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Over the next 12 years, the automobile and truck industries will diversify their powertrains considerably. Besides internal combustion engine (ICE) vehicles, popular automobiles will more than likely include plug-in hybrid electric vehicles (PHEVs), fully battery-powered electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs) running on hydrogen. It’s still not clear precisely which vehicles customers will prefer; nevertheless, auto makers need to make strategic decisions today regarding their fuels and powertrains.

This report provides a detailed analysis that compares the total cost of ownership (TCO) for each type of fuel and powertrain — today and projected through 2030. The estimates are based on factors such as required infrastructure, cost of fuel, taxes, regulations, mileage requirements, efficiency improvements, depreciation, maintenance, and insurance. Knowing the total cost of ownership can help auto makers generate a strategic road map during this period of disruption.

Although TCO will rise for the ICE, it will remain the most cost-effective vehicle for many drivers. However, technological advances in batteries, and other factors, will make BEVs increasingly competitive. FCEVs will also drop in cost. To be strategically ready for change, auto makers and suppliers should consider four broad actions today: prepare to ramp up production for the vehicles they choose to produce; optimize product costs across powertrains; focus on innovation (including more collaborative innovation); and recruit and train engineers familiar with the new powertrain alternatives.
The changing economics of powertrains

It’s not necessary to consult a crystal ball to realize that, by the end of the next decade, the variety of automobiles on the road won’t resemble today’s relatively homogenous fleet at all. Today’s internal combustion engine (ICE) vehicles will be complemented by a mixture of powertrains, all legitimate suitors for customer attention. Besides ICE vehicles, there will more than likely be plug-in hybrid electric vehicles (PHEVs), fully battery-powered electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs) running on hydrogen.

Faced with this array of possible powertrains, auto makers are in a difficult spot. Clearly, a significant shift in their markets is under way, and customer preferences are just beginning to change in profound ways, but the precise contours of this marketplace transformation are not yet discernible. As a result, auto makers and suppliers are hard-pressed to make strategic decisions. To determine their investments in competing powertrains, they need to better anticipate how customer attitudes and progress in generating and storing alternative fuels will unfold.

To bring some clarity and direction to this challenge, Strategy&, PwC’s strategy consulting business, recently undertook a detailed analysis that compares the total cost of ownership (TCO) for each powertrain currently and at landmark years through 2030. We projected the cost and required infrastructure to produce and distribute alternative fuels. We plugged these factors into TCO analyses covering three separate automotive segments — budget, volume, and premium — and four different mileage ranges that a car can travel before refueling. In our estimates for 2030, we also included the impact of technological gains (mainly for batteries and power electronics), more stringent regulatory requirements for combustion engines, efficiency improvements, fuel costs, and depreciation. Taxes, maintenance, and insurance were also considered but were weighted less heavily.

An intriguing picture emerges from this analysis (see Exhibit 1, next page). In 2018, ICE is the cheapest powertrain for all the automobile segments, except the low-range midsized and premium
categories, where BEVs are the best TCO option. This is primarily because for a low-range vehicle, the significant savings in fuel costs from BEVs compensate for the higher cost of battery powertrains. However, for longer-range vehicles, ICE comes out on top. The price of an ICE powertrain for a given car does not increase with greater range (except perhaps for the minimal expense of a larger gas tank), whereas battery prices for electric vehicles (EVs) do rise as the range (and, hence, the size of the batteries) expands.

Between 2018 and 2030, cost differences among powertrains will change considerably, thus altering the TCO analyses. For each type of vehicle, here is how we anticipate that TCOS will be affected by these cost shifts:

- **Internal combustion engine**: Higher emissions standards will drive up the TCO considerably. This is primarily due to new equipment in
these vehicles to reduce pollution, including particle filters, exhaust gas recirculation, and catalyst heaters for tailpipes. One opposing factor will be new efficiency improvements, such as mild hybridization. These will soon be commonplace and will lower the cost of gasoline, but not enough to overcome cost reductions in the BEV category.

