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Impact of Fuel Cell and Storage System Improvement on Fuel Consumption and Cost

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Summary

The U.S. Department of Energy (DOE) Vehicle Technologies Program (VTP) is developing more energy-efficient and environmentally friendly highway transportation technologies that will enable America to use less petroleum. The VTP includes studies of the potential benefit of advanced technologies and also attempts to clarify and refine the requirements for vehicle components. Owing to the large number of component and powertrain technologies considered, the benefits of the VTP research and development portfolio were simulated using Autonomie, Argonne National Laboratory's vehicle simulation tool.

This paper evaluates advanced fuel cell and hydrogen storage systems for a midsize car in different model years, in conjunction with advancements in the rest of the powertrain, as part of DOE baseline and scenario analysis (BaSce). In addition, this paper quantifies the fuel displacement and costs of advanced hydrogen storage and fuel cell systems, without considering advancements in the rest of the powertrain.

Keywords: fuel cell, hydrogen, HEV (hybrid electric vehicle), series HEV, simulation

1 Introduction

The U.S. Department of Energy (DOE) through different alternatives is pursuing the development of more energy-efficient and environmentally friendly transportation technologies that will reduce U.S petroleum dependence. One of the pathways is led by the Hydrogen and Fuel Cells Program, which focuses on hydrogen and fuel cell-related activities. Fuel cells (FCs) are an important enabling technology for the nation's energy portfolio and have the potential to revolutionize the way we power our nation, offering cleaner, more-efficient alternatives to the combustion of gasoline and other fossil fuels. Fuel cells have the potential to replace the internal-combustion engine in vehicles and provide power in stationary and portable power applications because they are energy-efficient, clean, and fuel-flexible. The long-term aim is to develop "leapfrog" technologies that will provide Americans with greater freedom of mobility and energy security, while lowering costs and reducing impacts on the environment.

The objective of the study is to quantify the vehicle energy consumption and cost of FC hybrid electric vehicles (HEVs) for a midsize car in different timeframes (2015, 2020, 2025, and 2030). Uncertainties were also included for both performance and cost aspects by considering three cases (10%, 50%, and 90% uncertainty) representing technology evolution aligned with original-equipment-manufacturer improvements based on regulations (10%) as well as aggressive technology advancement (90%) based on the Vehicle Technologies Program (VTP). These simulations were performed as a part of DOE baseline and scenario analysis (BaSce) process [1].

In addition, simulations were performed on the evolution of the FC system and hydrogen tank over time (up to 2045), while maintaining technology of the rest of the powertrain at 2010 levels. This isolated the vehicle-level impacts of advancements in FC and hydrogen tank technologies, contrasting the BaSce results where all technologies were evolving at the same time.

2 Method

To properly assess the benefits of future technologies, different timeframes representing different sets of assumptions were considered. However, this paper focuses on a single vehicle class, i.e., midsize. For this study, we will use "lab years" 2015, 2020, and 2030. It should be noted that lab year 2015 would reflect a vehicle available in the market in 2020 (current technology). Similarly, lab or simulation year 2025 would reflect a vehicle in the market in 2030, and a 2030 simulation vehicle would be in the market in 2035.

Additionally, to address uncertainties, a triangular distribution approach (low, medium, and high) was employed. For each component, assumptions (e.g., efficiency, power density) were made and three separate values were defined to represent the 90th percentiles, 50th percentiles, and 10th percentiles. A 90% probability means that the technology has a 90% chance of being available at the time considered [2, 3]. For each vehicle considered, the cost assumptions also follow the triangular uncertainty. For each vehicle case (particular class, technology uncertainty, simulation year), simulations were performed with evolution of all vehicle technologies simultaneously. This uncertainty is represented in this paper's bar charts with an error bar.

2.1 Modeling Software

All simulations discussed in this paper were performed with Autonomie, a modeling tool developed by Argonne National Laboratory. Autonomie is a plug-and-play model development environment that supports the rapid evaluation of new powertrain technologies [4]. The model and control library provided by Autonomie is forward-looking and written in Matlab, Simulink, and Stateflow.

