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Fuel Displacement and Cost Feasibility Study of Fuel Cell Vehicles Based On U.S. Department of Energy Targets

Ehsan Sabri Islam[1], Namdoo Kim[1], Ayman Moawad[1], Aymeric Rousseau[1]
[1] *Argonne National Laboratory, Lemont, IL 60439-4815, USA*

Abstract

The U.S. Department of Energy (DOE) is developing more energy-efficient and environmentally friendly highway transportation technologies that would enable the United States to burn less petroleum on the road. System simulation is an accepted approach to evaluate the fuel economy potential of advanced (future) technology targets. The DOE defines the targets for advancements in powertrain technologies (e.g., engine efficiency, battery energy density, light weighting) Vehicle system simulation models based on these targets have been generated in Autonomie to reflect the different U.S. Environmental Protection Agency (EPA) classifications of vehicles for six different time frames — 2010, 2015, 2020, 2025, 2030, and 2045 — as part of DOE Benefits and Scenario Analysis (BaSce).

This paper will present an assessment of fuel cell systems' impacts on cost and energy consumption based on a large-scale simulation process. The simulations are performed over standard regulatory driving cycles for the midsize vehicle class over a range of time frames by implementing the technology advancement targets set by DOE.

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

1 Introduction

The impact of advances in powertrain technology is evaluated using a fuel consumption (or fuel economy or CO_2 g/mile) metric on standard regulatory drive cycles [1]. Such advances include those made in the engine, battery, vehicle electrification, and material (light weighting) areas. Simulating vehicle model systems incorporating the technology advancements is an accepted approach to evaluating the fuel economy potential of such advanced technologies [2].

The Fuel Cell Technologies Office (FCTO) of the U.S. Department of Energy (U.S. DOE) promotes and fosters advancements in technology associated with fuel cell technologies [3], including vehicle electrification, hydrogen tank assumptions, light weighting, etc., over a given time frame [4]. The vehicle system simulation tool Autonomie [5] is used to perform simulation on vehicle models that incorporate baseline and advanced vehicle technology targets as established by DOE. The vehicle models used for the simulation include fuel cell hybrid and plug-in hybrid vehicles of different all-electric ranges (AERs). The technology advancements are generally evaluated over standard regulatory driving cycles for fuel economy and cost impact.

2 Procedure

The different vehicle technology targets set by the DOE are used to build the assumptions that are evaluated over a range of time frames. This paper will cover the results from 2010, 2015, 2020, 2025, 2030, and 2045 “lab years,” which corresponds to “model year - 5 years.” For example, a 2015 lab year vehicle would be a vehicle that is projected to be available in the market in 2020, and similarly, a 2045 lab year vehicle would be a vehicle that is available in the market in 2050.

To implement uncertainties in the assumptions, a triangular distribution approach is implemented that states the low, medium, and high uncertainty cases. These uncertainties have been assigned to each component assumption (e.g., engine efficiency, power density, costs), and values have been assigned accordingly to represent the 90th percentile, 50th percentile, and 10th percentile, respectively [6].

2.1 Fuel Cell Configuration

For the purpose of this study, series configurations are considered for the different fuel cell powertrains. Figure 1 describes the configuration of the fuel cell hybrid electric vehicle (FC HEV) powertrain. It includes a gearbox in addition to the final drive, as well as a direct current (DC/DC) converter for the high-voltage battery and the 12-V accessories.

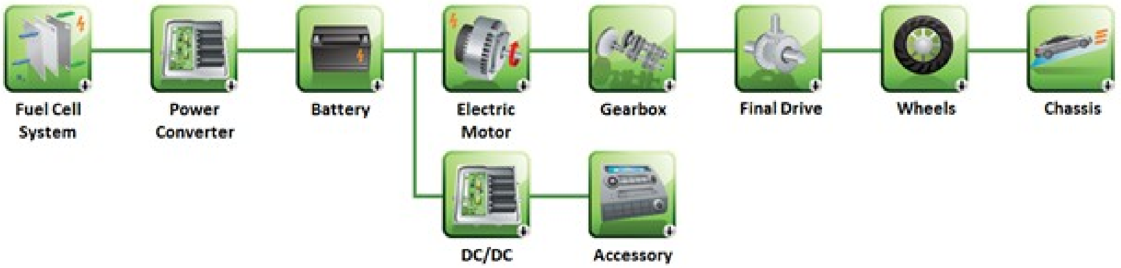

Figure 1: Fuel Cell HEV Configuration

Because of the higher efficiencies in fuel cell systems, the battery is not used as the primary power source. The vehicle-level control strategies have been implemented for the core functionality of the battery to store the regenerative braking energy from the wheel and return it to the system when the vehicle operates at low speed. The battery also provides power during the transient operation when the fuel cell is unable to meet the demand. The state-of-charge (SOC) of the battery is monitored and regulated to ensure that the battery remains within the defined operating ranges.

3 Technology Target Assumptions

The technology target assumptions received from FCTO have been assigned accordingly over the pre-defined time frame for the different vehicle classes. Table 1 illustrates a sample of the assumptions associated with the fuel cell system technologies over time. The vehicle simulations (and results to follow) represent the lab years 2010, 2015, 2020, 2025, 2030, and 2045; however, the assumption values from years 2010, 2015, 2025, and 2045 have been provided in the table for simplicity.

