Target Explanation Document: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles

2017

This target explanation document is a document of the U.S. DRIVE Partnership. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) is a voluntary, non-binding, and non-legal partnership among the U.S. Department of Energy; USCAR, representing FCA US LLC, Ford Motor Company, and General Motors; five energy companies – BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US; two utilities – Southern California Edison and DTE Energy; and the Electric Power Research Institute (EPRI).

The Hydrogen Storage Tech Team is one of 13 U.S. DRIVE technical teams that work to accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure.

For more information about U.S. DRIVE, please see the U.S. DRIVE Partnership Plan, www.vehicles.energy.gov/about/partnerships/usdrive.html or www.uscar.org

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1.0 Background:

Hydrogen (H_2) storage is a key enabling technology for the advancement of hydrogen vehicles in the automotive industry. Storing enough hydrogen (4-10 kg) onboard a light-duty vehicle to achieve a 300 to 500 mile driving range is a significant challenge. On a weight basis, hydrogen has nearly three times the energy content of gasoline when comparing lower heating values (33 kWh/kg for H_2 compared to 12 kWh/kg for gasoline). However, on a volume basis, the situation is reversed (approximately 1.3 kWh/L for 700 bar H_2 at 15°C compared to 8.8 kWh/L for gasoline). In addition to energy density, hydrogen storage systems face challenges related to cost, durability/operability, charge/discharge rates, fuel quality, efficiency, and safety, which may limit widespread commercialization of hydrogen vehicles.

Hydrogen storage activities within the U.S. DRIVE Partnership,[1] in conjunction with the DOE's Fuel Cell Technologies Office (FCTO) in the Office of Energy Efficiency and Renewable Energy,[2] are focused on applied research and development (R&D) of technologies that can achieve a 300 to 500 mile driving range for the full span of light-duty vehicles, while meeting packaging, cost, safety, and performance requirements. Such technologies, incorporated within a fuel cell vehicle, would be competitive with incumbent vehicle technologies as illustrated in Figure 1.

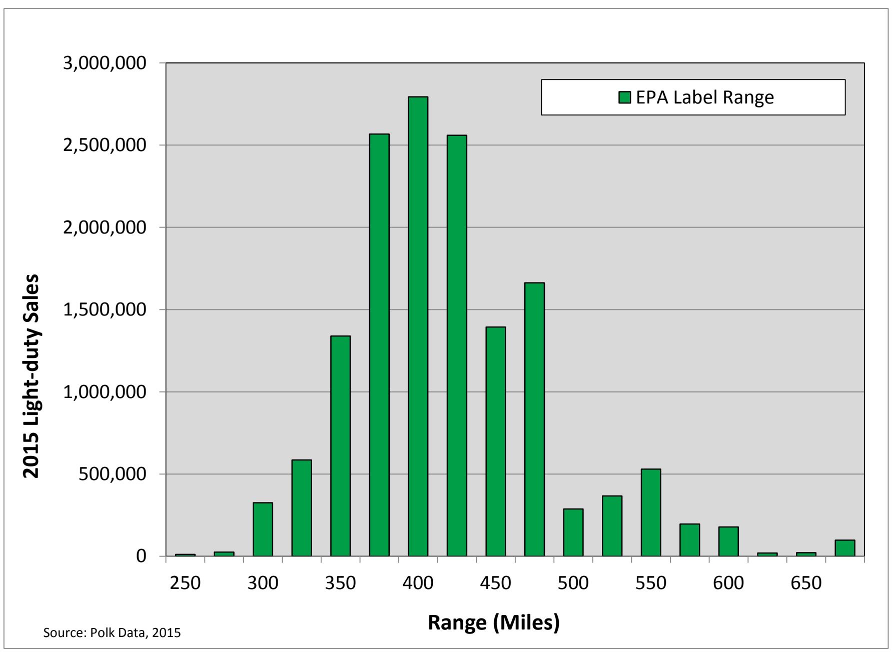

Figure 1: Distribution of 2015 Light-duty Vehicle Sales in the U.S. Market by Driving Range (EPA Label Range)[3]

From conventional vehicle data, the driving range of 300 miles has been identified as the minimum entry point for the market. In comparison, hydrogen vehicles in DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project had an Environmental Protection Agency (EPA) adjusted driving range from 100 miles (Generation 1 observed minimum) to 250 miles (Generation 2

[1] http://www.uscar.org/guest/partnership/1/us-drive

[2] http://energy.gov/eere/fuelcells/fuel-cell-technologies-office

[3] Courtesy of Marc Melaina / Eleftheria Kontou (NREL) and David Greene (ANL)

observed maximum).[4] Since this demonstration fleet, there have been examples of fuel cell vehicles that have approached or exceeded the minimum driving range target of 300 miles, even though significant effort regarding cost and packaging is still required to achieve commercial viability across various vehicle classes. Thus, it is clear that hydrogen storage systems must be improved in order to provide the customer with the expected driving range across all vehicle platforms.

To address all of these various challenges, hydrogen storage system performance targets for light-duty vehicles were developed through the U.S. DRIVE as shown below in Table 1. The targets apply to system-level properties and are customer and application driven. It is intended that U.S. DRIVE will review and update the hydrogen storage system targets approximately every 5 years to assess technology improvements and to ensure continued alignment with market driven requirements. Additional information on the U.S. DRIVE Partnership can be found in the Hydrogen Storage Technical Team Roadmap.[5] In addition, further information on FCTO's Hydrogen Storage Program can be found in the Multi-Year Research, Development, and Demonstration Plan.[6]

The original targets were set in 2003 based on attempting to be competitive with conventional gasoline fuel systems and revised in 2009 to enable greater than 300-mile range within the allocated package space and weight for hydrogen storage systems in representative fuel cell vehicles. Although hydrogen storage systems have shown continuous improvement since 2003 and many targets have been met in isolation, further advancements are still needed to meet all of the performance targets simultaneously. The automotive original equipment manufacturers (OEMs) have introduced many fuel cell electric vehicles (FCEVs) to a wide range of prospective customers since the original targets were formulated. Valuable information has been and continues to be gathered with regard to vehicle performance and customer requirements and expectations. From the experience gained with FCEV fleets and continued hydrogen storage system development, the targets have been further refined to align with these current advancements and implementation. Almost all FCEVs demonstrated to date have employed some degree of hybridization. Speculation on the effects of heavily hybridized vehicles (e.g. plug-ins, range extended etc.) was minimized in the development of these targets. If included in the future for consideration in the target calculation assessments, significant hybridization can both positively and negatively impact the suggested hydrogen storage system requirements and performance. For example, a 50-mile all electric range extended vehicle would reduce the hydrogen storage system range requirement by approximately 10 percent and potentially relax start-up time and system response, however it would also compete for packaging volume, weight, and cost.

This document presents the Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles Technical Targets, describes the relevant changes since the last major target revision was completed in 2009, and describes in length the details behind each target.

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[4] National Renewable Energy Laboratory, "Innovation for Our Energy Future," http://www.nrel.gov/hydrogen/docs/cdp/cdp_2.ppt.

