

Comparative Analysis of Battery Electric Vehicles and Hydrogen Fuel Cell Vehicles

Ironically, the first internal combustion engine (ICE) was powered by hydrogen and was produced by Francois Isaac de Rivaz who designed the De Rivaz engine in 1806 (Lindqvist and Overby 1). Moreover, at the dawn of the automotive industry, most vehicles were electrically-powered beginning in approximately 1890 and being effectively phased out by the early 1920s (Santini 36; Guarnieri (no pages)), and served largely urban areas. The decline in electric vehicles was due to the advent of paved highways creating the need for cars capable of long-distance driving, the discovery of large quantities of oil and the consequent precipitous drop in gasoline prices, as well as decreasing manufacturing costs of internal combustion engine cars (Guarnieri). Until relatively recently, fossil fuels have been the virtually-exclusive means of powering essentially all types of vehicles. Despite the implementation of emission control devices, largely beginning in the 1970s with mandated catalytic converters and the exclusive use of unleaded fuel, vehicle emissions have continued to deteriorate the environment. The result has been escalating pollution from carbon monoxide and dioxide emissions and, more recently, accelerated global warming and climate change with their associated effects, which have become increasingly alarming. According to Zhang et al.,

“...the transport [sic; transportation] industry, as the world’s second largest carbon emission sector and the critical driver of global warming, is responsible for about 26% of global carbon emissions in 2020 according to International Energy Agency, [and] road transport [sic; transportation] [is responsible for] ... the most significant proportion of ... greenhouse gases [sic gas] emissions in the transportation sector. ...” (p. 118019)

Initially, the introduction of alternately-fueled vehicles was brought about by a number of impetuses, including,

“...planning to find substitutes for fossil oil in the transportation sector. This could trace back to the Arab oil embargo in 1973 that triggered the first oil crisis. The soaring oil prices and gasoline shortage were blasting fuses as a prelude to exploring the alternative paths of oil in the United States, Japan, and other developed economies. The United States Congress passed the Electric and Hybrid Vehicle Research, Development, and Demonstration Law in 1976. Many car manufacturers began to seek substitutes for traditional fuel vehicles at roughly the same time. For example, General Motors (GM) developed a prototype of urban electric vehicles exhibited at the first low-pollution powertrain development seminar organized by the U.S. Environmental Protection Agency (EPA) in 1973.” (Zhang et al., 118020)

More recently, both battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs) have been increasingly recognized as viable alternatives. This paper will compare the advantages and disadvantages of BEVs and HFCVs based upon the following criteria: first, environmental impact in terms of vehicle emissions, the manufacture of fuels, as well as the materials used in vehicle components; second, fuel transport and transmission mechanisms, their maturity, and associated costs; third, fueling infrastructure availability and construction costs; fourth, fueling infrastructure safety and simplicity of fabrication; fifth, fueling time; sixth, driving range; seventh, fuel costs; eighth, purchase cost; ninth, lifecycle cost; and tenth, safety of the vehicles. Other considerations which will be introduced include “precautions for daily use,” for instance consequences of over- and under-charging a BEV battery, the necessity to charge batteries prior to storage, and avoiding exposure to extremely hot and cold settings. Additional mention will be made of HFCVs’ “dynamic response” (the ability to adapt to complex driving conditions) low-temperature operation; and use in heavy-duty vehicles or “long-distance or heavy-duty trips.”

However, there is some disagreement among scholars regarding the strengths and weaknesses of the two powertrains. In addition, towards the final portion of this essay, recent developments in solid-state battery technology will be briefly

examined, including their potential advantages over current lithium-ion batteries as well as potential obstacles to their manufacture to assess their practical impact on BEV technology and to make this discussion as comprehensive and current as possible.

Basic Mechanics of BEVs and HFCVs

In order to be able to meaningfully compare the advantages of BEVs and HFCVs, it is first necessary to explain their basic functioning.

1.1 BEV Function

BEVs consist of a number of key components. These include a charge port, an onboard charger, a traction battery pack, an electric traction motor, an electric transmission, an DC-to-DC converter, a power electronics controller, and an auxiliary battery. The BEV's charge port connects the vehicle to an external power supply which sends AC current to an onboard charger. This charger converts the AC current to DC power to charge the traction battery pack, which stores electricity for use by the electric traction motor. The power electronics controller governs the electrical current from the traction battery to the electric traction motor, thereby controlling its speed and torque. The resulting mechanical power from the electric traction motor is then transferred to the electric transmission which transmits this mechanical power to drive the

vehicle's wheels. Additionally, the onboard charger interfaces with other charging components and monitors battery condition including voltage, current, temperature, and state of charge during charging. The DC-to-DC converter converts the higher-voltage DC power from the traction battery pack to the lower-voltage DC power used to recharge the auxiliary battery and for vehicle accessories. The auxiliary battery provides electricity to power vehicle accessories. There is also a thermal cooling system which maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components. (Faraz et al. 137).

HFCV Function

HFCVs produce electricity using a fuel cell powered by hydrogen, rather than extracting electricity from only a battery, the size of which largely determines the power and range of a BEV vehicle. The power and range of the HFCV are based upon the size of the hydrogen fuel tank and electric motor(s) that receive(s) electric power from the proportionately-sized fuel cell and battery combination. Most HFCVs use the battery to recapture braking energy, to provide extra power during rapidly changing traffic conditions requiring frequent brief acceleration, to equalize the power delivered from the fuel cell, and to allow the fuel cell to be disengaged during low power requirements. HFCVs use a propulsion system somewhat similar to that of electric vehicles, where energy stored as hydrogen is converted to electricity by the fuel cell or fuel stack.

The fuel cell contains a polymer electrolyte membrane (PEM) fuel cell which contains an electrolyte membrane placed between a positive electrode (or cathode) and a negative electrode (or anode). Oxygen (from air) is transmitted to the cathode and hydrogen is transported to the anode. The anode forces the hydrogen molecules to break apart into protons and electrons due to an electrochemical reaction in the fuel cell catalyst, most often platinum. Protons then pass through the anode and travel through the membrane to the other side of the fuel cell where the cathode is located, while the electrons travel through an external circuit to provide electricity. These electrons then recombine with the protons on the cathode side where the protons, electrons, and oxygen molecules combine to form water vapor and produce heat. While water vapor is technically a greenhouse gas, it does not remain in the atmosphere or retain or radiate heat like other greenhouse gasses like carbon dioxide and is therefore essentially harmless (Rubaiyat Reza Habib and Butler 26).

Nomenclature

The literature contains several different terms which must be distinguished for the purposes of this paper. BEVs are, as implied by the term, battery electric vehicles as described above; however, the term "HFCV" is sometimes used in the literature interchangeably with the term "FCEV." The latter term is arguably more accurate because it denotes that hydrogen vehicles also utilize electricity to operate, also as described above. Technically, HFCVs are a type of FCEV.

Both are electric vehicles that use a fuel cell to power an electric drive system. The difference is that FCEVs use hydrogen and oxygen to generate electricity through a chemical reaction, while HFCVs use hydrogen and oxygen to power a fuel cell.

By contrast, the term “FCHEV” denotes a fuel cell hybrid electric vehicle, which contains components of both HFCVs and BEVs. These vehicles are hydrogen-based and are also plug-in electric vehicles. Therefore, they operate differently than either HFCVs or BEVs and are not within the scope of this paper.

Points of Comparison

This paper will now discuss the strengths and weaknesses of BEVs and HFCVs across a number of dimensions. Notably, there is significant disagreement in the literature concerning several key criteria. One example of this is environmental impact. This paper will first review environmental impact related to vehicle emissions, the manufacturing of fuels, and the materials incorporated in vehicle components since the origin and design impetus of both types of vehicles stems from the intent to mitigate environmental damage and concomitant climate change generated by traditional ICE vehicles.

3.1 Environmental Impact

There are three major categories of environmental impact discussed in the literature: emissions due to vehicle exhaust, emissions originating from the manufacture of fuels, and pollution due to the contents of vehicle components

3.11 Emissions due to Vehicle Exhaust

As the table below indicates, by and large, BEVs are more environmentally friendly, particularly related to global warming (35.65 kg of C02 equivalent vs. 96.38 kg of C02 equivalent for HFCVs), acidification (.21 kg of C02 equivalent vs. .49 kg of C02 equivalent for HFCVs), and abiotic depletion (.27 kg of C02 equivalent vs. .67 kg of C02 equivalent for HFCVs) (see table 1).