Table 1: Fuel Cell System Assumptions

Lab Year	2010	2015	2025			2045		
Technology Case	Low	Low	Low	Medium	High	Low	Medium	High
FC System – Specific Power (W/kg)	650	650	659	665	710	670	760	870
Peak Fuel Cell System Efficiency at 25% Rated (%)	60	60	64	64	64	68	69	70
Conventional Engine Efficiency (Gasoline) (%)	36	36	38	40	43	43	47	50
Power-split HEV Engine Efficiency (Gasoline) (%)	39	40	40	43	46	42	47	52

The hydrogen storage tank weight is evaluated using the equation:

$$HydrogenStorageWeight = A + B \times FuelMass \tag{1}$$

The values for the coefficients *A* and *B* and across the time frames are defined in Table 2. The assumptions have been given for the lab years 2010, 2015, 2025, and 2045.

Table 2: Hydrogen Storage Weight Assumptions

Lab Year	2010	2015	2025			2045		
Technology Case	Low[a]	Low	Low	Medium	High	Low	Medium	High
A	28	28	24	17	14	14	10	9
B	21	21	21	20	20	20	15	12

[a] Values for weights are given in kg

The *FuelMass* is determined through sizing the fuel cell vehicles to run for 320 miles on the combined procedure (adjusted). A full 100% of the available hydrogen in the storage tank is assumed to be usable hydrogen. The fuel cell system costs for the different time frames are calculated using the equation:

$$FuelCellSystemCost = A + [B + (C \times PlatinumPrice)] \times FuelCellPower \tag{2}$$

The values for the coefficients *A*, *B*, and *C* across the time frames are defined in Table 3. The assumptions have been given for the lab years 2015, 2025, 2030, and 2045 to evaluate the acceleration of cost assumptions.

Table 3: Fuel Cell System Cost Assumptions (in 2015$)

Lab Year	2015	2025			2030			2045		
Technology Case	Low	Low	Medium	High	Low	Medium	High	Low	Medium	High
A	1516	1785	1414	1312	1500	1200	1140	1300	1080	1060
B	19.676	17.24	13.73	12.78	16	12.2	11.6	15	12	11.6
C	0.009579	0.00799	0.00480	0.00348	0.007	0.0045	0.00346	0.0066	0.0044	0.00346
Platinum Price	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500

The hydrogen storage tank costs are evaluated using the equation:

$$HydrogenStorageCost = A + B \times FuelMass(kg) \tag{3}$$

The values for the coefficients A, B across the timeframes are defined in Table 4. The assumptions have been given for the lab years 2015, 2025, 2030, and 2045 to evaluate the acceleration of cost assumptions.

Table 4: H_2 Storage Tank Cost Assumptions (in 2015$)

Lab Year	2015	2025			2030			2045		
Technology Case	Low	Low	Medium	High	Low	Medium	High	Low	Medium	High
A	983	863	649	559	649	559	476	559	420	326
B	428	397	384	358	384	358	304	358	268	215

4 Results and Analysis

The results and analysis of the vehicle simulations would comply with the full range of time frames as mentioned earlier.

4.1 Vehicle Components Size

4.1.1 Fuel Cell Power

Fuel cell systems show a decrease in peak power over time owing to vehicle lightweighting and improved fuel cell system efficiencies. Figure 2 illustrates the fuel cell system's peak power for midsize vehicles for the different fuel cell vehicle powertrains (HEV and plug-in HEV [PHEVs] of different AERs).

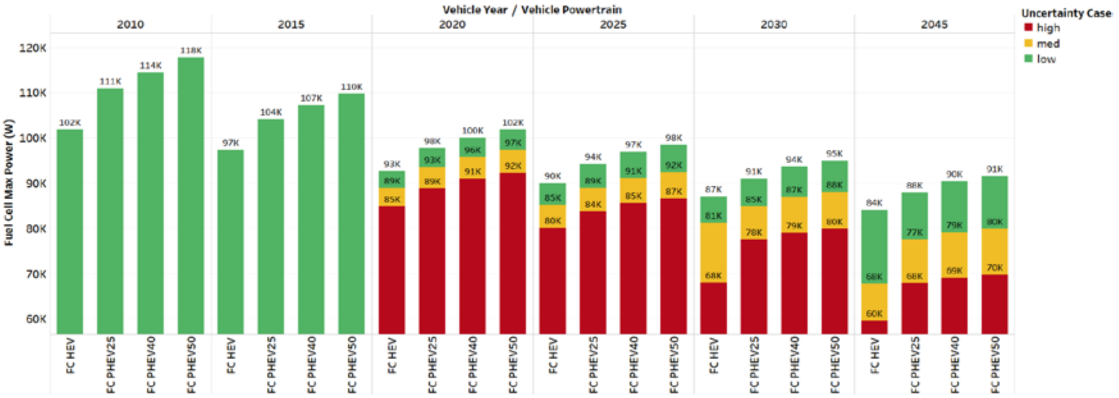

Figure 2: Fuel-cell system power for midsize FC HEVs and PHEVs of different AERs

The reduction in power requirements that occurs from lab years 2010 to 2045 ranges from 17% to 41.5% for FC HEVs, from 20.6% to 38.6% for FC PHEV25 AERs, from 21% to 39.6% for FC PHEV40 AERs, and from 22% to 40.8% for FC PHEV50 AERs.

4.1.2 H_2 Fuel Mass

Figure 3 shows the evolution in hydrogen fuel mass for the different midsize fuel cell vehicles across the specified time frames.

