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THE RELATIVE MERITS OF BATTERY-ELECTRIC VEHICLES AND FUEL-CELL VEHICLES

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This report discusses the major advantages and disadvantages associated with battery-electric vehicles (BEVs) and fuel-cell vehicles (FCVs). As a reference for comparison, information for current gasoline-powered internal combustion engines is also presented. In addition to reviewing the technical literature, interviews were conducted with experts in the automotive and energy sectors regarding their views concerning these issues. The main findings are highlighted below.
BEVs currently offer the most readily available fuel source via the existing electric grid. Additionally, more BEV models are available to the public (relative to fuel-cell vehicles) and they offer the best fuel economy, resulting in the lowest cost to operate (per mile). BEVs also tend to produce the lowest amount of greenhouse gases (well-to-wheels) per mile. However, the driving ranges of these vehicles are currently the lowest of any vehicle type, while also requiring the longest time to refuel or recharge.
FCVs have significantly longer driving ranges and lower refueling times than comparable BEVs, and it is also possible for them to use the least amount of petroleum (well-to-wheels) per mile, depending on the type of hydrogen used. On the other hand, only a small number of vehicle models are available, and only in the most recent model years. Similarly, the hydrogen-refueling infrastructure is practically nonexistent outside of California. There is a general consensus among the experts that expansion of the hydrogen infrastructure needs to precede the mass introduction of FCVs in order to raise consumer confidence in the availability of hydrogen fuel.
Both alternative fuels and vehicle types require additional training for emergency responders and mechanics, but also generally require lower overall maintenance than a traditional gasoline-powered vehicle.
Additionally, hypothetical trips of varying lengths are modeled and described for each vehicle type in terms of the required number of refueling stops, and combined driving and refueling time.</td></tr>
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Abbreviations used in this report

Abbreviation	Definition
AC	alternating current
BEV	battery-electric vehicle
Btu	British thermal units
CO_2	carbon dioxide
DC	direct current
FCV	fuel-cell vehicle
g	gram
gal	gallon
GGE	gasoline gallon equivalent
GHG	greenhouse gas
hr	hour
ICE	internal combustion engine
J	joule
kg	kilogram
km	kilometer
kWh	kilowatt-hour
L	liter
lb	pound
mi	mile
min	minute
MJ	megajoule (million joules)
mpg	miles per gallon
mpge	miles per gallon equivalent
MY	model year
psi	pounds per square inch
V	volt
Wh	watt-hour
ZEV	zero-emission vehicle

Contents

Introduction

As automobile manufacturers face increasingly stringent requirements to achieve significant fuel economy performance gains and lower CO_2 and other greenhouse gas (GHG) emissions in the coming model years, vehicles that require little to no fossil fuel consumption to operate have begun to proliferate. However, questions remain regarding the best alternative fuel source (or sources) to potentially replace or supplement traditional fossil fuels. No alternative fuel sources have the energy density, ease of use, and ease of transport as current liquid fossil (i.e., hydrocarbon) fuels. A U.S. Department of Energy presentation stated the problem succinctly in 2002: "Presently we know of no energy source which can substitute for liquid hydrocarbon fuels" (Eberhardt, 2002). However, Eberhardt also indicated that two existing non-fossil fuels have the best potential to replace traditional liquid hydrocarbon fuels: electricity and hydrogen. Both alternative fuel types have the potential to power vehicles while producing zero GHG emissions at the vehicle (and also potentially producing no GHGs during fuel production when using renewable energy sources).

Specifically, battery-electric vehicles and hydrogen fuel-cell vehicles have been developed as so-called zero-emission vehicles (ZEV) to help reduce overall fossil fuel consumption and GHG emissions occurring at the vehicle. (ZEV only applies to tailpipe emissions when operating the vehicle and does not consider up-stream emissions occurring prior to vehicle operation, such as in the vehicle manufacturing process or in the process of producing the specific fuel required.)

Battery-electric vehicles (BEV; sometimes called plug-in electric or simply EV) operate entirely on electricity stored in on-board battery systems that are charged from the main electrical grid, usually via a special high-voltage charging station and using special electrical connectors. Hydrogen fuel-cell vehicles (FCV; also called hydrogen fuel-cell electric vehicles [FCEV]) operate on electricity generated in a fuel cell within the vehicle. The fuel cell combines (via chemical reaction) oxygen from the atmosphere with compressed hydrogen fuel stored on the vehicle to produce electricity, as well as some heat and a small amount of water. Both vehicle types ultimately use electricity to power electric motors for propulsion.

This report will discuss the major advantages and disadvantages associated with each vehicle type and fuel type. As a reference for comparison, information for current gasoline-powered internal combustion engine (ICE) vehicles and gasoline fuel will also be presented. In addition to reviewing the technical merits, we also conducted confidential interviews with BEV and FCV experts in the automotive and energy sectors regarding their views on each vehicle type and fuel type.

Refueling infrastructure

Key aspects of this section and the following section on vehicles are summarized at the end of this report in Tables 4 and 5.

Current and future availability

Substantial differences exist regarding the extent of refueling infrastructure for electricity for BEV and hydrogen for FCV, both relative to each other and relative to the current gasoline-refueling infrastructure. For comparison, there are approximately 114 thousand individual gasoline stations covering all 50 states and the District of Columbia (U.S. Census Bureau, 2012). The cost of installing a gasoline station is typically in the range of $1 million to $2 million (NPC, 2012).

