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Impact of U.S. DOE R&D on Light Duty Fuel Cell Vehicle Efficiency and Cost

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Summary

The U.S. Department of Energy's (DOE) Hydrogen & Fuel Cell Technologies Office (HFTO) supports research, development (R&D), and deployment of efficient and sustainable transportation technologies that will improve energy efficiency, fuel economy, and enable America to use less petroleum. To accelerate the development and adoption of new technologies, both HFTO and the Vehicle Technologies Office (VTO) has developed specific targets for a wide range of powertrain technologies (e.g., fuel cell system, hydrogen storage, engine, battery, electric machine, lightweighting, etc.).

The objective of the paper is to quantify the impact of HFTO R&D on vehicle energy consumption and cost compared to expected historical improvements across vehicle classes, powertrains, component technologies and timeframes with specific focus on fuel cell vehicles. A large scale simulation process was used to develop and simulate tens of thousands of vehicles on US standard driving cycles using Autonomie. Results demonstrate significant additional reduction in both cost and energy consumption due to HFTO R&D targets compared to historical predicted trends.

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

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 advances in engine, battery, vehicle electrification and material (light weighting). System simulation of vehicle models incorporating the technology advancements is an accepted approach to evaluate the fuel economy potential of such advanced technologies [2].

Hydrogen & Fuel Cell Technologies Office (HFTO), U.S. Department of Energy (U.S. DOE) generates the 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 generated by U.S. DOE. The vehicle models used for the simulation include conventional vehicles, power-split hybrid electric vehicles and fuel cell hybrid. The advancements in technologies 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 is used to build the assumptions that is evaluated over a range of time frames. This paper will cover the results from 2015, 2020, 2025, 2030 and 2045 'lab years', which corresponds to 'model year - 5 years'. For example, a lab year 2015 vehicle would reflect a vehicle that is available in the market in 2020 and similarly a 2045 lab year vehicle would imply a vehicle that is available in the market in 2050.

To implement uncertainties in the assumptions, two different set of targets have been implemented for all years - low technology progress (business as usual), and high technology progress (U.S. DOE goals). The following subsections represent the breakdown involved during the vehicle simulation. The latest report from Argonne [6] details the vehicle level assumptions and procedure involved behind the vehicle modeling and simulation efforts.

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 FC HEV powertrain. It includes a gearbox in addition to the final drive, as well as DC/DC converter for the high-voltage battery and the 12-V accessories.

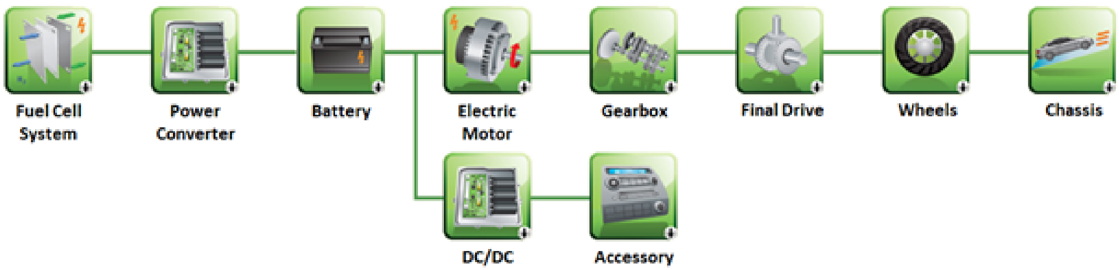

Figure 1: Fuel Cell HEV configuration

Due to the higher efficiencies in fuel cell system, 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 HFTO has been assigned accordingly over the pre-defined timeframe for the different vehicle classes. Table 1 below 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" 2015, 2020, 2025, 2030, and 2045.

Table 1: Fuel Cell System Assumptions

Lab Year	2015	2020		2025		2030		2045	
Technology Progress	Low	Low	High	Low	High	Low	High	Low	High
Conventional Engine Peak Efficiency (%)	36	38	43	40	43	42	45	44	47
Power-split HEV Engine Efficiency (%)	39	40	46	41	46	43	48	45	50
FC System - Specific Power (W/kg)	650	659	675	659	800	675	900	700	1000
FC System Peak Efficiency ($\%$)	61	62	63	63	65	65	68	65	68
FC System - Specific Cost ($\$/kW$)	160	111	111	77.7	66	60.6	51.5	37.0	30.0
H_2 Tank Weight (kg tank / kg H_2)	21	22.7	22.7	22.7	22.7	22.7	22.7	22.7	22.7

The hydrogen storage tank costs are evaluated using the equation:

$$HydrogenStorageCost = A + B \times FuelMass(kg) \tag{1}$$

The values for the coefficients A, B across the timeframes are defined in table 2. The assumptions have been given for the lab years 2015 - 2045 to evaluate the acceleration of cost assumptions.