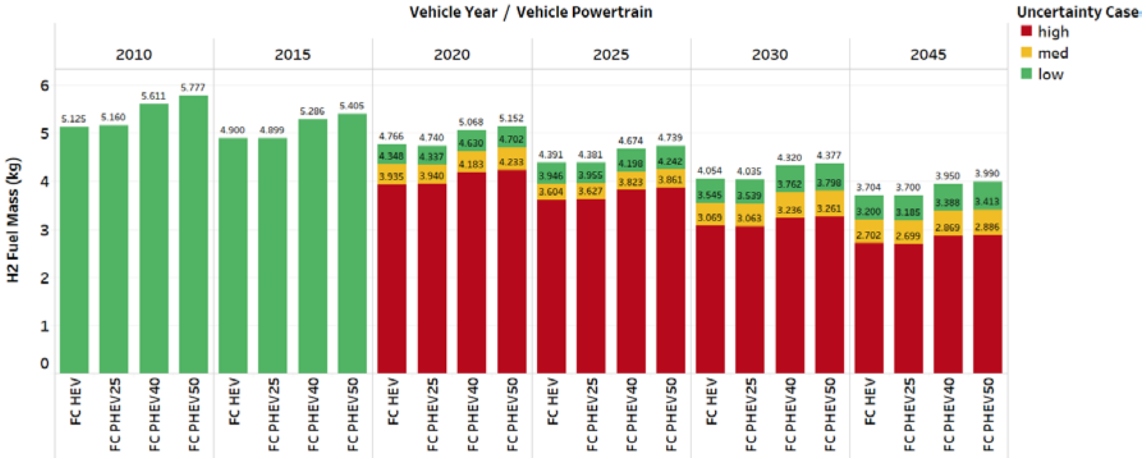

Figure 3: H_2 Fuel Mass (kg) for midsize FC HEVs and PHEVs of different AERs

The hydrogen fuel mass represents the amount of hydrogen present in the tank and is used by the fuel cell vehicle during the simulations, given that 100% of the available hydrogen is considered to be usable.

4.1.3 H_2 Storage Mass

Figure 4 shows the evolution in hydrogen storage mass for the different midsize fuel cell vehicles across the specified time frames.

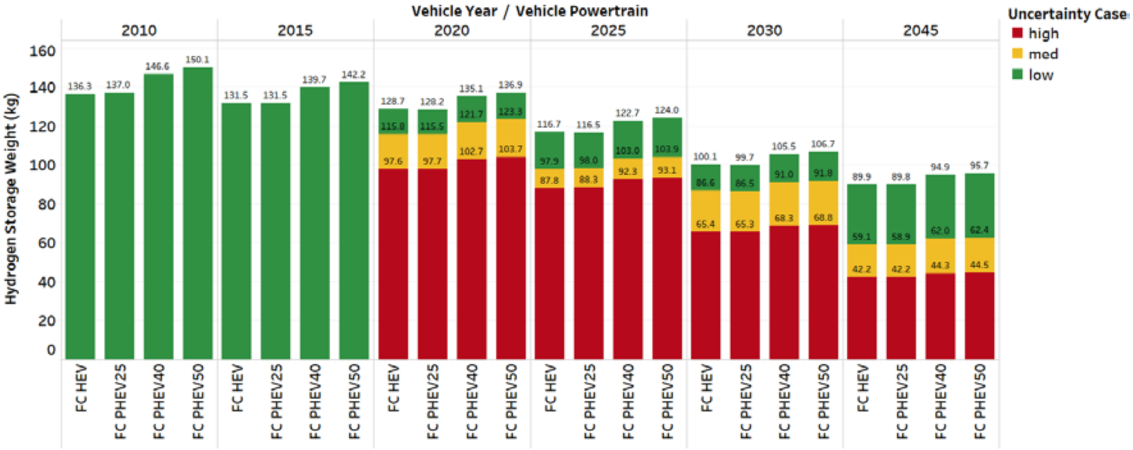

Figure 4: H_2 Storage Mass (kg) for midsize FC HEVs and PHEVs of different AERs

The reduction in hydrogen storage mass reflects the storage weight assumptions across the different time frames. It is a combined effect of the reduction in the coefficient values used in the formula, along with the reduced H_2 fuel mass. From lab years 2010 to 2045, the hydrogen storage mass reduces by 34% to 69% for FC HEVs, by 34% to 69.2% for FC PHEV25 AERs, by 35.3% to 69.8% for FC PHEV50 AERs, and by 36.2% to 70% for FC PHEV50 AERs.

4.2 Evolution of Fuel Displacement

Figure 5 illustrates the fuel consumption evolution of fuel cell midsize vehicles across the defined time frames of lab years 2010 to 2045. The metric used for illustration is the gasoline equivalent fuel consumption for the combined drive cycles using the unadjusted values.