Table 1

Impact Assessment Results of the 7 Analysed Scenarios, According to CML2000

ENVIRONMENTAL IMPACT	UNITS	BEVs [BEV_IT]	HFCVs [FC_IT]
Abiotic depletion	kg Sb eq	0.27	0.67
Acidification	kg SO2 eq	0.21	.49
Eutrophication	kg PO4 3 _ eq	0.10	0.12
Global Warming	kg CO2 eq	35.65	96.38
Ozone layer depletion	kg CFC-11 eq	1.86 e-5	1.40e-4
Human toxicity	kg 1,4-DB eq	69.79	57.28
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	24.13	23.69
Marine aquatic ecotoxicity	kg 1,4-DB eq	58685.3	50859.2
Terrestrial ecotoxicity	kg 1,4-DB eq	0.29	0.47
Photochemical oxidation	kg C2H4 eq	0010	0021
Non-renewable, fossil	(no units specified)	501.9	1290.5

Source: Bartolozzi, Irene, et al. "Comparison between Hydrogen and Electric Vehicles by Life Cycle Assessment: A Case Study in Tuscany, Italy." *Applied Energy*, vol. 101, Jan. 2013, pp. 103–11, table 5, academia.edu, <http://dx.doi.org/10.1016/j.apenergy.2012.03.021>.

Likewise, Bartolozzi et al. report that,

Results show that despite HFCVs showing better performance compared with EVs in impact categories such as human toxicity, fresh water aquatic ecotoxicity, and marine aquatic ecotoxicity, HFCVs have higher impacts in impact categories such as abiotic depletion, acidification, eutrophication, and ozone layer depletion. (107).

They conclude that, "BEV scenarios have in general better environmental performances compared to the hydrogen scenarios." (110). Similarly, Zhang et al. (118025), determine that BEVs are superior to HFCVs vis-à-vis environmental repercussions, estimating that BEVs utilize 10-15 kWh per 100 kilometers which results in just over seven kg to just over 10.5 kg of CO₂ emissions. They state that by contrast, HFCVs emit nearly 17 kg over that same distance.

3.12 Emissions Originating from the Manufacture of Fuels

The manufacture of fuels for both BEVs and HFCVs may also produce harmful emissions depending upon the manufacturing process involved. Both hydrogen and electricity must be produced from other sources. For example, hydrogen can only be extracted and processed from other substances. According to Zhang et al.,

Whether EVs or HFCVs contributing [sic; contribute] to carbon neutralization depends on power sources. If the power source is fossil energy, such as coal and oil, the above vehicles ... cannot play a role in emission reduction[,] but [can] improve local air quality in urban cities. Only by taking renewable energy including light energy, wind energy [though both energy sources are prone to very significant fluctuations], and hydropower, as the final power source of new energy vehicles, can we achieve real emission reduction and greener transportation (118021).

Zhang et al. further explain that the two most common methods of hydrogen production (extraction) are powered by fossil fuels or industrial byproducts such as coke oven gas, chloralkali gas, or biogas produced from organic waste. Both processes require great amounts of energy and also produce substantial pollutants. Similarly, Bartolozzi et al. conclude that, "... the ... performance of hydrogen scenarios descends also from the lower efficiency in the fuel (H₂) production..." (110). However, even hydrogen production through electrolysis (in which hydrogen is extracted from water), which is becoming more common, may generate pollutants; The process itself results in no CO₂ emissions (Rubaiyat Reza Habib and Butler 31), but nonetheless has a 75%-85% efficiency (Zhang et al. 118022). In sum, whether and how much pollution may be generated again depends on the energy source ultimately utilized to produce the electricity required.

Zhang et al. also note that while solar energy is becoming a production option, it is not yet viable because it remains largely experimental. They cite the example of "solar-driven production from water using particulate photocatalysts" (118022), in which a photocatalyst such as titanium dioxide (TiO₂) absorbs sunlight and is used to split water molecules into hydrogen and oxygen. They also mention Microwave-Driven Hydrogen Production (MDHP), a type of electrolysis utilizing microwave radiation to heat water and activated carbons, thereby splitting water molecules into oxygen and hydrogen with high energy efficiency, and production from wastewater as potentially useful but still largely experimental as well (118022).

3.13 Pollution Due to the Contents of Vehicle Components

Rubaiyat Reza Habib and Butler assert that the materials utilized in BEV batteries may contain more environmentally-toxic components than the materials utilized in hydrogen fuel cells. Lithium-ion batteries typically consist of materials such as lithium, nickel, and cobalt, which are often considered less environmentally friendly and more resource-intensive compared to the materials used in hydrogen fuel cells, which primarily rely on hydrogen and oxygen, with platinum often utilized as a catalyst (31). To the extent that batteries are a component of HFCVs, utilized for recapturing braking energy, providing extra power during periods of frequent brief acceleration, and allowing the fuel cell to be disengaged during low power requirements, HFCVs may also contain the same environmentally-harmful materials as BEVs, though on a considerably smaller scale due to the smaller size of the batteries installed.

3.2 Fuel Transport

A second point of comparison relates to fuel transport, including transmission mechanisms, their maturity, and associated costs. Rubaiyat Reza Habib and Butler contend that although the extraction of hydrogen through electrolysis causes a slight efficiency loss by converting electricity into hydrogen, distributing hydrogen can be more efficient than distributing electricity over long distances due to lower energy losses during travel (31). By contrast, Zhang et al. conclude that “popularizing hydrogen fuel cell passenger vehicles faces several insurmountable obstacles in the short run, [including the transport] process” (118019). They argue that measured by weight, hydrogen has a high energy density per a given amount of mass; however, given hydrogen’s immense volume in proportion to its mass, it has a very low energy density per a given unit of volume. Therefore, one method of transport is to compress it (118022).

3.21 Hydrogen Transport

To economically transport hydrogen, it must be compressed in some manner. There are three basic means to transport hydrogen: compressed transport by trailer, liquified by rail, and in solid-state form.

3.211 Compressed Hydrogen Transport by Trailer

The ideal level of compression is between approximately 5000 – 10,000 pounds per square inch for optimal mechanical simplicity, reliability, and energy efficiency and is well suited for transport by “high-pressure[,] long[-]tube trailer” (Zhang et al. 118023). This is most effective when small gaseous quantities are involved and the transport distance is less than roughly 300 miles. For distances greater than that and with larger quantities of hydrogen, pipelines are generally the most economical transportation method (118023).

3.212 Liquified Hydrogen Transport by Rail

Alternatively, hydrogen may be transported by rail using modified tank wagons (essentially a rail-car mounted Dewar) designed to operate with the extremely low temperatures required to keep hydrogen liquid. Zhang et al. state that hydrogen must be maintained at roughly -420oF and remain in vacuum-insulated, double-sided (often stainless steel) cryogenic liquid tank cars (with aluminized Mylar or similar insulation between interior and exterior walls) to prevent vaporization and evaporation. Nonetheless, to date, this transportation method has quite high costs which have thus far limited its use largely to aerospace and military applications (118023).

3.213 Hydrogen Transport in Solid-State Form

Yet another option is transportation of hydrogen in solid-state form. While solid-state transport allows for hydrogen to be transferred efficiently at high density, and enables superior safety and low working pressure during the process, this is still largely a laboratory-based procedure (Zhang et al. 118023).

3.214 Hydrogen Transport via Pipeline

Hydrogen may also be transported by pipeline. Stainless steel is generally used for this purpose, due to its ability to withstand high pressures and the low temperature of the hydrogen being transported. If type 316 stainless (containing relatively high molybdenum, nickel, and chromium content) is used to resist corrosion and embrittlement, costs may become “exorbitant” for “pipelines of more than thousands of kilometers” (Zhang et al. 118024). Even when other, somewhat less expensive types of stainless are used (e.g., 304), pipelines may still be inordinately expensive due to general design and construction costs.

3.22 Electricity Transport

While Rubaiyat Reza Habib and Butler contend that “the distribution of hydrogen is more efficient than the distribution of electricity due to travel” (31), Zheng et al. state that based upon the costs of the several types of hydrogen transport outlined above, electricity distribution is more efficient than the transport of hydrogen. They explain that,

[T]he biggest superiority of EVs is that the power source is electricity generated and used at any time. On one hand, it can be directly transmitted to the electric terminal of electric vehicles through the power grids, omitting the intermediate storage segment. . . . [P]ower grid transmission is more mature, safe, efficient, economical, and convenient than hydrogen transmission. (118024).