With the ability to tap into the existing electrical grid, the electricity required for BEV charging is readily available. However, for the more advanced Level 2 charging[1] that is the current standard, installation of special charging equipment is required. Approximately 14 thousand stations (individual charging sites) offering 34 thousand charging outlets (individual charging plugs) will be available across the U.S. in the coming year (including all public and private charging stations, both existing and planned[2]) (AFDC, 2015a). Expansion of the BEV charging network is relatively inexpensive, costing approximately $1000 for home-based charger installation, and ranging from approximately $10,000 to $100,000 for public stations (Plug In America, 2015a).

The infrastructure for hydrogen distribution required for fueling FCVs is in the very early stages of development and is generally nonexistent in most of the U.S. Specifically, a total of 14 public stations currently exist in only 4 states (11 in CA, and 1 each in CT, MA, and SC), expanding to 35 stations in 14 states when private stations are included, with a grand total of 90 stations in 14 states and the District of Columbia when all currently planned[2] stations are included (AFDC, 2015a). Hydrogen refueling stations have a relatively high cost for construction and installation, costing approximately $3 million to $5 million for a public station (Melaina and Penev, 2013).

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[1] For detailed descriptions of each level and type of charging, see Plug In America (2015b) and SAE (2011).
[2] "Planned" stations include those scheduled to open within the next year.

Fuel pricing and effective cost per mile

Fuel pricing poses a significant challenge for customer acceptance and understanding when comparing the different fuel types. Units of sale are not standardized across these different fuel types (gallons versus kWh versus kilograms), and the conversion factors to the gasoline-gallon equivalent (GGE: the amount of one fuel required to equal the energy in one gallon of gasoline) are generally not easily understood by most consumers. A basic understanding of these factors and the corresponding vehicle fuel economy is necessary to effectively assess the cost per mile to operate a vehicle when making a purchasing decision.

For BEVs, the GGE conversion factor is 33.7 kWh to equal 1 gallon of gasoline, with a national average fuel price of $0.12/kWh (AFDC, 2014; 2015b). The average fuel economy for MY2016 BEVs is 105.2 mpge (EPA, 2015a), resulting in an effective cost per mile of $0.04. For FCVs, the GGE conversion factor is approximately 1 kg, with a national median fuel price of $5.00/kg (AFDC, 2014; AltFuelPrices.com, 2015). The average fuel economy for MY2016 FCVs is 58.5 mpge (EPA, 2015a), resulting in an effective cost per mile of $0.09. For current gasoline-powered ICE vehicles, an average fuel economy of 23.3 mpg (EPA, 2015a), coupled with a fuel price of $2.35 per gallon (AFDC, 2015b), results in a cost of $0.10 per mile.

Fuel production and renewable power sources

Both of the alternative fuel types rely upon municipal electrical grids to supply power. In the case of BEVs, the useful application of this power consists of several basic steps including transmission of the electricity, conversion within a charger, and ultimately storage of the electricity in the vehicle's battery pack. For FCVs, the process is more complex. The two main sources of hydrogen production use electricity from the municipal electrical grid to power either 1) a chemical process involving fossil fuels (steam reformation), or 2) a process involving electricity to split water into hydrogen and oxygen (electrolysis). Though other hydrogen production methods exist, these are the two dominant processes in the U.S. (DOE, 2015c).

Refueling safety

While both alternative fuel types are not without risk, BEV refueling currently consists of merely plugging the vehicle in to a charger (or wall plug with adapter), posing minimal risk. Hydrogen refueling involves a process very similar to refueling a current gasoline-powered vehicle. A pump with a connector is attached to the vehicle, and the pumping system handles the transfer of fuel into the vehicle. Still, some additional risk does exist due to the pressure the compressed gas is stored under (3,600 to 10,000 psi) and, in the case of liquid hydrogen (as opposed to gaseous hydrogen), the extreme cold temperature of the fuel (-250° C or colder) (DOE, 2015d). However, an analysis published by NHTSA concluded that such vehicles are no more or less dangerous than current gasoline-powered vehicles (Flamberg, Rose, and Stephens, 2010).

The main reason for requiring such high pressures when storing hydrogen onboard a vehicle is the need to supply a similar amount of energy (in joules [J]) as would be found in a traditional tank of gasoline to enable similar driving distances on a single tank of fuel. While hydrogen contains more energy per unit of mass (i.e., gravimetric density), having 120 MJ/kg versus 44 MJ/kg for gasoline, the volumetric energy density is significantly lower, containing just 8 MJ/L for liquid hydrogen versus 32 MJ/L for liquid gasoline; the volumetric density is even lower for gaseous hydrogen, with energy density decreasing as fuel-system pressure decreases (DOE, 2015d). (Gravimetric energy density is the same for liquid or gaseous hydrogen.)

Carbon capture and storage potential

The concept of capturing and storing carbon (CO_2) produced when operating vehicles has been discussed as a potential means for reducing the overall carbon footprint of vehicles with internal combustion engines (Sullivan and Sivak, 2012; Schoettle and Sivak, 2014). However, significant challenges exist regarding the ability to effectively capture and store carbon on a compact, mobile platform such as a light-duty vehicle. With either of the alternative fuel sources discussed here, the potential to shift this carbon capture to centralized production facilities (whether for electricity generation or hydrogen production) is more readily achievable and offers efficiencies on an industrial-scale that are not possible on individual vehicles. For example, up to 90% of CO_2 produced during electricity generation and other large-scale industrial processes can be captured and stored (CCSA, 2016). Furthermore, such a centralized model also facilitates sequestration/storage, rather than requiring the offloading of carbon from millions of vehicles distributed throughout the country (and requiring the offloading facilities to exist at each refueling station).

Vehicles

Vehicle availability

BEVs have been available in the U.S. beginning in 2008, with the majority of models being introduced within the past 5 years. For model year 2016, 13 unique models of BEV are offered for sale by 10 different automobile manufacturers (EPA, 2015a). Table 1 shows the recent history of BEV availability by manufacturer and model year. In total, 18 automobile manufacturers have offered 72 models (by company and model year) of BEVs for sale in the U.S. since model year 2008.

