1. Rise of the modern electric vehicle

There is a new quest underway to replace the 125-year-old petroleum-based transport system with vehicles powered by electricity. Excluding electric bikes, scooters and neighborhood carts, the plug-in electric vehicle (PEV) was virtually nonexistent as recently as 2009. Ten years later, 7.2 million PEVs were operating on roads and highways around the world. Sales of new PEVs are growing so rapidly that the International Energy Agency forecasts approximately 130 million PEVs on the road worldwide in the year 2030.¹

The global PEV market share of new vehicles in 2019 was only 2.5%, but virtually all global automakers are planning to introduce new PEV models by 2025.² Public announcements suggest that at least 100 new PEV models will be available by 2023.³ Thirteen market studies showed enormous variation in 2040 PEV forecasts ranging from a low of 8% of new vehicle sales to a high of 75%, but all forecasts show substantial growth.⁴

The trend to PEVs is international in scope but the transition is moving at different speeds in various regions of the world. The United States, led by California, was fast out of the gate from 2008 to 2015 but China and Europe are now moving faster to electrify than the United States. The unexpected national leader in PEV deployment is oil-rich Norway, where the PEV share of new vehicle sales reached 56% in 2019.⁵

Why has there been a resurgence of interest in PEVs, and why is it happening now? Why are some jurisdictions of the world moving faster than others? This book seeks to answer these questions. A secondary objective of the book is to supply a unified introduction to the modern plug-in vehicle, covering basic issues in engineering, business, economics, environmental science, politics and public policy. My goal is not to make a case for or against the transition to PEVs but to shed light on how and why commercial interest in modern electric cars is emerging.

We may be standing on the precipice of a revolution in propulsion not seen since the horse and buggy. It is crucial to understand why it is happening, how it will impact the economy, society, consumers, international trade, and the environment, how quickly the transition might occur, and what factors should be monitored in the years ahead to inform predictions about the pace of the transition.
ELECTRIC PROPULSION SYSTEM

The basics of an electric propulsion system are an electric motor, a power converter, an electronic controller, and an energy storage device, pictured in Figure 1.1. The electric motor converts the electric energy stored in the battery into mechanical energy to propel the vehicle. The power converter converts the energy stored in the battery to the appropriate voltage and current for use in the electric motor. The electronic controller directs the power converter to control the electric motor to the torque and speed desired by the driver. The energy storage device, a battery pack, stores the electric energy from the electric grid (and vehicle deceleration) until it is needed by the electric motor. Charging of the battery occurs through either an on-board power converter or an off-board converter.

![Figure 1.1 The basic architecture of an electric vehicle](image)

The capabilities required of an electric motor in a vehicle are different from electric motors used in other industrial applications. Those special capabilities include frequent stops and starts; high rates of acceleration and deceleration; high torque and low-speed climbing of hills; low torque and cruising at high speed.

An electric vehicle is somewhat complex, but far simpler than a gasoline- or diesel-powered vehicle. A teardown study found that the number of moving parts in the all-electric Chevrolet Bolt was 24; the number in the gasoline-powered Volkswagen Golf was 149. The simplicity of the all-electric vehicle, together with the absence of high-temperature, corrosive combustion gases, helps explain why maintenance and repair costs are relatively low, assuming the battery does not deteriorate and need to be replaced.

INVENTION OF THE ELECTRIC CAR

The plug-in electric car (e-car) is not a new idea. The first steps were taken in Europe: invention of rechargeable batteries (France – 1859); improved batteries suitable for e-car production (France – 1881); the first two-wheeled and
three-wheeled e-bikes (Austria – 1867; France – 1881); the first production e-car (UK – 1884); and demonstration of performance e-cars with all-wheel drive (Germany – 1888).

In the USA, William Morrison of Des Moines, Iowa constructed the first electric car in 1891, an all-electric six-passenger wagon. A Chicago public exhibit in 1893 featured several electric cars, before the first e-taxi appeared in New York City in 1891.

The process of commercialization occurred a decade faster in the US than in Europe. At their peak of commercialization, 27 companies were in the business and e-cars captured 28% of new vehicle sales in the US. In 1900 up to one third of the cars on the roads of New York City, Boston, and Chicago were electric. Considered a niche “city car” for wealthy urban households, the quiet e-cars were particularly popular among women because the internal combustion engine was dirty, noisy and difficult to start. Figure 1.2 features an early 20th century electric vehicle model.

*Source:* The Museum of Innovation and Science Collection, New York.

*Figure 1.2* A woman charging her electric Columbia Mark 68 Victoria vehicle in 1912
The demise of the early e-cars occurred quickly, as commercial interest evaporated by 1916. Several factors explain the extinction of the early e-car: Progress in low-cost mass manufacturing of the gasoline engine; invention of the electric starter to replace the unwieldy hand crank starter used in gasoline vehicles; invention of the noise-reducing muffler for gasoline vehicles; enhanced road infrastructure between cities, thereby diminishing the value of short-range vehicles; and discovery of plentiful, low-cost oil in the United States. Serious interest in auto electrification did not resume until late in the 20th century.

Advocates of plug-in vehicles cannot believe it has taken so long for a revival of interest. They argue that a plug-in vehicle offers zero vehicle emissions and zero use of petroleum. They recognize that the power plant that generates electricity to charge the vehicle’s battery may generate pollution but not if the source of the electricity is the sun, wind, flowing water or nuclear fission. The plug-in electric vehicle also offers ample power, a quiet ride, a simpler design with fewer maintenance and repair issues, and a source of energy (electricity) that is typically much less expensive than petroleum-based fuels or biofuels. As valid as these arguments may be, it took an unplanned technological advance in the consumer electronics sector to give the PEV another chance.

THE LITHIUM-ION BATTERY

Lead-acid batteries emerged in 1859, followed by the less efficient but more compact nickel-cadmium battery in 1899. The demise of the early e-car did not destroy the automotive market for batteries, as lead-acid batteries found widespread use in starters for gasoline- and diesel-powered cars. For decades a revival of electric cars was discussed but the lack of adequate battery technology was a formidable obstacle. The development of the lithium-ion battery (LIB) for consumer electronics provided invaluable knowledge that paved the way for LIB applications in the automotive sector.

To appreciate the virtues of LIB technology, some basic background on battery design and operation is necessary. A battery is a device for storing energy as electrically charged atoms (ions) travel from the anode (negatively charged) to the cathode (positively charged). The ions move through a substance called an electrolyte while a separator film prevents the two electrodes from shorting.

As the ions move between the two electrodes, they create an electric current used as a source of power. Figure 1.3 is a simple diagram of a LIB. If the battery is rechargeable, plugging a depleted battery into a socket pumps electricity back into it by forcing the ions to shuttle back from the cathode to the anode, where they are stored until needed again. When charging, the current
goes one way; when discharging, it goes the other way. When energy is stored, there is no current.

**Figure 1.3 A simplified model of a lithium-ion battery**

The materials that make up the anode, cathode, and electrolyte are crucial in battery design. Those materials determine the quantity of ions stored and how fast the ions move. Since the early 20th century, lead-acid chemistry dominated automotive batteries; the lead for the electrodes and sulfuric acid for the electrolyte.