Additionally, Zhang et al. (118026) state that “grid transmission has matured for the storage and transport of [electricity for] EVs.” Further, the use of photovoltaic infrastructure (including solar collectors and power inverters) better enables even remote areas to receive electricity (Giliomee 100,007). In fact, currently, EVs may be used to provide power to the electricity grid at times of peak grid power demand. In contrast, hydrogen must first be produced via electricity which is an additional step, before being transported and stored (Zhang et al. 118024). Zhang et al. also contend that while electricity transported through damaged power lines and dispensed at malfunctioning electric chargers at charging stations may result in wildfires and electrocutions, the risks inherent in hydrogen transport and storage include leakage and explosion (118024).

3.3 Fueling Infrastructure Availability, Construction Costs, Safety, and Simplicity of Fabrication

There appears to be a general consensus that BEVs have a more extensive fueling infrastructure and that this is in part due to considerably lower costs of construction of fueling facilities.

3.31 Fueling Infrastructure Availability

While Ajanovic and Hass contend that one of the “... major reasons for the slow diffusion of electric vehicles [is the] . . . restricted fueling infrastructure” (“Economic and Environmental Prospects...” 522) and Doğan Üçok cites the limited number of BEV fueling stations available for long-distance travel (5), others point to the lack of hydrogen refueling infrastructure as compared to BEV fueling infrastructure as a major deterrent to HFCV adoption. For example, Zhang et al. assert that the largest impediment to the growth of HFCVs is fuel accessibility due to the lack of hydrogen refueling stations (118025) and Rubaiyat Reza Habib and Butler state that “Overall BEVs have a much larger amount [sic; number] of fueling stations” (28). Furthermore, De Wolf and Smeers conclude that “The main advantage of battery-powered vehicles [is] the . . . wide availability of the electricity grid” (262).

acknowledge the limited availability of hydrogen refueling stations during long-distance travel and the need to increase HFCV charging infrastructure construction (118019), they conclude that for many purposes, the range of BEVs is adequate for local urban or suburban driving where there is a greater concentration of charging stations (118025).

Zhang et al. also characterize the HFCV refueling infrastructure as “inadequate” (118020), adding that “... [T]he number of . . . hydrogen refueling stations is extremely few nowadays and . . . increases [sic; and have increased] from 214 to 685 in the past seven years with an average annual growth rate of 21.53%” (118022-118023). They also conclude that hydrogen refueling infrastructure is one of the most significant impediments to the expansion of HFCV acquisition (118024). Similarly, Ajanovic and Haas (“Prospects and Impediments”) state that “Another important barrier for the adoption of FCVs is [the] requirement for new and expensive infrastructure. Currently there are worldwide just 376 hydrogen refueling stations. . . . there are just five countries with more than 20 HRS [hydrogen refueling stations]” (10056).

Fueling Infrastructure Construction Costs

Several authors discuss the high cost of hydrogen fueling infrastructure. For example, Rubaiyat Reza Habib and Butler assert that infrastructure cost is “...the dominating issue for hydrogen fuel” (28), and Zhang et al. discuss the “...expensive hydrogen refueling station infrastructure” (118019). They further conclude that it costs \$1.86 million to construct a hydrogen refueling station and that the operation of hydrogen stations is quite expensive, including “special equipment maintenance,” operating, and labor costs, averaging \$1000-\$1400 daily (118024). Part of the higher cost of building hydrogen stations is attributable to the safety measures which must be incorporated to mitigate the dangers inherent in hydrogen refueling (11024).

By comparison, BEV charging infrastructure is relatively inexpensive, with comparatively low installation costs (Zhang et al. 118024). The authors cite a range of purchase costs for charging piles from \$310-\$465 for a slow charging pile to \$1550-\$46,500 for a rapid charging pile. Moreover, they state that an “ordinary” charging station costs approximately \$155,000 and that Tesla’s “supercharging stations” cost roughly \$310,000 (118024).

3.33 Fueling Infrastructure Safety and Simplicity of Fabrication

Electric vehicle charging infrastructure has been characterized as safer than hydrogen charging facilities (Zhang et al. 11024). Specifically, vast quantities of hydrogen must be stored under high pressure. Therefore, hydrogen concentration must be monitored and leakage must be prevented at refueling stations. Moreover, rapid hydrogen fueling may quickly increase the internal temperature of storage tanks. These temperature rises may also damage tank walls and cause safety hazards. Special training and equipment may be necessary to offset these risks (118024). Furthermore, Zhang et al. cite the “...flexible installation, convenient use, and small floor space [of BEV recharging piles] . . . because [they] can be fixed on the ground or wall” (118024), “...while such situations are the opposite for the hydrogen refueling station” (118027).

3.4 Fueling Time, Driving Range, Fuel Cost, Vehicle Purchase Price, and Maintenance Expenses

In addition to driving range, fuel costs, and vehicle purchase and maintenance expenses, fueling time is likely one of the most significant factors in consumers’ choice between BEVs and HFCVs.

3.41 Fueling Time

In terms of fueling time, there is a consensus that HFCVs have a clear advantage. Zhang et al. conclude that “HFCVs usually tend to own [sic; have] shorter refueling time...” (118020) and that HFCVs only require several minutes of charging for “hundreds of kilometers [of range]” (118025). They cite the example of the hydrogen-powered Hyundai Nexo SUV, which they assert has a range of over 600 km (378 miles) following five minutes’ refueling (118025). Similarly, Manoharan et al. state that “FCVs have above a 300-mile driving range and can be refueled in less than 10 min at a hydrogen refueling station...” (no page numbers). Likewise, according to Rubaiyat Reza Habib and Butler, “Refueling times for HFCVs are like those of gasoline that is used today, around three to five minutes” (31). Additionally, Li and Taghizadeh-Hesary state that “...[R]efueling can be done as quickly as gasoline and diesel” (112707). By contrast, Zhang et al. contend that if a non-hybrid electric vehicle requires a full charge, recharging can take eight to 10 hours with an AC charging receptacle, one and one-half to three hours with a fast-charging receptacle, and roughly 80 minutes with Tesla’s “supercharging” receptacle (118025).

Several authors (Ajanovic and Haas 10050) cite limited infrastructure as negatively impacting the convenience of BEVs and their propagation. For instance, Ajanovic and Haas (“Economic and Environmental Prospects”) state that “There are few major reasons for the slow diffusion of electric vehicles [including] . . . long charging time...” (522) and Zhang et al. conclude that one challenge to the adoption of BEVs is “user anxiety” based upon lengthy charging time (118020). Further, Doğan Üçok determines that constructing an adequate number of BEV refueling stations, particularly for “long distance travel” might prove difficult given the extended time recharging typically requires (5).

3.42 Driving Range

Some authors imply that HFCVs are at somewhat of a disadvantage compared to BEVs in terms of range (e.g., Manoharan et al. state that highly compressed hydrogen (at nearly 5000 PSI) would require a tank in excess of 49 gallons for a 310-mile range. They further state that this size tank is large for consumer vehicles (no pages). The consensus, however, is that range is a disadvantage of BEVs as compared to HFCVs. For instance, Ajanovic and Haas (“Prospects and Impediments”) cite driving range as one of the most important weaknesses in BEV technology (10050). Similarly, Zhang et al. assert that HFCVs tend to have longer ranges than BEVs and that promoting BEVs faces the hurdle of user anxiety based upon range (118020). Likewise, Giliomee concludes that,

Without a doubt, the biggest benefit of HFCVs is their similarities to an ICE vehicle in terms of range and refueling method. A BEV’s range has a large discrepancy depending on vehicle parameters, and driving-style and environment, and can vary from 200 - 600 km [124-373 miles], with an average range of 430 km [267 miles] [[W]ith] a range of 600 - 700 km [373-435 miles] a HFCV has a clear advantage (100003).

This conclusion is echoed by the United States Department of Energy which asserts that HFCVs are comparable to internal combustion engine vehicles in that fueling time is roughly five minutes and provides a driving range of over 300 miles (1).