[5] http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/hstt_roadmap_june2013.pdf

[6] http://energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf

2.0 Target Table:

Table 1. Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles [a] (updated May 2017)				
Storage Parameter	**Units**	**2020**	**2025**	**Ultimate**
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass) [b]	kWh/kg (kg H_2/kg system)	1.5 (0.045)	1.8 (0.055)	2.2 (0.065)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L (kg H_2/L system)	1.0 (0.030)	1.3 (0.040)	1.7 (0.050)
Storage System Cost : • Fuel cost [c]	\$/kWh net (\$/kg H_2) \$/gge at pump	10 333 4	9 300 4	8 266 4
Durability/Operability: • Operating ambient temperature [d] • Min/max delivery temperature • Operational cycle life (1/4 tank to full) • Min delivery pressure from storage system • Max delivery pressure from storage system • Onboard Efficiency [e] • "Well" to Powerplant Efficiency [f]	 °C °C Cycles bar (abs) bar (abs) % %	 -40/60 (sun) -40/85 1500 5 12 90 60	 -40/60 (sun) -40/85 1500 5 12 90 60	 -40/60 (sun) -40/85 1500 5 12 90 60
Charging / Discharging Rates: • System fill time [g] • Minimum full flow rate (e.g., 1.6 g/s target for 80kW rated fuel cell power) • Average flow rate • Start time to full flow (20°C) • Start time to full flow (-20°C) • Transient response at operating temperature 10%–90% and 90%–0% (based on full flow rate)	 min (g/s)/kW (g/s)/kW s s s	 3-5 0.02 0.004 5 15 0.75	 3-5 0.02 0.004 5 15 0.75	 3-5 0.02 0.004 5 15 0.75
Fuel Quality (H_2 from storage) [h]:	% H_2	Meet or exceed SAE J2719		
Dormancy: [i] • Dormancy time target (minimum until first release from initial 95% usable capacity) • Boil-off loss target (max reduction from initial 95% usable capacity after 30 days)	Days %	7 10	10 10	14 10
Environmental Health & Safety: • Permeation & leakage [j] • Toxicity • Safety	- - -	• Meet or exceed SAE J2579 for system safety • Meet or exceed applicable standards • Conduct and evaluate failure analysis		

Useful constants: 0.2778 kWh/MJ; Lower heating value for H_2 is 33.3 kWh/kg H_2; 1 kg H_2 ≈ 1 gal gasoline equivalent (gge) on energy basis

Footnotes to Target Table:

[a] For a normalized comparison of system performance to the targets, a usable H_2 storage capacity of 5.6 kg H_2 should be used at the lower heating value of hydrogen (33.3 kWh/kg H_2). Targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and all other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell system. All targets must be met at the end of service life.

[b] Capacities are defined as the usable quantity of hydrogen deliverable to the fuel cell system divided by the total mass/volume of the complete storage system, including all stored hydrogen, media, reactants (e.g., water for hydrolysis-based systems), and system components. Capacities must be met at end of service life. Tank designs that are conformable and have the ability to be efficiently package onboard vehicles may be beneficial even if they do not meet the full volumetric capacity targets.

[c] Hydrogen threshold fuel cost is calculated to be competitive with a gasoline hybrid vehicle, and thus is independent of pathway. It is defined as the untaxed cost of hydrogen produced, delivered, and dispensed to the vehicle [http://hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf]. For material-based storage technologies, the impact of the technology on the hydrogen threshold fuel cost (e.g., off-board cooling, off-board regeneration of chemical hydrogen storage materials, etc.) must be taken into account.

[d] Stated ambient temperature plus full solar load (i.e., full exposure to direct sunlight). No allowable performance degradation from -20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[e] Onboard efficiency is the energy efficiency for delivering hydrogen from the storage system to the fuel cell powerplant, i.e., accounting for any energy required operating pumps, blowers, compressors, heating, etc. required for hydrogen release.

[f] Well-to-powerplant efficiency includes onboard efficiency plus off-board efficiency, i.e., accounting for the energy efficiency of hydrogen production, delivery, liquefaction, compression, dispensing, regeneration of chemical hydrogen storage materials, etc. as appropriate. H2A and HDSAM analyses should be used for projecting off-board efficiencies. Efficiencies less than the target may be acceptable if evidence can be given that well-to-powerplant carbon intensity (including delivery and dispensing of H_2) can achieve less than 5 kg CO_{2e}/kg H_2. Argonne National Laboratory's GREET model (https://greet.es.anl.gov/) should be used to calculate the carbon intensity of well-to-powerplant energy use.

[g] When applicable, the fill time should comply with SAE J2601, the Fueling Protocol for Light-Duty Gaseous Hydrogen Surface Vehicles.

[h] Hydrogen storage systems must be able to deliver hydrogen that meets acceptable hydrogen quality standards for fuel cell vehicles (see SAE J2719 and ISO/PDTS 14687-2). Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case-by-case basis as more information becomes available.

[i] Dormancy targets assume vehicle is parked in 35°C ambient temperature and dormancy performance is maintained over the 15 year life of the vehicle.

[j] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage systems must comply with applicable standards for vehicular fuel systems including but not limited to SAE J2579 and the United Nations Global Technical Regulation No. 13 (hydrogen and fuel cell vehicles). This includes any coating or enclosure that incorporates the envelope of the storage system.

3.0 Summary of New / Revised Targets:

Since the last major target revision in 2009, significant progress has been made on the development and implementation of FCEVs thus necessitating the need to add and revise several targets. Tables 2 and 3 below provide a summary of the various targets that have been revised and added since the last major target update in 2009.

Note that in 2009, the targets were developed for 2015 and "Ultimate Full Fleet" targets were added to capture virtually all light-duty vehicle platforms ("significant market penetration"). The original 2015 targets were developed based on an assumption that the DOE funding for hydrogen storage research and development would remain fairly constant. Since 2009, funding for the DOE Hydrogen Storage Program has been at reduced levels as shown by the DOE Hydrogen and Fuel Cells Program Record #16010 (https://www.hydrogen.energy.gov/pdfs/16010_historical_fuel_cell_h2_budgets.pdf), thus impacting the ability to meet the 2015 targets and shifting these targets to 2025, which were added to Table 1.