In the 1960s, Ford Motor Company tried to revive the PEV with a new battery design using sulfur for the cathode and sodium for the anode. The
sulfur-sodium battery was much more effective at storing energy than a lead-acid battery but it operated at temperatures that proved to be too high for safe use in automobiles.

Invention of the LIB did not occur quickly. In the mid-1970s, Stan Whittingham, a British chemist, explored the potential use of lithium, the smallest and lightest metal in the periodic table of elements. Lithium readily gives up its electrons, a favorable property for a battery material. Whittingham ultimately discovered that titanium sulfide, an energy-rich material, could comprise the cathode while the anode could be made of pure (metallic) lithium. Whittingham made the first lithium-titanium disulfide battery, but it had a serious safety drawback that blocked its commercialization: it could be unstable and explode. A physicist named John Bannister Goodenough explored alternative materials for battery design. He ultimately replaced titanium sulfide with another layered material, lithium cobalt oxide, for cathode construction. As a result, his battery was both more stable and more powerful. In 1985, a Japanese chemist, Akira Yoshino, made two additional changes in materials: lithium ions replaced metallic lithium in the anode while petroleum coke encased the anode. As a result, electrons flowed in the battery more easily and safely, without reacting with surrounding materials. As a result, Yoshino’s battery lasted a long time and recharged numerous times without losing performance.13

Commercialization began in 1991, when Sony exploited the LIB in the consumer electronics sector using a variant of Yoshino’s battery. LIBs are appealing because they are lightweight, can run a long time between charges, can be charged quickly, and are durable.14 Since then, LIBs have had a “transformational impact on personal electronics, affecting communication, computation, entertainment, information and the fundamental ways in which we interact with information and people.”15 LIBs are commonly used in portable electronic devices (e.g., laptops and cell phones), but they are also used in power tools, bicycles and scooters, and military and aerospace applications.

It is no exaggeration to say that LIBs have changed daily life for virtually everyone. In 2019, Whittingham, Goodenough and Yoshino shared the Nobel Prize in Chemistry.16

Japan established a dominant global position in LIB production in the 1990s but Chinese and Korean companies have been challenging Japan’s position for the last twenty years. In contrast, North American and European countries are positioned poorly to compete in LIB production. In Chapters 7 through 9, I explore the global scramble for access to LIBs, required components, and raw materials.
AUTOMOTIVE-GRADE LIBS

A LIB for consumer applications is made of one or several battery cells, but a LIB pack for a PEV using small consumer-grade battery cells contains literally thousands of cells. The most common 85 kWh battery pack supplied for Tesla vehicles contains 7,104 cells – each cell measures 18 millimeters in diameter by 65 millimeters in length – in modules that are packed together.\(^\text{17}\)

The term volumetric energy density refers to the amount of energy stored in a particular battery system per unit of volume. When searching for battery chemistries, auto engineers require high energy density because it reduces the cost per kWh and engineers seek to preserve volume in the vehicle for seating capacity, crush space, and trunk (or other cargo-carrying) space.\(^\text{18}\) Mass energy density refers to the amount of energy stored per unit of mass of the battery system. Since the battery increases the mass of the vehicle and, therefore, the energy required to propel it, auto engineers require high mass energy density to minimize the added weight of the battery in order to extend the range of the vehicle. LIBs have four times the energy density of lead-acid batteries.

LIBs are not without risks. The safety of passengers, pedestrians and rescue teams is central to LIB design. In the automotive crash environment, battery safety requires that a crash will not cause dangerous voltages, venting of toxic or flammable gases, or excessive heat or fires. The simplest kinds of solutions (e.g., limiting the available battery space in the car and adding heavy structural protection measures in the vehicle) are in contradiction to the design goal of increasing the driving range of the PEV by reducing vehicle weight and using batteries with high capacities. Advances in battery and crash modeling are facilitating the development of creative designs that accomplish both safety and performance goals.\(^\text{19}\)

Preventing fires and explosions is of paramount importance because, even if infrequent in occurrence and less frequent than gasoline fires, such events could undermine public confidence in the technology before it is widely used. Each battery cell contains a highly flammable liquid electrolyte. If the battery’s electrodes get too hot, the electrolyte ignites. Under abuse conditions (overcharge, over-discharge, and internal short circuits), battery temperatures can rise far above manufacturer ratings, leading to exothermal reactions that cause further temperature increases. This catastrophic self-accelerated degradation of the LIB is thermal runaway; it generates highly flammable gases. Fires associated with modern PEVs have led to recalls and government investigations to ensure consumer safety.\(^\text{20}\)

Thus, a key challenge in LIB design is how to protect the battery from overheating.\(^\text{21}\) A tradeoff in battery design occurs because cell chemistries with higher energy density tend to perform worse in temperature-related safety
testing. Modern devices are equipped with battery temperature and voltage monitoring; if an abnormal state occurs, the devices shut down automatically, though this does not eliminate the risk of thermal runaway. Ongoing research is working toward robust energy storage systems that can withstand foreseeable abuse conditions.22

In order to ensure reliable operation in automotive applications, cell monitoring and controls ensure safety, battery performance, and battery life. Extreme operating temperatures, whether hot or cold, have the potential to degrade the LIB pack’s capacity to store energy. An active battery management system is required to cool LIBs. Some manufacturers use a liquid cooling system that pumps a glycol-water mixture around the batteries to a radiator, which cools by fan. In contrast, other manufacturers use an air-cooling system that is simpler but somewhat less effective.

The LIB pack is the single largest cost item in a PEV. Currently, the cathode is made of lithium metal oxide; the anode is made of graphite; and the electrolyte is made of a mixture of different substances (e.g., lithium salt, organic solvents, and various additives). As LIBs have moved from low-volume to high-volume production, the cost of raw materials is relatively more important, since economies of scale are less for materials than for production of battery cells, modules and packs. Overall, LIBs are currently the best-performing rechargeable battery technology in terms of energy density, far superior to the two commercially viable competitors: nickel metal hydride and nickel-cadmium.23 Nonetheless, it is too early to know for sure whether LIBs, once fully refined and optimized for automotive applications, will enable PEVs to achieve mass commercialization and replacement of the internal combustion engine.

Some experts believe that even the best possible LIB will not perform well enough to serve all motor vehicle applications, as there are theoretical limits on what LIBs can do. Breakthroughs in battery technology may be required. Scientists in governments, universities and companies around the world are engaged in intensive R&D to find promising refinements to LIBs or alternatives to LIBs. One promising possibility, which Toyota and several startups are developing, is solid-state battery (SSB) technology.24 Another promising option is lithium-metal, which Tesla is developing.25 Given the long lead times required to develop new supply chains for battery systems, alternatives to LIBs are unlikely prior to 2025 but could penetrate the market prior to 2030.

THE PLUG-IN HYBRID ELECTRIC VEHICLE

The hybrid-electric vehicle (HEV), exemplified by the Toyota Prius, combines electric power with an internal combustion engine in an integrated propulsion system. The batteries in a HEV are constantly recharged during braking
Rise of the modern electric vehicle

(regenerative braking”) or, if necessary, by the gasoline or diesel engine. The plug-in hybrid electric vehicle (PHEV) is different because the battery charges from a standard electrical wall socket.

