

**Center for Entrepreneurship & Technology
University of California, Berkeley**

**Electric Vehicles in the United States
A New Model with Forecasts to 2030**

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Contents

Introduction.....	1
Part 1: Modeling Consumer Adoption	2
1. Network Externalities and a Comparison of Costs.....	3
1.1. Network Operators and Switchable Batteries.....	3
1.2. Economic Model	5
1.3. Internal Combustion Car Costs.....	5
1.4. Electric Car Costs.....	7
2. Model of Adoption	11
2.1. Regional Deployment and Fleet Mix	13
Part 2: Macroeconomic Impacts	15
1. Trade Balance	16
2. Capital Expenditures	19
3. Employment.....	21
4. Health and Environment.....	22
5. Greenhouse Gas Emissions.....	23
6. Government Policy	24
Conclusion	25
References	27
Appendix	30
Biography	32
About UC Berkeley Center for Entrepreneurship & Technology.....	32

Summary of Findings

This paper was commissioned by the Center for Entrepreneurship and Technology at the University of California, Berkeley. It estimates the rate of market adoption of electric vehicles in the United States through 2030 and analyzes the impact of electric car deployment on the trade balance, business investment, employment, health care costs, and greenhouse gas emissions. The market adoption analysis uses a network externalities model that accounts for the purchase price and operating costs of electric vehicles using switchable batteries and charging networks financed by pay-per-mile contracts.

The market penetration rate of electric cars and the accompanying estimates of macro-economic impacts are a function of world oil prices and the relative purchase price of drivetrains. This paper forecasts three electric vehicle adoption scenarios based on two oil price scenarios and possible purchase price incentives for electric cars. The following summarizes the main findings of the paper:

- **ELECTRIC CAR SALES:** In the baseline forecast electric cars account for 64% of U.S. light-vehicle sales by 2030 and comprise 24% of the U.S. light-vehicle fleet. The rates of adoption are driven by the low purchase price and operating costs of electric cars with separate battery ownership or battery leasing. The estimates include the cost of installing charging and battery switching infrastructure to extend the range of electric vehicles.
- **LOWER OIL IMPORTS:** U.S oil imports in 2030 under the electric vehicle deployment scenarios are projected to be 18-38% lower than the scenario of improved internal combustion engine fuel efficiency, equivalent to 2.0-3.7 million barrels per day. For reference, the United States in 2008 imported 2.3 million barrels per day from the Persian Gulf.
- **IMPROVED TRADE DEFICIT:** The U.S. imported \$400 billion of petroleum in 2008, which accounted for 59% of the trade deficit. This paper estimates that electric car adoption lowers the annual trade deficit by between \$94 and \$266 billion by 2030 over a scenario of improved internal combustion engine fuel efficiency.
- **NEW SOURCES OF INVESTMENT:** Business investment in a domestic battery manufacturing industry and the deployment of charging infrastructure grows to account for between 1.1% and 1.5% of total U.S. business investment by 2030. With additional investment in battery manufacturing, the United States has the potential to become an exporter of automotive batteries.
- **HIGHER OVERALL EMPLOYMENT:** There is a net employment gain of between 130,000 and 350,000 jobs by 2030. New jobs are created in the battery manufacturing industry and in the construction, operation, and maintenance of a domestic charging infrastructure network. The job gains outweigh modeled job losses among gas station attendants, mechanics, and parts industry manufacturers.
- **HEALTH CARE COST SAVINGS:** Health care cost savings stem from lower emissions of airborne pollutants. The net present value of the health impact of electric vehicle deployment to 2030 is between \$105 and \$210 billion when vehicles are charged using non-polluting sources of electricity. Health care cost savings remain positive when electric vehicles are charged using the current electricity grid.

- **REDUCED GREENHOUSE GAS EMISSIONS:** When powered by non-polluting sources of electricity, electric vehicle deployment results in a 20-69% decline in 2030 greenhouse gas emissions from U.S. light-vehicles over 2005 levels. Emissions are 8-47% lower when electric vehicles are charged using the current electricity grid.

Introduction

It took over sixty years and six generations of gasoline engines for the Chevy Corvette to accelerate from zero to sixty miles per hour in under four seconds. The first version of the Tesla Roadster, which is the world's first Lithium-ion battery powered car, achieved that feat immediately. Whereas earlier generations of electric cars were plagued by poor performance, high cost, and short ranges, a new generation of affordable, high-performance electric cars is about to enter the U.S. market.¹

Previous versions of electric vehicles have failed to achieve any significant market share. The shortcomings of these vehicles included expensive and toxic batteries with limited lifespans, severely limited driving ranges, poor performance, and high overall costs. The improvements in battery technology over the past two decades, in particular the advances in Lithium-ion (Li-ion) battery technology as well as automotive technological advances ushered in by hybrid vehicles, have made it possible to design and manufacture electric vehicles with better performance than their gasoline-powered counterparts. Though the number of electric vehicles on U.S. roads is currently in the thousands, that number will soon change. Spurred by the breakthroughs in battery and automotive technology, many vehicle manufacturers have indicated their intention to begin mass producing electric vehicles with Lithium-ion batteries within the next five years.

This paper forecasts the U.S. adoption rates and macroeconomic impacts of these new Lithium-ion powered electric cars through 2030, but does so for an upcoming innovation that will radically change the pricing, reliability, and driving range of these vehicles: switchable batteries with pay-per-mile service contracts. This vision of separating the ownership of the vehicle from the battery was first proposed by the company Better Place two years ago. It has since been endorsed by leading car manufacturers, a number of high-profile investors, countries, and U.S. states. Renault-Nissan has announced that it will produce its first electric car with switchable batteries in 2010 and will have a lineup of electric cars by 2012.² Tesla, which to date has been a niche producer of high performance electric cars, recently received government loan guarantees to produce an electric sedan manufactured in America with removable battery technology by the end of 2011.³ Israel, Denmark, Australia, Hawaii, and the San Francisco Bay Area have all begun to deploy electric vehicle charging infrastructure in anticipation of the upcoming supply of electric vehicles.⁴

The production of electric cars with switchable batteries creates the possibility for a new service-based model of electric car ownership. Under this model, electric car network operators will offer customers pay-per-mile contracts that combine the financing costs of the battery with charging and range extension services. These network operators will be able to overcome range concerns by installing and maintaining systems of battery charging and switching infrastructure that provide customers with a driving range

¹See the August 3, 2009 *Financial Times* article by Jonathan Soble that cites Nissan forecasts for the Leaf, the first full scale production electric vehicle, to have a production volume of 200,000 vehicles in 2012 with prices comparable to their existing lineup of comparable gasoline-powered vehicles.

²See the May 13, 2008 *New York Times* article by Bill Vlasic.

³Tesla, Nissan, and Ford all received Department of Energy loan guarantees to build manufacturing capabilities to mass produce electric cars in the United States, but Ford has not yet publicly committed to manufacturing switchable battery vehicles (Carty 2009). The German auto manufacturer Daimler recently purchased a ten percent stake in Tesla, which will bolster its efforts to mass produce an all-electric sedan by 2011 (Palmeri 2009).

⁴See the December 9, 2008 *Wired* article by Chuck Squatriglia. The article also notes that the Japanese government is committed to having 50% of new car sales be electric by 2020.

comparable to that provided by the existing gas station network and in excess of the 200 mile range of the Tesla Roadster. A system centered on network operators has additional advantages which are discussed in this paper, including: a lower purchase prices for these electric vehicles (EVs), an elimination of consumer uncertainty over the durability of the battery, and the centralized purchase of the charging electricity.

An analysis of vehicle adoption can look at both the initial purchase price as well as the total cost of ownership, which includes fuel, maintenance, and other costs over the life of the car. Section 1 confirms the findings of other industry reports that the total cost of ownership of Li-ion powered electric cars is lower than efficient gasoline-powered cars, but it also shows that electric cars with pay-per-mile contracts will have a lower purchase price compared to fuel-efficient gasoline vehicles.⁵ It presents an economic model that forecasts the sales of electric vehicles with switchable batteries and pay-per-mile service contracts. Depending on the future price of oil and the relative purchase price of internal combustion engine vehicles, electric cars are predicted to account for 64-86% of new light-vehicle⁶ sales by 2030.⁷

To understand the full impact of this ground transportation overhaul on the U.S. economy, Section 2 calculates the impact of electric vehicle deployment on key macroeconomic indicators such as the trade balance, investment, employment, health, and the environment. It also summarizes the current government policies that pertain to electric car deployment and battery technology. Some of the key findings are: 1) electric vehicles will result in a substantial improvement in the U.S. trade deficit; 2) there is a net positive creation of jobs if the U.S. develops a domestic battery manufacturing industry and deploys a charging infrastructure network; 3) the health care cost savings are significant and greatly influenced by the source of electricity used to power the electric fleet; and 4) greenhouse gas emissions are reduced substantially, even compared to a scenario of improved fuel economy for internal combustion engine vehicles.

1 Modeling Consumer Adoption

There are two strands of the economic literature that are directly relevant to modeling the consumer decision to switch to electric cars. The first characterizes consumer-level decision and the second uses a set of models to predict the diffusion of new, cost-competitive technologies into the market. The variety of factors involved in the purchase decision for large, durable goods such as automobiles makes estimating consumer adoption of electric cars particularly complex. In order for consumers to switch from the entrenched technology of internal combustion engines, with their benefits of a fully deployed refueling and repair network, consumers must perceive benefits to electric car ownership in excess of the uncertainties involved in adopting a new technology. Section 1.1 compares the direct benefit to consumers stemming from the lower purchase price and lower cost of ownership of electric cars under different oil price scenarios. It also describes how a network operator model of centralized battery ownership funded

⁵Deutsche Bank (2008), Thomas Weisel (2009), and McKinsey (2009) are three comprehensive analyses of Li-ion electric cars with fixed-batteries. The breakdown of the prices for electric cars with removable batteries is discussed in detail in Section 1.1.4.

⁶Light-vehicles (also known as passenger vehicles) are classified as cars, SUVs, and trucks with a curb weight of less than 8,500 pounds.

⁷This paper forecasts a range of estimates based on two different oil price scenarios and a potential purchase price incentive from network operators.

by pay-per-mile service contracts overcomes two potential disadvantages of electric car ownership, limited battery range and uncertainty over the deployment of charging infrastructure and battery life.

Section 1.2 uses a set of management science models to transform the micro-economic analysis of Section 1.1 into concrete forecasts for the market adoption of electric vehicles serviced by network operators. To do so requires both an estimate of the number of consumers willing to purchase the new product and a model that predicts the likelihood in each year that consumers will shift their purchases to the new technology. The total achievable market of electric cars with switchable batteries is forecasted using survey data on the driving patterns of U.S. drivers scaled under different oil price scenarios. The annual sales rates are then estimated using a model of new technology adoption.⁸ Only with a set of well-founded forecasts for the deployment of electric cars can we reliably estimate the macroeconomic effects of the technology's deployment in Section 2.

1.1 Network Externalities and a Comparison of Costs

The decision of which type of drivetrain to buy is not only a function of price and vehicle characteristics, but also of network externalities.⁹ A network externality is the effect that one consumer's usage of a product has on the value of that product to other users. These network effects are common in markets with a high degree of consumer interdependence such as telephones, operating systems, and audio-video recording formats. The market for electric cars has an important network externality component in the form of the necessary battery charging or switching infrastructure. For electric cars to achieve wide-scale deployment in the United States, new battery service networks must be competitive with the existing gasoline fueling infrastructure in terms of price, range, and reliability.

The 2007 figures from the U.S. Census Department list 117,000 gas stations servicing the U.S. fleet of nearly 250 million fossil fuel powered light-vehicles. There is also an extensive network of mechanics with training in internal combustion engine repair. In order to achieve wide-scale deployment, electric cars will require an investment in a new set of networks that offer drivers a viable alternative to the existing fossil fuel-based network. This subsection explains how separating the purchase of an electric vehicle from the purchase of the battery is the best strategy for achieving the wide-scale deployment of an electric car fleet. It describes a service-based model for electric car ownership, develops an economic model of network externalities to highlight the important factors in drivetrain choice, and then compares the operating costs and purchase prices of similarly sized internal combustion vehicles and electric cars.

1.1.1 Network Operators and Switchable Batteries

A number of companies, including Better Place, Coulomb Technologies, and ECOtality, have plans to deploy charging infrastructure for electric cars in the United States.¹⁰ The basis for the analysis in this

⁸The Bass (1967) model of new technology adoption has been empirically validated across a number of new technologies. The model has been used to forecast the market penetration of a diverse range of goods including color televisions, satellite radio, mobile telephones, and social networking sites.

⁹Katz and Shapiro (1986) developed the first model to demonstrate how consumer purchasing decisions incorporate both the current size of each technology's network as well as their expected future sizes. Further description of the network externalities model as it pertains to electric cars can be found in the Appendix.

¹⁰Better Place plans to deploy an infrastructure network to service switchable battery electric vehicles. Coulomb Technologies has developed and deployed charge spots to charge electric and plug-in hybrids in public parking areas. ECOtality, a leader in airport and industrial electric vehicles, plans to deploy public fast-charge spots that can charge batteries in under

paper is the Better Place model of switchable batteries financed with pay-per-mile service contracts. This section describes the advantages of this business model over a fixed-battery electric car network relying only on public charging infrastructure.

In an electric transportation system with switchable batteries, network operators offer electric car drivers pay-per-mile service contracts that finance the cost of the battery, the charging infrastructure, and the charging electricity. The vehicles, developed and sold by existing manufacturers, will have removable, rechargeable batteries with a range of approximately 100 miles. Network operators will install home and office-based charging stations as well as charge spots in public locations to allow customers to recharge their batteries between short trips and commutes. In order to extend electric vehicles' range to exceed the 100 mile battery range, the system will rely on the demonstrated technology known as battery switching stations.¹¹ By installing these switching stations along highways, the overall range of electric cars will eventually rival that of gasoline powered vehicles. An electric transportation system centered on a network operator business model offers drivers an attractive value proposition while also overcoming the range and convenience shortcomings of previous iterations of electric cars.