Table 2. Revised Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles

Storage Parameter	Units	2020 (previous)	2020 (new)	2025 (new)	Ultimate (previous)	Ultimate (new)	Notes
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass) [b]	kWh/kg ($kg H_2/kg$ system)	1.8 (0.055)	1.5 (0.045)	1.8 (0.055)	2.5 (0.075)	2.2 (0.065)	Previous 2020 target shifted to 2025 target
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L ($kg H_2/L$ system)	1.3 (0.040)	1.0 (0.030)	1.3 (0.040)	2.3 (0.070)	1.7 (0.050)	Previous 2020 target shifted to 2025 target
Storage System Cost :	$/kWh net ($/kg H_2)	TBD TBD	10 333	9 300	TBD TBD	8 266	Cost target provided in 2009 was TBD
• Fuel cost [c]	$/gge at pump	2-4	4	4	2-4	4	Both 2020 and Ultimate targets were revised to be consistent with HPTT goal
Durability/Operability: • Min delivery pressure from storage system	bar (abs)			5	3	5	2020 unchanged; only Ultimate target was revised
Charging / Discharging Rates: • System fill time	min	3.3	3-5	3-5	2.5	3-5	Both 2020 and Ultimate targets were revised

Table 3. New Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles					
Storage Parameter	**Units**	**2020 (new)**	**2025 (new)**	**Ultimate (new)**	**Notes**
Charging / Discharging Rates: • Average flow rate	(g/s)/kW	0.004	0.004	0.004	New Target to Differentiate between Average flow rate & Minimum full flow rate
Dormancy: • Dormancy time target (minimum until first release from initial 95% usable capacity) • Boil-off loss target (max reduction from initial 95% usable capacity after 30 days)	Days %	7 10	10 10	14 10	New Targets to Address Dormancy (challenge for system operating at less than ambient temperate)

In addition to the changes noted above, the target for release of hydrogen was removed for clarity as this system metric is now more specifically covered by the targets for dormancy as well as permeation and leakage. Also, targets relating to internal combustion engine were removed. At one time, hydrogen powered internal combustion engines (ICE) were seen as a logical evolution step to fuel cell vehicles powered by hydrogen. Focus has shifted entirely to FCEVs and thus there is no longer a need to include specific targets as related to ICEs. As a result all hydrogen storage system targets related to ICEs have been removed.

Further explanation of the new and modified targets are included in Section 5.0 which provides a detailed breakdown of the individual targets.

4.0 Assumptions:

1. All targets must be met simultaneously on a total system level. The performance targets apply to a complete storage system, including the tank, storage media, safety system, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and any other necessary balance-of-plant components (see Figure 1 below for example system diagrams showing single-tank and dual-tank configurations with necessary balance-of-plant components).
2. Targets are based on what is required to meet the application requirements and customer expectations; not on what the state-of-the-art technology can achieve.
3. The targets should enable greater than 300-mile range across the majority of the current light-duty vehicle fleet (i.e. many makes and models).
4. The targets are based on providing a sufficient amount of net available hydrogen onboard the vehicle to satisfy driving range.
5. These targets must be maintained until the end of the vehicle's service life.
6. Depending on progress in other areas related to FCEV development, these targets may have to be altered and will be periodically revisited approximately every 5 years.
7. A wide variety of vehicle types from small subcompact cars to light-duty trucks were considered in the target calculations; the fuel storage requirement varied between approximately 4 to 10 kg of hydrogen, based on the corresponding vehicle type (class) and expected driving range.
8. The targets include the "Ultimate Full Fleet" targets. The "Ultimate Full Fleet" targets are meant to capture virtually all light-duty vehicle platforms ("significant market penetration"). The "Ultimate Full Fleet" target is intended to facilitate the introduction of hydrogen-fueled propulsion systems across the majority of vehicle classes and models.
9. Some volumetric allowance can be adopted in the targets for conformable (geometrically speaking) storage systems. The volumetric and gravimetric targets (revised approach in 2009) utilized the packaging and design space allotted for compressed hydrogen storage in the actual fuel cell demonstration fleet vehicles. That is, the majority of vehicles in the fleet have demonstrated the OEMs' abilities to design and modify vehicle architecture around the hydrogen systems. Two examples of such modifications include the redesign of floor pan to accommodate larger hydrogen storage systems and the alteration in vehicle architecture to accommodate fuel cell/electronic systems components. Varying degrees of increased mass and volume acceptance (due to the fuel cell and H_2 storage systems) have been demonstrated in these vehicles. Experience has shown that it is generally easier to accommodate extra weight compared to extra volume (i.e., accommodating additional packaging volume is more challenging). Importantly, all vehicle modifications must be performed without making compromises to customer expectations for cargo/passenger space, performance, or safety.

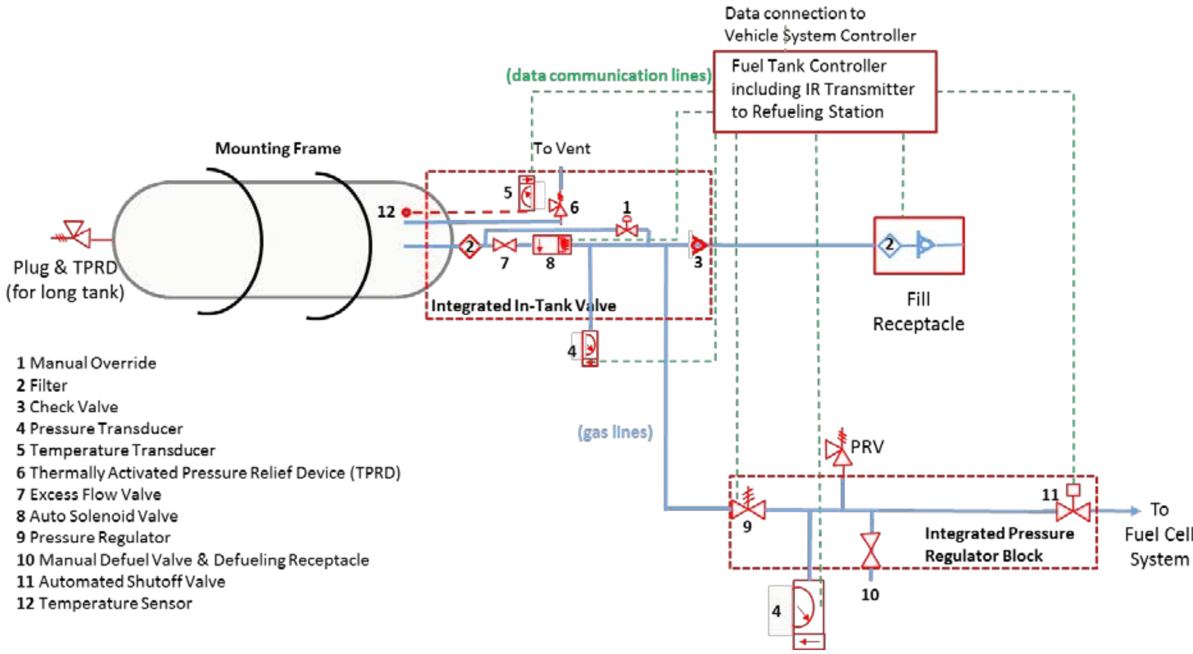

Figure 1a: Example 700 bar Hydrogen Storage System Diagram Showing a Single-Tank Configuration[7]