2.2 Process

To evaluate the fuel efficiency benefits of advanced FC and hydrogen tank systems, each vehicle is designed with individual component assumptions to meet the same vehicle technical specifications (VTS) (i.e., acceleration, gradeability, etc.). The fuel efficiency is then simulated with the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET). The vehicle costs are calculated using the aggregated cost of each component. Figure 1 illustrates the process, which comprises two distinct phases. The objective of the first phase is to set up the simulations, launch all the runs through a distributed computing toolbox, and perform analyses of individual results to ensure the simulations are performed properly.

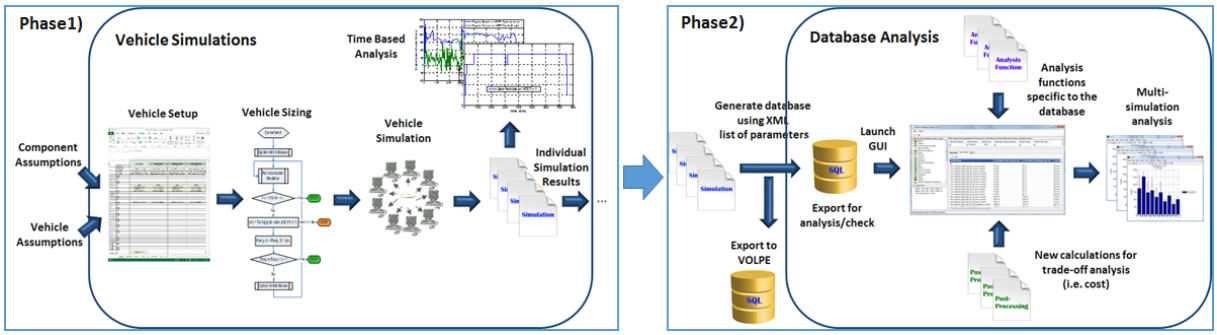

Figure 1: Process for running and analyzing large-scale simulations

The second phase of the process allows users to analyze a limited number of parameters from the individual simulations to perform large-scale analysis [5]. As shown in Figure 1, this process starts with the development of a standardized query language database based on a list of parameters defined by the user. The objective of the database analysis tool is then to, for example, select the most cost-beneficial technologies and understand uncertainties.

2.3 Series Fuel Cell HEVs

In this study, series configurations are considered for FC HEVs. The FC system powertrain, described in Figure 2, includes a gearbox in addition to the final drive, as well as DC/DC converters for the high-voltage battery and the 12-V accessories.

Figure 2: Series configuration for FC HEVs

Because of the FC system's high efficiency, the energy storage is not used as the primary power source. The vehicle-level control strategy has been developed so that the main function of the battery is to store the regenerative braking energy from the wheel and return it to the system when the vehicle operates at low power demand (low vehicle speed). The battery also provides power during transient operations when the FC is unable to meet driver demand. Component limits, such as maximum speed or torque, are taken into account to ensure the proper behavior of each component. Battery state-of-charge (SOC) is monitored and regulated so that the battery stays in the defined operating range. The three controller outputs are FC state (on or off), FC power, and electric machine (EM) torque.

Several variations of the series configuration could been considered. One of the important considerations in the design of a series HEV is related to the use of a single gear ratio versus a two-speed transmission. In this study, a two-speed transmission is used, since a single gear ratio usually leads to low maximum vehicle speed and poor performance at high speed due to the low EM torque in that operating regime.

2.4 Sizing

To compare different vehicle technology combinations, all study vehicles were sized to meet the same requirements:

- Acceleration from initial vehicle movement to 60 mph: less than 9 sec ±0.1 sec.
- Acceleration from 50 mph to 80 mph: less than 9 sec ±0.1 sec.
- Maximum grade: 6% at 65 mph at gross vehicle weight.
- Maximum vehicle speed: greater than 100 mph.

Improperly sized components would lead to differences in energy consumption and influence the results. On this basis, we developed an automated sizing algorithm to provide a fair comparison between technologies. The algorithm is based on the following concept: the vehicle is built from the bottom up, meaning each component assumption (e.g., specific power, efficiency) is taken into account to define the entire set of vehicle attributes (e.g., weight). This process is always iterative in the sense that the main component characteristics (e.g., maximum power, vehicle weight) are changed until all VTS are met. On average, the algorithm takes between 5 and 10 iterations to converge. Figure 3 shows the iterative process for the FC HEV powertrain.