Andrew A. Frank, a University of California-Davis engineering professor, coined the term PHEV. Frank and his teams of students were the first to demonstrate the practical feasibility of a PHEV. A key advantage of the PHEV over an all-electric vehicle is that it does not compromise driving range, since it can travel as far or farther than a gasoline car without needing to be charged or fueled. Thus, the fear called “range anxiety” should not occur with a PHEV as it does with an all-electric vehicle. Some experts view the PHEV as a bridge technology to the all-electric vehicle while others see PHEVs – if designed to rely primarily on electric propulsion – as a long-term sustainable solution. Some consumer research suggests that mainstream car buyers are more interested in a PHEV than a BEV.

The success of a PHEV in reducing fuel consumption or carbon dioxide (CO₂) emissions depends on the all-electric range of the vehicle. It also depends on variables such as driver behavior, ambient temperature, and charging behavior. Early experience with PHEVs suggests that some owners do not routinely recharge the batteries, often using only the gasoline engine. New technology called “geofencing” automatically switches vehicles into electric mode in inner cities where zero emissions is required. Absent such technology, PHEVs will vary enormously in their promise as an alternative to conventional powertrains, and two owners of the same PHEV can have very different experiences.

The optimal battery designs for HEVs, PHEVs and BEVs are not identical. For HEVs, large amounts of power help accelerate the vehicle and capture the energy released during braking, but these events are brief and amount to a relatively small amount of energy compared with BEVs, which must travel hundreds of miles on a single charge. BEVs require large batteries with high energy density in order to minimize the size and cost of the battery pack. Power density is a lesser concern for BEVs because power demands are spread over a larger number of battery cells and the demand on each cell is relatively small. Breakthrough batteries for one application (e.g., HEVs) do not necessarily provide practical advances for other applications (e.g., PHEVs and HEVs).

Avoidance of battery deterioration is crucial in HEVs, PHEVs and BEVs. Most battery deterioration occurs at extremely high and low states of charge. Those states are avoided by the battery management system. HEVs typically use only 40% of the battery capacity while PHEVs use 70% of capacity and BEVs use 80% of capacity, since deep discharges occur less frequently. The development of high energy density batteries for BEVs coincided with the trend toward more long-range BEVs that needed even lower power density. As a result, the most recent BEV batteries are not suitable for PHEV applications,
which need higher power density to support temporary acceleration and regenerative braking. In Chapter 3, I explore the crucial role that governmental R&D played in sorting out the important factors in battery design.

HYDROGEN FUEL CELL ELECTRIC VEHICLE

Burning hydrogen in the internal combustion engine is feasible, but fuel cell electric vehicles (FCEVs), or FCVs for short, have proven to be a better and cleaner way to use hydrogen for transport. Pure hydrogen gas is stored in a tank on the vehicle. A fuel cell uses the hydrogen to produce electricity that powers the vehicle. The fuel cell combines oxygen from the air with hydrogen from the tank, facilitating an electrochemical reaction, which in turn generates an electric current that runs an electric motor. The only byproducts of the reaction are water and heat; zero pollution.

Multiple types of fuel cells are available but the Proton Exchange Membrane (PEM) technology is state-of-the-art due to its ability to warm up quickly. Pioneering research occurred in the early 1980s at Ballard, a startup in Vancouver, British Columbia working under contract with the Canadian Department of National Defense. Building on 1950s-era work that General Electric abandoned, Ballard made sufficient progress to interest Daimler-Benz, which entered a four-year, $35 million partnership with Ballard, ultimately leading to Daimler’s prototype FCVs of the 1990s.

The State of California was the first large political jurisdiction in the world to enact strong pro-FCV policies. The State was the first jurisdiction in the world to develop a significant network of hydrogen fueling stations.

DEFINITION OF TERMS

Throughout this book the umbrella term “plug-in electric vehicles” (PEVs) is used to encompass both battery-electric vehicles (BEVs), which operate entirely on electric power, and PHEVs, since both types of PEVs have plug-in capability for charging. The conventional HEV is not a PEV because it does not have plug-in capability. The hydrogen fuel-cell vehicle (FCV) is typically an electric vehicle. The phrase “electrified vehicles,” as used in the industry, encompasses HEVs, PEVs and FCVs.

THE ROLE OF PUBLIC POLICY

The rise of the modern PEV is only partly explainable by advances in battery technology. Politicians around the world have adopted a wide variety of public policies to assist the penetration of PEVs into the automotive marketplace.
On the supply side of the market, pro-PEV policies help companies produce PEVs and establish the necessary supply chains to expand production. On the demand side of the market, pro-PEV policies enhance the attractiveness of PEVs in the eyes of consumers. PEVs penetrate the market even better when policies disfavor gasoline and diesel vehicles. Some political jurisdictions are planning – or have enacted – policies that tax, restrict or prohibit use of the internal combustion engine. Thus, corporate pioneers of PEVs have a leg up in political jurisdictions that are pro-PEV.

Most of the PEV-related policymaking is occurring at the nation-state level, but there are some complications from multiple levels of government operating simultaneously. As a subnational authority, California has played a central role as a determined promoter of PEVs since 1990. Subnational authorities also play an influential role in China, despite the myth that China’s central government is all-powerful. Provincial and municipal politicians in China have nurtured new automobile companies (e.g., BYD and NIO) that have boosted the fortunes of the modern PEV. As a supranational authority, the European Union has only recently had a major impact on PEV promotion. As I show in Chapter 10, a turning point in Europe occurred in 2015, with public disclosure of Volkswagen’s use of defeat devices to cheat on compliance with diesel-engine emissions standards. The VW scandal tarnished both the diesel engine and the credibility of Germany’s pro-diesel stance, thereby liberating the European Union to take a more aggressive posture toward a possible regime shift favoring PEVs. Thus, in this book, the actions of multiple levels of government are considered together.

To appreciate the perspective of the politician, I outline briefly the multiple rationales advanced in favor of public policies to promote PEVs. In broad terms, the rationales relate to energy security, urban air quality, climate change and economic development.

**Energy Security**

The modern case for PEVs received its first big boost not from environmental concerns but from the Arab oil embargo of 1973–1974. Triggered by war in the Middle East, an embargo by Arab-affiliated oil producers against pro-Israel countries led to a sudden quadrupling of the world price of oil, causing a massive transfer of wealth from oil-importing to oil-exporting countries. The concept of “energy insecurity” became a major policy concern in oil-importing countries. Vehicles that run on alternative fuels, such as electricity, biofuels and natural gas, became a priority in many oil-importing countries. The policy rationale, which I explore in Chapter 3, is that PEVs contribute to both economic and national security by reducing dependence on oil.


Urban Air Quality

When motor vehicles combust gasoline or diesel fuel, pollutants are emitted that contribute to smog (ozone), particulate matter and acid rain. Over the last fifty years, a large body of scientific evidence linked inhalation of urban air pollution to adverse effects on human health: cardiopulmonary problems, heart attacks, cancer, and aggravation of asthma and bronchitis. The most susceptible populations are senior citizens, infants and children, and adults with respiratory and cardiopulmonary impairments.

One of the appealing features of a BEV is that it has zero emissions of pollutants during vehicle operation. Even if emissions from a gasoline or diesel vehicle are controlled 99% with advanced technology, real-world experience shows that malfunctions occur periodically and the pollution-control efficiency declines as the vehicle ages. Thus, a BEV interests environmental regulators and public health professionals because it accomplishes zero vehicle emissions throughout a vehicle’s entire 10–30 year lifetime.