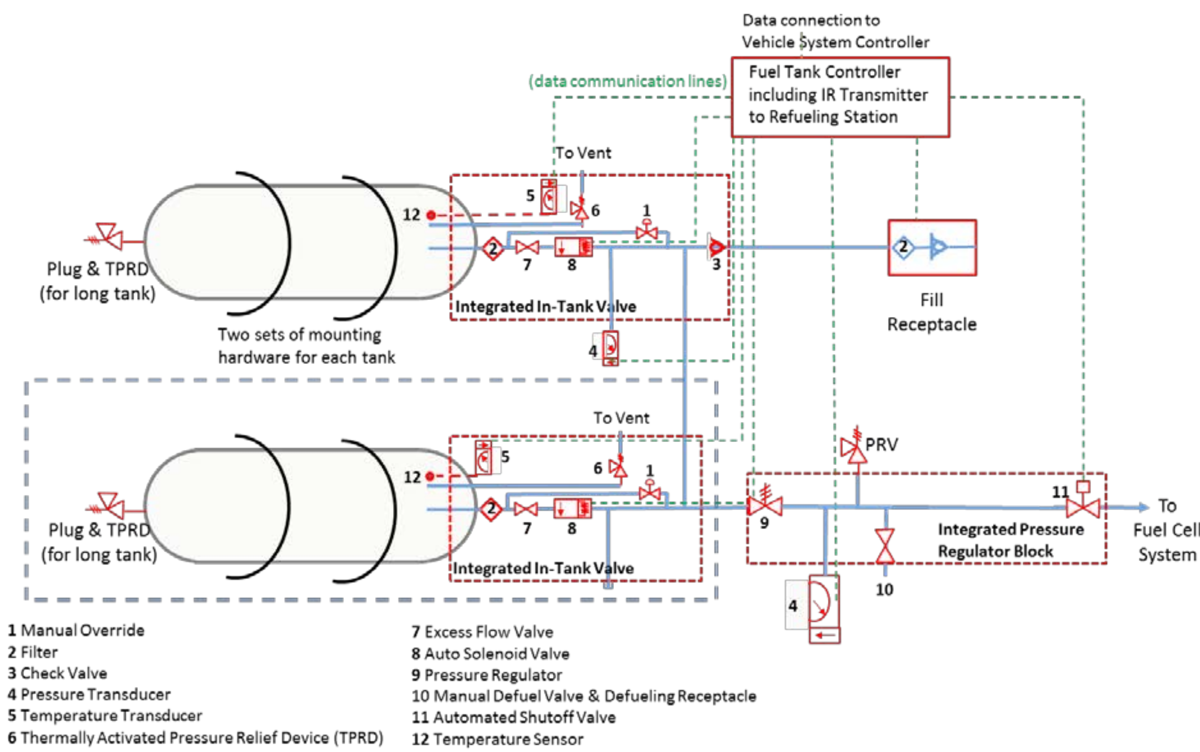

Figure 1b: Example 700 bar Hydrogen Storage System Diagram Showing a Dual-Tank Configuration

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[7] G. Ordaz, C. Houchins, and T. Hua, "Onboard Type IV Compressed Hydrogen Storage System – Cost and Performance Status 2015," DOE Hydrogen and Fuel Cells Program Record #15013, Nov. 25, 2015. https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

5.0 Detailed Breakdown of the Individual Targets:

The following section provides the detailed background and explanation for each target in Table 1. For a normalized comparison to these targets, a usable hydrogen storage capacity of 5.6 kg hydrogen should be used at lower heating value of hydrogen (33.3 kWh/kg hydrogen). In addition, the targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and all other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell system and all targets must be met at the end of service life. While certain targets are expressed in terms of kWh/kg, kWh/L and $/kWh, it should be acknowledged that the hydrogen system is not exactly scalable by the useable capacity since the balance-of-plant components will be fixed regardless of the capacity. Based on this understanding that hydrogen systems have a scalable and fixed element, a target comparison based on the absolute weight, volume, and cost can also be performed to allow for the practical application of onboard efficiency advancements and acceptable limits for actual storage systems.

Storage Parameter	Units	2020	2025	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass)	kWh/kg (kg H_2/kg system)	1.5 (0.045)	1.8 (0.055)	2.2 (0.065)

System Gravimetric Capacity:
This is a measure of the specific energy from the system standpoint of net useful energy per total onboard storage system mass, not just the storage medium. The term specific energy is used interchangeably with the term gravimetric capacity. “Net useful energy” excludes unusable energy (i.e. hydrogen left in a tank below minimum fuel cell system pressure, flow, and temperature requirements) and energy used to extract the hydrogen from the storage medium (e.g. fuel used to heat a hydride or material to initiate or sustain hydrogen release). The system gravimetric capacity refers to end of life net available capacity. The storage system is all encompassing meaning it includes everything necessary for the storage system. This includes, but is not limited to: interfaces with the refueling infrastructure, safety features, storage vessel, storage media, insulation or shielding, temperature/humidity management equipment, regulators, electronic controllers, sensors, all onboard conditioning equipment necessary to store the hydrogen (compressors, pumps, filters, etc.), and the mounting hardware and delivery piping. The target is in units of net useful energy in kWh per maximum system mass in kg. “Maximum system mass” implies that all of the equipment enumerated above plus the maximum charge of hydrogen are included in the calculation. Reactive systems may increase in mass as they discharge hydrogen; in such systems the post hydrogen discharged mass must be used.

Table 4: Second Generation

FCEV Data	Units	Range of Values		
		Lower "Gen 2"*	Upper "Gen 2"*	2017 Commerical Example[8]
Fuel Economy	mi/kg H_2	43	58	66
Range	mi	196	254	312
H_2 Capacity	kg H_2	4.6	4.4	4.7
Gravimetric Capacity	wt% H_2	2.5	4.4	4.4
Volumetric Capacity	kg H_2/L	0.018	0.025	0.025
Storage System Mass	kg	182	100	108
Storage System Volume	L	253	175	185
*Old 2009 data based on DOE's National Hydrogen Learning Demonstration				

Vehicle Data from the DOE "National Hydrogen Learning Demonstration" Project

To determine the capacity targets developed back in 2009, data from operational fuel cell fleet vehicles associated with the DOE "National Hydrogen Learning Demonstration" were used, including small, compact, mid-size and crossover light-duty vehicles. The vehicles had a varied degree of hybridization. As shown in Table 4, these vehicles were unable to achieve the expected driving range, which in North American is 300 miles (at a minimum) up to nearly 500 miles for the light-duty vehicle market. Based on the allocated weight for hydrogen storage systems, the targets were determined by calculating the increased capacity required to allow these fuel cell vehicles to meet the desired driving range within the current vehicle using the fixed allocation for system weight. From these initial fleet examples, recent fuel cell vehicles have demonstrated improvements in fuel economy (e.g. Toyota Mirai[8]) with the capability of achieving over a 300 mile range. Therefore, the upper range vehicle example in Table 4 can be replaced with these recent vehicle data (e.g. 66 miles/gge) along with the respective hydrogen storage allocations (e.g. 4.7 kg useable capacity, 108 kg). The target values were modified based on these recent fuel cell vehicles. The 2020 gravimetric targets aligned directly with these current storage system examples capable of achieving the minimum of 300 miles. The 2025 target was based on achieving a 400 mile driving range using the current fuel cell electric vehicle example in the Table 4 for the upper values, which results in a hydrogen capacity of 6.1 kg to 9.3 kg. Using this capacity and the weight allocation (108 kg to 182 kg), the resulting average gravimetric capacity target is 5.5 wt%. The same approach was used for the ultimate target based on a 500 mile driving range resulting in a target value of 6.5 wt%.