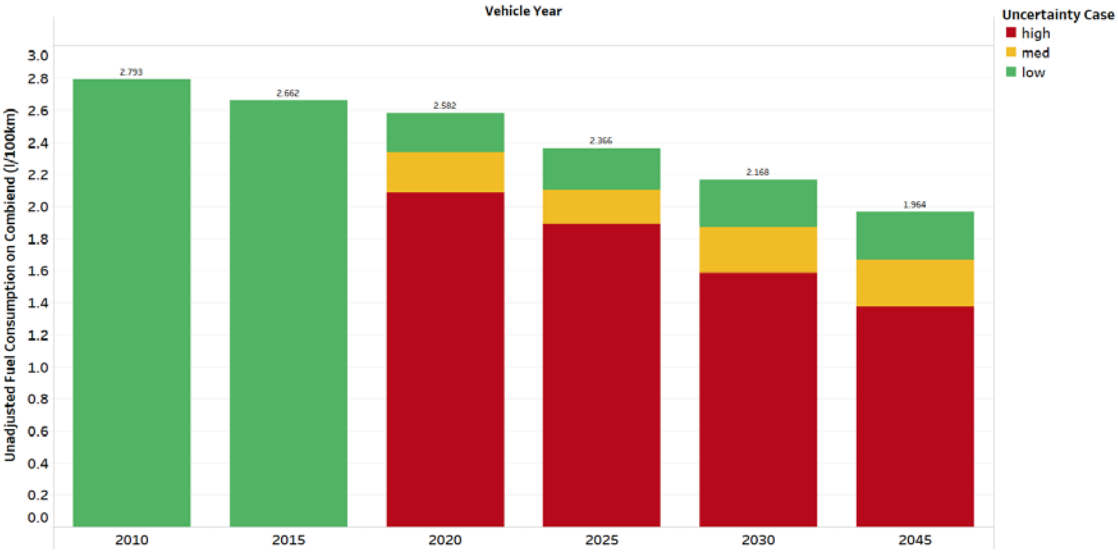

Figure 5: Gasoline-equivalent fuel consumption for midsize FC HEVs

The figure illustrates that the FC HEV consumes about 35%–56% less fuel by lab year 2045 when compared to the 2010 reference lab year.

Fuel economy evolution for FC PHEVs is illustrated in Figure 6. As can be observed in the figure, the fuel consumption decreases slowly as the AER increases to a higher range.

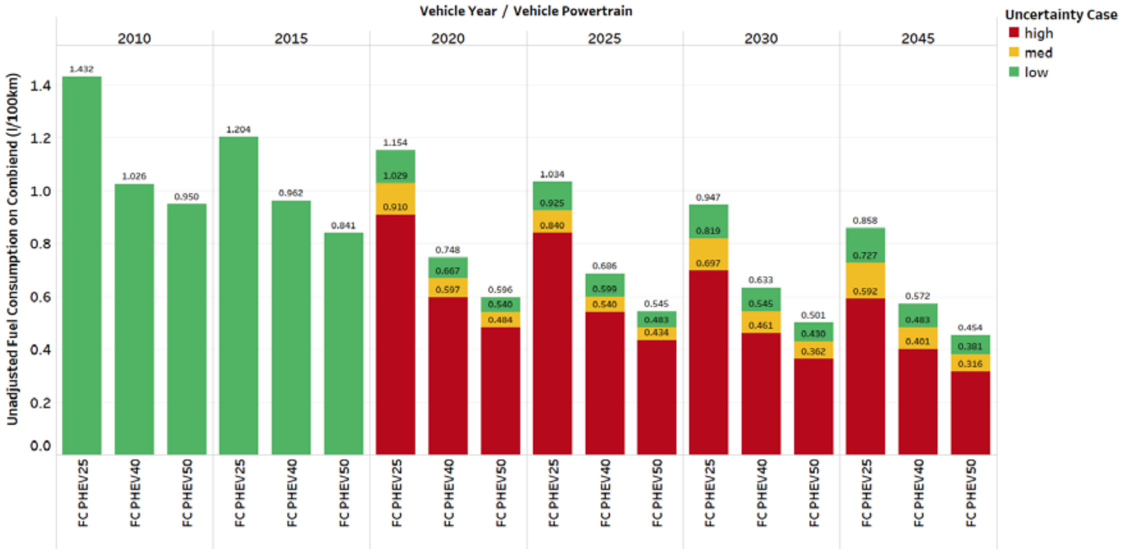

Figure 6: Gasoline-equivalent fuel consumption for midsize FC HEVs

From lab year 2010 to lab year 2045, the consumption decreases by 40% to 58.6% for PHEV25 AERs, by 44.2% to 60.9% for PHEV40 AERs, and by 52.2% to 66.7% for PHEV50 AERs. This rate of change coincides with the decrease in FC HEV fuel consumption.

Figure 7 illustrates the evolution in electrical consumption from lab year 2010 to lab year 2045 for FC PHEVs.

