Electric Vehicle Transportation Center

Analysis of Fuel Cell Vehicle Developments

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I. Abstract

A fuel cell electric vehicle (FCEV) is a type of electric vehicle that uses a fuel cell to power its electric motor. FCEVs are targeted to provide customers with the benefits of battery electric vehicles such as low to zero emission, high performance, and low maintenance, without compromising range and refill time. This report investigated over a hundred FCEV models that have been developed in the past fifty years. A historic timeline of FCEV development was presented. The fuel cell powertrain configurations and fuel cell sizes of these FCEV models were statistically studied. The analysis reveals that for pure fuel cell cars, most of the fuel cell sizes range from 80-100 kW, while for fuel cell/battery hybrid cars, the fuel cell sizes range from 20 to 100 kW.

II. Introduction

A FCEV uses a fuel cell and an electric motor as its propulsion system. The onboard fuel cell directly converts chemical energy to electric energy. A hydrogen fuel cell is the most popular type that has been used in fuel cell vehicles. It consumes hydrogen and oxygen as fuels and only produces water vapor and heat as exhaust products. Therefore a hydrogen fuel cell vehicle produces zero tailpipe greenhouse gas (GHG) emission. Since hydrogen can be produced in several methods such as steam methane reforming and electrolysis of water, the adoption of FCEVs would significantly reduce a country's dependence on foreign oil. Unlike battery electric vehicles which has limited ranges and requires prolonged charging time, FCEVs can be refilled in the matter of minutes and have ranges up to several hundred miles.

FCEVs have been in and out of the spotlight of the auto industry a couple of times and this technology has been considered by many skeptics to be the "technology in the distant future". Despite numerous technical and political obstacles during its development, FCEVs have recently regained public attention with the announcements of their commercialization in 2015 by two major automakers. To better understand the future of the FCEV, and its role in the electric vehicle arena, it is important to look at this technology from both historical and technical points of view. This report systematically examines the historical background and technical specifications of FCEVs from automakers worldwide. It should serve as one of several mechanisms in the Electric Vehicle Transportation Center's (EVCT's) Fuel Cell Vehicles Project to help stakeholders to gain insight on the opportunities and challenges associated with FCEVs market introduction.

III. Results and Discussion

3.1. Timeline of Major Events in the Fuel Cell Vehicle History

Since the invention in 1838, fuel cells had been used in various applications such as in spacecraft, submarine, and stationary power plants. The first fuel cell powered vehicle was produced by General Motors (GM) in 1966, named GMC Electrovan.[1] It was the result of two year development effort lead by Dr. Craig Marks and utilized 32 fuel cell modules with a continuous output of 32 kW and a peak power of 160 kW. The fuel used was pure liquid hydrogen and liquid oxygen. The Electrovan achieved a top speed of 70 MPH and had a range of 120 miles. However, the whole fuel cell system turned the 6-seat van into a 2-seater due to the large hydrogen and oxygen tanks along with the piping. Figure-1 shows an illustration of its internal structure. After test driving in the GM facility and being shown off to journalists, the project was discontinued due to the prohibitive cost and lack of hydrogen infrastructure at that time.