- **Battery-powered electric vehicles:** The TCO will drop gradually and consistently between now and 2030 as industrialization of the battery value chain brings down battery and production costs. Increased energy density will reduce the number of battery cells that an automobile needs. In addition, the continued integration of batteries, powertrain electronics, and electric motors will reduce the cost of EV systems.

- **Fuel cell electric vehicles:** The TCO will decline over time, although not as rapidly as for BEVs. The fuel cell stack costs will decrease due to the augmented power density, and the cost of hydrogen tanks will decline as production methods improve. Also, FCEVs use largely the same components as BEVs for electric motors and power electronics. Hence, as these components improve with more widespread adoption of BEVs, FCEVs will benefit as well.

- **Plug-in hybrid electric vehicles:** These have a mixed future for the TCO because they are affected by BEV gains and ICE slippage.

The more detailed TCO comparisons in the rest of this report are intended to arm auto makers with enough data to generate a strategic road map during this period of disruption. Conventional wisdom does not offer a sufficiently deep understanding of the fundamental dynamics that will influence automobile purchases in the coming years, at least not enough of one around which to plan a strategy. Our TCO analysis is an effort to provide that deep understanding — to offer a more granular set of calculations, linked closely to real-world conditions. It can be used for strategic product planning, technology adoption, and recruitment and training linked to skill sets needed for new products. By examining the shrinking cost gap between alternative powertrains and ICE vehicles in each segment, auto makers can begin to formulate a program and timetable for investing in powertrain technologies that are suited to their customer base and brand portfolio. They can structure their investments to bear fruit when the TCO for alternative powertrains in their best-performing segments reaches near parity with traditional vehicles.
What’s driving change?

Powerful forces propel the momentum toward alternative powertrains. One such factor is technological advance. For ICE vehicles, most of the advances will involve engine efficiency improvements aimed at minimizing emissions of CO$_2$ and other pollutants. Among these improvements are diminishing friction in cylinders and valves with new coatings, increasing fuel injection pressures for cleaner exhaust, and mild hybridization, which amounts to an added electric motor that, for instance, can turn the car off at a stoplight but does not actually propel the car.

PHEVs and BEVs will benefit from battery advances, such as the use of cathode materials with higher energy capabilities and better power electronics. This will reduce costs, increase range, and speed up charging. FCEVs will mostly be bolstered by technologies that enhance fuel stack efficiency due to higher current density and better hydrogen storage equipment. This will make the vehicles less expensive and expand their life cycle.

As a result of these trends, in 2025, BEVs will have extended their TCO advantage over ICE through the entire low-range segment and into premium models in the midrange category. And by 2030, BEVs will even offer superior TCO in the long-range premium segment. Also by that year, FCEVs will be attractive (although not quite as inexpensive as ICE vehicles) for cars with a range of more than 800 kilometers (497 miles). BEVs with ranges above 500 kilometers (311 miles) will still generally be expensive, and refueling will be time-consuming.

Another major factor is the urgency to curb greenhouse gas emissions, the generally accepted primary factor in global warming. Although the U.S. has withdrawn from the agreement, nearly 100 countries signed the Paris climate accord that in effect set a goal of net zero global carbon discharges, which are the dominant component of greenhouse gases, by 2050. Because automotive vehicles contribute approximately 17 percent of CO$_2$ emissions, regulators are turning to original equipment manufacturers (OEMs) to sharply lessen the carbon footprints of their products, which will naturally lead to more EVs in their fleets.
Reducing air pollution is also an increasing regulatory priority, particularly in metropolitan areas. More than 80 percent of the world’s urban population is exposed to air quality levels below World Health Organization (WHO) minimum standards. Ambient air pollution contributes to 4.2 million premature deaths worldwide, according to the WHO — and a lot of the pollution begins as waste products generated by automobile engine combustion. Disturbed by statistics like these, many central governments and municipalities are moving toward banning ICE vehicles from congested cities, or at least sharply limiting their use. Some of the impetus for this is coming from local residents — and local environmental activists — who are fighting back against pollution from ICE vehicles.

