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Evaluation of the Economics of Light-Duty Battery-Electric and Fuel Cell Passenger Cars, SUVs, and Trucks: Methods, Issues, and Infrastructure

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STEPS+ and the Hydrogen Program

April 29, 2022

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Executive Summary

This report assesses and projects the initial purchase costs, total cost of ownership (TCO), and infrastructure needs and costs for light-duty battery-electric and hydrogen fuel cell vehicles, covering the period 2020-2040. The vehicle types considered are compact and mid-size passenger cars, small, mi-size, and large SUVs, and light-duty trucks. The economics of the electrified and corresponding gasoline vehicle of each type are analyzed using a model that treats the performance, powertrain, and component costs in detail. We compare resulting estimates in given years and for given vehicle classes across the various vehicle technology types to identify relative cost-effectiveness, and years when battery electric and hydrogen fuel cell vehicles may become more competitive with internal combustion engines vehicles than they are today.

The analysis uses a range of assumptions, as shown in Table ES-1. The key inputs to the model are the costs of the battery and fuel cell system and the energy use of each vehicle and the cost of electricity and hydrogen in 2020-2040. The battery, fuel cell, and energy costs used in the calculations are given in Table ES-1. The assumed driving range of the battery-electric vehicles is 300 miles and the range of the fuel cell vehicles is 400 miles. The energy use inputs for each vehicle were based on runs of UC Davis's version of the **Advisor** simulation model that estimates fuel economy for various vehicle types using an appropriate driving cycle.

Table ES-1: Battery, fuel cell, and energy inputs

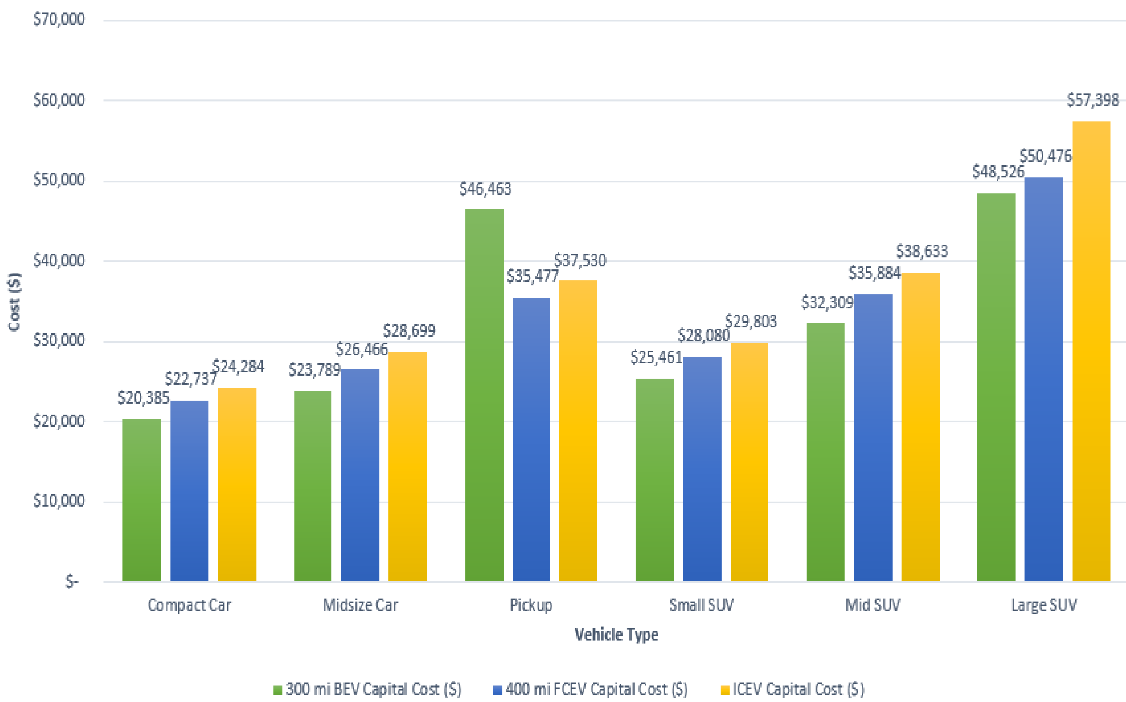
Parameter	2020	2025	2030	2035	2040
Battery ($/kWh)					
low	140	100	75	60	50
base	160	125	85	75	60
Fuel cell ($/kW)					
low	175	60	50	45	40
base	225	100	70	50	45
Electricity ($/kWh)					
low	.1	.1	.1	.1	.1
base	.2	.2	.2	.2	.2
high	.3	.3	.3	.3	.3
Hydrogen ($/kg)					
low	10	7	6	5	4
base	12	8.5	7	6	5
high	17	12	9	7	6
Gasoline($/gal)					
base	4.0	4.0	4.0	4.5	4.5

The results of the vehicle cost analyses are summarized in Figures ES-1, ES-2, and ES-3. These compare first cost and TCO across vehicle types and propulsion systems for 2025, 2030 and 2040, respectively.

These show that, given the assumptions summarized in Table ES-1, by 2030 both the initial cost and TCO of battery-electric vehicles are equal to or less than that of corresponding gasoline vehicles. This is true for all the light- duty vehicle types considered from compact passenger cars to large SUVs. In the case of the hydrogen fuel cell vehicles, the results of the vehicle cost analyses indicate that by 2035 the initial vehicle costs are close to that of the corresponding gasoline vehicles and their TCO are lower for all the light-duty vehicle types. By 2040, the projected costs of all the fuel cell vehicles are less than the corresponding gasoline vehicle. These comparisons are made for the low battery cost and low fuel cell costs, with ranges of 300 miles and 400 miles respectively. Comparisons made for the higher base battery and fuel cell costs would delay the years in which the electrified vehicles would compare favorably with the corresponding gasoline fueled vehicles. Decreasing the range of the electrified vehicles would result in favorable economics for them at slightly earlier years. In general, the results of this cost analysis indicates that if suitable infrastructure is established by 2030, large sales of both battery- electric and fuel cell light-duty vehicles can be possible without subsidies, to the extent that first cost and TCO advantages drive sales.

Figure ES-1: First (purchase) cost and TCO comparisons of electrified vehicles in 2025

Figure ES-2: First (purchase) cost and TCO comparisons of electrified vehicles in 2030



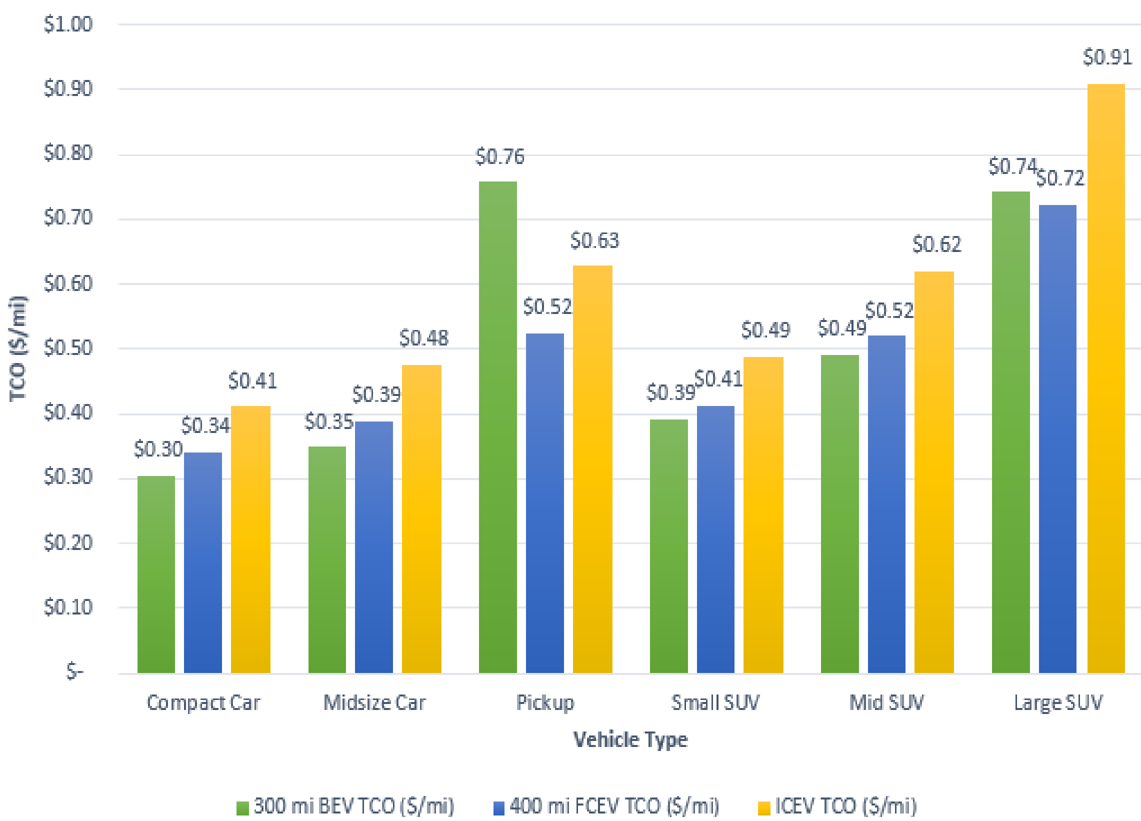


Figure ES-3: First (purchase) cost and TCO comparisons of electrified vehicles in 2040

An analysis of the infrastructure and its cost were also made as part of this study for both fast charging of the battery-electric vehicles and hydrogen refueling of the fuel cell vehicles. We also considered the effects on final prices from the Low-carbon Fuel Standard (LCFS) and the credit system for clean fuels associated with it.

It was assumed that the batteries in the vehicles could be fast charged in about 10 minutes, which requires charging at the 4.4 C rate with 350 kW chargers. Hydrogen refueling was done in 2.3 minutes at the rate 1.5 kgH2 /min. At the present time, there is considerable uncertainty in the cost of high power chargers and their installation and hydrogen refueling stations of specific capacity (kgH2/day). In the present analyses, it was assumed the chargers cost $700-1000/kW and H2 refueling stations cost $1500-2500/kgH2/day. These costs are for future infrastructure. It is expected that the utilization factor will be .4-.6 for large fleets (> 1 million) of electrified vehicles. In those cases, the cost of both the battery-electric and hydrogen fuel cell infrastructure is projected to be $1.5-2 billion for a 1.8 million vehicle fleet.

Overall, the costs of the public fast charger infrastructure for battery-electric vehicles and for the H2 refueling stations for fuel cell vehicles are about equal, but the cost of the infrastructure for the battery-electric vehicles are higher when the cost of both home and work charging are included.

The effect of LCFS credits on the energy costs for both battery-electric and hydrogen fuel cell vehicles will be significant, especially if the CO_2 /MT values is over $100 (in 2021 they tended to be between $150 and $200, with the latter as a soft cap). The LCFS station credits are also important in determining the business case for both fast charging battery-electric vehicles and hydrogen refueling of fuel cell vehicles. The effect of the LCFS credits on the profitability of both batter-electric and hydrogen fuel cell vehicles are summarized in Table ES-2. Including both station ad fuel LCFS credits the profitability of both stations is good with high 5 yr. IRR values but without both credits, neither station is profitability. The profitability with only the fuel credit is reduced, but it is still reasonably high.

Table ES-2: The effect of LCFS credits on the economics of electric and fuel cell vehicles

		5 year return ratio	**5 year IRR**
Fast Charging • 350 Kw • $800/kW • 1.25 install factor • Elec. Buy $.15/kWh • Elec. Sell $.30/kWh • Station cost $350k	All LCFS credits	2.84	.23
	Only energy credit	2.28	.18
	No LCFS credits	.98	NA
Hydrogen refueling • 800 kgH2/day • $2000/kgH2/day • H2 buy $5/kg • H2 sell $8/kg • Station cost $1.6M	All LCFS credits	3.0	.246
	Only energy credit	1.92	.14
	No LCFS credits	.67	NA

1. Introduction

This report is concerned with the economics of light duty battery-electric (EVs) and fuel cell (FCVs) vehicles (ZEVs) for the period 2020-2040. Various types of light vehicles are considered in detail, including passenger cars, SUVs, vans, and pickup trucks. Light-duty vehicles (GW<8500 lbs) account for about 70% of GHG (primarily CO_2) of the transportation sector and 28% of the total CO_2 emissions in California. The State of California has set goals to reduce GHG emission to near zero by 2045. On September 23. 2020, Gov. Newsom signed an Executive Order requiring 100 percent of new passenger car sales (i.e. light duty vehicles) be ZEVs (EVs and FCVs) by 2035. For this to occur, both the economics and the infrastructure for battery-electric and fuel cell vehicles will need to be favorable compared to the corresponding ICE, gasoline fueled vehicles. The objectives of this report are to project the costs (initial and operating) of light-duty ZEVs and the infrastructure to mass market these electrified vehicles. These costs will vary significantly between 2020 and 2040 as the ZEV technologies mature, production volumes increase, and the battery charging and hydrogen refueling stations are built. Projecting these costs will be the focus of the report.