Storage Parameter	**Units**	**2020**	**2025**	**Ultimate**
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	1.0 (0.030)	1.3 (0.040)	1.7 (0.050)

System Volumetric Capacity:

This is a measure of energy density from a system standpoint of net useful energy per onboard storage system volume, rather than from a storage media standpoint. The term energy density is used interchangeably with the term volumetric capacity. As noted above, the onboard hydrogen storage system includes every component required to safely accept hydrogen from the delivery infrastructure, store it onboard, and release conditioned hydrogen to the fuel cell system. Also, as before, any unusable

[8] Estimates based on data from http://www.fueleconomy.gov/feg/fcv_sbs.shtml and other available information

fuel must be taken into account and storage system volumetric capacity refers to end of life net available capacity. Today's gasoline tanks are considered conformable. For conformable tank concepts, the required volumetric energy density may be reduced because space not allocated for fuel storage may be used without a penalty. The system volumetric capacity refers to end of life net available capacity. The volume should be considered as the external water displacement volume of the entire system. The targets are in units of net usable energy in kWh per system volume in liters.

As discussed for gravimetric capacity, data from operational fuel cell fleet vehicles associated with the DOE "National Hydrogen Learning Demonstration" was used to determine the volumetric capacity targets developed back in 2009. In the same manner, the targets were determined by calculating the increased capacity required to allow these fuel cell vehicles to meet the desired driving range within the current vehicle using the fixed allocation for system volume. As recognized in the gravimetric target explanation, the fuel economy of recent fuel cell vehicles (e.g. Toyota Mirai) have improved since the demonstration vehicles noted in Table 4 with the capability of achieving just over 300 miles driving. This improvement allows for the upper range vehicle in Table 4 to be replaced with these recent vehicle data (e.g. 66 miles/gge) along with the respective hydrogen storage allocations (e.g. 4.7 kg useable capacity). The target values were modified based on these recent fuel cell vehicles. The 2020 gravimetric targets aligned directly with these current storage system examples capable of achieving the minimum of 300 miles with a 15% correction factor. The correction factor adjustment is motivated by two key points. First, as the volumes quoted in Table 4 refer to exact or water volumes, they represent the minimum volume required by the storage vessel. The practical enclosure volume available onboard the vehicle is typically less. In fact, the examples in the fleet fuel cell vehicles had notable intrusion into the customer or cargo space. The correction factor to estimate the packaging inefficiency may vary significantly based on the type of vehicle platform and design requirements of each OEM. Second, vehicles in the DOE demonstration dataset along with recent vehicles are SUV-type or large sedan vehicles. Packaging of hydrogen storage systems in these larger vehicles will generally be easier than in smaller ones. Taking these two points into account, a target value slightly higher than the represented volumes was adopted based on these correction factors. Similar to the gravimetric target explanation, the 2025 target was based on achieving a 400 mile driving range requiring between 6.1 kg to 9.3 kg useable hydrogen based on the fuel cell electric vehicle examples in the Table 4 with the replacement of the recent fuel vehicle attributes for the upper values. Using this capacity and the volume allocation (185 L to 253 L) along with the correction factor, the resulting average volumetric target is 0.040 kg/L. The same approach was used for the ultimate target based on a 500 mile driving range resulting in a target value of 0.050 kg/L.

Storage Parameter	Units	2020	2025	Ultimate
Storage System Cost :	$/kWh net ($/kg H_2)	10 333	9 300	8 266
• Fuel cost	$/gge at pump	4	4	4

Storage System Cost:
This is the cost of the entire hydrogen storage system including the initial charge hydrogen. As noted above, the onboard hydrogen storage system includes every component required to safely accept hydrogen from the delivery infrastructure, store it onboard, and release conditioned hydrogen to the fuel cell system.

U.S. DRIVE performed extensive modeling to evaluate the targets for advanced vehicle technologies, including FCEVs. The purpose of the analysis was to provide guidance for the U.S. DRIVE targets, such that vehicles using the advanced technologies being developed through the U.S. DRIVE partnership would be comparable on a cost (initial + operational) and performance basis to incumbent technology by 2020. The effort considered three levels of technology advancement, 10%, 50% and 90% confidence levels with 10% being the most aggressive within the 2020 timeframe based on a high volume assumption of 500,000 units produced per year. The levelized cost of driving for the analysis was developed based on midsize vehicle using 2011 Annual Energy Outlook (AEO11) High Oil Scenario for gasoline in 2020 ($5.05/gallon of gasoline), 14,000 miles per year, 3-year payback period, and 7% discount rate. Figure 2 provides the levelized cost results at the 50% confidence level for the FCEV compared to an advanced spark ignition (Adv SI) and hybrid electric (SI HEV) vehicle. From this analysis, the fuel cell vehicle at the 2020 baseline would require cost reductions to be competitive on a levelized cost of driving.

The U.S. DRIVE analysis for the 2020 FC HEV baseline assumed a hydrogen fuel cost of $3.50 per gallon gasoline equivalent (1 kg H_2 is approximately 1gge); fuel cell system costs of $46/kW; and onboard hydrogen storage system costs of $15/kWh ($500/kg H_2). After adjusting the FC HEV assumptions to the Department of Energy's 2020 fuel cell system target of $40/kW, a hydrogen storage system cost target of $10/kWh would enable an FCEV to approach the levelized cost of the SI HEV at the 50% confidence level and Adv SI at the 90% confidence level. For a competitive levelized cost to a Adv SI, the fuel cell system would need to achieve their ultimate target of $30/kW and the onboard hydrogen storage system would require a cost target of $8/kWh, which is also shown in Figure 2 as a comparison to the baseline gasoline vehicle levelized cost.

Therefore onboard hydrogen storage cost targets of $10/kWh as an intermediate target in 2020, $9/kWh in 2025, and $8/kWh as a long-term ultimate target are appropriate.

