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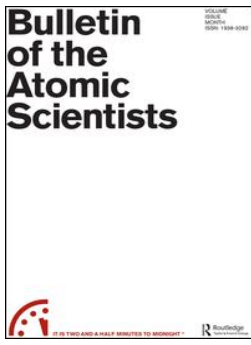
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Electric vehicles: Approaching the tipping point

Daniel Sperling

ABSTRACT

A revolution is underway in transportation, with a variety of electric vehicles rapidly coming to the fore. The switch from internal combustion engines to electric motors will change the world in many ways and is expected to help reduce the world's carbon dioxide emissions. Inspired by this vision, leaders in China, France, and Britain have all proclaimed that they will effectively ban cars that aren't electric by about 2040, while Volvo says all of its vehicles will be powered by electric motors in a few years. Other automakers have also announced that they are headed that way. But how far along is this revolution really? What challenges still need to be overcome to gain truly widespread acceptance on a scale that can combat climate change? Will the costs and the benefits of these new vehicles be equally spread among countries and companies? And while we all benefit in the long term, who will be the winners and the losers in our short-term world where Wall Street thinking predominates?

KEYWORDS

Electric vehicles; hybrid vehicles; plug-in hybrid; zero-emission passenger vehicles; hydrogen fuel cell; batteries

In the last three decades, electric vehicles (EVs) have vastly improved in every way – in cost, performance, efficiency, styling, and availability to consumers. For the first time in history, electric vehicles are in many ways the equal of gasoline cars (though not yet in cost). And they are actually superior in quietness and driving experience for most drivers, according to surveys. Every major automaker now offers a variety of EVs for sale, often at attractive prices, and more of them are now selling hydrogen fuel cell EVs as well. Many politicians around the world are calling for banning internal combustion engines and replacing them with EVs. A growing number of analysts foresee the demand for EVs accelerating sharply in the coming years as costs continue to fall, driving ranges increase, and governments become more insistent.

For now, EVs are considerably more expensive to produce than gasoline cars, even with dropping battery costs. Automakers offer them on showroom floors at prices that are sometimes lower than the cost of manufacturing – to satisfy government mandates in some areas, to help meet aggressive fuel efficiency and greenhouse gas standards – and to get an early foot in the door for what promises to eventually become a huge market.

The transition is just getting started. Market share is higher in locations where there are lots of incentives and electric charging stations, and where government leaders tout the future dominance of EVs. The largest single market is China, with more than

half of the world's 800,000 EV sales in 2016 – including 120,000 buses, 320,000 cars, and 60,000 medium- and heavy-duty trucks (China Association of Automobile Manufacturers 2017). As one close observer of the technology scene put it: “Global automakers see the future of electric cars, and it looks Chinese” (Bradsher 2017a). The president of General Motors, Dan Ammann, seemed to come to the same conclusion in a mid-November interview with the *New York Times*: “We do see China being, in the near and medium term at least, by far the largest market for electric vehicles in the world... But we believe ultimately that the whole world will go that direction.” (Bradsher 2017b)

Currently, about one-fifth of total EV sales are in the United States. The country with the highest market share is Norway, with more than 30 percent of auto sales being EVs. But Norway has only 5.2 million people. Overall, though, EVs accounted for only one percent of total vehicle sales in the world in 2016.

With all this in mind, what is the long-term prognosis for electric vehicles? Why does society need them? What are the biggest challenges that this technology needs to overcome, in terms of engineering and consumer acceptance? What about resistance from those invested in the status quo, as in the fossil fuel industry? And assuming all these obstructions can be dealt with, how quickly can we realistically expect a transition to EVs?

Why does the world need electric vehicles?

The modern embrace of electric vehicles is fairly recent. In many polluted cities – in the rich industrialized world as well as across Asia and increasingly in Latin America and Africa – the most compelling argument for EVs is unhealthy and unsightly air. Indeed, worsening urban air pollution is central to China's commitment to EVs (Wang et al. 2017).

And besides local air pollution, another compelling argument for EVs is that petroleum-powered motor vehicles are a major contributor to climate change, emitting about 20 percent of all greenhouse gases worldwide (Sims et al. 2014). Consequently, electric vehicles represent the best hope for dramatic reductions in transportation emissions.

Exactly how much of a reduction depends on the type of electric vehicle – which is where things get tricky. Pure battery EVs and hydrogen fuel cell EVs (cars which combine hydrogen and oxygen to produce electricity, which then powers an electric motor) emit zero greenhouse gases and zero pollutants from the vehicle during driving. Plug-in hybrid electric vehicles (PHEVs) also have zero emissions, but only when operating in electric mode – and PHEVs do emit greenhouse gases when their gasoline engines are operating.