If electric power is produced from fossil fuels, charging of PEVs from the grid will induce additional air pollution at the power plant. The concentrations of those emissions, emitted from a large stack, will be more diffuse than occurs in auto-dependent inner cities, though a precise comparison requires detailed air quality modeling of both vehicular and power plant emissions. Chapter 4 examines the rationale for BEVs as a measure to enhance urban air quality.

Climate Change

Gasoline- and diesel-powered vehicles contribute to climate change because of the carbon dioxide and other greenhouse gases emitted from the internal combustion engine and its supply chain. Shifting the transport sector from petroleum to electricity offers promise in climate policy as long as regulators control the greenhouse gas emissions from the electricity sector and the PEV’s supply chain. As the use of coal in electric power generation has been replaced by low-carbon fuels such as natural gas and renewables (wind and solar), the promise of PEVs as a climate-policy measure has improved. In Chapter 5, I explore the connections between international climate policy and pro-PEV policies.

Economic Development

The transition to PEVs will harm the economies of jurisdictions that host gasoline and transmission plants and their supply chains, as well as facilities associated with the petroleum supply chain such as gasoline stations, refineries and oil production facilities. Given that a transition to PEVs is underway,
jurisdictions will compete for the economic development associated with the new propulsion system.

Insofar as PEVs are commercially successful, an entire new industry will provide employment and tax revenues in regions where production facilities are located. The economic development occurs not only where vehicle assembly plants are located but also where production of battery cells and packs occurs, where manufacturing of anodes and cathodes occurs, and where mining and processing of raw materials (e.g., lithium, cobalt) occurs. Likewise, economic opportunities will expand in the production of electric motors, inverters, chargers, controllers and associated raw materials (e.g., neodymium and other rare earths).

The stimulus provided by the PEV industry is important to a host jurisdiction’s economic well-being but international ramifications also flow from economic development. If a country becomes a global leader in the supply chain for PEVs, the resulting economic development is a source of “soft (diplomatic) power” and provides supportive conditions for acquisition of “hard (military) power.” Germany and Japan wield soft power internationally partly because of the strengths of their auto-dependent economies; the United States and China are even more influential due to their acquisition of hard military power. If a country loses out in the transition to PEVs, it faces a potential loss of soft and hard power in international relations. Thus, the economic development associated with the supply chain for PEVs is a valued chess piece in the international competition for power among political jurisdictions.

PRO-PEV ADVOCACY

In 1989, a trade association of companies with commercial interests in PEVs formed in the United States, the Electric Drive Transportation Association (EDTA). Members of EDTA include companies that assemble PEVs, produce LIBs and other components, and companies in the charging-service and LIB-recycling sectors. Based in Washington, DC, EDTA has emerged as an influential player in national PEV political discussions.

Parallel organizations exist in Asia, the Electric Vehicle Association of Asia Pacific (EVAAP), and in Europe, the European Association for Battery Hybrid and Fuel Cell Electric Vehicles (AVERE). The three regional trade associations have also formed the World Electric Vehicle Association (WEVA), which organizes the annual International Electric Vehicle Symposium (EVS) to facilitate global networking within the sector and exchange of new scientific and technical information related to PEVs. The last five symposia took place in Lyon, France (2019), Kobe, Japan (2018), Stuttgart, Germany (2017), Montreal, Canada (2016) and Kintex, Goyang, Korea (2015). The 2020 symposium scheduled for Portland, Oregon did not convene due to COVID19.
WEVA also publishes the international scientific journal World Electric Vehicle Journal.

In August 2008, a national non-profit advocacy group called Plug-in America formed with offices in Washington, DC. It emerged from an activist group of PEV owners in California who learned from California’s turbulent efforts to mandate PEVs that a national voice in favor of PEVs is required. The group claims, as one of its major accomplishments, the 2009 orchestration of more than 50,000 citizen letters to Congress supporting adoption of the $7,500 federal tax credit for qualified PEVs. Plug-in America also co-hosts each year the National Drive Electric Week with the Sierra Club and the Electric Auto Association, an organized group of PEV owners.

More recently, as the PEV industry has grown, new advocacy groups have formed on different aspects of the issue. Securing America’s Energy Future (SAFE) was formed in 2006 to reduce dependence on foreign oil; currently it emphasizes the need to build a PEV supply chain in the US to counter China’s dominance of the PEV sector. More recently, the Zero Emission Transportation Association was formed to advocate for 100% PEV sales in the US by 2030. The new group is sponsored by a group of electric utilities, charging companies, lithium mining companies and Tesla. And, to support the beginning of the PEV supply chain, the new Battery Materials and Technology Coalition brings together companies with interests in mining, processing and recycling the critical raw materials used in PEVs.

POLITICAL ECONOMY

The public-policy rationales mentioned above are valid “public interest” rationales for using governmental power to promote PEVs. I also encourage readers to consider PEV-promotion policies from a more skeptical “political economy” perspective.

Political economy predicts that corporate leaders will be tempted to persuade politicians to tweak public policies in ways that advance the pecuniary interests of the company, without necessarily advancing the public interest. Persuasion occurs through corporate political activity, including lobbying, litigation, constituency building, coalition formation, and contributions to political campaigns. Likewise, politicians are tempted to tweak public policies in ways that favor the welfare of the city, province, country, or region they represent, without necessarily accomplishing broader society-wide benefits. Such behaviors are “rent seeking” – a phrase that arose in a setting where the amount of income paid to a factor of production (e.g., labor or land) was inexplicably in excess of what is required to keep that factor of production in its current use. In extreme forms, rent seeking may be a form of corruption on the part of the politician and the corporation that receives the “rent.”
Readers are encouraged to look for seemingly pro-PEV policies that are rent-seeking policies designed to favor a particular company, group of companies, specific technologies, and specific geographical areas or political jurisdictions. Historically, the fossil-fuel industry has engaged in rent seeking, so we should not be surprised if the PEV industry plays the same game. It is not always easy to distinguish policies rooted in the public interest from policies rooted in rent seeking but I return to this theme in the last chapter.

CORPORATE INNOVATORS

Over the last two decades, the global auto industry experienced tremendous upheaval. The chart in Figure 1.4 reports the top automakers in the world by global sales volume (2018). Toyota and Volkswagen surpassed General Motors and Ford as the largest automakers around the year 2000. The 1999 alliance of France’s Renault with Nissan of Japan formed the third largest global automaker (the alliance added Mitsubishi in 2016). Chinese manufacturers grew rapidly from 2000 to 2015 but only one (SAIC, a large state-owned enterprise) cracked the top fifteen in the world. The 2019 merger of Fiat Chrysler and PSA, once integrated, will create one of the largest global automakers by volume of production.

Figure 1.4  A comparison of global corporate leaders in PEV production to leaders in total passenger-vehicle production
Automakers vary enormously in how much priority they have given to PEV development. The big PEV producers are Tesla (a Silicon Valley startup), Nissan–Renault–Mitsubishi, BYD in China, and a few other Chinese companies with very different histories (see Chapter 6 on China’s auto sector).