2. Economic decision factors

The economic decision factors evaluated in this study are both straightforward and limited in number. The factors are those that would be of interest to light-duty vehicle buyers making decisions whether to purchase ZEV vehicles or to continue to purchase conventional engine-powered vehicles. One key factor is the initial cost of the ZEV compared to the conventional vehicle of the same size and utility. The cost of the ZEV will depend to a large extent on its range due to the relatively high cost of the battery ($/kWh), which is expected to continue to decrease in 2020-2040. Another key factor, which affects both the initial and the energy use cost of the ZEV is the energy use (kWh/mi or kgH_2 /mi) of the ZEV in average operation and how it can vary depending on changes in the route, speed, weather, and traffic. This factor is critical because the energy use cost ($/mi) of a ZEV, especially EVs, is significantly less than that of engine-powered vehicle and that difference can be used to offset the higher initial cost of the ZEV. This affect can be quantized in terms of the time (years) or miles it would take for the lower energy cost of the ZEV to compensate for its higher initial cost. These breakeven times and miles are calculated in the cost model.

Another category of decision cost factor is the accumulated operating cost of the ZEV over its lifetime. This factor is often referred to as the total ownership cost (TCO) for the vehicle and can be given in total dollars ($) or $/mi for a specified time period. The TCO depends both on the initial cost of the vehicle and the energy and maintenance costs as well as the discount rate (%) appropriate for the time period of the calculation. The TCO also depends on how the annual miles decrease as the vehicle ages and at what mileage it may be necessary to replace the battery or refurbish the fuel cell. The residual values of both the aged battery pack and the vehicle at various times during its life are important in the calculation of the TCO.

For light-duty vehicle buyers, the key economic factors are the initial purchase price/cost of the vehicle and the cost of the fuel (electricity or hydrogen) to operate the vehicle. In most cases, the light-duty vehicle owner does not track TCO and likely does not know how to calculate it. Hence, we will focus directly on energy costs and differences in maintenance costs of ZEVs and conventional ICE vehicles. The calculation of the initial vehicle purchase cost and operating costs depend on many assumptions and input parameters which are identified and discussed in the next section. Other important factors to ZEV buyers are the convenient availability and cost of fuel (electricity or hydrogen) for their vehicle. In the case of EVs, it is important to have battery charging readily available with electricity at a reasonable cost. This will require the establishment of a public battery charging infrastructure. In the case of FCVs, the vehicles will be refueled at public hydrogen stations much like gasoline stations for conventional ICE vehicles. This will require the construction of hydrogen stations and the production of large amounts of hydrogen at a relatively low cost. Providing the hydrogen infrastructure for the FCVs will be particularly challenging. All these economic and infrastructure factors for ZEVs will be discussed in this report.

3. Vehicle design and cost issues

3.1 Battery and powertrain cost factors

The major costs of battery-electric and fuel cell vehicles are the costs of the battery, fuel cell and electric powertrain components and their integration into the vehicle. The costs of these components are usually specified in terms of their cost to the vehicle OEM and a markup factor is used to reflect their integration into the vehicle. In past work dealing with passenger electric vehicles or hybrid-electric vehicles with small batteries [1], an integration factor of 1.5 was used to account for all aspects of the integration of new components. In the case of batteries, it has often not been clear whether the cost ($/kWh) specified for the batteries is to the OEM and is the cost of cells, modules or the battery system. It is now more clear that the battery cost projections are for the battery system to the OEM. Anderman's cost estimates [2] shown in Figure 1 are the most detailed available. In 2018, they indicate a material cost of $84/kWh for the cell and about a 50% increase between the cell cost and the battery system cost. The cost increase from the material cost to the cell and battery system costs are expected to be significantly smaller as the battery technology matures and the production volumes increase, but eventually the material cost will set a lower limit on the battery cost.

56-Ah EV Pouch Cell Price*

4.5-GWh plant, 2018 timescale

56 Ah EV Pouch Cell Price			
NMC 5,3,2 Cathode, Pouch, 24 Million Cells / Year			
Component	$	Per kWh	%
Materials	17.4	84	62%
Factory Depreciation	3.7	18	13.4%
Manufacturing Overhead	1.49	7	5.4%
Labor	1.20	6	4.3%
Un-yielded COG	23.8	115	85%
Scrap, 4%	0.74	4.8	3.0%
Yielded COG	**24.5**	**120**	**88%**
SG&A	3.3	16	12.0%
Burdened Cost	**27.9**	**136**	**100%**
Warranty & Profit	2.2	11	8.0%
Price	**30.1**	**145**	**127%**
Gross Margin	5.6		19%

EV Battery Cost Estimate

Pack, Cell, and Cell Materials

For a 60-kWh Battery, CY 2018

Volume	Cell Materials	Cell Price	Pack Price
Cell Technology	$/kWh	$/kWh	$/kWh
Pouch cells, 4.5 GWh plant	85-110	145-210	215-280
20-700 , 7GWh plant	85-110	135-170	210-260

Figure 1: Battery cost forecasts

Source: Anderman [2]

Information on projections of battery costs by Bloomberg [3, 4] are given in Figures 2 and 3. The most recent data in Figure 2 shows data for cells and battery packs for 2013-2020. In 2020-2028, the increase in cost from cell to pack is 35-40% which is somewhat less than that projected by Anderman. Figure 3 is an earlier cost projection by Bloomberg of battery costs. Comparing those costs with those shown in Figure 2, one finds good agreement for 2015-2020 and with a stated projected cost of $100/kWh in 2030 and $58/kWh in 2030. However, the stated 2030 battery cost assumes that the advanced solid-state lithium battery technology is well developed by 2030. The Bloomberg article also states that battery costs in China for buses are $105/kWh. These details concerning the Bloomberg projections indicate they are a reasonable basis for projecting battery costs in the future at least up to 2030.

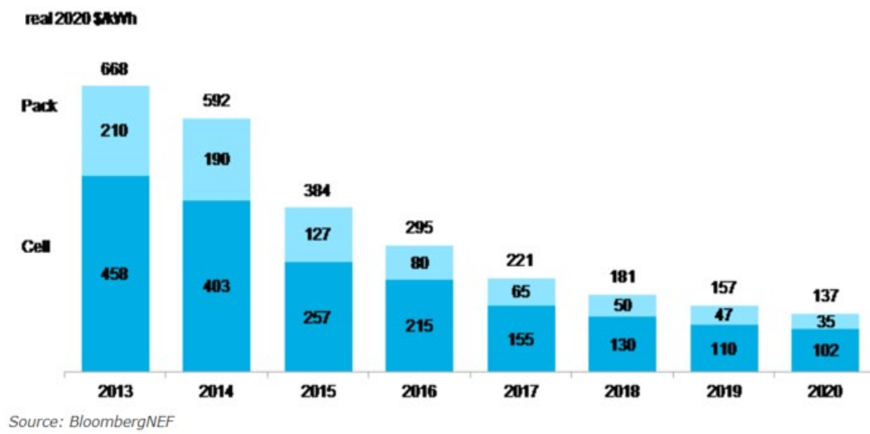


Figure 2: Recent Battery prices from Bloomberg (4]

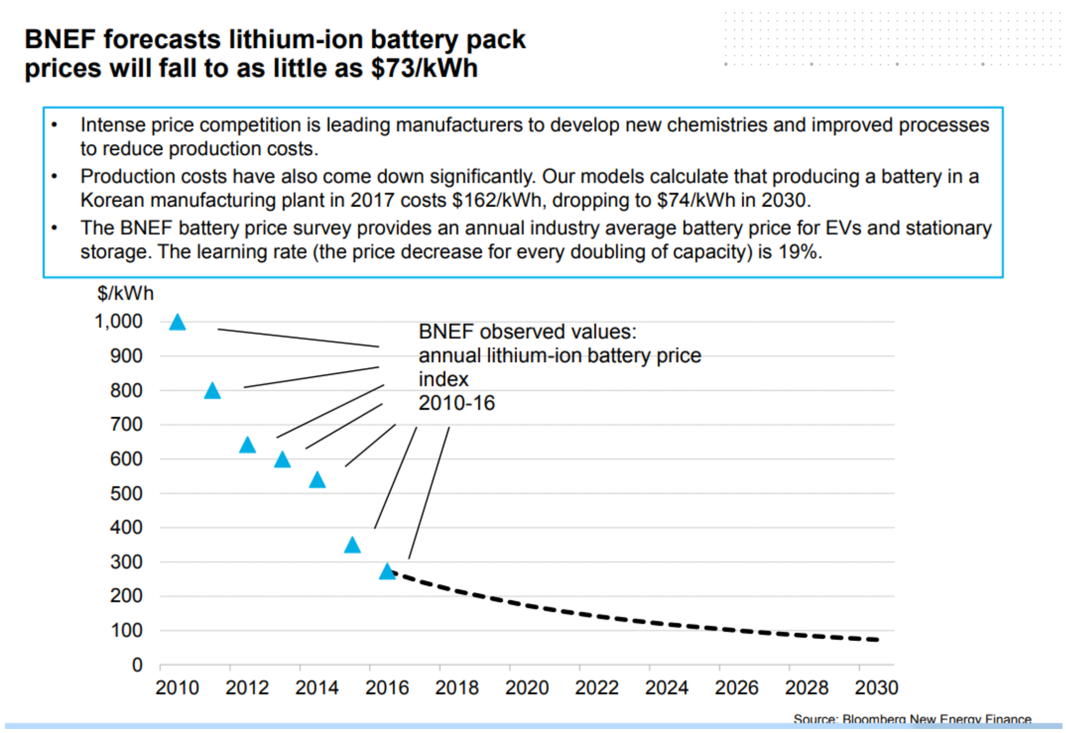


Figure 3: Battery price forecasts by Bloomberg [3]

The battery cost estimates in Figures 2-3 indicate a cost of $ 140/kWh in 2020, decreasing to about $100/kWh by 2025 and $ 70/kWh by 2030. These battery costs to the OEM (high, base. and low cases) used in this study are shown in Table 2. The low cost case was taken directly from the Bloomberg projections in Figures 2 and 3. The base and high cost cases were increased systematically from the low price case. In the vehicle cost calculations, the costs in Table 2 are multiplied by a vehicle integration factor to account for cost mark by the OEM and the cost of integrating the battery into the vehicle powertrain.

Table 2: Battery pack costs for 2020-2040

Battery cost $/kWh	**2020**	**2025**	**2030**	**2035**	**2040**
Battery costs to OEMs					
- Hi cost case	180	140	110	90	70
- Base cost case	160	125	85	75	60
- Low cost case	140	100	75	60	50
Battery integration factor	1.2	1.15	1.11	1.05	1.05

The costs of the powertrain components (motor, power electronics, and DC-DC converters) will be given as $/kW of the system. As in the case of the batteries, the powertrain cost will be assumed to be the cost to the OEM and the retail vehicle cost will be calculated using a powertrain integration factor. Information on the costs of the electric powertrains in the literature [5, 6] shows a large variation as well as whether the cost is to the OEM or is the retail cost. DOE has studied the present cost of the electric powertrains and has set long-term goals (2030). Based on the available information, the electric powertrain to the OEMs shown in Table 3 will be used in this study. It should be recognized that there is considerable uncertainty in the present costs and as a result, the costs shown for future years forecast significant cost decreases as the powertrain technologies mature.