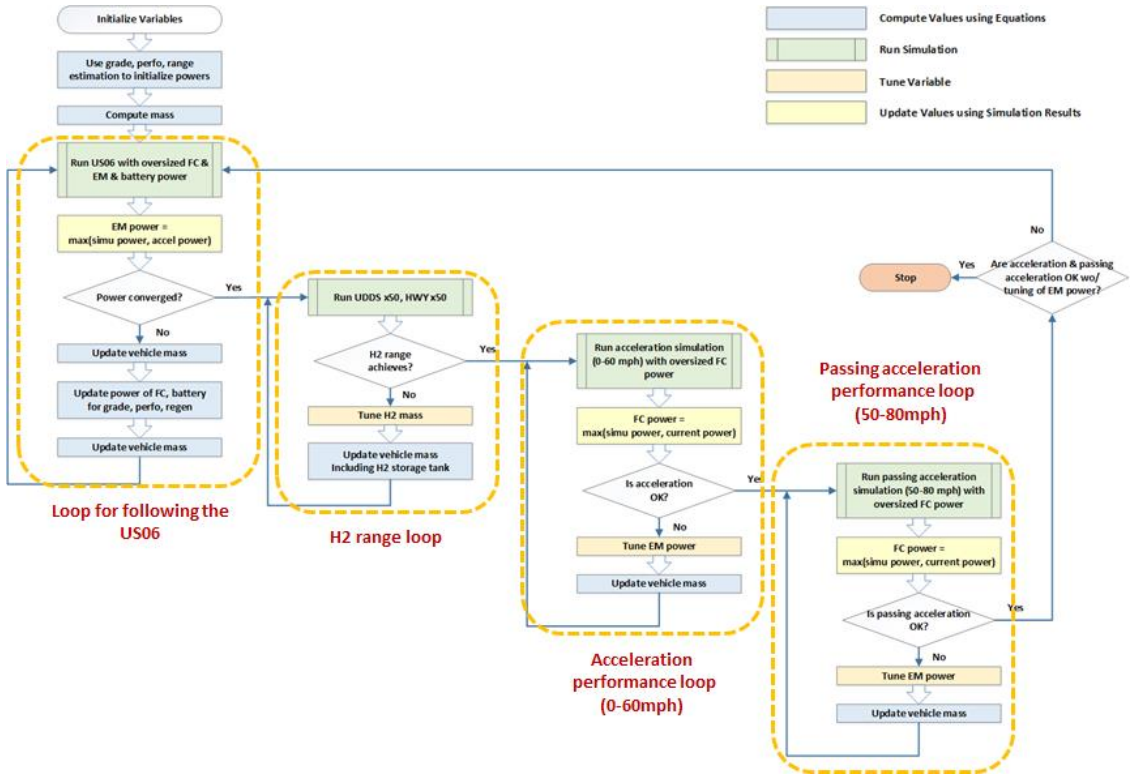

Figure 3: FC HEV powertrain sizing algorithm

The main assumptions for the sizing algorithm are as follows:

- FC power: sized to meet 70% of peak power required to meet VTS (acceleration performance or gradeability); FC peak power is a function of the vehicle weight.
- Battery power: sized to recuperate 100% energy on UDDS; battery cell number is function of the vehicle weight.
- EM power: sized to be able to follow the US06 in EV mode at low SOC or to meet the requirement of acceleration performance.
- Vehicle weight: function of the FC peak power, EM peak power, and number of battery cells.

3 Assumptions

The assumptions for each component were developed in collaboration with experts from DOE, national laboratories, industry, and academia. When available, the high-case assumptions were based on U.S. DRIVE program goals [6]. The following sections only provide information regarding a very limited set of assumptions, since most of the assumptions were provided by industry partners and are considered proprietary.

3.1 Fuel Cell Assumptions

Table 1 shows the evolution over time of the different FC system assumptions used as inputs to the simulation model. Between the reference case and 2030, the specific power increases from 659 W/kg to 740 W/kg, or an increase of 12%.

The FC system model used for the study was based on a steady-state look-up table. The FC system map (5x mass activity) was provided by the Argonne Fuel Cell Group using the General Computational Toolkit. As a result, the additional losses from the balance of plant due to transient operating conditions were not taken into account. The peak FC efficiency was assumed to be at 59% for the reference year and it will increase up to 68% by 2030.