Table 2: H_2 Storage Tank Cost Assumptions (2015$)

Lab Year	2015	2020		2025		2030		2045	
Technology Case	Low	Low	High	Low	High	Low	High	Low	High
A	1934.7	1934.7	1934.7	1934.7	1926.6	1934.7	981.02	1934.7	751.92
B	363.81	363.81	363.81	363.81	212.65	363.81	189.17	363.81	132.12

Table 3 details the different vehicle classifications defined for various performance times (0-60 mph time) in seconds as well as corresponding vehicle attributes.

Table 3: Vehicle classification, performance categories and characteristics

Vehicle Class	**Performance Category**	**0-60 mph time (s)**	**Frontal Area (m^2)**	**Drag Coefficient**	**Rolling Resistance**
Compact	Base (NonPerfo)	10	2.3	0.31	0.009
Compact	Premium (Perfo)	8	2.3	0.31	0.009
Midsize	Base (NonPerfo)	9	2.35	0.3	0.009
Midsize	Premium (Perfo)	6	2.35	0.3	0.009
Small SUV	Base (NonPerfo)	9	2.65	0.36	0.009
Small SUV	Premium (Perfo)	7	2.65	0.36	0.009
Midsize SUV	Base (NonPerfo)	10	2.85	0.38	0.009
Midsize SUV	Premium (Perfo)	7	2.85	0.38	0.009
Pickup	Base (NonPerfo)	7	3.25	0.42	0.009
Pickup	Premium (Perfo)	7	3.25	0.42	0.009

3.1 Approach

Autonomie is used for simulation of the vehicles over the defined timeframe. The vehicles are sized for the given timeframe according to the component assumptions as stated earlier. A large scale simulation approach is undertaken to evaluate the high volume of vehicle uncertainties. It uses a distributed computing method that accelerates and facilitates the simulation runs [2]. The vehicles are assessed using the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) drive cycle. The vehicle component sizing procedure is used to calculate the costs associated with the components.

The simulations are performed under hot conditions. The cold-start penalties associated are assessed accordingly after the simulations, on the basis of review of the EPA test car data. A two-cycle test procedure is implemented that is based on the UDDS and HWFET drive cycle (55% UDDS + 45% HWFET). The calculations are consistent with the latest EPA procedure.

4 Results & Analysis

The results and analysis of the vehicle simulations would comply with the full range of timeframes 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, due to vehicle lightweighting and improved fuel cell system efficiencies. Figure 2 illustrates the fuel cell peak power for fuel-cell HEVs across different vehicle classes and performance categories.