There are a number of advantages to financing a the battery of electric vehicles with a service contract. From the customer's perspective it eliminates the up-front cost of the battery. A switchable battery also eliminates the risk of purchasing a car whose battery life is shorter than the life of the vehicle and allows new battery technology to be installed in older electric vehicles. From the perspective of the overall market for electric cars, switchable batteries have the advantage of allowing all parties to focus on and compete within their core competencies. Car manufacturers can focus on designing and manufacturing cars with electric drivetrains without sourcing, producing, or insuring built-in battery packs. Battery manufacturers can compete across the variety of battery designs and chemistries, which encourages rapid improvement in battery technology and allows advanced batteries to reach consumers more quickly.¹² Battery network operators must offer services and products that provide customers with an improved driving experience that is price competitive with plug-in hybrids and the range extension network of the gas station infrastructure.

Coordination among car manufacturers and the preemptive installation of charge spots is required for this service-based model to succeed. Two car manufacturers, Renault-Nissan and Tesla, have announced large-scale production plans for switchable battery electric cars beginning in 2011 and recently received financing from the Department of Energy's loan guarantee program.¹³ Better Place has begun installing public charging infrastructure in Israel, has raised \$45 million from a recent state bond measure in Hawaii, and has announced plans to deploy a \$1 billion infrastructure network around the San Francisco

an hour.

¹¹Battery switch technology allows a depleted battery to be quickly swapped for a fully charged battery. The technology was recently demonstrated at a Better Place demonstration facility in Yokohama, Japan (<http://www.betterplace.com/global-progress/japan/>).

¹²Automotive battery applications are currently dominated by nickel metal hydride (NiMH) chemistries, which while reliable and long-lived are heavier and more expensive than Lithium-ion (Li-ion) batteries. Various battery manufacturers are developing a variety of Li-ion battery chemistries tailored to electric vehicle applications. These include: Lithium Cobalt Oxide, Lithium Manganese, Lithium Titanate, and Lithium Iron Phosphate. Each chemistry has tradeoffs between energy density, power, cost, safety, and toxicity. The annual rate of improvement in Li-ion battery technology over the past two decades has average six percent. See the 2008 Deutsche Bank industry report for a more detailed comparison of Li-ion battery chemistries and manufacturers.

¹³See the June 26, 2009 *USA Today* article by Sharon Silke Carty on the \$8 billion in Department of Energy loans to Ford, Nissan, and Tesla to produce electric vehicles.

Bay Area.¹⁴ Section 2.6 discussed the billions of dollars that the federal government is directing towards the deployment of electric charging infrastructure as part of the February 2009 stimulus package.

1.1.2 Economic Model

A network externalities model highlights some of the most important trade-offs involved in the consumer-level decision to purchase an electric car. Though the model abstracts from the full set of factors that customers account for in their auto purchase decision, it offers insights into the motivations and drawbacks for purchasing an electric car. The model singles out three of the most important factors for electric cars to achieve wide-scale adoption: 1) purchase price relative to gas powered cars; 2) uncertainty over operating costs; and 3) concerns/questions over their range. A full description of the network externalities model is provided in the Appendix.

Consumers of products that have network externalities also place value on the number of other adopters of these products. For electric cars with switchable batteries, this exists to the extent that consumers are uncertain that switchable battery operators will deploy a network extensive enough to provide them with ample driving range over the lifetime of the automobile. By incorporating the cost of the charging and switching infrastructure into pay-per mile service contracts, a transportation system centered on network operators can assure an adequate deployment of charging infrastructure in each region. The following sections compare the prices of gas-powered cars with electric cars and then discusses the role of uncertainty and network externalities in influencing consumer choices.

1.1.3 Internal Combustion Car Costs

Forecasts by the Energy Information Agency (EIA), which form the basis for our oil and gasoline price predictions, anticipate a return to rising oil prices over the next two decades. The EIA baseline oil price scenario is consistent with the price estimates of the International Energy Agency (IEA), which is another large energy price forecasting agency. Oil price increases in the EIA baseline and high price scenarios stem from a widening imbalance between the supplies of cheap and accessible conventional oil supplies and rising world demand.¹⁵ Price increases will be driven by rising oil extraction costs for future oil supplies along with increases in energy demand from developing countries, particularly China and India.¹⁶ These oil price forecasts and the corresponding U.S. average gasoline price are presented in Exhibit 1. The inflation-adjusted price of gasoline in the U.S. is predicted to rise to \$4 per gallon by 2030 in the baseline

¹⁴See the June 26, 2009 *Hawaii Advertiser* article by Eloise Agular and the November 20, 2008 *CNET* article by Elsa Wenzel. Agreements and financing for charging infrastructure have also been reached with governments in Denmark, Australia, and Canada.

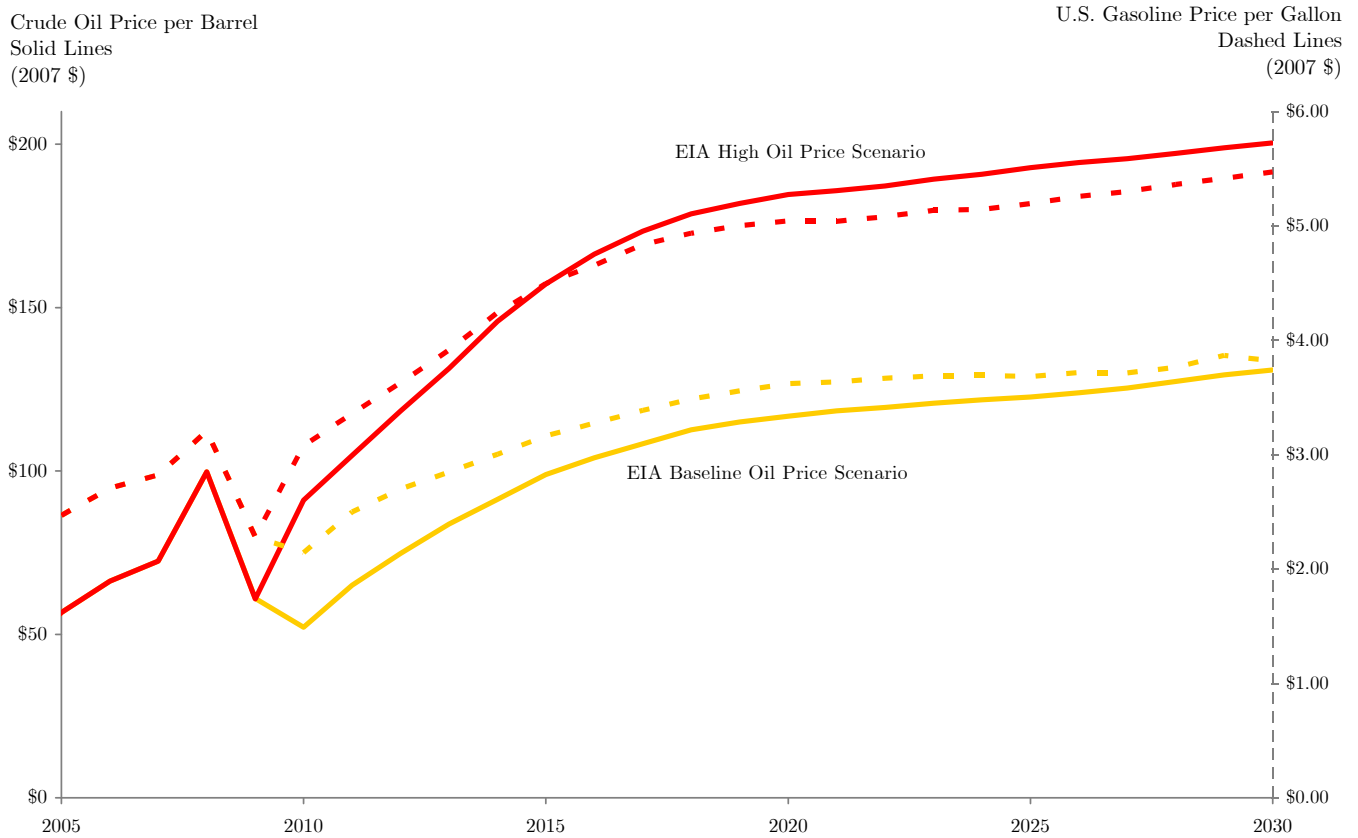
¹⁵The EIA also published a low oil price scenario, predicting domestic gasoline prices to remain constant at \$2 per gallon through 2030, which is not used in this paper. It is a scenario based on a number of assumptions that we deem unlikely: 1) all state-controlled oil supplies are privatized; 2) worldwide extraction costs for liquid crude decline as production increases from 81 to 108 million barrels per day (33% higher); and 3) OPEC increases output to 50% of total world oil output (currently it has a 33% share).

¹⁶McKinsey (2009) estimates a compound annual growth rate for light-vehicle energy demand of 12.2% in India and 9% in China through 2020. The extraction costs and environmental constraints of non-conventional oil supplies are discussed in Farrell (2006). Goldman Sachs recently justified its June 4, 2009 oil price forecast of \$85 per barrel by the end of 2009 by saying "even a full return of spare OPEC production will be insufficient to avoid a sharp decline in inventories as non-OPEC production continues to decline amidst rising demand."

Exhibit 1

EIA Forecasts of Global Oil Price and U.S. Gasoline Prices to 2030

The price estimates are from the 2009 Annual Energy Outlook published by the Energy Information Agency. The U.S. gasoline price is a weighted average of all grades of unleaded gasoline and assumes that state and federal excise taxes remain constant.



scenario and to over \$5.50 per gallon in the high price scenario.¹⁷

Car buyers have extensive experience evaluating the purchase price and fuel economy of gasoline-powered cars. As oil prices rose sharply between 2006 and 2008, so too did concerns about the fuel costs associated with fuel inefficient vehicles. Consumers reacted to rising prices by purchasing more fuel efficient cars.¹⁸ Though increased fuel efficiency lowers the impact of oil prices on the cost of driving, consumers are still vulnerable to rising and volatile oil prices.

New federal regulations will soon force manufacturers to increase the supply of fuel efficient vehicles. The newly announced Corporate Average Fuel Efficiency (CAFE) standards mandate manufacturers to more rapidly increase the fuel economy of their light-vehicle offerings.¹⁹ These fuel efficiency improvements are achievable through an increased use of diesel engines and hybridization, though the additional

¹⁷The gasoline price forecasts do not include increases to state or federal gasoline taxes, nor do they include the potential price impact of cap-and-trade legislation. These factors are discussed further in Section 1.1.5.

¹⁸Hybrids have gained market share in each year since their introduction. In 2008 they represented 2.6% of the U.S. light-vehicle market (Polk 2009).

¹⁹The Energy Independence and Security Act updated these guidelines in 2007. The Obama Administration recently announced its intentions to accelerate the existing timeline so as to achieve the 35.5 m.p.g. new light-vehicle average by 2016.

cost of these changes will add between \$1,000 and \$10,000 to the purchase price of these vehicles.²⁰ The higher purchase prices of these more fuel efficient cars is offset over the life of the car by the lowering per-mile fuel costs.²¹ A car with a fuel efficiency of 35 miles per gallon costs approximately 9¢ per mile to fuel at \$3 per gallon gasoline costs.

Higher oil prices have recently led to sharp declines in the demand and resale values of large SUVs and trucks.²² Aside from the forecasts of rising global oil prices, there are looming regulatory and tax changes that could further raise the domestic cost of transportation fuels. The greenhouse gas cap-and-trade legislation being considered by Congress has been accused by some oil industry executives of disproportionately impacting oil refiners over electricity producers and thereby acting as a relative tax on gasoline.²³ Though the 18.4¢ federal gasoline tax looks unlikely to increase, there have been calls by legislators and governors in budget strapped states to increase revenue by raising state gasoline taxes.²⁴

1.1.4 Electric Car Costs

The equipment and operating costs associated with electric cars include the price of the battery, the cost of the electricity to charge the battery, and the cost of deploying a charging infrastructure. Each of these costs and the corresponding assumptions for their future development are presented in this section. The costs are then combined into a hypothetical pay-per-mile service contract for a network operator that owns and finances a fleet of switchable battery electric vehicles. The possibility for network operators to offer purchase price incentives is also discussed.

The price of electric cars is dominated by the price of the battery. A battery that can achieve a 100 mile range for a small sedan must have an energy capacity of approximately 24 kWh.²⁵ The most recent price estimates from a leading Li-ion battery manufacturer is that automotive batteries will achieve the Department of Energy price goal of \$500 per kWh in 2012, which translates to an estimate of \$12,000 for the price of the battery.²⁶ Though current battery prices represent a great improvement over previous generations of electric cars, it remains unclear whether consumers will be willing to pay the additional up-front cost in return for lower future operating costs. The per-mile cost for these batteries depends

²⁰Diesel engines are the cheapest means of increasing the fuel efficiency of an internal combustion engine. The other option, hybridization, supplements the combustion engine with a parallel electric drive system. The cost of the additional equipment for traditional hybrid systems, like that found in the Toyota Prius, adds between \$1,600 and \$2,200 to the purchase price of these cars. Manufacturers have also announced plans to begin producing plug-in hybrid vehicles by 2010. The larger battery and additional equipment in these cars will allow them to travel tens of miles completely on the electricity stored in the battery. Plug-in hybrids are forecast to cost between \$8,000 and \$10,000 more than a standard car (Deutsche Bank 2008).

²¹The unsubsidized payback period for hybrids varies with the price of gasoline, but is around 4 years for traditional hybrids and between 8-10 years for plug-in hybrids (Deutsche Bank 2008).

²²See Mike Spector's June 6, 2008 *Wall Street Journal* article "Plunging SUV Prices Can Make Them a Bargain."

²³See the July 8, 2009 *Wall Street Journal* article by Guy Chazan "Conoco's Mulva: Waxman-Markey 'Unfair' to Refiners."

²⁴Oregon enacted a 6¢ per gallon tax increase on gasoline and diesel fuel in June of 2009. A June 9, 2009 *Boston Globe* article by Matt Viser cites Massachusetts legislators as being resigned to the need for "a 19-cent-per-gallon increase in the gasoline tax."