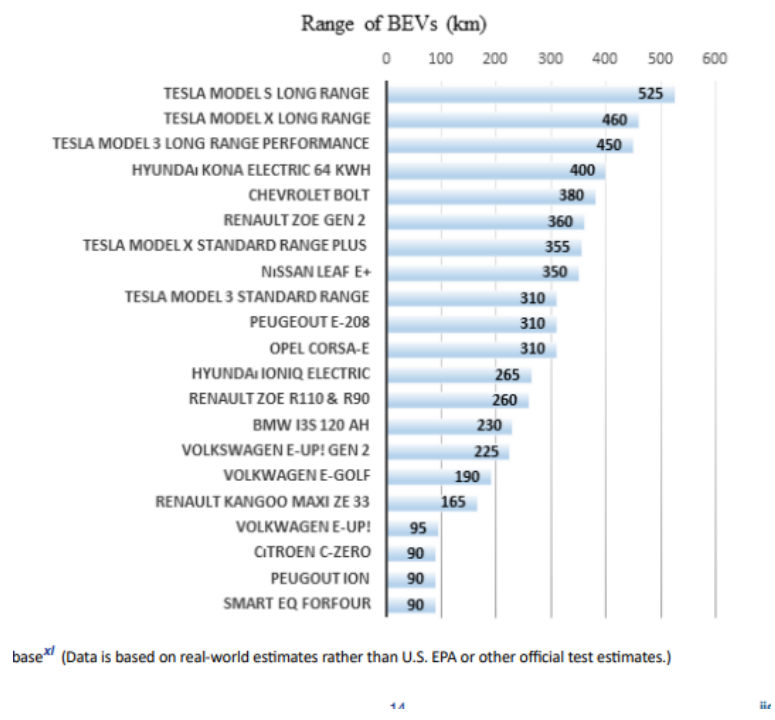
Doğan Üçok, though providing somewhat different range figures, is more specific in comparing BEV/HFCV ranges. For instance, he states that, “The ranges of current HFCV offerings are between 500 km-610 km [310-379 miles] . . . Only one long-range BEV model (the Tesla Model S Long Range) can travel this far (more than 500 km [311 miles]).” (13). He then provides sample ranges of several HFCV models: “Ranges: Hyundai Nexo Blue 380 miles (608 km)[,] Honda Clarity 366 miles (586 km)[,] Hyundai Nexo 354 miles (566 km)[, and] Toyota Mirai 312 miles (500 km)” (14). Following this, he provides a very detailed listing of maximum BEV traveling distances by model as contained in the following table which shows the Tesla Model S Long Range capable of traveling the longest distance at approximately 326 miles (525 km) to the Citroen C-Zero, “Peugout” [sic; Peugeot] Ion, and the Smart Eq Forfour, all capable of roughly 56 miles (90 km). The table also illustrates how even the HFCV cited with the lowest range, the Toyota Mirai at 312 miles (500 km), significantly exceeds the ranges of all vehicles except the Tesla Model S Long Range. The model with the second longest range, the

Tesla Model X Long Range, with a maximum distance of roughly 286 miles (460 km) has a maximum traveling distance significantly shorter than the Mirai at 312 miles (500 km)) (see table 2).

Table 2

Range of BEVs (2019) Per Full Charge

Source: Source: Doğan Üçok, Mehmet. “Hydrogen Fuel Cell Vehicles.” IICEC (Istanbul International Center for Energy and Climate), Aug. 2019, pp. 1-40, table 9, iicec.sabanciuniv.edu/sites/iicec.sabanciuniv.edu/files/2020-11/iicecenergyandclimatepaperhfvcdoganucok_0.pdf



Additional sources break down BEV ranges by type of receptacle, corresponding range, and fueling time to illustrate HFCVs' advantage as compared to BEVs. For example, Doğan Üçok states that a 120-volt outlet provides two to five miles of range for each hour of charging; a 240-volt outlet (the most common type) provides 10 to 30 miles of range for each hour of charging; and a fast-charging DC outlet provides 50 or more miles of range . . . in 20 minutes. He adds, however, that some vehicles are not equipped to receive fast charging (15). While it may potentially appear that equipping BEVs with larger batteries has some potential to mitigate range limits, Ajanovic and Haas briefly address this, asserting that, “To increase the driving range of BEVs, it is necessary to increase battery capacity, and this leads to increasing weight of vehicles and consequently to efficiency reduction” (10050).

3.43 Fuel Cost

There is something of a disparity in conclusions regarding hydrogen versus electricity prices. For instance, Rubaiyat Reza Habib and Butler contend that fueling costs for HFCVs have an advantage over those of BEVs per full refuel and that hydrogen will be “...the cheaper alternative fuel source by half the amount per tank” (31). Conversely, other scholars contend that BEVs have an advantage in terms of lower fuel costs. For instance, Doğan Üçok states that, “A BEV costs 4.3 cents per mile (at average U.S. electricity prices) and an HFCV costs 22.1 cents per mile based on typical U.S. retail hydrogen costs” (12).

Additionally, Zhang et al. set forth the following figures regarding cost per unit of fuel and efficiency differences between BEVs and HFCVs:

[BEVs have lower] operating and charging costs [and lower] energy consumption expenses per hundred kilometers and [higher] energy conversion efficiency. . . . For one thing, EVs cost less per 100 km. As for [sic; the] Tesla Model 3, for instance, the average power consumption per hundred kilometers is about 17 kWh and only costs \$3.72 to \$4.74 based on the super-fast charging. Instead [sic; By contrast,] the operating cost of an HFCV is higher. . . . [T]he current price of hydrogen is about \$11.53/kg in Germany, \$16.48/kg in the United States, \$10.85/kg in Japan, and \$9.3/kg to \$10.85/kg in China. . . . [A]n HFCV consumes 1 kg of hydrogen per hundred kilometers, an HFCV costs \$9.3 to \$10.85 per hundred kilometers in China. . . . Also[,] the lower . . . efficiency of hydrogen fuel cells leads to increased use costs. . . . [T]he final efficiency of HFCVs is only 25%–35%, while that of EVs can reach 70%–90% . . . (118025).

Based upon these figures, they conclude that BEVs are not only less expensive to fuel, but also use less energy than HFCVs (118027).

Additionally, Offer et al. assert that, “The BEV [is] relatively insensitive to electricity costs but the FCV [is] sensitive to hydrogen cost” (24). Likewise, Zhang et al. state that fuel cell vehicles utilize a PEM (proton exchange membrane, which is a type of polymer electrolyte membrane, used as an electrolyte to generate electricity from hydrogen and oxygen). They further explain that the PEM largely depends upon imports to function and that the expense of water electrolysis is strongly influenced by electricity costs, in excess of 70% of the final cost (118023-118024). Thus, an overarching conclusion appears to be that HFCVs cost more to power compared to BEVs (Ajanovic and Haas 10050).

3.44 Vehicle Purchase Price and Lifecycle Costs

There appears to be somewhat limited information related to vehicle purchase prices and lifecycle costs for consumer BEVs and HFCVs. In general, however, scholars suggest that BEVs are both less expensive to purchase and maintain than HFCVs. For example, De Wolf and Smeers state that “The main advantages of BEVs are the lower purchase cost of the vehicle...” (266), while Zhang et al. assert that, “A major barrier [to HFCV adoption] is the high purchase prices [sic; price] of HFCVs compared to EVs” (118020). Further, they observe that “...EVs have a larger purchase cost range...” (118027). The authors explain that the purchase prices of BEVs are generally lower than for HFCVs and there is a wider range of purchase prices because there are a greater number of BEV models available. Conversely, they assert that there are comparatively fewer HFCV models available, with generally higher prices. They provide the example of the second-generation Toyota Mirai HFCV, for which they quote a price range of approximately \$69,000-\$78,300 (118025). They also cite the expensive fuel cell systems and rising parts prices “due to the lack of economies of scale” as additional contributors to higher HFCV purchase prices (118020). Similarly, Eaves and Eaves discuss the costs of several drivetrain components and conclude that the propulsion system for HFCVs totals just over \$29,000 including the expense, “...of the electric motor, control electronics and hydrogen-storage tank...” while the propulsion components for BEVs total just under \$19,000 (6).

With reference to lifecycle costs, Offer et al. maintain that while HFCVs’ lifecycle costs could become equivalent to those of ICE vehicles, BEVs’ lifecycle costs are “significantly lower” than HFCVs. They conclude that, “In the 2030 scenario, powertrain lifecycle costs of FCEVs range from \$7,360 to \$22,580 whereas those for BEVs range from \$6460 to \$11,420 ... “(24).