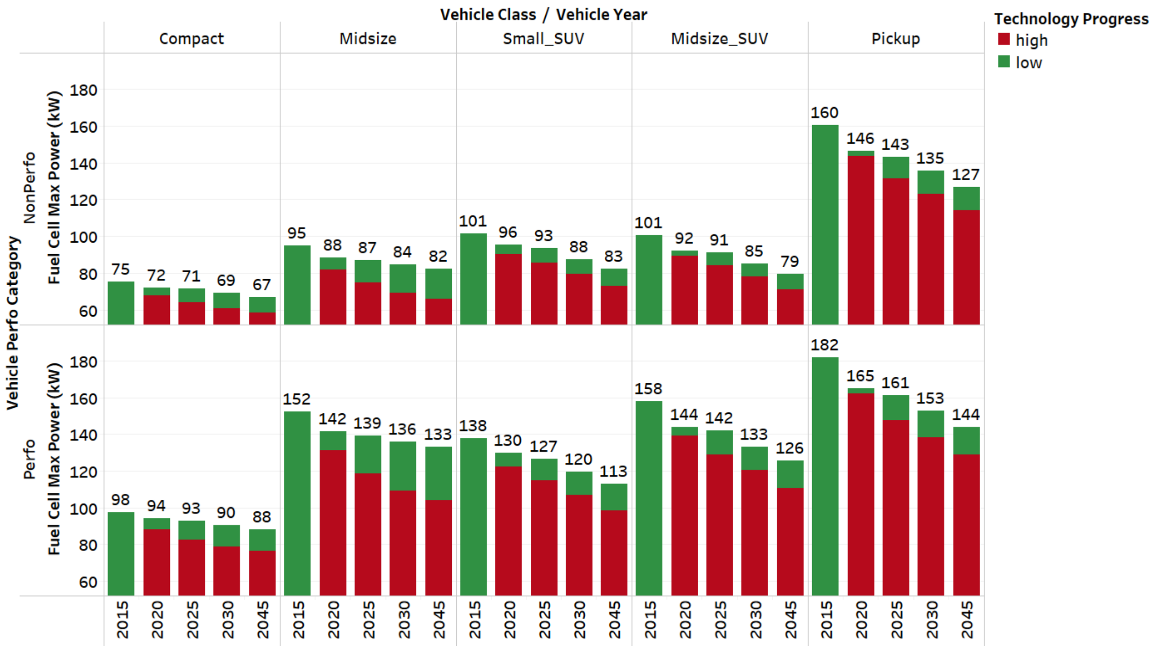

Figure 2: Fuel-cell system power fuel-cell HEVs across different vehicle classes

The reduction in FC HEV power requirement going from 2015 to 2045 lab year ranges from 11% to 13% for Compact class, 13% to 19% for Midsize class, 18% to 19% for Small SUV class, about 21% for Midsize SUV, and about 22% for Pickup class.

4.1.2 H_2 Fuel Mass

Figure 3 shows the evolution in hydrogen fuel mass for fuel cell HEVs for different vehicle classes and performance categories, across the specified timeframes.

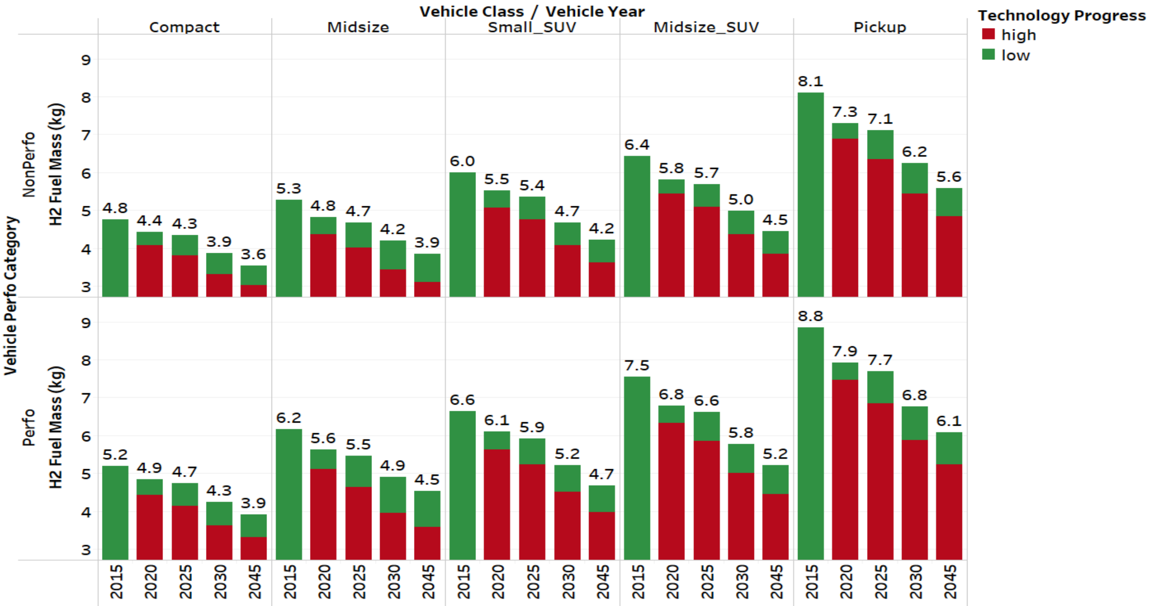

Figure 3: H_2 Fuel Mass (kg) fuel-cell HEVs across different vehicle classes

The hydrogen fuel mass represents the amount of hydrogen present in the tank and is used by the fuel cell vehicle during the simulations since 100% of the available hydrogen is considered as usable.