²⁵The recently unveiled Nissan Leaf has a 24 kWh battery with an advertised 100 mile range. For reference, the Tesla Roadster has a 53 kWh Li-ion battery and an over 200 mile range, a traditional hybrid has a 1-2 kWh NiMH battery, and plug-in hybrid designs are for 12-16 kWh Li-ion batteries. Lithium-ion batteries for automotive applications have usable energy densities of between 0.14 kWh/Kg and 0.17 kWh/Kg, which translates to a removable battery with a 100 mile range having a weight of between 140 and 170 kg (310-380 lbs) (Deutsche Bank 2008).

²⁶The \$500 per kWh price estimate for 2012 is from the battery manufacturer A123 and is also the Department of Energy's price goal for Lithium-ion batteries (Howell, 2009). A123 has announced plans to build a \$2 billion Lithium Iron Phosphate battery production facility in Michigan that will have an annual production capacity for 500,000 electric vehicles.

on the purchase price, the lifetime of the battery, and the annual miles driven. We estimate a range of per-mile costs based on two battery life assumptions. A conservative estimate for the life of these batteries is that they achieve a ten year life before they hold an 80% charge and no longer useful for transportation applications.²⁷ The 2012 per-mile cost under this scenario will be 10¢ per mile. If the batteries are able to achieve 3,000 100 mile charge cycles and the vehicle is driven 15,000 miles per year, the 2012 per-mile cost is approximately 6.7¢ per mile.²⁸ The likely lifetime of electric vehicle batteries is likely to fall somewhere within this range.

The cost of electricity for electric cars is on the order of 2¢ per mile, though electricity prices vary by region across the U.S.²⁹ The emissions required to power a fleet of electric cars varies according to the type of power plants used to generate the electricity. In Sections 2.4 and 2.5 we compare the particulate and greenhouse gas emissions for different electricity generation scenarios. An advantage of a system of switchable batteries with centralized ownership is that network operators can purchase electricity directly from suppliers and choose the electricity source that best meets their customers' demands.³⁰ If the vehicles are charged using variable time pricing, it could lower the charging costs and facilitate their being charged during non-peak periods.

The final cost associated with the large-scale deployment of electric vehicles is the cost of deploying a charging infrastructure. The primary method of charging will be at home, though drivers with longer commutes could also require a charge spot at work. We assume that each driver will require the installation of between one and two 220 Volt (Level 2) battery charge spots at an approximate total cost of \$2,000 per vehicle.³¹ Additionally, we assume that every 1,000 electric car drivers will require a battery switching station costing \$1 million that can switch the batteries for electric cars on trips that exceed the 100 mile range.³² This infrastructure can be aggregated to support a regional cell of 100,000 electric car drivers at a cost of \$300 million. Though these infrastructure costs are substantial, once divided over a network of drivers that drive 12,000-15,000 miles per year, the per-mile cost is between 1-2¢ per driver per mile.³³

²⁷These batteries will likely retain residual value after the ten year calendar life for non-transportation applications. This calculation assumes a discounted 15% residual value.

²⁸The 3,000 charge cycle life is based on discussions with A123 and is the Department of Energy battery goal for 2012 (Howell, 2009). Both A123 and LG-Chem have demonstrated Li-ion batteries with a 4,000 charge cycle 10 year life during the selection process for the Chevy Volt battery supplier. Batteries are assumed to be financed at the corporate A interest rate of 5.5 percent.

²⁹According to the EIA, the average retail price for electricity across the entire United States and in the four Western States in 2008 was 11¢ per kWh. The estimated energy to drive conversion for a small electric car sedan is between 4.0 and 4.5 miles/kWh (Deutsche Bank, 2008).

³⁰Electric cars will be able to provide electricity storage from intermittent renewable sources such as wind and solar. The cost of the newest wind power generation is under 5¢ per kWh (American Wind Association). Non-peak, wholesale electricity prices are also significantly lower than the 11¢ per kWh residential rate used for this analysis (EIA). Network operators of fleets of electric cars could also potentially earn fees from electric utilities for providing spinning reserve and ancillary services to the electric grid.

³¹The installation of 220 Volt charging stations allow rechargeable batteries to be recharged at double the rate of conventional 110 Volt outlets. A 2008 Department of Energy report estimates the cost to installing a Level 2 charge spot to be between \$1,500 and \$2,000 (Morrow, 2008). The labor cost for the electrical installation is estimated to be \$500 per site. As the production of charging hardware increases, the equipment costs will likely decline.

³²The \$1 million swap station cost is based on the Better Place cost estimate of \$500,000 for the switch station demonstrated in Japan (see the May 13, 2009 *New York Times* article by Kate Galbraith) and includes the cost of the additional batteries. The 1:1000 ratio of switch station to drivers, though half the ratio of gas stations to drivers, is a conservative estimate given that the driving habits of U.S. drivers are such that only 20% of vehicles make daily trips in excess of the 100 mile range of the battery (see Section 1..

³³The infrastructure is assumed to have a useful life of 20 years. Since the infrastructure costs are the most uncertain inputs in the model, a cost sensitivity analysis for costs of up to \$500 million per 100,000 drivers was analyzed and had only

Exhibit 2

Five Year Total Cost of Ownership Comparison Under Two Oil Price Scenarios

This table calculates the five year total cost of ownership for a small sedan (2009 Nissan Sentra SL) with an electric or gasoline drivetrain in 2012 and 2017. The total cost of ownership includes the depreciation of the vehicle, the cost of fuel or per-mile electric service contract, the insurance, the maintenance and repairs, the financing cost, and taxes and fees. Each of these costs is estimated on an annual basis and then discounted at 6% per year to calculate the total cost. All costs except for fuel/per-mile electric costs and maintenance costs are assumed to be the same for both drivetrains. The per-mile fueling costs are from Exhibit 3. An electric drivetrain is assumed to have 25% lower maintenance costs (oil changes, brake replacement, transmission maintenance). The 2017 price of the gasoline powered vehicles is \$1,250 higher due to equipment necessary to achieve CAFE standards (see EIA 2005). The 2012 subsidized car price includes a \$7,500 federal tax credit is applied to the purchase price of the vehicle and assumed to expire by 2017. The federal and operator subsidized electric car price includes both the federal subsidy and a \$2,250 network operator subsidy that subsidizes the purchase price of the electric vehicle by adding 3 cents per-mile to the 5 year service contract for a driver that drives an annual average of 15,000 miles. The battery is financed over 3,000 100 mile charge cycles or over 10 years with a discounted 15% residual value.

Purchase Year		Gasoline Powered Car		Electric Car					
		Baseline Oil Price Scenario	High Oil Price Scenario	3,000 Charge Cycle Amortization			10 Year Battery Amortization		
				Unsubsidized	Federal Tax Subsidy	Federal and Operator Subsidy	Unsubsidized	Federal Tax Subsidy	Federal and Operator Subsidy
2012	Purchase Price (excluding battery or fuel)	\$20,000	\$20,000	\$20,000	\$12,500	\$10,250	\$20,000	\$12,500	\$10,250
	Total Cost	\$33,058	\$35,554	\$32,837	\$25,337	\$25,103	\$34,973	\$27,473	\$27,238
	Per-Mile Cost	\$0.44	\$0.47	\$0.44	\$0.34	\$0.33	\$0.47	\$0.37	\$0.36
	Unsubsidized, Per-Mile EV Cost Savings	-\$0.03-\$0.00	\$0.00-\$0.03						
2017	Purchase Price (excluding battery or fuel)	\$21,250	\$21,250	\$20,000			\$20,000		
	Total Cost	\$34,108	\$36,897	\$31,486			\$33,053		
	Per-Mile Cost	\$0.45	\$0.49	\$0.42			\$0.44		
	Unsubsidized, Per-Mile EV Cost Savings	\$0.01-\$0.03	\$0.05-\$0.07						

Pay-Per-Mile Contracts Separating the purchase of the battery from the car and incorporating its financing into a service contract that pays for the electricity and charging infrastructure radically changes the pricing possibilities for electric vehicles. The most notable difference is that an electric car need not have a higher purchase price than a comparable gasoline-powered car. Furthermore, depending on the gross margin of the network operator, pay-per-mile contracting could also allow an operator to subsidize the purchase price of electric cars just as cell phone networks subsidize the up-front price of cell phones. An integrated battery network operator could subsidize the purchase of electric cars by offering a purchase price subsidy in exchange for more expensive long-term service contracts. Pay-per-mile service contracts are potentially appealing to drivers not only from a price perspective, but also because they eliminate most of their uncertainty over the future operating costs of the vehicle.³⁴

We use 2009 model-year data on the depreciation, insurance costs, repair and maintenance costs, and taxes and fees for a small sedan as the basis for comparing the five year total cost of purchasing an electric or gasoline-powered car.³⁵ Exhibit 2 compares the five year cost of ownership of an electric drivetrain with a switchable battery to that of a gasoline version of the same platform and shows the associated purchase prices of both drivetrains.³⁶ In 2012, the unsubsidized electric drivetrain is between 3¢ more expensive or 3¢ less expensive than the gasoline version on a per-mile-basis, depending on oil prices and the lifetime of the battery. Both vehicles will likely have a similar purchase price. By 2017, improvements to battery technology and the additional costs for gas-powered cars to meet CAFE standards makes the electric version 1-7¢ less expensive on a per-mile basis and \$1,250 less expensive to purchase.

a small effect (less than 1¢) on the per-mile operating costs of electric cars.

³⁴The ability of an operator to purchase forward contracts for electricity delivery on the wholesale market allows it to lock-in future prices and offer long-term, fixed price contracts.

³⁵Since Nissan is the first major manufacturer to announce mass production plans for electric vehicle, the Nissan Leaf, we use the 2009 Nissan Sentra as the basis for cost comparison. The non-per-mile costs of ownership (depreciation, insurance, financing, taxes, registration, and repairs) are based on data from Edmunds.com.

³⁶The equal price assumption is probably overly conservative. Electric induction motors are much simpler mechanical devices compared to combustion engines. Engines require a lubrication system, ignition system, and a transmission, whereas electric cars rely on a self-contained motor with fewer moving parts. However, the production of these motors for automotive applications has not yet achieved economies of scale.

A \$7,500 federal tax credit will lower the cost of electric vehicles when they are first introduced in mass production volumes in 2012.³⁷ This federal subsidy will make electric cars considerably less expensive to purchase than a comparable gasoline-powered drivetrain and 10-13¢ less expensive on a per-mile basis over five years. These initial government subsidies will both guarantee initial demand for these vehicles while also allowing manufacturers to achieve economies of scale in the production process which will bring down the production costs in subsequent years.

An integrated service contract for an electric car that pays for the battery, network, and electricity can be less expensive than the per-gallon price of fuel for an efficient gas powered car. Exhibit 3 compares the per-mile driving cost of an electric car using an integrated service contract to the fueling costs of an internal combustion engine that meets federal fuel efficiency standards in each year to 2030. It highlights the continually improving operating cost advantage that electric drivetrains have over internal combustion engines under both oil price scenarios. The per-mile costs of gasoline-powered cars decline in the near term due to increases in vehicle fuel economy, but reverse in later years as oil price increases outpace efficiency improvements. The per-mile costs for electric cars decrease due to two factors: continued improvements to battery technology and slight improvements in electric motor efficiency.³⁸ An integrated service contract for electric vehicles eliminates the trade-off of higher purchase prices in exchange for lower operating costs that is inherent to gas-powered, hybrid, and fixed-battery electric cars. Instead, electric cars with switchable batteries and pay-per-mile service contracts can have both lower up-front prices and operating costs.

Operator-Subsidized Scenario The difference between the Electric Mile line and the Gas Powered Mile lines in Exhibit 3 represent the potential gross margin for an integrated electric car operator. That is to say that any per-mile contract price that is below the cost of operating a gasoline-powered vehicle but above the Electric Mile line will be cost competitive with internal combustion engine cars and profitable for a system operator. Under the high oil price scenario, operators have positive gross margins even in 2012, which is the first year switchable battery electric cars reach the market. An operator could subsidize the purchase price of an electric vehicle in exchange for customers signing extended contracts that are slightly more expensive on a per-mile basis. Operators would have an incentive to offer this type of contract as it would speed electric car adoption rates and allow them to more rapidly achieve economies of scale. The extent to which the purchase price can be lowered in exchange for slightly higher per-mile costs that are competitive with gasoline prices will increase electric vehicle purchases.

This operator-subsidized scenario is more likely under the high oil price scenario, where the difference between the Electric Mile cost and the Gas Powered Mile cost are significant. Therefore we model a third adoption scenario that includes an additional electric car purchase subsidy of \$2,250 in the initial years in exchange for a 3¢ higher per mile cost.³⁹ The overall achievable market size for the operator-subsidized

³⁷The \$7,500 federal tax credit is for consumers who purchase an automobile with at least a 16 kWh battery. It is limited to 200,000 cars per manufacturer. See Plug-In America (2009) for a detailed breakdown of the stimulus package as it applies to electric cars.