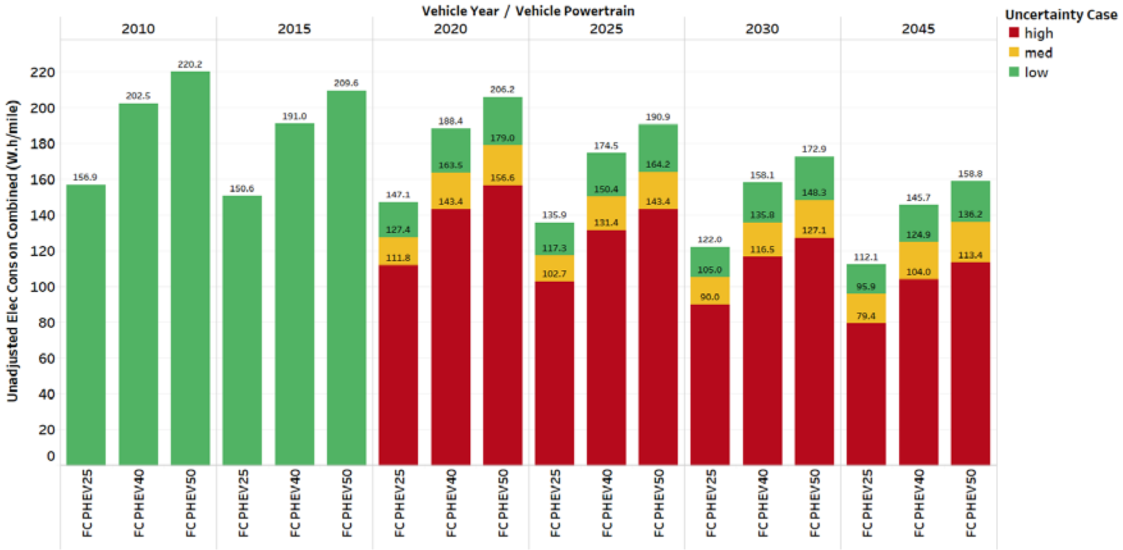

Figure 7: Electrical consumption in CS+CD mode for midsize FC PHEVs

As can be observed in the figure, the electrical consumption increases with increasing AERs. This finding is attributable to larger battery sizes as vehicles attain higher electrical ranges. However, the trend line ends up decreasing over time because of lightweighting and advanced vehicle technologies with highly efficient components.

4.2.1 Fuel Cell vs. Conventional/Split HEV Powertrains

Figure 8 shows the comparison of the evolution in fuel consumption on combined procedure runs for fuel cell HEVs, along with conventional and power-split HEVs.

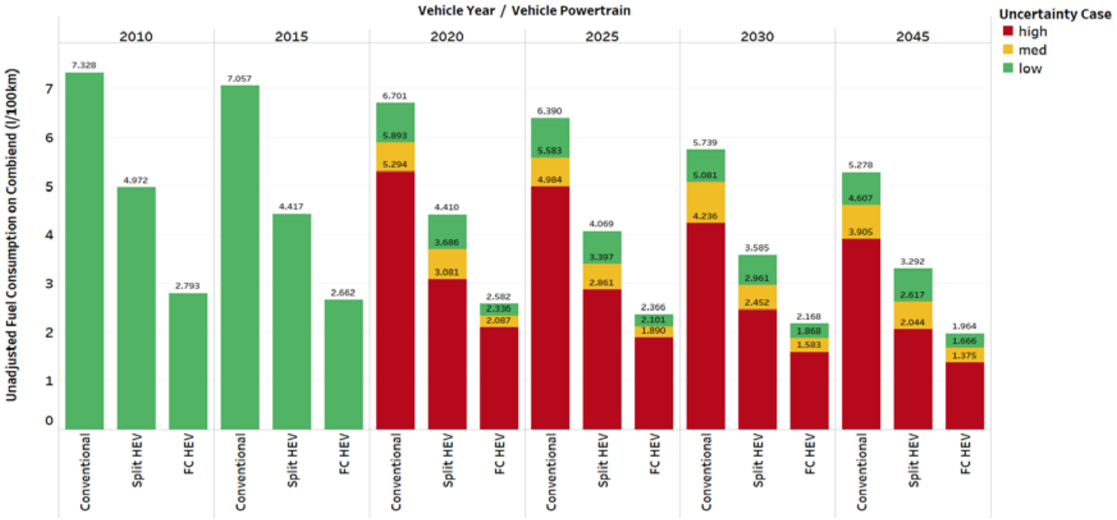

Figure 8: Gasoline-equivalent fuel consumption across powertrains for the midsize vehicle class

The comparison between conventional and fuel cell midsize vehicles can be further developed in terms of fuel consumption ratios between the FC HEV and the gasoline conventional vehicle as shown in Figure 9.

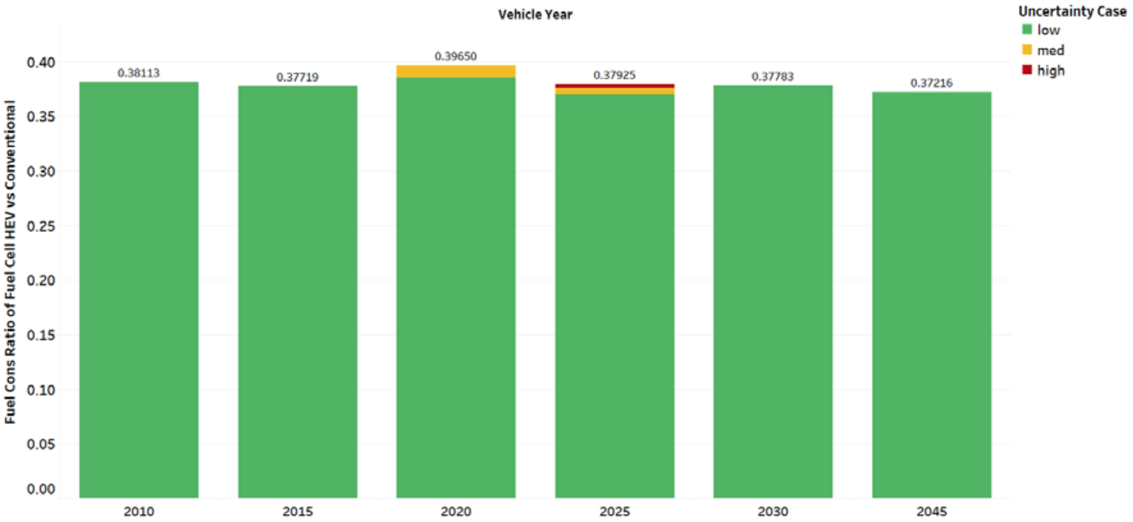

Figure 9: FC HEV vs. conventional fuel consumption for same year/same case

The graph makes evident the effects of technology improvements on the evolution of conventional vehicles. It can be seen that in the reference year (lab year 2010), the FC HEVs consume about 55% less fuel compared to the gasoline conventional vehicle. However, this improvement increases to about 63% to 65% for the high case in lab year 2045. This result shows that the FC HEVs respond to a much more aggressive advancement in technologies that result in reduced fuel consumption.

