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BATTEN REPORT

IMPROVING THE WORLD THROUGH ENTREPRENEURSHIP AND INNOVATION **NOV 2017**

PATH TO 2060:

Decarbonizing the Automobile Industry

The Future is Electric and it's Complicated

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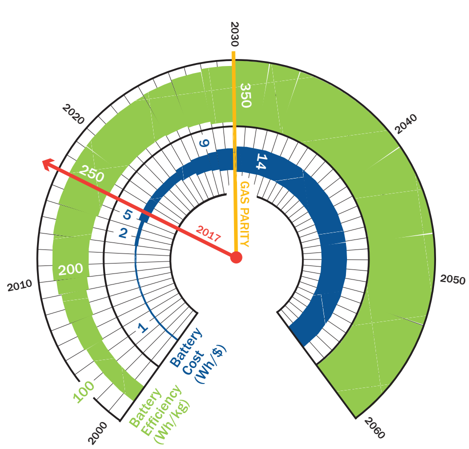
SNAPSHOT

Scientists assert that global warming must be kept below two degrees Celsius to avoid insurmountable global disruption. Getting there will require near total ***decarbonization of economic activity by 2060.***

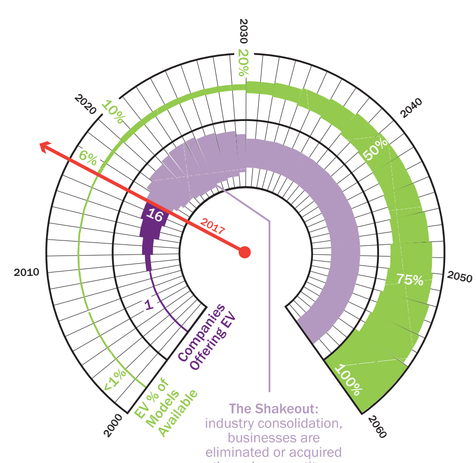
Innovative technologies being introduced by forward-thinking companies like Tesla and Toyota are ***disrupting the automobile industry*** *and changing the way we own and operate cars.*

Electric technologies have the potential to decarbonize the passenger car market by 2060 but will benefit from ***continued support through government policies and other market forces.***

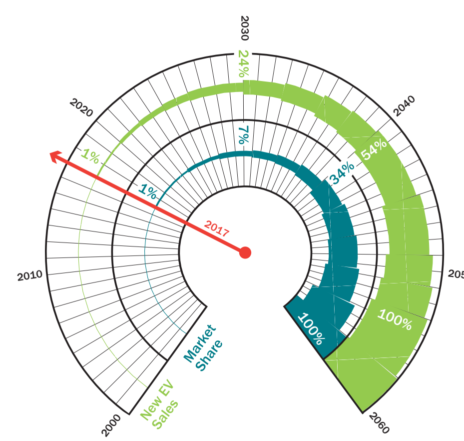
Technology Efficiency



Competitiveness



Market Penetration



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WHY LOOK AT AUTOMOBILES?

IN THE 2015 PARIS CLIMATE ACCORD, countries pledged to commit to greenhouse gas emission reductions so as to limit global warming to no more than two degrees Celsius from preindustrial levels. According to research by Climate Interactive and MIT, achieving this goal would require limiting total cumulative global emissions to 2,900 gigatons of CO_2. Since the Industrial Revolution, we have emitted 2,100 gigatons of CO_2, which leaves a remaining carbon budget of 800 gigatons.[1] To limit global emissions to this number within the century would require near total decarbonization of global economic activity by 2060.

The transportation sector alone accounts for a quarter of U.S. greenhouse gas emissions.[2] In this report, we assess the potential for decarbonization of the automotive industry by 2060. First, we take a look at the evolution of the electric car over the last 100 years, and the government policies and market conditions that paved the way for zero-emission vehicles. Then, we take a closer look at battery and fuel cell electric technologies, including where they are on their respective S-curves, and projections for growth in the U.S. and globally. We conclude with our hypothesis on the future of the automobile industry and the levers that need to be pulled to help facilitate the transition from fossil fuels to electric. For the purposes of this analysis, we define decarbonization as the adoption of zero-emission technologies such as battery-powered or hydrogen fuel cell–powered electric vehicles. We do not analyze potential upstream carbon emissions due to the need to create electricity to power batteries or create hydrogen to power fuel cells, nor the potential for greenhouse gas emissions during the manufacturing of vehicles. While we recognize the importance of innovation across all transportation subsectors we focused our research on passenger vehicles. One might expect that the technologies and levers discussed in this report would be applicable to electrification efforts in other transportation subsectors as well.

THE ROAD TO DECARBONIZATION

THIS PAST YEAR, TESLA STARTED DELIVERY of the much-anticipated Model 3, a price-conscious electric vehicle able to compete with gasoline on cost and performance, filling orders for a waiting list of more than 400,000 customers.[3] Volvo announced plans to discontinue sales of all gasoline-only vehicles by 2019,[4] and Toyota predicts it will sell 30,000 fuel cell vehicles by 2020.[5] Fully autonomous cars are expected to appear on highways by 2021, and Uber and Google are working on smart cars. The automobile industry is in the midst of a major disruption, one that will likely unseat previous industry goliaths and have significant impacts on other sectors.

Concern about the impact of fossil fuels on the climate is helping drive this disruption. The share of worldwide greenhouse gas emissions attributed to the transportation sector is estimated at 14%.[6] Last year at the Marrakech Climate Change Conference (COP22), eight nations, including Canada, China, France, Japan, Norway, Sweden, the UK and the U.S., signed a declaration of commitment to increase the share of electric vehicles in government fleets.[7] Norway, India, France, and Britain have announced gasoline and diesel bans by 2025–2040.[8] More recently China, now the world's largest vehicle market, announced plans for putting regulations in place that will ban the sale of all fossil fuel vehicles (although timing is still under discussion).[9] With future U.S. Corporate Average Fuel Economy (CAFE) standards now being reviewed by the current administration, California and more than a dozen other states are moving forward with their own zero-emission vehicle strategies.

THE ROAD IS LONG

Even if 100% of all new sales are zero-emission vehicles going forward, we would expect it would take at least 20 years to completely decarbonize the industry as the stock of existing vehicles slowly turns over. Of course, policies to accelerate the retiring of old gasoline-powered cars may shorten this time period. However, given that zero-emission vehicles currently make up less than 1% of all new vehicle sales,[10] the time to decarbonization will likely be substantially longer even under the most optimistic of scenarios. A 2017 report by Bloomberg New Energy Finance estimates that only 33% of cars on the road will be electric vehicles by 2040.[11]

On a more positive note, trends in the automotive industry in terms of technology, innovation, and competition give reason to believe that it is in the early stages of a major technology disruption. Hybrid electric vehicles have been instrumental in preparing the market for this disruption. The technology has been successful at serving as a bridge between gasoline and fully electric cars, slowly building a green customer base and opening the door to new, innovative technologies that go beyond the pump. Several zero-emission alternatives to gasoline-powered internal combustion engines exist today that could move us into a clean transportation future, primarily battery-powered and fuel cell–powered electric vehicles. While overall sales of electric vehicles are small, they are growing at a robust rate.

WE ARE IN THE EARLY STAGES

We assert that we are in an "era of ferment" for electric vehicles. We see significant entry by both new ventures and by established incumbents. A dominant design for electric vehicles has yet to emerge. While battery-powered electric vehicles have established an early lead, hydrogen fuel cell-powered electric vehicles are receiving considerable attention from major players within the industry. Over the next five years, we predict that we will see increased activity in this space as more start-ups find opportunities to enter the market and incumbents diversify into electric vehicles. Partnerships will form around specific technologies and these relationships will be critical to determining the long-term technology winners. As technologies improve and mature, costs will come down, increasing demand. Eventually, a competitive shakeout will likely ensue with a heavy turnover as many new entrants and established car manufacturers struggle and exit the market. In the wake of this shakeout, we expect new leaders will emerge that may not be traditional car manufacturers.

While there are no guarantees, there are reasons to believe that the automotive industry could be decarbonized by 2060, especially if policies are adopted to help accelerate the adoption and advancement of zero-emission technologies. In this briefing, we explore the factors impacting the speed of disruption and the levers that could be pulled so as to accelerate decarbonization of the transportation sector. One thing is clear, after more than 80 years of dominating the automobile market, the future does not appear to be gasoline internal combustion engines.

ELECTRIC: THE 100-YEAR-OLD "NEW" TECHNOLOGY

JUST HOW LONG WILL IT TAKE TO DECARBONIZE the automobile industry? The last time the automobile market saw a major technology battle was during its advent at the turn of the 20th century. Often forgotten is that electric vehicles dominated the U.S. market in the late 1800s. Gradually, electric vehicles lost out to gasoline internal combustion engines, though that replacement was not complete until 1935 (see Early Electric Cars). Why will electric vehicles emerge triumphant this time around, and how long will it take? To answer that question, we need to first take a look back at the last 40 years and the evolution of the modern electric car and the market influences that paved the way for the technology's more recent success.