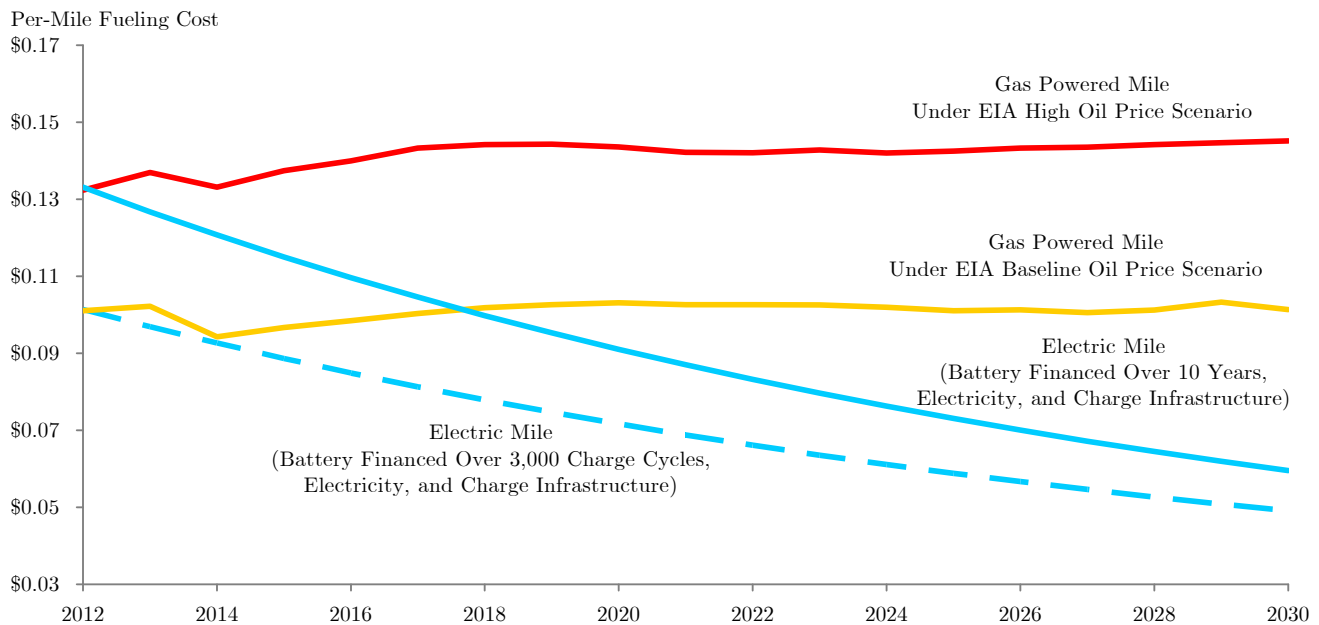
³⁸This paper models Li-ion battery technology to continue improve at its historical rate of 6 percent per year (see Deutsche Bank 2008). These improvements are modeled as a declining cost for batteries of the same size. Battery-to-wheels efficiency is forecast to improve at 2 percent per year, as efficiency improvements are made to electric motors and vehicle electronics.

³⁹This purchase price subsidy is in exchange for a 3¢ per mile more expensive service contract over the course of a five year 15,000 mile per year contract.

Exhibit 3

Comparison of Per-Mile Fueling Costs

This graph compares the per-mile cost of fueling an internal combustion engine achieving the CAFE fuel economy average in each year with the cost of a per-mile electric car contract from a network operator that owns the battery, charging infrastructure, and pays for the electricity. The oil price estimates are from the 2009 *Annual Energy Outlook* published by the Energy Information Agency. In 2012 and 2013 the per-mile fueling cost uses a blended average of West Coast gasoline prices, which have slightly higher state gasoline taxes. From 2014 onward, the average nationwide price of regular unleaded gasoline is used to reflect nationwide deployment. The battery in 2012 is a \$12,000 24 kWh Li-ion battery with an estimated annual price decline of 6 percent. It is financed under two scenarios- the solid line represents a 10 year amortization schedule with a 15% residual value and the dashed line is financed over 3,000 100 mile charge cycles. Both are financed at the corporate A interest rate of 5.5%. The cost of electricity is \$0.11/kWh with an initial range per kWh of 4.5 miles that improves at an annual rate of 2 percent. The charge infrastructure costs are assumed to be \$300 million for each 100,000 drivers with 100 battery switching stations and 200,000 charge spots.



scenario is equivalent to the high oil price scenario, but electric vehicle adoption is modelled to occur more rapidly because of higher initial adoption rates stemming from the larger purchase price incentives.

1.2 Model of Adoption

Previous studies that have forecast the penetration rates of electric cars have done so using a break-even methodology that calculates payback periods for electric cars that include the battery and have a higher purchase price.⁴⁰ This paper uses a different approach because pay-per-mile service contracts make electric cars fully cost competitive with gasoline vehicles and eliminate purchase price trade-offs. The Bass model is particularly well suited to estimate the adoption rates of these types of electric cars because it works well for pre-production products and accounts for network effects.⁴¹ This section explains the model, uses demographic and driving survey data to estimate maximum market penetrations for electric cars under different oil price scenarios, and forecasts annual sales for two geographic regions: the four West Coast states and the rest of the United States.

The Bass model is a non-parametric conditional likelihood model that uses three inputs to forecast

⁴⁰See McKinsey (2009), Deutsche Bank (2008), and Morgan Stanley (2009).

⁴¹The original Bass (1969) paper was recently voted one of the top ten most influential papers published in the 50 year history of *Management Science*.

Exhibit 4

Vehicles Unlikely to be Replaced by Electric Vehicles at Different Oil Prices

This table uses data from the 2001 National Household Travel Survey to estimate the percentage of U.S. light-vehicles unlikely to switch to electric cars with switchable, 100 mile batteries. It adapts the methodology used by McKinsey (2009) to estimate the addressable market size for alternative powertrain vehicles. The oil price scenarios are from the EIA 2009 Annual Energy Outlook. There is some double counting of vehicles across categories, but this effect is small. Sums may be slightly different due to rounding.

Oil Price Scenario	Types of Vehicles Excluded	Percentage of Excluded U.S. Light-Vehicles
High Prices	SUVs and trucks used by construction and agricultural workers	5%
	Vehicles with more than 20% of trips with five or more occupants	3%
	SUVs owned by high-income households with two or more children	1%
Total		10%
Baseline	Single-vehicle households with at least one monthly trip of over 80 miles	5%
	Vehicles in a multiple-vehicle household with at least one monthly trip of over 80 miles	16%
Total (including those excluded in High Price Scenario)		30%

the annual number of buyers of a new technology: the maximum market size, a parameter that captures the percentage of buyers whose purchase decision is not influenced by the purchasing behavior of others, and a parameter that captures the likelihood that additional consumers adopt the technology in response to the purchasing experience of others.⁴² This model is well-suited to predicting market penetration for products with network externalities, as the third scaling parameter captures the adoption behavior of those consumers who delay purchases until the size of the network is more extensive.

Calibrating the first parameter of the Bass model requires an estimate of the number of drivers who could potentially switch to a battery-powered car.⁴³ The maximum market share can be estimated as a function of gasoline prices and driving habits. We use the most recent survey data on the demographics and driving habits of U.S. drivers to estimate the percentage of vehicles whose drivers might be unlikely to purchase an electric car with a switchable battery.⁴⁴ Exhibit 4 shows the groups excluded from the addressable market for electric cars under the two EIA oil price scenarios.

Under the baseline scenario, the maximum market penetration is estimated to be 70 percent. With gradually increasing gasoline prices, a subset of drivers could still place a high premium on the unconstrained driving range of vehicles with combustion engines. This scenario excludes any vehicle that is used for at least one monthly trip in excess of 80 miles or vehicle with weight or usage patterns unsuited to battery energy density from the potential market. We view this as a conservative estimate, as it assumes that only those vehicles with daily driving patterns within the range of a 100 mile battery would potentially switch to electric cars.⁴⁵

⁴²See Mahajan et. al. (1995) for an overview of empirical applications of the Bass model.

⁴³A complete description and discussion of the calibration of the second and third parameters of the model can be found in the Appendix.

⁴⁴These data are from the 2001 National Household Travel Survey conducted by the U.S. Department of Transportation and released in 2004.

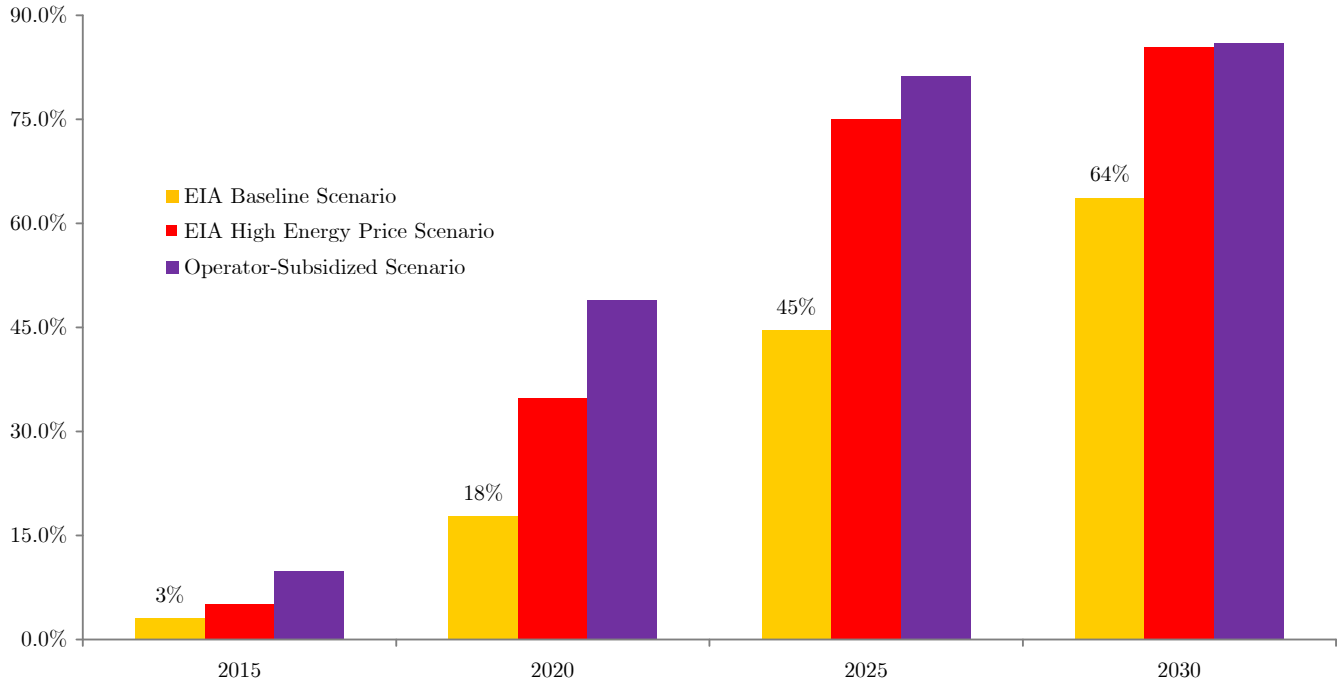
⁴⁵McKinsey's 2009 industry report uses a similar analysis of the survey data to estimate the market share for alternative powertrain vehicles. Its estimates are based on electric cars with a fixed battery and a 50 mile range. The report concludes that the maximum market share for alternative powertrain vehicles is 60%, because of the more limited range of electric cars with smaller batteries.

Exhibit 5

Three Scenarios for the U.S. Market Share of Electric Vehicles

The market share forecasts are based on the Bass (1969) model of new technology adoption. The Baseline and High Oil Price Scenarios are from the EIA 2009 Annual Energy Outlook. The operator subsidized scenario uses the EIA high oil price scenario, but adds the possibility that network operators could use a portion of their gross margin to subsidize the purchase of electric cars in exchange for customers signing long-term per-mile contracts. The maximum market size is 64% in the baseline scenario, 85% in the high price scenario, and 86% in the operator -subsidized scenario.

EV Percentage of U.S.
Light-Vehicle Sales



Under the high oil price scenario, we estimate a maximum EV market penetration of 90 percent of the light-vehicle market. The high gasoline prices in this scenario make a greater share of the driving public willing to make the behavioral changes that come with owning an electric vehicle.⁴⁶ In this scenario, only those vehicles whose weight or commercial use would require a battery much larger than the one modeled in this analysis are excluded from the potential market. That includes construction and agricultural workers that use a truck/SUV for work, vehicles that make over 20% of their trips with 5+ passengers, and high income households with an SUV and 2+ children.

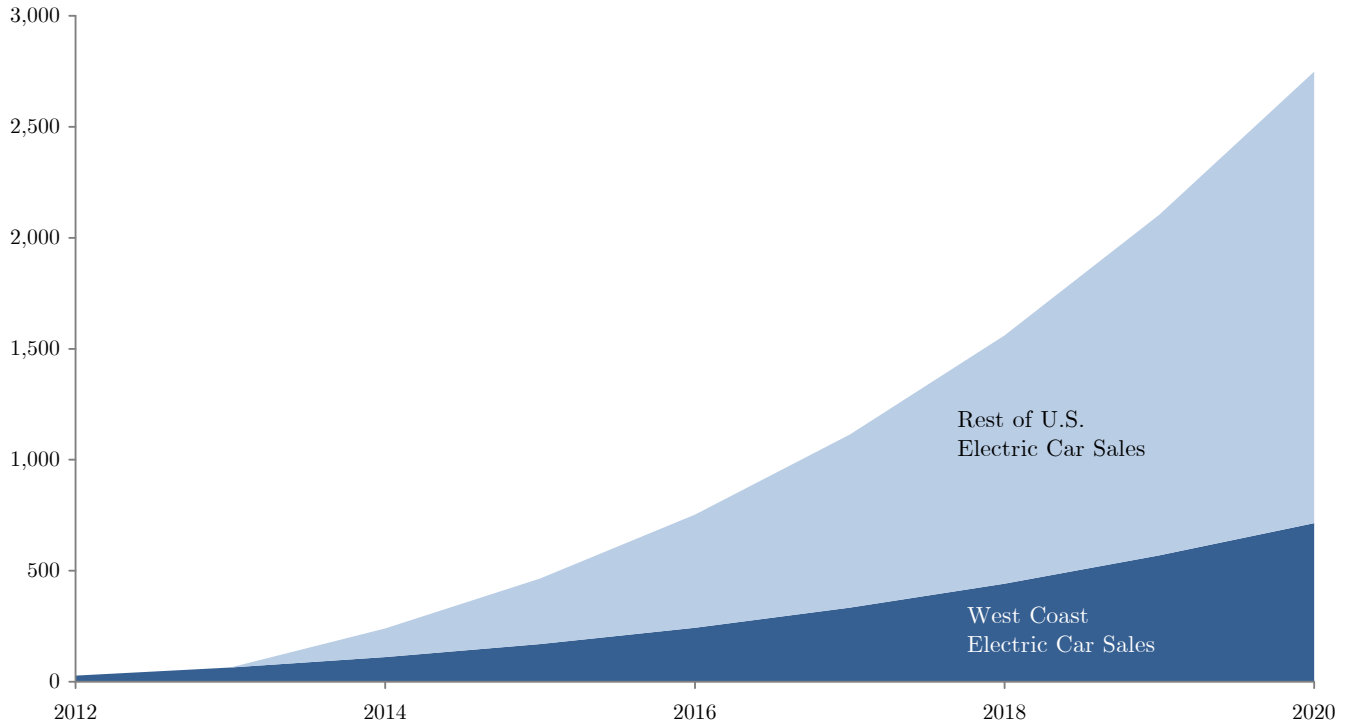
The estimates of electric vehicle adoption under the two EIA oil price scenarios and the third operator-subsidized scenario are shown in Exhibit 5. The market shares of electric cars are shown as a percentage of U.S. new light-vehicle sales. The baseline scenario has electric vehicles comprising 64 percent of new vehicle sales by 2030 and nearly 90 percent in each of the two high oil price scenarios. The characteristics of the baseline adoption scenario are analyzed in detail in the following subsection.