FCVs lack the production and sales history of BEVs, having only very recently been introduced for sale to the general public in the U.S. Currently, two FCV models are offered by two automobile manufacturers for model year 2016. Of the two companies currently offering FCVs, one had previously offered BEVs but discontinued them in model year 2016 (Toyota), while the other never previously offered either vehicle type (Hyundai). Several other automobile manufacturers are developing FCVs planned for introduction in future model years (Ars Technica, 2016; DriveClean, 2015). Furthermore, numerous manufacturers are cooperating on the development and manufacturing of fuel cells (Cheat Sheet, 2016; Green Car Reports, 2016; Nissan, 2013). Table 2 shows the recent history of FCV availability by manufacturer and model year. In total, 4 automobile manufacturers have offered 7 models (by company and model year) of FCVs for sale in the U.S. since model year 2010.

Table 1
Number of individual models of battery-electric vehicles (BEV) available in the U.S., by company and model year (EPA, 2015a).

Company	Model year									*Total*
	2008	2009	2010	2011	2012	2013	2014	2015	2016	
Azure Dynamics					2					*2*
BMW				1			1	1		*3*
BYD					1	1	1	1		*4*
Chevrolet							1	1	1	*3*
Coda Automotive					1	1				*2*
Fiat						1	1	1	1	*4*
Ford					1	1	1	1	1	*5*
Honda						1	1			*2*
Kia								1	1	*2*
Mercedes-Benz							1	1	1	*3*
Mini	1									*1*
Mitsubishi					1	1	1		1	*4*
Nissan				1	1	1	1	1	2	*7*
Scion						1				*1*
Smart				2		2	2	2	2	*10*
Tesla					1	3	3	6	2	*15*
Toyota					1	1	1			*3*
Volkswagen									1	*1*
Total	*1*	*0*	*0*	*4*	*9*	*14*	*15*	*16*	*13*	***72***

Table 2
Number of individual models of fuel-cell vehicles (FCV) available in the U.S., by company and model year (EPA, 2015a).

Company	Model year							*Total*
	2010	2011	2012	2013	2014	2015	2016	
Honda	1				1			*2*
Hyundai						1	1	*2*
Mercedes-Benz		1	1					*2*
Toyota							1	*1*
Total	*1*	*1*	*1*		*1*	*1*	*2*	*7*

Vehicle fuel economy

The average fuel economies of both BEVs and FCVs are significantly better than their traditional ICE counterparts. Compared to the average fuel economy of 23.3 mpg for current ICE vehicles[3], the fuel economy of FCVs is 58.5 mpge (miles-per-gallon equivalent) and 105.2 mpge for BEVs (2.5 times higher and 4.5 times higher, respectively). Furthermore, the ranges of fuel economies for each vehicle type do not generally overlap, with ICE vehicles ranging from 12 to 50 mpg, FCVs from 50 to 67 mpge, and BEVs from 84 to 119 mpge. A comparison of the ranges of fuel economy values across vehicle types is shown in Figure 1.