As for gasoline/electric hybrid vehicles – better known as “hybrid vehicles” – models such as the Toyota Prius are up to 35 percent more energy efficient than comparable gasoline cars, but they almost never operate in all-electric mode and thus are not zero-emitting.¹

These vehicle types are often confused by the public. A pure battery-powered electric vehicle such as the Chevy Bolt operates entirely off of electricity that comes from a large battery in the vehicle; it has no other source of power. The battery is charged by plugging a cord into a wall outlet or public charging station. The EPA rates the Bolt as getting a range of 238 miles on a single charge.

In contrast, a plug-in hybrid combines a gasoline engine with its electric engine and a battery pack. The electric portion is still charged by a wall plug or public charger. When the electricity is drained from the battery, it switches to the gasoline engine. The benefit of a plug-in hybrid is that it overcomes “range anxiety.” If the electricity runs out, the driver is not stranded. These plug-in hybrids, such as the Chevy *Volt* (a model name confusingly similar to the Chevy *Bolt*), can generally travel 25-to-50 miles on a single charge, during which the PHEV is generating zero emissions as long as it remains in all-electric travel mode.

Standing apart from both the pure battery-powered electric vehicle and the plug-in hybrid are the gasoline/

electric hybrid car, such as the Prius, which have very small batteries and electric motors and are not designed to run solely on electricity. Instead, the battery and the electric motor are complementary, intended to boost energy efficiency. The battery in gasoline hybrids gets its electricity by reclaiming energy from everyday operations of the car, such as capturing the energy created during braking and storing it in the battery; a gasoline/electric hybrid does *not* take any electricity from a wall outlet or public charging station, like a plug-in hybrid does.²

To give a sense of the scale of the markets for the various vehicles, Americans have bought about 4 million gas/electric hybrids since the first ones became commercially available in 1999, said the publication *HybridCars* in June, 2016 – with 384,404 gas/electric hybrids sold in 2015 alone (Cobb 2016). Plug-in hybrids saw 42,825 sales in the United States in the year 2015 (Bureau of Transportation Statistics 2016). Meanwhile, the *Los Angeles Times* reported that Americans purchased 80,000 pure electric cars in 2016, and 1,082 hydrogen fuel cell vehicles, citing a report from the automotive industry trade publication *WardsAuto* (Los Angeles Times 2017). About 17.5 million vehicles of all kinds were sold in the United States in 2016.

In the rest of this article, when the terms “electric vehicle” or “EV” is used, they refer to pure battery EVs, plug-in EVs, and fuel cell EVs. They do *not* refer to gasoline/electric hybrids.

What's on the road ahead

The transition to EVs, including all the versions highlighted above, is well underway. While political proclamations to ban conventional gasoline-powered cars are more aspiration than reality at this point, they signify the embrace of electric vehicles as one of the best ways to cut pollution and reduce global warming. And as we will see, these aspirations are increasingly being converted into aggressive government regulations and ambitious incentives.

One complicating factor: Although the energy and pollution advantages of electric vehicles can be large, they depend upon the source of electricity used to charge the vehicles. After all, it somewhat defeats the purpose if a new, ultra-efficient, zero-emissions electric vehicle is charged by a dirty, coal-fired power plant. EVs provide the greatest air quality and climate benefits when electricity is generated from renewable energy, including wind and solar, as well as hydropower and nuclear. When electricity generation is switched from fossil to

renewable and nuclear energy, the climate benefits of electric vehicles are huge – almost a 100-percent reduction in greenhouse gas emissions. In California, most of the electricity already comes from zero-emitting wind, solar, nuclear, and hydropower sources. In this case, all-electric vehicles provide huge improvements over gasoline- and diesel-powered vehicles, measured on a life-cycle basis. Likewise, in France, where most electricity comes from nuclear power, the environmental benefits are enormous.

Electric vehicles are less attractive where most of the electricity comes from coal, such as in China and India, and to a lesser extent in parts of Germany and the United States. In these cases, however, there are still local pollution benefits, because the actual exposure to the pollution is limited, with power plant emissions often located in remote areas.

But perhaps more important, the electricity grid is being decarbonized virtually everywhere. Many countries, including Germany, the United States, and China, have aggressive initiatives to increase the use of renewable energy to generate electricity. As the world decarbonizes its electricity generation and eventually the production of low-carbon hydrogen, electric vehicles become even more attractive environmentally.