Exhibit 6

Forecasted U.S. Electric Car Sales From 2012 to 2020 by Region

These forecasts of electric car adoption are for the baseline oil price scenario. The West Coast region includes California, Oregon, Washington, and Hawaii. Deployment in the West Coast states is forecast to begin in 2012 and in the rest of the United States in 2014.

Sales of Electric Vehicles
(thousands)



1.3 Regional Deployment and Fleet Mix

The adoption of electric cars will likely occur first in the West Coast states. The governments in California, Oregon, Washington, and Hawaii have each enacted policies to encourage the adoption of electric vehicles.⁴⁷ California, Oregon, and Washington are also the three states with the highest hybrid registrations which suggests that they will be attractive initial markets for manufacturers.⁴⁸ The islands of Hawaii and the primarily north-south long distance driving patterns in the Pacific states limits the corridors for switching station deployment and the total number of stations required. Since these four states are the furthest along in terms of planning the deployment of charging infrastructure and will also most likely have the highest customer demand for electric cars, they are modeled initial market for electric cars between 2012 and 2014. Beginning in 2014, networks of switchable electric cars are deployed

⁴⁶These behavior changes include plugging in the car when it is parked and planning longer trips along routes with battery switching stations.

⁴⁷Each state has initiated important legislation in the past year to facilitate an early deployment of electric cars. Hawaii issued \$45 million in special purpose bonds to fund charging infrastructure deployment (Wenzel 2009). Washington exempted electric vehicle batteries and the installation of electric vehicle infrastructure from retail sales and use taxes (Gregoire 2009). The governor of Oregon proposed a \$5,000 state tax credit on electric vehicle purchases (Kulongoski 2009). The mayors of the San Francisco Bay Area agreed to ease permitting requirements to install charging infrastructure (Aguilar 2008).

⁴⁸Polk (2009) calculates the number of new hybrid registrations in these states to be 5.9%, 5.5%, and 5.1%, respectively.

across the remainder of the United States. Exhibit 6 shows the number of electric cars sold in each region under the baseline oil price scenario out to 2020. By 2020, 700,000 of the 2.7 million electric cars sold in the United States are forecast to be sold in the four West Coast States.⁴⁹

Though electric cars surpass 60% of the market for new car sales by 2030 in each of the three adoption scenarios shown in Exhibit 4, their share of the U.S. light-vehicle fleet grows much more slowly. The average age of the U.S. light vehicle stock is 9.3 years and McKinsey (2009) estimates that the fleet takes somewhere between 15 and 20 years to turn over. Exhibit 7 shows how the composition of new car market shares leads to a more gradual change to the composition of the U.S. light-vehicle fleet under the baseline oil price scenario. In the near-term hybrids represent a growing share of U.S. light-vehicle sales, but their higher cost as compared to electric vehicles causes their share of the alternative powertrain market to decline starting in 2019.⁵⁰ Exhibit 7 shows that though electric cars are forecast to comprise 63% of new light-vehicle sales by 2030, their share of the overall U.S. light-vehicle fleet is only 24%. Even the most aggressive estimate of electric vehicle adoption, based on high oil price forecasts and incentives from network operators, has electric vehicles achieving only a 46% market share by 2030. Were these forecasts to be extended another decade, each scenario would have the fleet share of electric vehicles fleet approaching the maximum market shares.

2 Macroeconomic Impacts

The overhaul of the U.S. light-vehicle infrastructure stemming from electric vehicle deployment will have large macroeconomic consequences. Approximately seven percent of U.S. households' expenditures goes toward personal motor vehicle expenses.⁵¹ The ground transportation sector as a whole accounts for over 41% of worldwide petroleum demand, one sixth of the U.S. greenhouse gas emissions, and approximately 20% of U.S. employment.⁵² A technological shift as large as the one promised by electric cars will cause large economic changes to the ground transportation sector.

The model developed in the preceding section provides a solid basis for understanding the impact of electric car deployment on the U.S. economy. The following section forecasts how each scenario of electric vehicle adoption will impact the trade balance, business investment, employment, health care costs, and greenhouse gas emissions. All of the calculations in this section are of the marginal effect of electric vehicle adoption over the scenario of improving fuel efficiency standards according to the CAFE timetable. The final sub-section discusses the current government policies directed at accelerating the transition to electric cars and discusses some important no-cost changes to federal, state, and local policy to encourage electric vehicle adoption.

⁴⁹The 2.7 million vehicles estimate represents 17% of 2020 new light-vehicle sales.

⁵⁰Estimates for hybrid sales are based on industry reports by McKinsey (2009), Deutsche Bank (2008), Credit Suisse (2008), and J.D. Power (2008).

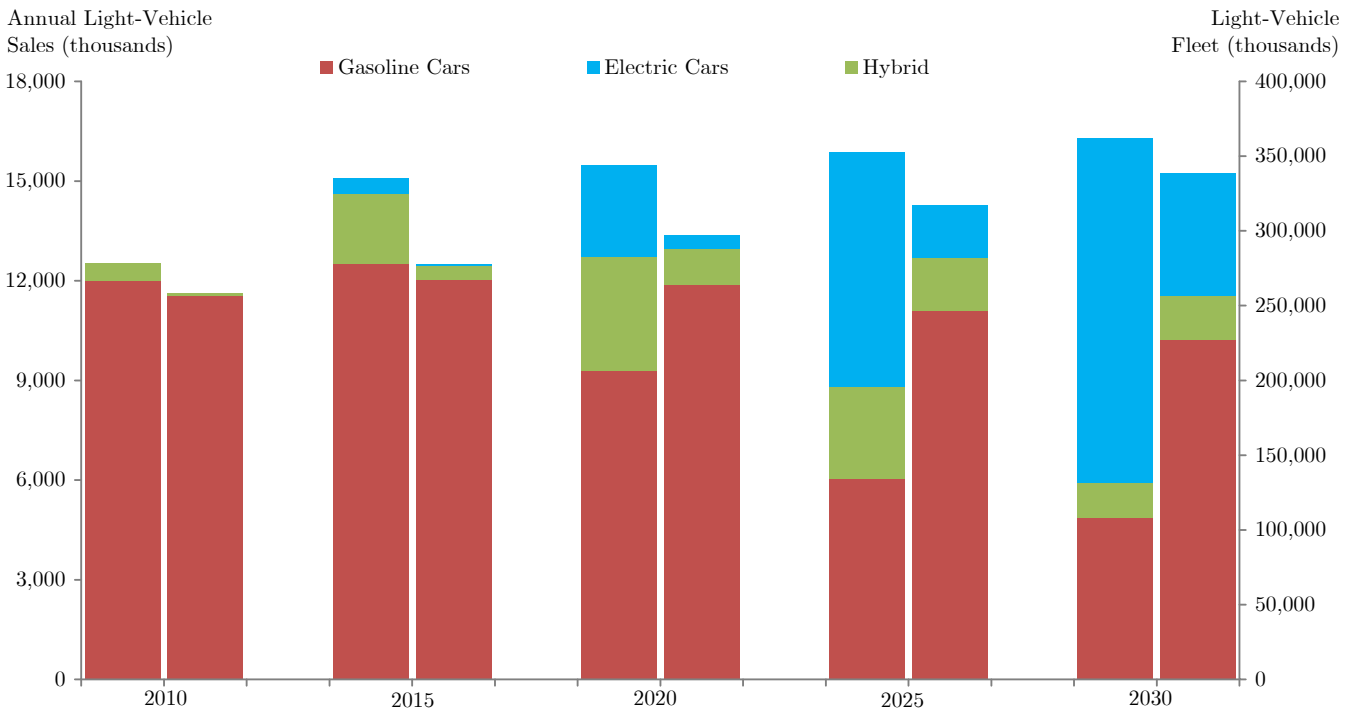
⁵¹Expenditure data from the U.S. Department of Commerce.

⁵²Sources are McKinsey (2009), the Environmental Protection Agency, and the U.S. Bureau of Labor Statistics, respectively.

Exhibit 7

U.S. Light-Vehicle Sales and Fleet Composition Under Baseline Scenario

The left columns and axis represent forecasts for the composition of U.S. light-vehicle sales under the baseline oil price scenario from the EIA. The right columns and axis represent the corresponding mix of vehicles in the U.S. light-vehicle fleet. Total U.S. light-vehicle sales estimates from 2010 to 2020 are from R.L. Polk, thereafter estimates are based on historical averages of new car sales and scrappage rates. Forecasts for electric car sales are based on the Bass new technology diffusion methodology. The estimates for the overall alternative powertrain market use estimates from the McKinsey (2009) industry report. Estimates for hybrid sales are based on industry reports by McKinsey (2009), Deutsche Bank (2008), Credit Suisse (2008), and J.D. Power (2008).



2.1 Trade Balance

The most direct impact of the electrification of the U.S. light-vehicle fleet will be to decrease the economy's consumption of petroleum.⁵³ In 2008 the United States spent nearly \$600 billion dollars on oil, over two thirds of which was imported. Depending on its price, oil has accounted for between 30% and 59% of the U.S. trade deficit over the last decade.⁵⁴ Approximately 70% of petroleum is used for transportation and over 40% of oil is used for light-vehicle transportation.⁵⁵ Each of the electric vehicle deployment scenarios modeled in our analysis lead to significantly lower oil consumption and a correspondingly lower trade deficit.

The amount of oil imported by the United States makes it challenging to imagine how the U.S. could close its trade deficit or current account deficit without decreasing its oil consumption. Exhibit 8 shows how increases in monthly oil imports have coincided with a gradual 1.8% decline in domestic oil production over the past two decades.⁵⁶ Its reliance on imported oil exposes the U.S. economy to

⁵³In his presidential acceptance speech President Obama stated his objective to "set a clear goal as president: in ten years we will finally end our dependence on oil in the Middle East."

⁵⁴Trade balance numbers from the U.S. Bureau of Economic Analysis.

⁵⁵McKinsey (2009)

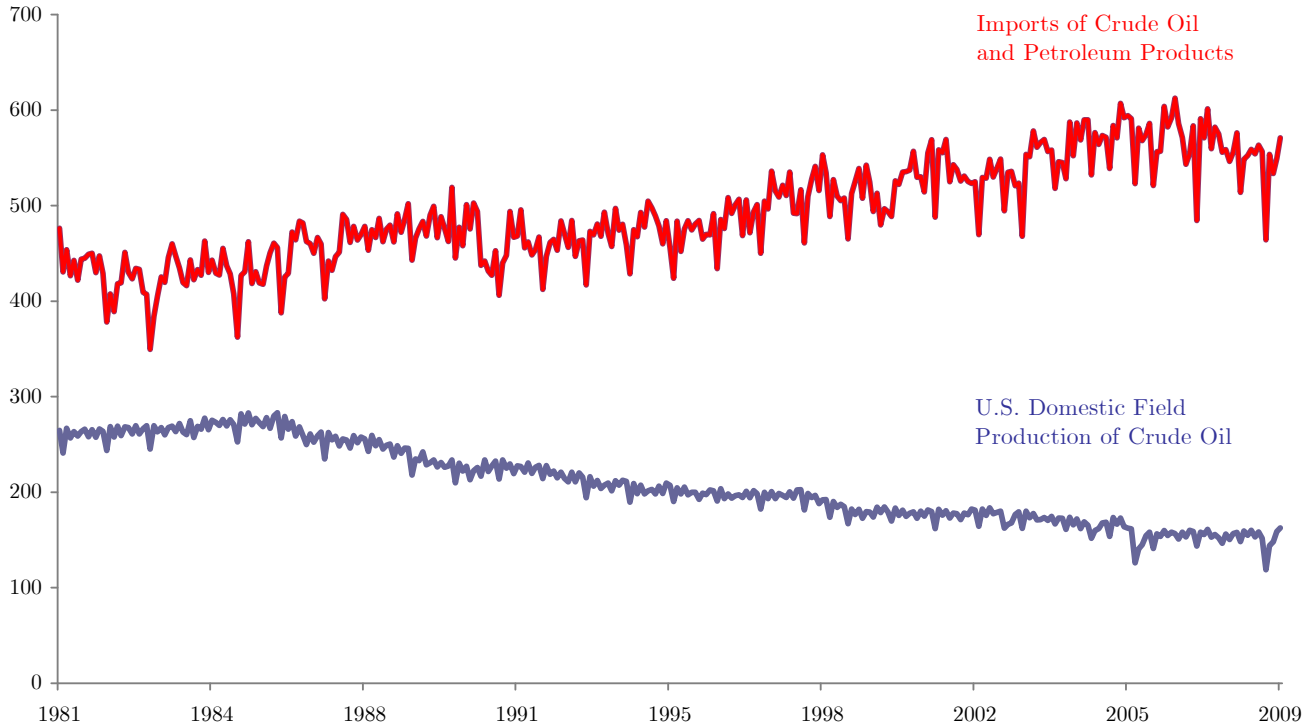
⁵⁶The EIA forecasts significant increases to U.S. domestic liquid fuel production in the coming decades stemming from

Exhibit 8

Foreign and Domestic Sources of U.S. Petroleum

These data are from the Energy Information Agency and report the monthly sources of crude oil between 1981 and January of 2009. Since 1985, U.S. domestic oil production has declined at an average rate of 1.8%.