Table 1: FC system assumptions

Parameter	Units	2015	2020			2025			2030		
			Low	Med	High	Low	Med	High	Low	Med	High
FC System-Specific Power	W/kg	659	659	670	680	659	665	710	659	680	740
Power Density	W/L	640	640	720	850	640	730	890	640	740	970
Peak FC Efficiency at 25% Rated Power	%	59	63	65	66	64	66	67	65	67	68
Platinum Price	$/troy oz	1,100	1,500			1,500			1,500		

The FC system costs are driven by the following equation:

$$(1{,}246.5 * x * S^{0.2583} + P * y) * FC_{pwr}.\left(\frac{FC_{pwr}}{80}\right)^{z} \quad (1)$$

Where $x, y,$ and z are coefficients; P is the platinum price; S is the stack unit per year; and FC_{pwr} is the fuel cell power. The cost is based on high production volumes (500,000 per year).

3.2 Hydrogen Storage Assumptions

Table 2 shows the different hydrogen storage assumptions.

Table 2: Hydrogen storage assumptions

Parameter	Units	2015	2020			2025			2030		
			Low	Med	High	Low	Med	High	Low	Med	High
System Gravimetric Capacity	Useable kWh/kg	1.5	1.5	1.6	1.8	1.6	1.7	2.0	1.6	1.8	2.3
	Useable kg H_2/kg of tank system	0.045	0.045	0.048	0.054	0.048	0.051	0.060	0.048	0.054	0.069
Tank Cost	$/Useable kg H_2	576	450	391	335	430	375	310	391	317	274
H_2 Used in Tank	%	96	96	96	96	96	96	97	96	96	97
Range*	miles	320	320	320	320	320	320	320	320	320	320

** Based on combined, adjusted mpg gasoline equivalent.*

The hydrogen storage costs and mass are calculated as follows:

$$H_{2_{cost}} = C_{H_2} * M_{fuel} \quad (2)$$

and

$$H_{2_{mass}} = M_{fuel} * Cap_{H_2} \quad (3)$$

Where C_{H_2} is the hydrogen cost coefficient ($/kg H_2), Cap_{H_2} is the hydrogen gravimetric capacity (kg H_2/kg tank), and M_{fuel} is the hydrogen fuel mass (kg).

4 Results

This section describes the maximum power, weight, and cost of the different model years after sizing. In order to evaluate the potential of FC and hydrogen tank technologies in isolation, the simulations of midsize FC vehicles were performed in four iterations: with all technologies being 2015 (reference baseline from BaSce results), improved hydrogen storage only (H2) (iteration 1), improved fuel cell system only (FC) (iteration 2), concurrent improved FC system and hydrogen storage (H2 + FC) (iteration 3), and all technologies (All: FC + H2 + electric machine + battery + light-weighting…) (iteration 4, from BaSce).

4.1 Fuel Cell Peak Power

Based on assumptions of technology improvements for FCs and hydrogen storage with light-weighting or improvement in other component technologies, it can be seen that FC system power required to meet the vehicle technical specification decreases significantly over time, as shown in Figure 4. However, the FC

system power is expected to decrease by up to 1.8% due to the FC system and hydrogen storage only technology improvements.