Advancements in vehicle lightweighting and aggressive fuel cell component targets result in reduced hydrogen mass requirements. From 2015 to 2045 lab year, the hydrogen fuel mass reduces by 36.3% for compact, 41.2% for midsize, 40% for Small SUV, 41% for Midsize SUV and 40% for Pickups. Similar range is also observed across the different performance categories.

4.1.3 H_2 Storage Mass

Figure 4 shows the evolution in hydrogen storage mass for fuel cell HEVs for different vehicle classes and performance categories, across the specified timeframes.

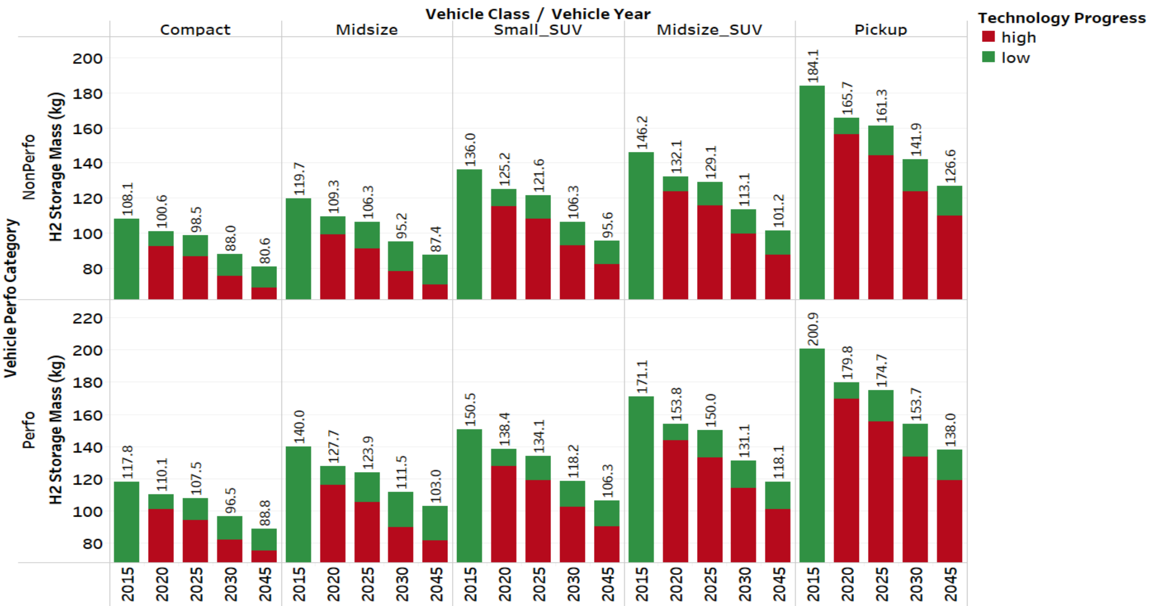

Figure 4: H_2 Storage Mass (kg) for fuel-cell HEVs across different vehicle classes

The reduction in hydrogen storage mass reflects the storage weight assumptions across the different timeframes. 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 2015 to 2045 lab year, the hydrogen storage mass reduces by 25% to 29% for compact, 27% to 30% for midsize, 29% to 32% for Small SUV, 31% to 34% for Midsize SUV and 32% to 35% for Pickup class across the different technology progresses and performance categories. It can be seen that with increasing vehicle weight, the rate of reduction in the hydrogen storage mass is higher.

4.2 Evolution of Fuel Displacement

Figure 5 illustrates the fuel consumption evolution of fuel cell midsize vehicle across the defined time frames of 2015 - 2045 "lab year". The metric used for illustration is the gasoline equivalent fuel consumption for the combined drive cycles using the unadjusted values.