The comparison of FC HEV fuel consumption to a power-split HEV for a midsize vehicle is shown in Figure 10.

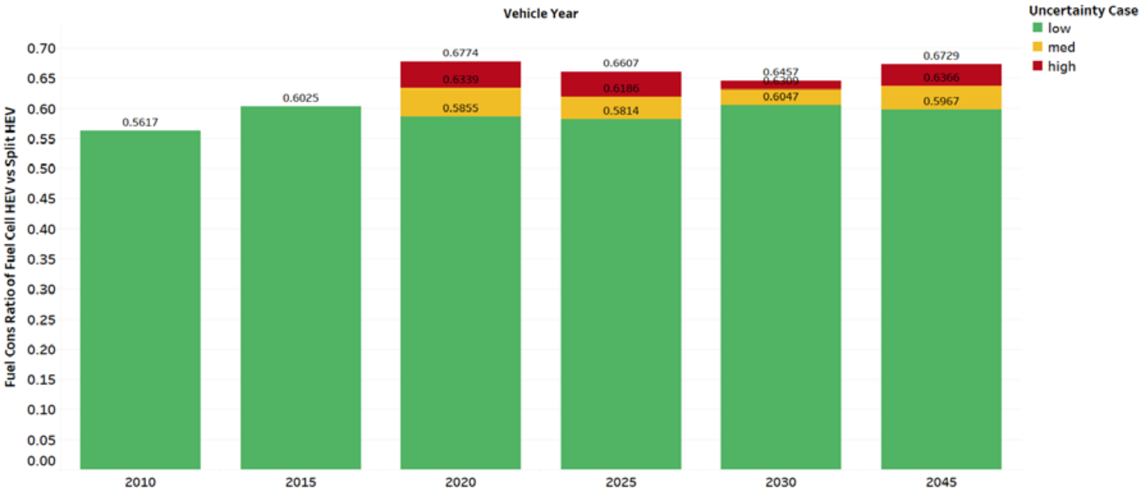

Figure 10: FC HEV vs. power-split HEV fuel consumption for same year/same case

Figure 10 indicates that from lab years 2010 to 2045, the ratio slightly increases, suggesting that the overall impact in the advancement of power-split HEVs is projected to be greater than that of FC HEVs.

4.3 Cost Feasibility

4.3.1 Fuel Cell System Cost

Figure 11 shows the evolution in the costs of fuel cell systems from lab years 2015 to 2045 for the various fuel cell powertrains.

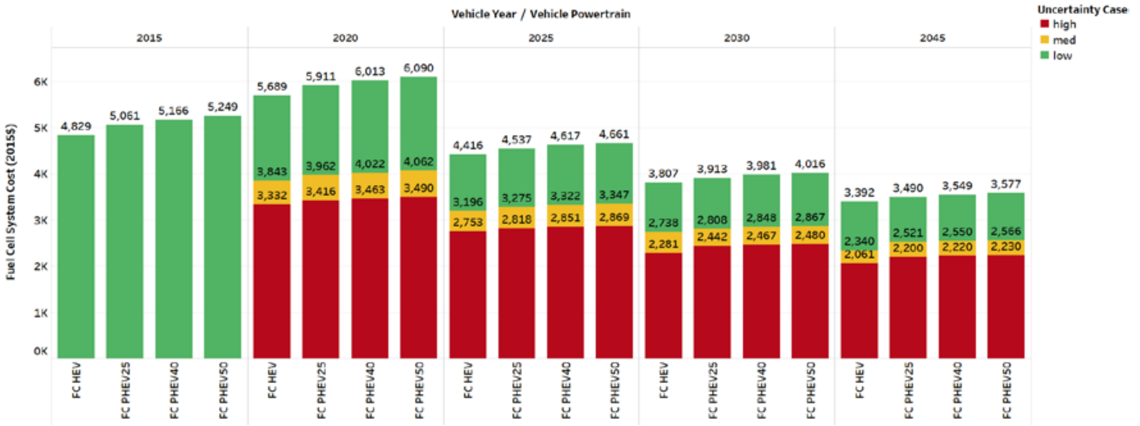

Figure 11: FC system costs (in 2015$)

The evolution in fuel cell system costs represents the effects of accelerated cost targets set by FCTO. It is further affected by the reduction in fuel cell power over this period resulting from the advancement in fuel cell technology targets. Over the years, the figure indicates that the cost reduces by 29.8% to 57.3% for FC HEVs, 31% to 57% for FC PHEV25 AERs, 31% to 57% for FC PHEV40 AERs, and 32% to 57.5% for FC PHEV50 AERs.

4.3.2 H_2 Storage Cost

Figure 12 shows the evolution in the hydrogen storage tank costs over the defined time frame from lab years 2010 to 2045 for the different midsize fuel cell vehicles.