Table 3: Electric powertrain costs in the future

Year	**$/kW DOE HD**	**$/kW DOE LD**		**$/kW Heavy-duty**	**$/kW Medium-duty**	**$/kW Light-duty**
2020	38	19		45	30	22
2030	14	6		20	16	10
2040	12	6		15	13	8
2050	12	6		15	13	8

3.2 Fuel cell vehicle cost considerations

DOE has funded studies of the cost of fuel cells [7, 8] for light-duty vehicles. The cost projections indicate a large reduction in cost ($/kW) with increasing production volume. Hence relating the projected costs to specific years in 2020-2040 requires some judgement concerning the size of the market for light-duty vehicles in each of the 5 year periods. The results of the DOE studies are summarized in Figures 4 and 5 and Table 4. Those results will be the basis of the fuel cell cost projections used in this study. Light-duty cars and SUVs are being marketed by Toyota, Honda, and Hyundai. Hence, there is reasonable expectation that sales of fuel cell vehicles will increase rapidly before 2030. Another detailed study of the cost of fuel cell vehicles is presented in [9]. In that study, 37 experts were asked to make their best estimates of the cost of fuel cell systems for 2020-2050. The results from those experts are shown in Figure 6. There is considerable variation in the assessments of the experts, but they fall in the same ranges for future years as the projections by DOE.

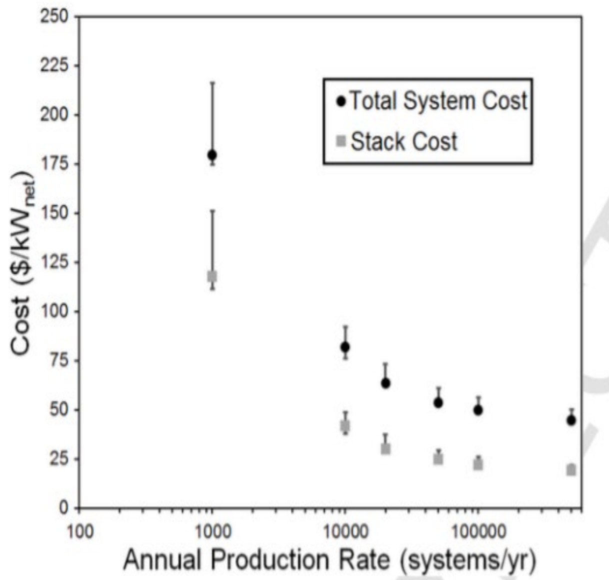


Fig. 6. Estimated fuel cell stack and total costs for 80 kW_{net} automotive fuel cell system at various annual production rates. The error bars represent the middle 90% confidence range of Monte Carlo sensitivity analysis of system cost.

Figure 4: Fuel cell stack and system cost at very production volumes [8]

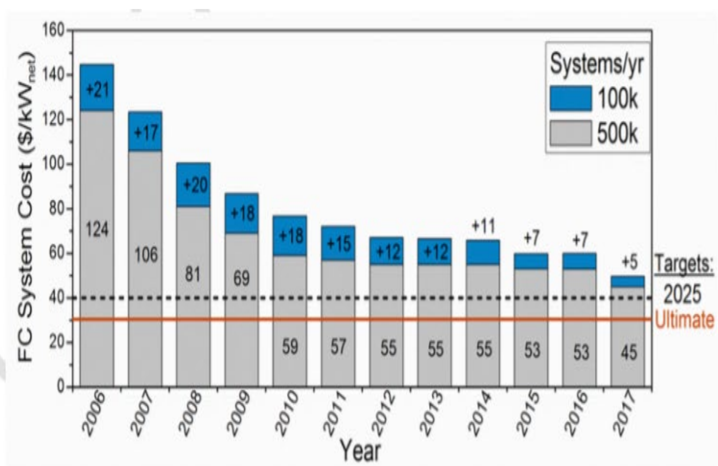


Fig. 7. Total 80 kW_{net} automotive FC system cost estimates at high annual production volumes (100,000 and 500,000 systems/yr). 2025 and ultimate system cost targets are \$40- and \$30/kW_{net}. Previous and current year values in nominal US\$; target values in out-year US\$.

Figure 5: Estimated automotive fuel cell costs at high production volumes [8]

Table 4: Fuel cell system costs vs volume of production for LDV applications

Production volume/yr	$/kW
300 units/yr	250
1000	175
3000	135
10000	85
30000	60
100000	50
300000	45
500000	40

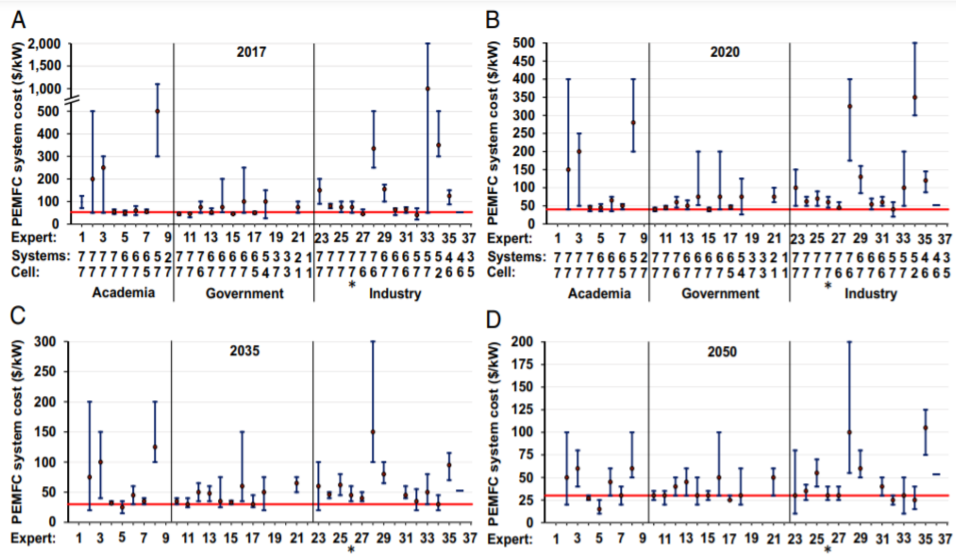


Fig. 3. Experts' assessments of PEMFC system cost (2017 USD). Each data point represents an expert's best estimate, and the uncertainty ranges represent experts' judgments of a 95% CI. Expert 36 provided only a lower bound across all years. The group interview is marked by an asterisk. (A) 2017 values. The horizontal line represents the DOE's 2015 estimate of $53/kW. The vertical axis is broken between $500/kW and $1,000/kW. (B) 2020 values. The horizontal line represents the DOE's 2020 target of $40/kW. (C) 2035 values. The horizontal line represents the DOE's ultimate target of $30/kW. (D) 2050 values. The horizontal line represents the DOE's ultimate target of $30/kW.

Figure 6: Expert assessment of fuel cell costs [9]

The fuel cell costs can be expected to decease significantly in the future as the fuel cell system and manufacturing technologies mature, much like has happened for lithium batteries in the last 10-15 years. In the case of fuel cells, the cost decrease is likely to be considerably slower as the volume of sales and production will likely be much less than was the case for lithium batteries. In the case of batteries, the cost reduction was dominated by the rapid expansion of battery manufacturing capability in China and Korea and the successful efforts of the Chinese government to market very large numbers of electric passenger cars and buses over the last 5-10 years. It seems unlikely that these types of rapid capacity expansion events in China in connection with batteries will occur for fuel cells.

For the present cost study, three sets of fuel costs – high, base, and low – will be used in the economic calculations. The high cost projection assumes a modest rate of market development. The low cost projection is based on a rapid development of the market assuming Toyota, Honda, Hyundai and some Chinese car companies decide to emphasize sales of fuel cell vehicles rather than battery-electric models. The third set of fuel cell costs between low and high is termed the base case and it is represents the most likely market development. The fuel cell costs used in this study are shown in Table 5 along with the associated production volumes needed to support the costs in each year.

Table 5: Fuel cell cost ($/kW) projections for high, base, and low cases

HD $/kW	2020	2025	2030	2035	2040
High cost case	300	135	85	60	50
Production volume (units/year)	300	3000	10000	30000	100000
Base case	225	100	70	50	45
Low cost case	175	60	50	45	40
Production vol. (units/year)	1000	30000	100000	300000	>500000
Fuel cell system integration factor	1.2	1.15	1.1	1.1	1.05

3.3 Cost of hydrogen

The cost of hydrogen produced with electrolysis and solar/wind electricity in the future is uncertain especially if low cost curtailed/dumped electricity is used to produce the hydrogen. At the present time (2020-2025), most of the hydrogen is produced by steam reforming natural gas (SMR). That hydrogen is low cost ($1-3/kg), but it has a high CI near 100. The CI of hydrogen from solar electrolysis will be 5-10 or even lower. The quantity of hydrogen produced will vary from day-to-day and season-to-season requiring storage before it can be used to refuel vehicles. This will add further uncertainty to the cost of hydrogen dispensed to fuel cell vehicles in the future. The effect of LCFS credits for hydrogen will be set by the owner/operator of the hydrogen refueling station.

Recent estimates [18-22] of the cost of delivered hydrogen are summarized in Table 6.

Table 6: Recent estimates of produced and delivered electrolytic H2 (production to refueling)

Study	2020	2025-30	2030+	Notes
US DOE targets [11]				Targets, but considered achievable in time frame
- Low volume (higher cost)	16	10		
- High volume (lower cost)	13	5	4	For long term target, only a high volume one ($4)
Sinha (UC Davis 2020 draft-[12])	12.9	6.6	3.4	Midsized truck stop, low electricity cost, does not include H2 transportation, if needed
H2 Council/McKinsey 2020 [10]	10.4	4.4		Mid-range electrolysis cost with trucking (pipeline very similar)
IEA (2019) [13]	12	7		Mid case, based on mid electricity price, electrolyser cost, capacity factor
Ballard-Deloitte [14]	13	4		Not clear that the station cost includes all components of getting hydrogen from production to vehicle.

Using the results in Table 6, high, base (average) and low estimates for cost of H2 in 2020-2040 were made for use in the economic calculations for fuel cell vehicles. The cost of the hydrogen ($/kg) was varied for 2020-2040 as shown in Table 7.

Table 7: Hydrogen costs ($/kg) for fuel cell trucks produced from electrolysis

	2020	2025	2030	2035	2040
High cost	17	12	9	7	6
Base (average)	12	8.5	7	6	5
Lower cost	10	7	6	5	4

3.4 Maintenance costs of electrified vehicles

Maintenance costs for electrified LD vehicles are also uncertain. Limited experience with EVs [15] indicates their maintenance ($/mi) will be significantly less than for gasoline ICE vehicles. In the case of fuel cell vehicles, there is no experience as yet on which to base the cost of maintenance. Maintenance values ($/mi) for battery- electric and fuel cell LD vehicles are assumed to be 50% and 75% of the ICE values, respectively. These values are shown in Table 8.

Table 8: Maintenance costs for various LD electrified vehicle

Vehicle Type	EV $/mile	FCV $/mile	ICEV $/mi
Compact car	.031	.05	.062
Mid-size car	.031	.05	.062
Small SUV	.031	.05	.062
Mid-size SUV	.04	.06	.07
Large SUV	.04	.06	.07
LD pickup	.04	.06	.07

3.5 Infra-structure considerations

It is of interest to compare the costs of providing the infra-structure for EVs and FCVs. A spreadsheet model has been developed to make this calculation. In the case of the EVs, it is assumed that a fraction (50%) of the EVs have home charging and the remainder must use public chargers for city travel. All the EVs require public chargers for highway travel. In this analysis, all the public chargers are DC fast chargers capable of completing a charge in less than 10 minutes. In the case of the FCVs, all the refueling in the cities and along the highways is done in public hydrogen stations. These stations can complete the refueling in less than five minutes. The outputs of the model are the number of battery fast chargers and H2 refueling stations needed and the total costs of providing that infrastructure for large fleets of vehicles. Typical results from the model for the number of stations and associated costs for large fleets of vehicles are shown in Table 9. The number of stations needed and thus their total cost depends on the utilization factor (Ut) of the stations which was varied from .3 to .6. It is expected that Ut will be relatively low early in the development of the EV market and increase as the number of the electrified vehicles becomes larger. The costs ($/kW for the battery chargers and $/kgH2/day for the H2 stations) were reduced for the larger values of Ut, which is an indicator of market development. The cost values in Table 9 correspond to the total market being developed at that Ut for the number of vehicles cited for the market.