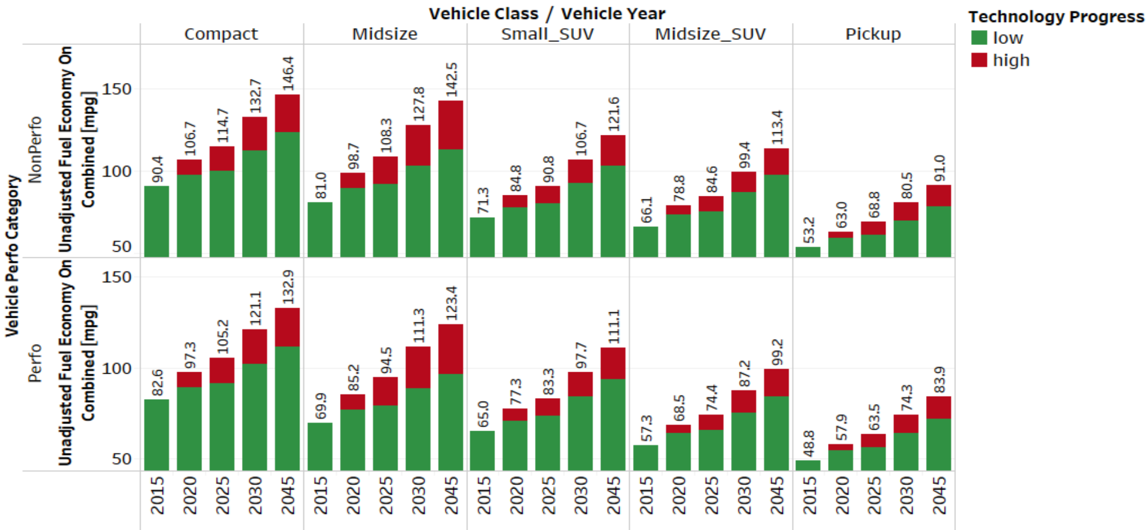

Figure 5: Gasoline-equivalent fuel consumption for midsize fuel cell HEVs

4.2.1 Fuel Cell vs. Conventional/Split HEV Powertrains

Figure 6 shows the evolution in the comparison of fuel consumption on combined procedure for fuel cell HEV vehicles, along with conventional and power-split HEVs

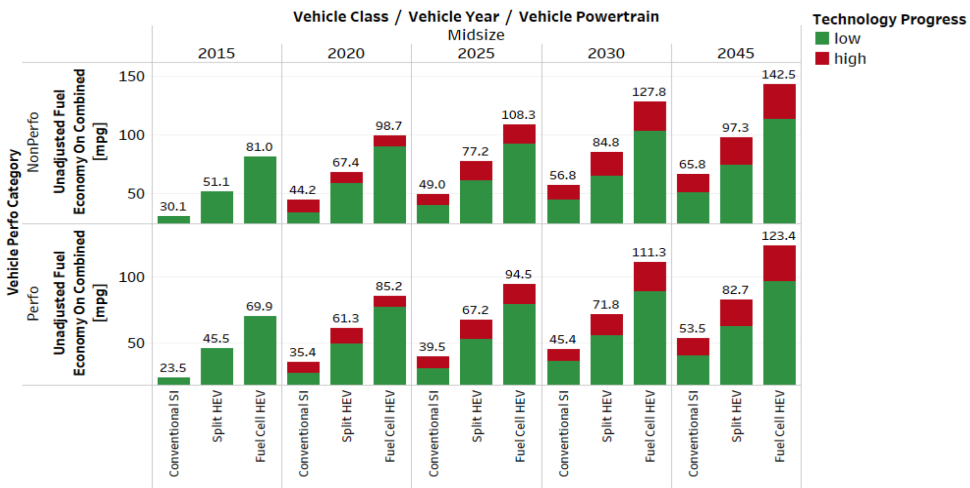

Figure 6: Gasoline-equivalent fuel economy across powertrains for midsize vehicle class

The effects of technology improvements in the evolution of conventional vehicles can be observed from the graph. It can be seen that in the reference year (2015 lab year), the gasoline-equivalent fuel economy of fuel-cell HEVs is about 63% - 66% higher compared to the gasoline conventional vehicle and 35% to 37% higher compared to Split HEV. However this improvement decreases to about 55% to 57% for the high case in lab year 2045 for gasoline conventional vehicles and 35% for Split HEVs. This shows the fuel-cell HEVs respond to a less aggressive advancement in technologies that result in lesser fuel consumption compared to gasoline conventional vehicles and Split HEVs.

4.3 Cost Feasibility

4.3.1 Fuel Cell System Cost

Figure 7 shows the evolution in the costs of fuel cell systems from 2015 to 2045 lab years for the midsize fuel cell vehicles.