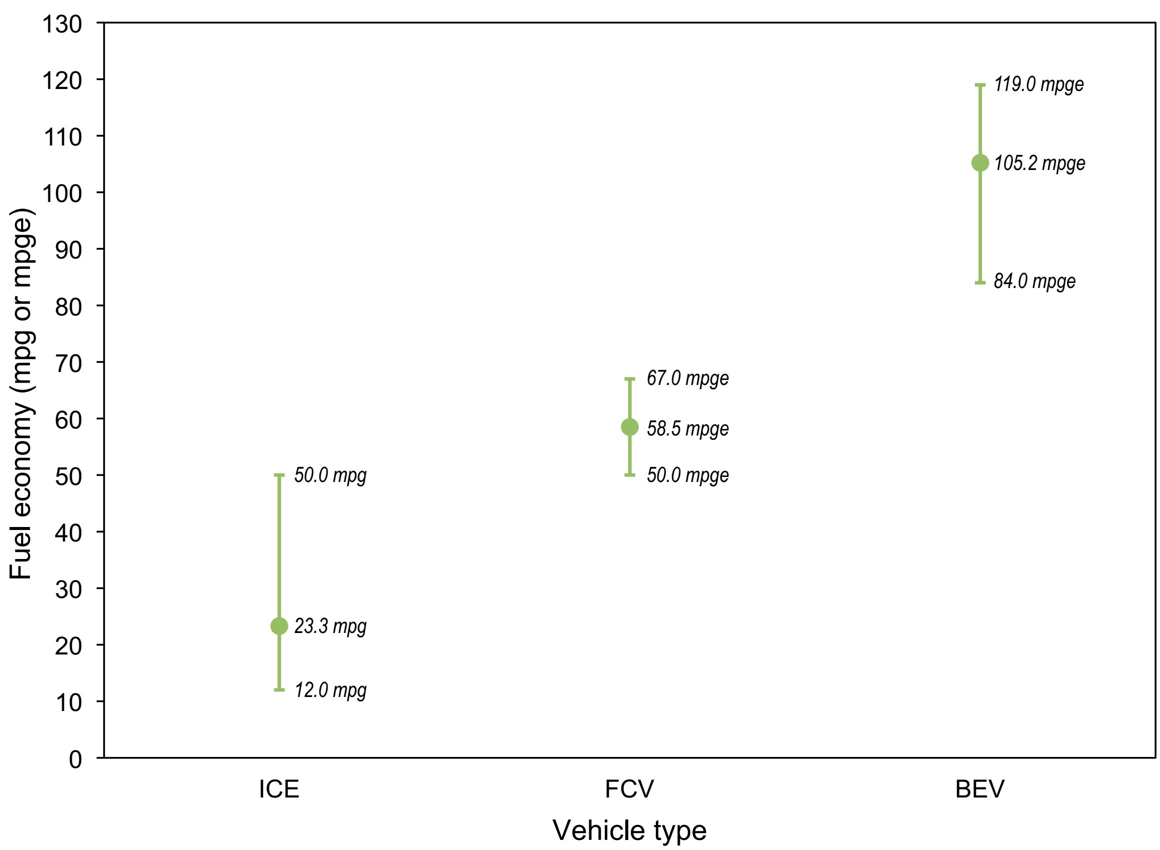

Figure 1. A comparison of the range of fuel economy values (combined city/highway window-sticker value [EPA, 2015a]) for each vehicle type. The dots mark the average fuel economy value for each vehicle type, while the ranges represent the minimum and maximum fuel economy values.

[3] Average (non-sales-weighted) combined city/highway window sticker values for model year 2016 (EPA, 2015a).

Well-to-wheels GHG emissions and petroleum usage

The following well-to-wheels calculations use the GREET model (2015 release) for model year 2015 passenger cars to calculate greenhouse gas (GHG) emissions and petroleum usage during vehicle operation (ANL, 2015). (Results do not include GHG emissions or petroleum usage during the vehicle manufacturing process.)

Based on the average mix of renewable and non-renewable electric power sources in the U.S., the average well-to-wheels GHG emissions for BEVs is the lowest, at 214 g/mi. Depending on whether gaseous or liquid hydrogen is used, the corresponding values for FCVs range from 260 to 364 g/mi, respectively. Gasoline-powered vehicles produce the most GHGs per mile, ranging from 356 to 409 g/mi, depending on the specific type of ICE (direct versus traditional fuel injection, respectively).

Somewhat different patterns emerge when total well-to-wheels petroleum usage is compared (in British thermal units [Btu]). For example, gaseous hydrogen-powered FCVs use the least amount of petroleum at 27 Btu/mi, with BEVs ranking the second lowest in usage at 54 Btu/mi, and liquid hydrogen-powered FCVs using the third lowest amount at 67 Btu/mi. Predictably, gasoline-powered vehicles use considerably more petroleum per mile, with direct fuel injection ICEs averaging 3791 Btu/mi and traditional fuel injection ICEs 4359 Btu/mi.

Thus, while petroleum usage (per mile) is generally lower for gaseous hydrogen-powered FCVs, GHGs emitted are lowest for BEVs (based on the average mix of renewable and non-renewable electric power sources in the U.S.). Furthermore, due to the additional energy required to compress, store, and transport liquid hydrogen (DOE, 2015d), FCVs may actually emit more GHGs per mile than a comparable direct-injection ICE vehicle (364 g/mi versus 356 g/mi, respectively). A comparison of well-to-wheels GHG emissions and petroleum usage for each vehicle type is shown in Figure 2.

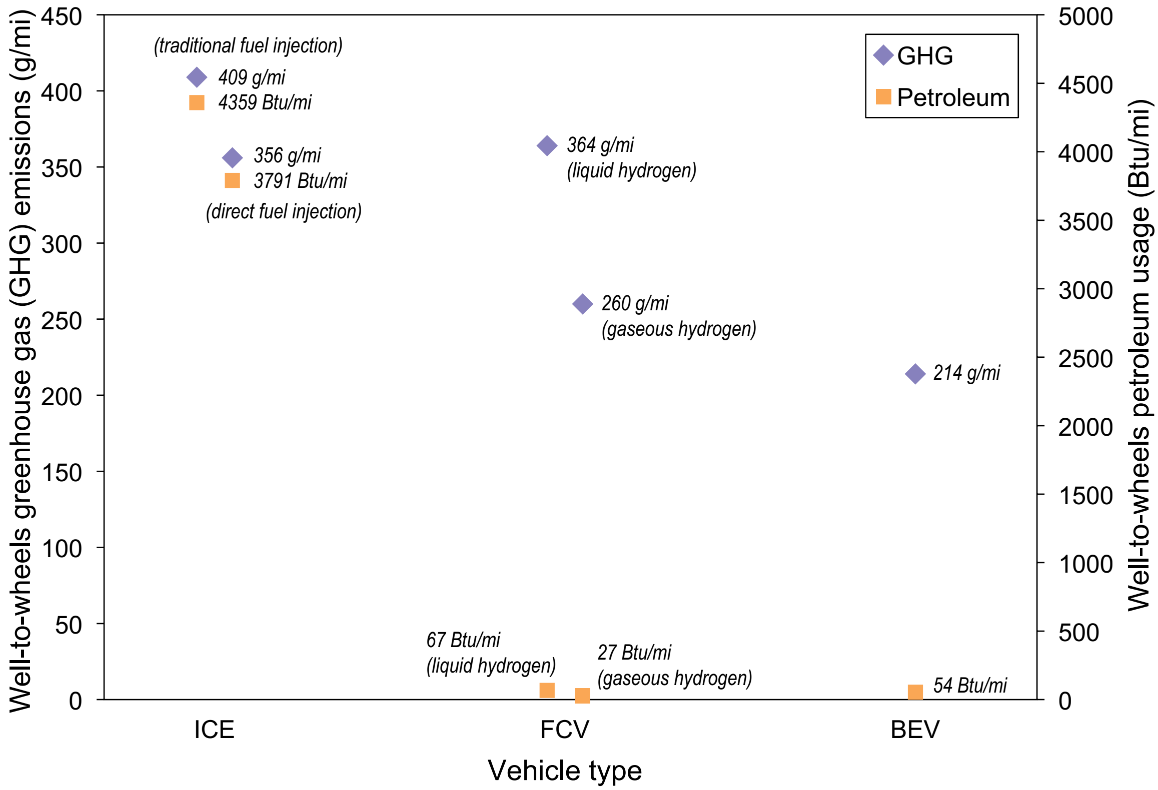

Figure 2. A comparison of well-to-wheels greenhouse gas (GHG) emissions and petroleum usage for each vehicle type (GREET model [ANL, 2015]).