Table 9: Results for infrastructure for battery-electric and fuel cell vehicles

	EVs					FCVs			
Utilization factor by fleet size (headings show vehicles in fleet)	No. city FChargers	No. HW FChargers	Cost** FC$M	Size FC kW*		No. city H2Sta***	No. HW H2 Sta.	Cost H2 Sta $M	Size H2 Sta kg/da
$50x10^3$ Vehicles									
.3	129	100	96	350		44	17	82	330
.4	97	75	48	350		32	13	57	418
.5	77	60	29	350		24	10	43	494
.6	64	50	20	350		20	8	31	560
$200x10^3$									
.3	516	401	385	350		179	70	329	330
.4	387	301	193	350		130	50	226	418
.5	309	241	116	350		100	38	171	494
.6	258	202	80	350		80	31	125	560
$500x10^3$									
.3	1289	1002	963	350		447	174	822	330
.4	967	752	481	350		323	126	565	418
.5	774	602	289	350		249	97	428	494
.6	645	502	201	350		200	80	312	560
$1.8x10^6$									
.3	4642	3610	3470	350		1612	627	2960	330
.4	3481	2707	1730	350		1165	453	2030	418
.5	2785	2166	1040	350		897	348	1540	494
.6	2321	1805	722	350		721	280	1120	560
$5x10^6$									
.3	12895	10029	9630	350		4479	1742	8220	330
.4	9671	7522	4810	350		3237	1258	5650	418
.5	7737	6017	2890	350		2492	969	4280	494
.6	6447	5014	2010	350		2003	779	3120	560

*fast charging time 7.5 minutes (4.4C), ** does not include cost of home chargers, *** H2 refueling time 2.5 minutes (1.5kg/min.)

The results of the model for vehicle fleet sizes from 50,000 to 5,000,000 are shown in Table 9. Results are given for the number of public fast chargers and H2 refueling stations needed to support the operation of the fleets of the various sizes. In the case of the battery electric vehicles, it was assumed that ½ of the vehicles had home charging and public chargers were needed only for highway travel for those vehicles. Cost results are also shown in Table 9 for only the public chargers and the H2 refueling stations. The results indicate the public cost of providing infrastructure for battery fast charging is less than for refueling fuel cell vehicles except for Ut=.3. When the costs of the home battery chargers are included the costs of providing the infrastructure for the electric and fuel cell vehicles are nearly equal. Comparisons of the results for the number of H2 stations with those given in CARB reports [16-18] for several size fuel cell vehicle fleets indicate the results in Table 9 are reasonable.

The infrastructure costs in the model (Table 9) do not include LCFS credits for the stations, which will reduce the effective cost to the station operators and make their operation profitable sooner than without the credits. In California, there are LCFS station credits that can off-set the cost of developing both battery fast charger and hydrogen refueling stations for LDV during the early period of infrastructure development. In addition, there are electricity and hydrogen LCFS credits that can lower the operating costs of the stations and the electricity and hydrogen dispensed. These LCFS credits will lower the direct costs of providing the infrastructure for both battery-electric and fuel cell vehicles, but their major effect to the public will be to lower the cost of the energy they will purchase to operate the battery-electric and fuel cell vehicles.

The development of the infra-structure for electrified light-duty vehicles is complex and expensive and key to their mass marketing. In the case of battery electric vehicles, charging the batteries must be convenient for car owners living in single family homes and multi-family apartments for both city and highway travel. The cost of charging ($/kWh) must be low enough to off-set possible differences in the purchase price of the EV compared to a conventional ICE vehicle. Fortunately, access to electricity is not a problem as it is widely available. In the case of refueling hydrogen fuel cell vehicles, access to hydrogen is difficult as the use of hydrogen as a fuel is presently very limited and the hydrogen infrastructure is only now being developed. Hydrogen refueling is nearly as fast as with gasoline in an ICE vehicle, but the character of the hydrogen refueling station is very different from that of the gasoline station because the hydrogen fuel is a high pressure gas [16, 17]. Hence, the infra-structure for fuel cell vehicles requires both the establishment/construction of large numbers of hydrogen stations in the cities and along highways and the production of a very large amount (billions of kgH2) of hydrogen from renewable resources in the long term. Unlike battery-electric vehicles, none of the fuel cell vehicles can be refueled at home and all the refueling must be done at public stations. As in the case of electricity, the cost of the hydrogen must be low enough to off-set the expected higher cost of the fuel cell vehicle compared to the ICE vehicle it replaces. The development of the infra-structure for fuel cell vehicles will be more difficult and expensive than for EVs, but fuel cell vehicles have significant advantages in refueling time and range (miles) for long distance travel.

3.6 The Low Carbon Fuel Standard (LCFS) and its effect on refueling station economics

The infrastructure costs in Table 9 do not include LCFS credits for the stations, which will reduce the effective cost to the station operators and make their operation profitable sooner than without the credits. In California, there are LCFS station credits that can off-set the cost of developing both battery fast charger and hydrogen refueling stations for LDV during the early period of infrastructure development. In addition, there are electricity and hydrogen LCFS credits that can lower the operating costs of electricity and hydrogen dispensed. These LCFS credits will lower the direct costs of providing the infrastructure for both battery-electric and fuel cell vehicles, but the major effect to the public will be to lower the cost of the energy they will purchase to operate the battery-electric and fuel cell vehicles.

The cost of the energy to operate the electrified vehicles will be important in assessing their economic attractiveness. As discussed in [18-20], the Low Carbon Fuel Standard (LCFS) credits for electricity and hydrogen can be large as California and the United States transition to renewable energy. LCFS credits will be available for both electricity and hydrogen. These credits should be available continuously up to 2040, but at a decreasing level as the carbon intensity (gCO2/MJ) of gasoline is reduced (see Table 10). In the case of battery-electric vehicles and home and work place charging, the vehicle owners will certainly be using relatively low cost electricity. In the case of public refueling of both battery-electric and fuel cell vehicles, the effect of LCFS credits on the cost of operating the vehicles will be felt through reduced fuel costs, but the magnitudes of the savings are difficult to assess because they are dependent on the details of the financing and operation of the public stations. The cost of public charging battery-electric vehicles using high power chargers will be significantly higher than home charging. This makes the analysis of the effect of LCFS credits on the economics of battery-electric vehicles uncertain. All refueling of hydrogen fuel cell vehicles will be done at public stations so a fixed cost can be assigned to the H2 dispensed.

The formulae for calculating the LCFS credits for stations and energy for electricity and hydrogen are given below [21- 23].

Formulae for LCFS credits [21]

Energy

Electricity**:** Credit ($/kWh) = $(CI_0 - CI_{elec,} / (EER)_{EV} * (EER)_{EV} * 3.6*10^{-6} *$ ($/Mt CO2), $EER_{EV} = 5$

Hydrogen: Credit ($/kgH2) = $(CI_0 - CI_{H2} / (EER)_{FCV} * (EER)_{FCV} * 120*10^{-6} *$ ($/Mt CO2), $EER_{FCV} = 2.5$

Refueling stations

Fast charging battery

Electricity Credit ($/sta/yr) = $(CI_o - CI_{H2} / (EER)_{FCV}) * (EER)_{FCV} * 3.6*10^{-6} * 43$ (kWchg)^.45*365*($/Mt CO2)

Refueling hydrogen

Hydrogen Credit ($/sta/yr) = $(CI_o - CI_{H2} / (EER)_{FCV}) * (EER)_{FCV} * 120*10^{-6} *$ ($/kgH2/da)*(1-Ut)*365*($/Mt CO2)

The LCFS credits are based on the reduction in CO_2 emissions by substituting low carbon electricity and hydrogen for fuels produced from fossil sources. The credits depend on the relative carbon intensity (gCO_2/MJ) of the hydrogen and electricity available in a given year with the target fuel carbon intensity for that year. As indicated in Table 10, it is expected that in 2020-2040 the carbon intensities (CI) of the electricity and hydrogen will decrease markedly and the target carbon intensity CI_0 n California will also decrease due to policies currently in place [14, 15]. The value of the LCFS credits are also dependent on the value of a ton of CO_2 reduction ($/mt$CO_2$) set by state auction, which is expected to be $ 150-200. The magnitude of the LCFS credits for electricity and hydrogen shown in Table 10 are large although they decrease significantly as we approach 2040.

Table 10: LCFS Credits for 2020-2050

Year	target CI_0	Hydrogen CI SMR	Hydrogen CI renbl	Electricity CI Grid	Electricity CI renbl	LCFS Credit $/kWh Grid	LCFS Credit $/kWh renbl	H2 Credit $/kgH2 SMR	H2 Credit $/kgH2 renbl
2020	91	98	10	110	10	.22	.29	2.80	4.70
2025	8	98	10	100	10	.21	.27	2.53	4.43
2030	80	73	10	90	10	.20	.25	2.67	3.99
2035	72	49	10	75	10	.15	.19	2.36	3.06
2040	64	24	10	50	10	.14	.16	2.29	2.52
2045	50	15	10	30	10	.11	.12	1.78	1.86
2050	40	10	10	15	10	.09	.09	1.46	1.46

A spreadsheet model was prepared to evaluate the economics of refueling stations including the effects of LCFS credits. The electricity and hydrogen credits are straight-forward to include because they are directly related to the energy dispensed at the station and as a result, they are calculated from the utilization factor Ut of the station. The station credits are dependent on details of CARB regulations limiting the value the station credits. In the case of fast chargers, CARB has set the daily charger output as kWh= 43 (charger KW).[43] regardless of the utilization of the charging station. For both charging and hydrogen stations, the accumulation of station credits for a project can not exceed its cost. Both of these regulations can limit the value of station LCFS credits. Results from the LCFS model are shown in Table 11 for typical fast charging and hydrogen refueling projects. Both of these projects are evaluated based on the 5 year return on investment and IRR (internal rate of return). In both calculations, Ut was varies from .25 to .5 over the 5 years. The capital recovery factor (CFR) assumed was .13. The energy cost assumptions are summarized in Table ES-1. Results are shown for IRR including both LCFS credits, only the energy credit, and no LCFS credits. The importance of the LCFS credits in making a business case for both the refueling stations is very clear. Without the credits, the business case is poor, but with the credits the business case is good. The business case including the energy credit is also reasonably good. Hence in evaluating the economics of establishing the infrastructure for battery-electric and hydrogen fuel cell vehicle, the contribution of LCFS credits should/must be included.

Table 11: The effect of LCFS credits on the economics of electric and fuel cell vehicles

Fast Charging • 350 Kw • $800/kW • 1.25 install factor • Elec. Buy $.15/kWh • Elec. Sell $.30/kWh • Station cost $350k	All LCFS credits	2.84	.23
	Only energy credit	2.28	.18
	No LCFS credits	.98	NA
• Hydrogen refueling800 kgH2/day • $2000/kgH2/day • H2 buy $5/kg • H2 sell $8/kg • Station cost $1.6M	All LCFS credits	3.0	.246
	Only energy credit	1.92	.14
	No LCFS credits	.67	NA

3.7 Decision factors for purchasers of light-duty battery-electric and hydrogen fuel cell vehicles

Purchasers of electrified vehicles to replace their gasoline ICE vehicles seem most concerned about the initial cost of the vehicle and the availability and cost of electricity or hydrogen to refuel the vehicles. Long-term cost (TCO) and resale value of the vehicle are of secondary importance, especially if they lease the vehicle. Reliability/durability and maintenance costs are important to all vehicle owners. For battery-electric vehicles, range and battery life are important. With the range (=> 200 miles) of EVs presently on the market, range for city driving should not be a concern for most buyers. Range and fast charging are a concern for long distance driving/trips. The cost of the EV depends significantly on its range so vehicle range (miles) is an important factor in the economic analysis. We will consider ranges of 200, 300, and 400 miles for all types of EVs. Battery life (years) should not be a problem/concern for the long range EVs using lithium batteries having cycle life of at least 1500 deep discharge (to 80%) cycles. As shown below, these batteries have a projected cycle life of about 300,000 miles and over 20 years in LD EVs. The annual mileage [24] of various types of LD vehicles are shown in Table 12. Hence, for LD EVs, the calendar life [25] of the lithium batteries will be the major concern - not cycle life.