Millions of Barrels
of Crude Oil per Month



unemployment and economic downturns stemming from foreign oil supply interruptions, can lead to sub-optimal monetary policy to control oil-induced price inflation, and imposes a high military cost to secure foreign oil supplies.⁵⁷ Economists have also shown the financial flows associated with petrodollars to be a primary contributor to global financial imbalances.⁵⁸ The deployment of electric cars will significantly reduce the transportation sector's reliance on petroleum-based fuels and thereby diminish the problems associated with the oil dependency of the U.S. economy.⁵⁹

Our estimates of the trade balance single out petroleum imports as the only traded good or service impacted by electric vehicle deployment. This assumption is valid for the energy used to power electric vehicles, as nearly all of our domestic electricity is generated from domestic sources, but requires assumptions about the future of the domestic automotive industry. We assume that the percentage of light-vehicles produced domestically remains constant through 2030.⁶⁰ This assumption is based on the

deepwater offshore drilling and enhanced oil recovery in the lower 48 states. This paper makes the more conservative estimate that domestic production will continue to decline at its historical rate of 1.8% given the industry's inability to increase production when prices rose steeply between 2005-2008.

⁵⁷See Bernanke et. al. (1997) and Carlstrom and Fuerst (2005) for a discussion of oil and monetary policy, and Greene (2005) and Delucchi (2008) for estimates of the military costs to secure oil imports.

⁵⁸See Caballero et. al. (2008) for a discussion of petrodollars and global imbalances.

⁵⁹According to the EIA, petroleum accounts for 97% of the energy used in the transportation sector.

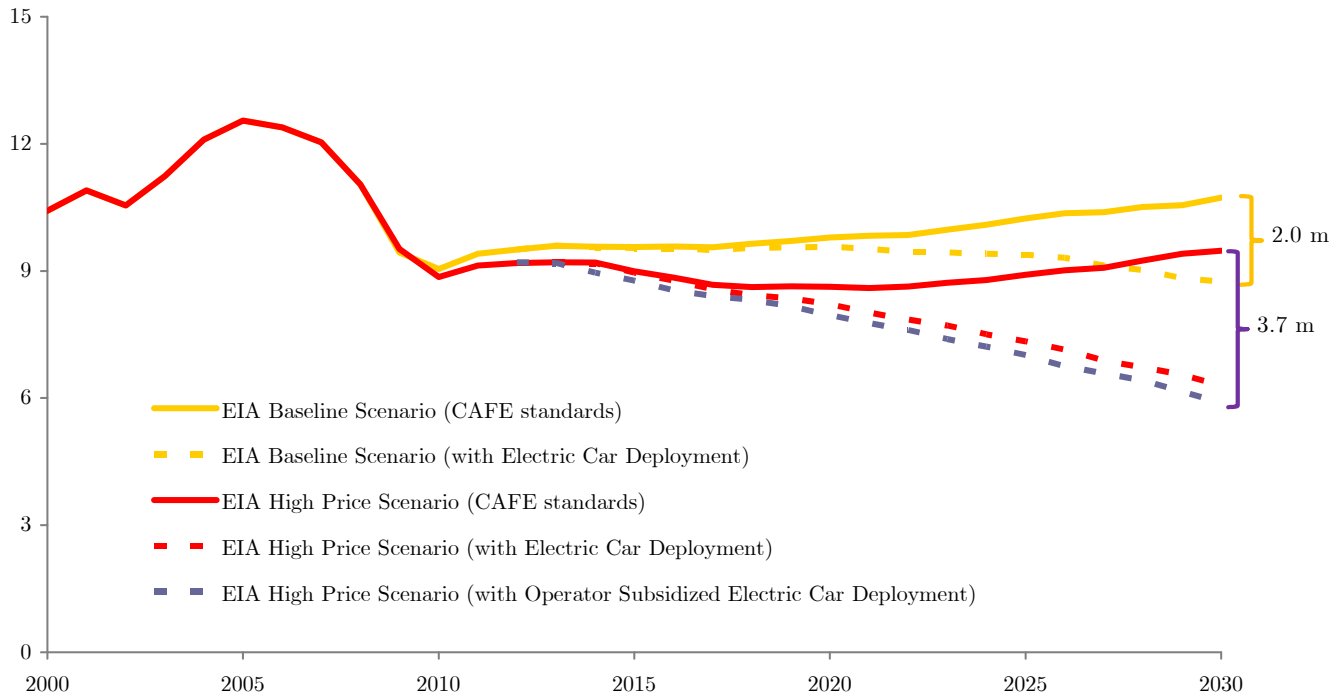
⁶⁰Though the share of light-vehicle sales from U.S. manufacturers has declined sharply over the last five years, the share

Exhibit 9

Oil Imports Under Three Scenarios for Electric Vehicle Adoption

The oil price estimates are from the 2009 Annual Energy Outlook published by the Energy Information Agency. In contrast to the EIA forecasts for a future growth of domestic oil production, this analysis makes a more conservative estimate that U.S. domestic oil production continues to decline at an annual rate of 1.8%. The solid lines represent the daily barrels of oil imported with CAFE mandated increases to internal combustion fuel economy under the baseline and high oil price scenarios. The dashed lines represent the daily barrels of oil imported under the three electric vehicle adoption scenarios in this paper.

U.S. Oil Imports
(millions of barrels per day)



fact that the share of light-vehicles for the U.S. market produced domestically by domestic or foreign owned firms has remained roughly constant at 65% over the last decade and that a domestic manufacturer, Tesla, was the first to market with an electric car.⁶¹ The analysis also assumes that the automotive battery manufacturing industry will grow over the next decade such that by 2019 it captures the same share of domestic light-vehicle battery sales as domestically produced autos. The investment required to establish a domestic battery industry and the basis for this assumption are examined in the next section.

Exhibit 9 shows the impact of the three electric car deployment scenarios presented in Section 1.2 on U.S. crude oil imports in excess of increasing the federal fuel economy standards. Each scenario results in a substantial decline of oil imports by 2030, ranging between 2.0 and 3.7 million barrels per day.⁶² That is equivalent to an 18-38% decline in the quantity of oil used by 2030.

The deployment of electric cars and the corresponding lower demand for oil shown in Exhibit 9 will put downward pressure on world oil prices. The calculation of the impact of electric cars on the U.S. trade

of domestically produced light-vehicles has been more stable (Standard and Poors industry data).

⁶¹The data on the domestic share of auto production is from Standard and Poors industry data.

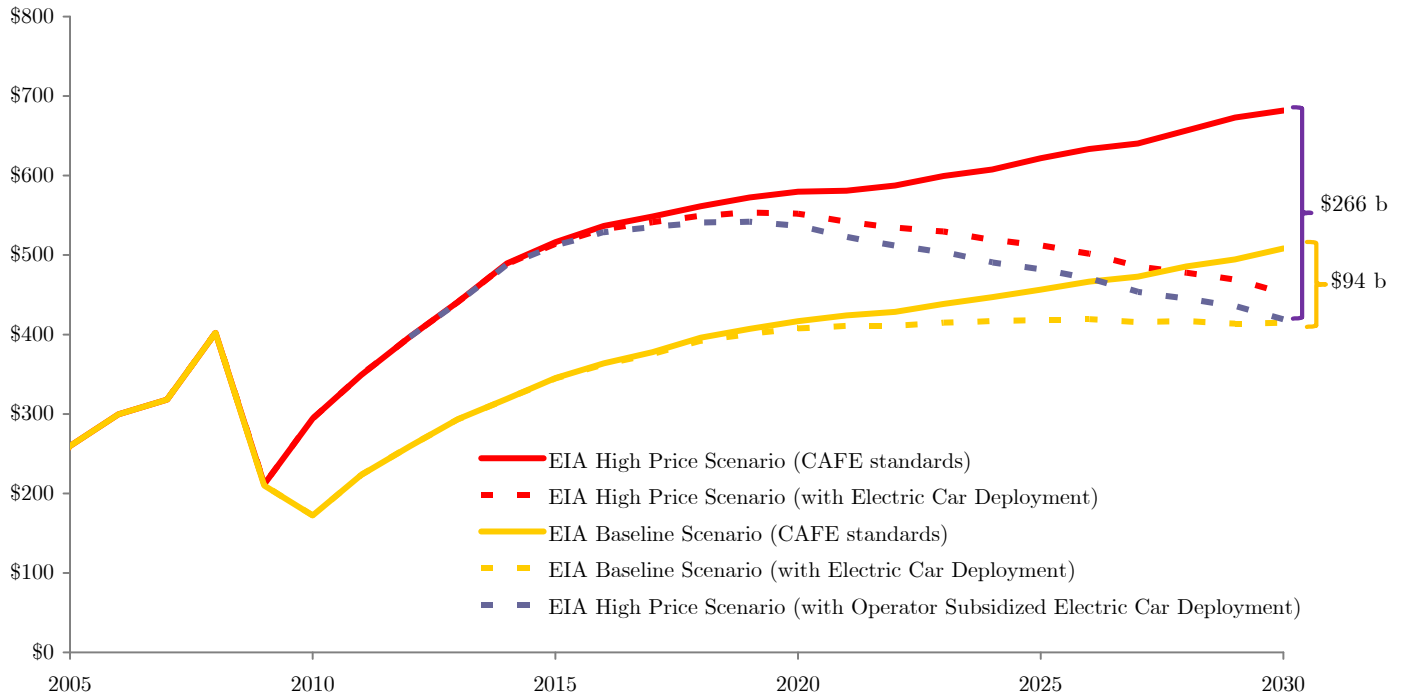
⁶²In 2008, the U.S. imported 2.3 million barrels per day from the Persian Gulf and 5.3 from OPEC (EIA).

Exhibit 10

Oil Trade Balance Under Three Scenarios for Electric Vehicle Adoption

The oil price estimates are from the 2009 Annual Energy Outlook published by the Energy Information Agency. In contrast to the EIA forecasts for a future growth of domestic oil production, this analysis makes a more conservative estimate that U.S. domestic oil production continues to decline at an annual rate of 1.8%. The solid lines represent the annual imports of oil in 2007 dollars with CAFE mandated increases to internal combustion fuel economy under the baseline and high oil price scenarios. The dashed lines represent the annual imports of oil in 2007 dollars under the three electric vehicle adoption scenarios in this paper. The estimates for the U.S. oil price elasticity of demand are from Cooper (2003).

Annual U.S.
Oil Imports
(billions of 2007 \$)



balance in Exhibit 10 accounts for this price effect.⁶³ Though the eventual impact of EV deployment is largest in the higher price scenarios, the trade balance initially deteriorates in these scenarios before electric vehicle deployment reaches sufficient mass to reverse the outflow of petrodollars. It is also important to note that without domestic battery production, electric vehicle deployment would offset a reduction of the trade deficit with oil producing countries of \$94-\$266 billion with a \$37-\$51 billion increased trade deficit with battery producing countries.

2.2 Capital Expenditures

The electric transportation system modeled in this paper relies on a dense network of charge spots and battery switching stations. To deploy this infrastructure throughout the country will require substantial financing and investment. This section forecasts the domestic capital expenditures associated with the deployment of electric vehicles relying on a system of network operators. It shows the relative levels of

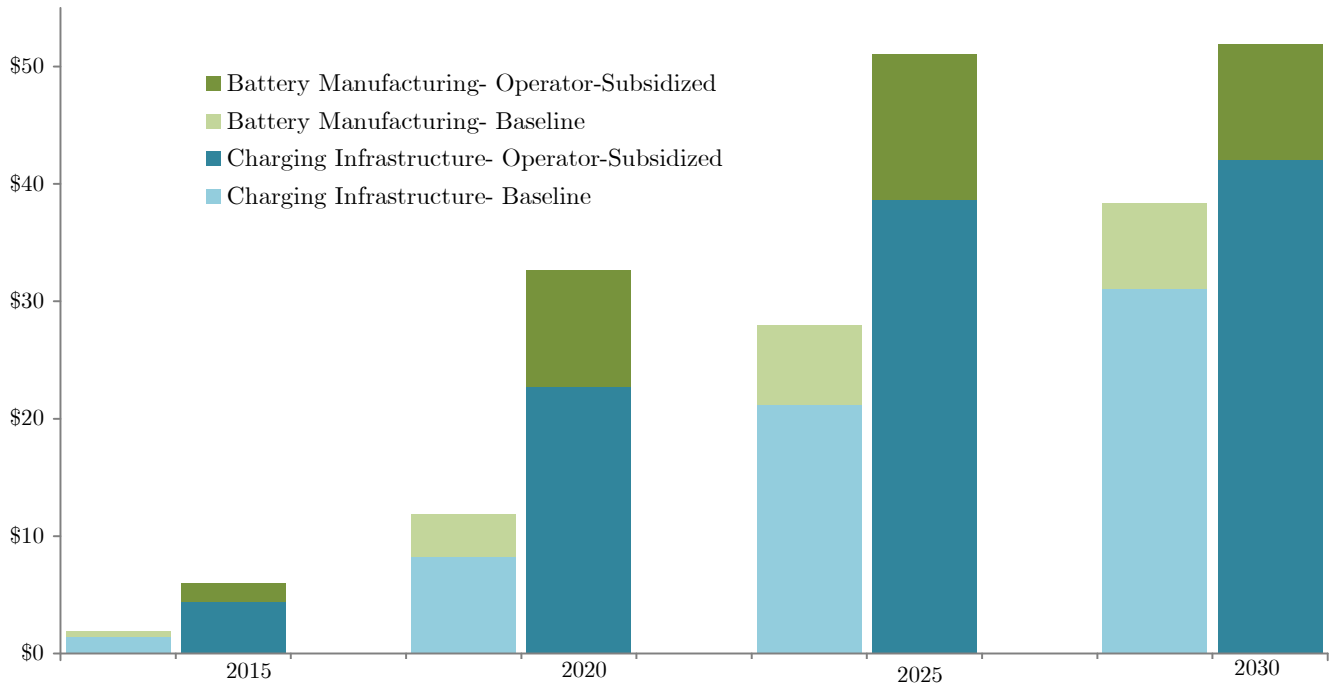
⁶³Electric car adoption in the U.S. is estimated to lower total world oil demand by between 1.8% to 4% by 2030. The U.S. price elasticity of oil demand is estimated to be 0.45 by Cooper (2003) and similar estimates are used by Bodenstern et. al. (2007) at the Federal Reserve Board. This means that the lower oil demand stemming from U.S. electric car deployment causes world oil prices to be \$1.10 to \$3.70 lower than they otherwise would be by 2030.