At the same time, technological advances are rapidly speeding the day when alternative powertrains become more convenient and perform as well as traditional cars. Because of breakthroughs in battery technology, the range of EVs — mileage between full charges — has been trending upward. Battery prices are dropping due to manufacturing economies of scale and improvements in storage capabilities and materials. Meanwhile, from a driving standpoint, EVs are also becoming more attractive: Already, EVs from Tesla and Daimler, among others, can go from 0 to 60 mph in less than four seconds, due to the ability of an electric motor to provide maximum torque instantly at zero revolutions.

Certainly, solutions to CO₂ emissions and pollution — at least to the degree that the auto industry is responsible — are in sight. Battery power, hydrogen, and synthetic fuels are each evolving at their own speed, and all show real promise in varying measures. But knowing that, alone, is not particularly helpful for auto makers or suppliers that are trying to plan for how the global vehicle market will look in the next decade or so, because it just offers a broad window into the future and lacks specificity.

Indeed, contrary to what is often prof ered, there is no single break-even moment when all alternative powertrains will become more economically viable than ICE vehicles. The timing of that moment for each type of vehicle will depend on factors related to the powertrain itself — particularly the fuel it runs on — and the automobile segment. Thus, throughout the entire period covered by our study, ICE will hold its own in the budget category for ranges above 300 kilometers (186 miles), a popular category for car buyers. Customers in that market will begin to switch in higher numbers to alternative powertrains as CO₂ emissions restrictions are mandated and enforced.
After depreciation of the vehicle, the most integral factor in automobile TCO is the price of fuel. This is responsible for about 30 percent of the TCO. Consequently, to come up with an accurate gauge of fuel costs for alternative powertrains, we considered a range of scenarios from least to most expensive for generation and distribution of different power sources — and from that estimated a median fuel price for our final target year of 2030, assuming that a mixture of these scenarios would be the likely result.

As an example, the electricity for pure battery EVs and hybrids could come from two possible places. Power outlets at people’s homes are less expensive, but they charge at slower speeds. They also are not feasible in many urban settings, because few apartment dwellers have power outlets accessible from the outside. The more costly but speedier option is public charging stations, which require the continued rollout of infrastructure.

FCEVs need hydrogen for power. This requires electrolyzers in filling stations, which will be at a premium when overall energy demand is at peak levels and less costly when energy demand is more flexible.

Finally, synthetic fuel for ICEs, created from coal or natural gas, could affect the TCO. However, it’s unlikely that this fuel could be commercially available before 2025. The costs of this fuel (either liquid or gaseous) will vary primarily by whether the fuel is imported or made domestically. For most Western nations, producing CO₂-neutral synfuels in solar-rich countries such as in the Middle East, where renewable electrical energy needed for synfuel processing in large amounts is plentiful and extremely inexpensive, will be a more economical option, even accounting for the cost of shipping.

After adding taxes to these hypotheticals — current value-added tariffs as well as taxes levied at the pump and on electricity — the Strategy& analysis concluded that for the midsized vehicle category in 2030, electricity for BEVs would be the least expensive fuel, at approximately €7 per 100 kilometers (62 miles) of driving. This would compare to
€11 per 100 kilometers for fossil fuels, including taxes. Hydrogen would also be less costly than gasoline or diesel, but the price of synthetic fuels would be exorbitant.

It’s important to note, however, that fossil fuels are much more heavily taxed than electricity or EV charging stations, which adds significantly to their end-user price. In virtually every region of the world, if alternative fuels were “levelized” to have a tax burden comparable to that of fossil fuels, alternative fuels would be more expensive (see Exhibit 2).