Battery life (miles)= $(kWh)_{pack}$ x 1500 x .8/Wh/mi; $(kWh)_{pack}$=70, Wh/mi =300, Battery life miles =280,000 miles or 22.4 years

Table 12: Annual mileage for various types of LD vehicles [24]

Vehicle/ Class	Miles/yr*
Passenger cars	12300
SUV	15000
LD pickup truck	12500

*annual mileage for year 1

4. Methods of economic analysis - model development

4.1 Basic inputs

The spreadsheet model is configured on a number of sheets. The sheets consist of the inputs and calculations for each of the battery-electric and fuel cell vehicle types being analyzed. The vehicle inputs as they appear in the spreadsheet for battery-electric and fuel cell vehicle are shown in Table 13. The outputs calculated directly from the inputs are shown in Table 14. There are tables like Tables 13 and 14 for each of vehicles being analyzed. **Advisor** simulations were run for each of the electrified vehicles and the baseline gasoline vehicle varying the inputs to reflect improvements expected in 2020-2040. The energy consumption values (kWh/mi and kgH2/mi) used the cost analyses were based on the **Advisor** simulations.

The calculation of the initial cost of the vehicles, their total operating cost (TCO) for the 5 year and 15 year time periods, and payback miles and years are discussed in detail in the remainder of this section.

Table 13: Vehicle inputs and directly related vehicle characteristics used in the model calculations

Inputs for Battery-electric vehicles

Year	Input Parameters												
	Vehicle Parameters Input						Cost Parameters Input						
	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kWh/mile)	Over Energy Factor	Battery Pack Energy Density by Mass (Wh/kg)	Battery Pack Energy Density by Vol (Wh/L)	Glider Cost ($)	Electric Drive ($/kW)	Electric Drive Integration Markup Factor	Energy Battery ($/kWh)	Electricity Cost ($/kWh)	Battery Integration Markup Factor	Maintenance Cost ($/mi)
2020	1640	150	0.188	15%	150	375	20000	22	1.2	140	0.2	1.2	0.031
2025	1511	145	0.171	15%	200	500	20000	15	1.15	100	0.2	1.15	0.031
2030	1432	140	0.15	15%	250	625	20000	10	1.1	75	0.2	1.1	0.031
2035	1360	135	0.144	15%	300	750	20000	8	1.05	60	0.2	1.05	0.031
2040	1288	130	0.137	15%	350	875	20000	8	1.05	50	0.2	1.05	0.031

Fuel Cost ($/mi)	Vehicle & Non-Battery Residual Value (%)	Battery Residual Value (%)	Maintenance Cost ($/mi)	Energy Consumption (mpgD)	Gasoline Price ($/gal)	Fuel Cost ($/mi)	Vehicle Residual Value (%)
0.043	50%	15%	0.062	37.0	3.0	0.08	50%
0.039	50%	15%	0.062	39.1	3.5	0.09	50%
0.035	50%	15%	0.062	43.4	3.8	0.09	50%
0.033	50%	15%	0.062	46.8	4.0	0.09	50%
0.032	50%	15%	0.062	50.2	4.0	0.08	50%

Inputs for fuel cell vehicles

	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kgH2/mile)	Over Energy Factor	FC Power (kW)	FC Specific Power (W/kg)	FC Power Density (W/L)	Battery Pack Size (kWh)	kgH2/kgH2 of tank	kgH2/Lt of tank
2020	1447	130	0.0096	15%	100	670	720	0.75	0.048	0.02
2025	1379	125	0.0096	15%	100	675	730	0.75	0.051	0.03
2030	1300	120	0.0081	15%	100	680	740	0.75	0.054	0.04
2035	1220	115	0.0076	15%	95	710	810	0.75	0.057	0.05
2040	1140	110	0.0070	15%	90	760	880	0.75	0.065	0.06

Glider Cost ($)	Electric Drive ($/kW)	Electric Drive Integration Markup Factor	Fuel Cell ($/kW)	Fuel Cell Integration markup	H2 Storage ($/kgH2)	H2 Fueling Cost ($/kgH2)	Battery Cost ($/kWh)	Maintenance Cost ($/mi)	Fuel Cost ($/mi)	Vehicle Residual Value (%)
17000	22	1.2	175	1.2	1400	10	300	0.047	0.111	50%
17000	15	1.15	80	1.15	800	7	200	0.047	0.077	50%
17000	10	1.1	60	1.1	400	6	175	0.047	0.056	50%
17000	8	1.05	50	1.05	350	5	150	0.047	0.044	50%
17000	8	1.05	40	1.05	300	4	125	0.047	0.032	50%

Table 14: Battery and vehicle cost outputs

Outputs for mid-size battery-electric passenger car

Year	Required Range (miles)	Battery Oversize factor	Battery capacity (kWh)	Battery Pack Weight (kg)	Battery Pack Volume (L)	Total Vehicle Cost ($)
2020	200	1.25	47	313	125	$ 31,856
	300	1.25	71	470	188	$ 35,804
	400	1.25	94	627	251	$ 39,752
2025	200	1.25	43	214	86	$ 27,418
	300	1.25	64	321	128	$ 29,876
	400	1.25	86	428	171	$ 32,334
2030	200	1.25	38	150	60	$ 24,634
	300	1.25	56	225	90	$ 26,181
	400	1.25	75	300	120	$ 27,728
2035	200	1.25	36	120	48	$ 23,402
	300	1.25	54	180	72	$ 24,536
	400	1.25	72	240	96	$ 25,670
2040	200	1.25	34	98	39	$ 22,890
	300	1.25	51	147	59	$ 23,789
	400	1.25	69	196	78	$ 24,688

Outputs for a mid-size fuel cell passenger car

Year	Required Range (miles)	H2 Oversize factor	H2 capacity (kg)	H2 System Weight (kg)	H2 System Volume (L)	Total Vehicle Cost ($)
2020	300	1.11	8	456.3	656.6	$ 99,881
	400	1.11	10	508.9	782.8	$ 103,416
	500	1.11	13	561.6	909.1	$ 106,952
2025	300	1.11	7	402.8	478.1	$ 66,447
	400	1.11	9	448.2	555.2	$ 68,299
	500	1.11	12	493.6	632.4	$ 70,151
2030	300	1.11	6	354.0	376.5	$ 55,718
	400	1.11	9	393.6	429.9	$ 56,573
	500	1.11	11	433.1	483.3	$ 57,427
2035	300	1.11	6	324.6	312.6	$ 52,234
	400	1.11	8	360.1	353.0	$ 52,941
	500	1.11	10	395.5	393.4	$ 53,648
2040	300	1.11	6	285.8	266.2	$ 49,901
	400	1.11	8	315.3	298.2	$ 50,476
	500	1.11	10	344.7	330.1	$ 51,051

4.2 Analysis of the initial cost of the vehicles

Analysis of the initial cost of the BEV

The initial cost of the battery-electric vehicles can be estimated as shown below using the vehicle inputs in Table 9.

$(\text{Vehcost})_{BEV.}$ = glider + Electric drive cost + battery cost

Glider = Price ICE Vehicle – cost of engine and transmission of the gasoline vehicle

Electric drive cost = \$/kW x kW of EM x system integration factor (IF_{pt}) for the driveline

Battery kWh = $(\text{kWh/mi})_{level}$ x range requirement (miles)/ bat. usable factor $(UBF)_{bat}$

Battery cost = Battery kWh x $(\$/\text{kWh})_{bat}$ x system integration factor (IF_{bat}) for the battery pack

The battery usable factor (UBF) is needed because the battery can not be completely discharged on a regular basis without greatly reducing cycle life. UBF=.8 has been used in the present model. The integration factors used for the powertrain and the batteries were decreased from 1.2 to 1.05 from 2020 to 2040 to reflect the maturing of the component and manufacturing technologies over time.

Analysis of the initial cost of the fuel cell vehicle

For the hydrogen fuel cell vehicles, the initial vehicle cost is given by

$(\text{Vehcost})_{H2\ FC.}$ = glider + Electric drive cost + Power battery cost + fuel cell system cost

fuel cell cost = (\$/kW x kW of fuel cell x integration factor

hydrogen storage cost = \$/kgH_2stored x kg stored H_2 x integration factor

kg stored H_2 = $(\text{kg/mi})_{on\ level}$ x H_2 usable factor (H2UBF=.9)

fuel cell system cost = fuel cell cost + hydrogen storage cost

power battery cost =$(\$/\text{kWh})_{powerbat}$ x $(\text{kwh})_{powerbat}$ x integration factor

4.3 Calculation of the total ownership costs

The calculation of the total ownership cost for a specified period (5 or 15 years) requires the determination of operating expenses in each year of the period and then summing the annual expenses over the total period. Then at the end of the period, residual values of the vehicle and the batteries are needed. All the separate expenses must be discounted by the appropriate amount given by $[1/(1+d)^{n-1}]$ where d is the discount percent and n is the year of the expense. In this study, the discount % used was 10% for the 5 year period and 2% for the 15 year period. At the end of the 15 year period, the residual value of both the vehicle and the battery are taken as zero. At the end of the 5 year period, it is assumed that the residual value of the gasoline ICE vehicle is 50% of its initial value and that of the battery-electric vehicle is 50% of its initial cost minus the cost of the battery pack. It is further assumed that the residual value of the batteries after 5 years is 15% of their initial cost. We have assumed no battery replacement will be needed in the LD vehicles. A cycle life of 1500 deep discharge cycles is assumed for the batteries. For light-duty EVs, the assumed cycle life results in very high vehicle mileage (1500 x pack kWh x UBF/vehicle kWh/mi) before the batteries would need to be replaced. Depending on the vehicle range, the mileage is 250-500k miles, which corresponds to 15-30 years. Hence it is not necessary to include battery replacement in the TCO cost analysis.

The present value of the operating expense for the nth year of a battery-electric vehicle life is calculated as follows:

$$(TCO)_n = [(Energy)_{elecv} + (maint.)_{elecv}] / (1+d)^{n-1}$$

$$= [[(kWh/mi) \times (OEF) \times (\$/kWh)_{elec}) + (\$/mi)_{maintEV.}] \times (miles/yr.)_n]/(1-d)^{n-1}$$

The discounted total cost of ownership is then given by the following:

$$(TCO)_{total} = (Veh\ cost)_{BEV} + \sum_n (TCO)_n + (Residual\text{- } Veh + bat)/ (1+d)^{N-1} \ , N=n_{max}$$

$$(TCO/mi)_{total} = (TCO)_{total} / \sum_n (miles/yr.)_n$$

The corresponding relationships for the baseline ICE vehicle are the following:

$$(TCO)_n = [[(mi/gal)_D \times (\$/gal)_D + (\$/mi)_{maintD.}] \times (miles/yr.)_n]/(1-d)^{n-1}$$

$$(TCO)_{total} = (Veh\ cost)_{Diesel} + \sum_n (TCO)_n + (Residual\text{- } Veh)/ (1+d)^{N-1} \ , N=n_{max}$$

$$(TCO/mi)_{total} = (TCO)_{total} / \sum_n (miles/yr.)_n$$

The relationships above for TCO apply to both the short 5 year and long 15 year periods of analysis. Both lifetime periods are considered in the model. It is expected that TCO is not considered by most potential buyers of light-duty vehicles.

Similar assumptions and relationships were used for the fuel cell vehicles to calculate the TCO.

4.4 Calculation of the payback time and miles

A simple approach to assessing the economic attractiveness of the electrified vehicles is to calculate the time (years) and/or mileage of operating the electrified vehicle compared to the ICE engine vehicle to recovery from energy and maintenance savings the difference in the initial purchase price of the vehicles.

$$(payback\ years) = [(veh\ cost)_{elecv} - (veh\ cost)_{ICE}]/[(\Delta\$/mi)_{fuel\ cost} + (\Delta\$/mi)_{mainten\ cost}]$$

$$(payback\ miles) =([(veh\ cost)_{elecv} - (veh\ cost)_{ICEI}]/]/[(\Delta\$/mi)_{fuel\ cost} + (\Delta\$/mi)_{mainten\ cost}]) / (miles/yr.)_{n=1}$$

If the payback time and miles are deemed to be short by potential electrified vehicle buyers in terms of their expected operation of the vehicle, the economics of their purchase will be attractive to them. The pay back periods could be easily understood by most potential buyers of electrified vehicles if it was explained to them.