Exhibit 11

Capital Expenditures

The left columns represent baseline scenario forecasts and the right columns the operator-subsidized scenario forecasts for the capital expenditures (CapEx) on battery manufacturing and charging infrastructure. The battery manufacturing capital expenditure estimates are based on the estimated sales of automotive Li-ion batteries from domestic producers multiplied by a 30% CapEx-to-Sales ratio. The 30% CapEx-to-Sales ratio is based on discussions with the battery manufacturer A123. The capital expenditures for the charging infrastructure are based on the estimates for a \$300 million cell of charge spots and battery switching stations for each 100,000 electric car drivers.

Capital Expenditures
(billions of 2007 \$)



investment in the two main growth industries that accompany electric car deployment in this system: the charging infrastructure deployment and the battery manufacturing. Other sectors will also require large investments to accommodate growth in electric vehicles, particularly electricity generation and grid infrastructure, but forecasting the magnitude and composition of the investments in those industries is beyond the scope of this analysis. Exhibit 11 shows the forecasts for business investments in these two industries under the baseline and operator-subsidized scenarios described in Section 1.3.

The investment estimates for the deployment of a charging infrastructure are based on the network operator model of electric vehicle deployment using battery switching stations and public charge spots. The costs for this type of system are described in Section 1.1.4 and include \$300 million of charging infrastructure to support a regional cell of 100,000 electric car drivers. The baseline scenario for electric car deployment estimates there to be networks of over 800 overlapping cells deployed across the United States supporting the roughly 81 million electric car drivers by 2030. The necessary capital expenditures to deploy this network will be nearly \$328 billion over the next two decades, \$240 billion of which would be for charging infrastructure. The operator-subsidized scenario forecasts 151 million electric car drivers by 2030 and will require nearly 80% more infrastructure investment. By 2030, the annual capital investment

in charging infrastructure is estimated to account for between 1% and 1.5% of total U.S. investment.⁶⁴

The United States currently has no large-scale, domestic automotive battery manufacturing facilities. Though many of the research and development breakthroughs in Lithium-ion battery technology have been made by scientists in U.S. research universities, the manufacture of the batteries occurs almost exclusively in Asia. Since the forecasted domestic demand for automotive batteries will be between \$37-\$50 billion by 2030, it is important that the U.S. incentivize the development of a domestic battery industry to close the U.S. trade deficit and to ensure employment in a major growth sector.⁶⁵ In the first half of 2009 there have been a number of announcements by leading battery manufacturers of plans to construct U.S. production facilities in the coming years.⁶⁶ Using the available data on battery plant construction, the estimates in Exhibit 11 are based on the assumption that this domestic sector continues to grow over the next decade to eventually supply the same proportion of automotive Li-ion batteries as the domestic auto industry supplies autos.⁶⁷ If the United States were to invest an even greater amount in battery manufacturing and become an eventual exporter of automotive batteries, the exports from that industry would further close the trade deficit and would lead to even larger employment gains than those forecast in the next section.

2.3 Employment

The deployment of electric cars will trade-off employment gains in new "green collar" industries with losses in industries involved in petroleum delivery and internal combustion engine maintenance. The net effect is significant job creation. The projections for employment gains are made for both the charging network and battery manufacturing industries, though as discussed in the previous section there will likely be additional job creation in the domestic electricity sector. We assume that the deployment of electric cars does not directly impact employment in automobile manufacturing and that the share of domestically produced light-vehicles remains stable (though not necessarily produced by American firms). We also assume that domestic petroleum production continues at full capacity, as determined by the price of oil and the federal and state regulations on oil extraction.

Exhibit 12 shows the projected employment gains and losses under each adoption scenario in 2030. Estimates for the employment in the charging infrastructure and automotive battery manufacturing industries are based on the annual revenue projections for each industry and the revenue-to-employee ratio of industries with similar characteristics.⁶⁸ The employment gains under each adoption scenario are substantial, with between 130,000 and 250,000 net new jobs created. The largest source of job creation

⁶⁴Ground transportation's share of private fixed investment in structures was approximately 2% in 2008 (U.S. Bureau of Economic Analysis).

⁶⁵Deutsche Bank (2008) forecasts the global market for automotive Li-ion batteries to grow to \$30-\$40 billion by 2020 and acknowledges that their forecasts could prove to be conservative.

⁶⁶There have been four announced plans this year to build Li-ion manufacturing facilities in Michigan: A123 announced its intention to build a \$2 billion production facility, Kokam-Dow is building a \$665 million plant, LG Chem-Compact Power will build a \$244 million battery plant, and Johnson Controls-Saft announced a \$220 million retrofit to an existing auto parts plant to produce Li-ion batteries.

⁶⁷The CapEx to sales ratio for the automotive battery industry is assumed to be 30%, based on discussions with the battery manufacturer A123.

⁶⁸The revenue-per-employee ratios are from the 2009 Forbes survey of U.S. industries. The revenue-per-employee in the charging infrastructure industry is estimated to be comparable to the semiconductor and network communication devices industries. The revenue-per-employee in the automotive battery manufacturing industry is estimated to be comparable to the network communication devices industry and the utilities industry.

Exhibit 12

2030 Employment Impact of Electric Vehicle Deployment

This exhibit shows the jobs created and job losses associated with the three scenarios of electric light-vehicle adoption. The job creation estimates are based on the projected domestic revenue of each industry. Forecasts for the employment in the charging infrastructure industry use an average of the revenue to employee ratios in the utilities and the network device manufacturing industries. Battery manufacturing employment estimates use an average of the revenue to employee ratios in the semiconductor and the network device manufacturing industries. Revenue to employment ratios are from the 2009 Forbes survey of U.S. corporations. Job loss estimates for gas station attendants decline linearly as a percentage of the light-vehicle fleet that is electric. One quarter of employment amongst parts manufacturers and mechanics is estimated to be subject to job losses as electric vehicles are deployed.

	Industry	Baseline Scenario	High Price Scenario	Operator-Subsidized Scenario
Employment Gains	Charging Infrastructure	178,163	411,579	472,778
	Battery Manufacturing	60,065	80,630	81,168
	Total Gains	238,229	492,209	553,946
Employment Losses	Gas Station Attendants	-23,152	-37,353	-42,906
	Parts Manufacturers	-39,287	-63,386	-72,809
	Mechanics	-46,605	-75,192	-86,370
	Total Losses	-109,043	-175,931	-202,085
Net Employment Impact		129,185	316,278	351,861

comes from the deployment of a nationwide charging infrastructure. These jobs include construction, electrical services, and service sector jobs associated with the deployment, operation, and maintenance of public charge spots and battery switching stations. Though the eventual market size of the high price and the operator-subsidized scenarios are the same, there is greater net job creation under the operator-subsidized scenario due to the larger share of electric vehicles in the U.S. fleet under that scenario.

The adoption of electric cars, driven primarily by their lower purchase price and costs of maintenance and fueling, will negatively affect industries that supply parts and services for the petroleum-based light-vehicle fleet. Job losses are projected to occur among gas station attendants, auto parts suppliers, and mechanics. Gas station attendant employment declines linearly as a proportion of the fleet that converts to electric cars. The maintenance cost savings of electric drivetrains stems from their being much simpler mechanical devices than combustion engines and having fewer components. As such, the parts supply industry and mechanics will have fewer parts to produce and maintain on electric vehicles.⁶⁹ Overall, these job losses are more than offset by the gains in domestic battery manufacturing and charging infrastructure deployment.

2.4 Health and Environment

The health and environmental effects of transportation-related pollutants are significant. The pollutants associated with emissions from light-vehicle transportation include airborne emissions (sulfur dioxide, nitrous dioxide, particulate matter, and volatile organic compounds) as well as runoff pollutants (heavy metals, oils, and grease). The airborne pollutants, all monitored by the Environmental Protection Agency under the Clean Air Act, are known to cause respiratory disease, aggravate existing heart disease, and are known carcinogens. These pollutants are also the leading causes of smog and acid rain. We use the

⁶⁹Section 2.1.4 assumes that electric drivetrains have a 25% lower maintenance cost compared to similar internal combustion vehicles. By the same logic electric cars are assumed to require 25% fewer parts and mechanics.

Exhibit 13

Net Present Value of Health Impacts of Electric Vehicle Deployment

This exhibit shows the net present value of the health cost savings associated with each of the three scenarios of electric vehicle deployment in thousands of 2007 \$. The health care cost savings are calculated by multiplying the number of vehicle miles traveled (VMT) by the fleet of electric vehicles in each year by the health cost of each pollutant used by the Department of Transportation (2009). The net present value calculation uses a 5% discount rate to discount the health care costs for each year through 2030 back to 2009. The non-carbon power generation scenario (renewables plus nuclear and hydroelectric) has 100% of the power for electric vehicles sourced from zero polluting sources. The current grid generation mix scenario uses the 2007 electric generation and pollution profile.

(thousands of 2007 \$)	Pollutant	Baseline Scenario	High Price Scenario	Operator-Subsidized Scenario
Current Grid Generation Mix	Particulate Matter	\$15,302	\$25,121	\$29,496
	Nitrous Oxide	\$12,978	\$21,383	\$25,298
	Sulfur Dioxide	-\$37,776	-\$61,237	-\$71,025
	Volatile Organic Compounds	\$14,045	\$23,165	\$27,468
	Total	\$4,549	\$8,432	\$11,237
Non-Carbon Power Generation	Particulate Matter	\$47,266	\$77,959	\$92,440
	Nitrous Oxide	\$19,267	\$31,778	\$37,680
	Sulfur Dioxide	\$24,500	\$41,708	\$51,607
	Volatile Organic Compounds	\$14,081	\$23,224	\$27,538
	Total	\$105,114	\$174,670	\$209,265

estimates of the health care costs associated with each type of pollutant from the U.S. Department of Transportation to estimate the health impacts of electric vehicle deployment.

As electric vehicles grow to be a larger proportion of the U.S. light-vehicle fleet, the airborne pollution stemming from motor vehicle operation declines significantly. Exhibit 13 shows the net present value of the health care costs savings associated with each forecast of electric vehicle deployment between 2009 and 2030.⁷⁰ The top panel includes the emissions from the electricity production from the 2007 energy mix of the entire U.S. grid. The bottom panel shows a scenario where the additional electricity to power electric cars is produced exclusively by non-polluting power sources (renewables, nuclear, and hydroelectric). The health benefits of electric vehicle deployment are nearly twenty times larger when vehicles are charged using non-polluting sources of electricity. Much of this difference stems from the negative health impacts of increasing the sulfur dioxide emissions from the existing stock of coal-fired power plants. This difference in health outcomes as a function of the electricity source highlights another advantage of electric vehicle network operators: centralizing the purchasing power of electric car drivers into a few network operators will allow them to source their electricity from the wholesale market.⁷¹

Though Exhibit 13 contains the monetary value of measurable health cost savings, a transition to a fleet of electric cars also promises a number of positive health and environmental impacts that are not as easily directly measured. The runoff pollutants associated with petroleum powered vehicles contaminate fresh water supplies and cause significant damage to fish stocks.⁷² Electric cars are also less noisy than their internal combustion powered counterparts, an environmental benefit that the residents of dense,

⁷⁰ All of the health care costs savings are discounted to 2009 at 5% annual rate.

⁷¹ Electric car deployment under a system of network operators would allow operators to purchase electricity directly from renewable energy producers. By 2030 the annual electricity demand from electric vehicles in the baseline scenario is 190 million MWh, or 4% of total U.S. electricity generation in 2007.

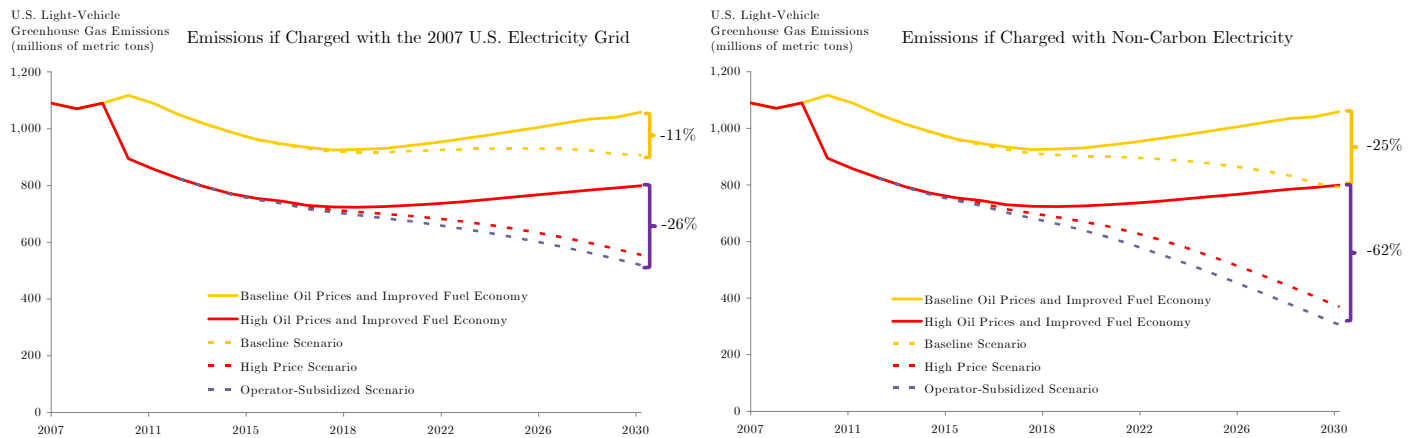
⁷² A study by McIntyre et. al. (2007) finds that trace amounts of copper in Washington freshwater bodies are highly toxic to native salmon populations. A leading source of copper runoff is from vehicle brakepad linings. Electric vehicles use mostly regenerative braking and therefore could reduce copper runoff pollution.