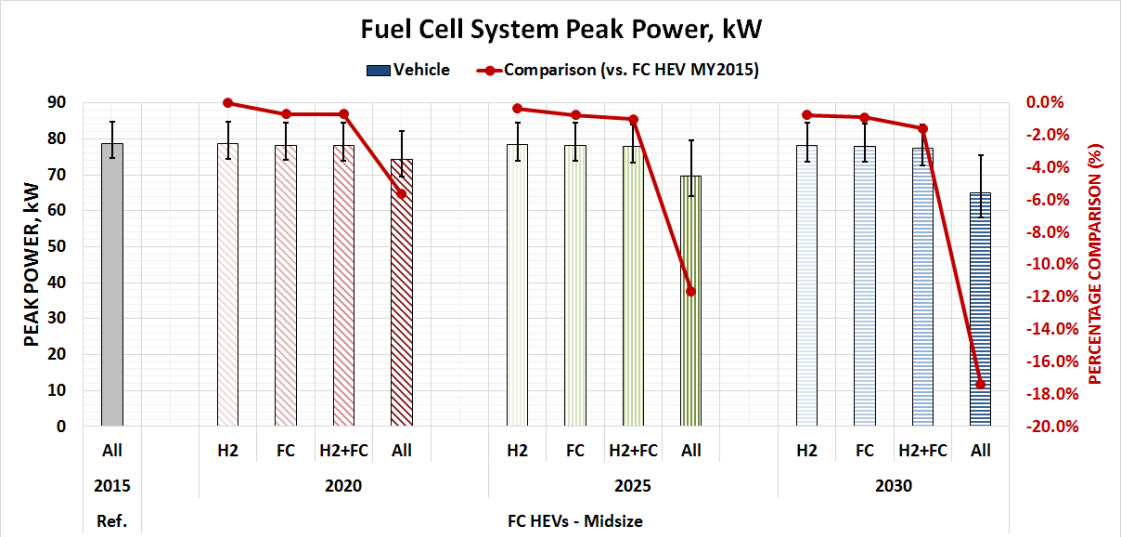

Figure 4: Evolution of FC peak power

4.2 Vehicle Weight

The simulation results show that FC HEV weight will decrease slightly over time, without light-weighting and improvement in other component technology. Figure 5 shows that advanced FC and hydrogen storage systems affect total vehicle weight by less than 2% compared to all advanced technologies. Most of the weight reduction comes from light-weighting material technologies.

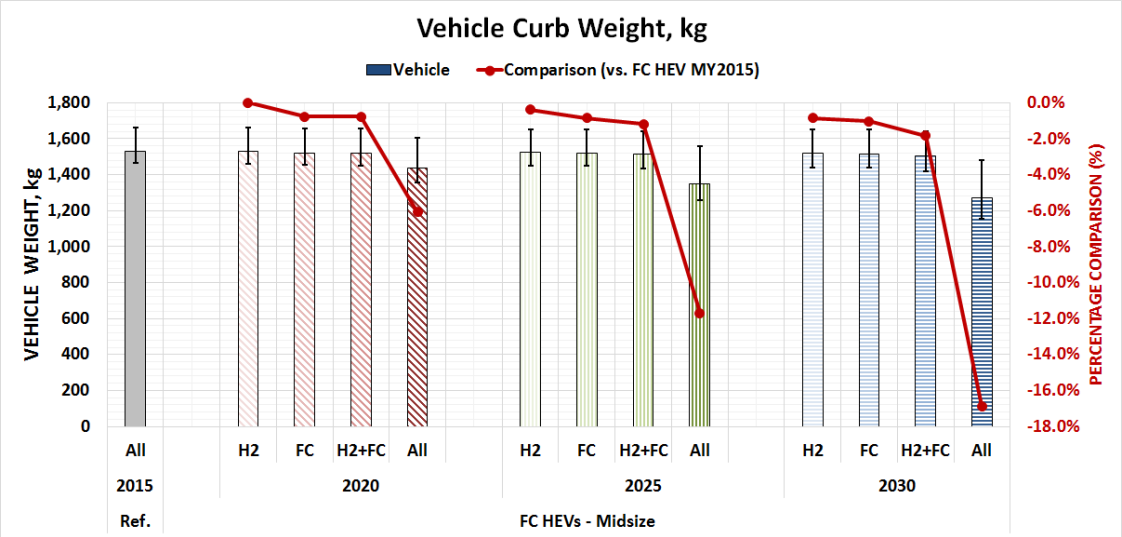

Figure 5: Progression in vehicle curb weight due to improvements in FC and hydrogen storage technologies

The vehicle hydrogen storage has been sized to provide a range of 320 miles on the combined driving cycle (UDDS and HWFET). Figure 6 shows that required onboard hydrogen fuel mass could drop by 12% due to FC system technology improvements only. However, the technology improvement for FC and hydrogen storage systems with light-weighting or improvement in other component technologies could lead to 30% reduction in onboard hydrogen weight by 2030.