According to innovation theory, a disruptive technology typically arises from startups or smaller firms that seek to dislodge entrenched technologies championed by dominant firms. The innovators may succeed in finding “early adopters” in the marketplace but often fail – or become restricted to niche markets – when they strive to leap over the “valley of death” to mass commercialization. Innovation does not usually occur among dominant firms unless innovation is an incremental refinement of established technologies, since dominant firms and their suppliers benefit from current technologies. Once dominant firms in the industry perceive that a radical technological change may have legs in the marketplace, they will respond aggressively to counter the early successes of the first movers. The “evolutionary” perspective on industrial innovation holds that radical technologies have a better chance of success if “the government sows the seeds for transformative change,” a process of “transition management” that focuses on the dynamics of innovation.

In the next section, I review pioneering initiatives of the modern PEV manufacturers. The pattern is somewhat similar to the predictions of innovation theory.

TESLA: THE FIRST MODERN BEV

In 2003, Martin Eberhard and Marc Tarpenning launched Tesla Motors Inc of Silicon Valley and led the company until their departures in 2008. The founders abhorred the 2003 decision of General Motors to recall and destroy the all-electric EV1 cars sold in California in the late 1990s. The company name honors the Serbian-American scientist, inventor and futurist Nikola Tesla, known for his contributions to the design of the modern alternating current electricity supply system.

Elon Musk, a 37-year-old technology entrepreneur, joined Tesla in 2004 and became CEO in 2006. Musk acquired wealth from the eBay purchase of PayPal after he had become a majority shareholder. Among his supporters and critics, Musk is recognized as a visionary due to his revolutionary ideas about future transportation systems.

Musk eschewed pressures for near-term profitability and set out to establish Tesla as a technology company that would use LIBs to disrupt the global auto industry. He shocked the industry with the news in 2008–2009 that he was developing a mass-market BEV that would sell for $35,000. Tesla began by commercializing an all-electric sports car and followed with several
premium all-electric vehicles. Established industry leaders in Detroit, Japan and Germany did not know what to make of Musk, but they took comfort in the fact that startups in the global auto industry have a high mortality rate.

The company’s first product, the Roadster (2008–2012), was a low-volume, high-performance sports car propelled entirely by electric power. It is a highly modified Lotus Elise, a two-seat, rear-wheel drive sports car. The Roadster boasted a top speed of 150 miles per hour and could travel from 0 to 60 miles per hour in 3.9 seconds. Offered by Tesla at a stiff minimum price of $109,000, the Roadster’s large LIB pack facilitated travel for 227 miles on a single charge.

Through the Roadster, Musk’s reputation, and the company’s location in Palo Alto, California, Tesla established an image of high tech innovation. The company terminated the Roadster but followed up in 2012 with the Model S, a luxury hatchback starting at $75,000 and in 2015 with the Model X, an upscale SUV starting at $108,000. The company’s largest-selling product is the Model 3, an alternative to established compact premium sedans. Launched in 2017 at a starting price of $35,000 to $41,100, it usually sells for closer to $60,000 with desired options included. The Model 3 has a minimum range of 220 miles per charge and an advertised 0–60 mile-per-hour time of 5.6 seconds.

Tesla’s most important achievement to date occurred in 2017–2019: It was the number 1 seller in the US near-luxury market, outselling the prestigious sedans offered by German, Japanese and American brands. Due to the success of the Model 3, Tesla in 2018 sold more all-electric vehicles than any automaker in the world.

Two unexpected developments helped Tesla in the company’s launch stage. In late 2008 a board member of the large German firm Daimler, Dr. Thomas Weber, visited Elon Musk, looking for assistance in technology for an electric version of Daimler’s Smart car, a minicar. Musk cultivated the Daimler relationship and in May of 2009 Daimler bought a 10% interest in Tesla for $50 million. A year later, Toyota – seeking technology assistance for the electric version of the popular RAV4 SUV – reached out to Musk. Toyota ultimately (May 2010) bought a 2.5% interest in Tesla for $50 million and sold its idled factory in Fremont, California to Tesla for $42 million. Daimler and Toyota later terminated their alliances with Tesla but both alliances boosted Tesla’s credibility early in the company’s life.

With the boost provided by the Roadster rollout and the two alliances, Tesla prepared for its initial public offering of stock (even though the company had not yet reported a profit). On June 29, 2010, after selling only 1,063 cars, Tesla listed its price at $19 per share; by the end of the day the company had raised $226 million with a closing price of $23.89. Investors showed fascination with Tesla’s vision, as the average price of Tesla’s stock continued an explosive
The global rise of the modern plug-in electric vehicle

The market value of Tesla’s shares exceeded the market value of General Motors and Ford combined in 2019. In 2020, Tesla’s market value ($205 billion) — excluding debt — grew larger than #2 VW and #1 Toyota.58

Tesla’s road to credibility has not been without significant setbacks. The productivity and quality of its manufacturing has been subpar.59 The CEO’s tweets have led to adverse verdicts and restructuring orders from the Securities Exchange Commission.60 The rate of worker injuries at Tesla plants is elevated.61 The National Labor Relations Board has cited Tesla for anti-union activities.62 EPA has cited Tesla facilities for environmental violations.63 The National Highway Traffic Safety Administration has an ongoing defect investigation related to fires occurring in Tesla vehicles.64 The company has a pattern of making public pledges that it cannot meet.65 Significant executive turnover occurred in key positions.66 Most importantly, the company has not yet demonstrated impressive profitability.67

Despite those setbacks, Tesla is expanding production and globalizing sales with an exciting brand. Future plans include a new SUV (the Model Y), an all-electric pickup truck (“Cybertruck”), a small affordable compact car for the European market, and possibly a new sports car following in the tradition of the Roadster. Wall Street continues to be impressed with the company’s vision for the future and Tesla delivered for the first time in 2019–2020 five profitable quarters in succession.68 In 2020, Tesla was included in the Standard and Poor’s 500, a substantial boost to the company’s somewhat controversial reputation.69

BYD: THE FIRST MODERN PHEV

The founder and chairman of BYD, Wang Chuanfu, began his career studying rare earths in one of Beijing’s government laboratories but he shifted to the private sector to launch a private battery-manufacturing company. After making a fortune selling lithium-ion batteries for handsets, power tools, note- books and iPhones, Chuanfu took BYD public on the Hong Kong exchange (2002). A year later BYD bought a majority stake in Xi’an QinChuan Auto Company, a troubled state-owned automaker, signaling his intent to be a first mover in production of PEVs based on LIBs.70 BYD gained credibility in global financial markets when Warren Buffet’s Berkshire Hathaway Inc. bought a 10% stake in BYD in September of 2008.71

BYD introduced in 2008 the world’s first PHEV, the F3DM, a variant of the company’s popular F3 compact sedan. The F3DM offered 37 miles of all-electric range and a total range of 337 miles. The vehicle’s top speed was 93 MPH. The F3DM was the first official “New Energy Vehicle” (NEV) recognized by the central government in China’s inaugural catalogue of NEVs.
BYD had difficulty selling the F3DM. Cumulative sales of the F3DM were only 3,284 units when the offering ended in October 2013. The gasoline-powered F3 sold for $8,750 while the F3DM sold for $21,900. Consumers also noticed that the F3DM transitioned somewhat awkwardly between electric and gasoline propulsion. Retail sales in China were also hurt due to a lack of charging infrastructure and the absence of consumer incentives to purchase a PHEV. In 2010, five Chinese cities added a $7,320 cash incentive to buy a PHEV but the F3DM still had a price more than 50% larger than the popular F3. BYD had more early success producing electric buses for large cities around the world (Shenzhen, Amsterdam, Frankfurt, Albuquerque, and Los Angeles). Electric taxis for the city of Shenzhen (BYD’s headquarters) helped launch the company’s fleet sales of PEVs.72