### Exhibit 2
**Comparative fuel cost per kilometer, Germany**

<table>
<thead>
<tr>
<th></th>
<th>Fossil</th>
<th>Electrical energy</th>
<th>Hydrogen</th>
<th>Synfuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel cost</strong></td>
<td>€11/liter</td>
<td>€6.9/kWh</td>
<td>€10.4/kg</td>
<td>€19/liter</td>
</tr>
<tr>
<td>with current</td>
<td>€4.2/liter</td>
<td>€1.6/kWh</td>
<td>€8.7/kg</td>
<td>€15/liter</td>
</tr>
<tr>
<td>effective tax</td>
<td>€1.38/liter</td>
<td>€0.292/kWh</td>
<td>€9.5/kg</td>
<td>€3.8/kg</td>
</tr>
<tr>
<td>VAT (19%)</td>
<td>€0.654/L</td>
<td>€20.5/MWh</td>
<td>€13.9/MWh</td>
<td>€2.6/liter</td>
</tr>
<tr>
<td><strong>Net cost</strong></td>
<td>€6.9/liter</td>
<td>€5.3/kWh</td>
<td>€6.9/kg</td>
<td>€3.1/liter</td>
</tr>
<tr>
<td><strong>Fuel cost</strong></td>
<td>€11/liter</td>
<td>€12.2/kWh</td>
<td>€15.6/kg</td>
<td>€21.9/liter</td>
</tr>
<tr>
<td>with hypothetical</td>
<td>€4.2/liter</td>
<td>€5.3/kWh</td>
<td>€8.7/kg</td>
<td>€15/liter</td>
</tr>
<tr>
<td>levelized tax</td>
<td>€1.38/liter</td>
<td>€0.52/kWh</td>
<td>€14.4/kg</td>
<td>€4.4/kg</td>
</tr>
<tr>
<td><strong>Net cost</strong></td>
<td>€6.9/liter</td>
<td>€6.9/kg</td>
<td>€6.9/kg</td>
<td>€6.9/liter</td>
</tr>
</tbody>
</table>

*SNG tax rate of €13.9/MWh effective until 12/2023; €27.3/MWh planned for 2026

Note: Fuel calculated for a midsize vehicle (€/100km). Fuel prices are shown in standard metric.

Source: Strategy& research
To further calculate the true cost of CO₂-neutral fuels, we examined how much waste and energy loss occurs during production and distribution as well as during powertrain conversion in the car itself. We found dramatic differences in the so-called well-to-wheel efficiency for each fuel. For electric power, the distribution and supply pathways for BEVs and PHEVs are less efficient than those for hydrogen and synfuels, mostly due to energy losses on the grid. But the overall power efficiency level of electricity as an automobile fuel is quite high, about 70 percent. The primary reason is that there is very little energy wasted in converting electricity from batteries into automobile propulsion. By contrast, because of significant amounts of wasted heat energy built up during powertrain conversion, hydrogen well-to-wheel efficiency is only 36 percent, and synfuel fares even worse at 11 percent (see Exhibit 3, next page).

Another essential factor in fuel cost is the level of capital investment required to generate energy to produce fuel for these cars. This is often ignored in assessments of alternative vehicles. Considering how expensive a wider network of power plants could be and how long it could take to build this network, decisions about fuel production infrastructure should be high on the agenda for auto makers, power providers, and government policymakers if the anticipated tipping point of alternative powertrains is to occur in the next decade or so.

To include the costs of utility build-outs in our TCO analysis, we modeled supply scenarios for Germany, in which one of the three fuels is the sole energy supply for all licensed automobiles. We found that for all alternative fuels, the demand for electrical energy would rise substantially. For instance, in a pure electric car scenario, approximately one-third of today’s total annual energy demand in the country would have to be added to the power infrastructure. To cover this demand, investments in additional power plants, grid-level electrical storage, and improvements to the transmission and distribution grid would be required. Demand management systems to prevent the overloading of systems linked to vehicle charging would also be needed, as would a network of private and public charging stations.