3.5 Vehicle Safety Considerations

Both BEVs and HFCVs have been cited as having the risks of fire and/or explosion. According to Hatzell and Zheng, a lithium-ion battery (used in currently-available electric vehicles) “...contains flammable liquids which make it susceptible to explosions at elevated temperatures ...” (33). Similarly, Robinson and Janek refer to the potential for fire

“... associated with flammable organic electrolytes when short circuits drive up the temperature” (1046). Likewise, Kjosevski et al. state that there may be a flammability risk associated with leaking electrolyte and the danger of “thermal hazards” due to excessively high battery temperatures (1200+ degrees) (39). They also list the risks of explosion due to the water-based electrolyte which produces hydrogen, particularly towards the end of charging, as well as the need for protection against short circuits and shocks, in addition to “...electrical, mechanical [and], chemical...” threats. Furthermore, they assert that the great weight of the battery pack requires placement to avoid destabilizing the vehicle and being damaged itself in a collision (38).

Other concerns include the need to maintain electrical components, particularly resistance testing of insulation and the “earth leakage functioning controller,” which is designed to prevent electrical current over a set value from flowing to the earth. Inadequate insulation or a malfunctioning controller can lead to electrical shock if an individual contacts an insufficiently insulated component and current runs from that component through the individual into the earth (Kjosevski et al. 39).

Yet another issue is the condition of the battery following damage, particularly if the battery terminal connectors are damaged. In this situation, there may be unknown residual energy remaining in the battery, in which case, handling and/or replacing the battery may be hazardous. Moreover, there are threats to individuals attempting to intervene following an accident and/or those involved with towing the vehicle, for instance, electric shock from compromised systems. Still another concern relates to BEV’s reduced engine noise, which may present risks to pedestrians, particularly those who are visually impaired. People with compromised vision tend to rely more on traffic sounds to navigate intersections, cross the street, and determine walking positions with respect to the roadway (Kjosevski et al. 39).

Despite these risks, Zhang et al. conclude that “...electric passenger vehicles have more advantages in . . . safety . . . in comparison with hydrogen fuel cell passenger vehicles” (118019). For example, they note that rapid hydrogen refueling poses potential safety threats (118024). In addition, according to Jiang et al., there are several possible causes of hydrogen explosion. They assert that,

Due to the highly sensitive nature of hydrogen, the explosion is the most important risk [T]here have been a number of explosion accidents caused by hydrogen leakage An explosion is a phenomenon that forms when energy is released instantaneously [The types of detonation of hydrogen and air mixtures include:] . . . [1,] explosion after static electricity ignition (1272)[, 2] after a leak . . . in high-pressure hydrogen storage . . . (1273) [and 3,] self-initiated detonation in non-uniform mixtures (1273) [caused by] . . . the inhomogeneity . . . of the hydrogen-air mixture. In such mixtures, the locations of the inhomogeneous hydrogen concentration [in which lighter hydrogen aggregates near the upper regions of the storage tank] become local ignition cores ... and rapidly detonate the unignited hydrogen-air mixture” (1274).

Further, despite HFCVs being fabricated with fuel tanks constructed of carbon-fiber-wrapped cylinders resistant to collision impacts (Manoharan et al. no pages), Jiang et al. also discuss the risk of “hydrogen embrittlement,” in which storage tank cracks cause a loss of pliability in storage tank metals leading to leakage as a source of fire or explosion. They state that embrittlement is due to the damage caused by hydrogen to surrounding metals which eventually results in fatigue of those metals. They explain this phenomenon as follows: hydrogen atoms can dissolve in metals and combine to form larger hydrogen molecules which may then react with one another to reduce cohesion between metal atoms. This produces stress points at irregularities (micropores or inclusions) in the metals. This in turn can result in microcracks, causing embrittlement. As hydrogen atom concentration increases near the crack, there is a decrease in cohesion between metal atoms at the crack tip. As microcracks multiply, this may eventually result in fracture. Under pressure, this may result in failure of the material (1271, 1272).

Moreover, Zhang et al. conclude that hydrogen additionally poses greater risks of leakage, dissemination, and explosion than gasoline because it is odorless and therefore more difficult to detect. Further, it is natural for it to disperse in the air following leakage, and even low concentrations may result in explosion, particularly in “... confined space [sic; spaces] with poor ventilation, such as underground garages, tunnels, roofed buildings, etc. ...” (118024).

3.6 Other Considerations

The literature also touches upon a number of other points of comparison between BEVs and HFCVs including many rather specific dimensions of operation. For example, Zhang et al. mention precautions for ordinary use for BEVs. These encompass reduced battery life due to overcharging, undercharging, and over-discharging and the need to charge the vehicle prior to long-term storage. They also point out that lithium-ion batteries' charging life may be decreased through "extreme hot and cold," extended storage, and that long-term exposure to sunlight increases plate aging (battery plates store energy and are responsible for charging and discharging). Additionally, they contend that batteries stored in a long-term-discharged state may sulfate (sulfation is a build-up of lead sulfate on battery plates and terminals; it can hinder the chemical-to-electrical conversion and impede battery performance), though this conclusion does not appear to be widely accepted (118025).

By contrast, Pengli et al. discuss the "slow dynamic response" of fuel cells in HFCVs, particularly in "complex" driving conditions. Further, they conclude that "rapid acceleration and deceleration and frequent start-stop operations during driving will affect the durability of the fuel cell." (172). However, Zhang et al. mention the advantage of HFCVs in very low temperatures, citing the ability of HFCVs to start and perform well at -30 degrees Celsius (-22 degrees Fahrenheit) as well as the superiority of fuel-cell-powered medium- and heavy-duty vehicles (118027). Similarly, Li, and Taghizadeh-Hesary comment that hydrogen-powered vehicles are "...especially suitable for long-distance or heavy-duty trips, such as inter-city buses and cargo delivery by trucks" (112707) and Ajanovic and Haas assert that hydrogen and fuel cells are best suited to "...large[-]capacity vehicles" (10049).

Solid-State Batteries

Though not yet in commercial use, solid-state batteries (SSBs) are the holy grail component of the BEV powertrain.

4.1 Differences in Lithium-Ion and Solid-State Battery Materials

There are several fundamental differences between the components of lithium-ion batteries (LIBs) as they have been discussed in this paper to this point, and experimental or proposed SSBs. For example, LIB electrodes are porous (Hatzell and Zheng 36) and may be fabricated from graphite (Bates et al. 742) or carbon (Ulvestad no pp.). Additionally, often LIB electrolytes are comprised of binary lithium salt (an organic liquid electrolyte contained within a moist paste (Robinson and Janek 1046) which incorporates compounds containing lithium ions and other media dissolved in solvents). This paste penetrates the electrodes and facilitates robust ion transport within the cathode (Hatzell and Zheng 37). There is also a porous separator which permits ion transport through the electrolyte while electronically insulating the area between porous electrodes (Boz. et al. 90502).

By contrast, "... [SSB electrodes] may be comprised of Li-metal. . .," (Bates et al. 742; Ulvestad no pp.). More specifically, they may consist of lithium, nickel, manganese and cobalt oxides (Ulvestad no pp.). Perhaps most significantly, rather than utilizing the type of liquid electrolyte (LE) with additives as employed in LIBs, SSBs use three types of solid electrolytes (SEs): sulfides, polymers, and oxides (Ulvestad no pp.). In particular, there may be "...[i]norganic options like lithium aluminum titanium phosphate . . . , [o]rganic alternatives such as polyethylene oxide and polyvinylidene fluoride . . . , and [s]olid composite electrolytes..." which exhibit good conductivity but face obstacles in synthesis and stability (Thomas et al. 1).

Nonetheless, one of the commonalities between LIBs and SSDs is the growth of dendrites. Dendrites are essentially "whiskers" of lithium that grow inside batteries (see figure 1).