EARLY ELECTRIC CARS. *Due in part to health and environmental concerns that manure from horse-drawn carriages created on city streets during the late 1800s, people looked to the newly invented automobile as a "clean" alternative. Early automobiles varied greatly in their design and included electric-, steam-, and gas-powered offerings. While early steam- and gas-powered technologies were off-putting—steam required long start-up times and gas-powered engines required a hand crank to get started and were dirty and noisy—electric cars were clean, quiet, and easy to operate. With greater access to electricity came an increase in demand for electric cars. But the dominance of the electric car was short lived. In 1908, Henry Ford introduced the Model T, the first mass-produced and affordable gas-powered vehicle. By 1912, the gas-powered car cost only $650 compared to electric vehicles with prices almost three times that amount. By 1920, the cost of the Model T was cut in half due to assembly line production. Charles P. Kettering's invention of the electric starter, national expansion in road infrastructure, and the discovery of Texas crude oil put gasoline-powered cars firmly in the lead. By 1935, electric passenger cars were extinct.*[12]

STARTING THE INNOVATION ENGINE

In 1975, the U.S. government imposed new standards for sales-weighted vehicle fleet fuel economy (27.5 mpg by 1985) largely in response to the 1973 oil embargo, forcing the automobile industry to innovate. During this time, the first production catalytic converter was introduced, scrubbing tailpipe emissions, and was quickly adopted due to new federal regulations on air pollutants. A renewed interest in electric car technologies emerged, facilitated by the 1975 Electric and Hybrid Vehicle Research, Development, and Demonstration Act under which the U.S. government partnered with industry to improve batteries, motors, controllers, and other hybrid-electric components. Manufacturers like General Motors (GM) began developing electric car prototypes. The technology, however, was hampered by limited performance compared to gas-powered cars—maximum speeds of 45 mph and driving range of around 40 miles.[13]

By the 1980s, with a new administration in the White House, automobile manufacturers lobbied to lower CAFE standards to 26 mpg. But the innovation engine continued to hum, with manufacturers working to improve designs for electronic ignition and introducing electronic fuel injection and valve timing and lift technologies increasing fuel efficiency and further reducing tailpipe pollutants. By 1990, the 27.5 mpg level was restored and new vehicle average fuel efficiency had surpassed this limit, reaching 28 mpg.[14]

The Energy Policy Act (EPACT) of 1992 and the 1993 Partnership for New Generation of Vehicles initiative continued to support alternative fuel vehicle innovation. The 1993 industry partnership initiative resulted in three hybrid-diesel cars developed by GM, Ford, and Chrysler, all of which reached fuel efficiencies greater than 70 mpg. The initiative was criticized by some for its diesel fuel focus but the research and development led to several breakthroughs in technology, including reductions in lighter-weight component costs and advancement of Li-ion batteries and fuel cells.[15] EPACT set requirements of federal fleets to acquire alternative fuel vehicles and provided authority to the U.S. Department of Energy (DOE) to create the Clean Cities initiative with the goal of providing resources and support to regulated and nonregulated fleets looking to adopt alternative fuel approaches.

THE REBIRTH AND DEATH OF ELECTRIC VEHICLES

In 1990, a new zero-emission vehicle mandate put forth by the California Air Resources Board (CARB) opened the door once again to electric cars. The mandate required that 2% of vehicles sold in California must have zero emissions by 1998, 5% by 2001, and 10% by 2003.[16] By the mid-1990s, other states began to adopt the standards and automakers worked to modify existing gasoline models. GM was the first to introduce an electric vehicle in response to the CARB standards. GM's EV1 model introduced in 1997 could compete with gas-powered cars on speed (0–60 mph in 9 seconds) and price ($35,000), but offered suboptimal ranges between 70–90 miles along with a 15-hour charge time.[17] Car battery R&D efforts ramped up as the industry moved from lead acid to nickel metal hydride (NiMH) technologies that promised longer ranges, and other companies became interested in pursuing electric options.

GM launched a leasing program in California putting 1,000 cars on the road but by 2002 discontinued EV1 production citing low consumer demand and profits.[18] GM repossessed and crushed all of the cars on the road, donating a few to museums. Due to challenges posed by automakers in meeting the timeline and lawsuits filed against CARB, zero-emission standards were relaxed and the scope expanded to hybrids.[19] The documentary "Who Killed the Electric Car" places blame on several parties, including automakers, oil companies, and consumers. GM is accused of lobbying against the mandate even while producing the EV-1 model.[20] Once again, electric cars disappeared from the market.

HYBRIDS: THE BRIDGE BETWEEN PAST AND FUTURE

THE FIRST DECADE OF THE 21ST CENTURY saw an explosion of innovative activity around fuel efficiency as federal regulations tightened, gasoline prices increased, and consumer interest in alternative fuel vehicles grew.

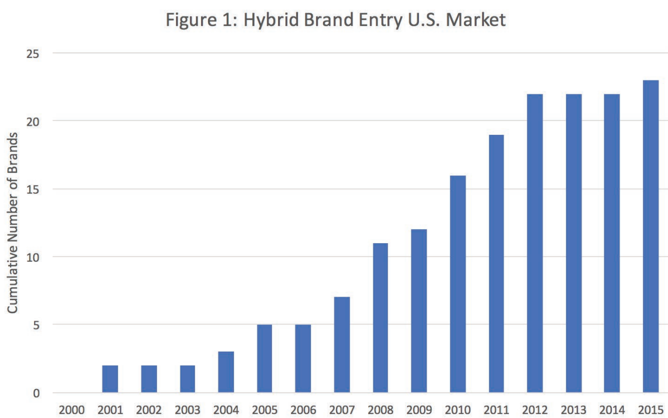
In 2000, after success in the Japanese market, **Toyota** introduced its Prius hybrid model to the U.S. and worldwide. Not only was the Prius the first mass-produced electric hybrid, but it came with a reasonable price tag—just under $20,000 at retail.[21] At the end of that first year, Toyota had sold 5,500 cars and by 2005 Prius annual sales exceeded 100,000 in the U.S.[22]

But Toyota wasn't the first to market. A few months before the Prius, **Honda** released its Insight hybrid car in the U.S. Offering an impressive 53 mpg, the Honda seemed poised to be the market leader. Its two-door and covered rear wheel design, however, lost to the Prius's more family-friendly four-door design and expansive cargo space despite the Prius's lower 41 mpg EPA rating,[23] suggesting that form and function reign when it comes to consumer choice.

In 2001, the Freedom Car Initiative was launched under the George W. Bush administration to assist in the development of emission- and petroleum-free vehicles. However, the initiative would receive criticism from some in the environmental community for focusing on longer-range technologies such as fuel cells and ignoring more immediate opportunities.[24]

WHERE TOYOTA LEADS OTHERS FOLLOW

Recognizing increasing consumer interest, other companies began to more heavily invest in hybrid technologies and the number of hybrid electric vehicle class U.S. patents filed in 2000 doubled by 2002.[25] Over the next five years, **Chevy, Lexus, Ford, Mercury, Saturn, GMC,** and **Cadillac** all introduced at least one hybrid model and annual U.S. hybrid vehicle sales exceeded 350,000 by 2007,[26] or 3% of total new car sales (up from 0.17% in 2000).[27]



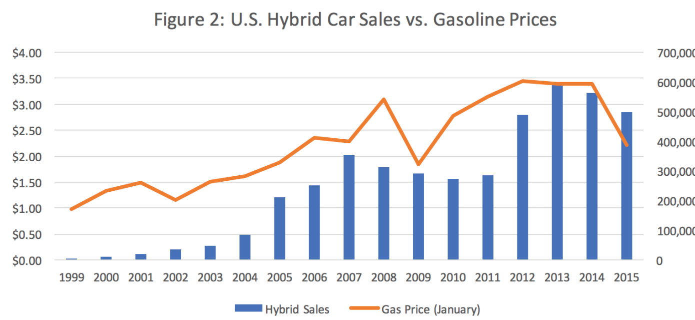
Source: U.S. DOE Alternative Fuels Data Center (Hybrid Vehicle Sales by Model Table)

Gasoline prices continued to rise, breaking $3 per gallon in May 2007,[28] and hybrid sales in the U.S. continued to rise alongside these increasing costs (see Figure 2).

By July 2008, the price of gasoline reached an all-time high of $4.11 per gallon[29] and the U.S. entered into a recession created by the subprime mortgage crises and collapse of the housing bubble. In 2009, total vehicle production in the U.S. dipped to its lowest level since 1960.[30] While hybrid sales also saw a slight decrease, overall demand remained fairly steady due, in part, to high gasoline prices.

NEW CAFE STANDARDS DRIVE CONTINUED INNOVATION

Continued industry investment in hybrid technologies was also driven by President Obama's announcement in 2009 of revised CAFE standards set at 35 mpg by 2020 under the Energy Independence and Security Act. More stringent CAFE fleet-wide average standards followed three years later—54.6 mpg by 2025 along with a CO_2 limit for passenger cars—and U.S. hybrid sales responded, increasing by 60% compared to 2011.[31] Customers purchasing hybrid vehicles after 2010 received a federal income tax credit up to $7,500, further incentivizing the switch to alternative vehicles.