5. Model inputs and results for battery-electric and fuel cell light-duty vehicles

5.1 Inputs for each vehicle type

As mentioned, the model is set up to handle six light-duty vehicle types- compact and mid-size passenger cars, small, mid-size, and large SUVs, and a LD pickup truck. Input parameters are provided for battery-electric and hydrogen fuel cell vehicles as well as comparable gasoline ICE vehicles of each type. All the vehicles were simulated using the UCD Advisor program to determine their energy consumption values (Wh/mi, kg H2/mi, and mpg). The inputs to the simulations were changed to reflect improvement in vehicle and component design for 2020-2040. Improvement in battery energy density and fuel cell efficiency were also included in the vehicle assessments. As discussed previously, the costs of all the powertrain components were decreased between 2020 and 2040 to reflect maturing of the technologies and expected mass production. The decrease in the cost of the batteries and fuel cells are particularly important. Calculations were done for both the base and low cost projections of the battery and fuel cell costs.

For mass marketing of the light-duty electrified vehicle to be successful, it seems necessary that their prices approach close to those of comparable gasoline ICE vehicles of each type. In the case of battery-electric vehicles, the cost of the vehicle depends significantly on its range (miles). In the case of fuel cell vehicles, a key design parameter is the power (kW) of the fuel cell system. The effect of these parameters on the costs of the electrified vehicles of various types are shown in Table 14 for 2030 when the vehicle technologies are mature. The costs of all the electrified vehicles are approaching or have reached that of the comparable ICE vehicles for modest values of range and fuel cell power. All these calculations were done using the low costs of the batteries and fuel cells. The vehicle cost results indicate that it will be necessary to meet these battery and fuel cell costs for the electrified vehicle costs to approach the ICE vehicle costs by 2030.

Table 15: Variation in costs of battery-electric and hydrogen fuel cell LD vehicles for different ranges and fuel cell powers

EVs 2030		**compact**	**mid-size**	**pickup**	**smallSUV**	**midSUV**	**largeSUV**
Range mi		**Vehcost K$**					
100		19.8	23.1	30.9	23.5	31.3	46.2
200		21.2	24.6	33.7	26.4	33.6	50.2
300		22.6	26.1	36.5	28.8	35.8	54.2
400		24.1	27.7	39.3	30.3	38.0	58.2
EV elect. $/mi		.032	.035	.063	.043	.05	.089
ICE veh cost K$		23.5	27.5	35.5	28.0	36.5	54.0
ICE fuel $/mi		.07	.09	.13	.08	.11	.17
FCV2030							
Fuel cell kW		**Vehcost K$**					
2035		24.2 100 kW	28.4 115 kW	37.5 150 kW	29.6 110 kW	38.1 150 kW	52.9 160 kW
2030 kW ratio		26.5 100 kW	30.9 115 kW	40.9 150 kW	31.8 110 kW	41.3 150 kW	56.6 160 kW
.8		25.2	29.4	38.9	30.4	39.3	54.5
.7		24.5	28.6	37.9	29.6	38.3	53.4
.5		23.2	27.1	35.9	28.2	36.3	51.3
FCV H2 $/mi		.058	.075	.11	.067	.092	.14
ICE fuel $/mi		.07	.09	.13	.08	.11	.17

Gasoline $3.80/gal, electricity $.20/kWh, hydrogen $5/kg, FCV range 400 miles

5.2 Cost results for 2020-2040

The cost results for the various types of light-duty vehicles are given in tabular form in Table 16 and in bar chart form in this section of the report. The data presentations will emphasize how the projected costs of the electrified vehicles varied between 2020 and 2040 and how the projected costs of the battery-electric and fuel cell vehicles compared with each other and with the baseline ICE vehicles. Results will be shown for TCO as well as vehicle costs, but TCO is less important for LD vehicles than for commercial MD/HD vehicle applications. Energy costs are also shown in Table 16 because owners of light-duty vehicles will be very aware of what they are paying to refuel their new electrified vehicles and how it is different than what they had been paying for gasoline to refuel their ICE vehicles.

Table 16: Summary of results for battery-electric and fuel cell LD vehicles of various types

	Battery electric vehicles 300 mi range						**Fuel cell vehicles 400 mi range**						**ICE gasoline vehicles**		
Vehicle type	Vehicle cost k$ (1)	(2)	TCO 5 yrs $/mi (1)	(2)	Electricity cost $/mi (3)	(4)	Vehicle cost k$ (5)	(6)	TCO 5 yrs $/mi (5)	(6)	Hydrogen cost $/mi (7)	(8)	Vehicle cost k$	TCO 5yr $/mi (9)	Gasoline cost $/mi (9)
Compact car															
2020	31.1	32.5	.47	.50	.019	.058	47.6	53.6	.70	.78	.111	.131	22.0	.39	.104
2025	26.0	27.7	.40	.42	.018	.055	31.9	34.2	.49	.51	.077	.094	22.6	.39	.104
2030	22.7	23.2	.34	.35	.016	.049	26.5	27.6	.40	.42	.056	.065	23.1	.39	.092
2035	21.1	21.9	.32	.33	.015	.045	24.2	24.2	.37	.37	.044	.052	23.7	.40	.092
2040	20.4	20.9	.30	.31	.014	.042	22.7	23.2	.34	.35	.032	.040	24.3	.40	.092
Mid-size car															
2020	35.8	37.5	.54	.57	.022	.065	55.8	63.1	.82	.90	.126	.152	26.0	.45	.127
2025	29.9	31.7	.45	.48	.020	.065	37.5	40.3	.56	.59	.084	.102	26.7	.45	.115
2030	26.2	26.8	.39	.40	.017	.052	30.8	32.1	.46	.48	.060	.070	27.3	.45	.104
2035	24.5	25.4	.36	.38	.017	.050	28.3	28.4	.42	.42	.047	.057	28.0	.46	.115
2040	23.8	24.3	.35	.36	.016	.047	26.5	27.0	.39	.39	.035	.044	28.7	.47	.104
Pickup truck															
2020	50.0	52.7	.79	.83	.034	.103	76.1	85.7	1.13	1.24	.198	.238	34.0	.59	.173
2025	41.6	44.6	.66	.71	.033	.098	50.0	53.7	.75	.80	.128	.155	34.9	.59	.161
2030	36.5	37.6	.58	.60	.031	.094	40.9	42.5	.62	.64	.101	.118	35.7	.60	.173
2035	33.6	35.1	.53	.55	.029	.088	37.5	37.5	.56	.57	.079	.095	36.6	.61	.161
2040	32.2	33.2	.51	.52	.028	.083	35.5	36.2	.52	.53	.058	-073	37.5	.62	.173
Small SUV															
2020	38.6	40.6	.59	.62	.025	.075	58.5	65.7	.87	.95	.149	.179	27.0	.46	.115
2025	32.7	35.0	.50	.53	.025	.074	38.9	41.7	.59	.62	.095	.115	27.7	.46	.115
2030	28.4	29.2	.43	.44	.022	.065	31.8	33.0	.48	.50	.071	.083	28.4	.46	.104
2035	26.4	27.4	.39	.41	.021	.062	29.6	29.6	.44	.44	.058	.069	29.0	.47	.104
2040	25.5	26.1	.38	.39	.019	.058	28.1	28.7	.41	.42	.041	.052	29.8	.48	.104

	Battery electric vehicles 300 mi range						Fuel cell vehicles 400 mi range						ICE gasoline vehicles		
	Vehicle cost k$		TCO 5 yrs $/mi		Electricity cost $/mi		Vehicle cost k$		TCO 5 yrs $/mi		Hydrogen cost $/mi		Vehicle cost k$	TCO 5yr $/mi	Gasoline cost $/mi
Vehicle type	(1)	(2)	(1)	(2)	(3)	(4)	(5)	(6)	(5)	(6)	(7)	(8)		(9)	(9)
Mid-size SUV															
2020	47.9	50.1	.72	.75	.028	.086	75.3	84.9	1.09	1.21	.167	.20	35.0	.59	.15
2025	40.4	42.9	.60	.64	.027	.081	49.1	52.5	.73	.77	.106	.129	35.9	.59	.138
2030	35.8	36.7	.53	.55	.025	.076	41.3	42.9	.61	.63	.081	.095	36.8	.60	.127
2035	33.4	34.6	.49	.51	.024	.071	38.1	38.1	.56	.56	.065	.078	37.7	.61	.138
2040	32.3	33.1	.47	.49	.022	.067	35.9	36.6	.52	.53	.046	.058	38.6	.61	.127
Large SUV															
2020	73.5	77.1	1.1	1.16	.049	.146	103.4	115.4	1.43	1.57	.261	.313	52.0	.85	.23
2025	61.4	65.7	.92	.99	.047	.140	68.3	72.4	1.01	1.06	.168	.204	53.3	.85	.207
2030	54.2	55.8	.81	.83	.045	.134	56.6	58.3	.84	.86	.133	.155	54.6	.87	.207
2035	50.2	52.4	.74	.78	.042	.126	52.9	52.9	.77	.77	.105	.125	56.0	.89	.219
2040	48.5	49.9	.71	.73	.040	.121	50.5	51.3	.72	.73	.079	.099	57.4	.90	.207

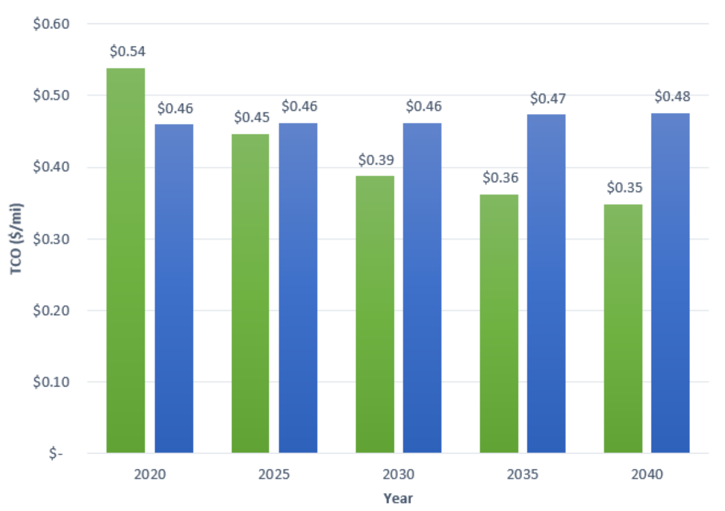
(1) low bat. Cost, (2) base bat. Cost, (3) low Elec. Cost, (4) high elec. Cost, (5) low FC cost, (6) base FC. Cost, (7) low H2 cost, (8) high H2 cost, (9) gasoline cost $4.5/gal

5.2.1 Results for mid-size passenger cars and SUVs (2020-2040))

Selected results from Table 16 are shown in bar chart form in Figures 6-10 as the basis for discussing the results for battery-electric and fuel cell vehicles of various types. Of particular interest is how the projected cost of the vehicles will decrease from 2020-2040 as the technologies mature and the differences in the costs of the battery-electric and fuel cell vehicles of the various types over that time period. The effects of the costs of electricity and hydrogen energy on the economic attractiveness of the electrified vehicles will also be discussed. Recent cost projections by Argonne National Laboratory for advanced light-duty vehicle are given in [26].