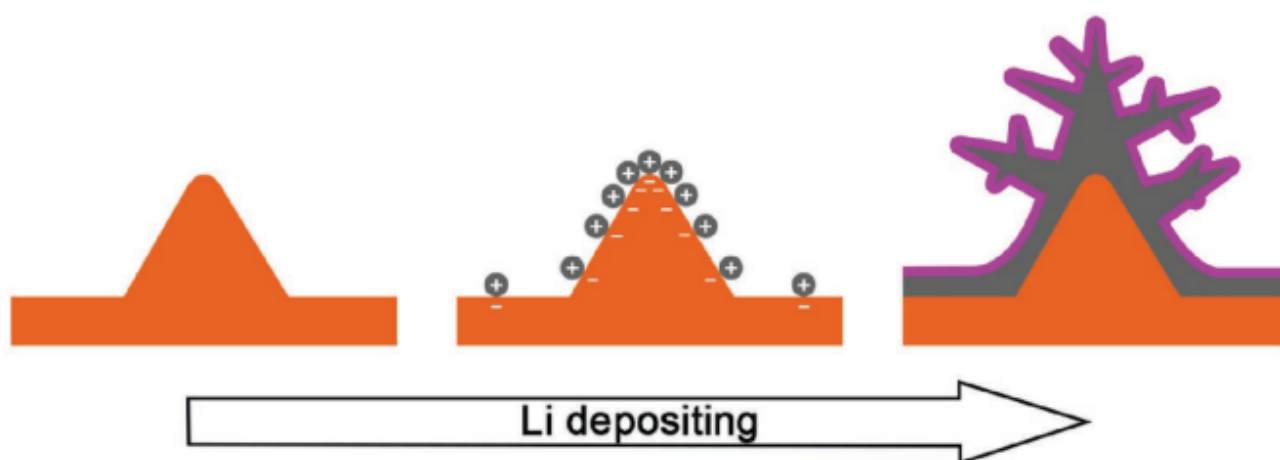


Figure 1. Schematic Diagrams of Li Deposition. Source: Cheng, Xin-Bing, et al., “Dendrite-Free Lithium Deposition Induced by Uniformly Distributed Lithium-Ions for Efficient Lithium Metal Batteries,” *Advanced Materials*, vol.28, no. 15, 2016, pp. 2888-2895, Wiley, <https://doi.org/10.1002/adma.20150612>, p. 2889.

While LIBs may develop dendrites, “... a [sic; an] SE replaces the liquid electrolyte and acts as a physical barrier to lithium dendrite penetration” (Ulvestad no pp.). However, “...some solid electrolytes allow dendrite growth through grain boundaries” (Ulvestad no pp.). Further, “...Li dendrite formation due to repeated charge and discharge cycles that could lead to a short circuit, result in battery failure (Sun et al. no pp.), and ignite the flammable electrolyte” (Ulvestad no pp.). This is particularly true at high current densities (Sun et al. no pp), and is “... the primary factor limiting the application of Li metal” (Sun et al. no pp). “These dendrites can connect from the anode through the separator [The main function of a microporous separator is to keep the two electrodes apart to prevent electrical short circuits] to the cathode . . . , thereby providing a low resistance path for electron transport (electrons will no longer flow through the external circuit and perform work), leading to high self-discharge currents that can ignite the flammable electrolyte, resulting in fires/explosions” (Ulvestad no pp).

4.2 Advantages and Disadvantages of LIBs and SSBs

SSBs are promoted as having several significant advantages over LIBs: the ability to charge and discharge rapidly, offer longer and life cycles, and provide a higher energy density (Ahmad et al. 101,002), (potentially facilitating greater range) (Jiang et al. 1046). They are also championed as costing less and providing greater safety (Boaretto et al. 1), reliability, and stability (Ahmad et al. 101,002), in part because the LE is “...both volatile and flammable” (Bates et al. 743). Moreover, it has been asserted that “SSBs . . . will last longer” (Bindra 16; Robinson and Janek 1046).

While SSBs have several advantages over LIBs, as noted above they also share some shortcomings and exhibit drawbacks unique to themselves. For example, while some recycling methods for SEs have been initiated, recycling of SSBs requires further development with issues regarding commercialized implementation, such as costs and segregating components including composite SEs and hybrid cells. SEs would eventually be manufactured that could be recycled (Janek and Zeier 9).

Another concern is safety. According to Janek and Zeier (9),

“...SSB are often regarded as being safer than LIB. However, whether increased safety exists still needs to be unequivocally proven as short circuits, the use of toxic solid electrolytes or even percolation of a liquid fraction of electrolyte to the anode may provide additional safety risks Even more, recent work shows the self-ignition and thermal runaway of . . . [some] composites above 150°C.....”

Furthermore, given the greater density of SEs, they “...are generally slow at transporting Li ions because ionic diffusion in a solid tends to be orders of magnitude slower than ionic diffusion in a liquid...” (Ulvestad no pp.). Additionally, Bates et al.

specify that there is significant resistance to the flow of ions (“interfacial thermal resistance”) at the interface between the SE and the cathode; however, they contend that mixing some LE with the SE may reduce this resistance (Bates et al. 742). Despite this, they assert that “...[T]he safety impact of a small amount of LE is unclear...” and that this design may increase manufacturing costs and impact manufacturing feasibility (Bates et al. 743). Alternately, according to Thomas et al, inorganic SEs comprised of lithium aluminum titanium phosphate have superior ionic conductivity as do “composite electrolytes” comprised of organic and inorganic materials (1). Nonetheless, composite electrolytes also face some obstacles in terms of “...synthesis intricacies and material stability...” as well as the aforementioned intra-SSE and interfacial impediments to ion transfer (1). Yu et al. (13) suggest gradually reducing the proportion of LE to SE, eventually resulting in all solid-state batteries (ASSBs); however, they conclude that the feasibility of this has not been fully proven. Additionally, Boaretto et al. discuss the “...compatibility of the cell components... [and] the properties of the interfaces within the cell (anode-electrolyte, cathode-electrolyte, intra-electrolyte) ...” (1).

Likewise, the manufacture of SSBs presents intricacies. According to Hatzell and Zheng, “[e]lectrolyte thickness, ‘electrode microstructure,’ and interfaces need to be controlled in solid-state batteries during materials processing and/or manufacturing.” They contend that electrolyte thickness must be controlled because this thickness affects attainable energy density (the amount of energy contained in a given volume). They also assert that electrode microstructures are vital for ion transport within the cathode (unlike LIB porous electrodes which permit LE penetration for ionic conductivity within their structure, SSB cathodes are constructed of solid electrolyte and cathode components which may hinder transport). Similarly, they argue that SE – electrode interfaces are essential for battery longevity in that irregular interfaces result in reduced SSB longevity (36-37).

Rather than the SSB design reviewed to this point (cathode, anode, and separator), Yu et al. (13) discuss bipolar batteries, which replace individual separators with a “common bipolar plate” (A bipolar plate connects the entire surface of one cathode and the entire surface of one

anode of the next cell and provides a series of electrical connections between adjacent cells) (see figure 2).

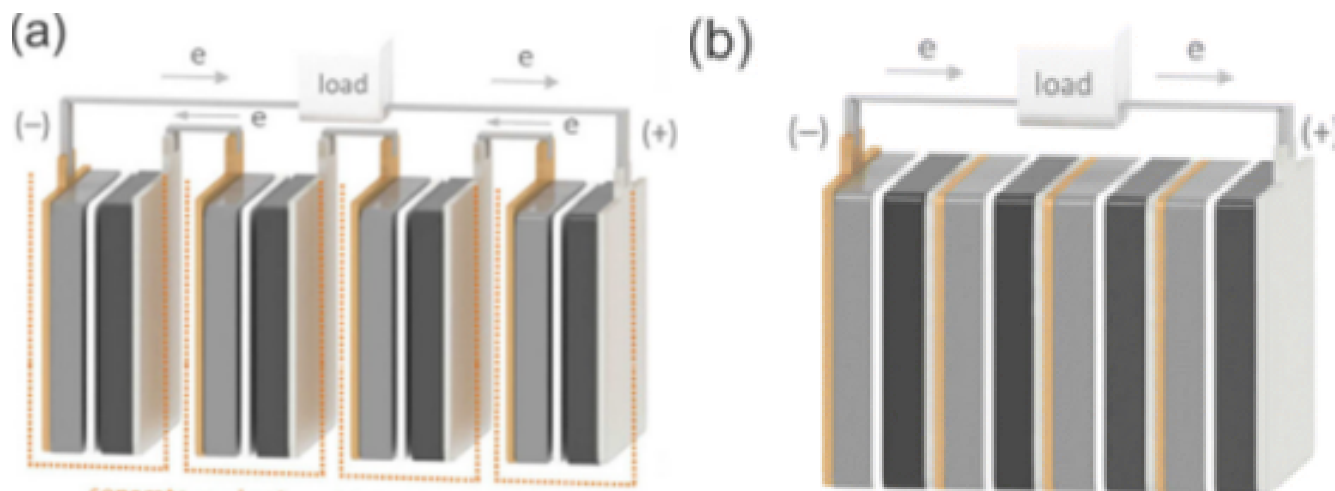


Figure 2. Schematic Diagrams of (A) the Monopolar Design of Current LIBs with Liquid Electrolytes and (B) the Bipolar Design of SSBs with SEs., Source: Sharma,Vikas, et al., “A review on the transition from conventional to bipolar designs of anode-less all-solid-state batteries,” Royal Society of Chemistry, vol. 2024, no. 3, May 2024, pp. 1222-1237, rsc.org, <https://doi.org/10.1039/D4YA00138A>, p. 1229.