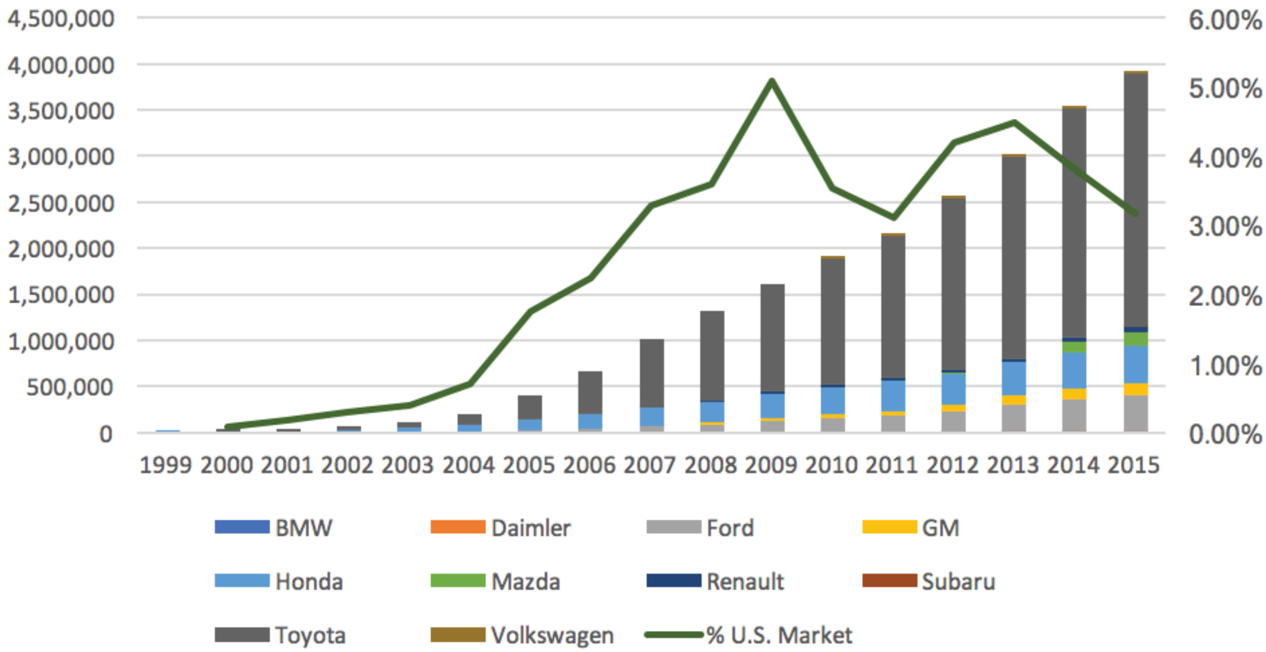
Sources: U.S. DOE Alternative Fuels Data Center (Hybrid Vehicle Sales by Model) and U.S. Energy Information Administration (U.S. All Grades All Formulations Retail Gasoline Prices Dollars per Gallon)

Since 2000, manufacturers have introduced into the U.S. market more than 100 hybrid models[32] across all car types—cars, trucks, and SUVs. With more stringent CAFE standards on the horizon, automakers continued to expand their model lines to offer consumers more choices.

HYBRID SALES SLOW IN THE U.S....

Despite buy-in from car companies and federal incentives, U.S. sales of hybrids has begun to slow. Market share for hybrids has held relatively constant around 3% to 4% of annual automotive sales since 2007. Some industry analysts point to improvements in gasoline engine efficiency. The continued decline in gas prices may also be a deterrent to customers not necessarily committed to environmentally friendly purchases.[33] The green customer segment could simply be tapped out, while mainstream purchasers continue to be reluctant to make the switch. Finally, commercialization of plug-in electric vehicles may be a reason why hybrid sales penetration isn't growing.[34]

Figure 3: Cumulative U.S. Hybrid Sales by Parent Company



Sources: U.S. DOE Alternative Fuels Data Center (Hybrid Vehicle Sales by Model) and U.S. DOT, Bureau of Transportation Statistics, Annual U.S. Motor Vehicle Production and Factory Sales (Table 1-15)

…WHILE WORLDWIDE SALES GROW WITH ASIA LEADING

While the growth of hybrids in the U.S. has stalled, worldwide hybrid sales are gaining momentum, especially in Asia. Toyota, which owns more than 60% of the global hybrid market, recently announced that cumulative hybrid sales surpassed 10 million cars in February of 2017.[35] A market report released by JATO Dynamics in 2016 states that the global hybrid market is projected to grow to seven million by 2023.[36] Japanese sales are a large force driving worldwide hybrid sales; according to the JATO report, Japan represented 61% of total hybrid vehicle sales and 31% of in-country new car sales in the first eight months of 2016.[37] Government subsidies and tax breaks introduced in 2009 helped to drive initial demand for these vehicles in Japan.

China also seems to be propelling increases in demand in alternative vehicles in general, as population and rising per capita income increase along with concerns about air pollution. In October 2016, the Chinese government announced a hybrid target of 25% by 2030.[38] In Europe, it's estimated that hybrid sales will triple over the next three years to more than 750,000 as companies work toward stringent 2020 CO_2 reduction targets.[39]

Ultimately, hybrids have done a great job at pushing widespread adoption of alternative drive trains but may see the demise of their own success at the hands of electric vehicles. While Toyota has had more than a decade to learn from and improve their power-split powertrain design, seeing a 10% improvement with each generation of the Prius, for others this is not the case and companies have not seen their next big jump in innovation.[40] Ironically, the next big advancement in hybrid vehicles will likely be tied to improvements in battery technologies and those improvements may be more beneficial to battery-powered electric vehicles, which are closing the gap on hybrids.

Hybrids are increasingly looking like a bridge between traditional gasoline and electric designs as consumers become more comfortable with alternative fuel vehicles.

ELECTRIC: DISRUPTIVE AT LAST?

INCREASED CONSUMER DEMAND FOR HYBRIDS opened the door once again for electric, but like many other mature industries, the larger, established manufacturers wouldn't be the ones to take the lead in innovation.

Enter Tesla Motors. Founded by Martin Eberhard and Marc Tarpenning, Tesla unveiled its first production battery electric car, the Roadster, in 2006. With the help of financing by the chairman of the board, Elon Musk, the Roadster would be the first highway-legal mass-produced all-electric car, offering consumers a travel range of 200 miles per charge at a hefty $110,000 price tag. The company sold 2,250 Roadsters by 2012. In 2008, Musk became CEO of the company and he brought with him a long-term vision for Tesla. His initial strategy was to use the profits from the Roadster to develop future models that appealed to the broader customer base, improving the design and driving down manufacturing costs along the way. In 2008, Tesla unveiled the Model S, a more affordable family sedan that seated seven people and came with a $50,000 base price. In 2009, Tesla joined forces with Daimler AG for a 10% stake in the company. But like many car companies coming out of the recession, Tesla struggled to stay afloat and in 2010 received a $465 million loan from DOE to help the company scale production. That year Musk won the Automotive Executive of the Year Innovator Award and the company went public, the first automobile manufacturer to do so since Ford in 1956.[41]

Tesla was not alone. Fisker Automotive, a start-up automotive company founded in 2007, promised to build the first commercialized plug-in hybrid. The company secured millions in funding over the next two years, including a $587 million loan from DOE through the Advanced Technologies Vehicle Manufacturing Loan Program. Of the total DOE funding, $169 million was initially given to Fisker to complete their first Karma vehicle with one caveat; the company had to meet a February 2011 commercial production milestone. Fisker missed this deadline and in June 2011, DOE issued a drawstop notice, essentially cutting off funding. The company pushed forward and in July delivered its first models to a chosen few investors and high profile parties, including Al Gore, followed by a retail offering before the end of the year.

Unfortunately in the years that followed, the Karma was plagued by battery fires and recalls, among other technical issues, which resulted in company bankruptcy by 2014.[42] Often in these situations, one company's demise leads to another's opportunity. Chinese auto parts company Wanxiang purchased Fisker's assets in 2014 for $149 million, as well as the assets of the battery company A123, which manufactured the defective cells in 2013, and rebranded the company as Karma Automotive. In the fall of 2016, the company revealed its first Revero model and announced plans to build a manufacturing facility in China capable of producing 50,000 electric vehicles.[43, 44] In May 2017, Wanxiang officially launched production of the Revero and distributed vehicles to Karma dealer showrooms.[45]

TESLA VS. FISKER. *Two start-up companies new to the automotive industry, offering cutting edge technology and poised to lead the industry toward an electric future. Why did only Tesla survive? Many industry experts say that it was Tesla's focus on developing battery, electric motor, and system control technologies in-house that gave them the advantage, both in terms of cost to manufacture and performance over other companies that were outsourcing. Today, Tesla is seeing even more benefits of this early focus as the company expands to other battery systems, closing the electric car loop with solar and home charging. Fisker's focus on simply making a beautiful car that would appeal to the luxury buyer while outsourcing battery and other manufacturing put much of the quality control in the hands of its vendor and at a steeper price, which contributed to the company's downfall.*

INCUMBENTS GET INTO THE ACTION

As is often the case, the efforts of entrepreneurial entrants attracted the interest of industry incumbants. Soon, established automakers were offering electric vehicles. In 2010, **Chevy** and **Nissan** released their own battery electric cars, the Volt (plug-in hybrid) and Leaf (battery electric).

GM would redeem itself after a disappointing first attempt with the EV-1 more than a decade prior to the release of the Volt, winning several awards for its design including the 2011 North American Car of the Year and 2011 Motor Trend Car of the Year.[46] Positioning the Volt as an extended-range electric vehicle suggests that GM recognized consumers' electric car range anxiety and made the safe bet to offer a hybrid solution. The Volt offered 40 miles in electric mode and an additional 300 miles in gasoline mode.