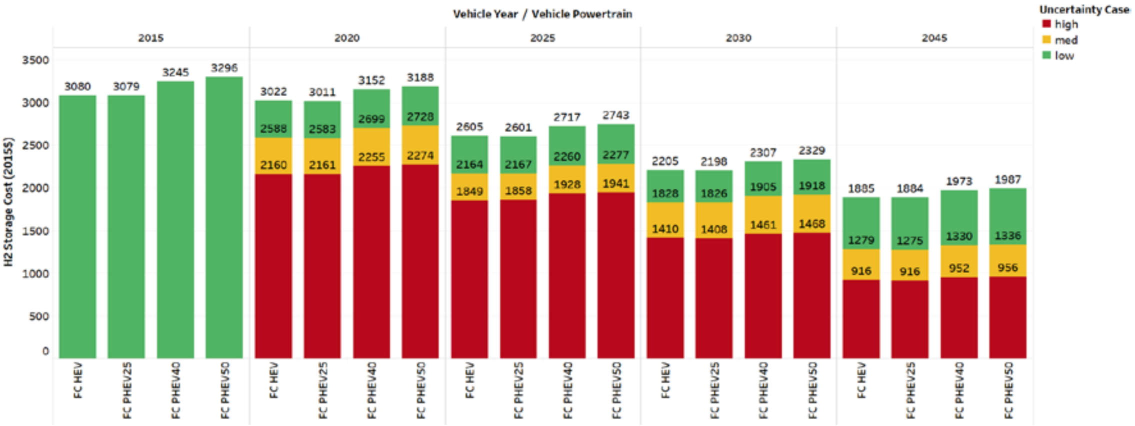

Figure 12: Hydrogen Storage Costs (2015$)

As can be seen in the figure, over the years, the cost reduces by 40% to 70% for FC HEVs, FC PHEV25 AERs, FC PHEV40 AERs, and FC PHEV50 AER vehicles.

4.3.3 Vehicle Manufacturing Cost

Figure 13 shows the evolution in the manufacturing costs of midsize fuel cell vehicles.

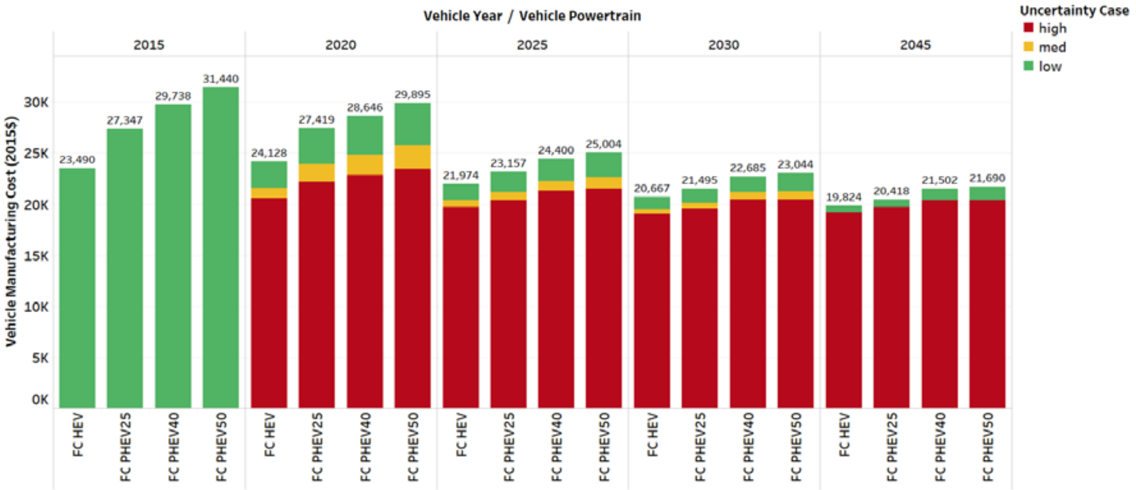

Figure 13: FC vehicle manufacturing costs

As the figure shows, the decreasing fuel cell system costs and hydrogen storage costs influence the reduction in vehicle manufacturing costs. From lab years 2010 to 2045, the cost reduces by 13% to 16% for FC HEVs, 26.5% to 29.2% for FC PHEV25 AERs, 30% to 33.7% for FC PHEV40 AERs, and 34.1% to 38% for FC PHEV50 AERs.

4.4 Vehicle Manufacturing Cost vs. Fuel Consumption

Figure 14 shows the trend lines in fuel consumption vs. vehicle manufacturing costs for the different fuel cell powertrains for all vehicle classes.