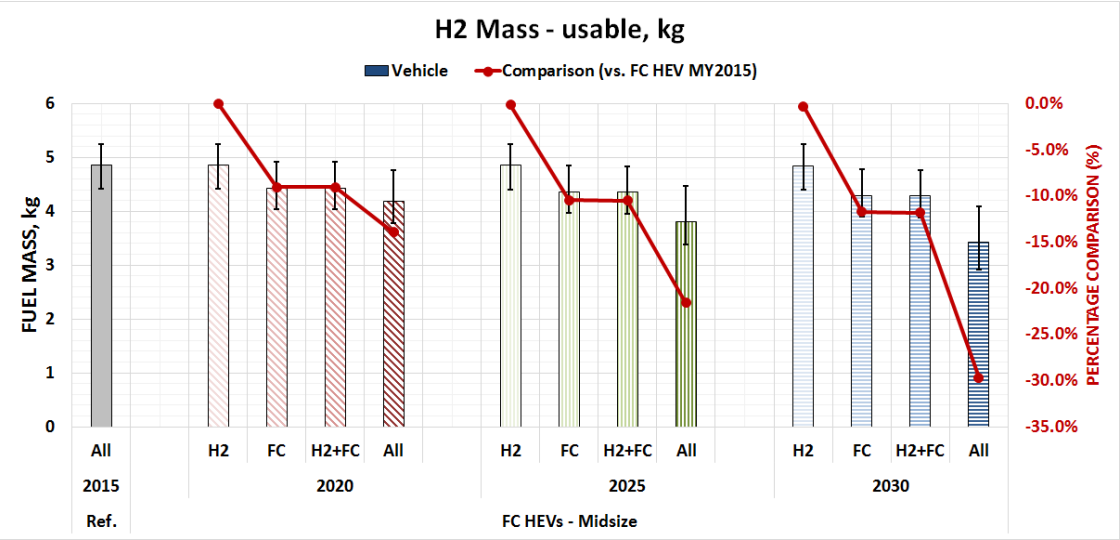

Figure 6: Progression in usable hydrogen storage due to improvements in FC and hydrogen storage technologies

4.3 Vehicle Cost

Figure 7 shows the FC system cost with the advances in hydrogen tank only, FC system technology only, and all technology improvements. The results show that the FC system cost could decrease by 46% due to the FC system technology improvements only.

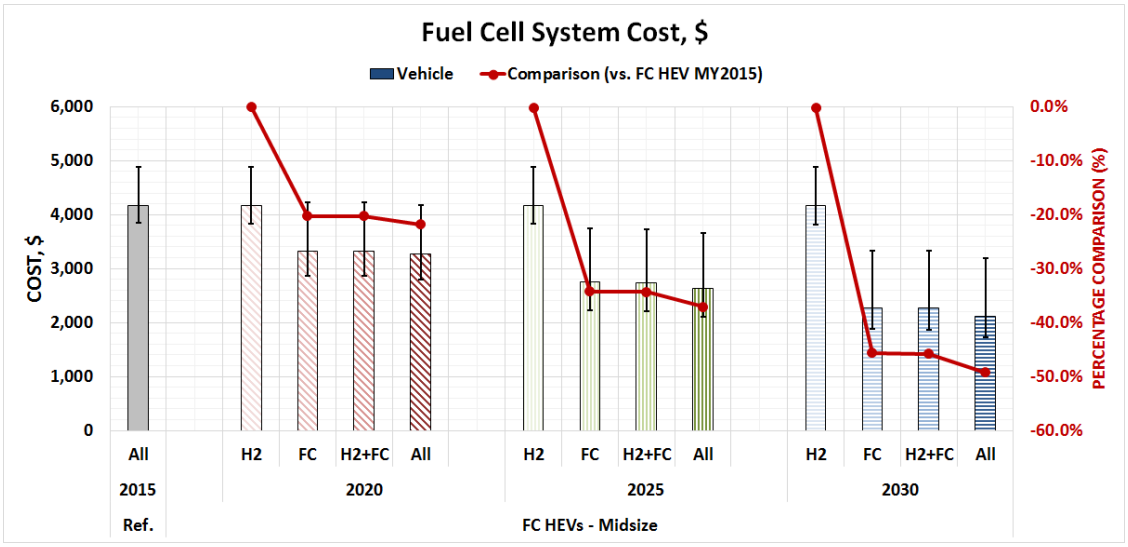

Figure 7: Progression in FC system cost with improvements in FC and hydrogen storage technologies

Figure 8 shows that hydrogen storage cost could decrease by 40% due to hydrogen storage technology improvements only. Figure 9 shows the FC HEV manufacturing cost of the different FC systems considered. Manufacturer retail suggested price (MSRP) values have been computed by setting the retail-price-equivalent value at 1.5 times the manufacturing cost. The results show that the cost decrease is mostly due to the decrease of hydrogen storage cost (by up to 40%) and fuel cell system cost (by up to 46%).