Driving range and time required to refuel

Significant differences in driving range on either a full tank or full battery charge exist between the vehicle types. The average driving range of BEVs is less than half that of FCVs (110 miles versus 289 miles, respectively) (EPA, 2015a). However, the average range of current gasoline-powered ICE vehicles (418 miles) is 1.4 times that of FCVs, and 3.8 times the range of BEVs (EPA, 2015a).

Ranges described above are currently inversely related to average refueling times for each vehicle type. The current average ICE vehicle has the greatest driving range and also the shortest refueling time (about 5 minutes). Refueling time for FCVs, having the second longest driving range, can span from 5 to 30 minutes, depending on the pressure of the refueling system in use. Finally, BEVs have not only the shortest average range, but also require the longest refueling times, ranging from 3.5 to 12 hours using AC Level 2 charging (but can be reduced to 20 to 30 minutes at 80% of a full charge with DC

Level 2 "fast charging") (EPA, 2015a). (DC Level 3 fast charging is currently being developed, with the goal of 80% charge in about 10 minutes [SAE, 2011].)

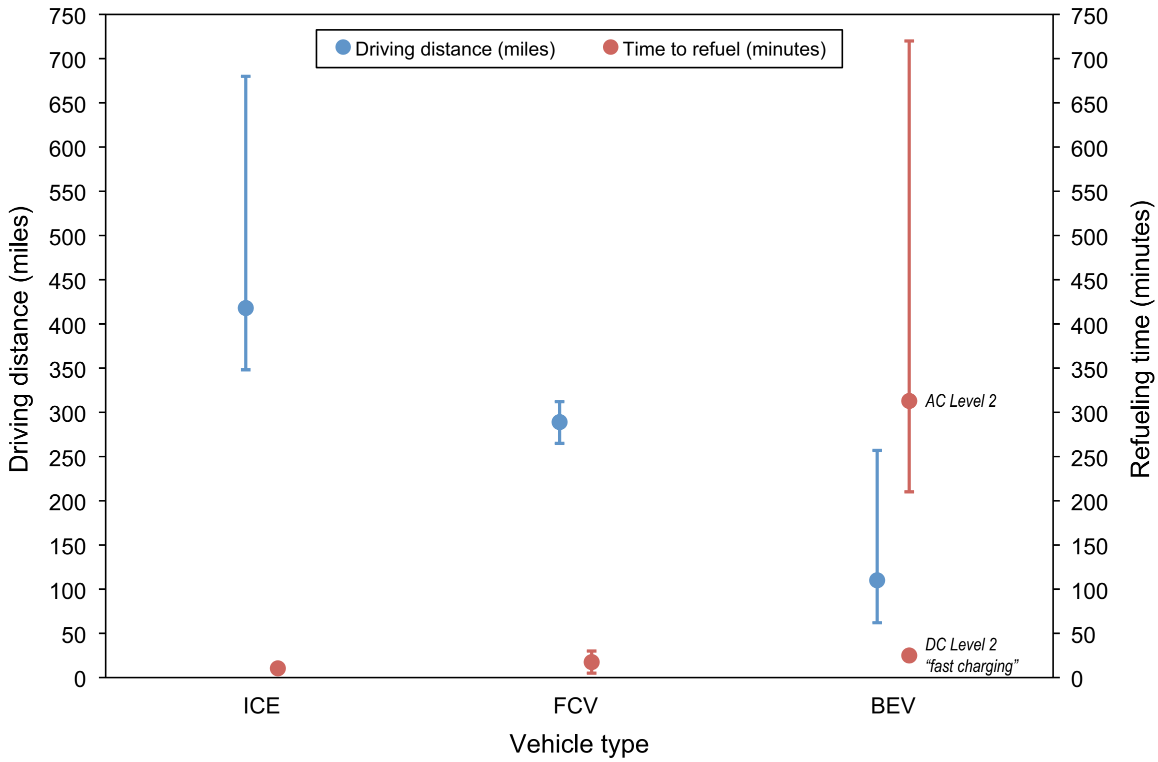

Figure 3. A comparison of driving distances (miles) on a full fuel tank or battery charge versus time required to refuel (minutes) from empty to full for each vehicle type. The dots mark the average driving distance or refueling time for each vehicle type, while the ranges represent the minimum and maximum distances or times. (For BEV, DC Level 2 "fast charging" is shown for comparison, although fast charging may not completely replenish the battery, instead providing 50 to 80 miles of range on a 20- to 30-minute charge—approximately 80% of a full charge depending on the specific vehicle.)

Fuel portability

The ease with which the three fuel types discussed in this report may be transported varies considerably. A key difference, as discussed above, relates to the basic properties of the fuels and/or their corresponding storage media. For convenient portability of energy-dense fuels, neither alternative fuel is comparable to gasoline.

For example, the volumetric energy density (in joules [J]) of hydrogen is significantly lower than gasoline, containing 8 MJ/L for liquid hydrogen (the volumetric density is even lower for gaseous hydrogen) versus 32 MJ/L for liquid gasoline (DOE, 2015d). This situation requires 4 times the volume to transport a similar amount of energy relative to gasoline. Additionally, to achieve this energy density, the liquid hydrogen must be stored under extremely high pressure and cold temperature.