The Nissan Leaf received global recognition including the 2011 European Car of the Year, 2011 Japan Car of the Year, and 2011 World Car of the Year.[47] The 58-mile range Leaf would surpass the Volt in electric mode but without a vast supporting charging infrastructure would be characterized as a "second car" or "car for getting around town." In addition to fuel efficiency, early adopters liked its family-friendly hatchback design and roomy interior.[48] With the ability to quickly scale production, Chevy and Nissan would lead Tesla in sales of plug-in and battery electric vehicles for several years by offering vehicles at a lower price point and by leveraging their existing dealer network.

THE BATTLE FOR THE FUTURE OF ELECTRIC VEHICLES

IN HIS 2011 PRESIDENTIAL ADDRESS, U.S. President Obama set the goal to be the first country to reach one million electric cars on the road by 2015. This was an aggressive plan but one that was backed by $2.4 billion in government funds for R&D on electric cars and batteries.[49] Several states offered additional incentives such as rebates or state income tax credits. Further, nine states—Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont—joined California by 2013 in implementing new zero-emission vehicle regulations, with a goal of reaching a 15.4% sales target by 2025.[50]

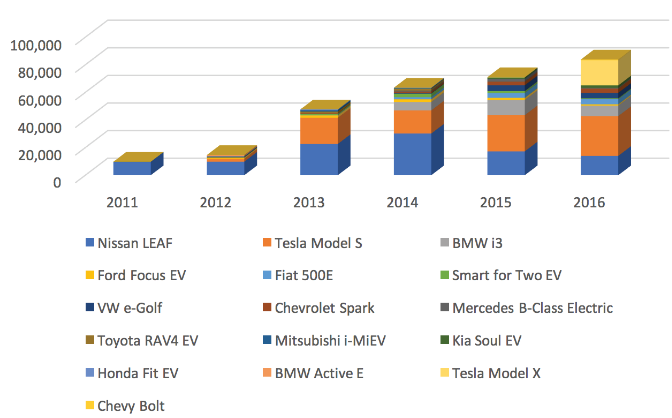
Other automakers would add to the list of plug-in and battery electric vehicles available, including Toyota, Ford, BMW, and Honda. Around this time, Chinese and European governments were laying out their own emission-reduction plans and offering incentives for alternative fuel vehicles. Over the next few years, corporate innovation and support from the U.S., Chinese, and European governments—representing more than 50% of global passenger car sales worldwide[51]—coupled with investments in technology improvements, expansion of the fueling infrastructure, and falling prices, would provide battery electric vehicles the market conditions needed to seriously compete with fossil fuels for the first time in 100 years. And while the hype is certainly around battery electric technology and Tesla, another electric car technology is quietly emerging—fuel cells. With Toyota and other Asian-based manufacturers investing heavily in fuel cells, and many carmakers looking at both technologies, a battle for electric vehicle market share could unfold over the next decade.

BATTERIES GET A JUMP START

In 2013, battery-powered electric vehicles got a boost when the Tesla Model S won the Motor Trend Car of the Year Award, beating out other gasoline models and putting a stake in the ground for all-electric vehicles. One year before, Tesla had unveiled its new Model X, the first battery electric SUV and in 2013, the company paid back its DOE loan.[52] In mid-2014, the company announced plans to introduce the significantly less expensive Model 3, which would have a starting price of $35,000. Sales of battery electric cars and plug-in hybrids in the U.S. continued to climb, and by 2015, with almost 30 models to choose from, U.S. consumers had purchased a cumulative 395,000 vehicles.[53] The Model S topped the list of battery electric vehicle sales in 2015 and by the end of that year[54] the Model X was delivered to customers. Then, on March 31, 2016, Tesla unveiled the long-awaited Model 3 with plans to deliver in 2018. Leading up to this announcement Tesla already had 110,000 pre-orders.[55]

Seeing the success of Tesla, other automakers began introducing battery electric options. Since 2012, **BMW**, **Daimler**, **GMC**, **Honda**, **Mitsubishi**, **Ford**, **Fiat**, **Toyota**, and **Volkswagen** have introduced at least one battery electric model in the U.S.[56] By 2016, the Tesla Model S increased its lead over the Nissan Leaf and together with the Model X represented more than 50% of U.S. electric sales.[57]

Figure 4: U.S. Battery Electric Vehicle Sales



Source: U.S. DOE, Alternative Fuels Data Center, U.S. Plug-In Electric Vehicle Sales by Model, updated January 2016.

For a company like Tesla that only builds battery electric cars, success depends on other players entering the market. As such, all of Tesla's patents are open sourced, allowing for the use by any company that wishes to design and sell battery electric vehicles. In doing so, Tesla hopes to grow the overall market for electric vehicles and displace fossil-fueled cars. In an interview with *USA Today* in 2014, Elon Musk suggested that Tesla had fielded interest from other carmakers in their more than 200 patents.[58] Perhaps the biggest beneficiaries of Tesla's work in this space are more-specialized, start-up companies new to the automobile industry which, like Tesla, are approaching car design with a focus on the battery. Faraday Future and Lucid Motors are two of those start-ups, both of which hired former Tesla engineers for product design, and both of which are using cylindrical cell designs similar to Tesla.[59]

LITHIUM ION BATTERIES: SETTING AN EARLY STANDARD

Today, lithium ion (Li-ion) is the dominant technology used in plug-in vehicles and next-generation hybrids. The batteries are known for their efficiency, high power to weight ratios, low self-discharge, and temperature performance. The NiMH battery, known for its power and longer lifecycle, had dominated the hybrid market but is not expected to compete with Li-ion's high energy densities and lightweight footprint.

The Li-ion battery market is seeing significant growth due largely to the rise in demand for electric vehicles. In 2016, sales of Li-ion electric vehicle batteries grew 66%, from 12.3 GWh to 20.4 GWh with production up 40%.[60] Panasonic continues to lead the race for capacity through strategic partnerships with Tesla and Toyota. LG Chem, due to its partnership with the Chevy Bolt, continues to live in the top three, while Samsung narrowly beat out CATL for fifth place thanks to increases in sales by BMW and Mercedes.[61] Rankings will continue to change over the next several years as Tesla builds out its 35-GWh Gigafactory in Nevada (partially opened in 2016) and CATL, China's fastest growing battery manufacturer, moves ahead with plans to produce 50 GWh by 2020.[62] Tesla has also announced plans to build other Gigafactories around the world. Overall, the Asia-Pacific region is expected to lead in battery manufacturing, followed by North America.[63]

To be competitive, battery electric vehicles need to perform the same as, or better than their gasoline counterparts and the key metric is *range*. Energy density, which is the amount of energy stored within the battery expressed in Watt hours per kilogram

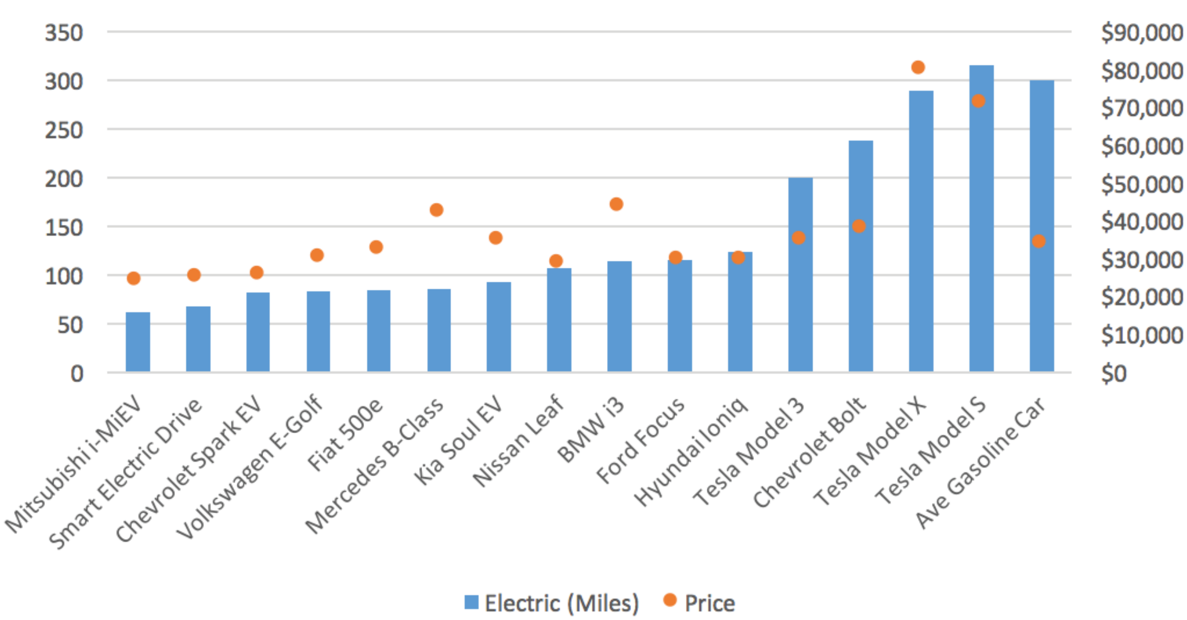
(Wh/kg), drives range. The higher the energy density the further the vehicle can travel between charges. Since first being commercialized in 1991, Li-ion energy density doubled from 100 Wh/kg to 200 Wh/kg in 2010.[64] More recently, Tesla boasted battery densities of 200–250 Wh/kg. To truly compete with gasoline, electric cars need to offer batteries with higher densities—at least 350 Wh/kg[65]—and longer range.