A second large attraction of EVs is technological. Although today's automakers are weighed down by the legacy of 100 years of internal combustion engines and mechanical engineering designs, they are well along in converting the car's infrastructure to electronic controls. For example, since the mid-1970s, automobile manufacturers have slowly embraced the use of electricity and electric motors to manage everything from opening and closing windows to steering, braking, and accelerating. The advantages of a nearly all-electric vehicle architecture are reduced cost and weight, greater reliability, and easier maintenance as a result of fewer moving parts, along with more precision in braking, managing combustion, and shifting gears. Hydraulic braking with fluids and hoses is disappearing, as are steering wheels connected to long heavy steel rods. Electric motors are proliferating to control sunroofs, windows, seats, and much more.

Many of the electronic and digital attractions in the car's infrastructure carry over to electric propulsion as well. Not only do vehicles benefit from the replacement of transmissions, mechanical drivelines, and heavy combustion engines by electric motors and components – which are physically lighter and easier to manage – but they also benefit from the ability to capture energy from braking. Consequently, vehicle electrification represents a huge advance in energy efficiency.

Third, electrification opens up design opportunities. With modular batteries that can be placed in and under the frame, the car is more stable, allowing more opportunities to enhance performance. And when the car no longer has a metal transmission and driveline through its middle, there is no longer an impetus to have the radiator and engine block in the front – a development that allows the automobile to be completely redesigned to better serve passengers, with advantages that include easier access and egress.

This design flexibility also allows automakers to use just a few vehicle platforms – perhaps just three, for small, medium, and large vehicles – as opposed to the ten or 20 platforms needed for today's more complex combustion engine vehicles. The resulting cost savings that come from the economies of scale and simplified manufacturing (from the reduced number of platforms) could be massive.

Fourth, vehicle electrification is good for consumers. Pure battery EVs – and to a lesser extent, plug-ins and hybrids – reduce dependence on foreign oil and consumer vulnerability to volatile fuel prices. They are much more energy-efficient than conventional vehicles, so they generally cost less to operate. This efficiency will steadily improve as components are improved, overall energy management optimized, and “parasitic losses” – processes that rob power from the engine, due to friction, wind resistance, and drag – are reduced. Electric vehicles are also quieter and drive more smoothly than combustion engine vehicles. They are less expensive and easier to maintain because they have fewer moving parts, with no oil changes required. The possibility of home recharging is also attractive to most consumers. Plugging in would be difficult for apartment dwellers and some homeowners, but it's a comfortable experience for most people and a preferred option for many (Singer 2016).

While it's clear that electric vehicles are in the public interest and the electric vehicle revolution is likely to be inevitable at some point down the road, what is less clear is how fast this transition will occur – and how it might be accelerated to capture the many benefits of electric vehicles as quickly as possible. The train has left the station on electrification, and automakers and governments are aligned in their commitment to electric vehicles. But the full embrace of electrified transportation by modern society is still in its infancy, and faces some stiff headwinds.

Battery blues – and breakthroughs

Other than gaining consumer acceptance, the big challenge for EVs involves batteries (Chu 2016). They have been the bane of electric vehicles since the beginning. After decades of slow progress with battery chemistry

from the time of Thomas Edison and Henry Ford, battery innovation began to accelerate in the 1980s, motivated first by the proliferation of battery-powered consumer goods and later by cars. Companies around the world experimented with and eventually commercialized a variety of battery chemistries.

The first big breakthrough came during the latter part of the 1990s with major advances in nickel-metal hydride batteries. This new battery technology was used in the first gasoline-electric hybrids, such as the Honda Insight and the Toyota Prius. Then a decade later, a still better set of batteries, based on lithium, swept into the automotive world (though Nissan used them in demonstration vehicles in the 1990s). The new advanced batteries had far higher energy density (energy per unit volume), used low-cost materials, and were durable. Battery costs began a steep decline.

Costs will continue to fall and the scale of battery production will ramp up considerably as Tesla's Gigafactory in Nevada and other new factories come on line in the coming years.

At the same time, research on battery chemistry continues. Steven LeVine, author of *The Powerhouse: Inside the Invention of a Battery to Save the World*, calls the quest for a better battery "one of the single most important engineering and scientific pursuits currently going on. It's the Holy Grail" (Fawcett 2015). Still, the continuing reductions in battery costs through at least 2030 are expected to come from incremental refinements in lithium-ion batteries, not brand-new battery chemistries.