There are several advantages to bipolar plates. When monopolar SSBs short circuit, they can attain temperatures greater than LIBs which can ignite packaging or nearby materials (Bates et al. 742). However, bipolar plates produce lower heat during use improving safety during fast charging and collision-based short-circuits. This design also facilitates the ability to increase battery cell size (Yu et al. 12).

4.3 Feasibility Concerns

Previously, potential manufacturing issues have been discussed, including the need for precisely-controlled electrode thickness, electrode microstructures, and SE-electrode interfaces (Hatzell and Zheng 36-37). However, there are a number of other potential obstacles to mass SSB manufacturing on the scale which would be required to supply the BEV market. Most generally, these can be described as "...ease of fabrication" (Robinson and Janek 1046). For example, according to Hatzell and Zheng, SSB solid oxide fuel cells take longer to manufacture than LIB cells and this may impact their cost and output quantity. They will also require greater capital expenditures, larger factories, and human investments (34). More specifically, one possible contributing factor is that the causes of SSB failure are not yet fully explained, in part due to an insufficient understanding of the "chemomechanical factors" by which they operate (Ahmad et al. 101,002). Mass production of SSBs would require that the potential advantages of rapid charge and discharge, high energy density, long life, and affordability all be met concurrently. Further, SEs will require the ability to be mass produced with low defects. Some of the issues which must be addressed include solid electrolyte cracking, void formation as well as other concerns, ideally in unison and by one SE compound (101,001, 101,003). Additionally, Thomas et al. assert that all categories of SEs have weaknesses. Inorganic SEs display "mechanical fragility," Composite SEs are difficult to synthesize and require greater stability, and organic SEs have reduced conductivity (1). Moreover, to fabricate SEs with high ionic conductivity and stability (particularly the inorganic SE, antiperovskite), ionic transport must also be "...understood . . . at an atomic level." This will also help preserve the SE's efficacy across temperature conditions by utilizing stable SSB anodes with parallel "thermal characteristics." The Anode-SE interface, stability, the anode's longevity "...during charge-discharge cycles, and the volumetric alterations during ion movement" are also essential issues (Machín et al. 28).

Perhaps Robinson and Janek summarize the likely future prospects of SSBs most clearly:

Despite these theoretical advantages, there is a long way to go before all-solid-state lithium-ion batteries begin appearing in electric vehicles. A battery revolution is not just waiting for us around the corner. ... Solid-state batteries require serious efforts not only in fundamental science but also in processing technology. ... Among the key choices to be made for any battery are the electrode and electrolyte materials. Once these are identified and workable laboratory-scale prototypes are developed, then comes the perhaps even more difficult chore of perfecting fabrication and packaging technologies that are inexpensive, rapid, and reliable on a large scale. It is just as important to produce a device with sufficient mechanical stability, since large volume variations in the battery materials during operation [of the vehicle] have to be taken into account. The impact of additional mechanical stress [on the batteries] . . . also deserves careful evaluation." (1046).

Thus far, this paper has compared the basic design of BEVs and HFCVs and described their advantages and disadvantages along several dimensions including environmental impact, fuel transport expense and practicality, and fueling infrastructure availability, construction cost, safety, and efficiency of fabrication. Other concerns which have been examined include fueling time, fuel cost, driving range, vehicle purchase price and lifecycle costs, and safety issues, along with several other more specific matters, for example factors diminishing BEV battery life and considerations impacting fuel cell durability. This was followed by a review of SSBs and the differences in components from LIBs, some common drawbacks of both designs, and an assessment of several of their strengths and weaknesses. Lastly, obstacles to manufacturing SSBs on a commercial scale were briefly addressed.

While the literature differs on the overall strengths and weaknesses of BEVs and HFCVs, given the factors reviewed in this paper, it would appear that BEVs are at an advantage. While HFCVs are faster to fuel with greater range, BEVs tend to be more environmentally friendly, with greater fueling infrastructure availability. Compared to hydrogen, electricity is also cheaper as a fuel and safer to transport. Further, there is a greater selection of available BEVs with lower purchase and lifecycle costs than HFCVs. Moreover, BEVs tend to be safer than HFCVs. While SSBs have the potential to improve on currently-available LIBs across several parameters, they present several unique problems, as well as technical feasibility and manufacturing concerns.

Nonetheless, the comparative designs of HFCVs, BEVs, and experimental SSBs must be contextualized within the accelerating global environmental crisis. Each of these designs and their present and/or future implementation is a means to help counteract the roughly 100 years of progressive automotive pollutants and address future concerns. However, continuing unsustainable worldwide carbon emissions, the accumulation of greenhouse gases, and global warming with its well-documented, far-reaching, and profound repercussions have already begun to make clear their effects. Therefore, humanity is facing an imperative to respond with pollution-free technology which will decisively dissuade consumers from purchasing ICE vehicles. While it may be that humankind may be unable to rise to this challenge sufficiently and in time, humanity has repeatedly demonstrated the capacity to generate solutions to problems previously believed to be insurmountable. It is therefore quite possible that the dire consequences of failure to adequately address the crisis may serve to motivate the emergence of technologies which may successfully manage it.

Works Cited

- Ahmad, Zeeshan, et al. "Chemomechanics: friend or foe of the 'AND problem' of solid-state batteries?" *Current Opinion in Solid State and Materials Science*, vol. 26, no. 4, Aug. 2022, pp. 101,002-101,051, ScienceDirect, <https://doi.org/10.1016/j.cossms.2022.101002>.
- Ajanovic, Amela, and Reinhard Haas. "Economic and Environmental Prospects for Battery Electric and Fuel Cell Vehicles: A Review." *Fuel Cells*, vol. 19, no. 5, July 2019, pp. 515–29, Wiley, <https://doi.org/10.1002/fuce.201800171>.
- Ajanovic, Amela, and Reinhard Haas. "Prospects and Impediments for Hydrogen and Fuel Cell Vehicles in the Transport Sector." *International Journal of Hydrogen Energy*, vol. 46, no. 16, Apr. 2020, pp. 10049-10058, Tuwien.ac.at (Vienna University of Technology), <https://doi.org/10.1016/j.ijhydene.2020.03.122>.
- Bartolozzi, Irene, et al. "Comparison between Hydrogen and Electric Vehicles by Life Cycle Assessment: A Case Study in Tuscany, Italy." *Applied Energy*, vol. 101, (no no. avail) Jan. 2013, pp. 103–11, academia.edu, <http://dx.doi.org/10.1016/j.apenergy.2012.03.021>.
- Bates, Alex M., et al. "Are solid-state batteries safer than lithium-ion batteries?" *Joule*, vol. 6, no. 4, Cell Press, April 2022, Cambridge, MA 02139, pp. 742-755, ScienceDirect, <https://doi.org/10.1016/j.joule.2022.02.007>.
- Bindra, Ashok. "Electric Vehicle Batteries Eye Solid-State Technology: Prototypes Promise Lower Cost, Faster Charging, and Greater Safety." *IEEE Power Electronics Magazine*, vol. 7, no. 1, Mar. 2020, pp. 16-19, (no second container), <https://doi.org/10.1109/MPPEL.2019.2961203>.
- Boaretto, Nicola, et al. "Lithium solid-state batteries: State-of-the-art and challenges for materials, interfaces and processing." *Journal of Power Sources*, vol. 502, (no no.), Aug. 2021, pp. 1-34, ScienceDirect, <https://doi.org/10.1016/j.jpowsour.2021.229919>.
- Boz, Bucket, et al. "Review—Electrolyte and Electrode Designs for Enhanced Ion Transport Properties to Enable High Performance Lithium Batteries." *Journal of The Electrochemical Society*, vol. 168, no. 9, Sep. 2021, pp. 90501-90526, IOPscience, <https://doi.org/10.1149/1945-7111/ac1cc3>.
- Cheng, Xin-Bing, et al. "Dendrite-Free Lithium Deposition Induced by Uniformly Distributed Lithium-Ions for Efficient Lithium Metal Batteries." *Advanced Materials*, vol.28, no. 15, 2016, pp. 2888-2895, Wiley, <https://doi.org/10.1002/adma.20150612>.
- Doğan Üçok, Mehmet. "Hydrogen Fuel Cell Vehicles." IICEC (Istanbul International Center for Energy and Climate), Aug. 2019, pp. 1-40, (no second container available) iicec.sabanciuniv.edu/sites/iicec.sabanciuniv.edu/files/2020-11/iicecenergyandclimatepaperhfvcdoganucok_0.pdf
- Eaves, Stephen, and James Eaves. "A Cost Comparison of Fuel-Cell and Battery Electric Vehicles." *Journal of Power Sources*, vol. 130, nos. 1-2, May 2004, pp. 208–12, <https://doi.org/10.1016/j.jpowsour.2003.12.016>.
- Faraz, Ahmad, et al. "Battery Electric Vehicles (BEVs)." *Electric Vehicles. Green Energy and Technology*, Patel, Nilay, et al., editors, 26 November 2020, pp. 137-160, Springer, Singapore, ResearchGate, https://doi.org/10.1007/978-981-15-9251-5_8
- Giliomee, Johan H., et al. "Swappable green hydrogen trailers as an additional energy source to electric minibus taxis." *African Transport Studies*, vol. 1, [no no.] 2023, pp. 100,001-100,009, ScienceDirect, <https://doi.org/10.1016/j.aftran.2023.100001>
- Guarnieri, Massimo. "Looking Back to Electric Cars." *Third IEEE HISTory of ELECTro-technology CONference (HISTELCON)*, (no vol. or no.), Institute of Electrical and Electronics Engineers, 2012, (no pages), ResearchGate, <https://doi.org/10.1109/HISTELCON.2012.6487583>