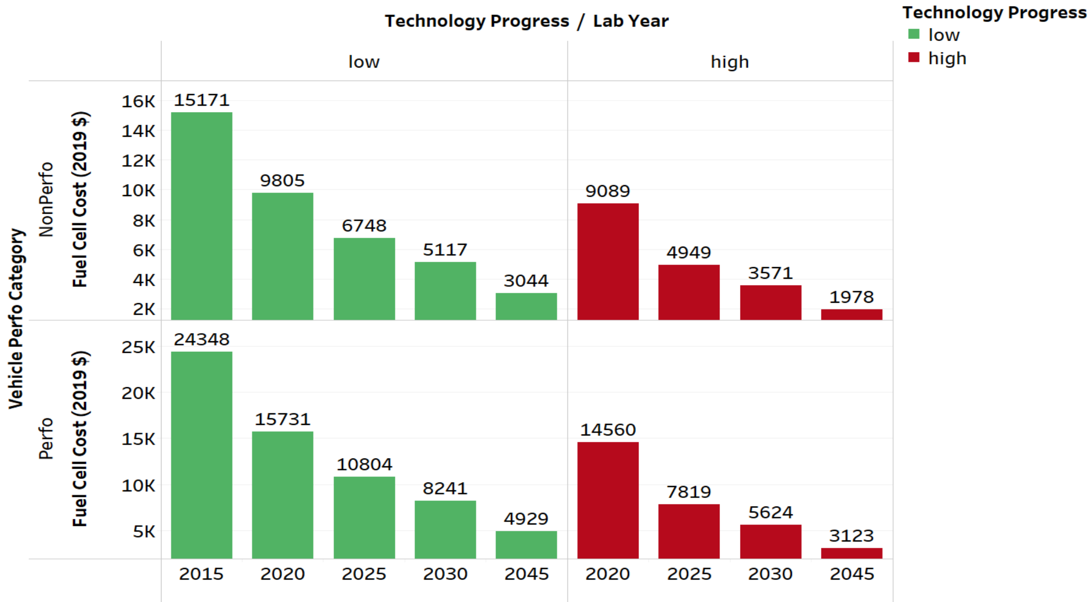

Figure 7: Fuel Cell System Costs (2019$)

The evolution in fuel cell system costs represent the effects of accelerated cost targets from HFTO. It is further impacted by the reduction in fuel cell power over the period due to the advancement in fuel cell technology targets. Over the years, it can be seen that the fuel cell system cost reduces by 80% to 87% by 2045 lab year across the different performance categories.

4.3.2 H_2 Storage Cost

Figure 8 shows the evolution in the hydrogen storage tank costs over the defined timeframe from 2015 to 2045 lab years for the midsize fuel-cell vehicles.

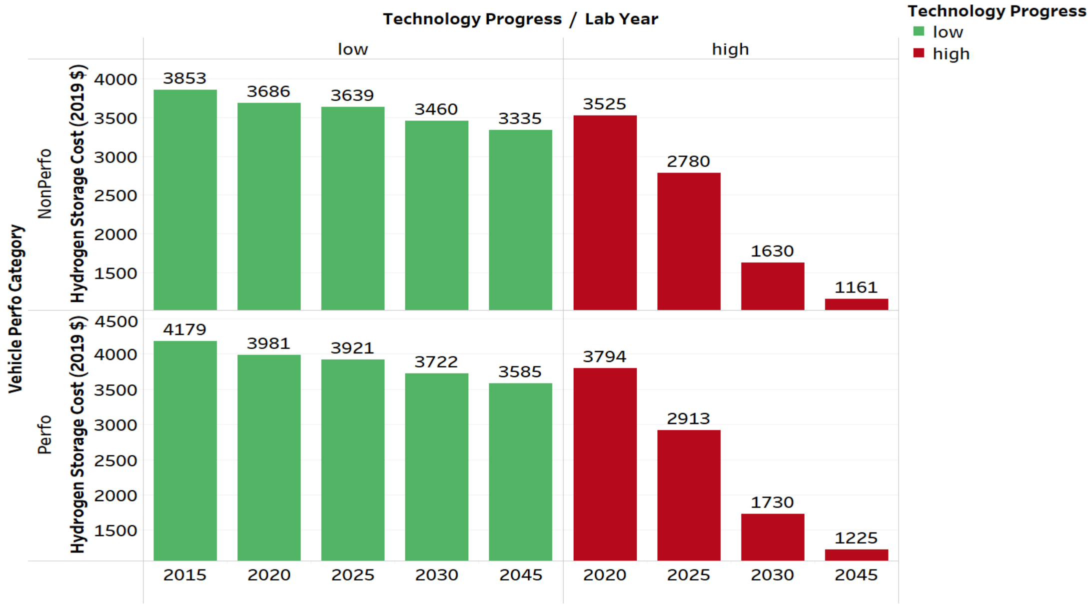

Figure 8: Hydrogen Storage Costs (2015$)

It can be seen that over the years, the cost reduces by 13% to 14% for low performance category and 70% to 72% for high technology progress, across the different performance categories.