Consumers and charging

Although technological challenges remain, the bigger challenge now comes in the form of consumers – specifically, how to motivate them to embrace battery-powered electric vehicles, plug-in hybrids, and hydrogen fuel cell EVs. While some members of the vehicle-buying public are highly knowledgeable about EV offerings and the various incentives from governments, most are not. In a series of studies of consumer attitudes toward electric vehicles, Ken Kurani of the University of California at Davis found that car owners are remarkably ignorant of EVs, even in a state as committed to fighting climate change as California (Kurani, Caperello, and TyreeHageman 2016). For instance, fewer than 2.5 percent of his sample of new-car buyers from California for the period through December 2014 reported extensive driving experience with electric vehicles, and only 10 percent reported that they had anything more than a cursory experience – and this in a region that has been aggressively

promoting EVs for 25 years, with a wide range of models available in dealerships, the state offering significant financial incentives, and local electric utilities promoting subsidized home charging.

The same survey of households found that only 7-to-8 percent of the households that shopped for or bought new vehicles in 2015 in California, Oregon, and the northeastern states actively shopped for or bought an electric vehicle. And in Germany, where the government enacted an EV subsidy in July 2016, the subsidies were sitting largely unused by the end of the year, with EVs capturing only one-half of one percent of sales (Schmitt 2016).

The key elements to making it easier for consumers to embrace all-electric vehicles are easy and fast charging and fueling. They are critical for two related reasons: (1) the psychological value of a large visible network of charging stations is huge in convincing prospective buyers that they will not be stranded, and (2) the revenue from electricity sales is so small, especially for electricity chargers, that there is no compelling business model for investment in public chargers. In practice, most people charge most of the time at home and thus make little use of public chargers, further eroding the business model for public chargers. Home charging is not only convenient but also often subsidized, as in the United States, where federal and state tax incentives are available for purchasing and installing 240-volt home charging systems (Guinn 2016).

Perhaps the easiest path toward away-from-home chargers is for employers and retail establishments such as shopping malls, parking garages, transit hubs, college campuses, and hotels to subsidize chargers (and the companies that install and operate them) as a fringe benefit for their workers, students, and customers. As the market for electric vehicles expands to include residents of apartments and condominiums, the use of public chargers will increase; for example, according to apps such as SolvingEV (<http://solvingev.com/charging-stations/9dh-77-massachusetts-ave-cambridge-ma-02139>) there are already 498 publicly available electric vehicle charging stations within a 30-mile radius of downtown Cambridge, Massachusetts – which is little surprise, given that the locale is full of technology companies and universities. The most compelling public chargers are high-power versions that will charge a vehicle in 30 minutes or less, versus 4-to-8 hours for 240-volt chargers. These fast chargers are far more expensive and require more safety precautions. But they are most urgently needed to convince buyers that they can recharge any time and use their vehicles for long trips.

With charging and fueling, the question is how much, when, where, and who pays. In August 2016, Nissan released a report arguing that based on current trends in the United Kingdom, EV charging stations there would outnumber gasoline stations within four years (Murray 2016). In late 2016, Ford, VW Group, BMW, and Daimler joined forces to set up a network of fast-charging stations for electric vehicles in Europe (McVeigh 2016). In Japan, where the greatest commitment has been made to public charging, more than 6,000 fast chargers were in place by 2016. They were funded through various public-private arrangements.

The case for hydrogen stations and the need for initial subsidies is similar. While hydrogen stations are substantially more expensive than EV chargers (more than \$1 million for each hydrogen charging station, compared to thousands of dollars for a 220-volt charger and tens of thousands of dollars for a fast charger), the difference is that eventually the hydrogen stations will become profitable, since the refueling time – and thus customer turnover – is quick and the revenue per fill is much greater. Plus, drivers will not have the option of fueling a hydrogen fuel cell powered vehicle at home.

But again, who pays the initial subsidy for these hydrogen stations? There are roughly 150,000 gasoline stations in the United States, but as of 2017 fewer than 40 hydrogen fueling stations, almost all in California. The state of California has committed \$20 million per year through 2022, including some leveraged funds from Toyota and Honda, which will result in close to 100 stations. But many more public subsidies are needed because hydrogen stations will not be profitable for many more years, and oil companies – with the notable exception of Shell – do not see a significant competitive advantage to being a pioneer, at least so far.