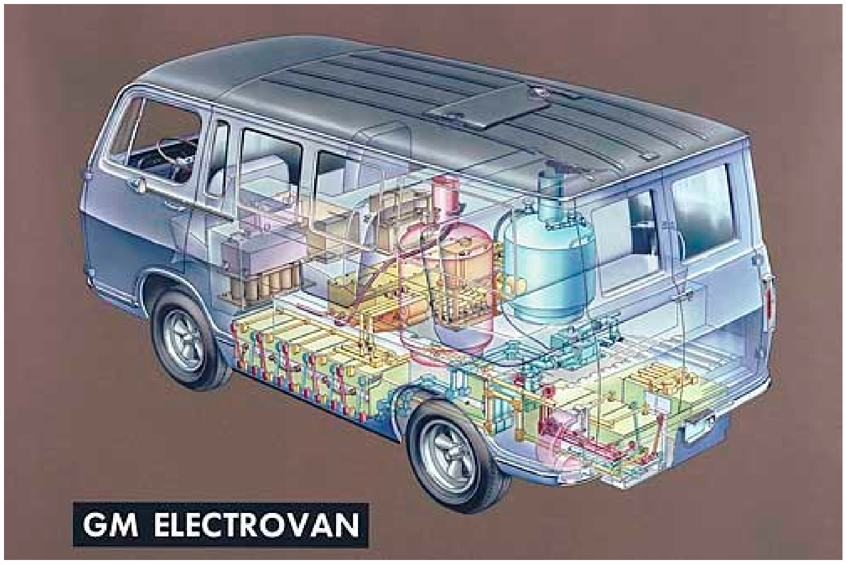

Figure-1. Illustration of the GM 1966

Almost thirty years later, the fuel cell technology was revisited by automakers. Daimler-Benz introduced the NECAR 1-the New Electric Car Number 1- to the public in 1994.[2] The 50 kW Proton Exchange Membrane (PEM) fuel cell was manufactured by Ballard which has become one of the leading PEM fuel cell manufacturers. The NECAR-1 utilized a compressed hydrogen tank that stored the gas at 300 bar and achieved a top speed of 56 mph and range of 81 miles. The fuel cell and the storage system, like the GM Electrovan, also took up the entire cargo space and left only two-seat space in the van. NECAR-2, introduced two years later was featured a fuel cell system one third of the weight of its predecessor.

During 1996 to 1999, several major automakers such as Toyota, GM, Mazda, Ford, Honda, Nissan, and Volkswagen also brought fuel cell vehicles projects to fruition. They employed fuel cells ranging in power from 10 to 75 kW and demonstrated vehicle ranges of up to 310 miles. Many of these auto companies had set goals to commercialize fuel cell vehicles in 2003-2004 timeframe, however, none of these goals were realized.

In 2002, Toyota launched the world's first limited leasing of its fuel cell hybrid vehicle (called FCHV) in the USA and Japan. Its powertrain comprised a 90 kW fuel cell and a nickel-metal hybrid battery. At low speed the FCHV runs on battery alone. The fuel cell and battery supplied power in tandem when higher performance was required. The combined range of the fuel cell and battery was 155 miles. Since then, eight major automakers have put in significant efforts to test the real-world performance of the fuel cell vehicles. Table-1 lists notable real world demonstration projects, out of which GM, Honda, and Toyota all had fuel cell fleets in excess of 100 vehicles.

Table-1. Real-world demonstration projects of fuel cell vehicles and their specifications.

Year	Automaker	Model	Engine	FC Power (kW)	Range (miles)	Max speed (mph)	Hydrogen Pressure (Bar)	Note
2002	Toyota	FCHV	Fuel cell/ battery hybrid	90	180	96	350	18 leased in California and Japan
2002	Daimler	A-Class F-CELL	Fuel cell/ battery hybrid	85	90	87	700	60 vehicles in US, Japan, Singapore, and Europe started in 2003
2002	Ford	Advanced Focus FCV	Fuel cell/ battery hybrid	85	180	n/a	350	30 fleet vehicles in Sacramento, Orlando, and Detroit
2002	GM	Advanced HydroGen3	Fuel cell	94	170	100	700	6 placed in Washington DC
2002	Nissan	X-TRAIL	Fuel cell/ battery hybrid	75	n/a	78	350	3 leased to Japanese government
2004	Hyundai	Tucson	Fuel cell/ battery hybrid	80	185	93	350	Demonstration project in the US between 2004-2009 and in Korea between 2006-2010
2004	Kia	Sportage	Fuel cell	80	185	93	n/a	Demonstration project in the US between 2004-2009 and in Korea between 2006-2010
2006	GM	Equinox FCEV	Fuel cell/ battery hybrid	93	200	100	n/a	Leasing started in 2007. 100 vehicles in California, New York, and Washington DC
2007	Honda	FCX Clarity	Fuel cell	100	354	100	350	Small scale production of 200 vehicles between 2008-2010, Leasing in Southern California and Japan
2008	Kia	Borrego/Mojave FCEV	Fuel cell/ super capacitor	115	426	93	700	Leasing to Seoul, Korean residents starting in 2009
2008	Toyota	FCHV-adv	Fuel cell/ battery hybrid	n/a	97	n/a	n/a	Limited leasing in Japan started in 2008. More than 100 leased in Connecticut, California and New York.
2009	Daimler	Mercedes-Benz B-Class F-CELL	Fuel cell	90	239	105	n/a	Small series production started in 2009. 70 Deployed in Los Angeles and San Francisco by 2012
2011	Hyundai	Tucson IX	Fuel cell/ battery hybrid	100	403	n/a	700	Tested 50 vehicles in 2011
2012	Hyundai	ix35	Fuel cell/ battery hybrid	100	365	100	n/a	Leasing in Sweden and Denmark started in 2012