The situation for BEV energy density is even worse, with current automotive lithium-ion battery packs containing approximately 1 MJ/L (270 Wh/L) (Thomas, 2009), or 1/32 the volumetric energy density of a similar volume of liquid gasoline. Furthermore, battery packs suffer a considerable weight disadvantage versus gasoline and hydrogen (Thomas, 2009). Current, relatively heavy batteries contain energy per mass (i.e., gravimetric density) of approximately 0.5 MJ/kg (150 Wh/kg) (Thomas, 2009), compared with 44 MJ/kg for gasoline and 120 MJ/kg for hydrogen (gravimetric density is the same for liquid and gaseous hydrogen) (DOE, 2015d), or 88 times less energy density by mass than gasoline.

For comparison, liquid gasoline may be carried in nearly any vessel capable of containing liquid (though some jurisdictions require gasoline to be dispensed into approved containers), at normal atmospheric pressure, throughout the range of normal ambient temperatures, with no special equipment required to safely dispense the fuel into a vehicle.

Special maintenance and service for vehicles

Since both BEVs and FCVs utilize drivetrains with electric motors to propel the vehicle, regular maintenance is different than for current gasoline-powered ICEs, and generally less maintenance is required. Furthermore, the need for petroleum-based lubricants is significantly reduced with either vehicle type. (However, some BEVs do employ fluid-based cooling systems for thermal management of the battery pack.)

With such relatively new and advanced technology in BEVs and FCVs, the ability to obtain service is generally limited to brand-specific dealerships or dealer-authorized repair shops. (This is especially true for any newer vehicle requiring warranty-based repairs, regardless of the technology involved.)

Special safety considerations

Two significant differences between these two vehicle types and current ICEs are 1) the presence of high-voltage electrical systems and batteries, and 2) for FCVs, high-pressure fuel tanks for storing compressed hydrogen. These systems require special training and procedures for emergency personnel responding to a crash involving such vehicles (Hydrogen Tools, 2015; NFPA, 2015). Furthermore, these vehicles include safety measures to automatically disconnect the high-voltage systems when the vehicle senses that a significant crash has occurred (such as a crash with air-bag deployment).

Though generally safer under normal conditions relative to gasoline, the electricity and battery packs used in BEVs are not without risk. The charging stations for Level 2 charging operate at 240 V and with high current (30 or more amps), creating an electrocution risk similar to large household appliances. And while the potential for explosion or fire is significantly lower when the fuel system (battery pack) is punctured or otherwise damaged, both of these scenarios are still a possibility (Automotive News, 2012; New York Times, 2013).

While both gasoline and hydrogen are flammable and potentially explosive, the risks involved do not appear to be greater with one or the other fuel type. However, the nature of hydrogen means that familiarity with its flammability characteristics is required, for both vehicle operators as well as emergency responders. For example, gasoline presents a risk of flowing from punctured tanks and potentially soaking the vehicle, persons, and the environment in flammable liquid (while naturally flowing down into the lowest physical location, such as sewer systems). Unburned gasoline from large spills requires specialized hazardous material cleanup procedures. With hydrogen, the highly compressed gas would disperse from a punctured pressurized-tank at a high rate, diffusing upward into the atmosphere (it is the lightest element on the periodic table). Hydrogen used in fuel cells is odorless, making leak detection more difficult than with gasoline leaks (Hydrogen Tools, 2015). Similar to gasoline, enclosed areas where vapors or gases may be trapped and accumulate pose flammability and explosion risks.

Extreme operating conditions

More so than with ICE vehicles, both BEVs and FCVs tend to experience performance losses under extreme temperature conditions (ambient conditions that are either very cold or, to a lesser extent, very hot) (FleetCarma, 2013). Extreme temperatures can affect battery performance including the ability to hold a charge, in addition to putting extra electrical load on the system to heat or cool the passenger compartment. (In ICE vehicles, heat that would otherwise be wasted is recycled from the engine to warm passengers, thus suffering lower overall performance losses in cold weather. Furthermore, the performance degradation experienced by ICE vehicles at extreme temperatures tends to occur for similar reasons as with BEVs and FCVs, such as reduced battery performance. Poor performance of system components such a lubricants or the cooling system can also lead to reduced efficiency for ICE vehicles.) Additionally, fuel-cell performance can be challenging at below-freezing temperatures if residual water in the system freezes, and fuel cells must reach an optimal operating temperature to function at full efficiency (EPA, 2015b).

Similar to traditional ICE vehicles, BEVs and FCVs tend to exhibit reduced performance when climbing roadways with steep grades. For all vehicle types, the requirement for additional power, whether from gasoline or electricity, adds additional load (to maintain vehicle speed) to engines or electric motors and reduces overall efficiency.

Public opinion regarding battery-electric and fuel-cell vehicles

Public opinion about both vehicle types is generally positive, and individuals have expressed an interest in both technologies over traditional ICE vehicles as gasoline prices climb (Schoettle and Sivak, 2015). However, general knowledge regarding the workings of either BEVs or FCVs is low, with only 39% of individuals having passable knowledge of BEV technology and 26% having a passable level of knowledge about FCV technology (Krulikowski, 2015).

Government support

Support from the U.S. government for both alternative fuel types and vehicle types is relatively strong. In 2014, funding support for battery research and development was approximately $85 million (DOE, 2015a). Several goals of this research for plug-in hybrid and fully-electric vehicle batteries include: "(1) significantly reducing battery cost, (2) increasing battery performance (power, energy, durability), (3) reducing battery weight & volume, and (4) increasing battery tolerance to abusive conditions such as short circuit, overcharge, and crush" (DOE, 2015a). More specific goals include reducing battery cost by a factor of 4, and reducing size and weight, both by a factor of at least 2.