And, of course, there is the unfortunate reality that when most of the public hears the phrase hydrogen gas, they associate it with a Hindenburg airship-style explosion, rightly or wrongly (mostly wrongly). For the purposes of this discussion, such a perception suggests that there might be hurdles to the public acceptance of hydrogen fuel cell technology that go beyond dollars and cents – though the growing base of consumers operating fuel cell EVs in Germany, California, and Japan (including by the author) provides strong evidence that the vehicles are safe.

Consequently, there are many monetary, non-monetary, and regulatory incentives that will be needed to accelerate the transition to EVs. One promising approach is for governments to support electric vehicle sales by giving EVs special treatment in the vehicle regulatory process. For instance, the United States

and Europe allow EVs to be rated as vehicles that generate zero grams per mile of carbon emissions, and even to count double in determining the compliance of automakers with greenhouse gas regulations. This means that sales of electric vehicles become much more attractive to auto manufacturers in the United States, Japan, China, and the European Union – countries which impose aggressive fuel economy and greenhouse gas performance standards on new cars.

Government leaders can also encourage consumers to embrace electric vehicles by using their bully pulpit. This is a way to provide confidence to consumers and industry that government really is committed to nurturing the transition to EVs. Reducing risk and uncertainty is hugely important in the early years of a transition.

A slow transition ahead

The transition to electrification of vehicles will probably be gradual, for three primary reasons: consumer caution when it comes to large purchases, the high initial cost of manufacturing electric vehicles, and pushback from vested interests. There will be special circumstances, such as in Norway, where rapid transitions are possible. But in places such as the United States, where the automotive market is large and diverse, and many players are involved – including the thousands of cities and states that impose rules and offer incentives – the pace will be slower.

Cost reductions will take time. Gasoline cars have benefited from a century of intensive development, while electric cars have been the focus of major manufacturers on a commercial scale only since about 2010. Had electric vehicles and their large battery packs benefited from a century of intensive development – as gasoline cars have – the electric vehicle story might be quite different. As it is, pure battery-powered electric cars cost about \$10,000 more to manufacture than comparable gasoline cars. Though to put this figure into perspective, it should be noted that while a new, all-electric vehicle like the Chevy Bolt lists for \$37,000 (before the \$7500 federal tax incentive), the 2017 version of *Consumer Reports'* famous annual April car-buying issue notes: “Midsized SUVs span from almost \$30,000 to more than \$50,000 for the upscale versions.... Large SUVs can cost in the high-\$30,000s range to more than \$60,000 for a premium model...” (Consumer Reports 2017a). And pickup trucks don't fare much better: “Base prices range from \$20,000 to almost \$60,000...” (Consumer Reports 2017b).

Nonetheless, costs are still a critical variable when it comes to consumer acceptance of all-electric vehicles. While shrinking rapidly, battery costs will remain substantial into the foreseeable future. Battery costs have fallen from more than \$1,200 per kilowatt-hour (kWh) in 2005 to as low as \$300 for some suppliers in 2017, and they are widely expected to drop to \$200 by 2020. But even with this 85-percent drop, the cost premium is still large; for the Chevy Bolt, with more than 200 miles of range, its 60 kWh of batteries will still cost \$12,000. When the cost falls to \$150 per kWh, the Bolt batteries will cost \$9,000. This additional cost is only partly offset by the removal of combustion engines, transmissions, and pollution control equipment. (The economics are rosier for gas-electric hybrids, which are cheaper than fully electric vehicles – a hybrid can only cost about \$3,000 more when new than the average compact sedan – but then again, hybrids by definition are not fully electric, and hence not zero-emissions vehicles.)

The question of when purely electrically powered vehicles will become cost competitive, taking into account the full cost of ownership – including future maintenance and energy savings – is difficult to answer. *Bloomberg New Energy Finance* analysts predicted in 2016 that the cost of owning smaller-sized battery electric cars would equal that of gasoline cars in 2022 (Carrington 2016). That prediction is more optimistic than most. International Council on Clean Transportation analysts, those who uncovered the Volkswagen emissions cheating scandal in 2015, forecast that EVs will be cost-competitive about 2025 for small EVs with less than 150 miles of range, and about 2030 for 200-mile-range cars (Slowik and Lutsey 2016). The break-even point will be somewhat sooner in Europe, where fuel prices are much higher – typically over \$6 per gallon of gasoline as of this writing.