One of the biggest pushes in recent years to mature hydrogen and fuel cell technology for transportation was the $1.2 billion funding issued by the Bush Administration in 2003. One of the key projects was the U.S. Department of Energy's (DOE's) $ 170 million Controlled Hydrogen Fleet and Infrastructure Validation and Demonstration Project. The objective of this project was to test small fleets of FCEVs plus fueling stations to demonstrate their use in five regions in the United States. The five test regions were located in Northern California, Southern California, Southeastern Michigan, the Mid-Atlantic, and Central Florida, covering a range of temperature and humidity conditions. DOE selected four automobile manufacturer/energy company teams to participate in the project— Hyundai-Kia/Chevron, DaimlerChrysler/BP, Ford/BP, and GM/Shell. Together, they deployed 183 FCEVs, and more than 500,000 individual vehicle trips covering 3.6 million miles were traveled.[3] The DOE's 2009 targets of 250 mile range, fuel cell durability of 2000 hours, and fuel cell efficiency of 60% were met during the demonstration. Real-world driving conditions such as climate compatibility were also tested. In a separate demonstration project in 2009, Toyota collaborated with Savannah River National Laboratory to evaluate the on-road performance of the Toyota FCHV-adv vehicles. An average range of 431 miles was obtained during a 1-day test in Southern California, well exceeding the 250 mile DOE target.[3]

Toyota and Hyundai announced their first commercially available fuel cell vehicles for 2015 (limited lease program started in 2014). The leases will be first available in California where the public hydrogen fueling stations are located. The specifications of these vehicles are shown in Table-2. Both models show similar ranges that exceed the best battery electric car in the current market (the Tesla Model S-85 with 265 miles in range). The fueling time for both models is comparable to gasoline vehicles, which presents a significant advantage over the battery electric car which requires at least 30 minutes to get to ~80% of its range capacity. Toyota plans are to lower the price to achieve an anticipated full scale market penetration in the decade of 2020s.[4]

Table-2. Specifications of the 2015 Hyundai and Toyota FCEVs.[4-5]

Maker	Model	Fuel Cell Power (kW)	Range (miles)	Fueling Time	Price	Note
Hyundai	Tucson Fuel Cell	100	265	<10 min	Lease at $499/month, $2999 due at signing	Price includes fuel and maintenance
Toyota	Mirai	unrevealed	435	3 min	¥ 7 million in Japan ($68600)	n/a

In 2013, Ford, Nissan, and Daimler signed a deal to jointly develop affordable fuel cell vehicles to be commercialized by 2017.[6] A GM and Honda partnership is also aiming to bring fuel cell vehicles to the market by 2020.[7] A timeline summarizing major events in the fuel cell vehicle development is shown in Figure-2.

