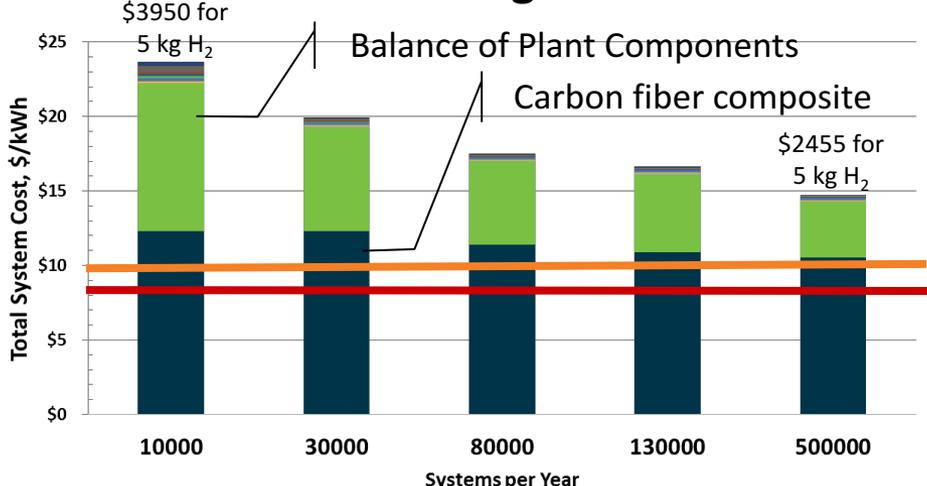
Conventional gasoline tanks are highly conformable



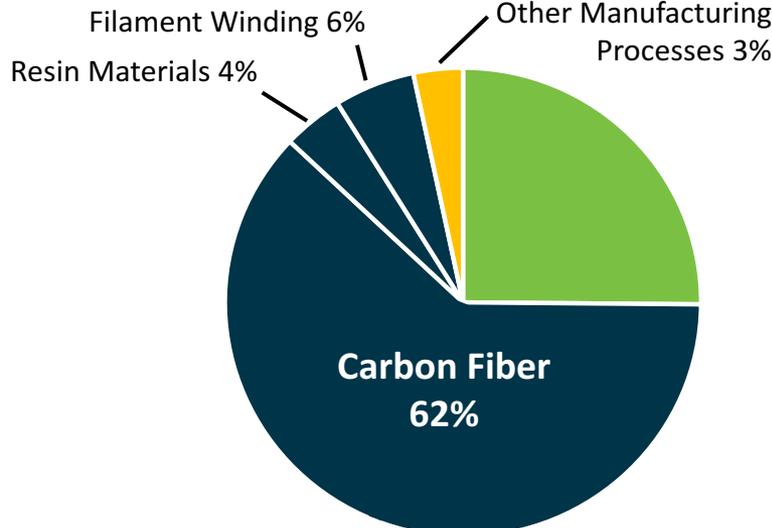
High-pressure H₂ tanks are larger and have rigid cylindrical shapes



Much higher costs!



Analysis for a single tank design — 2020 Target — Ultimate Target



https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

High-pressure H₂ storage tanks are expensive and difficult to package onboard vehicles



THE COMPOSITES INSTITUTE

Institute for Advanced Composites Manufacturing Innovation

- Institute of Manufacturing USA
- Managed by the EERE Advanced Manufacturing Office
- Technology Focus Areas:
 - Vehicles
 - Wind Turbine Blades
 - **Compressed Gas Storage Vessels**
 - Design, Modeling & Simulation
 - **Composite Materials & Processes**

Leveraged project: Thermoplastic Composite Compressed Gas Storage Tanks

- Project lead: DuPont
- Partners:
 - Composite Prototyping Center (CPC)
 - Steelhead Composites
 - University of Dayton Research Institute (UDRI)
- Kick-off: FY2017, Q1