If all vehicles shifted to hydrogen for FCEVs, 66 percent more energy would be needed. And beyond the expansion of the grid, additional investments would have to be made in electrolysers and filling outlets. Because each facility would store the hydrogen on-site, in containers similar to the underground oil tanks at today’s gas stations, energy supply and distribution would be decoupled, an advantage over electricity as a fuel. The synfuel scenario is by far the most expensive — and one of the reasons this alternative is not really a viable option. If synfuel were the single energy supply for light vehicles, energy demand costs would increase by as much as 206 percent — and that’s only in Germany.
### Exhibit 3
Fuel efficiencies in production, storage, and vehicle use

<table>
<thead>
<tr>
<th>Source</th>
<th>Electrical energy</th>
<th>Hydrogen</th>
<th>Synthetic natural gas (SNG)</th>
<th>Synthetic fuel oil (liquid)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical energy</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Production and storage</strong></td>
<td>94%</td>
<td>69%</td>
<td>50%</td>
<td>44%</td>
</tr>
<tr>
<td><strong>Produced fuel</strong></td>
<td>94</td>
<td>69</td>
<td>50</td>
<td>44</td>
</tr>
<tr>
<td>Distribution</td>
<td>89%</td>
<td>95%</td>
<td>97%</td>
<td>96%</td>
</tr>
<tr>
<td><strong>Distributed fuel</strong></td>
<td>84</td>
<td>65</td>
<td>49</td>
<td>42</td>
</tr>
<tr>
<td>Powertrain conversion</td>
<td>84%</td>
<td>55%</td>
<td>29%</td>
<td>27%</td>
</tr>
<tr>
<td>Mechanical energy</td>
<td>70</td>
<td>36</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>(overall well-to-wheel efficiency)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Per 100kWh of electrical energy.

Source: Strategy& research
These estimates, of course, are affected by the fact that the cost of each alternative fuel will be in flux in the coming years. Moreover, it's important to remember that cost should not be the only factor that OEMs use in determining when to incorporate an alternative fuel vehicle into a product portfolio. For instance, hydrogen for fuel cells today is produced by a process of breaking down natural gas that is not CO$_2$-neutral. Thus, it is not a viable option for large-scale automotive applications in the future when reduced carbon emissions will be necessary. However, in a decade or so, CO$_2$-neutral hydrogen electrolysis may be available. This will be cost-effective, but probably not as inexpensive as using electricity to power a vehicle. Nonetheless, a FCEV may be a good option for drivers such as traveling salespeople, who drive a few hundred miles a day and can't afford the inconvenience of having to wait a long time to charge an EV.

In general, EV acceptance will be held back until charging stations are more prevalent. As a result, many pioneering EV owners will probably charge their cars at home, because it will be less expensive and more convenient there than at high-speed public sites. Meanwhile, synfuels may be used primarily for commercial transport, such as trucking and aviation, and not for privately driven automobiles.
Factors affecting driver acceptance

Although TCO is a valid metric for peering into the future of automobiles, there are other pivotal considerations not included in it. Vehicles have always been emotional purchases, and dry TCO figures cannot in themselves predict when alternative powertrains reach their inevitable tipping point. Other factors could influence car owners to be more or less enthusiastic about alternative powertrains, and these could have an outsized impact on how quickly the era arrives for BEVs or FCEVs as mainstream mobility.

For instance, legislative initiatives could make ICE vehicles unwelcome in urban areas. The Paris city government has announced plans to ban diesel cars by 2024, and all petroleum-fueled cars by 2030. Rome will also ban diesel cars in 2024, while London is putting fines in place for fossil-fueled vehicles driven on certain streets or at peak traffic hours. The Chinese government announced that 10 percent of all cars made in China or imported into the country by major auto makers must be electric or hydrogen-powered by 2019 — and also made it easier and less expensive for people to register EVs. And India, Ireland, and Israel said they would ban new ICE cars by 2030. To be sure, as the news website Quartz reported, few measures have yet been passed as laws, but the momentum is building.