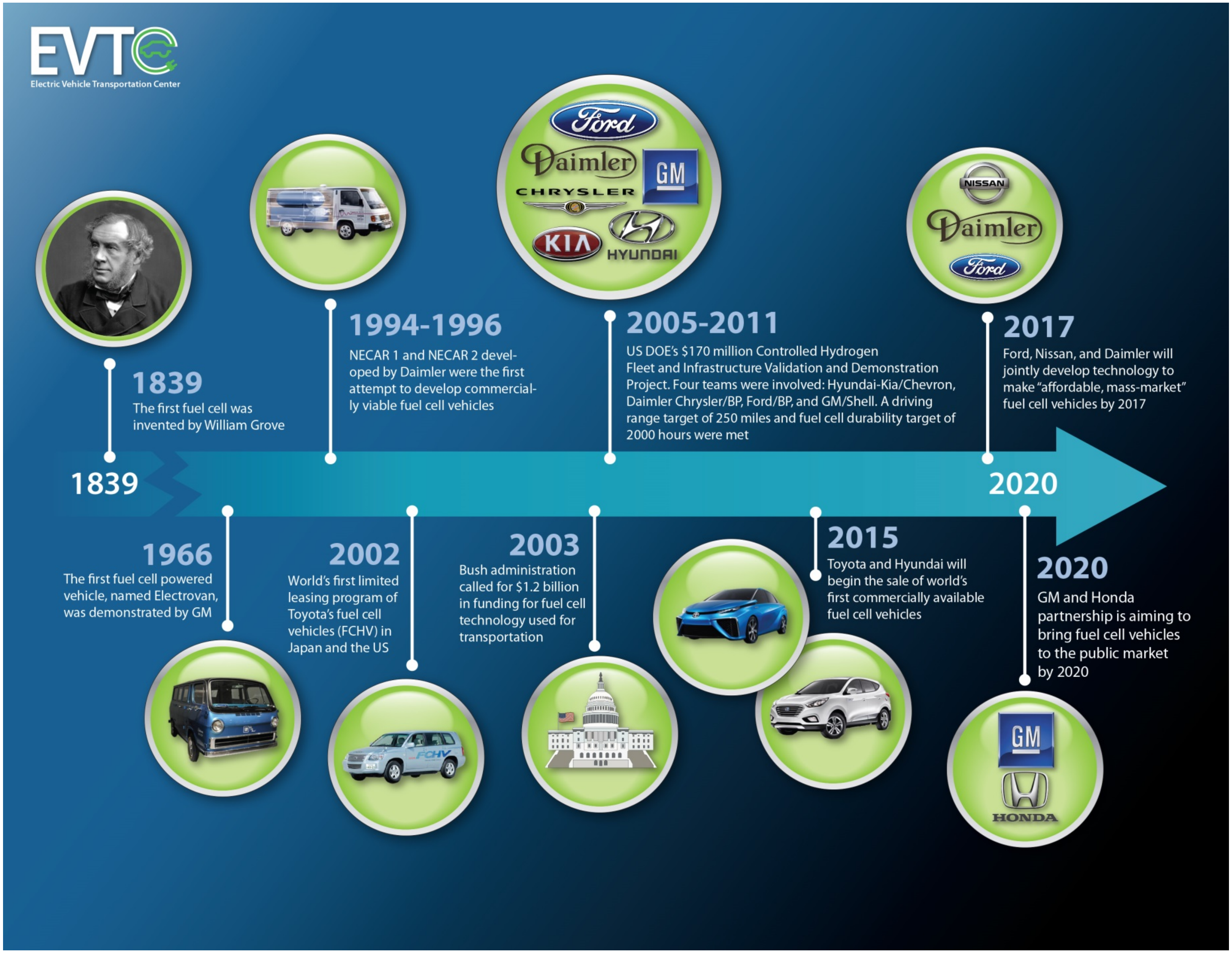

Figure-2. Timeline of major events in fuel cell vehicle developments.

3.2 . Analysis of Major FCEV Models

These analyses are based on the data collected by Fuel Cells 2000's.[8] It contains the specifications of major FCEV models including concept vehicles released since 1994. A total of 117 models from 31 automakers have been analyzed. Most models utilize hydrogen in the form of compressed gas, liquid, or in metal hydride. Only 9% of the models use other fuels such as methanol. Figure-3 shows the top ten automakers in terms of the number of FCEV models they produced. It reflects to a certain extent the research and development efforts of different automakers. Many of these top ten companies such as Daimler, GM, Honda, Hyundai, Toyota, and Ford are in the frontier of the FCEV commercialization, as mentioned in the section 2.1. Nissan is very active in the battery electric vehicle market with the success of Nissan Leaf so its attention on the FCEVs might be compromised.