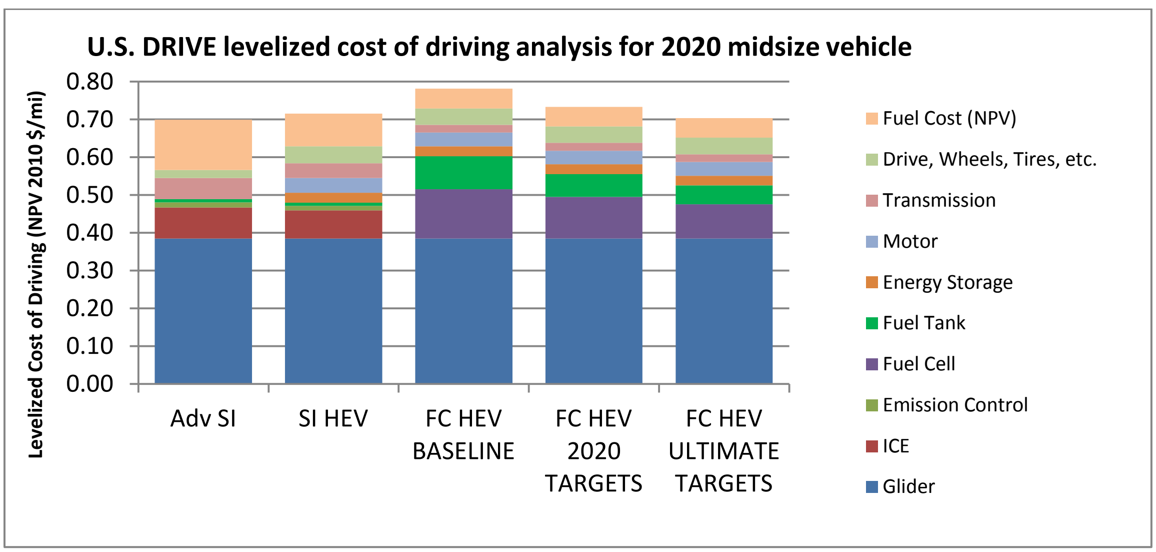

Figure 2: Levelized Cost of Driving Analysis for a FC HEV with baseline, 2020 targets, and Ultimate Target Assumptions in Comparison to Adv SI and SI HEV to establish the Onboard Hydrogen Storage System Cost Targets

- Fuel cost: This target includes costs for producing, compressing, liquefying, transporting and distributing, dispensing, chemical recovery, etc., as applicable for the fuel.[9] For material-based storage, if the fuel / storage system utilized, requires additional processing such as off-board cooling or off-board regenerated of spent fuel (e.g., chemical hydrogen storage material), then those extra costs (e.g., regeneration) must be included within the fuel cost. The storage system cost also includes the first charge of fuel as mentioned above. The unit of $/gallon gasoline equivalent (gge) is approximately equivalent to $/kg of hydrogen.

Storage Parameter	Units	2020	2025	Ultimate
Durability/Operability:				
• Operating ambient temperature	°C	-40/60 (sun)	-40/60 (sun)	-40/60 (sun)
• Min/max delivery temperature	°C	-40/85	-40/85	-40/85
• Operational cycle life (1/4 tank to full)	Cycles	1500	1500	1500
• Min delivery pressure from storage system	bar (abs)	5	5	5
• Max delivery pressure from storage system	bar (abs)	12	12	12
• Onboard Efficiency	%	90	90	90
• “Well” to Powerplant Efficiency	%	60	60	60

Durability / Operability:

- Operating ambient temperature: The storage system must dependably store and deliver hydrogen to the fuel cell system at all expected ambient conditions. The temperature units are degrees Celsius (°C). The notation (sun) indicates that the upper temperature is a hot soak condition in full direct sun, including radiant heat from the pavement. Note that storage operating temperatures in excess of 60°C can be achieved with solar loading. Thus the hydrogen storage system design should include a shield from this radiant heat or be designed to accommodate temperatures greater than 60°C. Also note that there is no allowable performance degradation between –20°C and 40°C. Allowable degradation outside these limits is to be determined.

- Min/max delivery temperature: This target refers to the inlet temperature of hydrogen to the fuel cell system. Fuel cells currently operate at approximately 80°C. Any hydrogen entering above the fuel cell operating temperature would add to the already significant water management and heat rejection requirements of the fuel cell system. Thus, an upper limit on temperature is desirable. The value of 85°C is selected based on today’s proton exchange membrane (PEM) fuel cell technology. As the fleet size is increased, it will also become increasingly important that the storage system comply more closely with the fuel cell preferred operating range. The lower limits reflect both wider acceptance of fuel cells in varying climates and fuel cell improvements for lower temperature operation. The temperature units are degrees Celsius (°C).

- Operational cycle life: This target refers to the minimum cycle life for the performance of the storage material/media. The number of operational cycles is calculated as the design lifetime mileage of the vehicle divided by the effective range of the vehicle. Customers expect the fuel system to last the life of the vehicle and typically 150,000 miles represents the minimum lifetime. Assuming a 300-mile range, this amounts to 500 full fill cycles as a minimum. However, many customers fill at partial capacity rather than at empty and extend the vehicle mileage beyond the minimum lifetime, requiring more fill cycles. The Sierra Research Report No.

[9] https://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf

SR2004-09-04 for the California Air Resource Board (2004) on vehicle lifetime mileage indicated all scrapped vehicles had mileage below 350,000 miles (6-sigma value was 366,000 miles). Using this maximum lifetime mileage and the partial cycle definition from a quarter full to full tank, the effective range is reduced to 225 miles resulting in the 1,500 cycle life target. This target is not equivalent to the durability test cycles, which require significantly more cycles to ensure safe performance. The safety critical components (i.e. cylinder, relief valves, etc.) involved in managing pressure and temperature conditions need additional durability cycle life as specified in the applicable codes and standards (i.e. SAE J2579 and the United Nations Global Technical Regulation ECE/TRANS/180/Add.13).

- Minimum delivery pressure from storage system: This target acknowledges that the onboard hydrogen storage system is responsible for delivering hydrogen in a condition that the fuel cell system can use. Since there can be no flow without a pressure differential, a minimum supply pressure is required just to move the hydrogen from the bulk storage to the fuel cell system. If the hydrogen were merely available at the entrance to a fuel cell system (i.e., less than 5 bar), then any pumps necessary to push or draw that fuel through the stack would be considered part of the fuel storage system. The pressure units are in gauge bar (bar).

  The Ultimate Target for the minimum delivery pressure from the storage system was updated from 3 bar to 5 bar. It should be recognized the delivery pressure is at the interface between the hydrogen storage system and the fuel cell system rather than directly to the fuel cell stack. The delivery pressure to the fuel cell system requires higher pressure than the operating conditions of the stack for pressure drop and passive recirculation within the fuel cell system balance of plant. In some fuel cell system designs, the desire is to increase this minimum delivery pressure even greater than 5 bar in order to further optimize the performance. Therefore, the Ultimate Target was updated to 5 bar to acknowledge the current direction for fuel cell system requirements and provide a consistent minimum delivery pressure throughout the target table.

- Maximum delivery pressure from storage system: This target is for the pressure delivered from the onboard hydrogen storage system to the fuel cell system. This target ensures that the onboard hydrogen storage system regulates the pressure before fuel is supplied to the fuel cell system.

- Onboard Efficiency: Hydrogen storage systems must be energy efficient. To ensure this, a target has been set for the efficiency of the storage system onboard the light-duty vehicle. It is defined as the ratio of the total amount of energy delivered to the fuel cell system (lower heating value) compared to the total energy contained in the tank (based on the tank rating). For onboard reversible storage systems, the target is greater than 90% energy efficiency for the energy delivered to the fuel cell system from the onboard storage system. For example, if a storage tank is rated as holding 5.6 kg usable hydrogen, the total amount of energy in the rated tank would be 5.6 kg multiplied by (33.3 kWh/kg) or approximately 186.5 kWh. For the target to be achieved, at least 90% of 186.5 kWh or 168 kWh needs to be delivered to the fuel cell system.