A landmark study at UC Davis attempted to quantify the extra costs to the economy associated with a transition to EVs (including plug-in hybrid and fuel cell vehicles). The researchers arrived at an estimate by doing a very detailed analysis of energy and vehicle costs that projected future prices of petroleum, electricity, and hydrogen; accounted for economies of scale; and forecast the costs of building an electric-charging and hydrogen-fueling infrastructure. They found that total transition costs for the United States would be \$300 to \$600 billion over a 20-year period (Ogden, Fulton, and Sperling 2016). Although this sounds like a lot of money, the authors note that “when these estimated transitional investment and subsidy costs are compared to the base cost that all US consumers spend on new vehicles and fuels (about \$1 trillion per year, or

\$20 trillion over 20 years), the cost is modest, even small” – roughly 2-to-3 percent. They note that the benefits from energy savings, not including greenhouse gas reductions, are likely to far outweigh the costs well before the 20-year transition is completed.

Pushback from vested interests

Besides being slowed by consumer caution and high costs, the transition to electric vehicles will be gradual for another real-world reason: There will be those who attempt to undermine public support and consumer interest in the adoption of this technology for ideological or financial reasons. They will use a variety of means to slow government support and dissuade consumers. Especially challenging is the oil industry. In a very fundamental and direct way, electric vehicles destroy the business of oil companies. An article in *Alberta Oil* magazine in July 2015 entitled “Is Tesla’s Model S the Beginning of the End for Oil?” asserted: “Creative disruption has already wracked most major industries, and it’s wrecked more than a few of them in the process. If it’s going to visit itself upon the fossil fuel industry, it’s almost certain to take the form of an electric vehicle” (Fawcett 2015).

Some large oil and gas companies are exploring ways to engage with electric vehicles, but for the most part they see little that is appealing. They could sell natural gas to electric utilities, which they increasingly are doing. But they don’t want to get into the electricity business, which they see as a low-margin, heavily regulated industry. They could get into the battery business, but that does not fit their core competencies. They are essentially highly capital-intensive companies that assemble massive amounts of money and collections of specialized companies to construct massive facilities – pipelines, refineries, offshore oil drilling platforms.

The one major opportunity for oil companies might prove to be hydrogen made from fossil energy. Oil companies could convert natural gas or coal into hydrogen, and then capture and sequester the associated carbon, creating a near-zero-emissions energy source. The economics could prove attractive as governments start to impose taxes and caps on carbon, and more experience is gained with carbon capture and sequestration. So far, though, the oil industry has been slower to invest in low-carbon technology than other key industries – including automakers and electric utilities.

In any case, the erosion of the oil business will be gradual. EVs are most attractive in the light-duty vehicle market, which accounts for less than half the total oil consumption in the world. The larger the vehicle, the more challenging and slow will be the embrace of

electrification. As a result, the changeover to the use of electricity and hydrogen by large trucks will be much slower than the changeover among passenger vehicles, and by trains and ships slower still. And still remaining for the oil industry is the large petrochemical market, where oil and natural gas is converted into chemicals and plastics for a wide variety of industrial and household applications. Biofuels will undoubtedly replace oil eventually for many trucks, planes, ships, and chemicals, but many issues confront biofuels as well, including cost, availability, and willingness to use land for energy.

Also slowing the demise of the oil business is the likelihood that fossil fuel subsidies – as much as \$5.3 trillion annually worldwide, according to the International Monetary Fund (Coady et al. 2015) – will not shrink much or fast. Renewable energy subsidies, in comparison, total only about \$120 billion each year.

How exactly the transition to battery, plug-in hybrid, and hydrogen fuel cell electric vehicles will unfold is unknown and unknowable. It will vary greatly from one region to another. Some strategies and paths are more expensive and complicated than others. But generally, the best policy approach is to provide visible incentives to consumers initially, assure that a network of public chargers and hydrogen stations is prominently accessible, offer incentives to automakers, mandate sales where politically acceptable, and be adaptive and agile as consumer preferences, technological innovations, and industry investments evolve.

Notes

1. Which is not to say that hybrids don't help combat climate change; they do greatly reduce the amount of carbon that is emitted, even if they don't get to the zero emissions level. For example, the US Energy Information Administration says that a hybrid car emits 51.6 pounds of carbon dioxide every 100 miles, while a conventional car will emit an average of 74.9 pounds in that distance [(Roos 2010)]. And hybrids have been around for a while now, making them a more established technology with extremely high reliability and customer satisfaction ratings from consumer organizations – a big step towards society-wide acceptance.
2. It should be noted that some of the technology that was originally developed for one type of vehicle is now used by others as well; the gas/electric hybrid's trick of capturing the energy created by braking and using it to charge the battery can be found in plug-in hybrids, pure battery EVs, and fuel cell EVs that have small batteries.

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