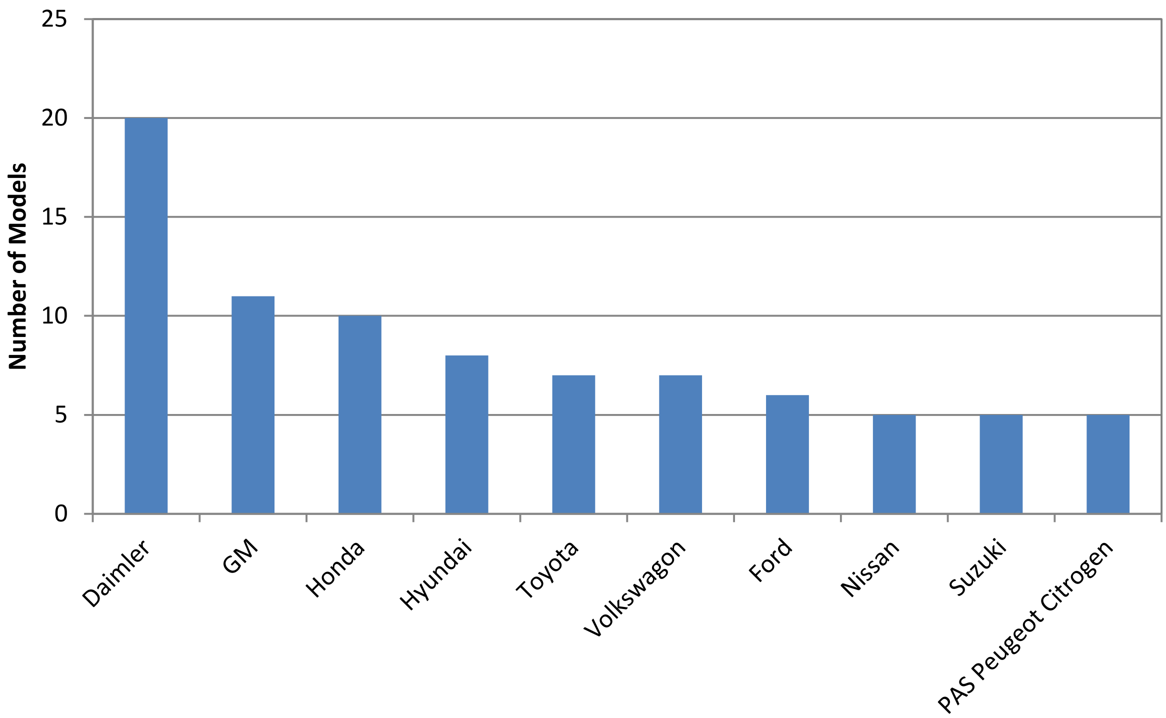

Figure-3. Top ten automakers with the most FCEV models.

Figure-4 depicts the number of models produced in three-year periods from 1994 to 2012. The numbers on each column are the number of automakers that produced FCEVs during that period. This data reflects the popularity and perception of the FCEVs in the auto-industry. Since the introduction of NECAR 1 by Daimler, there had been a race towards the commercialization of

FCEVs, as suggested in the increasing trend of both the models and automakers during the decade of 1994 to 2003. However, due to the technical difficulties such as the fuel cell size and durability, lack of efficient hydrogen storage options, prohibitive price of the metal catalyst, and lack of hydrogen fueling stations, the development of FCEVs slowed down after the first ten years of development. Then in 2003, the federal administration spurred a new round of intense FCEV research and development that led to the boost of models in 2008-2011, as shown in Figure-4. In 2009, the DOE shifted emphasis to lithium ion battery technology and reduced the funding to fuel cell R&D. This led to a decrease in the number of models introduced in the 2012-2014 period. At present FCEV development did also benefit from the California's zero-emission vehicle act which would require automakers to sell an estimated 1.4 million fuel-cell vehicles, electric vehicles and plug-in hybrids in California by 2025. California has pioneered adoption of FCEVs and is building public hydrogen fueling stations. The sale of Toyota and Hyundai's FCEVs will be limited to California initially.