Figure 6: Initial and TCO Costs of Battery-electric vehicles (2020-2040)

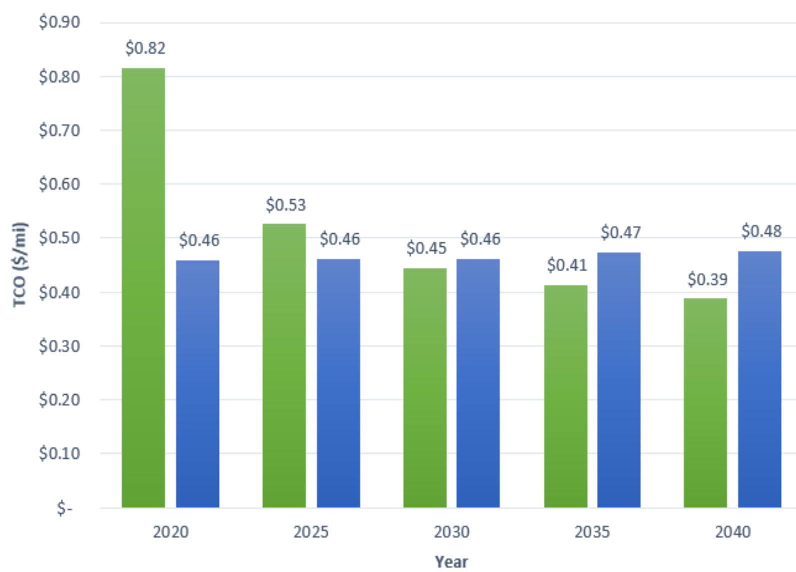
Mid-size Passenger cars



Mid-size SUVs

Figure 7: Initial and TCO Costs of fuel cell vehicles (2020-2040)

Mid-size passenger car



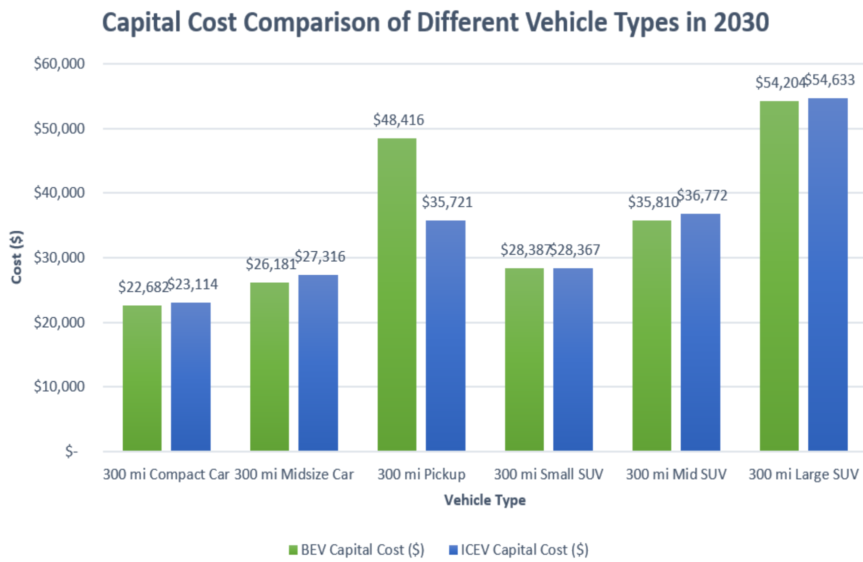
Mid-size SUV

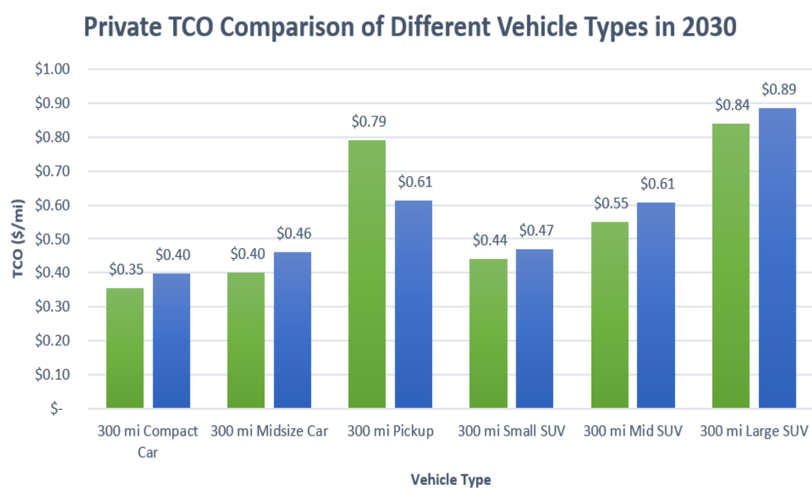

$80,000
$70,000
$60,000
$50,000
$40,000
$30,000
$20,000
$10,000
$-
Cost ($)
$75,348
$35,000
$45,606
$35,875
$39,639
$36,772
$37,356
$37,691
$35,884
$38,633
2020
2025
2030
2035
2040
Year
FCEV Capital Cost ($)
ICEV Capital Cost ($)


$1.20
$1.00
$0.80
$0.60
$0.40
$0.20
$-
TCO ($/mi)
$1.09
$0.59
$0.68
$0.60
$0.59
$0.60
$0.55
$0.62
$0.52
$0.62
2020
2025
2030
2035
2040
Year

Figure 8: Comparisons of various types of LD vehicles in 2030

Battery-electric vehicles





Hydrogen fuel cell vehicles

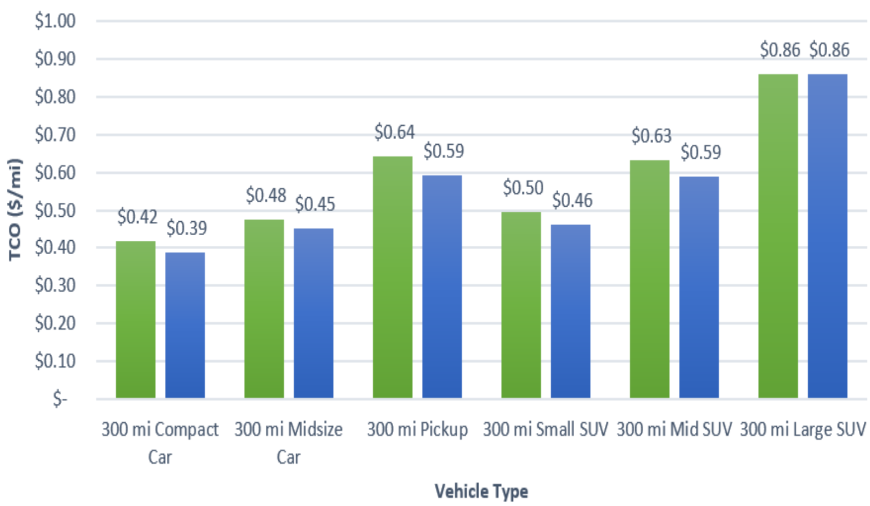
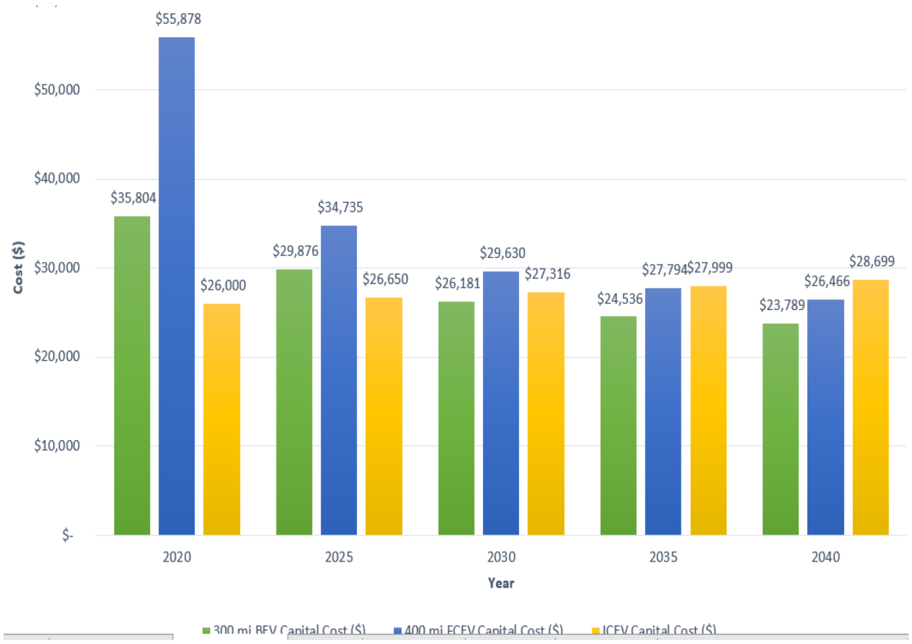
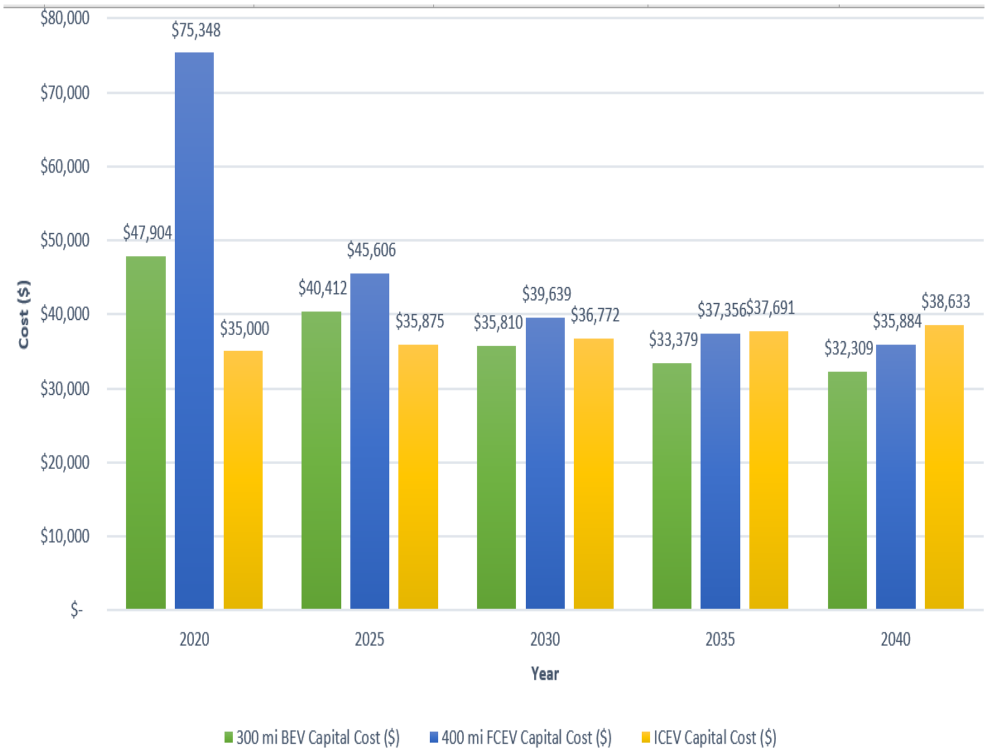


Figure 9: Comparisons of the costs of battery electric and fuel cell vehicles in 2020-2040

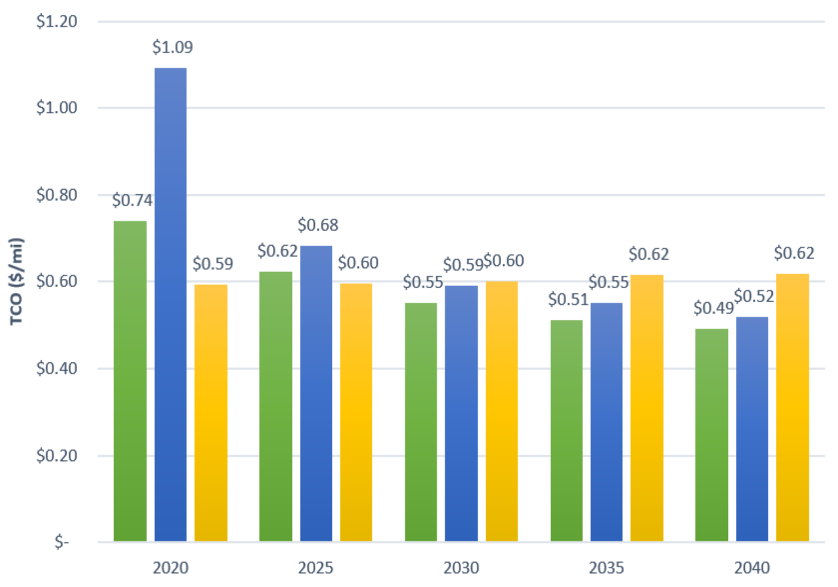
Mid-size car



Mid-size SUV



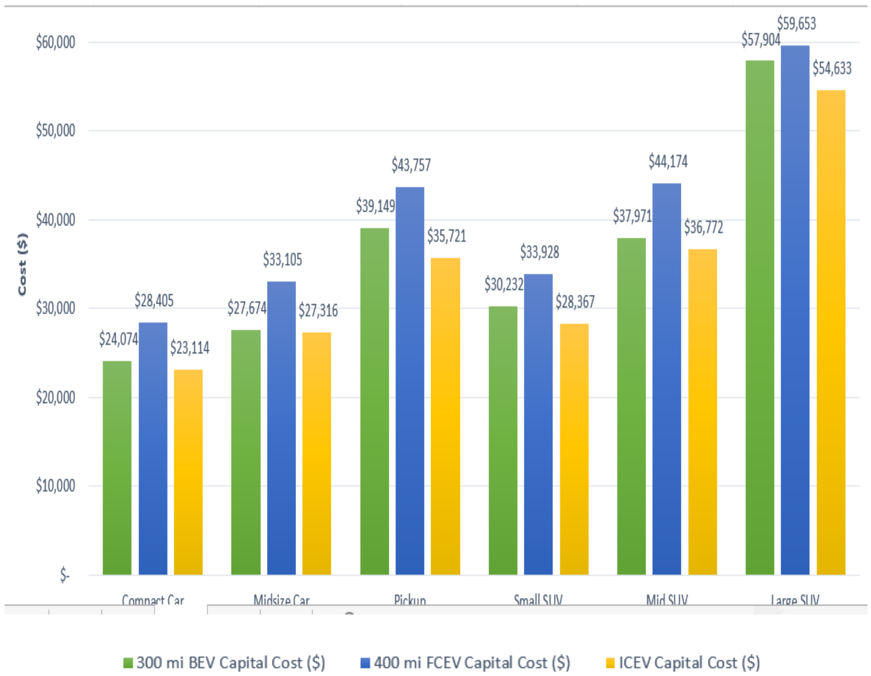
$80,000
$70,000
$60,000
$50,000
$40,000
$30,000
$20,000
$10,000
$-
Cost ($)
$75,348
$47,904
$35,000
$40,412
$45,606
$35,875
$35,810
$39,639
$36,772
$33,379
$37,356
$37,691
$32,309
$35,884
$38,633
2020
2025
2030
2035
2040
Year
300 mi BEV Capital Cost ($)
400 mi FCEV Capital Cost ($)
ICEV Capital Cost ($)