BYD’s success in China’s PEV market exploded from 2015 to 2018, as BYD offered new PEVs and the Chinese government favored PEVs with numerous policy instruments. BYD focuses on the affordable end of the new passenger vehicle market, where the growing Chinese middle class offers a huge potential customer base. By January 2019, BYD was selling the largest and third largest-selling PEVs in China: a subcompact crossover called the Yuan and a compact crossover called the Tang. While fewer than 5% of BYD vehicle sales in 2019 were PEVs, the company’s success selling PEVs far exceeded the success of other Chinese automakers.73

BYD faces many challenges sustaining its profitability, as China’s PEV subsidies are being phased out and many new startups and established automakers (domestic and foreign) are moving into China’s growing PEV market. In 2019, BYD announced a new joint venture with Toyota to develop PEVs for the Chinese market.74 BYD maintains a determination to become China’s first global automaker with sales on every continent. The company believes that sales of PEV are the most promising way to accomplish that vision.

NISSAN LEAF: THE FIRST AFFORDABLE BEV

In the late 1990s, Nissan started down a road toward HEVs with a plan to license Toyota’s technology.75 The alliance of Nissan and Renault in 1999 caused Nissan to shift its resources to BEV technology using LIBs.

Much of the credit for Nissan–Renault’s commitment to BEVs is attributable to Carlos Ghosn, a Brazilian native with partial French and Lebanese ancestry who studied engineering at the premier school in France (Ecole Polytechnique). As CEO of the French firm Renault, Ghosn restored the company’s profitability and arranged the alliance of Renault and Nissan. After assuming the leadership of the alliance (1999–2017), he also revived the profitability of Nissan. Ghosn departed from the strategies of other global automakers by launching a global plan to bypass HEVs and commercialize
affordable BEVs. From 1999 to 2008, Nissan–Renault spent together $5.85 billion on electric-vehicle technologies. Ghosn’s reputation suffered in 2018 after the Japanese government arrested and detained him for alleged wrongdoings: under-reporting of corporate assets and misuse of company assets for personal purposes. Prior to his trial, Ghosn’s wife helped organize his secret escape from Japan. He settled in Lebanon with his family. The three companies (Nissan, Renault and Mitsubishi) continue to invest in BEVs under new leadership.

In October 2007, Nissan–Renault stunned the industry with a pledge to bring an “entire lineup” of zero emission BEVs to the global market by 2012. This pledge was in direct contradiction to the positions of the two largest Japanese automakers, Toyota and Honda, whose leaders argued that battery technology was not adequate to support mass BEV commercialization. In Europe, Nissan–Renault also undermined Germany’s case for a pro-diesel strategy by touting the necessity and promise of BEVs.

To deliver on its pledge, Nissan–Renault formed a joint venture with Japanese electronics giant NEC Corporation. Called the Automotive Energy Supply Company, the venture’s mission was to start making LIBs for BEVs in 2009. The plan was to launch BEVs first in the US and Japan in 2010 and later in Europe and globally. At the fall 2008 Paris Auto Show, Nissan–Renault’s far-reaching global plan for BEVs – symbolized by a tiny concept car called the NuVu – overshadowed the modest steps toward PEVs announced by other automakers.

The company’s first BEV was the Leaf, a compact five-door hatchback with a base price under $30,000. It had a top speed of 93 miles per hour but consumed 9.9 seconds to go from 0 to 60 miles per hour and could travel only 73 miles on a charge, according to EPA’s testing. The Leaf went on the market in Japan and the United States in December 2010. The car won the 2010 Green Car Vision Award and the 2011 World Car of the Year.

The leadership of Nissan–Renault was nonetheless aware of the practical realities. They cautioned that successful commercialization of BEVs would require years of government subsidies, a continuation of high oil prices, and extensive cooperation and investments from the electric utility industry.

Sales of the Nissan Leaf consistently underperformed compared to Nissan’s goals, but Renault – working separately from Nissan – did deliver an entire line of BEVs in Europe, and Renault has offered the largest lineup of BEVs in Europe since 2011. In 2019–2020, both Nissan and Renault confronted serious financial problems requiring subsidies from the French and Japanese governments. Despite financial troubles, Nissan announced in 2020 plans to launch a new all-electric SUV (the Ariya) in 2021 with 280–380 miles of driving range.
MITSUBISHI’S I-MIEV: A MICRO BEV

Prior to its alliance with Nissan and Renault, Mitsubishi was a pioneer in PEV technology. Some industry experts argue that the Mitsubishi Innovative Electric Vehicle (i-MiEV), first offered in 2009, was the precedent-setting micro BEV in the modern era. A LIB pack for the i-MiEV was developed and manufactured jointly by Mitsubishi and GS Yuasa (a Japanese motorcycle and battery maker) through a joint venture called Lithium Energy Japan. Fleet testing occurred in 2007; the company announced commercialization plans in 2008; and sales began in Japan in April 2010 and in Europe in October 2010. Thus, the i-MiEV was on the market before the Nissan Leaf, Tesla Roadster and the Chevrolet Volt.

Japan ranked as the leading market for the i-MiEV, in part because the car’s tiny size is appealing to Japanese consumers and in part because of Mitsubishi’s strong reputation in Japan. The $30,000 five-door hatchback BEV has rebadged variants sold in Europe as the Peugeot iOn and the Citroen C-Zero. The car’s top speed was 80 miles per hour and its EPA-rated driving range was 62 miles per charge. The vehicle did not sell well in the US; the company ceased the US offering in August 2017.

Mitsubishi followed in 2017 with the Outlander SUV. It ultimately became the best-selling plug-in hybrid SUV in the world.

GM’S VOLT: A RANGE-EXTENDED BEV

As Tesla was launching the Roadster, General Motors responded with an innovative vehicle called the Volt. Originally seen as a “Prius fighter,” GM accelerated the Volt’s development in response to growing Wall Street interest in Tesla.

Announced first in concept at the January 2007 North American International Auto Show, GM leadership envisioned the Volt as a four-seat sedan that would employ a gasoline engine to recharge the Volt’s batteries. GM engineers acknowledged that the necessary batteries did not yet exist. The company worked first with A123, a Massachusetts-based startup, but ultimately turned to an established Asian electronics firm, LG Chem of South Korea, to supply the LIBs.

GM announced the first production design version of the Volt in September 2008. The first production car sold to a consumer in late 2010, branded as the Chevrolet Volt in North America and the Opel Ampera in Europe.

The original production version of the Volt had an all-electric range of 38 miles but the total range (buttressed by the gasoline engine) was more than 300 miles. It could travel from 0 to 60 miles per hour in 8.5 seconds and was
greeted with tremendous positive publicity by consumer-facing experts around the world. The Volt won the 2011 Green Car of the Year.