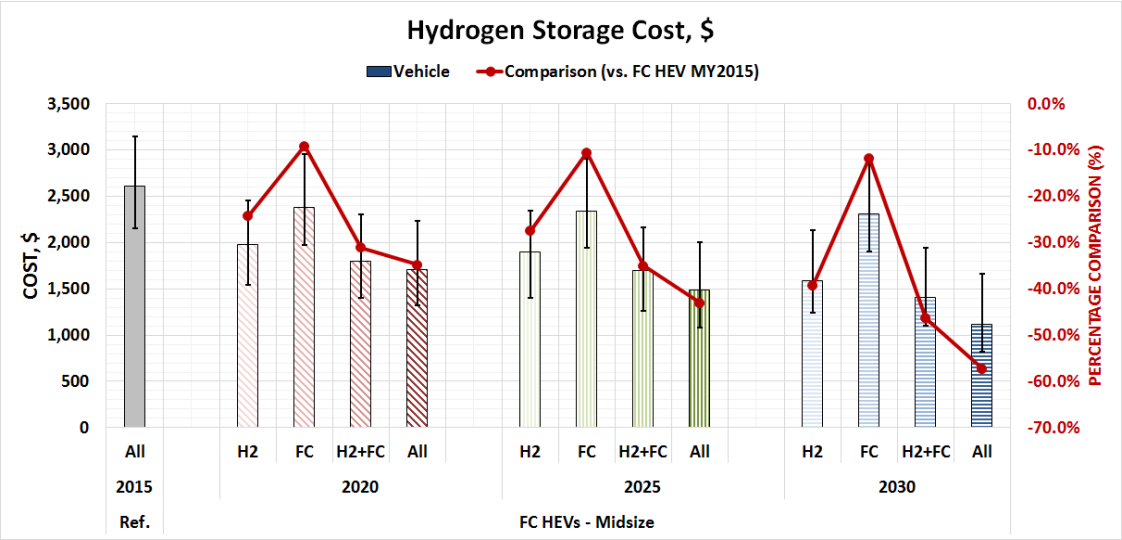

Figure 8: Progression in hydrogen storage cost with improvements in FC and hydrogen storage technologies