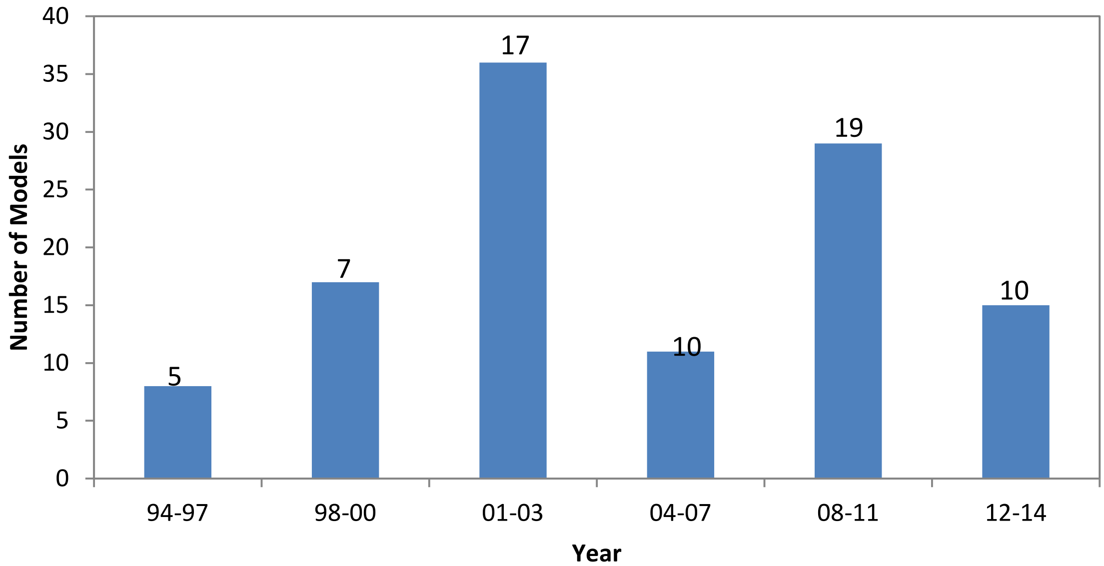

Figure-4. The historical FCEV model development trend. The value above the columns are the number of automakers.

3.3. Technology Development

The fuel cell powertrain is a modular assembly. Figure-5 compares the popularity of different power train configurations of all the FCEV models. Even though all fuel cell vehicles are equipped with a battery of a certain size, there are some notable differences between a fuel cell power train and a fuel cell/battery hybrid or a fuel cell/super capacitor power train. A fuel cell power train usually suffers from poor response time and low traction power during start up. The role of the energy storage system (ESS) in a fuel cell vehicle is to: 1) capture the regenerative braking to increase the fuel efficiency; 2) Provide traction assistance during acceleration to compensate fuel cell's slow ramp rate; 3) Provide traction assistance during high power transients so that a smaller fuel cell can be used; 4) power electrical accessories.[9] In other words, in a fuel cell/ESS hybrid vehicle, the fuel cell provides power for cruising, and when the vehicle is accelerating or climbing hills, both the fuel cell and the ESS provide power. The fuel cell/battery hybrid or the fuel cell/super capacitor hybrids were adopted in 30% more models than a pure fuel cell power train. A vehicle with a fuel cell range extender is a relatively new concept. In this case, the electric motor for propulsion is solely powered by a battery. The fuel cell generates electricity to recharge the battery, similar to the concept of the Chevy Volt which uses a gasoline engine as a range extender.[10]

A vehicle with this power train configuration is usually equipped with a larger battery than pure fuel cell or fuel cell/battery hybrid vehicles that can give a 20-50 mile range on the battery alone. Therefore, the vehicle can operate without the frequent need for hydrogen fueling. A fuel cell range extender vehicle is an active area of EVTC research.

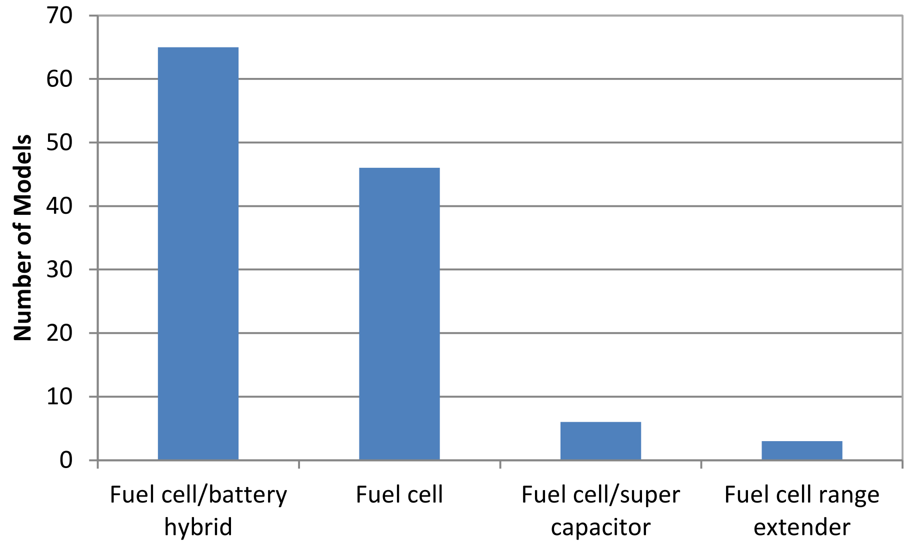

Figure-5. The power train configurations of different FCEV models.