The pricing of the Volt (starting at $41,000, base) was far above the Toyota Prius HEV ($27,000) but well below the Tesla Roadster ($109,000). Accounting for the federal tax benefit, GM’s original leasing plan called for a monthly payment of $350 per month, with a $2,500 down payment.

There are many skeptics of the Volt, including President Obama’s White House advisor for autos, Steven Rattner. Rattner was apparently startled to learn during the GM bailout deliberations (2009) that it cost GM $40,000 per vehicle to manufacture the Volt (development costs excluded). Rattner believed that GM did the right thing to offer the Volt, even though it would not be profitable, because the company needed to counter the widespread perception that GM was “behind the curve” in green technology.86 Disappointing sales of the Volt led to its termination in 2018. GM also offered the smaller Chevrolet Bolt, a BEV with a 238-mile range from the 60 kWh battery pack, using some of the experience gleaned from the Volt. Sales of the Bolt have also been lower than GM planned. Building on experience with the Bolt and Volt, GM has pledged to offer numerous new BEVs between 2020 and 2025.

BMW’S PROJECT “I”: THE FIRST ELECTRIC LINE

In 2007 BMW launched “Project I,” an ambitious, long-term program to develop a new sub-brand of electric vehicles called the “i” series.87 The vision was the invention of a lightweight, eco-friendly electric car to meet the mobility needs of people living in the world’s mega-cities (population 10 million and above).88 The project began with a demonstration of technology in the Mini E Trial. The real-world information generated in the trial – much of it made public by BMW – informed many of the subsequent PEV developments around the world.

In this pilot, BMW converted the tiny British Mini Cooper into the Mini E by using much of the back seat and cargo area for the LIB pack. The Mini E operated as a two-seater with a range of 100–156 miles and a 0–60 mph time of 8 seconds. The two-year trial (2009–2011) launched first in Los Angeles and New York/New Jersey, with 450 Mini Es leased to drivers.89 The leasing rate was $850 per month (about triple the rate for a conventional Mini Cooper car). Smaller demonstrations occurred in Berlin, Munich, London, and Paris; even smaller pilots unfolded in Japan and China. The priority BMW gave to the US market reflected a need to prepare for California regulations; early-adopter interest was also developing faster in the US than in Europe and Asia.

At the 2009 Frankfurt Motor Show, BMW affirmed its commitment to the new i series; the i sub-brand of BMW was formally established in 2011. The i3 (2013 launch) is a subcompact luxury hatchback with a top speed of 93 miles
Rise of the modern electric vehicle

per hour and 81 miles of all-electric range that can be supplemented with an optional gasoline engine. The vehicle, with its carbon fiber body, was the 2014 World Green Car of the Year. The base model was offered at $46,400 (before government incentives), with the optional gasoline range extender costing $3,850. BMW did not meet its sales goals for the i3, but for several years i3 sales were third globally among BEVs, behind the Nissan Leaf and the Tesla Model S. The i8 is a plug-in hybrid sports car that delivers 15 miles of electric range and 330 miles of total range. It accelerates from 0 to 60 miles per hour in 4.4 seconds. The i8 concept was originally unveiled as a diesel PHEV but offered as a gasoline PHEV. Despite its stiff price of $109,000, the i8 became one of the largest selling electric sports cars.

There are no plans for an i3 successor but BMW will soon bring electrification to its mainstream models. Critics of BMW argue the company, though far ahead of other German manufacturers in PEV engineering, was slow to commercialize its PEV innovations. BMW’s first long-range PEV, the iX3, will roll out in China and Europe by 2021, before the United States.

***

The six pioneers mentioned above will not necessarily be the global leaders in PEV sales in the decade from 2020 to 2030. It is not yet clear how durable “first-mover” advantages will be, since it is feasible for second movers to learn from the mistakes and successes of the first movers. The resource-rich global automakers (e.g., Toyota, Honda, Volkswagen, Daimler and Ford) have only recently made major investments in PEVs. Numerous startups in the US and China are also angling to dislodge BYD’s and Tesla’s pioneering positions. The vigorous competition underway is a good sign for the future of the PEV industry.

SCOPE AND METHODOLOGICAL CHOICES

I shed light on the advent of the modern PEV through comparative policy analysis using both longitudinal and cross-jurisdiction comparisons. The political jurisdiction is the unit of analysis, though I also offer some insights from individual corporate perspectives. Specifically, I compare political jurisdictions that are leading the transition to PEVs to jurisdictions that are lagging, based on information concerning production and consumption of PEVs and their components and raw materials. I analyze each jurisdiction from the perspective of energy security, urban air quality, climate change and economic development. The policy-analytic approach is primarily qualitative, since there are too few political jurisdictions to perform meaningful statistical analysis.
I use quantitative information to shed light on a variety of technical, economic, environmental and policy issues.

The period for study is 1973 to 2020. I give special emphasis to how jurisdictions responded to the oil crises of the 1970s, to problems of poor urban air quality, to concerns about global climate change, and to the hardships inflicted by the Great Recession (2007–2009) and the recent downturn related to COVID19 (2019–2020). My future time horizon includes 2020 to 2030 but I do not venture guesswork beyond 2030.

The focus of the book is “light-duty” passenger vehicles, cars and light trucks. I do not address motorcycles, scooters, bicycles, commercial vehicles, heavy trucks or buses. It is already apparent that electric propulsion is succeeding in some of these vehicle segments (e.g., e-bikes and e-buses).

I selected eight political jurisdictions for study: the United States, California, Japan, China, the European Union, Germany, France and Norway. Each of these jurisdictions is either host of a vibrant auto-manufacturing sector or is a contemporary leader in the promotion of PEVs, or both. From 2008 through 2018, these jurisdictions accounted for 96% of all PEVs sold in the world.93 The notable omissions among auto-intensive economies are South Korea, the United Kingdom and India. Among national leaders in PEV sales, notable omissions are the Netherlands, Iceland, Sweden and Denmark. It would be valuable for future studies to compare what is happening in each of the omitted countries.

I considered whether to include a rapidly developing country such as Brazil or India. While such countries are expressing interest in PEVs, history suggests that innovations in propulsion systems must first prove successful in developed countries before significant adoption occurs in the developing world. An exception was Brazil’s success at commercialization of biofuels made from sugar cane. At this stage of the global PEV industry’s development and the cost curve of technology, I concluded that a focus on developed countries is appropriate. I hope the book helps policy makers in the developing world learn from the experiences in developed countries.

I do not address some technologies that are promising from 2030 to 2050 but are unlikely to experience large deployment prior to 2030. Especially worthy of mention are natural gas vehicles, advanced biofuels and e-fuels.

Significant deployment of natural gas vehicles has already occurred in several countries (Argentina, China, Italy, Iran, and Pakistan).94 North America is a promising location for such vehicles because of large natural gas reserves and low natural gas prices but low prices of oil and gasoline stifle their deployment.95 If significant deployment occurs prior to 2030, it is more likely to occur in centrally fueled delivery trucks than in passenger cars. Some deployment in buses has already occurred.
Advanced liquid biofuels blended with gasoline or diesel fuel are also promising. Rapid increases in conventional biofuels, made from crops and animal-fat feed stocks, are feasible but not advised due to potentially perverse impacts on food prices, land use, greenhouse gas emissions, scarce water supplies and water quality. Advanced biofuels (e.g., produced from agricultural and municipal waste) could be affordable, efficient and clean. Nonetheless, they are developing more slowly than expected, and may not be economically competitive prior to 2030.