- Hatzell, Kelsey, and Yanjie Zheng. "Prospects on large-scale manufacturing of solid-state batteries." *MRS Energy & Sustainability*, vol. 8, (no no.), Mar. 2021, pp. 33–39, Springer, <https://doi.org/10.1557/s43581-021-00004-w>.
- Janek, Jürgen, and Wolfgang G. Zeier. "Challenges in Speeding up Solid State battery Development." *Nature Energy*, vol. 8, no. 3, Feb. 2023, pp. 1-21, ResearchGate, <https://doi.org/10.1038/s41560-023-01208-9>
- Jiang, Kangrui, et al. "Towards sustainable mobility: A systematic review of hydrogen refueling station security assessment and risk prevention." *International Journal of Hydrogen Energy*, 2025, vol.105, January 2025, pp. 1266–1280, ScienceDirect, https://www.sciencedirect.com/science/article/pii/S036031992500391X?ref=pdf_download&fr=RR-8&rr=920705aceaa842fc
- Kim, Joo Gon, et al. "A Review of Lithium and Non-Lithium Based Solid State Batteries." *Journal of Power Sources*, vol. 282, (no no.), May 2015, pp. 299–322, SienceDirect, <https://doi.org/10.1016/j.jpowsour.2015.02.054>.
- Kjosevski, Stevan, et al. "Risks and Safety Issues Related to Use of Electric and Hybrid Vehicles." *Trans Motauto World*, vol. 2, no. 1, 2017, pp. 37–40, stumejournals.com/journals/tm/2017/1/37.
- Li, Yanfei, and Farhad Taghizadeh-Hesary. "The Economic Feasibility of Green Hydrogen and Fuel Cell Electric Vehicles for Road Transport in China." *Energy Policy*, vol. 160, [no no.], Jan. 2022, pp. 112,703-112,746, Elsevier, <https://doi.org/10.1016/j.enpol.2021.112703>.
- Lindqvist, Hjalmar, and Petter Overby. "A Literature Review of Hydrogen Internal Combustion Engines: An evaluation of recent developments and challenges surrounding the use of hydrogen as fuel in internal combustion engines." 2024, Master's thesis in Mobility Engineering, Department of Mechanical and Maritime Sciences Division of Combustion and Propulsion Systems, Chalmers University of Technology, Gothenburg, Sweden, pp. 1-42, pdf.chalmers.se, <https://odr.chalmers.se/server/api/core/bitstreams/0c6a0b22-42e4-49cf-a7e2-8d84343f0746/content>
- Machín, Abniel, et al. "Advancements and Challenges in Solid-State Battery Technology: An In-Depth Review of Solid Electrolytes and Anode Innovations." *Batteries*, vol. 10, no. 1, Jan. 2024, pp. 1-36, Multidisciplinary Digital Publishing Institute, <https://doi.org/10.3390/batteries10010029>.
- Manoharan, Yogesh, et al. "Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect[s]." *Appl. Sci.*, vol.9, no. 11, 2019, article no. 2296 [according to publisher, this journal uses article numbers and not page numbers] [no pages], MDPI, <https://doi.org/10.3390/app9112296>
- Offer, Gregory J., et al. "Comparative Analysis of Battery Electric, Hydrogen Fuel Cell and Hybrid Vehicles in a Future Sustainable Road Transport System." *Energy Policy*, vol. 38, no. 1, Jan. 2010, pp. 24–29, ox.ac.uk (Oxford University Press), <https://doi.org/10.1016/j.enpol.2009.08.040>.
- Robinson, Arthur L., and Jürgen Janek. "Solid-State Batteries Enter EV Fray." *Energy Quarterly*, vol. 39, no. 12, Dec. 2014, pp. 1046–47, Springer/MRS Bulletin, <https://doi.org/10.1557/mrs.2014.285>.
- Rubaiyat Reza Habib, A. K. M., and Karyssa Butler. "Environmental and Economic Comparison of Hydrogen Fuel Cell and Battery Electric Vehicles." *Future Technology*, vol. 1, no. 2, Aug. 2022, pp. 25–33, fupubco, <https://doi.org/10.55670/fpl.futech.1.2.3>.
- Santini, Danilo J. *Electric Vehicle Waves of History: Lessons Learned about Market Deployment of Electric Vehicles*. Intech, Sep. 2011, (is a book – No pages required) 20file.org, <https://doi.org/10.5772/22411>. (only use page number if use above quotation)
- Sharma, Vikas, et al. "A review on the transition from conventional to bipolar designs of anode-less all-solid-state batteries." *Royal Society of Chemistry*, vol. 2024, no. 3, May 2024, pp. 1222-1237, rsc.org, <https://doi.org/10.1039/D4YA00138A>
- Sun, Huaihu, et al. "Lithium dendrites in all-solid-state batteries: From formation to suppression." *Battery Energy*, vol. 3, no.3, Jan. 2024, (no pp.), Wiley, <https://doi.org/10.1002/bte2.20230062>.
- Thomas, Felix, et al. "Technological Advances and Market Developments of Solid-State Batteries: A Review." *Materials*, vol. 17, no. 1, Jan. 2024, pp. 1-29, Multidisciplinary Digital Publishing Institute, <https://doi.org/10.3390/ma17010239>.
- Ulvestad, Andrew. "A Brief Review of Current Lithium-Ion Battery Technology and Potential Solid-State Battery Technologies." *arXiv*, 1803.04317, Mar. 2018, (no pages available) Top of Form <https://doi.org/10.48550/arXiv.1803.04317>.
- United States, United States Environmental Protection Agency. "Smog — Who Does It Hurt? What You Need to Know About Ozone and Your Health." EPA-452, July 1999, K-99-001, www.epa.gov/sites/default/files/2015-06/documents/smog.pdf.
- Yu, Pengli, et al. "Fuel Cell Hybrid Electric Vehicles: A Review of Topologies and Energy Management Strategies." *World Electric Vehicle Journal*, vol. 13, no. 9, Sept. 2022, pp. 172-191, MDPI (Multidisciplinary Digital Publishing Institute), <https://doi.org/10.3390/wevj13090172>.

Yu, Xiqian, et al. "Battery Safety: From Lithium-Ion to Solid-State Batteries." *Engineering*, vol. 21, (no no.), Aug. 2022, pp. 9–14, ScienceDirect, <https://doi.org/10.1016/j.eng.2022.06.022>.

Zhang, Wenyue, et al. "The Alternative Path for Fossil Oil: Electric Vehicles or Hydrogen Fuel Cell Vehicles?" *Journal of Environmental Management*, vol. 341, Sept. 2023, pp. 118,019-118,030, ScienceDirect, <https://doi.org/10.1016/j.jenvman.2023.118019>.