4.3.3 Vehicle Manufacturing Cost

Figure 9 shows the evolution in the manufacturing costs of midsize fuel cell vehicles. These values represent the manufacturing costs and do not account for retail price factors.

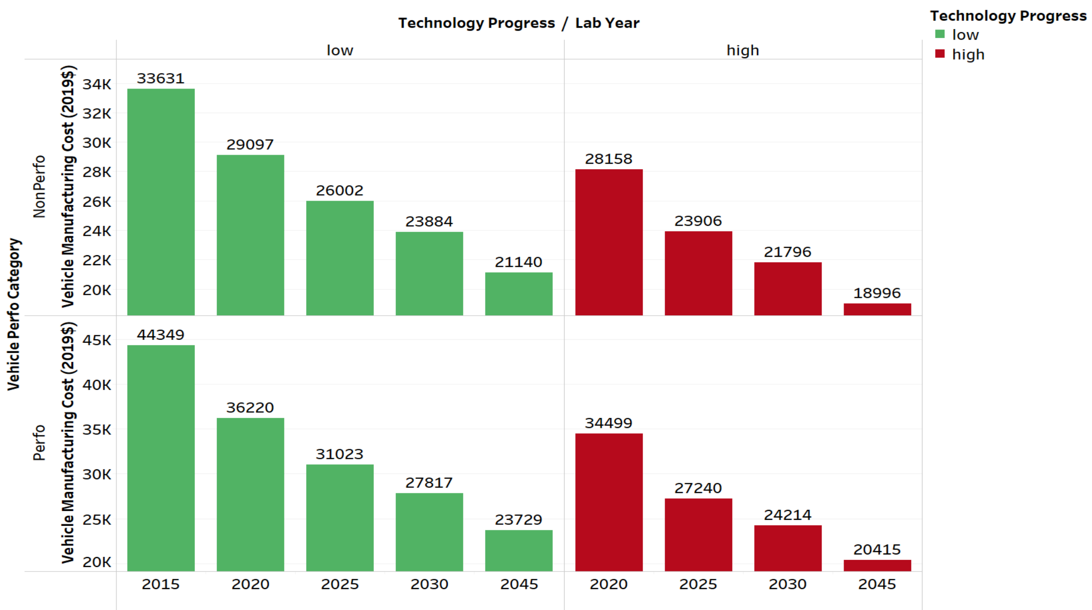

Figure 9: Fuel Cell Vehicle Manufacturing Costs

It can be seen here that the decreasing fuel cell system costs and hydrogen storage costs influences the reduction in vehicle manufacturing costs. From 2015 to 2045 lab year, the cost reduces by 37% to 46% for low technology progress and 44% to 54% for high technology progress, across the different performance categories.

4.4 Vehicle Manufacturing Cost vs. Fuel Economy

Figure 10 shows the trendlines in unadjusted fuel economy vs vehicle manufacturing costs for the different fuel cell powertrains, for all vehicle classes.