The analysis of FCEV models from the top ten automakers is shown in Figure-6. A total of 83 models were considered. Figure-6 shows the fuel cell power for pure fuel cell and fuel cell/ESS hybrid vehicles. For pure fuel cell cars, most of the fuel cell sizes range from 80-100 kW, with the exception of 50 kW size for the very early models developed in 1994-1998. The eletric motor in a Nissan Leaf battery electric car is 80 kW, so a 80-100 kW fuel cell is probably sufficient to achieve performance similar to a Nissan Leaf as it can power a similar size electric motor. For a fuel cell-ESS hybrid vehicle, the size range of the fuel cell is much larger, from 20 to 100 kW, as a smaller fuel cell can be compesented by a larger battery. However, fuel cells larger than 60 kW are favored.

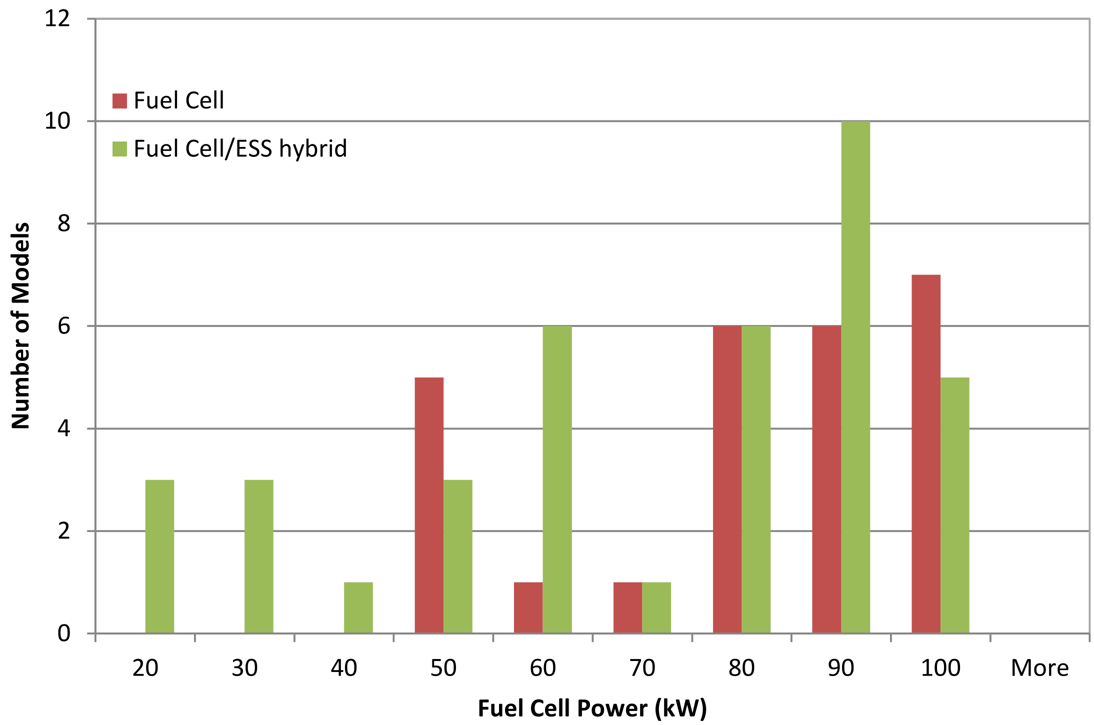

Figure-6. Range of FCEV powertrain for models from the top ten FCEV automakers.

IV. Conclusion

Since the first fuel cell powered vehicle was introduced by GM in 1966, the FCEVs have become a potential solution to the energy and environmental challenges caused by use of fossil fuels in transportation. A timeline showed an accelerated development of FCEVs since their first introduction in 1966. Over thirty automakers from around the world have demonstrated over one hundred FCEV models in the past two decades, representing a significant investment towards the research and development of FCEVs. The variety of fuel cell sizes and powertrain configurations in the different models appears to provide the automakers with a portfolio from which they can optimize future FCEV parameters. As a result of these efforts and government support, this technology is finally beginning to reach commercialization.

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