- "Well" to Powerplant Efficiency: Well-to-powerplant efficiency includes onboard efficiency plus off-board efficiency, i.e., accounting for the energy efficiency of hydrogen production, delivery, liquefaction, compression, dispensing, regeneration of chemical hydrogen storage materials, etc. as appropriate. The energy content of the hydrogen delivered to the automotive powerplant should be greater than 60% of the total energy input to the process. H2A and

HDSAM analyses should be used for projecting off-board efficiencies.

Efficiencies less than the target may be acceptable if evidence can be given that the carbon intensity (including delivery and dispensing of hydrogen) can achieve less than 5 kg CO_{2e}/kg H_2 (i.e., conceivable that a system is inefficient, but still allows for reduced greenhouse gas emissions). Argonne National Laboratory's GREET model (https://greet.es.anl.gov/) should be used to calculate the carbon intensity of energy use for hydrogen delivery and dispensing (from 20 bar, and ambient temperature of produced hydrogen). Default 2025 energy shares and efficiency values in GREET, when applicable, should be used for calculating carbon intensity.

To liquefy and dispense hydrogen, about 11-15 kWh of electricity are needed for liquefaction and pumping (depending on the scale and technology of liquefaction). Using the current (2015) carbon intensity of the U.S. electricity grid mix of about 550 g CO_{2e}/kWh, the carbon intensity of delivering and dispensing liquid hydrogen is 6-8 kg CO_2/kg H_2. This is true whether liquid pumping was used for 350 bar cryo-compressed dispensing, or in conjunction with a heat exchanger for 700 bar gaseous dispensing. The corresponding electricity consumption for tube-trailer delivery and 700 bar gaseous dispensing is in the range of 3-5 kWh/ kg H_2, which results in 2-3 kg CO_2/kg H_2 with the current U.S. electricity grid mix. Depending on the truck transportation and distribution (T&D) distance, and the truck payload of hydrogen, the GHG emissions associated with trucking hydrogen results in additional 1 kg CO_2/kg H_2 for each 100 miles T&D of 500 kg payload of hydrogen.

Storage Parameter	Units	2020	2025	Ultimate
Charging / Discharging Rates:				
• System fill time	Min	3-5	3-5	3-5
• Minimum full flow rate (e.g., 1.6 g/s target for 80kW rated fuel cell power)	(g/s)/kW	0.02	0.02	0.02
• Average flow rate	(g/s)/kW	0.004	0.004	0.004
• Start time to full flow (20°C)	S	5	5	5
• Start time to full flow (-20°C)	S	15	15	15
• Transient response at operating temperature 10%–90% and 90%–0% (based on full flow rate)	S	0.75	0.75	0.75

Charging / Discharging Rates:

- System fill time: Consumers expect to refuel a vehicle quickly and conveniently, especially on extended trips. The filling target is designed to parallel current customer experience. Currently, gasoline vehicles are filled in approximately 3 to 5 minutes, with small vehicles taking less time than large ones. Based on the expected efficiency of FCEVs, approximately 4 to 10 kg of hydrogen will be needed for light-duty vehicles. This target will achieve near parity with current gasoline filling times. For a comprehensive comparison of fill time, the storage system should comply with the performance in SAE J2601, the Fueling Protocol for Light-Duty Gaseous Hydrogen Surface Vehicles (http://standards.sae.org/j2601_201003/). The units are minutes.

  Note: the fill time involves not only delivery of the hydrogen to the storage system, but also any potential heat/mass transfer and/or kinetic factors associated with a particular storage system design. Thus all factors must be considered especially when scaling small prototype systems to determine fill time.

- Minimum full flow rate: This target is a measure of the maximum flow rate of hydrogen required by the fuel cell system to achieve the desired vehicle performance. It is based on an average midsize light duty fuel cell vehicle, which typically has a power plant of about 80 kW and maximum fuel flow from the EPA US06 aggressive drive cycle. This is not a continuous flow target since the vehicle would not accelerate through an entire tank of fuel although it might be called upon to tow a large, heavy trailer up an 18-mile grade, such as is found on Interstate 5 near Baker, California. However, because fuel cell efficiency is poorest at full load, while ICEs are at or near their highest efficiency at full load, FCEVs may require higher full flow rates than this minimum to be competitive with ICEs. Finally, this target is intended to indicate the potential for scalability for the hydrogen storage technology and thus the target is in units of mass/time normalized to fuel cell system rated power.

- <u>Average flow rate</u>: While the minimum full flow rate noted above defines the requirements for the storage system to supply hydrogen to the fuel cell system at peak load, it is also understood that an FCEV will not be operated at peak load through an entire tank of fuel. As described for the minimum full flow, an average midsize light duty fuel cell vehicle with a typically power plant of about 80 kW rated power was assumed for this target. This target is based on the average flow rate of hydrogen required by the fuel cell system for the EPA US06 aggressive drive cycle although it is still not expected that the flow demand will be continuous at this average flow rate value. For potential for scalability for the hydrogen storage technology, the target is in units of mass/time normalized to fuel cell system rated power.

- <u>Start time to full-flow (20°C)</u>: The vehicle may be able to start based on hydrogen in the lines, but to maintain adequate function without the need for a second energy storage medium (e.g. batteries), full flow must be available almost instantly. Customers are currently accustomed to sub-second start times and full power available on demand, any time after the key is released. The target cold start-up time to achieve 50% rated power for the complete fuel cell system at 20°C ambient temperature is 5 seconds. The storage system targets for start time to full-flow are set to meet the overall fuel cell system needs. In addition, the storage system must provide some flow to the fuel cell system within 25% of the time target for full-flow. The units for this target are seconds after start.

  Note: this doesn't mean that the entire storage system must start in 5 seconds; only that it is capable of delivering fuel at maximum flow if requested. A moderate pressure buffer could serve to lengthen the true start up time. In that case, the mass and volume of the buffer would then need to be included within the system mass and volume.

- <u>Start time to full-flow (-20°C)</u>: See Start time at 20°C for background explanation. The longer times reflect current customer expectation that in cold weather starting is more difficult. It is important to note that batteries are at their worst power capabilities at very low temperature. If a battery assist were contemplated, the battery system would likely have to be sized based on this starting condition, and thus would be rather large. This is why it has been desirable to avoid batteries for cold start if possible, unless sizing issues can be resolved. The target cold start-up time to achieve 50% rated power for the complete fuel cell system at -20°C is 15 seconds. Consistent with the above target, some flow will be required to the fuel cell system within 25% of the full-flow target time. Given the possibility that some hydrogen may be used to assist with cold start of the fuel cell system, the storage system is set to achieve full-flow within 50% of the start time for the fuel cell system. Units are in seconds.
- <u>Transient response 10%-90% and 90%-0% based on full flow rate</u>: Transient response is one of

the greatest challenges a vehicle powertrain faces. The storage system must provide fuel to meet the needs of the fuel cell system to deliver adequate power and a suitable driving experience. Therefore, the transient response must meet the fuel cell system requirement of 0.75 second (2010 and 2015 targets). The transient response is not necessarily symmetric. The 10 to 90% transient target is to meet the demand of the fuel cell during acceleration. The 90 to 0% transient reflects that the vehicle may need to stop using hydrogen almost instantly (e.g. safety shut-off) and the fuel supply must stop quickly enough to avoid over-pressuring any part of the system. This parameter impacts performance, fuel cell durability, and vehicle control. The units are seconds to change between 10% flow and 90% flow, or 90% flow and no flow.