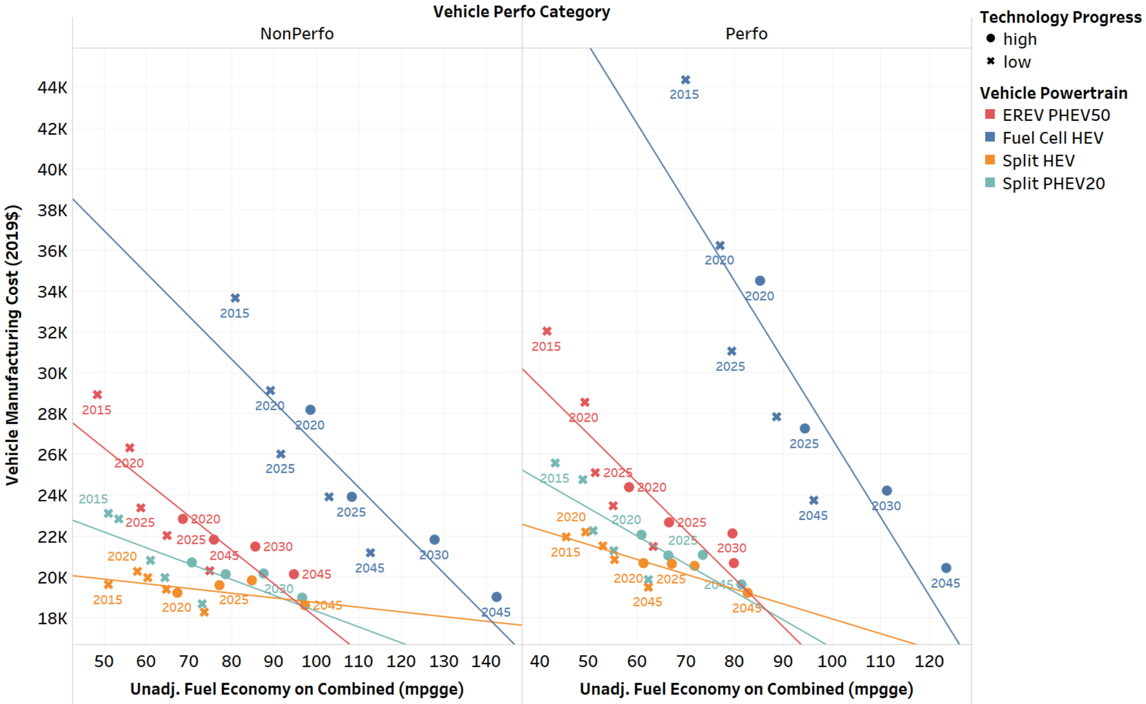

Figure 10: Unadjusted fuel consumption vs. manufacturing cost across electrified vehicle powertrains

Looking at the evolution of manufacturing costs with respect to fuel economy across the different vehicle powertrains, a rapid evolution in fuel cell HEVs can be observed. Moving from 2015 to 2045 lab years, it can be seen the fuel economy increases while the manufacturing cost decreases. The rate of this decrease with respect to the fuel efficiency improvement can be observed from the slope of the trendline for the different vehicle powertrains. The fuel cell HEV vehicles consume far less fuel in 2045 lab year compared to 2015 lab year, while the reduction manufacturing costs affect to a far greater extent. This is due to the acceleration of fuel cell cost targets, compared to the technology assumptions. Compared to the other midsize electrified vehicle powertrains, the fuel cell HEVs has a far more aggressive slope with respect to manufacturing cost reductions. The rank in order of vehicle manufacturing cost reduction is: Fuel Cell HEVs >EREV PHEV50 >Split PHEV20 >Split HEV.

5 Summary and Conclusion

The 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 economy.

The following conclusions can be drawn from the study:

- In terms of fuel cell power, the requirement decrease with time from 2015 to 2045 lab year, due to higher efficiencies, light weighted vehicles and the combined effect of advancements in other technologies. From 2015 to 2045 lab year, the fuel cell power decreases by 11% to 22% for compact, 13% to 31% for midsize, 19% to 28% for small SUV, 21% to 29% for midsize SUV, and 21% to 29% for pickup vehicle classes. The same is seen across the two performance categories.

- In terms of amount of hydrogen used during the EPA combined procedure runs, the amount decreases over time for the different fuel cell vehicles. From 2015 to 2045 lab year, the hydrogen fuel mass reduces by 36.3% for compact, 41.2% for midsize, 40% for Small SUV, 41% for Midsize SUV and 40% for Pickups. Similar range is also observed across the different performance categories.
- The improvement in fuel economy compared to that for conventional gasoline vehicles decreases over time across the different vehicle classes. It decreases from 63-66% in 2015 lab year to between 55% and 57% in 2045 lab year for midsize class. A similar trend is also seen across different vehicle classes.
- In terms of vehicle manufacturing costs, the value reduces by at most 54% across the different vehicle performance categories. This is due to the accelerated influence of lower fuel cell system and hydrogen storage costs.

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Presenter Biography

Ehsan Sabri Islam completed his M. Sc. in Interdisciplinary Engineering from Purdue University, USA in 2019 and B.A.Sc in Mechatronics Engineering from University of Waterloo, Canada in 2016. His skills set 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 and inputs for U.S. DOE-VTO and NHTSA/U.S. DOT SAFE regulations using innovative large scale simulation processes and applications of AI.