Gasoline vehicles typically have ranges of 300–400 miles (i.e., before refueling) and today, many hybrids offer ranges of 300–500 and beyond. Most of the battery electric cars available today have ranges of less than 150 miles, with a few exceptions.[66] Tesla is one of those exceptions, when earlier this year the company introduced its Model S, boasting a 315-mile range, well above the competition, but it comes with a $71,000 price tag.[67] Fisker Automotive founder Henry Fisker revived the company as Fisker Inc., and is currently taking orders for its EMotion electric vehicle, which promises a range of 400 miles and top speed of 161 mph with a list price $129,900.[68]

FINDING THE RIGHT BALANCE BETWEEN PRICE AND PERFORMANCE

Price continues to be a barrier for battery-powered electric cars seeking parity with gasoline models in terms of range (see Figure 5). Models like the Nissan Leaf and Ford Focus compete on sticker price but fall short on range, whereas the Tesla X and S Models start to compete in terms of range but cost double the price of the average car on the market in 2016. Of course, range and price are not the only points of comparison, performance is also very important. Take the Tesla Model 3 and BMW 330i, which Musk has used as a fair comparison;[69] similar in price ($35,000 and $38,750 for base models, respectively) and performance (Model 3 can go 0–60 mph in 5.6 seconds and the 3 series in 5.4 seconds), but the Model 3 falls short on range at 220 miles. Upgrading to a more powerful battery extends the range to 310 miles but at a $44,000 price tag.

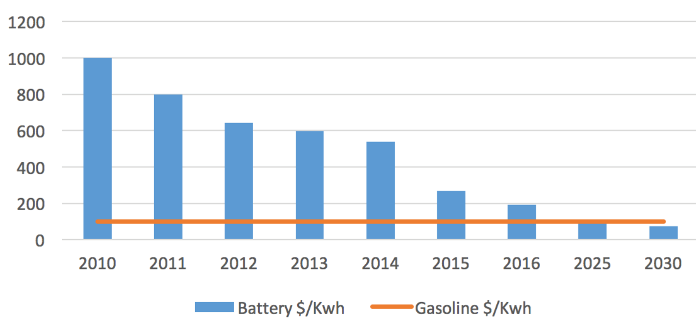
Figure 5: Electric Car Range and Price vs. Gasoline Vehicles



Source: Plug-In Cars.com, Compare Electric Cars and Plug-in Hybrids by Features, Price, Range (August 2017).

However, as efficiencies improve and production capabilities grow, battery pack prices are rapidly decreasing, falling 20% from 2010 to 2011 and again in 2012, followed by another sharp decrease by 50% in 2015.[70] Industry analysts like McKinsey & Company estimate average battery pack prices to be close to $100/kWh by 2025 and as low as $73/kWh by 2030 (Figure 6).[71] The 2016 data point represents Tesla's claim to reach the $190/kWh milestone; the company expects to drive down battery manufacturing costs another 30% with the help of its new Gigafactory. McKinsey and others believe that the price needs to get down to $100/kWh to be competitive with gasoline vehicles on price. According to a recent analysis by Bloomberg New Energy Finance, the cost of electric vehicles, driven largely by falling battery prices, is projected to fall below gasoline vehicles by 2026.[73]

Figure 6: Li-Ion Car Battery Pack Cost: Past and Projected



Source: McKinsey & Company.

Increased investments and pricing signals for the metals needed to manufacture Li-ion batteries support battery electric vehicle market growth estimates. For example, lithium, which is naturally abundant, saw prices jump 10–15% between 2014 and 2015 in response to the increase in demand for electric vehicles. The country best positioned to supply lithium globally is China.[74] More recently, after China's announcement banning gasoline vehicles, Bloomberg reported that the Global X Lithium & Battery Tech ETF increased 7.5% to the highest level in 6 years.[75] Another example is cobalt, which is used in Li-ion batteries to help extend range. Investors are buying up cobalt resources now in anticipation of increased global electric vehicle manufacturing over the next decade, driven primarily by China's market. By 2020, 75% of Li-ion batteries will contain cobalt and while electric vehicles consumed only 6.5% of refined cobalt in 2016, this demand is expected to increase to almost 17% by 2021.[76]

Advances in nanotechnology have helped manufacturers continue to improve the efficiency of Li-ion batteries. Manufacturers like Tesla have figured out ways to replace graphite with silicon, increasing energy density. Getting more silicon into Li-ion batteries is the focus of many companies, universities, and national laboratories including 3M, Penn State, and Argonne National Laboratory, which were funded by DOE in 2014 to do this research.[77] Silicon offers a charge capacity that is 10 times higher than graphite but can also suffer from a short lifecycle—this is where researchers are focused. However, many believe that Li-ion will reach its energy density limit before reaching parity with gasoline cars, estimated to be 350 kg/Wh.[78] Other new technologies being explored include Li-air and solid-state batteries, both of which have theoretical energy densities much higher than Li-ion. At least one battery manufacturer, Seeo, claims to have a solid-state prototype that offers an energy density of 350 kWh/kg with a long-term development goal of 400 kWh/kg.[79] There are also rumors of Dyson developing an electric car prototype, based on government funding received to reportedly develop an advanced battery technology and a 2015 purchase of solid-state battery maker Sakti3.[80] Toyota, not giving up on its longer-term vision of a fuel cell vehicle future, is now getting into the battery electric vehicle game. It announced late last year its efforts to set up an "in-house venture company," which will attempt to quickly make up ground lost to its competition through solid-state battery development.[81] While solid-state batteries seem promising, they are likely years away from mass commercialization.

RE-CHARGING THE FUELING NETWORK

The biggest challenge to "range anxiety" of battery electric vehicles is the lack of a charging infrastructure, which contributes to consumers' fear of being stranded somewhere without a station. Battery-electric vehicles today offer significant mileage between charges but a patchwork of stations doesn't provide the consumer confidence needed to go on long trips. Thanks to government and private investments, the number of electric charging locations in the U.S. jumped from 3,394 in 2011 to 18,000 stations (and 50,000 outlets) located across all 50 states today.[82] This is in addition to home charging systems that are available to the customer at the point of vehicle sale. Home access to charging, supported by existing electric power infrastructure already being provided to the building, is another benefit of battery electric cars, allowing the homeowner to charge the vehicle overnight.

Tesla also started to build its own network of electric car charging stations. At the beginning of 2017, Tesla alone had built more than 5,400 superchargers worldwide and has plans to increase that number to 10,000 by the end of the year.[83] Superchargers help to address time to recharge, another perceived barrier, offering 40 minutes to charge 80% compared to several hours for other chargers.

As battery electric sales grow worldwide, countries are ramping up infrastructure to support this growth. According to the International Energy Agency, in 2016 there were more than 2 million charging outlets available worldwide.[84] Growth in charging infrastructure is happening more quickly in China and Europe, with China announcing plans to build more than 800,000 charging points in 2017 adding to its existing network of 150,000 charging points. China has plans to expand as needed to support five million electric cars by 2020.[85] Across Europe there are more than 100,000 charging stations, with Belgium and Norway having the most sites.[86] In 2016, Volkwagen, Daimler, and BMW announced a joint venture to build 400 new charging stations across Europe.[87] Government incentives have played an important role in this growth in infrastructure. By 2020, the global charging market is estimated to reach almost 20 million units.[88]

FUEL CELLS ENTER THE MARKET WITH A LONG-TERM VISION

FUEL CELL STACKS HAVE BEEN USED in space exploration since the 1960s. They gained more attention in 2003 when President George W. Bush announced a $1.2 billion initiative to support fuel cell technology development and distribution, citing energy independence as well as environmental concerns. Critics argued that this was a move not in the interest of innovation but rather a way to protect automakers from more stringent fuel efficiency standards. By 2009, President Obama had greatly reduced the U.S. government's investment in fuel cell R&D to $68 million, electing instead to put more money toward battery electric vehicles, which appeared to hold more immediate promise.[89] Even so, innovation and industry investment continued forward and DOE has continued to support fuel cell R&D despite the reduced budget. More than 580 patents and 30 new fuel cell technologies entered the market in 2016 with the help of DOE funding.[90]

Fuel cell vehicles combine in-take air (oxygen) and hydrogen to create a chemical reaction, sending electricity to the motor, which powers the car. The only byproduct of this reaction is water, which exits out the tailpipe. Compared to battery electric cars, fuel cell electric cars offer higher energy densities and thus longer ranges as well as shorter refuel times (minutes compared to hours). Some manufacturers are betting that these benefits, along with declining manufacturing costs as more companies enter the space, will allow fuel cell technology to compete with battery electric and gasoline competitors longer term. Today there are three fuel cell electric car models available for sale or lease in the U.S.—**Toyota Mirai, Hyundai Tucson,** and **Honda Clarity**. These vehicles offer ranges that go head to head with the Tesla models (265+ miles range) and compete with gasoline models (Toyota Mirai at 365 miles). Audi, BMW, Ford, Daimler/Mercedes Benz, General Motors, and Lexus either have concept cars developed or plans underway.[91]

IT TAKES A VILLAGE: INDUSTRY PARTNERSHIPS FORM AROUND FUEL CELLS

New industry partnerships are forming around fuel stack development that could drive down the cost of these systems, making fuel cell technologies more cost competitive. In 2013, Ford announced a partnership with Daimler and Nissan to accelerate fuel cell technology development with the goal of releasing a mass-market vehicle by 2017. More recently Ford announced a change in this timeline as the company is focusing instead on the more immediate opportunity of battery electric vehicles.[92] Earlier this year, GM and Honda announced a joint venture, Fuel Cell System Manufacturing, with plans to start producing next-generation fuel cell stacks by 2020.[93] In Europe, 13 companies joined together to form the Hydrogen Council to discuss and promote the use of hydrogen as a fuel source, and in Japan, carmaker heavyweights Toyota, Honda, and Nissan signed a Memorandum of Understanding that provides for the collaboration needed to expand the hydrogen fuel infrastructure in that country.[94]

With the hope of stimulating the fuel cell electric car market, Toyota announced in 2015 that it would share more than 5,600 hydrogen fuel cell technology patents with other companies in the industry for free.[95] Toyota is continuing to benefit from its short-term success in hybrids, but longer term the company's success in retaining its market share in the global alternative vehicle market is riding on more widespread advancements in hydrogen technologies.