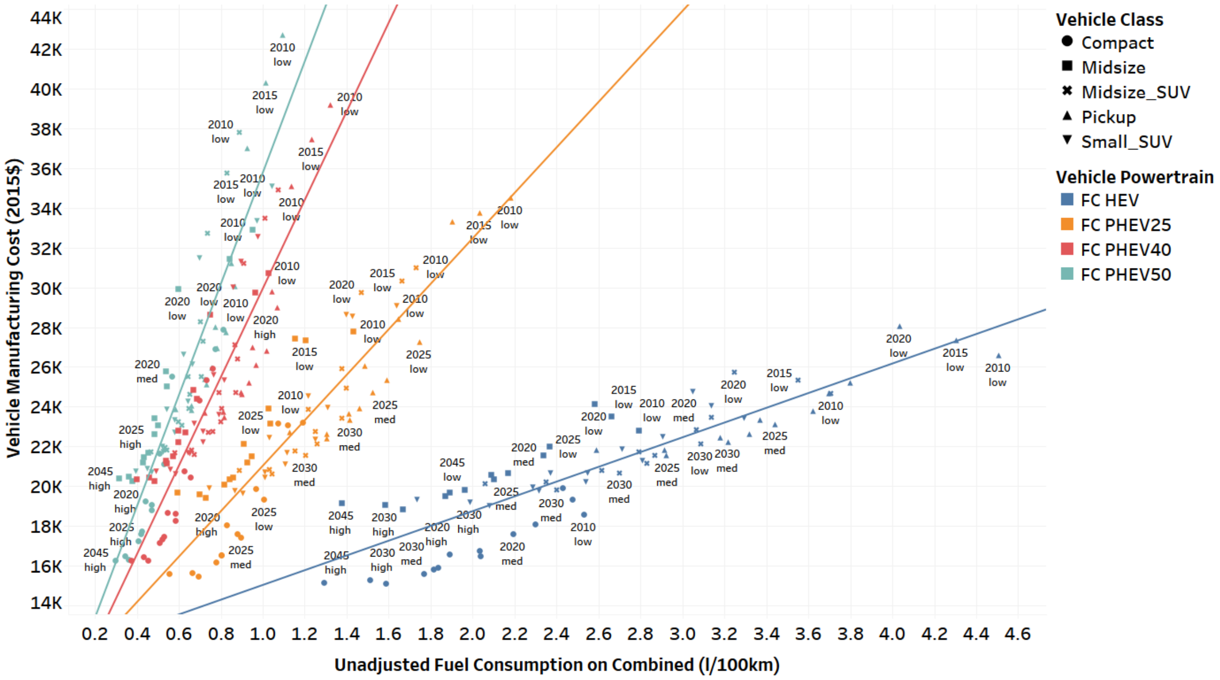

Figure 14: Unadjusted fuel consumption vs. manufacturing cost across vehicle classes

When examining the evolution of manufacturing costs with respect to fuel consumption, a rapid evolution in fuel cell PHEVs can be observed. Moving from lab years 2010 to 2045, fuel consumption decreases, along with manufacturing costs. The rate of this decrease can be observed from the slope of the trend line for the different fuel cell powertrains. The FC HEVs consume far less fuel in lab year 2045 compared to lab year 2010, while the manufacturing costs are not effected to that extent. This result can be attributed to the acceleration of fuel cell HEV technology assumptions compared to the cost assumptions. For fuel cell PHEVs, however, the cost decreases significantly because of the effects of accelerated battery cost reductions. According to the slope of the trend lines, the different fuel cell powertrains can be ranked for reduction in vehicle manufacturing costs as follows: FC PHEV50 AER > FC PHEV40 AER > FC PHEV25 AER > FC HEV.

5 Summary and Conclusion

This paper presents a large-scale simulation process used to evaluate the fuel displacement and cost impacts of fuel cell vehicles over a period of time, along with a comparison of fuel cell HEVs to conventional vehicles with respect to fuel consumption.

The following conclusions can be drawn from the study:

- In terms of fuel cell power, the requirement decreases with time from lab years 2010 to 2045, owing to higher efficiencies, lighter-weighing vehicles, and the combined effect of advancements in other technologies. From lab years 2010 to 2045, the fuel cell power decreases by 17% to 42% for FC HEVs, 21% to 39% for FC PHEV25 AERs, 21% to 40% for FC PHEV40 AERs, and 22% to 41% for FC PHEV50 AER vehicles.

- In terms of the amount of hydrogen used during the EPA combined procedure runs, the amount decreases over time for the different fuel cell powertrains. It decreases by 28% to 47% for FC HEVs, 29% to 47% for FC PHEV25 AERs, 29% to 48.8% for FC PHEV40 AERs, and 31% to 50% for FC PHEV50 AERs.

- For fuel consumption comparison of conventional and FC HEVs, a slowly decreasing ratio trend line can be observed. From lab years 2010 to 2045, the FC HEVs consume about 55% less fuel compared to the gasoline conventional vehicle in lab year 2010. However, this improvement increases to about

63% to 65% in lab year 2045. This shows the FC HEVs respond to a much more aggressive advancement in technologies that results in reduced fuel consumption.

- In terms of vehicle manufacturing costs, a higher drop rate in FC PHEVs is observed compared to FC HEVs. This result occurs because of the greater influence of lower costs in the fuel cell system, hydrogen storage, battery, etc., along with the effects of lightweighting and highly efficient vehicle components. From lab years 2010 to 2045, the cost reduces by 13% to 16% for FC HEVs, 26.5% to 29.2% for FC PHEV25 AERs, 30% to 33.7% for FC PHEV40 AERs, and 34.1% to 38% for FC PHEV50 AERs.

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Authors

Ehsan Sabri Islam completed his B.A.Sc in Mechatronics Engineering from University of Waterloo, Canada. His skillset and interests focus on applying Mechatronics principles to innovate systems and processes in advanced vehicle technologies and controls systems. At Argonne, he focuses his research on vehicle energy consumption analyses.

Namdoo Kim graduated in 2007 from the University of Sungkyunkwan, Korea, with a Masters Degree in Mechanical Engineering. He is currently working in Argonne National Laboratory's Vehicle Modeling and Simulation Group.

Ayman Moawad is a research engineer at Argonne National Laboratory. He graduated from the Ecole des Mines, France, in 2009 with a Master of Science degree in Mechatronics, Robotics, and Computer Science. His research interests include energy consumption prediction and analysis of electrified vehicles, large-scale simulation, high-performance computing, machine learning, and data analysis.

Aymeric Rousseau is the Manager of the Vehicle Modeling and Simulation Section at Argonne National Laboratory. He received his engineering diploma at the Industrial System Engineering School in La Rochelle, France, in 1997. After working for PSA Peugeot Citroen in the Hybrid Electric Vehicle Research Department, he joined Argonne National Laboratory in 1999, where he is now responsible for the development of Autonomie. He received an R&D 100 Award in 2004 and a 2010 Vehicle Technologies Program Award in 2010. He has authored more than 40 technical papers in the area of advanced vehicle technologies.