Storage Parameter	Units	2020	2025	Ultimate
Fuel Quality (H_2 from storage):	% H_2	Meet or exceed SAE J2719		

- Fuel Quality: Hydrogen must be relatively pure going to the fuel cell system or else vehicle efficiency and performance will be degraded. The fuel quality from the hydrogen storage system must maintain or exceed the levels specified in SAE J2719 (http://standards.sae.org/j2719_201511/). The levels of constituents in SAE J2719 were determined by experimental testing representative fuel cells with impurities. As indicated in SAE J2719, even inert impurities can degrade performance by progressively diluting the hydrogen in the fuel cell system, resulting in a higher necessitating of venting from the fuel cell anode. Other impurities react directly with the fuel cell catalyst resulting in immediate or long-term damage. The SAE J2719 fuel quality standard is the same requirement for the hydrogen delivered from the fueling station into the storage system. In other words, the hydrogen output from the storage system should not add significant contaminants beyond the fuel cell quality targets in SAE J2719 and ISO specification ISO/PDTS 14687-2. It is also assumed that impurities from the hydrogen source do not degrade storage system performance.

Storage Parameter	Units	2020	2025	Ultimate
Dormancy:				
• Dormancy time target (minimum until first release from initial 95% usable capacity)	Days	7	10	14
• Boil-off loss target (max reduction from initial 95% usable capacity after 30 days)	%	10	10	10

Dormancy:

- Dormancy time target: This target protects against loss of driving range after extended periods of vehicle at rest (e.g., parking during a vacation). The dormancy period is especially relevant for hydrogen systems that operate at low temperatures. As the temperature in the tank increases, the pressure increases to the point that it needs to be released due to exceeding the maximum pressure rating of the tank. The period of time prior to this release (or boil-off point) is defined as the dormancy time. Fuel cell vehicles purchased by typical consumers expect to have the same amount of fuel in their tank after extended parking, similar to gasoline vehicles today. For 2020, the dormancy time target of 7 days from initial 95% usable capacity was selected based on a typical period of time that a vehicle would be parked at the airport for a vacation. The 95% usable capacity qualifier was based on the consideration that the vehicle is unlikely to be parked immediately after a fueling event. The dormancy time target was extended for 14 days at the same peak capacity to accommodate a two week vacation that a vehicle would be parked. The evaluation of the dormancy time should be conducted at the high ambient soak temperature which is assumed to be 35°C for this target assessment. It should be noted that this is not the maximum ambient temperature although diurnal cycles reduce the average exposure temperature over a period of days. For most low temperature storage systems, the peak capacity condition will be the worst case for dormancy although lower states of charges should also be considered. The units for this target are in days.

- Boil-off loss target: This target is based on the desire to have minimal perceptible loss of driving range after the dormancy time is exceeded. As stated above, hydrogen systems with low storage temperatures experience heat loss that increases pressure and eventually requires hydrogen release or boil-off to avoid exceeding the maximum rated tank pressure. If the hydrogen released is not vented to the atmosphere, but used for other purposes (e.g., converted via a catalytic reactor or other uses) instead, then this additional balance of plant must be included as part of the storage system. The target is indicated as a 10% maximum capacity loss from the initial state of the tank over a 30 day period of time. It is assumed that this capacity loss would not be notable to the average consumer and the 30 days assumes a maximum time a vehicle would be at rest in normal operation. This target protects all storage system capacities equally and at all state of charge conditions. As specified for dormancy, the initial capacity condition is 95% of the rated usable capacity and the ambient soak temperature should be 35° C for this target assessment. For most low temperature storage systems, the peak capacity condition will be the worst case for boil-off loss although lower states of charges should be considered.

Storage Parameter	Units	2020	2025	Ultimate
Environmental Health & Safety:				
• Permeation & leakage	-	• Meet or exceed SAE J2579 for system safety		
• Toxicity	-	• Meet or exceed applicable standards		
• Safety	-	• Conduct and evaluate failure analysis		

Environmental, Health & Safety:

- Permeation & leakage: These targets are of great importance because they deal with protecting the health and well-being of individuals in contact with the storage system. The permeation and leak target are defined in SAE J2579 for the entire storage system, rather than per component or storage material. A system integrator or OEM could cascade the system leakage targets to various elements with the system as necessary. Permeation and leakage are differentiated from hydrogen release and boil-off loss in that hydrogen leakage leaves the storage system in an unintended manner while boil-off should be controlled and transformed into another species (e.g. water, via catalytic oxidation in a vent line). Permeation and leakage thus pertains to the possibility of generating a combustible hydrogen-air mixture outside the storage tank.

- Toxicity: Toxicity covers the possibility of consumer exposure to the storage material in normal, or abnormal conditions, plus worker exposure during manufacture and assembly. These types of toxicity criteria are generally regulated by applicable government standards. Materials with a known hazardous risk potential shall be avoided. For example, the EPA's Toxic Substances Control Act Chemical Substance Inventory (TSCA Inventory) and U.S. Department of Labor Occupational Safety and Health Administration (OHSHA) can be used as references.

- Safety: Safety covers all the typical safety statutes including certification and operation of vehicles, manufacture, transport, dispensing of fuel, and end of life issues. In each of these categories, compliance with federal standards and potentially state and local standards will be required. The onboard storage systems must comply with applicable standards for vehicular fuel systems including but not limited to SAE J2579 and the United Nations Global Technical Regulation No.13 (Hydrogen and fuel cell vehicles). These standards include the minimum level of testing to determine the robustness of these hydrogen storage systems including hydraulic/pneumatic durability, burst, pressure cycle life, bonfire, chemical resistance, drop, penetration, environmental, and vehicle crash impact testing. The hydrogen storage system design must account for the requirements in these standards along with the applicable international standards in the nations that the vehicle will be deployed. For certain countries, the storage system and high pressure components require certification by a specified regulatory organization prior to on-road usage. SAE J2578, J2600, J2601, J2719, and J2799 (http://standards.sae.org/) provide the necessary references for vehicle and fueling interface standards. CSA and ISO also provide standards for safety guidance along with component certification standards. For storage system technologies (e.g. material-based) not specifically addressed in these standards, the intent of these safety requirements still must be applied to the design with appropriate engineering rationale and documentation until the incorporation into the standards. Beyond regulated standards, hydrogen storage system developers should utilize automotive failure analysis tools such as Failure Mode and Effects Analysis (per SAE J1739) to identify and evaluate unique potential safety failure modes associated with their system. For example, metal hydrides are known to expand with absorption and can add strains to the storage tank, which should be included in the durability and safety testing as a potential failure mode in addition to the industry codes and standards.