Fuel cell patents account for 29% of all renewable energy patents issued since 2012, second only to solar at 42%.[96] The leaders in fuel cell patents are GM and Toyota with more than 750 each. Honda and Samsung are close behind, with over 500 patents each. Other auto industry stakeholders like Panasonic, Hyundai, Nissan, Ford, and Daimler are also playing in the fuel cell game.[97] Interestingly the total number of annual fuel cell patent applications has been declining since 2010 when there were 1,263 submitted to the United States Patent and Trademark Office (USPTO).[98] This could be a sign that the industry is slowly moving away from R&D toward commercialization. Of course, this could also signal that manufacturers are shifting their focus away from fuel cells and putting resources into battery electric vehicles, which hold more immediate promise.

LOOKING AT A STEEP COST CURVE FOR FUEL CELLS

Fuel cell vehicles have a way to go with regard to mass commercialization. One of the biggest barriers is cost. In the last few years, improvements in fuel cell research and manufacturing processes have driven fuel cell system costs down.

According to DOE, high volume fuel cell system costs fell almost 50% since 2005 to $53–59/kW (in 2002 the cost was $248/kW); the target for commercialization is closer to $30/kW. Onboard hydrogen storage is also still too high, coming in at $15–18/kWh; the commercialization target is $2/kWh.[99] As such, the Toyota Mirai base model retails for $57,000 while the electric Nissan Leaf starts at $29,000. In California, Toyota is offering $15,000 or three years of fueling and maintenance in addition to the state incentive of $5,000, essentially bringing the cost down to $37,000. The Toyota incentive helps to defray the cost of hydrogen, which is still too high at $13–16 per gallon; to be competitive with gasoline that cost needs to come down to $4 per gallon.[100]

Toyota sees the opportunity for hydrogen longer term in both grid energy storage and ease in scalability to other sectors (a challenge that current Li-ion batteries will face over time), as well as the similarity to current fueling infrastructure. Being first to market isn't new to Toyota, a company that prides itself on innovation and green ideals, but unlike the first-generation Prius, the cost of the Mirai, and fuel cell technologies in general, will be initially prohibitive to widespread adoption.

NEW HYDROGEN HYBRIDS EMERGE

Gasoline-Hydrogen: *Just as hybrid gasoline-electric cars have helped to bridge the gap between gasoline and electric, a hybrid gasoline-hydrogen car could do the same for fuel cell vehicles. Adding hydrogen gas to the air intake of an internal combustion gasoline engine can improve* *combustion efficiency—reducing fuel consumption and increasing range—while helping to build out the fueling infrastructure needed for fuel cells to compete longer term. This approach could also offer automakers a more cost-efficient way to reduce carbon emissions of current internal combustion engine designs. Fuel delivery could be done at existing gas stations if expanded to store hydrogen gas, providing ease of adoption for consumers weary of fuel switching. In 2013, Aston Martin, in partnership with Alset Global, demonstrated a prototype hybrid hydrogen Rapide S that could operate on gasoline, hydrogen, or both fuels. The car successfully completed the ADAC Zurich Nürburgring 24-hour race and was recognized as the 2013 PMW Powertrain of the Year. Alset Global continues to promote its patented technology to automakers on the company's website but further research suggests that little progress has been made toward wider adoption as companies like Toyota and BMW push forward with 100% hydrogen fuel cell designs, promising solutions in the next five years. However, the opportunity for this technology may be in bringing along reluctant automakers and consumers, helping them to transition longer term to hydrogen as opposed to preceding fuel cell technologies in the switch to a hydrogen economy.*

Electric-Hydrogen: *Another interesting hybrid concept is emerging, the plug-in hydrogen hybrid. Announcements were made by Hyundai and Daimler in the last year around electric-hydrogen SUVs being developed under luxury brands Genesis and Mercedes Benz. The concept GV80 fuel cell and GFC F-Cell models would be the first plug-in hydrogen drive trains available in the marketplace. In these designs, the electric battery has a limited range and the fuel cell is being used to extend driving between charges. Could this be a bridge between the shorter term growing electric infrastructure and longer term hydrogen market? More likely it's a result of manufacturers who have committed to 100% electric drive trains who are looking for interim solutions while the fuel cell infrastructure continues to build out.*

BUILDING THE HYDROGEN FUELING NETWORK

Fueling infrastructure is another challenge for fuel cells. The fueling stations themselves are nascent in their design and still expensive to build. Unlike battery electric, a national hydrogen fuel network doesn't exist and will need to be built at considerable cost and time. Today, most of the hydrogen produced in the U.S. uses a process called steam-method reforming, and natural gas is the source. However, there is a cleaner alternative called water electrolysis, where electricity is used to split water into hydrogen and oxygen. Water electrolysis would not only allow lower carbon emissions from refueling but also increase the ability of homeowners to install a system in their home. Water electrolysis is not a new technology but cost has been a barrier to commercialization. Earlier this year, one company, SimpleFuel, won a $1 million prize from DOE for their home hydrogen solution.[101]

Today less than 50 hydrogen filling stations exist in the U.S., most of which are limited to the greater Los Angeles and San Francisco/Silicon Valley areas of California.[102] California often serves as a market entry point for cutting-edge technologies and ideas, as well as tougher regulations, and often other progressive states soon follow suit. This will take time, however, and likely require government incentives. More likely, fuel cell vehicles will be more broadly adopted in other countries well before mass commercialization in the U.S. But growth will continue to be slow.

One study by Information Trends estimates that there were 285 hydrogen fueling stations globally in 2016 and projects that by 2032 there will be only 4,800. However, the report goes further to say that by 2020 there will be sufficient infrastructure in place in targeted regions around the world for fuel cell vehicles to more successfully compete with gasoline and battery electric vehicles.[103] While mass adoption of battery electric vehicles is in sight, fuel cell technologies would benefit from continued government support across all areas of commercialization.

PAVING THE ROAD FORWARD FOR ELECTRIC VEHICLES

TODAY, BATTERY ELECTRIC VEHICLES ARE WELL AHEAD of fuel cells on many dimensions of merit with the notable exception of range, which is quickly improving. However, many manufacturers see fuel cell vehicles as the likely winner long term, citing technical challenges that Li-ion batteries will face as manufacturers tackle the challenge of range (i.e., the bigger the density, the larger the battery). Fuel cells do not face the same size/weight challenges. As these new technologies move into larger car footprints, it seems that fuel cells have the advantage. However, work is underway to develop solid-state batteries, which have the potential to compete head-to-head with gasoline and fuel cell vehicles on range.

With regard to supporting infrastructure, battery electric is well ahead of fuel cells yet one could argue that shorter charge times and the customer's comfort with a gasoline fueling routine and a station infrastructure that is more closely aligned with traditional gas stations gives fuel cells an advantage. Industry investment isn't providing any clarity on the future of electric vehicles with Tesla, BMW, and others siding with battery electric and Toyota, Honda, and Hyundai siding with fuel cells. Electric vehicles could play out to be a standards battle along the lines of the Betamax/VHS and Blu-ray/HD-DVD. It's clear that the market is shifting but less obvious which technology will win. Perhaps the market is shifting toward a mixed-fuel infrastructure, where there is a place for battery- and fuel cell–electric vehicles as well as gasoline and diesel, depending on region and application.

GOVERNMENT INCENTIVES AS A DRIVER

An analysis conducted by the UC Davis Plug-in Hybrid and Electric Vehicle Research Center suggests that even with the existing battery-powered vehicle momentum, purchase incentives remain critical for stimulating demand for electric vehicles.[104] In the U.S., a maximum $7,500 federal tax credit is available for battery electric and plug-in hybrid vehicles bought after 2010. Incentives will be phased out once manufacturing reaches 200,000 vehicles sold. Fuel cell vehicles were eligible for a federal tax credit through 2016 in the U.S.; it is unclear whether this credit will be extended. The UC Davis study warns that if incentives are pulled back too early (i.e., before late majority buy-in), it could have a negative effect on widespread market adoption. With tax reform on the horizon in the U.S., there is a high likelihood of these incentives disappearing under the Trump administration.