Similarly, the U.S. government provided approximately $95 million in funding for fuel-cell research in 2014 (DOE, 2015b). The primary goals of government-funded fuel-cell R&D are reductions in cost, size, and weight of fuel-cell systems, increased system durability, safety research and training, and hydrogen infrastructure and production research.

Industry views

Several items of general consensus were evident in discussions with representatives from automotive and energy companies. The industry generally agrees on the following:

- The main advantages of BEVs relative FCVs are that they use a more established technology, with both vehicles and batteries moving into greater mass production in recent years; they also have a well-established electricity distribution network (i.e., the public electrical grid) that can be tapped with relative ease and for relatively low cost. The high fuel economy for these vehicles, coupled with a relatively low-cost fuel with stable pricing, results in a vehicle that is very inexpensive to fuel.
- The main drawbacks for BEVs are currently limited range and relatively long recharge times. Apprehension by potential BEV drivers regarding the combination of these two factors has been termed "range anxiety." The effects on battery packs in hot and cold weather, and the need to cool or heat the passenger cabin under such conditions, further limit the range of BEVs. Additionally, the overall vehicle cost is still significantly higher than current ICE vehicles.
- The main advantages of FCVs are that they are more adaptable and better suited for cross-platform usage, and they have a longer driving range with faster refueling times (relative to BEVs).
- The main drawbacks for FCVs relate to the current general lack of refueling infrastructure and, the potential to be no cleaner than comparable ICE vehicles (depending on how hydrogen is generated, and whether it is gaseous or liquid). Where available, there is currently a wide range of fuel prices.
- Expansion of the hydrogen infrastructure most likely needs to precede the mass introduction of FCVs in order to raise consumer confidence in the availability of hydrogen fuel.

Hypothetical trip scenarios

Several hypothetical trip scenarios are described below, illustrating the effects of the underlying driving ranges and refueling times on the number of required refueling stops and total trip time for each vehicle type. Also included in Table 3 are calculations of fuel costs, and well-to-wheels GHG emissions and petroleum usage by vehicle type.

In Table 3, four trip lengths that individuals might reasonably consider driving (versus flying) are summarized. The lengths examined (and approximate example trips in parentheses) are as follows:

- 1000 miles [1609 km] (e.g., Detroit, MI to New Orleans, LA)
- 500 miles [805 km] (e.g., Ann Arbor, MI to Washington, D.C.)
- 250 miles [402 km] (e.g., Ann Arbor, MI to Chicago, IL)
- 100 miles [161 km] (e.g., Detroit, MI to Lansing, MI)

Table 3
The number of required refueling stops, total trip time, fuel costs, GHG emissions, and petroleum usage for four hypothetical trip scenarios, by vehicle type.

Trip distance (mi)	Vehicle type	Refueling stops	Refueling time (min)	Driving time @ 60 mph (hr)	Total time [driving + refueling] (hr)	Fuel cost	Well-to-wheels		
							GHG emissions (kg)	Petroleum usage (Btu)	Petroleum usage [4] (gal)
1000	ICE	2	10	16.7	16.8	$100	356	3,791,000	27.02
	BEV	11	330		22.2	$40	214	54,000	0.38
	FCV	3	53		17.6	$90	260	27,000	0.19
500	ICE	1	5	8.3	8.4	$50	178	1,895,500	13.51
	BEV	5	150		10.8	$20	107	27,000	0.19
	FCV	1	18		8.6	$45	130	13,500	0.10
250	ICE	0	0	4.2	4.2	$25	89	947,750	6.76
	BEV	2	60		5.2	$10	54	13,500	0.10
	FCV	0	0		4.2	$23	65	6,750	0.05
100	ICE	0	0	1.7	1.7	$10	36	379,100	2.70
	BEV	0	0		1.7	$4	21	5,400	0.04
	FCV	0	0		1.7	$9	26	2,700	0.02

[4] Per EIA (2015), for 1 gal of petroleum: (5,892,000 Btu / barrel) / (42 gal / barrel) = 140,286 Btu / gal

Assumptions (from Tables 4 and 5) --

- ICE: 418-mile average range, \$0.10/mile, 5-minute refueling, direct fuel injection.
- BEV: 110-mile average range, \$0.04/mile, 30-minute refueling (fast charging from approximately 0% to 80% charge), assumes appropriate charger network exists as needed along route.
- FCV: 289-mile average range, \$0.09/mile, 18-minute refueling, gaseous hydrogen, assumes hydrogen refueling infrastructure exists as needed along route.

The following trends are evident from the results shown in Table 3:

- Except for the longest trip, overall trip times (in hours) are similar for ICE and FCV vehicles. For the longest trip, FCVs required an additional 48 minutes due to an additional refueling stop, and longer refueling stops in general.
- Except for the shortest trip, BEVs have notably longer overall trip times (relative to the other two vehicle types). This is caused by a combination of more refueling stops that take more time than the other vehicle types. For a 1000-mile trip, it would take 32% longer (5.4 additional hours) to complete compared to a traditional ICE vehicle. (Our scenario assumed a 30-minute fast charge to 80% of capacity; were a BEV to use the slower, 100% charge at a minimum of 3.5 hours, the trip times and refueling times would be substantially longer.)
- Across all trip lengths, average fuel costs for BEVs were 60% lower than ICEs and 56% lower than FCVs. Average fuel costs for FCVs were 10% lower than ICEs.
- Both BEVs and FCVs produced noticeably less GHGs, emitting 40% and 27% less, respectively, than comparable ICEs.
- BEVs and FCVs used significantly less petroleum in the course of operation, both consuming about 99% less than comparable ICEs.