Exhibit 14

Greenhouse Gas Emissions Comparison

For Electricity Generated from the U.S. Grid Average and Non-Carbon Sources

The solid lines represent the estimates for greenhouse gas emissions stemming from increased fuel economy from the 2009 EIA Annual Energy Outlook. Consumers change their driving habits under the two oil price scenarios (higher prices lead to lower vehicle miles traveled (VMT) and increases to engine fuel efficiency in excess of CAFE standards in high price scenario). The dashed lines in the left graph represent the greenhouse gas emissions of the light-vehicle fleet powered by an electric generation infrastructure with the carbon intensity of the 2007 U.S. electric grid under the three electric vehicle adoption scenarios in this paper. The dashed lines in the right graph represent the greenhouse gas emissions of the light-vehicle fleet powered by non-carbon electric generation sources (renewable plus nuclear and hydroelectric) under the three electric vehicle adoption scenarios in this paper. Electric car drivers do not reduce their VMT in response to higher oil prices.



urban areas can certainly appreciate.

2.5 Greenhouse Gas Emissions

Achieving the significant reductions in the greenhouse gas emissions called for by both domestic and international timetables is only possible by reducing transportation-related emissions.⁷³ The transportation sector currently accounts for nearly 30 percent of the United States' energy usage and motor gasoline accounts for 20 percent of the economy's greenhouse gas emissions.⁷⁴ By 2030 the fleet of electric cars is estimated to require between 190 and 350 million Megawatt hours of electricity per year. Each of the adoption scenarios in this paper results in substantial reductions in greenhouse gas emissions, but the magnitude of reduction is more than doubled by using non-polluting sources of electricity generation to charge electric cars.

Exhibit 14 shows the greenhouse gas impact of each electric vehicle adoption scenario in excess of the proposed increases to fuel efficiency standards. The right figure shows the emissions reductions associated with using electricity from non-carbon sources (renewables, nuclear, or hydroelectric) to power the forecasted fleet of electric cars. The new CAFE standards mandate auto manufacturers to produce new vehicles with a fuel efficiency of 35.5 miles per gallon by 2016, but a car with this fuel economy still emits four metric tons of greenhouse gases per year.⁷⁵ If the electricity to power electric cars is produced by non-carbon sources the range of greenhouse gas reductions across the scenarios is between 25% and

⁷³The most recent House of Representatives legislation, the 2009 Waxman-Markey Bill (H.R. 2454), would cap 2030 greenhouse gas emissions at 36% below 2005 levels. The most recent Senate legislation, the 2008 proposal by Boxer, Lieberman, and Warner (S. 3036), would cap 2030 emissions at 37% below 2005 levels.

⁷⁴The sources and uses of energy are tracked by the EIA and the greenhouse gas emissions by the EPA.

⁷⁵The EPA calculates that each gallon of gasoline emits 8.8 Kg (19.4 pounds) of carbon dioxide into the atmosphere. The 4 metric ton calculation assumes an 15,000 vehicle miles travelled.

62%. This is equal to a twenty percent reduction in light-transportation emissions below their 2005 levels in the baseline scenario.⁷⁶ The operator-subsidized scenario reduces light-vehicle transportation emissions nearly 70 percent below their 2005 levels.

These reductions in greenhouse gas emissions are lower if the electricity to power these vehicles is produced using the carbon intensity of the 2007 U.S. electricity grid, as shown in the left figure. The range of reductions under the different adoption scenarios is between 11% and 26%. The lower reduction in light-vehicle emissions under this scenario highlights the advantage of an electric vehicle charging system relying on network operators. By centralizing the purchase of electricity in these network operators, the additional generating capacity can be purchased wholesale from non-carbon sources.

2.6 Government Policy

The previous sections have mentioned some of the government initiatives to promote a transition to electric light-vehicle transportation. The calculations in Section 1.1 include the \$7,500 consumer tax credit for electric car purchases. The model in Section 1.3 accounted for early adoption of electric vehicles in the four Western States as a partial result of the government policies in those states directed at promoting electric vehicles. The projections for battery manufacturing employment and investment in Sections 2.2 and 2.3 accounted for the wave of announcements by battery manufacturers to construct facilities in Michigan resulting from the \$555 million in state tax credits.

There are additional federal government actions directed at promoting a transition to electric light-vehicles that were not included in this analysis because they are in progress. The stimulus bill passed in February of 2009 included a range of measures aimed at facilitating the transition to electric vehicles.⁷⁷ In the coming years, the Department of Energy will disburse billions of dollars in federal stimulus funds to subsidize the deployment of battery and charging infrastructure for electric cars. As mentioned in Section 1.1.1, \$8 billion in federal loan guarantees to Ford, Nissan, and Tesla will ensure a supply of electric vehicles to utilize this infrastructure in the near future.

In addition to stimulus dollars and tax credits there are a number of no cost actions that federal, state, and local governments will need to take to facilitate the deployment of electric vehicles, charging infrastructure, and battery manufacturing. At the federal level, the recent shift in funding and rhetoric at the Department of Energy away from transportation hydrogen fuel cell technology and toward advanced battery technology and charging infrastructure deployment sends an important signal to market participants that the government will focus its resources on the deployment of electric vehicles.⁷⁸ Since the networks to support electric cars are primarily locally-based networks, many meaningful actions are required at the municipality and state level. Beyond tax credits, important policy changes include streamlining the permitting process for the installation of charging infrastructure, changing vehicle procurement

⁷⁶The 2005 greenhouse gas emissions are calculated using the total light-vehicle miles traveled multiplied by the average fleet fuel economy in those years (EIA).

⁷⁷The website Plug-In America has a detailed description of the \$14.4 billion designated for electric vehicles in the \$787 billion stimulus bill. It includes: \$6 billion in loan guarantees for automakers to retool for electric cars and plug-ins, \$2 billion in advanced grants to battery manufacturers, \$2 billion for the plug-in vehicle tax credit, \$510 million in tax credits for plug-in vehicle manufacture, \$400 million for plug-in infrastructure, and \$300 million for federal procurement of high efficiency vehicles.

⁷⁸See Martin LaMonica's May 8, 2009 *Green Tech* article on Department of Energy funding cuts to the transportation hydrogen fuel cell program and Jennifer Knightstep's June 17, 2009 *All Cars Electric* article on Energy Secretary Chu's commencement speech at CalTech.

regulations to favor zero-emissions vehicles if their cost is lower than or equal to internal-combustion alternatives, and offering loan guarantees to network operators and battery manufacturers. The extent to which local and state governments facilitate the installation of charging infrastructure by network operators will positively impact the speed of adoption across different regions of the country.

Conclusion

Electric vehicles will overhaul the U.S. light-vehicle transportation network over the next two decades. An electric personal transportation network that combines switchable Lithium-ion batteries with network operators offering pay-per-mile contracts can provide consumers with a more affordable alternative to efficient internal combustion-powered vehicles and overcomes the range limits inherent to fixed-battery electric cars. It will also lower health-impairing and greenhouse gas emissions, provide new sources of domestic employment and investment, lower the nation's dependence on imported oil, and improve the trade balance.

The analysis in this paper relies on a network externality model focusing on relative prices, operating costs, and the network effects of battery switching stations. However, there are many other less quantifiable benefits that may motivate consumers to choose affordable and reliable electric cars. Some of these include improved driving performance, the reputational benefits of electric car ownership, or an internalization of some of the trade, health, and environmental costs associated with petroleum-based vehicles. These factors are left out of the analysis, but would only serve to reinforce the predictions made in this paper.

Cap-and-trade regulations and increases in state gasoline taxes are also not included in the analysis. Consumers' uncertainty over the future price of gasoline stemming from these possible changes would also accelerate adoption rates estimated in this paper. All of the predictions in this paper assume that network operators will have access to the large amounts of financing required to build the extensive infrastructure networks that accompanies switchable battery electric cars. The billions of dollars already committed by governments and private investors and the profitability of the network operator model indicate that these future financing needs can be achieved. The adoption forecasts in this paper are based on a model of consumer adoption with equal or lower price electric vehicles driven by technological improvement; it does not rely on government subsidies in excess of those already committed by the federal government.

At the 2009 California Institute of Technology commencement, Nobel Prize winner and current U.S. Secretary of Energy Stephen Chu told the graduating class that they must prepare for "the inevitable transition to electricity as the energy for our personal transportation." This paper provides the first set of forecasts for that transition under the likely system of electric cars with switchable batteries and battery network operators and quantifies a number of the macroeconomic benefits that accompany a transition to electric vehicles. As a knowledge-driven, high innovation economy, the U. S. stands to gain in other ways as well. The electrification of personal transportation plays to the comparative advantage of the U. S. by shifting a large sector of the economy from a natural resource-driven model to an innovation-driven model. Electric vehicles are an inevitable component of the future of ground transportation and the United States currently has the opportunity to establish itself as a global market leader in this technology.

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A Appendix

A.1 Model of Network Externalities

This model is an adaptation of the original Katz and Shapiro (1985) model of consumer adoption in markets with network externalities. There are two generations of consumers who purchase automobiles for use over two time periods. Multiple periods are an abstraction of automobiles being durable goods. Consumers must decide on the type of automobile to purchase (E for electric powered and G for gasoline powered). Car buyers base their decision on which technology maximizes their total value of ownership based on the following three factors:

1. the number of others buyers that chose each technology in this period and the expected number in the next period (E_t and $\mathbb{E}[E_{t+1}]$ for electric and G_t and $\mathbb{E}[G_{t+1}]$ for gas),
2. the price of the car in the current period (p_t for electric or q_t for gas),
3. the operating costs in this and the next period (e_t and $\mathbb{E}[e_{t+1}]$ for electric and g_t and $\mathbb{E}[g_{t+1}]$ for gas).

There is uncertainty as to the future market shares and operating costs for both drivetrains, which consumers estimate using the rational expectations function $\mathbb{E}[\cdot]$. The net benefit for a consumer that purchases an electric car is $B_e = v(E_t + \mathbb{E}[E_{t+1}]) - p_t - e_t - \delta\mathbb{E}[e_{t+1}]$, where $v(\cdot)$ is an increasing function of the number of adopters and δ is a discount factor applied to future fuel costs. Similarly, the net benefit for a consumer that purchases a gas powered car is $B_g = v(G_t + \mathbb{E}[G_{t+1}]) - q_t - g_t - \delta\mathbb{E}[g_{t+1}]$. The increasing function $v(\cdot)$ captures the positive network externality that consumers factor into their choice when choosing which car to purchase. Consumers chose to purchase electric cars if the benefits of electric car ownership outweigh those of gasoline powered cars, which can be simply expressed as $B_e \geq B_g$.

The standard solution method for this type of model is to make assumptions about the characterization of the market, eliminate uncertainty, and solve the model recursively. For our purposes the model is useful to gain insight into the factors that car buyers consider when choosing which type of drivetrain to purchase. The model's clear formulation allows us to analyze each of the decision factors individually and to forecast the appeal of electric cars with switchable batteries on a consumer-level basis.

A.2 The Bass Model of New Technology Adoption

The Bass (1969) model is a diffusion model that uses a conditional likelihood function to forecast the share of potential adopters of a new durable good between market introduction and market saturation. The pattern of adoption follows an S-shaped pattern. The discrete time version of the Bass model can be expressed mathematically as

$$f(t+1) = p[1 - F(t)] + qF(t)[1 - F(t)]$$

where $f(t+1)$ is the probability of purchasing an electric car in year $t+1$ and $F(t)$ is the fraction of potential customers that have purchased an electric drivetrain through date t . The total number of adopters in each period is $F(t)$ times the potential number of adopters m .

The central proposition of the model is that the probability of adopting the new technology in a given year can be modeled by estimating three variables:

1. m - the potential number of adopters of the new product. Estimates of the addressable market size most often rely on survey data. Exhibit 4 contains the estimates of the relevant driving and demographic behavior under the two oil price scenarios. In the baseline scenario m is estimated to be 70% of the light-vehicle market in each year and in the high price and operator-subsidized scenarios it is estimated to be 90% of the light-vehicle market in each year.
2. p - is the coefficient of innovation. It captures the subset of consumers who will purchase the new product due to external influences. In the model of electric vehicle adoption, this subset of purchasers make their purchase decision independently of other consumers and do not place a large value on the network effects of the charging or refueling infrastructure. These are likely consumers whose driving needs are easily met with an affordable, reliable, and slightly range-constrained electric vehicle. Mahajan et. al. (2004) cite empirical evidence of the adoption patterns of hundreds of goods as being between 0.01 and 0.03. Under the baseline oil price scenario p is calibrated as 0.01, which is the low end of the historical range. For the high oil price scenario, p is calibrated to 0.02, which is a middle estimate. In the operator-subsidized scenario, p is calibrated to 0.025 to reflect the affordability of electric cars in this scenario.
3. q - is the coefficient of imitation. It captures the behavior of those consumers for whom network effects and the purchasing decisions of others are important. These adopters are also known as word-of-mouth consumers and they formulate their buying decision both on the size of the deployed charging network as well as on customer satisfaction amongst the subset of innovators. Historical adoption patterns cited by Mahajan et. al. (2004) have parameterizations for q of between 0.3 and 0.7, though it is rarely larger than 0.5. Under the baseline oil price scenario q is calibrated to be 0.3, which is the low end of the historical range. For both the high oil price and the operator-subsidized scenarios, q is calibrated to 0.4, which is a middle estimate. Lower prices, while raising the value of p , are not assumed to change the willingness of customers concerned with range to adopt more quickly. That is why the value of q is the same in both high oil price scenarios.

Biography

Thomas Becker is a Ph.D. candidate in economics with a specialization in international finance and environmental economics at the University of California, Berkeley. He worked as an economic and finance consultant for Cornerstone Research and has also worked for BMW and the MIT Industrial Performance Center. He has an undergraduate degree in economics from MIT, was a U.S. Fulbright Scholar to Germany, and is currently a visiting graduate scholar at Harvard University. This research was partially funded by the STAR research grant from the U.S. Environmental Protection Agency.

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