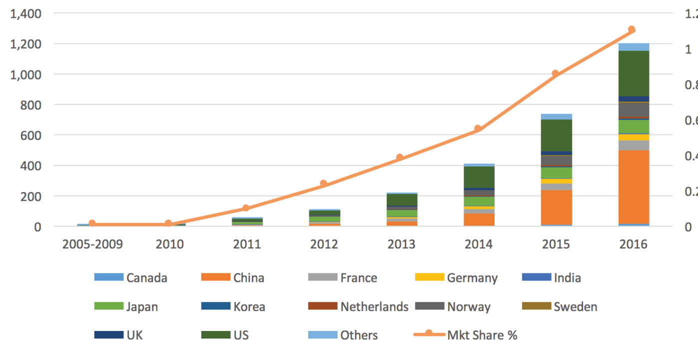
Perhaps the best example of impact through government incentives can be seen in China and Europe. In Europe, diesel emerged as a frontrunner as countries looked to reduce carbon emissions through the use of the more fuel-efficient diesel engines. Significant cuts in the diesel sales tax boosted sales of diesel vehicles, from 10% in 1990 to 60% market share in 2011.[105] Yet diesel fell out of favor by consumers and policymakers due to increased concerns over other environmental pollutants attributed to diesel use (e.g., NOx) as well as the distrust created by Volkswagen's misleading emissions claims on their diesel cars in 2015. By 2011, policymakers turned to alternative fuel vehicles to help them meet carbon emission–reduction goals, offering tax incentives on qualifying hybrid and electric vehicles—in five years, sales grew from 8,000 in 2011 to 80,000 by 2016.[106]

China saw an incredible surge in demand due to government incentives (see China highlight). While fuel cell vehicles are slow to take off in the U.S., countries strategic to Toyota, Honda, and Hyundai (i.e., Japan and Korea) are offering government incentives, spurring some interest in those regions. Global alliances are forming more widely in support of the deployment of fuel cell vehicles and supporting infrastructure.[107] However, for fuel cells to take off, investments must also be made in supporting infrastructure and continued R&D in addition to incentives for new vehicles.

CHINA. *Launched in 2010, government subsidies paid directly to Chinese automakers drove down the price of electric cars for consumers and resulted in explosive growth in hybrid and electric car sales. The subsidy program was limited to Shanghai, Shenzhen, Hangzhou, Hefei, and Changchun, where incentives of $7,000–8,700 were paid out per vehicle produced and sold. The government also committed to funding charging station infrastructure and battery recovery networks in these cities.*[108] *Incentives were extended in 2012 and the Chinese market saw an explosion in new car sales—from a mere 9,000 in 2012 to more than 250,000 in 2016.*[109] *Although successful, the incentive program attracted criticism for driving down costs but not ensuring the same level of quality as foreign companies. More recently, China announced tighter eligibility requirements and new auditing procedures as stories of wide-spread fraud emerged. Earlier this year, Chinese Finance Minister Lou announced that the government will scale back incentives for electric cars, citing concern over domestic dependence on the subsidies. Incentives will be reduced by 20% over the next two years, 40% in years 2019 and 2020, and will completely go away by 2021, letting the market decide the direction for electric vehicles and perhaps opening the door to foreign competition. To attract foreign automakers, Beijing is easing previous import fees and IP requirements and automakers like GM are planning multi-car roll-outs in China over the next few years. The Chinese government is also investing in an expanded network of charging stations with a goal of having 100,000 and 800,000 public and private stations in operation by the end of 2017.*[110]

There is some evidence that government support and incentives are helping with market adoption. Last year, cumulative worldwide battery electric vehicle sales surpassed the one million mark. China, Europe, and the U.S. represented 85% of these new vehicle registrations (see Figure 7).[111] Norway, albeit a small player in the global market, leads in market share with 29% as a result of tax incentives and waivers in that country. [112] China leads the U.S. in electric vehicles sales by twofold and with the Ministry's recent announcement to ban sales of all gasoline vehicles in the future, China could see a major shift toward plug-in vehicles even sooner than projected.

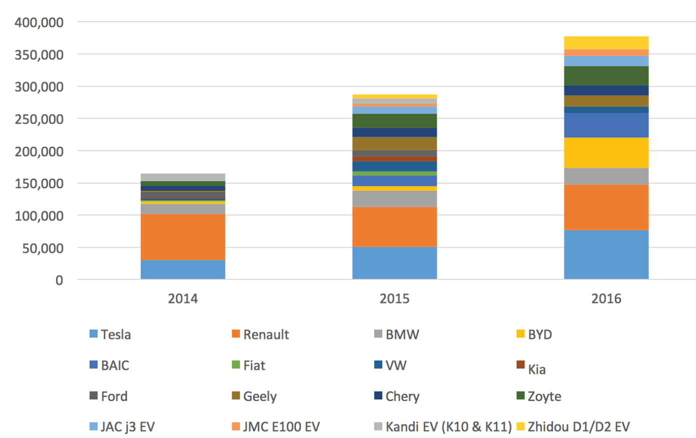
Figure 7: Cumulative EV Registrations by Country (thousands)



Source: IEA Global EV Outlook 2017.

Which companies are benefiting the most from this market shift? According to EV Volumes, Renault, including Nissan which the company has a controlling interest in, led global battery electric vehicles sales in 2014 and 2015 but in 2016 Tesla took over the number one spot followed by China's BYD and BAIC. With regard to models, the Tesla Model S, Nissan Leaf, and BMW i3 represent the top three globally. In the U.S., the Tesla S and Nissan Leaf own the top two spots while the Tesla X has pushed out BMW i3 for the third spot.

Figure 8: Global EV Sales By Parent Company



Source: EV Volumes Global Plug-In Sales for 2014, 2015, 2016.

While sales of electric vehicles are only 1% worldwide today, we expect to see a sharp increase in sales with China and Europe in the lead as a result of government regulation and/or subsidies.

With the expectation that battery electric vehicles will be cost competitive with gasoline by 2025, sales in Europe, China, and the U.S. are projected to jump from less than 5% in 2021 to 50–70% by 2040.[113] Global sales of battery electric vehicles are projected to be over 60 million by 2040.[114]

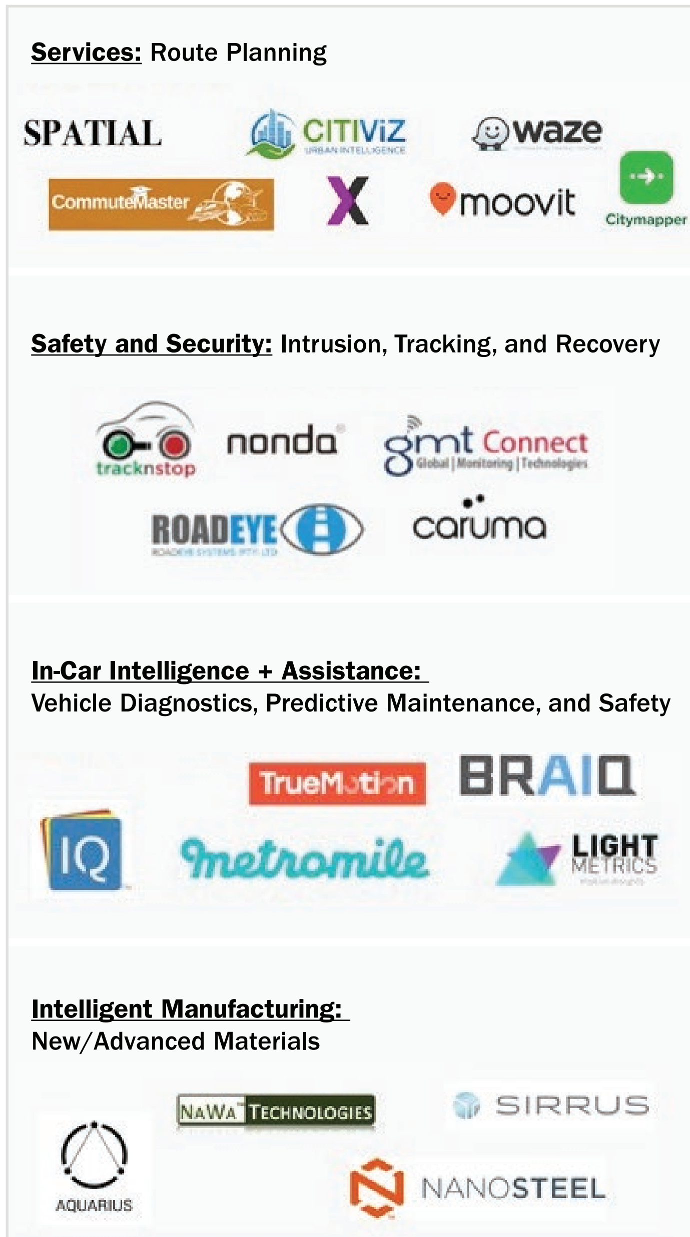
Overall, we see a slower market growth trajectory for fuel cell–electric cars, at least in the short-term, due to cost and infrastructure challenges. According to one market research source, global leases/sales in 2016 were a modest 2,500 vehicles,[115] compared to battery electric vehicles' 466,000 in the same year. By 2032, cumulative sales are projected to reach 22 million.[116] While this growth is impressive, fuel cells will have a hard time competing with the projected 60 million in annual battery electric vehicle sales by 2040.