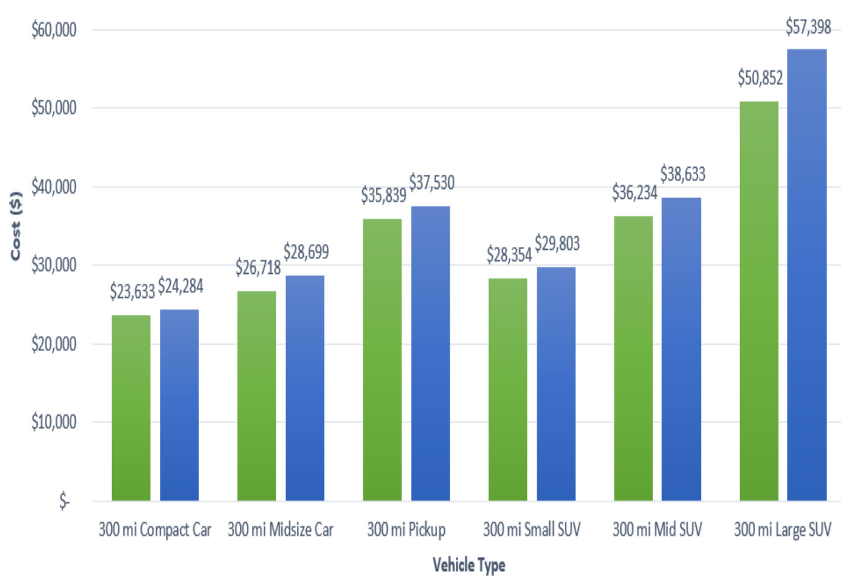
$1.20
$1.00
$0.80
$0.60
$0.40
$0.20
$-
TCO ($/mi)
$1.09
$0.74
$0.59
$0.62
$0.68
$0.60
$0.55
$0.59
$0.60
$0.51
$0.55
$0.62
$0.49
$0.52
$0.62
2020
2025
2030
2035
2040
Year

Figure 10: Comparisons of cost various types of battery-electric and fuel cell vehicles in 2030 and 2040

2030



2040



6. Discussion of the Economic results

The primary issues are when in 2020-2040 will the costs of the battery-electric and fuel cell vehicles approach the cost of comparable conventional ICE vehicles of the various types and what are the differences in the relative costs of the battery-electric and fuel cell vehicles of each vehicle type.   The effects of energy costs (electricity and hydrogen) on the economic attractiveness of the electrified vehicles will also be discussed. All the results shown in Figures 6-10 are for the low cost estimates for batteries and fuel cells (see Tables 2 and 7) and for electricity costing $.2/kWh and low cost hydrogen (see Table 9). Cost results for additional inputs are given Table 16.

Figures 5 show the initial costs and TCO of the battery-electric mid-size passenger car and mid-size SUV for 2020-2040. For both vehicle types, the cost of the electric vehicle approaches that of the ICE vehicle by 2030 and the TCO is close to or less than that of the ICE vehicle. In the case of the fuel cell vehicles (see Figure 7), it takes until 2035 for the cost of the fuel cell vehicles to be equal to or less than that of the ICE vehicles. The TCO of the fuel cell vehicles is close to that of the ICE vehicles by 2030. It seems clear that the maturing of the fuel cell technology is about 5 years behind that of the battery-electric technology. Figure 8 shows the costs and TCO for all the vehicle types for 2030. All the battery-electric vehicles have an economic advantage relative to the corresponding fuel cell vehicle. Much of the TCO advantage of the battery-electric vehicles is due to the lower cost of the energy (electricity) to operate the vehicle compared to the fuel cell vehicle (hydrogen). In 2030, the cost ($/kWh) of electricity for the energy cost ($/mi) for battery-electric and ICE gasoline vehicles to be equal (parity) is about $.50/kWh if gasoline is $4/gal.   For fuel cell vehicles, parity in energy costs with gasoline vehicles requires a hydrogen cost of about $8/kg.   Clearly, the price of electricity is much below the parity cost of electricity, but getting the dispensed price of hydrogen much below $8/kg by 2030 could be difficult. The effect on vehicle energy cost ($/mi) of the electricity and hydrogen costs are shown in Table 16. As expected, the differences on the vehicle energy cost ($/mi) are significant.

Figures 9 and 10 compare the costs of battery-electric and fuel cell vehicles directly with those of the corresponding gasoline ICE vehicles. In all the years, the economics of battery-electric passenger cars and SUVs look more attractive than for fuel cell vehicles.   Even in 2040, the battery-electric has a small advantage. However, it appears that in 2040 and beyond, the choice of a vehicle buyer between a battery and fuel cell vehicle will depend on the refueling infrastructure available to that buyer.

7. Summary and conclusions

In this report, the initial cost and TCO of light-duty battery-electric and hydrogen fuel cell vehicles are calculated for 2020-2040. In addition, the infrastructure needed to support those electrified vehicles was projected and its cost estimated. The results of the vehicle cost analyses indicated that by 2030 both the initial cost and TCO of battery-electric vehicles were equal to or less than that of corresponding gasoline vehicles. This was true for all the light-duty vehicle types considered from compact passenger cars to large SUVs.   In the case of the hydrogen fuel cell vehicles, the results of the vehicle cost analyses indicated that by 2035 the initial vehicle costs were close to that of the corresponding gasoline vehicles and their TCO were lower for all the light-duty vehicle types. These comparisons are made for the low battery and fuel cell costs and ranges of 300 miles and 400 miles for the battery-electric and fuel cell vehicles, respectively.   Comparisons made for the higher base battery and fuel cell costs show a delay of about 5 years in which the electrified vehicles would compare favorably with the corresponding gasoline fueled vehicles. Decreasing the range of the electrified vehicles would result in favorable economics for them at slightly earlier years. In general, the results of this cost analysis indicates that if suitable infrastructure is established by 2030, relatively large sales of both battery- electric and fuel cell light-duty vehicles can be expected.

An analysis of the infrastructure and its cost was also made as part of this study for both fast charging of the battery-electric vehicles and hydrogen refueling of the fuel cell vehicles. It was assumed that the batteries in the vehicles could be fast charged in 10 minutes, which requires charging at the 4.4 C rate with 350 kW chargers. Hydrogen refueling was done in 2.3 minutes at the rate 1.5 kgH2 /min. At the present time, there is considerable uncertainty in the cost of high power chargers and their installation and hydrogen refueling stations of specific capacity (kgH2/day). In the present analyses, it was assumed the chargers cost $700-1000/kW and H2 refueling stations cost $1500-2500/kgH2/day. These costs are for future infrastructure. It is expected that the utilization factor will be .4-.6 for large fleets (> 1 million) of electrified vehicles. In those cases, the cost of both the battery-electric and hydrogen fuel cell infrastructure is projected to be $1.5-2 billion for a 1.8 million vehicle fleet. The costs of the public fast charger infrastructure for battery-electric vehicles and for the H2 refueling stations for fuel cell vehicles are about equal, but the cost of the infrastructure for the battery-electric vehicles are higher when the cost of home and work charging are included. The effect of LCFS credits on the energy costs for both battery-electric and hydrogen fuel cell vehicles will be significant and should be included in the economic analyses. The LCFS station credits are important in determining the business case for both fast charging battery-electric vehicles and hydrogen refueling of fuel cell vehicles.

References

1. Burke, A.F., Zhao, H., and Miller, M., Comparing fuel economy and costs of advanced vs. conventional vehicles (Chap.4), UC Davis book, Sustainable Transportation Pathways (edited by . Ogden and L. Anderson), 2011
2. Anderman, M., Battery Industry review, 2016
3. Curry, C., Lithium Battery Costs and Markets, Bloomberg New Energy Finance presentation, July 5, 2017
4. Battery Pack Prices cited Below $100/kWh in 2020, while Market Average Sits at $137/kWh, Bloomberg NEF, Dec 20, 2020
5. Burak Ozpineci and Greg Smith, Electric Drive Technologies Roadmap, Oakridge Laboratory presentation, 2017
6. Lutsey, N and Nicholas, M., Update on electric vehicle costs in the United States through 2030, Working Paper 2019-6, ICCT, April 2, 2019 (internet)
7. James, .D and etals, Final Report: Mass Production Cost of Direct H_2 PEM Fuel Cell Systems for Transportation Applications (2012-2016), September 2016m
8. Thompson, S.T., James, B.D., Huya-Kouadio, etal, Direct Hydrogen fuel cell electric vehicle cost analysis: System and high-volume manufacturing description, validation, and outlook, Journal of Power Sources, July 2018 (internet)
9. Whiston, M.M., Azevedo, I.L., Litster, S., etal, Expert assessments of the cost and expected future performance of proton exchange membrane fuel cells for vehicles, PNAS, vol. 116,no. 11,4899-4904, March 12, 2019
10. Path to Hydrogen Competitiveness- A Cost Perspective, Hydrogen Council/McKinsey, January 20, 2020
11. DOE H2 cost targets
12. Sinha, A.K., Electrolytic H_2 Production and Refueling Cost Modeling, Presentation, May 2020
13. IEA H2 estimates
14. Deloitte and Ballard, Fueling the future of mobility-Hydrogen and fuel cell sources for transportation role, 2018
15. Hart, C., Electric Vehicle Ownership Costs: Chapter 2 – Maintenance, Consumer Reports, September 2020
16. Koleva, M. and Melina, M., Hydrogen Fueling Station Costs, DOE Hydrogen Program Record 21002, 11/2/2021
17. Hydrogen Refueling Station Analysis Model (HRSAM), Argonne National Laboratory
18. 2020 Annual Evaluation of Fuel Cell Electric Vehicle Deployment, CARB, September 2020

19. Hydrogen Station Network Self-Sufficiency Analysis per Assembly Bill 8, November 2020
20. Hydrogen Refueling Infrastructure (HRI) and DC fast charging infrastructure (FCI) pathway, CARB
21. Unofficial electronic version of the low carbon fuel standard regulation, CARB, January 4, 2019
22. Application Instructions for Direct Current charging Infrastructure (FCI) Pathway, CARB, August 21, 2019
23. Berger, J.M. and Barrow, D., Financing California hydrogen projects using LCFS credits, December 8, 2020, available on internet
24. Blackley, J., Cars with the most average miles driven per year, 6/27/21, available on internet
25. Wikner, E., Lithium battery aging: Battery life-time testing and physics-based modeling for electric vehicle applications, Power Engineering Thesis, Chalmers University of Technology, Sweden, 2017
26. E.S. Islam, R. Vijayagopal, A. Moawad, et.al., A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050, ANL/ESD-21/10, October 1, 2021