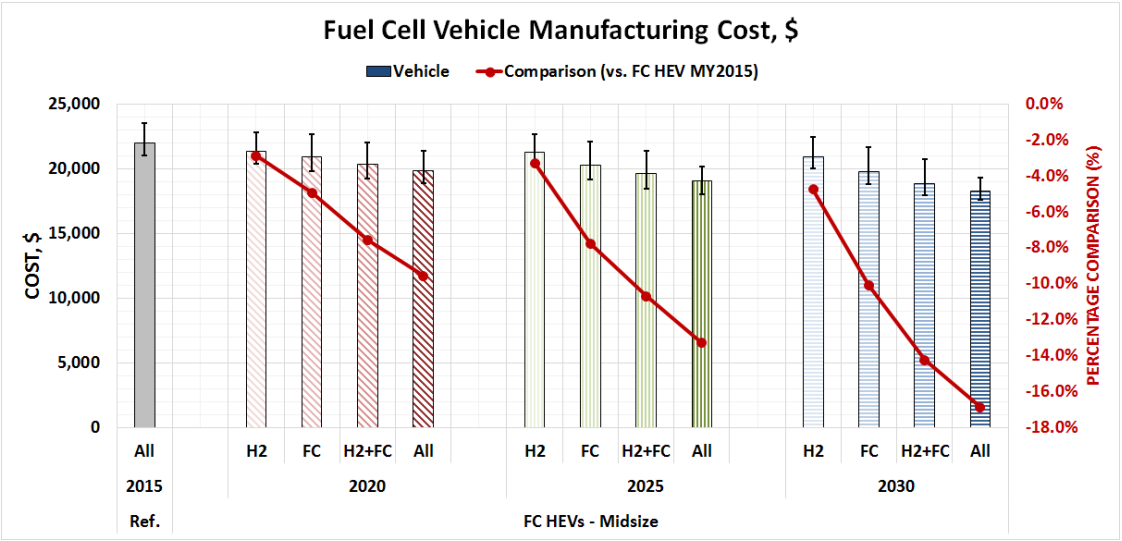

Figure 9: Progression in FC HEV cost with improvements in FC and hydrogen storage technologies

4.4 Vehicle Energy Consumption

While advanced FC system technologies have a small impact on vehicle weight, they do provide significant benefits for vehicle energy consumption. As shown in Figure 10, the FC system improvement leads to significant fuel savings on the U.S. Environmental Protection Agency (EPA) combined driving procedure. While better batteries, EM improvements, and light-weighting help, FC system improvements lead to significant fuel savings of about 40% by 2030.

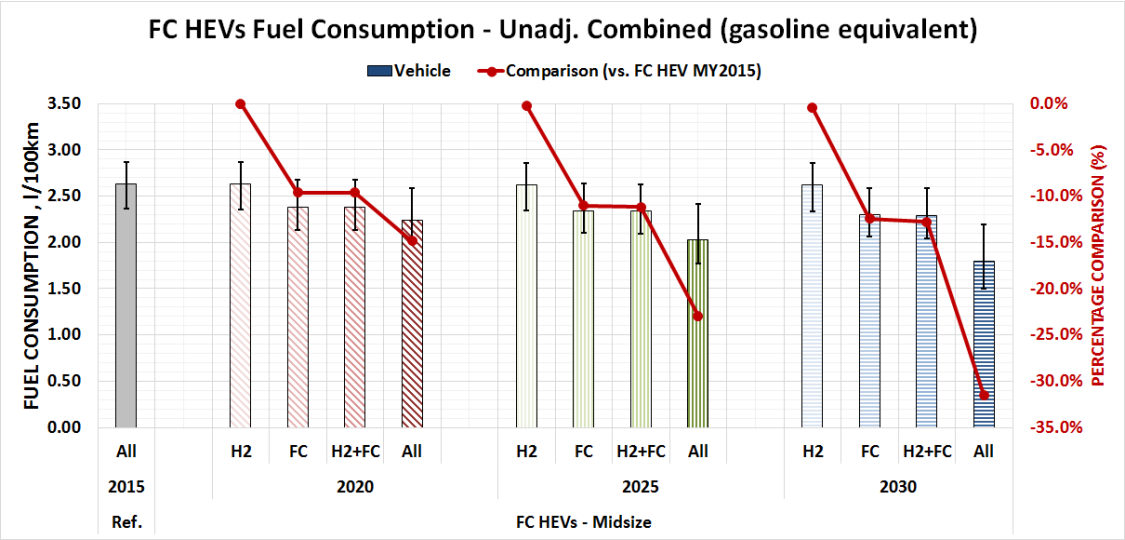

Figure 10: Progression in vehicle fuel consumption with improvements in FC and hydrogen storage technologies

5 Conclusion

Two sets of vehicle simulations were performed to assess the vehicle energy consumption and cost of FC HEVs compared to conventional powertrains. Different timeframes, FC system peak efficiencies, and hydrogen storage assumptions were considered. For one set of simulations, all vehicle assumptions (including drag coefficient, frontal area, glider mass, etc.) were varied over time (BaSce simulations), and for the second set of simulations, only FC system and hydrogen storage assumptions were varied with time.

- Vehicle weight decreases mostly due to light-weighting and other component improvements.
- When considering the impact of FC and hydrogen storage system technologies only (without considering improvements in the rest of the powertrain), required hydrogen mass could drop by 12% by 2030.
- Vehicle manufacturing costs decrease mostly due to the decrease of both FC system and hydrogen tank costs.
- While better batteries, EM improvements, and light-weighting help, FC system improvement mainly leads to significant fuel savings of about 40% by 2030 on the EPA combined driving procedure.

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