Summary of key aspects for refueling infrastructure and vehicles

Table 4 summarizes several key aspects of the underlying fuel sources and the related infrastructure, while Table 5 summarizes several key vehicle-specific aspects of battery-electric vehicles and fuel-cell vehicles. In both tables, gasoline and current ICE vehicle technology are presented for comparison to the two alternative fuel sources and vehicle types. Where appropriate, color-coding is used for the best (green), midpoint (yellow), and worst (red) performer in each category.

Table 4
Relevant aspects of the fuel sources for battery-electric vehicles (BEV) and hydrogen fuel-cell vehicles (FCV).
(Where appropriate, green = best, yellow = middle, and red = worst.)

Aspect	Current ICE	Battery electric (BEV)	Fuel cell (FCV)
Fuel type	Gasoline	Electricity	Hydrogen
Refueling infrastructure	Yes	Electric grid readily available; charging station required for Level 2 or higher	Limited
Number of public refueling stations [1, 2, ‡]	*114,223*	*11,606 (stations)* *29,508 (outlets)*	*14*
Number of private refueling stations [1, 2, ‡]	-	*1,963 (stations)* *4,376 (outlets)*	*21*
Number of planned refueling stations [1, 2, ‡]	-	*165 (stations)* *577 (outlets)*	*56*
Total number of existing and planned refueling stations [1, 2, ‡]	114,223	13,734 (stations) 34,461 (outlets)	91
Fuel price [3, 4]	$2.35 / gal	$0.12 / kWh	$5.00 / kg
Gasoline-gallon equivalent (GGE) [5]	1 gal	33.7 kWh	~ 1 kg (2.2 lb)
Gravimetric energy density (MJ/kg) [6]	44	0.5	120
Volumetric energy density (MJ/L) [6]	32	1	8 (liquid) 6 (gas, at high pressure)

[1] U.S. Census Bureau (2012).
[2] AFDC (2015a).
[3] National average prices for gasoline and electricity, October 1 – October 15, 2015 (AFDC, 2015b).
[4] National median price at public hydrogen stations as of December 4, 2015 (AltFuelPrices.com, 2015).
[5] AFDC (2014).
[6] DOE (2015d).
[‡] For BEV recharging, "stations" are the physical sites that contain one or more "outlets" (i.e., individual connectors); these counts do not include chargers installed in private residences.

Table 5
Relevant aspects of vehicle performance for battery-electric vehicles (BEV) and hydrogen fuel-cell vehicles (FCV).
(Where appropriate, green = best, yellow = middle, and red = worst.)

Aspect	Current ICE	Battery electric (BEV)	Fuel cell (FCV)
Fuel type	Gasoline	Electricity	Hydrogen
Number of vehicle models available [7]	287	13	3
Average fuel economy [7]	23.3 mpg	105.2 mpge	58.5 mpge
Fuel economy range [7]	12 – 50 mpg	84 – 119 mpge	50 – 67 mpge
Effective cost per mile	$0.10	$0.04	$0.09
Well-to-wheels GHG emissions (g/mi) [8]	356 – 409	214	260 – 364
Well-to-wheels total petroleum usage (Btu/mi) [8]	3791 – 4359	54	27 – 67
Driving range (average) [7]	418 mi	110 mi	289 mi
Driving range (min – max) [7]	348 – 680 mi	62 – 257 mi	265 – 312 mi
Time to refuel	~ 5 min	20 – 30 min (DC Level 2) 3.5 – 12 hr (AC Level 2)	5 – 30 min
High voltage	No	Yes	Yes
High pressure	No	No	Yes
Availability of qualified mechanics	Yes	Limited	Limited
Availability of qualified emergency responders	Yes	Yes	Limited
Vehicle maintenance issues [9]	-	Lower maintenance than gasoline; possible battery replacement required during vehicle lifetime	Lower maintenance than gasoline; high-pressure tanks may require inspection and maintenance

[7] Model year 2016 (EPA, 2015a).
[8] GREET 2015 release, using default settings for model year 2015 passenger cars (ANL, 2015).
[9] AFDC (2014).

Summary

This report discussed the major advantages and disadvantages associated with battery-electric vehicles (BEVs) and fuel-cell vehicles (FCVs). As a reference for comparison, information for current gasoline-powered internal combustion engines was also presented. In addition to reviewing the technical literature, interviews were conducted with experts in the automotive and energy sectors regarding their views concerning these issues. The main findings are highlighted below.

BEVs currently offer the most readily available fuel source via the existing electric grid. Additionally, more BEV models are available to the public (relative to fuel-cell vehicles) and they offer the best fuel economy, resulting in the lowest cost to operate (per mile). BEVs also tend to produce the lowest amount of greenhouse gases (well-to-wheels) per mile. However, the driving ranges of these vehicles are currently the lowest of any vehicle type, while also requiring the longest time to refuel or recharge.

FCVs have significantly longer driving ranges and lower refueling times than comparable BEVs, and it is also possible for them to use the least amount of petroleum (well-to-wheels) per mile, depending on the type of hydrogen used. On the other hand, only a small number of vehicle models are available, and only in the most recent model years. Similarly, the hydrogen-refueling infrastructure is practically nonexistent outside of California. There is generally consensus among the experts that expansion of the hydrogen infrastructure needs to precede the mass introduction of FCVs in order to raise consumer confidence in the availability of hydrogen fuel.

Both alternative fuels and vehicle types require additional training for emergency responders and mechanics, but also generally require lower overall maintenance than a traditional gasoline-powered vehicle.

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