These steps and other similar programs to establish zero-emission zones, which are likely to be adopted by many cities in the coming years, could so inconvenience drivers of ICE vehicles that their current advantages — longer range and faster refueling — would be diminished. The full extent of change will depend on whether local governments permit cars running on synfuel or plug-in hybrids to enter emission-free zones. If they don’t, BEVs and FCEVs will gain an even bigger boost from these emerging policies.

But sales of battery- and fuel cell-powered cars face a different unknown. Today, the necessary infrastructure for both types of vehicles is only beginning to appear. Hydrogen fill-up facilities are virtually unavailable, and although there are more electric charging points in well-traveled locales such as shopping malls and train stations, they are
hardly plentiful. By 2025, it is likely that high-speed chargers will be ubiquitous, at least compared to now, but this is not certain. Rather, it will take a combination of local and federal government backing for EVs and a logical path to profits for the private sector (particularly the energy industry) to buttress the development of electric and hydrogen charging stations.

Public perception about the value of alternative powertrains will depend on convenience. The distances they can be driven without recharging, the speed and simplicity of fueling up, and their level of reliability will ultimately determine whether ownership will expand beyond relatively few early adopters.
Many OEMs are already preparing their production systems primarily for the widespread adoption of BEVs. The first generation of these cars, such as the Tesla Model S, GM’s Chevy Bolt, and the Nissan Leaf, were all one-off models whose platforms were not shared with any other vehicles. But now, to increase the scale and efficiency of BEV manufacturing, OEMs are beginning to introduce EV platforms that can spread across multiple models and, eventually, even to FCEVs. Examples of these platforms include Volkswagen’s MEB, Daimler’s EVA2, and Renault-Nissan’s CMF-EV — all likely to be available from 2020 on.

Along with this step, we believe that auto makers and suppliers should use insights about TCO to plan for key moments in the next decade — and thus to be strategically and operationally ready to field an array of alternative powertrain vehicles and components. In particular, they should do the following:

1) **Prepare to ramp up production.** Alternative powertrain vehicles have different components and production requirements from those of traditional cars, which will make the relationships between OEMs and suppliers more difficult, at least at first. There’s a big difference between making 5,000 parts for a low-volume BEV run today and 300,000 parts for a production BEV. Use this time to set up systems and processes to deal with high-volume output and to manage quality issues that arise before they become major problems in the future.

2) **Optimize product costs.** When alternative powertrain vehicle volume increases, the costs to produce these cars will have to be reduced significantly or the losses will be staggering. It is one thing to take a small hit on a BEV with limited sales, but it would be unacceptable to carry that loss over into a popular model. For that reason, shared platforms are critical. Also, auto makers and suppliers should identify the commonalities among alternative powertrains and should scale product development and manufacturing to take advantage of design elements, systems, and components that can be included in both.
3) **Focus on innovation.** OEMs and suppliers should establish internal procedures that encourage new ideas and creative solutions. In some cases, particularly for auto makers, that means eliminating silos with not-invented-here syndromes that stand in the way of quickly adopting new technology, either in terms of vehicle design, manufacturing, or components. Meanwhile, suppliers should be cementing and expanding their relationships with OEMs by proactively developing conceptual ideas and automotive parts that can improve the performance of alternative powertrains.

4) **Recruit and train.** Engineering, design, and development skills for alternative powertrain vehicles are not the same as those needed for traditional cars. The knowledge of electronics and chemical processes that are at the heart of EVs and FCEVs is still a somewhat-rare commodity in the auto industry. OEMs and suppliers should set up programs to identify and hire talented engineers and designers who are enthusiastic about the sharply different future that awaits the automobile sector.
Conclusion

The auto industry is at a critical juncture, equivalent in its impact to a 100-year storm. Auto maker and supplier executives cannot afford to ignore the change staring them in the face. Our analysis of when alternative powertrains will be cost-effective provides an essential set of data points around which to build a design and production strategy. The auto industry must plan for a future when its portfolio will be nothing like the present. But without a clear awareness of the future of fuel and its costs, auto makers risk being left in the past.
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