E-fuels are renewable, liquid synthetic fuels (e-diesel and e-gasoline) that are not dependent on crude oil. Audi is a pioneer of a renewable e-gasoline (“e-benzin”) produced from biomass in two steps: biomass produces gaseous isobutene, and then hydrogen helps transform the isobutene into isooctane, a liquid fuel. Audi is also demonstrating e-diesel that is produced using only hydroelectric power as an energy supply. E-fuels are excellent anti-knocking agents, promise increased engine compression and achieve high levels of fuel efficiency. They are compatible with existing infrastructure and with gasoline and diesel vehicles. Although e-fuels are attracting substantial investment in Europe, substantial commercial application prior to 2030 is unlikely because significant production-cost efficiencies are necessary and a period for large-scale commercial demonstrations is required.

The resurgence of electric propulsion is only one of three “revolutions” now impacting the global automotive industry. The other two are autonomous transportation (self-driving vehicles) and ride-sharing (as exemplified by companies such as Didi Chuxing, Uber and Lyft). Since those two revolutions promise intensive, high-mileage use of vehicles, they may be boosted by electric propulsion, which – as I explore in Chapter 2 – has relatively low operating costs compared to capital costs. I do not address here the rapidly growing literature on the important interactions between the three revolutions such as the concern that the computers and sensors used in autonomous vehicles might cut the driving range of electric vehicles and accelerate battery degradation. Technical innovation is now focused on the unexpected interactions but this book argues that the transition to electric propulsion has its own drivers and thus the PEV transition is not fully dependent on the pace of the other two revolutions.

Given the wide variety of jurisdictions covered, I have consulted – via telephone, e-mail and/or personal interviews – with experts on PEV policies and developments in each jurisdiction/region. Those experts include John German and Wally Wade (the US), Allan Lloyd (California), Simon Godwin (Europe), Aki Yasoaka (Japan) and Hongyang Cui and Liu Bin (China). The appendix of this chapter provides a brief biographical sketch of each expert. When I confronted issues that perplexed me, I sought guidance from these experts. I also asked each expert to review an early draft of the book, which led to substantial
revisions. I of course remain responsible for all opinions and errors. I have also consulted a wide range of publicly available sources of information including newspaper accounts of key historical events, automotive websites, government documents that describe and justify PEV-related policies, auto-related reports from think tanks and advocacy organizations, and relevant books and academic articles.

Throughout the research for the book, I continually asked myself: *Why is the PEV being revived now? Why are some jurisdictions moving faster than other jurisdictions?* I return to these central questions in the last chapter.

**GOVERNMENTAL LEADERSHIP**

One of the themes of the book is that the modern PEV industry is as much a creature of governmental policy as it is a product of innovative capitalism. I do not discount the crucial role of influential scientists, engineers, and business leaders, but I make a special effort to highlight the roles of governmental leaders that have been instrumental in setting policy conditions that are conducive to PEV deployment.

Some of the key government officials are well-known politicians (e.g., Shinzo Abe, George W Bush, Wen Jiabao, Li Keqiang, Angela Merkel, Barack Obama and Arnold Schwarzenegger) whose role in PEV development is unknown, poorly understood or misunderstood. Other influential public servants are not household names (e.g., Peter Altmaier, Wan Gang, Kai Ma, Mary Nichols) but played influential roles in the emergence of the modern PEV. While there is much subjectivity in singling out particular public servants, I point to the work of some key public officials to underscore the central roles of political leaders and public administrators in building a PEV industry and thereby balance the tremendous attention that technical and business leaders receive.

**ORGANIZATION OF THE BOOK**

Chapter 2 evaluates the modern PEV from consumer perspectives, explaining why marketing PEVs is more difficult than expected. The public policy rationales for PEVs are covered in Chapters 3 (energy security), Chapter 4 (urban air quality), Chapter 5 (climate change) and Chapters 6 through 9 (different facets of the economic development rationale). Chapter 10 describes how the Volkswagen emissions-cheating scandal provided an unexpected boost to the modern PEV in both Europe and the US. Chapter 11 addresses innovations in the charging infrastructure necessary to support a PEV-based transportation system. Chapter 12 compares the packages of policy measures that politicians adopt to persuade consumers to use PEVs. Chapter 13 examines the key factors
that will determine PEV market shares in 2021–2030 based on synoptic summaries of 2010–2020 developments in China, Europe, California, the United States and Japan.
APPENDIX: CONSULTING EXPERTS

The author consulted with each expert below on various issues and received comments from each expert on an early draft of the book manuscript. All errors and opinions in the manuscript are strictly the responsibility of the author.

Hongyang Cui is a researcher with the China team of the International Council on Clean Transportation. Before joining ICCT, he interned at the World Resources Institute and the Brookings-Tsinghua Center for Public Policy. He holds a master’s degree in atmospheric science and a bachelor’s degree in vehicle engineering, both from Tsinghua University.

John German is an automotive engineering consultant. He previously worked in powertrain engineering for Chrysler Corporation, wrote regulations and conducted research for EPA’s Office of Mobile Sources, managed energy and environmental analyses for American Honda Motor Company, and was a Senior Fellow at the International Council on Clean Transportation. His work for ICCT helped expose the Volkswagen emissions-cheating scandal. He holds a BS degree in physics from the University of Michigan.

Simon Godwin is an automotive consultant in Brussels and co-founder of the non-profit Impact Assessment Institute. He is the former director of EUCAR, the European auto industry’s research association, and a former manager at Daimler. He holds a Ph.D. in mechanical engineering from Imperial College London.

Bin Liu holds a Ph.D. in industrial economics. He has been working at China Automotive Technology & Research Center Co., Ltd. since 2004 in automotive industry analysis and industrial policy study. He has participated in a number of studies on China’s NEV support policies.

Alan Lloyd is a senior research fellow at the Energy Institute, University of Texas at Austin. He previously served as President of the International Council on Clean Transportation, Secretary of the California EPA and as Chairman of the California Air Resources Board. After earning his BS and Ph.D. degrees in chemistry, he served as chief scientist at the South Coast Air Quality Management District in California.

Wallace R. Wade is a mechanical engineer who was chief engineer and technical fellow in powertrain systems technology and processes at Ford Motor Company where he worked for more than thirty years. He is an elected member of the National Academy of Engineering and served on several committees of the National Research Council of the National Academies. He holds 26 patents related to improvements in powertrains and an MSME degree from University of Michigan and a BSME degree from Rensselaer Polytechnic Institute.

Aki Yasuoaka is former senior vice president of American Honda Motor in charge of product regulatory issues and an advisory board member of the
University of California-Davis Energy Efficiency Center. He was originally an engineer developing emissions and engine control systems for automobiles. In 1991 and 1992, he worked for Honda Formula One team as a Race Team Director and took the championship in 1991.

NOTES

3. Ibid.
The global rise of the modern plug-in electric vehicle


Appendix: consulting experts

The global rise of the modern plug-in electric vehicle


91. Sean O’Kane. BMW’s First Long-Range EV Won’t Come to the US. The Verge. March 9, 2020.