FURTHER DISRUPTION AHEAD: AUTONOMOUS VEHICLES

While the battery-versus-fuel cell technology battle wages on, there is another technology that could further disrupt and dictate the future direction of the automobile industry—autonomous driving. The idea behind autonomous driving has been around since the 1940s, but it wasn't until the U.S. Department of Defense's Defense Advanced Research Project Agency (DARPA) Grand Challenge that the industry took the concept more seriously as an investment opportunity. The goal of the competition, held between 2004 and 2007, was to create the autonomous vehicle of the future. Attracting participants like Google, Cisco Systems, and Stanford, each year of competition brought improvements in the technology and increased interest from the IT and auto industries. Years later, in 2010, Google launched its Driverless Car Program, which reached the two-million-miles mark by 2016; now under Waymo, the project has reached three million miles driven in just seven months.[117]

Today, the field for autonomous vehicles is diverse, from incumbent car manufacturers to electronic mapping companies to entrepreneurs—in total, 44 different corporations and over 250 start-ups are currently working on the technology.[118] Partnerships are forming between car manufacturers and ridesharing companies, suggesting an initial focus on dense, urban areas. In 2016, Volvo entered into a venture with Uber to launch a fleet of self-driving ridesharing vehicles.[119] Ford announced that it will offer fully automated self-driving cars to rideshare companies by 2021.[120] GM is developing self-driving cars in partnership with Lyft after acquiring the start-up company Cruise Automation.[121] New companies established in the IT sector are entering the market as well, including Apple and Google.

Figure 9: Sampling of New Companies Entering Market



Source: Comet Labs

Several barriers must be overcome before autonomous cars will be more widely embraced including liability, privacy standards, road safety, and licensing and testing standards. Even with these challenges, the rate of adoption is expected to happen relatively quickly. Several car companies, including GM, Volvo, Nissan, and Ford, have announced that autonomous vehicles will begin appearing on highways as soon as 2021; Tesla is already incorporating autopilot capabilities into its cars and promises to go fully autonomous by 2018. After launching a self-driving pilot with 200 cars in Pittsburgh, Tempe, and San Francisco last year, Uber announced that after one year the company had reached the one-million-miles-driven mark;[122] yet even though the pilot has been largely accident free, Uber pulled all self-driving vehicles after one accident in Tempe earlier this year. Google and Waymo are continuing to test their technology, including under harsh weather conditions, before placing on the road.[123]

AUTONOMOUS AND ELECTRIC: COMPANION TECHNOLOGIES

What are the implications for zero-emission vehicles? Battery electric cars are a good candidate for autonomous technology for several reasons, including ease of computer operation (i.e., electronic controls vs mechanical) and recharging without human interaction. We will likely first see the technology become popular in ride-sharing applications, with these companies choosing electric powertrains due to lower fuel costs and greater reliability. According to a Securing America's Future Energy (SAFE) press release, "58% of autonomous light-duty vehicle retrofits and models are built over an electric powertrain, while a further 21% utilize a hybrid powertrain."[124] Broader consumer adoption will take longer, but within cities there will be a more rapid shift not only from gasoline to electric but also a decrease overall in car ownership. Without autonomous technologies, this shift is already happening as the number of new car sales slow and use of public transportation increases in urban centers. This trend is occurring even in the U.S.; according to the American Public Transportation Association, public transit ridership has grown 34% compared to 1995 numbers, while population growth is up 21%.[125] A 2017 BCG study predicts that "by 2035, 12 million fully autonomous units could be sold a year globally, and the market for partially and fully autonomous vehicles is expected to leap from about $42 billion in 2025 to nearly $77 billion in 2035."[126] Growth in this market will greatly impact changes already underway in the automotive industry.

ELECTRIC WILL DECARBONIZE THE AUTOMOBILE INDUSTRY, BUT WHEN?

WE BELIEVE THAT ZERO-EMISSION vehicles represent the likely future of the automotive industry. We hypothesize that hybrids, despite their success in the U.S. and globally, will phase out over time as electric vehicle technology improves and range anxiety subsides. The battery electric car is emerging as the early leader but continues to face barriers of cost and range performance. Hydrogen fuel cells ease range anxiety and offer a fueling infrastructure more compatible with current practice but face significant cost barriers with regard to the fuel stack system and fueling infrastructure. A battle for electric is emerging, with manufacturers like Toyota betting on fuel cells and others, like Tesla, leading the charge on battery electric. Both manufacturers have offered open-source technology patents to spur further investment in their technologies of interest. We are in an era of ferment where a dominant design for electric vehicles has yet to emerge. It remains possible that a mixed-technology infrastructure might emerge, with consumers choosing the technology that more closely reflects current designs and infrastructure (fuel cell), and commercial fleets choosing the more convenient and cost-effective technology (battery electric).

Autonomous technology is providing further disruption, bringing in start-ups and more established IT companies that until now played a small role in car design. Ride-sharing and digital-mapping companies are now major players in this industry and interesting partnerships are starting to develop across sectors. Strategic mergers and acquisitions are occuring within the automobile industry as well. With this merging of the IT and automobile industries will come a major disruption to the business model. More customers will decide against owning a car, and automakers will need to choose whether they will focus on car production or move into a role of longer-term customer engagement via digital communication platforms. Although autonomous technology is fuel-neutral, the electric car is a natural partner in creating the next generation smart car.

ACCELERATING ELECTRIC ADOPTION

All in all, electric vehicles are moving up the technology S-curve as improvements in performance correspond with increasing penetration in the market. As new entrants and incumbent firms race to develop electric vehicles, a competitive shakeout is looming on the horizon. Forbes conducted a mapping study in 2017 and identified more than 1,700 start-ups vying for a place in the new automobile market, thanks to artificial intelligence, mobility, and the connected car experience.[127] Battery electric vehicles are well positioned to benefit from the rise in on-demand mobility and autonomous driving, at least in urban areas. Fuel cell vehicles, although nascent in their design and product availability, hold promise longer term, primarily due to an infrastructure more compatible with current fueling processes.

How might the rate of zero-emission vehicle adoption be accelerated? The automobile industry historically has moved slowly when it comes to disruptive innovation. Anecdotally, the IT industry moves much more quickly, with companies releasing new generations of products each year. The very entry of hundreds of IT-related start-ups, willing to take risks with new ideas, will push the industry forward more quickly. Rumors of Apple and Google entries alone suggest disruption may happen quickly. Many existing automobile manufacturers recognize the need to nurture this kind of forward thinking and have set up their own innovation incubators, including GM Ventures, BMW Start-up Garage, JLR Tech Incubator, and Volvo Venture.[128] Efforts in the energy sector to expand renewables and build a nationwide storage network offer battery-powered and hydrogen fuel cell vehicles the opportunity to serve as a cross-sector solution, which could further increase demand for these technologies. Continued investment in R&D to innovate electric vehicles and the underlying technology are critical to driving further adoption and disruption of gasoline-powered vehicles. Government subsidies for research can be an important catalyst.

POTENTIAL ROADBLOCKS TO PROGRESS

What threatens to slow down progress? If federal incentives for new car purchases are discontinued, we could see slower growth of electric vehicles in the U.S. over the next few years. Efforts by the Trump administration to roll back funding to federal agencies that historically have been critical to innovation and continued improvement in technologies like fuel cells and batteries threaten to slow progress further. However, the overall impact could be limited as demand from Asia and Europe will continue to drive incentives to innovate and improve electric vehicles to parity, or better, with gasoline-powered vehicles.

Both battery and fuel cell electric vehicles will benefit from continued private investment in infrastructure. This is also an area where state and federal funds could be targeted. In November 2016, the Obama administration announced several actions to help expand the U.S. alternative fuel-charging network, including the creation of 48 national electric charging corridors covering 25,000 miles of highway by the U.S. Department of Transportation (DOT).[129] In September 2017, DOT released a call for location nominations from state and local officials. The irony is that growth in electric vehicles, and thus decreased demand for fossil fuels, could drive down the price of gasoline, which in the past has been a market impetus for alternative fuel vehicles. However, there are indications that these vehicles are being purchased for reasons beyond just the price of gasoline. Commitments from corporate entities to change over commercial fleets in order to achieve greenhouse gas emissions reduction targets, should influence the residential side of the industry, particularly if they result in expanded infrastructure.

With transportation representing a significant portion of greenhouse gas emissions worldwide, innovation in this sector can have a significant impact on efforts to decarbonize our global economy. Per the Intergovernmental Panel on Climate Change (IPCC) 2014 5th Assessment Report, "Substantial reductions in emissions would require large changes in investment patterns…. and energy efficiency in key sectors (transport, industry and buildings)."[130] To be clear, "zero-emission vehicles" are only zero emission to the extent that charging infrastructure or hydrogen production are done with no emissions. Thus, battery electric vehicles must rely on renewable energy in electricity generation to truly claim zero emissions. In many areas, coal is the dominant feed stock for electricity generation. As for fuel cells, water electrolysis offers a truly emission-free solution in fuel cells but until costs for this technology significantly decrease, there will be continued reliance on natural gas to generate hydrogen fuel. Even with water electrolysis, electricity is necessary and will require renewable sources to drive zero emissions.

DECARBONIZATION POSSIBLE BUT NOT GUARANTEED

Overall, we believe that rapid maturity and decreasing costs of electric vehicle technologies as well as a strong global demand, particularly in Asia, will drive a transition to electric vehicles. However, decarbonization of the automobile industry will take time simply due to the fact that we have so many existing fossil fuel cars on the road to replace. Meeting a 2060 target for decarbonization is possible but will be challenging. It will require continued investment and growth that matches what we have seen in the last two to three years. Make no mistake—a low carbon transportation sector is in the future and electric will get us there; it's just a matter of what technology and when.

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This briefing is the first in a series of sector-focused reports authored by the Batten Institute for Entrepreneurship and Innovation at the University of Virginia Darden School of Business. Upcoming research will take a look at the Energy sector. Visit ***www.darden.virginia.edu/innovation-climate*** *to listen to a podcast discussing the findings of this report and to learn more about Darden's Business Innovation & Climate Change Initiative.*

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